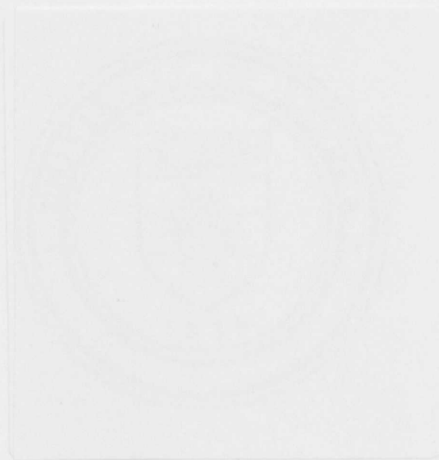


Photometric Redshifts and Luminosity Functions from the SPITZER SWIRE Survey

Thomas Sebastian Reed Babbedge
Astrophysics Group

Department of Physics
Imperial College London

University of London



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University of London

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Abstract

This Thesis presents a study of galaxies and quasars from the viewpoint of their optical and infrared properties. Rather than focusing in on individual objects, the general characteristics of extragalactic sources are explored by classifying them as one of a small set of generic ‘types’. This template-fitting approach opens up a wealth of possible applications, from deriving redshifts to tracing the distribution and evolution of different galaxy populations in both space and time.

The investigations carried out in this Thesis have been conducted in the context of, and building on, the field of infrared astronomy and the most important phenomenological and physical properties of galaxies at these wavelengths, in concert with their perhaps more familiar optical properties.

More precisely, this Thesis develops a photometric redshift technique that derives redshifts and dust extinction for both galaxies and quasars. This is first applied to optical data and then extended to incorporate infrared data as well. Following on from the recent successful launch and ongoing operation of the *SPITZER* infrared space observatory, this Thesis utilises data from the SWIRE extragalactic survey which combines *SPITZER* and ground-based observations in six extragalactic fields. As well as reducing ground-based optical photometry to produce band-merged source catalogues this Thesis uses the optical-infrared catalogues to derive redshifts and then applies an infrared template-fitting technique to the mid- to far-infrared emission of these sources in order to derive luminosities. The large-scale nature of the SWIRE survey then allows luminosity functions to be constructed in a number of *SPITZER* wavebands, which are an important probe of galaxy evolution and star formation.

Evolution of both the galaxy and quasar luminosity functions is seen with redshift, such that there are more high-luminosity sources to higher redshift. There is then a drop in space densities at redshifts of 1.5 to 2 for galaxies, and 3 to 4 for quasars, indicating the likely onset of main activity.

*Had I the heaven's embroidered cloths,
Enwrought with golden and silver light,
The blue and the light and the half-light,
I would spread the cloths under your feet.
But I, being poor, have only my dreams;
I have spread my dreams under your feet,
Tread softly because you tread on my dreams.*

‘He wishes for the cloths of Heaven’ - W.B. Yeats

Contents

Abstract	1
Declaration	8
Acknowledgments	9
Publications	12
1 The Infrared Universe	15
1.1 Cosmology - where we stand	15
1.1.1 The standard Big Bang model	16
1.2 A window on the Universe - the infrared view	17
1.2.1 The near-infrared region	17
1.2.2 The mid-infrared region	19
1.2.3 The far-infrared region	20
1.3 Infrared beginnings	20
1.3.1 <i>IRAS</i> - The Infrared Astronomical Satellite	21
1.4 The physical nature of IR sources	23
1.4.1 Source components	23
1.4.2 The sources	26
1.5 <i>ISO</i> and ELAIS	32
1.5.1 The European Large Area <i>ISO</i> Survey: ELAIS	33
1.5.2 The Preliminary Analysis catalogues	34
1.5.3 The Final Analysis catalogues	36
1.5.4 An investigation into the PA and FA catalogues	37
1.6 Star Formation	38
1.6.1 Quantifying star formation	40
1.6.2 Creating a Madau Plot	53
1.6.3 Current views on SFH	55
1.6.4 Alternatives	56

1.7	Continuation	57
2	<i>SPITZER</i> and <i>SWIRE</i>	60
2.1	Overview	60
2.2	<i>SPITZER</i>	60
2.2.1	IRAC: The Infrared Array Camera	61
2.2.2	MIPS: Multiband Imaging Photometer for <i>SPITZER</i>	63
2.2.3	IRS	65
2.3	The <i>SPITZER</i> Legacy Science Programme	65
2.4	The <i>SWIRE</i> survey	67
2.4.1	Survey details	68
2.4.2	Ancillary data	71
2.4.3	The data reduction pipeline	73
2.4.4	Current status of the survey	79
3	ImpZ: a new photometric redshift code for galaxies and quasars	85
3.1	Overview	85
3.2	Introduction	86
3.3	Method	88
3.3.1	χ^2 analysis	88
3.3.2	The ImpZ code	90
3.4	Template SEDs	92
3.4.1	SSP Populations	94
3.4.2	AGN Templates	94
3.4.3	Far UV treatment	99
3.5	Spectroscopic comparisons	101
3.5.1	ELAIS spectroscopic redshifts	101
3.5.2	CDFN spectroscopic redshifts	103
3.5.3	Comparison to HYPERZ	104
3.6	Spectroscopic redshift results	105
3.6.1	Results of ELAIS spectroscopic study	105
3.6.2	Results of CDFN spectroscopic study	110
3.6.3	Statistical properties	116
3.6.4	HYPERZ results	117
3.6.5	ImpZ summary parameters	117
3.7	Error analysis	119
3.7.1	Photometry	119
3.7.2	Templates	120

3.7.3	Filters	122
3.7.4	Overall errors	124
3.8	Discussion	124
3.9	Conclusions	125
3.10	Addendum	126
3.11	Acknowledgements	127
4	Can a photometric redshift code reliably determine dust extinction?	128
4.1	Overview	128
4.2	Introduction	129
4.3	The CNOC2 catalogue	131
4.3.1	Extension of the CNOC2 Survey	131
4.3.2	Measurement of the Balmer Decrement from CNOC2	132
4.3.3	Correction For [NII] Emission and Stellar Absorption	133
4.4	The Balmer Decrement and its Relation to Dust	134
4.4.1	Balmer extinction vs. photometry	136
4.5	Methodology	137
4.5.1	The ImpZ code	137
4.5.2	HYPERZ	138
4.6	Results	138
4.6.1	ImpZ	138
4.6.2	HYPERZ	139
4.6.3	Comparison of ImpZ and HYPERZ	142
4.6.4	The Calzetti ratio	143
4.6.5	Inherent A_v	144
4.7	Discussions and conclusions	146
4.8	Acknowledgements	148
5	Application to SWIRE	149
5.1	Overview	149
5.2	Introduction	150
5.3	The data	152
5.3.1	Infrared data	152
5.3.2	ELAIS-N1 optical data	158
5.3.3	Star/galaxy separation	166
5.4	Photometric Redshifts and extension to IR bands	167
5.4.1	The WIYN dataset	168

5.4.2	WIYN results	169
5.4.3	Fitting procedure	170
5.4.4	Extinction with redshift	173
5.5	Mid IR SED fitting	177
5.6	Luminosity function procedure	178
5.6.1	Incompleteness and selection functions	180
5.7	Results	182
5.7.1	Galaxy luminosity functions	183
5.7.2	Quasar luminosity functions	183
5.7.3	Evolution	184
5.8	Other studies	184
5.8.1	Bias	193
5.9	Discussion and conclusions	195
5.10	Acknowledgements	196
6	Overall Discussion and Conclusions	197
A	Appendix	204
A.1	An investigation into the PA and FA ELAIS catalogues	204
A.1.1	A 15 micron comparison	205
A.1.2	A 90 micron comparison	207
A.1.3	PA - FA conclusions	211
	Bibliography	214

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Thomas Babbedge

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Publications

Scientific Papers

ImpZ: a new photometric redshift code for galaxies and quasars

T.S.R Babbedge, M. Rowan-Robinson, E. Gonzalez-Solares, M. Polletta, S. Berta,
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2004, MNRAS, 353,654-672

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ImpZ - photometric redshifts: A combined galaxy-quasar approach

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I. Perez-Fournon, S. Oliver, M. Salaman, M. Irwin, S.J. Weatherley.
Poster at National Astronomy Meeting (NAM) 2004, Open University, UK, in
Cosmology 1. session.

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SWIRE - optical photometry in EN1

T.S.R Babbedge
Talk at SWIRE Team Meeting, Imperial College London, August 2004.

Photometric redshifts and SWIRE

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SWIRE

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Seminar, Imperial College London, June 2004.

ImpZ - photometric redshifts for SWIRE

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SIRTF and SWIRE

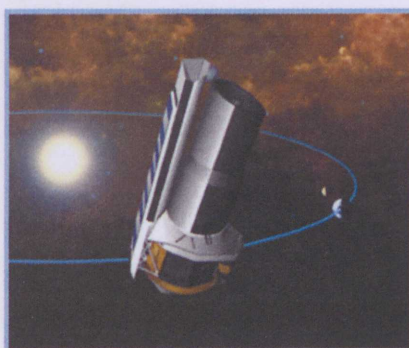
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The Universe - An Infrared Perspective

T.S.R Babbedge
Article in Aurora, the UKSEDs Magazine, Ed. Bhavini Patel, 2003.

Chapter 1

The Infrared Universe



1.1 Cosmology - where we stand

Cosmology is the quest for a cogent world view: something towards which cultures have struggled throughout the ages. As such it is perhaps one of the most profound and important directions of inquiry in astrophysics. Our place in the Universe and our understanding of it has undergone a dramatic leap forwards over the last century, yet we still have a long way to go.

Until well into the twentieth century, astronomers thought that the Milky Way was the entire Cosmos - there were no 'galaxies'. Although the island universe hypothesis had sprung up well before, discussed by thinkers such as Emanuel Swedenborg (1688 - 1772), Thomas Wright (1711 - 1756) and Immanuel Kant (1724 - 1804) - Kant suggested that M31 was another Milky Way, an 'island universe' - it remained for Edwin Hubble's 1925 paper on Cepheid variable stars in M31 to prove beyond doubt that the Andromeda Nebula lay outside of the Milky Way and was a separate galaxy (Hubble, 1925).

With the advances in observational and theoretical physics made since Hubble's conclusions in 1925, our cosmological model now envisages an evolving, expanding Universe constituting untold¹ numbers of galaxies distributed in great clusters, sheets and filamentary structures. Moreover, everything arose from a single 'creation' event ten to twenty billion years ago, and has expanded ever since. This is the 'Big Bang' paradigm (see reviews by Rowan-Robinson 1996 and Peacock 1999).

1.1.1 The standard Big Bang model

The standard model of cosmology, the 'Hot Big Bang', is a Friedmann-Lemaitre-Robertson-Walker (FLRW) cosmological model. This assumes that on the largest scales the universe is homogeneous and isotropic, and postulates that the Universe began around 10^{10} years ago in some form of rapid expansion. This model accounts for most of the observable features of the Universe. The two great successes of this model are the prediction of both the microwave background and the relative abundance of the elements (cosmic nucleosynthesis). Like the Standard Model of particle physics, the Hot Big Bang model breaks down in a few places, but can be extended to account for most of these problems (see Watson 2000, amongst many others, for a discussion on this).

A current 'best' set of cosmological parameters in the FLRW framework might be summarised as follows (here taken from a recent review; Freedman & Turner 2003):

Our Universe is flat (the density parameter $\Omega_0 = 1.03 \pm 0.03$ - e.g. Sievers et al. 2003) with a baryon density of $\Omega_B = 0.039 \pm 0.008$ (Turner, 2002), a cold dark matter component of $\Omega_{CDM} = 0.29 \pm 0.04$ (Fukuda et al. 1998 and Elgarøy et al. 2002) and a dark energy density of $\Omega_\lambda = 0.67 \pm 0.06$ (Turner, 2002) .

The dark energy equation of state implies it has a negative pressure ($w = -1 \pm 0.2$, e.g. Perlmutter et al. 1999), causing accelerating expansion, with a present expansion rate parameter of $h = 0.72 \pm 0.07$ (e.g. Freedman et al. 2001) and a deceleration parameter (the change in the universal expansion rate over cosmic time) of $q_0 = -0.67 \pm 0.25$ (from Supernovae and measurements of the total matter density).

The current age of the Universe is $t_0 = 13 \pm 1.5$ Gyr (e.g. Cowan et al. 1991; Oswald et al. 1996 and Krauss & Chaboyer 2003) and the temperature of the Cosmic Microwave Background is $T_0 = 2.725 \pm 0.001$ K (Mather et al., 1999).

¹a common estimate is that there are around 100 billion galaxies, though this is only within our current observable horizon

1.2 A window on the Universe - the infrared view

For the majority of the history of astronomy, observers have been limited to the narrow visual band from 400nm to 700nm. The Universe, however, is no respecter of the human eye, and much information lies outside of this range - in the infrared (IR), ultraviolet (UV), X-ray, microwave, radio and gamma-ray.

The IR spectral region roughly spans the wavelength range $1\mu\text{m}$ to $300\mu\text{m}$, broadly subdivided into the near-IR (NIR; $1\text{--}5\mu\text{m}$), the mid-IR (MIR; $5\text{--}30\mu\text{m}$) and the far-IR (FIR; $30\text{--}300\mu\text{m}$) regions, with longer wavelengths referred to as the sub-millimetre (sub-mm; $300\mu\text{m}\text{--}1\text{ mm}$) and millimetre ($\text{mm}; >1\text{mm}$) regions.

From the ground, only a few narrow bands from 2.5 to $30\mu\text{m}$, and wavelengths $> 300\mu\text{m}$ are accessible - the range from 30 to $300\mu\text{m}$ requires a space-based platform. This is because the atmosphere is an effective absorber of many IR wavelengths (see Figure 1.1), mainly due to water vapour, oxygen (and ozone) and carbon dioxide. Water vapour and carbon dioxide are particularly important absorbers throughout the IR, with water vapour making the atmosphere virtually opaque over large wavelength ranges from ground-based observing sites. Other absorbers, such as ozone, cause more limited (in wavelength) problems.

As well as being an effective absorber the atmosphere also emits molecular lines and a very broad thermal continuum.

1.2.1 The near-infrared region

The near-IR spectral region extends from 1 to $5\mu\text{m}$. The atmosphere here is transparent over several reasonably well-defined spectral regions, as seen in Figure 1.1, and several standard filters have been designed to exploit these windows: J centred at $1.25\mu\text{m}$; H at $1.65\mu\text{m}$; K at $2.2\mu\text{m}$; L at $3.6\mu\text{m}$ and M at $4.8\mu\text{m}$. Between 5 and $8\mu\text{m}$ there is then a gap in atmospheric transmission due to water vapour, contributing to the treatment of the near-IR as a distinct spectral region.

Blackbody (i.e. thermal) continuum emission from ‘room temperature’ bodies becomes important in the near-IR at wavelengths longer than $3\mu\text{m}$ meaning that the radiation emitted by the telescope and the atmosphere (water vapour) is a strong background against which celestial bodies must be detected. Providing the detector noise is small, it is the photon shot noise (proportional to the square root of the collected photons) associated with this background that is the principal source of noise in IR observations; such observations are then background-limited. Due to the large thermal background, observations at $\lambda > 3\mu\text{m}$ are generally much less sensitive than those at $1\text{--}3\mu\text{m}$ and, partly for this reason, most near-IR observations

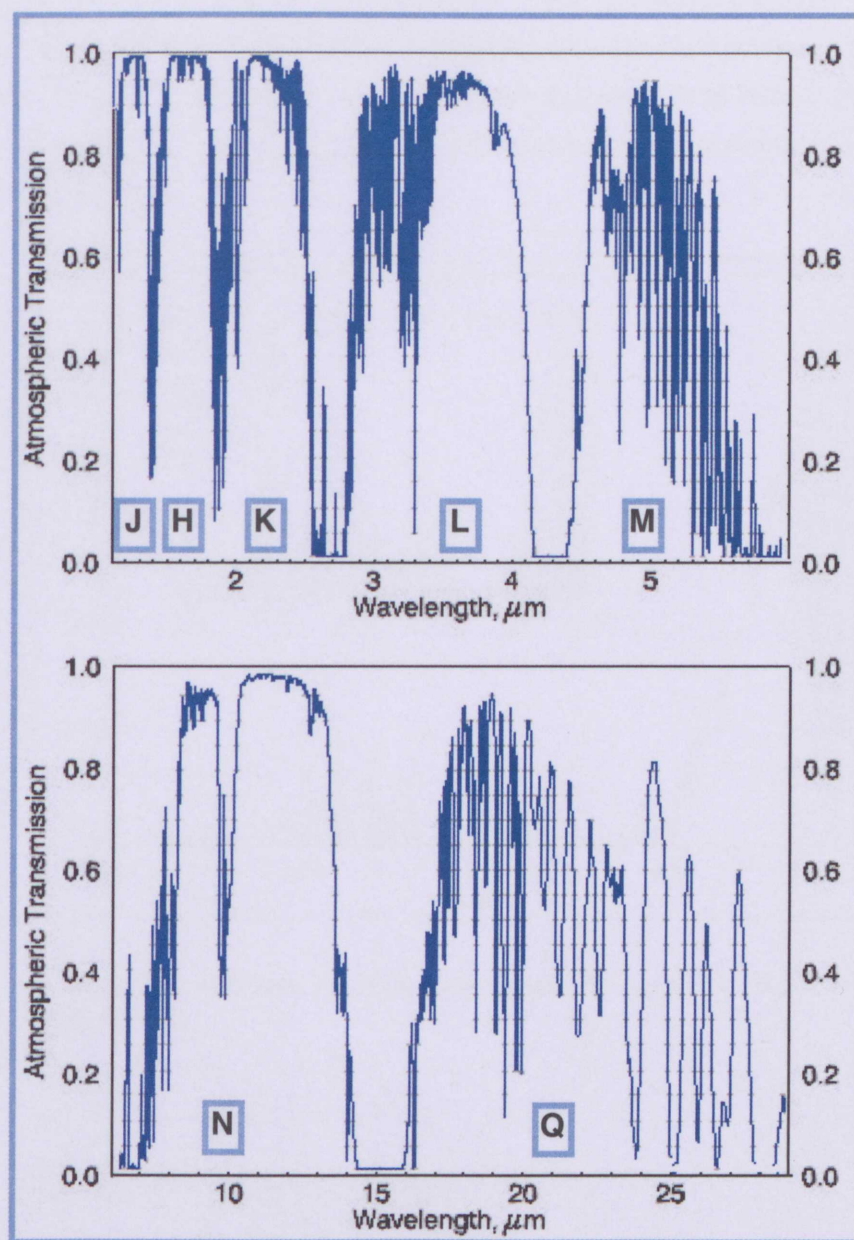


Figure 1.1: Atmospheric transmission in the IR (here calculated for Mauna Kea using Lord 1992). Common wide-band filters in each spectral window are labelled in purple boxes.

are made in the J, H and K bands. Although the thermal continuum radiation is relatively weak in the $1\text{--}3\mu\text{m}$ region, other types of atmospheric emission play a significant role there. In particular, OH lines are emitted by the atmosphere as a result of rotational/vibrational excitations. This line emission (see Figure 1.2), which can vary significantly with time, provides the main background against which earth-based $1\text{--}3\mu\text{m}$ observations must be made (though it is noted that OH sky lines can also be used to wavelength-calibrate spectroscopic observations such as in Weatherley et al. 2004).

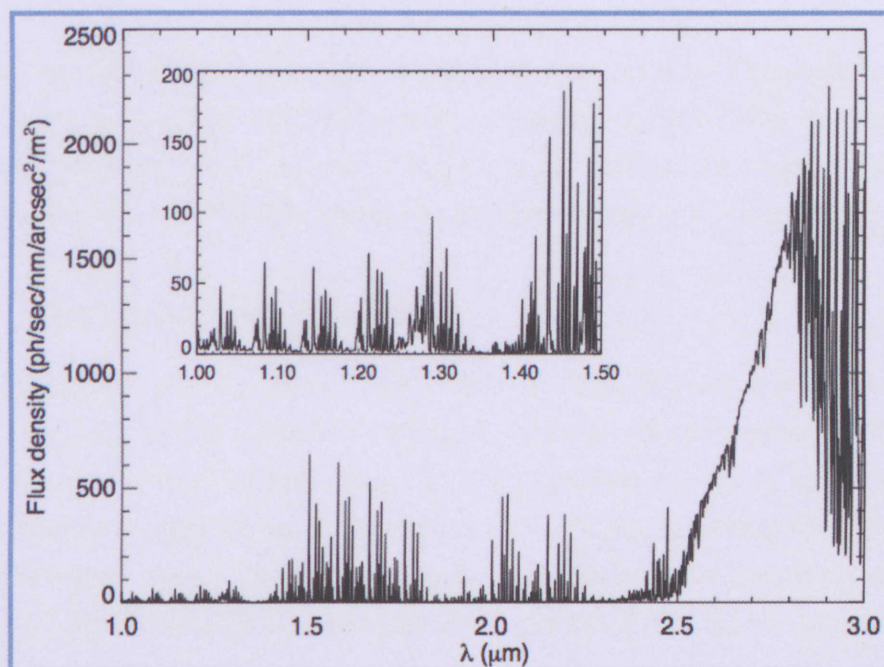


Figure 1.2: OH emission lines in the near-IR spectral region. Figure from Vaccari (2004).

1.2.2 The mid-infrared region

The mid-IR region extends from $\sim 5\mu\text{m}$ to the atmospheric cut-off near $30\mu\text{m}$. Significantly, a 300K black-body peaks at $10\mu\text{m}$. Hence the telescope thermal emission properties are important, and can dominate over the atmosphere's thermal emission, particularly in the more transparent atmospheric windows at 8 to $14\mu\text{m}$.

The clearest mid-IR atmospheric windows lie in the range 8 to $14\mu\text{m}$, spanned by the N band filter, with a weaker window extending from $\sim 16 - 25\mu\text{m}$ that is spanned by the Q band filter. Observations can be extended out to around $30\mu\text{m}$ at the best ground-based sites.

Water vapour is responsible for the short-wavelength cut-off of the mid-IR region near $8\mu\text{m}$ and for absorption lines throughout the mid-IR region with CO_2 causing deep absorption around $15\mu\text{m}$. To some extent the effect of the atmosphere can be reduced by siting telescopes above as much of the atmosphere (and moisture) as possible, such as at the top of Mauna Kea, Hawaii (4,500 m), or in using balloons (up to 20 km). The benefits of altitude arise since atmospheric pressure drops roughly exponentially with altitude, that is;

$$P_z = P_0 e^{-z/H} \quad (1.1)$$

where z is the altitude and H is the scale height, respectively. The scale height of air is about 8,000 m, whereas the scale height of water is about 3,000 m, except at the driest sites. However the OH lines originate at an altitude of about 90 km and so observing from even the highest ground-based sites does not reduce their influence.

1.2.3 The far-infrared region

The far-IR region extends from $\sim 30 - 300\mu\text{m}$. The Earth's atmosphere is completely opaque to far-IR radiation, primarily due to water vapour, and so far-IR astronomy must be carried out using airborne, balloon-borne, or space telescopes. The atmosphere is partially transparent at $\lambda > 300\mu\text{m}$, marking the beginning of the sub-millimetre region, as exploited by facilities such as the James Clark Maxwell Telescope (JCMT) and Caltech Sub-mm Observatory (CSO) on Mauna Kea, Hawaii.

1.3 Infrared beginnings

The formation of stars and galaxies and their evolution is accompanied by the release of radiant energy, powered by nuclear and gravitational processes. The absorption of short wavelength radiation by dust and re-emission at longer wavelengths will shift a large fraction of this radiant energy into the IR.

It was not until the 1960's that Harold Johnson in the near-IR (e.g Johnson 1964 defines the J, K, M and N filter windows; Johnson et al. 1968 defines the H band), and Frank Low in the mid-IR developed sufficiently sensitive IR detectors to allow practical *extragalactic* IR studies, with the first mid-IR observations of individual extragalactic sources being made by Low & Kleinmann (1968). A larger survey by Low & Rieke (1972) found several objects that were more luminous in the IR than in all other wavelengths combined. The natural question was: what mechanism was behind this IR emission? It could either be the thermal re-radiation

by dust of optical/UV light, or it could be direct synchrotron emission (acceleration of relativistic electrons in a magnetic field) from an unobscured Active Galactic Nuclei (AGN).

10 μ m imaging of NGC1068 and NGC4151 by Stein et al. (1974) showed that the emission was extended and showed no signs of variability, thus favouring thermal re-radiation by dust. Further work (Rieke & Low 1975; Rieke 1978) also found that in most cases thermal dust re-radiation best explained their observations.

In parallel to such surveys, the theoretical modelling of extragalactic IR sources was also being developed. Toomre & Toomre (1972) suggested that during galaxy interactions, vast amounts of dust and gas could be funnelled into the nuclear regions, thus leading to a dust-shrouded Quasi Stellar Object (QSO) or a starburst event. This theoretical explanation was validated by observations in the IR of nearby interacting galaxies by Heckman et al. (1983) and Joseph et al. (1984) who confirmed that strong IR emission was found at their cores. In addition, ‘ultrahigh’ IR emission, explained as extreme nuclear starbursts, was found to be present in all of a set of advanced mergers that were studied by Joseph & Wright (1985).

1.3.1 *IRAS* - The Infrared Astronomical Satellite

IRAS was launched in 1983 and was the first space-based, long-life, cryogenically-cooled infrared telescope. It would prove to be of profound significance for cosmology, extragalactic astronomy and for the study of star-forming regions. *IRAS* contained a liquid helium-cooled 0.6m Ritchey-Chretien telescope equipped with Ge:Ga detectors and in its ten month lifetime it covered 96% of the sky in four broadband filters centred at 12, 25, 60 and 100 μ m to ~ 0.5 Jy (Neugebauer et al. 1984; see reviews of Beichman 1987; Soifer et al. 1987). *IRAS* catalogued around 350,000 IR sources, of which perhaps 25,000 were galaxies, allowing the mapping of large scale structure in galaxy distribution (Saunders et al. 1991). These galaxies were primarily spirals, but there were also some QSOs (Neugebauer et al. 1986; Sanders et al. 1989), Seyferts (de Grijp et al. 1985) and a few early-type galaxies (de Jong et al. 1984; Knapp et al. 1989; Knapp et al. 1992).

Additionally, a new class of Luminous Infrared Galaxies (LIRGs) with IR luminosities $\geq 10^{11}L_{\odot}$ was discovered (Soifer et al. 1984). This was then outstripped by the Ultra Luminous Infrared Galaxies (ULIRGs) with infrared luminosities $\geq 10^{12}L_{\odot}$ (review by Sanders & Mirabel 1996).

With the discovery of IRAS P09104+4109, identified by Kleinmann et al. (1988), and the detection of the galaxy IRAS F10214+4724 (Rowan-Robinson et al. 1991b)

at the limit of *IRAS* sensitivity ($S_{60} > 0.2\text{Jy}$) came the definition of an even more luminous class, the hyper-luminous HIRGs ($L_{IR} > 10^{13}L_{\odot}$).

One of the *IRAS* surveys was the *IRAS* mini-survey (Rowan-Robinson et al. 1984). 86 sources were detected at $60\mu\text{m}$ in the high galactic latitude portion of the survey (Soifer et al. 1984). Furthermore, nearly a third were involved in ongoing interactions and most had $1 < L_{IR}/L_B < 50$, where L_B is the luminosity in the optical B band.

Interestingly, nine of these objects (Houck et al. 1984) had no known visual counterpart, implying L_{IR}/L_B ratios > 50 - a whole new population of previously ‘invisible’ sources had been discovered. Further observations of these nine sources found them to be ULIRGs ($>10^{12}L_{\odot}$) at $z \sim 0.1$, with IR to optical ratios of $30 < L_{IR}/L_B < 400$. Optical spectroscopy failed to find any obvious AGN activity, leading to the conclusion that massive star formation was occurring (Elston et al. 1985; Moorwood et al. 1986).

Other *IRAS* redshift surveys include: 2Jy survey (Strauss et al. 1990), FSS-redshift survey (Oliver et al. 1996), 1Jy sample (Kim & Sanders 1998), QDOT survey (Lawrence et al. 1999), and the PSCz redshift catalogue (Saunders et al. 2000). An important empirical trend from these galaxy redshift surveys was that as bolometric luminosity increases, the relative space density of luminous IR sources rises significantly - ULIRGs were found to be twice as common as QSOs, the only other population with comparable L_{bol} (Bertin et al. 1997; Kim & Sanders 1998).

In this picture, LIRGs were seen as galaxies with disturbed morphologies (implying advanced mergers) with starburst activity, whilst ULIRGs were seen as galaxies with disturbed morphologies and often members of close pairs (implying interactions/mergers) with both a starburst and AGN component ($\sim 20 - 50\%$ appear to have an AGN : Veilleux et al. 1995; Lawrence et al. 1999; Sanders et al. 1999; Veilleux et al. 1999). However, the AGN contribution is not the dominant fraction, as only $\sim 20 - 30\%$ of the energy of local ULIRGs is AGN-based (Genzel et al. 1998; Lutz et al. 1998; Farrah et al. 2003). A global estimate of the local Universe energy balance from *IRAS* observations (Soifer & Neugebauer 1991) is that $\sim 30\%$ of starlight is dust reprocessed to $8 - 100\mu\text{m}$. It can be seen that the *IRAS* results emphatically demonstrated the importance of the infrared for the determination of galaxy evolution and star formation history and was instrumental in driving more recent IR space astronomy missions. Two of these - *ISO* (§1.5) and *SPITZER* (Chapter 2) - are discussed later on in this Thesis. In particular, the *SPITZER* space telescope has played a central role in this Thesis.

1.4 The physical nature of IR sources

IR observations over the past thirty years have shown the importance of IR astronomy to extragalactic studies. It is instructive to consider the nature of extragalactic IR sources in more detail.

1.4.1 Source components

Usually the IR emission from an extragalactic source is best modelled as having several components. In such an approach a parameterised set of models is used to recreate the spectral energy distribution (SED) of the galaxy (e.g Guiderdoni et al. 1998; Blain et al. 1999c). For example, the study of Rowan-Robinson (2001a) utilised a cirrus SED, a starburst SED and an Arp220-like starburst SED (both from Efsthathiou et al. 2000b), and an AGN dust torus SED (from Rowan-Robinson 1995). See Figure 1.3 for an example plot. The physical meaning of each component will be expanded upon below:

- **Cirrus**

Cirrus was first identified in our Galaxy by Low et al. (1984). It was characterised as extended, structured IR emission. This cirrus is comprised of dust in interstellar neutral hydrogen clouds, illuminated by the general starlight radiation field and re-radiating in the IR (Rowan-Robinson & Crawford 1989). Detailed models were given by Rowan-Robinson (1992), but there was no treatment of line emission from a Polycyclic Aromatic Hydrocarbon (PAH) component.

PAH molecules (Sellgren 1984; Leger & Puget 1984) are required to explain emission at shorter wavelengths (e.g at 25 and $12\mu\text{m}$ as seen by Gautier & Beichman 1984; Boulanger et al. 1985) since to radiate significantly at these wavelengths, interstellar grains must include a grain population much hotter than the thermal equilibrium temperature. An alternative postulate is the existence of very small grains ($0.001 - 0.003 \mu\text{m}$ [~ 50 atoms]) absorbing individual photons. A theoretical cirrus spectrum for a grain mixture including small grains was first calculated by Draine & Anderson (1985), whilst Siebenmorgen & Kruegel (1992) included the effect of small grains and PAHs. More recent models (Silva et al. 1998; Granato et al. 2000) took account of dust and star distribution and incorporated a population synthesis model and changes in metallicity.

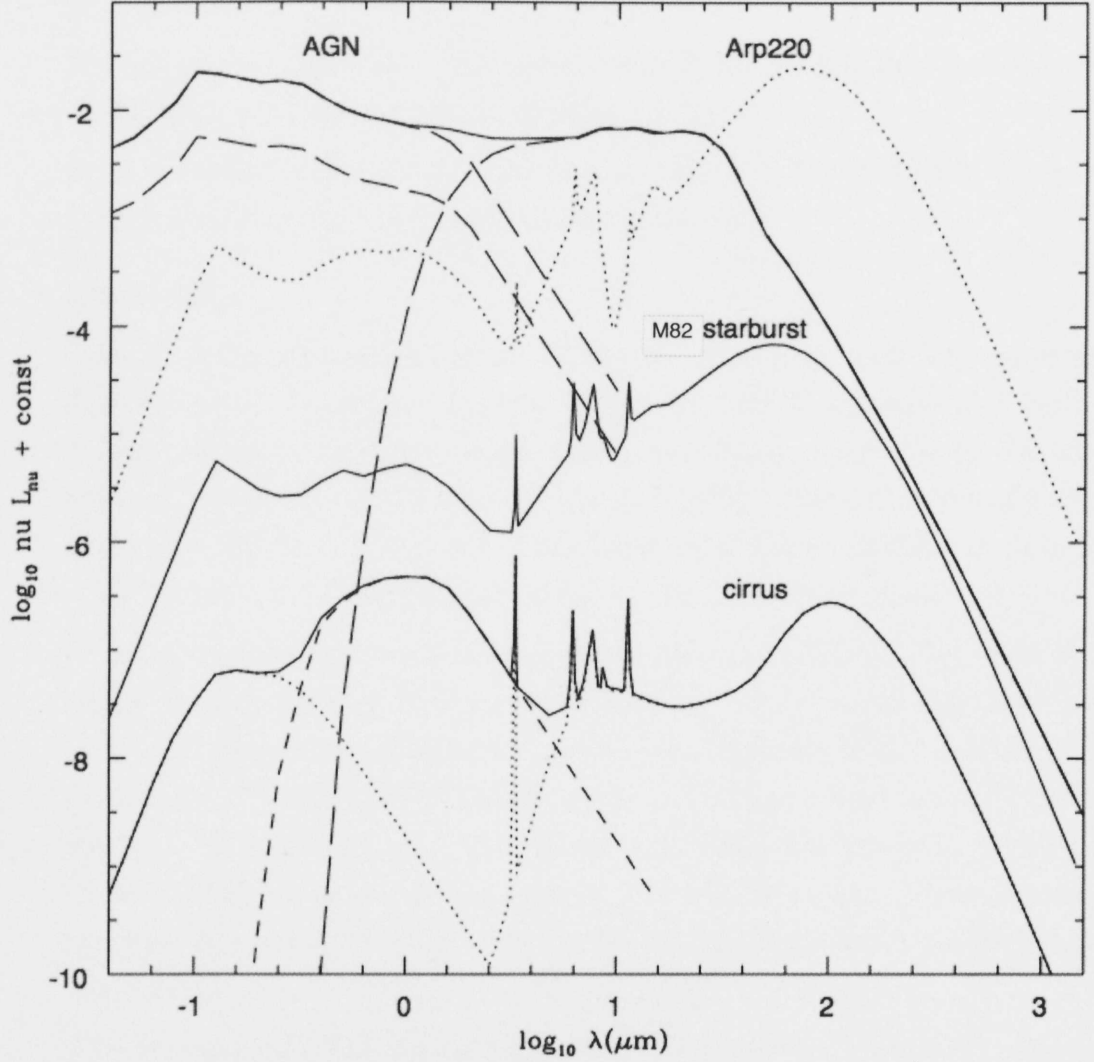


Figure 1.3: An example of spectral energy distributions: four components - cirrus (split into low-mass [dashed line] and high-mass [dotted line] components in the optical region), M82-like starburst [dashed-dotted line], Arp 220-like starburst [dotted line] and AGN torus, showing assumed optical/IR ratio at $\log L_0=14$ (upper curve) and 8. Taken from Rowan-Robinson (2001b)

Efstathiou & Rowan-Robinson (2003), ERR2003 from here on, use a simpler model but attain as good fits to nearby normal galaxies.

In general, a model of cirrus requires the following:

- i) Input stellar radiation field (spectrum and intensity) - ERR2003 used the Bruzual & Charlot (1993) code.
- ii) Interstellar dust model with assumptions about distribution and opacity - ERR2003 used Siebenmorgen & Kruegel (1992).
- iii) A radiative transfer treatment (not strictly true for ERR2003) of the interaction between the two - thus leading to an SED.

• Starburst

Starbursts were first identified by Weedman (1973) from their UV excess and characteristic emission-line spectra. Prior to *IRAS*, airborne and balloon measurements in the FIR showed that $L_{FIR} > L_{optical}$ for several starburst galaxies (see review by Sanders & Mirabel 1996). The definition of Larson & Tinsley (1978) characterised a starburst as a ‘burst’ in SFR of duration $\sim 10^{7-8}$ years, involving as much as 5% of the total stellar mass.

A classical analysis of two local starbursts - M82 and NGC253 - by Rieke et al. (1980) showed them to be galaxies undergoing a very active but short-lived ‘starburst’ of duration of order 10^7 years. For a Salpeter initial mass function (IMF: e.g. Salpeter 1955) of mass range 1- $100M_{\odot}$, a luminosity of $10^{10}L_{\odot}$ implies a SFR of $\sim 1M_{\odot}yr^{-1}$ (e.g Kennicutt 1998). For example, M82’s L_{IR} ($> 4 \times 10^{10}L_{\odot}$) and central gas content ($2.5 \times 10^8M_{\odot}$) means that it cannot continue its current SFR for more than ~ 62.5 million years - the archetypal ‘starburst’.

The starburst paradigm² is therefore that of massive star formation triggered by strong gravitational disturbances. Radiative transfer and SED models for the millimetre to UV emission from starbursts postulate that the bulk of the star formation occurs in giant molecular clouds. The interaction and eventual merging of two gas-rich galaxies is the most effective trigger (first proposed by Joseph et al. 1984), but bar-driven inflow can also be a cause (e.g. Hawarden et al. 1986).

ISOCAM observations of several samples of interacting, barred and collisional ring galaxies confirmed this paradigm (Appleton et al. 1999; Charmandaris

²Note, however, that there is no consensus on a precise definition of a ‘starburst’ galaxy.

et al. 1999; Roussel et al. 1999; Wozniak et al. 1999). Some famous examples include Arp 299 (NGC3690/IC694: Gehrz et al. 1983; Satyapal et al. 1999) and the Antennae system (NGC4038/39: Mirabel et al. 1998).

• AGN

Although the term ‘Active Galactic Nucleus’ (AGN) implies no specific underlying physical process, an AGN can be characterised as having both extreme luminosity and an extremely small angular size. As AGN are commonly classified by their (highly varied) observed properties, there is a large array of sub-classes (e.g. radio loud, radio quiet, Seyferts, LINERS, etc - see Krolik (1999) for more details). However, the basic concept behind the power source of AGN is that of accretion onto a super-massive black hole. The sub-classifications most plausibly arise from the large number of possible dust geometry/density and viewing angle configurations (see Figure 1.4), in conjunction with the overall luminosity of the source. An extensive review of AGN unification models can be found in Antonucci (1993), and of radio-loud AGN in Urry & Padovani (1995), but in most unification schemes the central black hole engine is encircled by a dust torus and also a distribution of gas and dust (Antonucci & Miller 1985; Barthel 1989). Interestingly, the mid/far IR is less sensitive to the viewing angle, allowing constraints to be placed on these unification schemes. The unification of radio loud with radio quiet AGN is more difficult since the appearance of relativistic jets needs to be accounted for. Most attempts focus on the spin rate (Wilson & Colbert 1995), accretion rate (Rawlings 1994) and mass of the central black hole.

One point to note is the possibility of having a purely starburst-powered AGN. Originally proposed by Terlevich & Melnick (1985) using extreme Wolf-Rayet stars ($T \sim 10^5 K$), later models (Terlevich et al. 1992) also incorporated compact supernova remnants (cSNRs), cSNRs being ordinary SNRs in dense circumstellar regions. However, such models fail to explain radio loud AGN or how to generate synchrotron jets.

1.4.2 The sources

Now that the main components contributing to a source’s IR emission have been explored, the systems and classes of galaxy these components are present in, or dominate, will be covered. A diagnostic diagram of the main contributors to an overall galaxy SED is given in Figure 1.5.

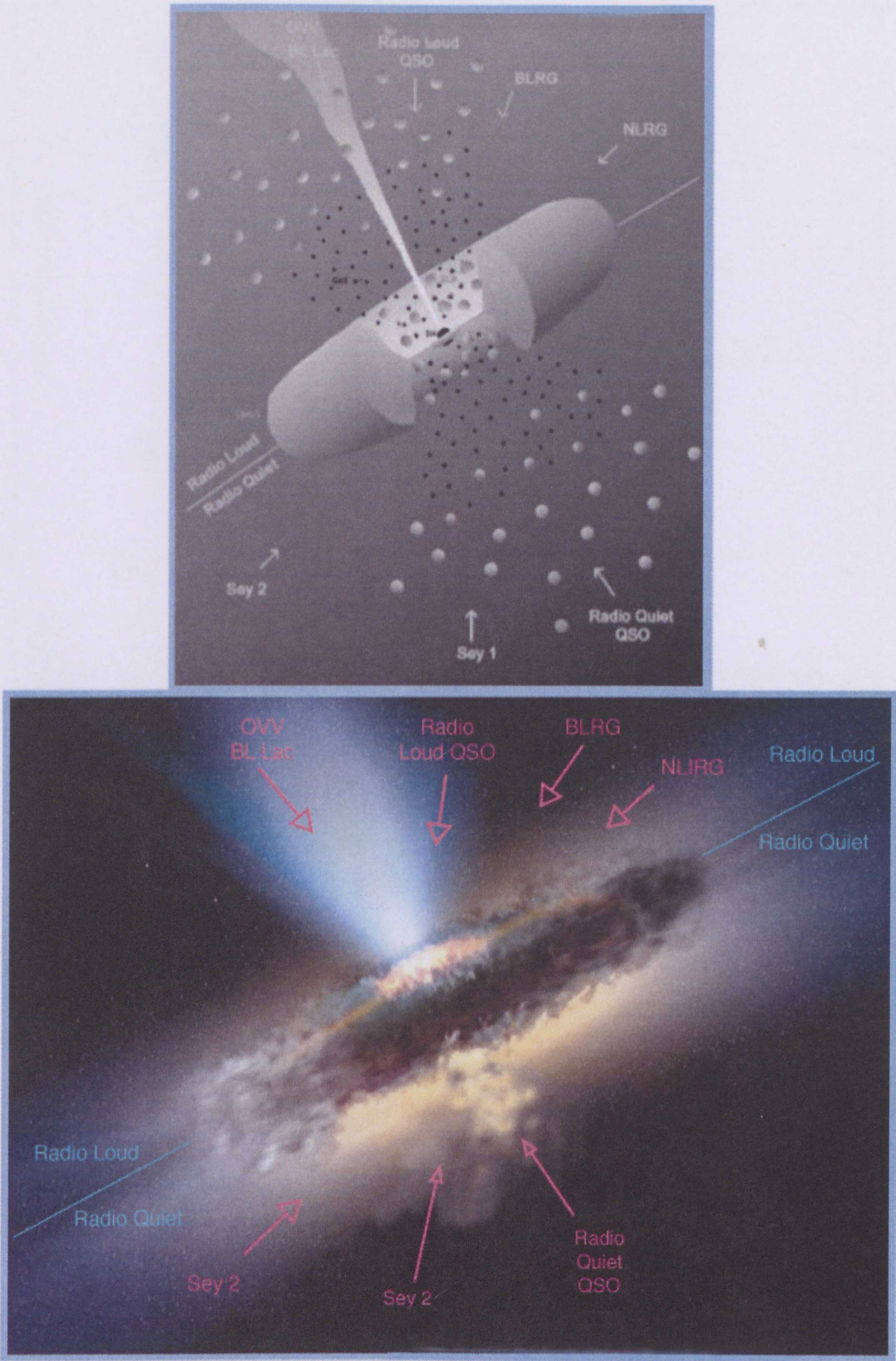


Figure 1.4: Diagrams of the standard AGN unification model. Classification depends on viewing angle - split into Radio Loud and Radio Quiet directions. Top image is a diagnostic version (from Krolik 1999) where the dust torus and dust clouds are shown in grey, gas distribution is shown as black dots. Bottom image is a more artistic version (image adapted from ESA publicity image, V. Beckmann).

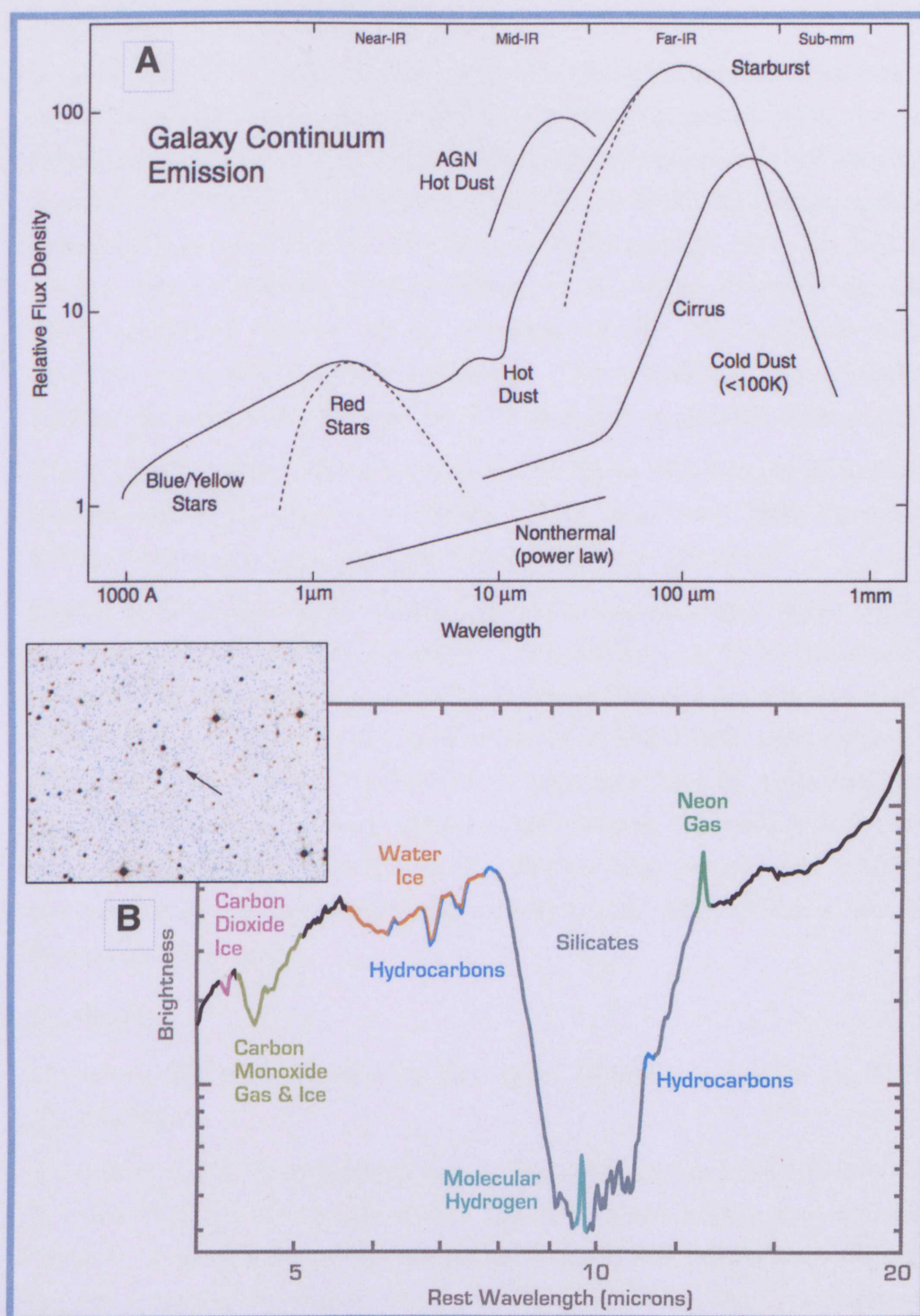


Figure 1.5: The SED of a galaxy from the viewpoint of the underlying physical contributors. **A:** Here the SED of a starburst galaxy undergoing an intense episode of star formation is shown (with thanks to Vaccari (2004) for this image). The contribution from cirrus is shown with two types of emission that appear in some Seyfert galaxies and other AGN: emission from dust heated by the central engine and non-thermal emission (power-law). It is possible for a galaxy to show at the same time emission due to starburst, cirrus and AGN, in differing ratios (for example, Telesco 1999). **B:** A recent *SPITZER* IRS observation of IRAS F00183-7111, a luminous galaxy with an AGN. The broad depression in the center of the spectrum is due to silicates. Emission lines and other features are also indicated. Credit: NASA/JPL-Caltech/L. Armus (SSC/Caltech), H. Kline (JPL).

• Luminous IR galaxies

As seen in §1.3.1, *IRAS* discovered luminous infrared galaxies that emit more in the IR (5 - 500 μ m) than at all other wavelengths combined, having $L_{IR} > 10^{11}L_{\odot}$. The LIRGs seen by ISOCAM have been studied at other wavelengths in detail in two fields: *Hubble* Deep Field³ North (HDF-N) (Mann et al. 1997; Rowan-Robinson et al. 1997; Aussel et al. 1999) and the 1415+52 field of the Canada-France Redshift Survey⁴ (Flores et al. 1999a; Flores et al. 1999b). They were found to have the optical colours of Sbc - Scd galaxies, with the majority being disc/interacting systems. The remainder were irregulars or E/SOs (the one elliptical in the HDF-N sample is associated with an AGN).

The trigger for most LIRGs seems to be the interaction/merger of (molecular) gas-rich spirals (cf. Sanders & Mirabel 1996; Moorwood 1996; Farrah et al. 2001). But what is (are) the dominant source component(s)?

Genzel & Cesarsky (2000) found that both starburst and AGN input was required to fuel LIRG IR luminosities. As mentioned in §1.4.1, starburst star formation is expected to occur in giant molecular clouds, and spectroscopic follow-ups (e.g. Knapp & Rupen 1996) of *IRAS* LIRG observations have found extensive CO lines, indicative of large quantities of molecular gas and therefore pointing to starburst activity. Additionally, molecular gas is expected in interacting regions (Stanford et al. 1990) so tidal mergers and interactions are most likely to be involved (Rowan-Robinson 1995; Blain et al. 1999a; Somerville et al. 2001).

• ULIRGs

Does a similar scenario hold for the higher luminosity classes: the ULIRGs and HLIRGs?

Sanders et al. (1988) proposed a picture (the ‘S88’ picture) of ULIRG evolution in which ULIRGs evolve into optical QSOs. In this scenario, interactions and mergers between gas-rich spirals funnel dust to the central regions, and in the latter stages of merging this fuels a central AGN which then dominates the IR luminosity of the ULIRG. In the final stages this ULIRG becomes an optical QSO as the dust shrouding the AGN is dispersed (Sanders et al. 1988; Lawrence et al. 1989; Leech et al. 1994; Clements & Baker 1996). The final state may then be a large elliptical galaxy with a massive quiescent central

³Williams et al. (1996); see also Ferguson et al. (2000).

⁴CFRS; Lilly et al. 1996

black hole (Kormendy & Sanders 1992).

This S88 scenario implies that AGN activity will be increasingly prevalent with merger advancement. However, Lutz et al. (1998) and Rigopoulou et al. (1999) used PAH emission features as a discriminator on *ISO* data, finding that ULIRGs were, in the main, starburst - rather than AGN - powered, and *not* finding that AGN activity increased with merger advancement. More recently, Genzel et al. (2001)'s spectroscopic study of gas and stellar kinematics in ULIRGs found that ULIRGs were likely to evolve to $\sim L_*$ ellipticals (but not more massive than this).

In Farrah et al. (2001) an alternative picture was proposed in which ULIRGs are a diverse population with a broad range of properties and evolution. Hence only some would end up as optical QSOs since their evolution is driven solely by their morphology and number of merger progenitors. This picture fits the variety of observations more successfully than the S88 scenario and is supported by more recent examination of archival IR and optical photometry of 41 local ULIRGs by Farrah et al. (2003) which showed that most ULIRGs undergo multiple starbursts, and by inference that multiple mergers may be common amongst ULIRGs.

Thus, ULIRGs can be said to be interacting/merging dusty systems ($\sim 90\%$ show evidence of interaction) with resulting starburst (dominant) activity and some degree of AGN activity, where:

$L_{IR} < 2 \times 10^{12} L_{\odot}$ are starburst dominated;

$L_{IR} > 3 \times 10^{12} L_{\odot}$ always have an important AGN contribution present. (e.g. Mirabel 2002).

• HLIRGs

Are HLIRGs a simple extrapolation of ULIRGs?

Studies of local ULIRG environments (Borne & Scott 1990; Sanders 1992) show that they do not reside in higher than average regions of density. *IRAS* showed that the interactions/mergers involved had relative mean velocities of $< 200 \text{ km s}^{-1}$, which is not typical of rich cluster environments (where mean velocities are higher: Sanders & Mirabel 1996).

Analysis of QSO host galaxies, however, suggests that some HLIRGs may reside in rich cluster environments (e.g the recent work by Farrah et al. 2004) - they may then be the cluster analogues of the ULIRGs, and so would provide

the formation mechanism for cluster ellipticals (e.g. by merger-induced dissipative collapse of disc-disc collisions; Kormendy & Sanders 1992). Indeed, if an elliptical galaxy underwent a massive star formation burst at $2 < z < 5$ and was observed in the IR, it would look like IRAS F10214+4724.

Hubble Space Telescope (*HST*) observations of 9 HLIRGs (Farrah et al. 2002a) found that of the 7 with sufficient photometry, 2 were starburst-dominated, 5 were AGN-dominated, and all showed some AGN contribution. Sub-mm photometry of 11 HLIRGs (Farrah et al. 2002b) found that all required starburst and AGN contributions, with a mean starburst fraction of 45% (the span was from 90% starburst - to 80% AGN - dominated). The trend of increasing AGN fraction with IR luminosity as observed for ULIRGs is then seen to peak in the HLIRGs.

HLIRGs appear to have a strong environmental diversity (some strongly interacting, some simply undisturbed QSOs). Most probably they are an extrapolation of ULIRGs, but they could also be *primaeval*⁵ (e.g. proto-elliptical) star-forming galaxies with SFRs $> 500 M_{\odot} \text{yr}^{-1}$ (Rowan-Robinson 2000; Farrah et al. 2002b)⁶. The AGN component is more noticeable than for ULIRGs, and the starburst and AGN activity appear to be coeval, suggesting governance by common physical factors - the amount of gas/dust available and/or the trigger event (Taniguchi et al. 1999; Farrah et al. 2001).

• QSOs and Seyferts

Although, in unified models (e.g. Antonucci 1993), QSOs and Seyferts are both sub-classes of AGN, the host galaxies do not tend to be modelled simply as AGN since there will be other contributors to the emission.

QSOs/Seyferts exhibit a mid-IR continuum. This was modelled by Rowan-Robinson & Crawford (1989) as dust in the narrow-line region (NLR) of an AGN, with a dusty distribution $n(r) \propto r^{-1}$. More realistic models treated the distribution as a toroidal geometry - Pier & Krolik (1993); Efstathiou & Rowan-Robinson (1995); Rowan-Robinson (1995). Rowan-Robinson (1995) suggested that most QSOs have a starburst (far-IR contribution) and toroidal dust in the NLR (mid-IR contribution).

⁵i.e. $z > 1$, major star formation episode, $M_{\text{star}} \geq 10^2 M_{\odot} \text{yr}^{-1}$, high gas fraction, $M_{\text{gas}} \sim 10^{11} M_{\odot}$, evidence of interactions, mergers, and dynamical growth : Rowan-Robinson (2000).

⁶Although Hughes et al. (1997) disagree.

1.5 *ISO* and *ELAIS*

Observations continuing on from *IRAS* were generally focused on uncovering the properties of the *IRAS* galaxies as a function of L_{IR} . For $L_{IR} < 10^{10} L_{\odot}$ they were mainly early-type galaxies (Rieke & Lebofsky 1986; Knapp et al. 1989; Knapp et al. 1992) but, contrastingly, for $10^{10} < L_{IR}(L_{\odot}) < 10^{11}$ the majority were late-type (but ~ 12 -25% were ongoing interactions: Soifer et al. 1984). As L_{IR} increases, the fraction involved in ongoing interactions rises, with $> 90\%$ for $L_{IR} > 10^{12} L_{\odot}$ (Armus et al. 1987; Hutchings & Neff 1987; Farrah et al. 2001).

At this stage, however, the IR observations were neither of sufficient numerical nor spectral coverage to allow quantification of the contribution of each power source to IR emission (be it Seyfert, HII, LINER, etc).

The natural successor to *IRAS* was the Infrared Space Observatory (*ISO*; Kessler et al. 1996), launched in November 1995. It was equipped with a multi-pixel near-IR/mid-IR camera (ISOCAM: Cesarsky et al. 1996), a multiband mid- and far-IR spectro-photometer (ISOPHOT; Lemke et al. 1996), a $2.4 - 4.5\mu\text{m}$ spectrometer (SWS: de Graauw et al. 1996) and a $43 - 197\mu\text{m}$ spectrometer (LWS: Clegg et al. 1996, Clegg et al. 1999).

An important improvement with the advent of *ISO* was that its sensitivity enabled it to observe far deeper than *IRAS* had, whilst its suite of instruments allowed detailed imaging, spectroscopy, and spectrophotometry of many galaxies that had been detected by *IRAS*.

There were numerous surveys carried out by *ISO* (see the review by Oliver et al. 2000) and in the mid-IR ISOCAM conducted several surveys of different depths and area. The deepest mid-IR fields were centred on the HDF-N (Serjeant et al. 1997; Aussel et al. 1999; Désert et al. 1999) and the HDF-S (Elbaz et al. 1999; Oliver et al. 2000).

ISO was able to solve a discrepancy that arose from *IRAS* observations of normal spirals - *IRAS* found that their $\lambda \leq 100\mu\text{m}$ emission was due to emission from dust at $\sim 30\text{K}$, giving total gas mass (HI + HII + He) to dust mass ratios of $\geq 10^3$ (e.g Devereux & Young 1990). This was approximately an order of magnitude greater than for the Milky Way (~ 170 in Haas et al. 1998), probably since *IRAS* could not detect the coldest dust (e.g Xu & Helou 1996). *ISO* could observe up to $\sim 200\mu\text{m}$, and it revealed dust with $T \sim 20\text{K}$ (Alton et al. 1998, Davies et al. 1999). This had an immediate and important consequence: a larger dust mass meant a significant optical dust extinction, and extinction-corrected spiral morphologies are

quite different to the uncorrected morphologies (Trewella et al. 1997). For example, M31 becomes a ring galaxy instead of an Sb (Trewella 1998).

ISO also resolved the origin of mid-IR emission from early-type galaxies that had been detected by *IRAS* (Madden et al. 1999; Vigroux et al. 1999; Fich et al. 1999). ISOCAM imaging showed that it was due to three things:

- i) The photospheres/shells of AGB stars.
- ii) The Interstellar Medium (ISM).
- iii) AGN.

In particular, Madden et al. (1999) found that $\sim 60\%$ of their sample galaxies had mid-IR emission consistent with a stellar origin, with the rest dominated by AGN (22%) or Unidentified Infrared Bands (UIB: cf. Allamandola et al. 1995; Verstraete et al. 1996; Onaka et al. 1996) ($\sim 17\%$). UIB emission can be a good tracer of star formation, as the radiation field of old stellar populations is too soft to excite these bands, thus implying an obscured UV source: massive star formation in dense interstellar clouds (e.g Mirabel et al. 1999 in Cen. A).

1.5.1 The European Large Area *ISO* Survey: ELAIS

The largest open-time scientific programme on *ISO* was ELAIS (Oliver et al. 2000; Rowan-Robinson et al. 2004a), the European Large Area *ISO* Survey. This covered ~ 12 square degrees of the sky at $15\mu\text{m}$ (ISOCAM) and $90\mu\text{m}$ (ISOPHOT), with subsets at $6.75\mu\text{m}$ and $175\mu\text{m}$ (the FIRBACK team: Puget et al. 1999). The areas were mainly selected for their low cirrus contamination, using the *IRAS* maps of Rowan-Robinson et al. (1991a), with the primary fields being ELAIS N1, N2, N3 and S1 - see Figure 1.6.

In order to allow follow-up targeting at an early stage in the campaign, it was decided that an initial data reduction would be carried out, to produce a Preliminary Analysis (PA). This was begun before a good understanding of the instrumental systematics and responses had been quantified. PA results have now been superseded by the Final Analysis (FA), which has involved recalibration of $6.7\mu\text{m}$ catalogues and re-reduction of $15\mu\text{m}$ (Vaccari et al. 2004) and $90\mu\text{m}$ (Heraudeau et al., 2004) observations via new methods optimised for the *ISO* instruments (Lari et al. 2001 and Heraudeau et al., 2004). Final Analysis catalogues will be discussed further in §1.5.3 and comparisons to the PA products are presented in §A.1.

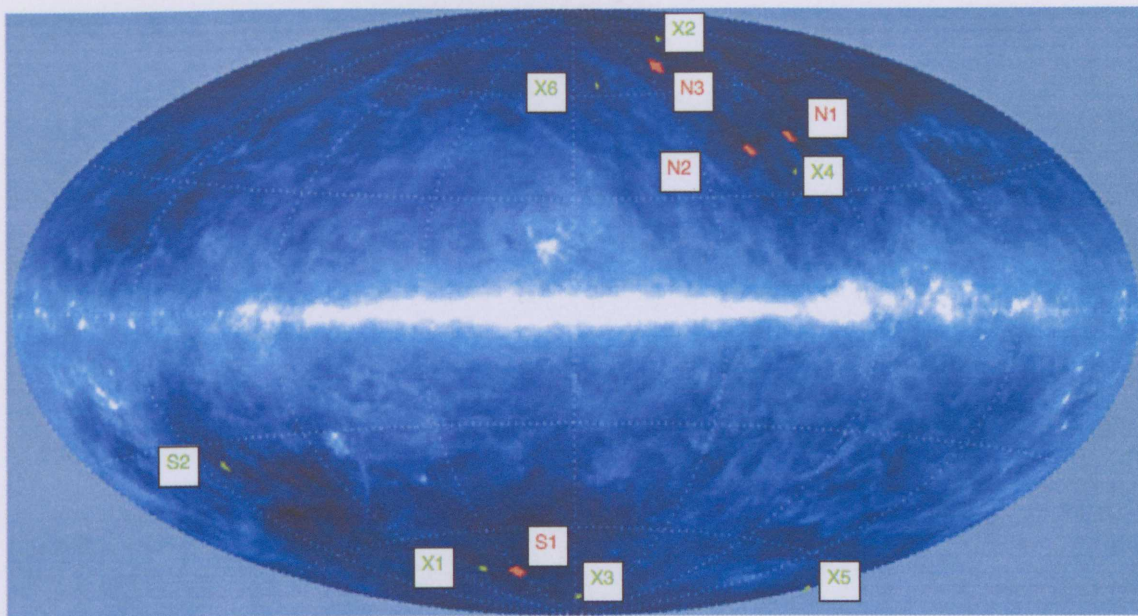


Figure 1.6: Location of ELAIS Fields on the Sky. Plot overlaid on an Hammer-Aitoff equal area projection of the *COBE*-normalized *IRAS* maps of Schlegel et al. (1998). Galactic latitude and longitude gridlines are overlaid. Main fields are marked in red, subsidiary fields in green. Plot from Oliver et al. (2000).

1.5.2 The Preliminary Analysis catalogues

Preliminary analysis was primarily designed with the intention of producing reliable source lists at 6.7, 15 and 90 μ m. In order to make data reduction as uniform as possible the pipeline was fixed at an early stage. Accordingly, the adopted pipeline did not incorporate the accurate field distortion corrections, which were not established at the start of the mission, nor the analytic models for cosmic ray transients and detector hysteresis which were developed in the course of *ISO*'s lifetime. Despite these issues, the resulting PA catalogues can certainly be considered a success:

Preliminary analysis found more than 1000 extragalactic sources at 15 and 90 μ m (Oliver et al. 2000) and gave evidence of evolution in IR populations. Modelling of the 15 μ m integrated number counts (Franceschini et al. 1994; Pearson & Rowan-Robinson 1996; Xu et al. 1998; Roche & Eales 1999) implied strong luminosity and/or density evolution of dusty star formation in bright normal spirals and starburst galaxies, with varying AGN contributions. The 90 μ m source counts in Efstathiou et al. (2000a) gave a similar picture, agreeing with the strongly evolving models of, for example, Guiderdoni et al. (1998). The PA methods at 15 and 90 μ m are now briefly outlined:

1.5.2.1 ISOCAM - 15 micron

The preliminary ELAIS ISOCAM data reduction was carried out using the CAM Interactive Analysis (CIA; Ott et al. 1998), creating the PA catalogues. Other techniques, suitable for data with multiple redundancy, such as the *PRETI method* (Starck et al. 1999) were found to be unsuccessful. The most reliable approach was to characterise source profiles in the time histories of individual pixels rather than by constructing sky maps.

Mid-infrared extragalactic source counts resulting from these PA products were presented in Serjeant et al. (2000), with limiting flux densities of $\sim 2\text{mJy}$ at $15\mu\text{m}$ and $\sim 1\text{mJy}$ at $6.7\mu\text{m}$. The stellar contribution was separated from the extragalactic using identifications with automated plate measurement sources made with the likelihood ratio technique. The completeness and reliability of the source extraction was quantified using

- (a) repeated observations over small areas,
- (b) cross-identifications with stars of known spectral type,
- (c) detections of the point spread function wings around bright sources and
- (d) comparison with independent algorithms.

Flux calibration at $15\mu\text{m}$ was performed using stellar identifications; the calibration did not agree with the pre-flight estimates, probably due to effects of detector hysteresis and photometric aperture correction, with an adopted Analogue-to-Digital-Unit (ADU) conversion to mJy of $1.96\text{ ADU/Gain/s/mJy}$. This conversion value is based on well-established bright sources with observations made over long timescales. This means that issues of detector stabilization and correct sampling of point-spread-function (PSF) issues are avoided. These issues are relevant to the ELAIS survey, however, and were later dealt with in a new reduction - see §1.5.3.1.

1.5.2.2 ISOPHOT - 90 micron

The ELAIS ISOPHOT $90\mu\text{m}$ data were initially reduced using the standard PHOT Interactive Analysis (PIA, Gabriel et al. 1997) and then further reduced using purpose-built IDL routines, creating the PA catalogues. The $90\mu\text{m}$ PA catalogue results and source counts were presented in Efstathiou et al. (2000a), with the completeness and reliability of the source extraction quantified via comparison to an independent pipeline and simulations. Comparison to *IRAS* fluxes and to model stars found that the uncertainty in the absolute flux calibration (for bright sources) was about 30 - 40 per cent and that below 50 mJy the reliability of sources decreased.

1.5.3 The Final Analysis catalogues

Since the Preliminary Analysis of the ELAIS data, new data reduction techniques have been developed, and the ELAIS ISOCAM and ISOPHOT data has been re-reduced to create Final Analysis (FA) catalogues.

1.5.3.1 15 micron

A new data reduction technique for ISOCAM LW data was developed by Lari et al. (2001) (more information can also be found on the technique in Vaccari (2004)). This method, known as the *LARI technique* and based on the assumption of the existence of two different time-scales in ISOCAM transients (accounting for either fast or slow detector response), was particularly designed for the detection of faint sources. The 15 μ m ELAIS FA catalogue calibration, completeness and reliability has been discussed in Lari et al. (2001), Gruppioni et al. (2002) and Vaccari et al. (2004).

In the ELAIS S1 field Lari et al. (2001) obtained a catalogue of 462 15 μ m sources with signal-to-noise ratios ≥ 5 and flux densities in the range 0.45-150mJy (filling the whole flux range between the Deep ISOCAM Surveys and the *IRAS* Faint Source Survey). The completeness at different flux levels and the photometric accuracy of this catalogue were tested with simulations, finding that the catalogue was “highly reliable” and $>98.5\%$ complete at 3mJy.

Following various improvements of the *LARI* Method with respect to the version used in PreFinal Analysis for the reduction of ELAIS 15 μ m observations in the S1 field only (Lari et al., 2001), a thorough re-reduction of all ELAIS 15 μ m observations was carried out: The 15 μ m ELAIS FA catalogue was presented in Vaccari et al. (2004), with 1923 sources with S/N > 5 in the range 0.5-100mJy and covering 10.85 square degrees in the four fields; ELAIS S1, N1, N2 and N3.

The standard sensitivity of the *ISO* LW3 channel is 1.96 ADU/Gain/s/mJy but, as mentioned in §1.5.2.1, this does not correct for loss of flux due to lack of detector stabilization, treatment of which will act to reduce the conversion factor. The FA sample is of sufficient size to carry out a test of this photometric calibration against the independently determined *IRAS* standard photometric calibration (Aussel & Alexander 2004, in prep.). Aussel & Alexander combined stars from the *IRAS* Faint Source Catalogue (Moshir 1988) with counterparts from 2MASS (Kleinmann et al. 1994) and Tycho-2 (Høg et al. 2000) catalogues and found good correlation. Vaccari et al. (2004) were able to use these correlations to predict the resulting 15 μ m flux of *ISO*-detected stars, requiring an ADU to mJy conversion factor for

the FA sources of $(1.96/1.098)=1.785\text{ADU}/\text{Gain/s/mJy}$ in order to be consistent with *IRAS*. It is important to note that the slight reduction of the conversion by a factor 1.098 is likely to be due to discrepancies between *IRAS* and *ISO* flux calibration procedures and any complete breakdown of causes would be complex and beyond the scope of this Thesis.

The Vaccari et al. (2004) result is in good agreement with that found by Väisänen et al. (2002) for the PA sources using J and K observations of stars. The calibration originally derived by Serjeant et al. (2000) for the PA versions, based on comparison with *IRAS* sources in common, is inconsistent with these - it was found to over-estimate source fluxes by a factor of ~ 1.5 -2. This was because the Serjeant et al. (2000) calibration did not include a correction for detector stabilisation and this decreases the number of ADU measured for a given source flux.

1.5.3.2 90 micron

A new data reduction for the ISOPHOT $90\mu\text{m}$ data has been developed, producing FA source catalogues (Héraudeau et al. 2004). Comparison with several recent evolutionary models shows that the best agreement with the observations is found for the models of Guiderdoni et al. which incorporate a heavily-extinguished population of galaxies. Comparisons with model prediction for standard stars and with *COBE*/DIRBE for surface brightnesses of individual *ELAIS* fields and with the *IRAS* Faint Source Catalogue (FSC) catalog for 35 sources in common have also been made by Héraudeau et al. (2004). The large number of rasters necessary to cover the wide *ELAIS* areas allows them to compute a relative uncertainty for the flux calibration based on the FSC of typically 7%. From the comparison with standard stars model predictions they show the absolute calibration to be better than 15%.

Differential number counts from these FA products (Serjeant et al., 2004b) show an excess of a factor up to 3.5 above the no-evolution model prediction (simple power-law) at the faintest end of the survey. This confirms the strong evolution detected at shorter ($15\mu\text{m}$) and longer ($170\mu\text{m}$) wavelengths in other *ISO* surveys (Elbaz et al. 1999; Puget et al. 1999; Gruppioni et al. 2002; Dole et al. (2001)).

1.5.4 An investigation into the PA and FA catalogues

There is clearly a need to investigate more fully the exact relationship between the FA products and the PA products. This need is driven, firstly, by the wish to validate, or refute, the findings presented from PA products, and, secondly, to

identify where the two techniques differ.

A final band-merged ELAIS catalogue has now been collated, incorporating data at multiple wavelengths (published in Rowan-Robinson et al. 2004a). The 15 and 90 μ m observations are incorporated into this release. Accordingly, a comparison between the 15 μ m PA and FA, and 90 μ m PA and FA catalogues has been carried out in this Thesis. A summary of some of the results of these comparisons was presented in Rowan-Robinson et al. (2004a). Results are laid out in more detail in the Appendix, §A.1.

1.6 Star Formation

Star formation rates (SFRs) and their global history (SFH) form the backbone of a slew of methods (both observational, numerical, and analytical) to investigate the processes of galaxy formation and evolution over cosmic time.

Whilst the overall cosmic evolution is driven by the evolution of the background dark-matter distribution, baryons are the observable tracers of the evolving large-scale structure. SFH is hence a fundamental descriptor of this cosmic evolution. Different cosmogonic models predict different rates of star formation and structure formation. In some models, the various morphological galaxy types have markedly different star formation epochs (e.g. between early/late-type galaxy systems). Others, however, do not. This means that an accurate knowledge of the SFH leads to insights into the evolutionary history of galaxies, the production of metals and dust, and the formation of structure. Being able to differentiate the SFRs of different morphological types of galaxy also indicates the different underlying processes and properties of those galaxy types.

To provide a context, two contrasting views of galaxy formation will be highlighted (see Bower et al. 1999 for a recent review and Sandage 1986); the ‘classical’ monolithic collapse picture, and the current view which is the hierarchical model.

The first is the ‘classical’ model, that in which galaxy formation is a monolithic collapse (proposed for our Galaxy in Eggen et al. 1962 and as a more general model for ellipticals in Larson 1975). This describes a single (relatively) rapid monolithic collapse, where the halo forms first. Following Arimoto & Yoshii (1987) the proto-gas cloud can initially be fragmented, but collapses to give rapid star formation. This star formation continues unhindered until the first supernovae form. From this point, the star formation only continues if the dark matter halo is sufficiently massive to retain the gas against the pressure of the supernovae ejecta. For massive systems

the star formation continues until eventually the gas is expelled by supernova-driven wind, to leave a spheroidal stellar system. Dependent on galaxy environment, the system can then reacquire this gas to form a gas disc and embark on quiescent star formation (if in a low density environment), or then loses its wind material to the intra-cluster medium if the system is a galaxy cluster member.

One statistical feature of this is that in a pure monolithic scenario, with no merging, the co-moving space density of massive galaxies is the same as seen today. The apparently unchanged number density of large spirals and ellipticals at $z \sim 6$ (Lilly et al. 1998; Schade et al. 1999) supports this view, where the majority of recent star formation has occurred in small mass galaxies (Cowie et al. 1996; Brinchmann & Ellis 2000); a picture known as ‘galactic downsizing’, which contradicts hierarchical model expectations.

The second view is the hierarchical galaxy formation model (Searle & Zinn 1978; White & Frenk 1991), the current best model we have for galaxy formation and evolution, where structure starts at small scales and grows to larger scales by a process of mergers and accretion. This model is in far better agreement with predictions based on a cold dark matter scenario than the monolithic collapse model. This is since a monolithic collapse starting with the largest structures would imply a hot dark matter dominated Universe in which smaller scale structures have been erased in the early Universe by streaming of the fast moving hot dark matter.

In the hierarchical model, in contrast to monolithic collapse, there is no intrinsic difference between star formation at different epochs since all galaxies are seen as similar star forming systems in which there is a balance between the inflow of gas and the rate at which it is consumed or blown out by supernovae-winds. The galaxy’s morphology is then a function of its exact merger history, in which it has grown from various sub-galaxy units.

In this scenario, modelling (e.g. Cole et al. 2001; Fontana et al. 2003; Rudnick et al. 2003) suggests that 30-50% of stellar mass was formed at $z < 1$, as supported by studies of dust-corrected or IR-based SFH (e.g. Flores et al. 1999b; Chary & Elbaz 2001), but which challenges the ‘classical’ view where most present-day stars formed early and are locked in spheroids; spiral bulges and ellipticals (Fukugita et al. 1998).

The key difference between the two scenarios is then that of morphology - in the ‘classical’ model, morphology is set early on and follows a fixed path, whereas in the hierarchical view there is no inbuilt link between morphology and the star formation history of that galaxy.

1.6.1 Quantifying star formation

Many techniques have been developed to measure the SFR over a range of redshifts. The first methods used evolutionary synthesis models of galaxy colours (e.g. Tinsley 1968, Tinsley 1972, Searle et al. 1973, Larson & Tinsley 1978 and Tinsley & Danly 1980). More recent and precise indicators of SFR (see later) use optical emission lines, UV continuum, radio, and infrared fluxes (e.g. Rieke & Lebofsky 1978; Kennicutt & Kent 1983; Donas & Deharveng 1984).

In order to calibrate an SFR indicator, a relation between the observed luminosity and SFR is needed. In principle, the SFR is then derived using a model of the duration and time behaviour of the starburst and of stellar evolution, with an assumed initial mass function (IMF). The SFR, $\dot{M}_*$, is defined by the IMF, $\psi(M)$, with stars formed over the mass range $[M_L, M_U]$, so that

$$\text{Total Stellar Mass } \dot{M}_* = \int_{M_L}^{M_U} M \psi(M) dM \quad (1.2)$$

The result is subject to imprecision, however, since folded into this are assumptions about the position of the stars in the Hertzsprung-Russell (HR) diagram, the evolution of stars on the HR diagram (e.g. the Padova group and Geneva group's stellar evolutionary models), and of metallicity and its evolution (e.g. Carollo & Lilly 2001; Maier et al. 2004). The model IMF (e.g. Salpeter IMF; Salpeter 1955) plays a key role since it is used to extrapolate from the stellar population(s) responsible for the observed emission (usually in just one part of the spectrum) to an entire distribution of stellar masses and their ensuing evolution. Hence uncertainty in the IMF has a large effect (in particular the choice of lower mass cutoff will drastically alter the model predictions; Leitherer et al. 1999). For example, there are indications that the IMF in the early Universe may have been top-heavy - there were proportionately more massive stars in comparison to the standard IMF - with stars preferentially forming in a top-heavy IMF with characteristic masses of a few $100 M_\odot$ when the gas metallicity is below a critical value (Bromm et al. 2001; Schneider et al. 2002; Schneider et al. 2003).

A new population of very massive stars at $z \sim 10 - 20$ may be able to explain the observed amplitude and anisotropy of the near-infrared background (Salvaterra & Ferrara 2003; Magliocchetti et al. 2003; Cooray et al. 2004) and the high Thomson optical depth initially detected by WMAP (if not revised by future data). However, a top-heavy IMF was not required to explain the metal abundance patterns in the broad emission-line regions of high-redshift quasars by Venkatesan et al. (2004), al-

though this does not rule out a top-heavy and a more standard IMF being coeval in the early-Universe.

The conversion to SFR from a chosen band(s) involves uncertainty since each band only traces a minor portion of the total energy output of stars (and there is always the possibility of contamination from AGN). Observations made at different wavelengths all have individual strengths and weaknesses. Techniques to derive SFR at various wavelengths will be discussed below:

1.6.1.1 Optical and UV

A star-forming galaxy without an AGN contribution will have an UV continuum dominated by the output of massive, short-lived stars. In comparison to the Hubble time, or even that of their host galaxy evolution, these stars are extremely short-lived ($\sim 10^6$ years). Hence they can be seen as a tracer of the instantaneous SFR of that galaxy (see review by Kennicutt 1998).

Following this argument, the co-moving UV luminosity density will be proportional to the SFR and via the use of an assumed IMF and population synthesis models such as Bruzual & Charlot (2003) the SFR can be determined. Accordingly, observations made at rest-frame wavelengths which are dominated by young stars (e.g. Lilly et al. 1996; Madau et al. 1996), so that SFR scales linearly with luminosity, will be the most direct measure of SFR. This conclusion, though, neglects the effect of reddening which has a large effect in the restframe UV and this inevitably leads to complications and increased uncertainties. The role of dust will be further discussed in §1.6.1.2.

Deep Optical Surveys

Deep optical surveys observe at restframe-wavelengths in the near-UV ($\sim 1250 - 2500\text{\AA}$) due to the action of redshift. This avoids contamination from the Lyman alpha ($\text{Ly}\alpha$) forest at shorter wavelengths and old stars at longer wavelengths, so the emission is dominated by young stars (e.g. Lilly et al. 1996) and SFR scales linearly with luminosity (ideally). The U band ($\lambda_{\text{eff}} = 3650\text{\AA}$) is often used, however it is not far enough into the UV for the effect of older stars to be minimal - main sequence stars (e.g. A, F, G) still emit in this waveband, though old stars such as K and M do not. This can be corrected for by using model spectra to extrapolate from the U band to, say $2500\text{\AA}$, where the emission is dominated by massive stars (Cram et al. 1998).

Emission line measurements

Nebular emission lines are another direct tracer of star formation (e.g. Gallego et al. 1995; Tresse & Maddox 1998; Teplitz et al. 2000; Pettini et al. 2001). These are due to reprocessed ionising radiation from massive young OB stars (spectral types B0.5 and hotter) which is then re-emitted long-ward of the Lyman limit, $912\text{\AA}$, as recombination lines.

$\text{H}\alpha$ at $6563\text{\AA}$, the first transition in the Balmer series (e.g. Gallego et al. 1995; Tresse & Maddox 1998), is perhaps the most widely used line for low to medium redshifts and is less effected by extinction than higher energy lines. In its favour, it gives a good direct measurement of the current SFR in the ionization-bounded nebulae of H II regions and star-forming galaxies since its luminosity scales directly with the total ionizing flux of the embedded stars, and it is less effected than other optical Balmer lines, such as $\text{H}\beta$ ($4861\text{\AA}$) or $\text{H}\gamma$ ($4339\text{\AA}$), by stellar absorption and reddening. Correction for stellar absorption and reddening brings the $\text{H}\alpha$ SFR into agreement with SFRs from FIR methods (described later) for active star-forming galaxies (e.g. Rosa-González et al. 2002; Charlot et al. 2002) and for the normal star-forming galaxies of all Hubble types in the Nearby Field Galaxy Survey (Kewley et al. 2002).

In Chapter 4, observations of $\text{H}\alpha$ lines will be combined with measurements of $\text{H}\beta$. In this way a measure of the amount of extinction can be derived, based on its differential effect on the two lines (altering the intrinsic Balmer ratio of 2.86, e.g. Osterbrock (1989)). This allows an extinction-corrected SFR to be calculated. In Chapter 4 these Balmer-derived extinction measures will be compared to extinction measures derived from photometry by photometric redshift codes, in order to quantify the accuracy and reliability of the extinctions derived from photometric redshift codes. This is of importance since photometric data is far more prevalent, and available to fainter magnitude limits, than spectroscopic data of sufficient quality to measure both $\text{H}\alpha$ luminosity and a Balmer decrement.

The forbidden [OII] doublet at $3727\text{\AA}$ (3726 and $3729\text{\AA}$) is the strongest line in the blue and is often used at intermediate redshifts ($z \geq 0.4$) where $\text{H}\alpha$ is less easily observed. One important benefit of using [OII], in contrast to the Balmer lines, is that by nature of it being a forbidden line transition there is no need to de-blend the line from a broad-line component in the presence of an AGN. This is because a narrow line can either be an allowed ($\text{H}\alpha$ etc), or a forbidden ([OII], [NII] etc) transition, whereas a broad line can only be an allowed transition. Forbidden transitions do not occur in the broad line region (BLR; the region containing high

velocity gas of $> \text{a few } 1000 \text{ km s}^{-1}$) as the ions get collisionally de-excited first, but allowed transitions do occur in the narrow line region (NLR). As a result of this, [OII] will only be seen in NLRs, whereas $\text{H}\alpha$ and $\text{H}\beta$ can be seen in NLRs *or* BLRs. This means that if [OII] is used as a SFR measure then there is only one major AGN contaminant, whereas if $\text{H}\alpha$ is used then there are two AGN contaminants.

The [OII] SFR has been calibrated by a number of authors (e.g. Gallagher et al. 1989; Rosa-González et al. 2002). However, [OII] is less directly coupled to the intensity of UV radiation of young stars than the $\text{H}\alpha$ recombination emission since it has a complex dependence on metallicity and excitation conditions - it is described as an indicator of SFR rather than a quantitative measure (see Kennicutt 1992) - and is badly effected by issues including reddening and abundance dependence (Jansen et al. 2001; Charlot et al. 2002). This leads to larger SFR uncertainties since as well as the same systematic errors present in $\text{H}\alpha$ -derived SFR, [OII] experiences the additional variation in its excitation due to variations in the [OII]/ $\text{H}\alpha$ (or $\text{H}\beta$) ratio used to calibrate it. Kennicutt (1992) suggests this leads to a variation of perhaps 30-50% in [OII] based SFR measures. More recently, Kewley et al. (2004) compared the Kennicutt [OII] and $\text{H}\alpha$ SFR calibrations for a sample of 97 galaxies and found that the two significant effects producing disagreement between $\text{SFR}([\text{O II}])$ and $\text{SFR}(\text{H}\alpha)$ were reddening and metallicity. Their new calibration, with optional metallicity correction, led them to conclude that after reddening and metallicity corrections, the two SFR measures agree to within $\sim 30\%$.

UV spectroscopy

A more recent, and arguably more reliable, method is the use of UV spectroscopy. Here, the UV spectrum of the galaxy can be fit by a spectral synthesis model such as Starburst99 (Leitherer et al., 1999) in which stellar evolution models and model atmospheres are used to characterise the observed stellar continuum and absorption line spectrum in terms of the underlying stellar populations. In contrast to optical wavelengths, where starbursts are dominated by nebular emission lines, the UV wavelengths are dominated by wind and photospheric absorption lines from massive stars.

The strength of stellar photospheric absorption lines (e.g. OIV $\lambda 1343\text{\AA}$, OV $\lambda 1371\text{\AA}$, FeV $\lambda 1360, 1380\text{\AA}$, SiIII $\lambda 1417\text{\AA}$, CIII $\lambda 1427\text{\AA}$, and SV $\lambda 1501\text{\AA}$) is an indicator of the starburst activity and they are strong in late O and early B stars (e.g Walborn et al. 1985; Walborn et al. 1995).

In addition, the spectra of the most massive stars show the presence of stellar winds due to radiation pressure (of perhaps 2000-3000 kms^{-1} ; Groenewegen et al. 1989). These wind lines (e.g. NIV] $\lambda 1488\text{\AA}$, NV $\lambda 1238, 1242\text{\AA}$, SiIV $\lambda 1393, 1402\text{\AA}$, CIV $\lambda 1548, 1550\text{\AA}$, and HeII $\lambda 1640\text{\AA}$) manifest as a broad, blue-shifted absorption (for weaker winds), or as P Cygni profiles if the wind density is high enough (Leitherer et al., 1995b). The profiles of these lines have been used to derive the stellar content and star formation history in starburst galaxies (e.g. Robert et al. 1993; Leitherer et al. 1996; Gonzalez Delgado et al. 1998).

The presence of wind lines mean one is then also able to pin down contributions such as the fractional contribution of Wolf-Rayet (WR) stars to the integrated UV luminosity - broad stellar HeII emission and the semi-forbidden NIV] line are predominantly produced by WR stars. This contribution reaches a maximum in a brief period following the initial star-forming burst, since WR stars are the evolved descendants of O stars (those with $M > 20 - 30M_{\odot}$), and is therefore an additional SFR marker. Similarly, the stellar wind feature only becomes apparent in SiIV for blue giant and supergiant stars, whereas the wind feature in CIV is strong for main-sequence, giant and supergiant O stars (Walborn & Panek, 1984). A conspicuous profile in SiIV indicates that the star formation occurred in a short period of time, since the relative number of O supergiants with respect to the total O stars is low (their relative life time is short). Therefore, the SiIV line is also good for discriminating between models of instantaneous bursts and continuous star formation.

Thus UV spectroscopy can provide quite a detailed knowledge of the populations of young massive stars and thence the star formation. Photoionization models of various starbursts and HII regions have successfully constrained the stellar content and hence the ongoing SFR in a number of studies (to mention just a few: Garcia-Vargas et al. 1997 modelled the HII regions of NGC 7714; Stasińska & Schaerer 1999 characterised the HII regions of IZw18; Shapley et al. 2003 applied Starburst99 to a large sample of Lyman Break Galaxies).

Again, assumptions about the underlying IMF, metallicity, the burst duration and stellar evolution tracks are required and these are the main roots of uncertainty.

Additionally, it should be borne in mind that if some fraction of the young stellar population is completely obscured by dust then they will not contribute to optical/UV measures, thus implying that the SFR's so-derived represent a lower-limit.

1.6.1.2 Infrared and sub-mm

A fundamental issue for SFR measures is the fraction of light from stars that has been reprocessed into the IR. Consider the following findings:

- From *IRAS* we know that in the local Universe this fraction is $\sim 30\%$, so local optical-UV based SFR studies are reasonably accurate. However, *IRAS* also showed that this fraction increased strongly with star formation activity - Sanders & Mirabel (1996) note that a sample of IR-selected galaxies range over 3 orders of magnitude in L_{IR} whereas the optical luminosity only varies by a factor of ~ 4 .
- The discovery by *COBE* of a cosmic FIR/Sub-mm background with an energy density at least as large as the optical/UV background (Puget et al. 1996; Fixsen et al. 1998; Hauser et al. 1998; Lagache et al. 1999) indicates that over cosmic time a large fraction of the energy from stars is hidden from the optical due to dust (Hauser, 2001).
- SCUBA surveys (e.g. Barger et al. 1998; Blain et al. 1999c; Chapman et al. 2001; Fox et al. 2002) have led to the discovery of significant populations of sub-mm sources at high redshift ($z > 1.5$). The luminosities of these sources, if due to dusty star formation, implies very high SFR and makes up a significant fraction of the IR background.
- *ISO* detections of a population of strong IR sources (the $15\mu\text{m}$ ISOCAM survey of Oliver et al. 1997; the $175\mu\text{m}$ surveys of Kawara et al. 1998 and Puget et al. 1999; Takeuchi et al. 2001) show significant active star formation at $0. < z < 1.3$, boosting the global star formation density by perhaps a factor 3 from estimates made in the optical for the same redshift range.

It appears likely, then, that at earlier epochs, when the Universe was younger and more active, the fraction of starlight reprocessed by dust was higher and optical/UV based SFR measures will underestimate the actual SFR. An instructive plot is shown in Figure 1.7 which illustrates the changing ability of UV and IR luminosities to trace the overall SFR in a Starburst99 spectrum with increasing dust extinction. It can be seen that with increasing dust extinction, more and more of the starlight is reprocessed into the IR. However, it is also clear that, apart from in the most dusty systems, some of the ionising radiation does escape, so that the most effective measure of SFR is perhaps to combine UV and IR-based estimates.

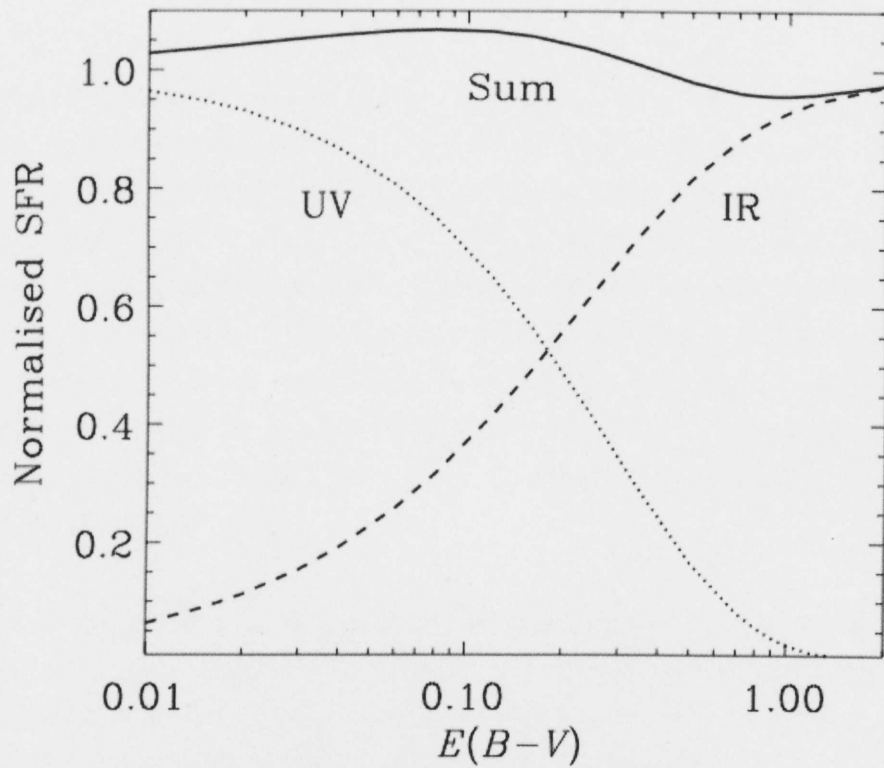


Figure 1.7: SFR measures with extinction. Plot from Hirashita et al. (2003) showing the SFR derived from UV (dotted) and IR (dashed) luminosities, as a function of extinction, for a Starburst99 spectrum. Clearly the most effective route to total SFR is to combine the UV and IR measurements.

The role of dust in high redshift galaxies has been discussed by many authors (e.g. Mushotzky & Loewenstein 1997; Rowan-Robinson et al. 1997; Pettini et al. 1998; Calzetti & Heckman 1999; Meurer et al. 1999; Steidel et al. 1999; Adelberger & Steidel 2000; Sullivan et al. 2001). For example, star forming galaxies detected via the Lyman break technique at $z \sim 2 - 4$ are highly extinguished in the rest-frame UV, meaning star formation rates are $\sim 3 - 10$ times higher than if dust is ignored (e.g. Meurer et al. 1999). Correction factors found for other high redshift star forming galaxies are of a similar order (for instance, Glazebrook et al. 1999; Hopkins et al. 2001).

In principle, the obscured optical/UV flux can be dust-corrected (Hopkins et al., 2001), but these corrections are both large and uncertain (especially at high redshift). Indeed, it is entirely possible in heavily-obscured objects for star formation to be completely hidden, which can not be accounted for at all by corrections to the optical/UV-derived SFR estimators (Franceschini et al. 1997; Guiderdoni et al. 1998; Elbaz et al. 1999)⁷. Additionally, the FIR:UV flux ratio that can be used to estimate dust obscuration has been shown to break down for ULIRGs (Meurer et al., 2000) and Lyman-break galaxies (Baker et al., 2001). This means that optical observations can only provide a lower limit to SFH measurements, and in extreme cases will be effectively useless.

To ‘avoid’ dust extinction bias it is therefore natural to make observations in the IR/sub-mm (e.g. Blain et al. 1999c). This is because thermal dust emission typically peaks in the rest frame $10\text{--}1000\mu\text{m}$ region, and this emission is essentially the thermally reprocessed radiation from dusty SF populations. Consequently, for dusty star forming galaxies there is a ‘negative’ K-correction (due to the shape of the SED) meaning that the sub-mm fluxes barely drop for $z \sim 1 - 10$ (Blain & Longair 1993; Fox 2000).

The accuracy of the FIR as an SFR tracer is dependent on the contribution of young stars to dust-heating and the optical depth of the dust. If the UV-visible radiation field is dominated by young stars and the dust opacity is high, then L_{FIR} measures the SFR ‘completely’. This is a reasonable assertion in dense circumnuclear starbursts and late-type star-forming galaxies where dust heating from young stars is expected to dominate the $40\text{--}120\mu\text{m}$ emission (for such galaxies, the FIR luminosity correlates with other SFR tracers - e.g. Lonsdale & Helou 1985; Buat & Xu 1996). For early-type (S0 - Sab) and the discs of normal galaxies, though, it is

⁷But this is disputed by Adelberger & Steidel (2000)

more complicated (e.g. Rowan-Robinson & Crawford 1989): the FIR spectrum then comprises ‘warm’ dusty star formation and cooler ‘IR cirrus’ due to the more extended dust being cumulatively heated by the interstellar radiation field (including colder stars : Rowan-Robinson & Crawford 1989; Sauvage & Thuan 1994; Walterbos & Greenawalt 1996)⁸. Kaviani et al. (2003) argue that a model in which the cirrus component is dominant sits more comfortably within the current galaxy formation paradigm, at least for high redshifts. In red galaxies, this dust heating due to older stars could be very important.

The conversion from L_{FIR} to SFR, or, at least, the rate of formation of stars whose light is obscured by dust, (e.g. Thronson & Telesco 1986; Rowan-Robinson et al. 1997) can be derived using synthesis models (e.g. Kennicutt 1998). An updated version is given in Rowan-Robinson (2000) where M_* is $SFR/M_\odot yr^{-1}$:

$$M_{*,all} = \left[\frac{2.2\phi}{\epsilon \times 10^{-10}} \right] [L_{60\mu m}/L_\odot] \quad (1.3)$$

Here ϕ takes account of the uncertainty in the IMF (=1 for standard Salpeter), and ϵ is the fraction of UV light absorbed by dust.

Cram et al. (1998) present a similar relationship, for a $\psi(M) \propto M^{-2.5}$ IMF,

$$M_{*,M \geq 5M_\odot} = \frac{L_\nu(60\mu m)}{5.1 \times 10^{23} WHz^{-1}} \quad (1.4)$$

Similar conversions can be derived for the integrated FIR/sub-mm emission, such as from the models of Devriendt et al. (1999) which yield, for a Salpeter IMF of mass range $[0.1, 120]M_\odot$,

$$M_{*,all} = \frac{L_{IR}(30 - 1000\mu m)}{3.0 \times 10^{36} WHz^{-1}} \quad (1.5)$$

A conversion formula for ‘normal’ galaxies, rather than when $L_{obsIR} \sim L_{bol}$, is given by Inoue et al. (2000) as:

$$M_{*,all} = \frac{3.3 \times 10^{-10}(1 - \eta)}{(0.4 - 0.2f + 0.6\epsilon)} \cdot [L_{obsIR}/L_\odot] \quad (1.6)$$

Typical values for f (fraction of ionising photons absorbed by HI) ~ 0.26 , ϵ (efficiency of dust absorption for non-ionising photons from OB stars) ~ 0.6 , η (cirrus fraction of observed IR luminosity) ~ 0.5 .

⁸But Devereux & Young (1990) and Devereux & Hameed (1997) argue it is still dominated by young stars.

However, there are major, but often unstated uncertainties in these methods:

A specific dust grain type and grain size distribution are assumed (usually Draine & Lee 1984). If the dust grain type and distribution are altered then the implied SFR is altered (recall sub-mm emission comes from only the large ‘fluffy’ grains).

Sub-mm observations suffer from a lack of sensitivity ($L_{\text{bol}} \geq 10^{12} L_{\odot}$) so they only see the highest SF galaxies, whilst the large beams (e.g. SCUBA $\sim 15''$) make optical ID’s and redshifts hard to determine.

The contamination from dusty AGN to the IR is also uncertain, perhaps $\sim 10 - 20\%$ of background light (Granato et al. 1997; Almaini et al. 1999; Brusa et al. 2001), though it is less of a problem as for radio-derived SFRs (Cohen et al. 2000; Franceschini et al. 2001).

FIR/sub-mm derived SFH exhibits a rise to $z \sim 1 - 2$ but then remains roughly constant for $z > 1$ (e.g. Rowan-Robinson et al. 1997; Dwek et al. 1998). At high redshifts it then declines.

1.6.1.3 Radio

Radio is a very indirect SFR indicator ($\leq 10^{-4}$ of bolometric luminosity) and relies on the complex and poorly understood physics of cosmic ray generation and confinement. The radio emission from normal galaxies is mainly synchrotron radiation from relativistic electrons (dominates for $\geq 1\text{cm}$ or $\leq 30\text{GHz}$), and free-free (thermal) emission from HII regions (see Condon 1992 for an extensive review). The thermal re-radiation by dust dominates for $\lambda \leq 1.5\text{mm}$ ($\geq 200\text{GHz}$).

The leading accelerator candidates for cosmic rays are type II and Ib Supernova Remnants (SNR’s) since they provide sufficient mechanical energy in shocks and are the strongest non-thermal sources in our Galaxy. SNIa are less important (an older stellar population) as they are much less common in late-type galaxies. Other accelerators are spiral shocks (spiral arms) and mergers/collisions.

The role of SNR’s has been reinforced by the very tight and general correlation between global FIR and the radio continuum (reviewed by Condon 1992). Such a correlation would suggest that massive stars dominate both radiation mechanisms, and hence that the supernova rate determines the non-thermal radio luminosity. Deviations from the correlation can usually be corrected by subtracting a FIR cirrus

contribution.

A problem with this interpretation arises since dividing the total radio luminosity of a galaxy by the typical luminosity of an SNR implies supernova rates that are far too high (Biermann 1976; Kirk 1994). This problem can be avoided if one is able to assume that the accelerated electrons, and perhaps the acceleration process itself, endure beyond the lifetime ($\sim 20,000$ yr) of detectable remnants (Condon & Yin, 1990). Using the Galactic supernova rate, Condon (1992) (and see also: Cram et al. 1998; Haarsma et al. 2000; Sullivan et al. 2001) derived the following relation, for a Salpeter IMF of mass range 0.1 to $120M_{\odot}$,

$$M_{*, M \geq 5M_{\odot}} = \frac{L_{\nu}(1.4\text{GHz})}{4.0 \times 10^{21} \text{WHz}^{-1}} M_{\odot} \text{yr}^{-1} \quad (1.7)$$

The $L_{1.4\text{GHz}}$ to SFR calibration may not be perfectly linear, particularly for low SFR sources where some fraction of the SNR-accelerated cosmic rays can escape the galaxy (Condon et al. 1991), meaning that the SFR would be underestimated.

An alternative route from the radio luminosity to SFR instead postulates that the major contributors to the non-thermal emission are radio supernovae (lifetimes of ~ 100 yr), rather than remnants (Colina & Perez-Olea, 1995). This model predicts a value of SFR within a factor of 2 of that given by Eqn. 1.7.

The thermal radio luminosity indicates the total photo-ionisation rate - the current number of massive short-lived stars - since it emerges directly from HII regions and its intensity is proportional to the production of Ly continuum photons. It can be distinguished from the steeper ($\alpha \sim 0.8$ where $S \propto \nu^{-\alpha}$) non-thermal emission via total flux densities, or maps at two or more frequencies, since the thermal emission is almost flat ($\alpha \leq 0.1$). However, the free-free component is usually weaker than the steeper synchrotron radiation so the observed thermal fractions S_{Th}/S are small and uncertain.

There is also a correlation between $S_{1.4\text{GHz}}$ and $\text{H}\alpha$, even though the total flux densities are completely dominated ($\sim 90\%$) by non-thermal emission at 1.4GHz (since there seems to be a correlation between thermal radio emission and the total radio emission).

Estimates of SFR based on $\text{H}\alpha$ luminosities follow the trend of those predicted by $S_{1.4\text{GHz}}$ or L_{FIR} , but tend to lie below the trend at high SFR and above the trend at low SFR. Again, this general correlation supports the view that the underlying source of both the $\text{H}\alpha$ and the FIR luminosity are massive stars. The systematic

deviations at low radio luminosity could be due to the difficulty in accounting for underlying $H\alpha$ absorption in the presence of weak $H\alpha$ emission. Deviations at high radio luminosities could be due to:

- increased extinction in these high SFR objects;
- the loss of $Ly\alpha$ photons by grain opacity or free escape;
- an IMF which weights the high-mass stars, mainly responsible for $H\alpha$, and the lower mass stars which dominate the supernova numbers, differently.

SFR via radio benefits from high positional accuracy ($\leq 1''$) to indentify star-forming regions and is able to detect the most intense starbursts, which are only 'visible' at radio and FIR wavelengths. Radio is also preferable to optical/IR (e.g. Hydrogen Brackett series) recombination lines for detecting HII, especially for the most luminous HII or compact starbursts with high dust extinction, even at near IR wavelengths.

Radio has its limitations however. Firstly, it biases towards luminous sources, and secondly, it suffers from AGN contamination ($\sim 20\%$). AGN domination can be recognised from radio morphology, and from FIR/radio flux density ratios or the FIR spectral index.

1.6.1.4 Pei, Fall and Hauser

A very different approach to SFH was carried out by Pei et al. (1999). They combined extragalactic IR background measurements and optical imaging/redshift surveys with QSO absorption-line systems (in particular, those with the highest column densities - the Damped $Ly\alpha$, $1215\text{\AA}$, systems), using a set of coupled equations linking the stellar, gaseous and radiation contents of the Universe to derive the cosmic SFH out to $z \sim 5$. They found a UV correction factor of 2.5, 3-4, 2-8 for $z=0$, 1, 3 respectively. Crucially, they were able to self-consistently account for dust using the IR background measurements. The resulting SFH exhibits a period of sustained SFR from $z \sim 2 - 3$. Their study, being optically selected, suffered from bias in that the highest column density, N, systems would have been missed. However the radio-selected QSO survey (CORALS) carried out by Ellison et al. (2001) found no $N \geq 10^{25} \text{m}^{-2}$ population, strengthening the previous findings.

1.6.1.5 X-ray

A galaxy undergoing star formation is also a source of X-rays. These X-rays arise from accreting X-ray binaries, both high mass (HMXBs) and low mass (LMXBs), from supernova remnants (SNRs), from Compton up-scattered IR photons, and also from diffuse hot gas which has been shock-heated by mergers, superwinds, stellar winds and supernovae. The contribution of SNRs and Compton scattering is not thought to contribute significantly to the total X-ray luminosity.

In the soft X-ray band (0.5 to 2 KeV) the emission from the diffuse hot gas often dominates, whereas the hard X-ray band (2 to 10 KeV) is usually dominated by emission from X-ray binaries.

HMXBs require an O or B star companion and have a short evolutionary timescale - ‘turning’ on after $\tau \leq 2 \times 10^7$ years and lasting for $\sim 100,000$ years. This short timescale means that they trace the star formation rate. In contrast, LMXBs only turn on after $\sim 10^{10}$ years and have lifetimes of $\leq 10^7$ years so are therefore not a tracer of current star formation. In an elliptical galaxy, it is the LMXBs that dominate the hard X-ray flux, but in starforming and starbursting galaxies the HMXBs dominate the flux and can be used as an SF-tracer (e.g Grimm et al. 2003). An important benefit of hard X-ray-based SFR is that hard X-rays are largely free from the effects of absorption and hence are not biased by extinction.

Soft X-rays, on the other hand, suffer from absorption by the neutral gas intrinsic to the SF regions and galaxies, as well as some Galactic absorption. The weaker link between soft X-rays and SFR makes them a less robust SF indicator. However, correlation between soft X-ray luminosity and other SFR indicators such as $L_{1.4\text{GHz}}$ the FIR have been seen. Additionally, all X-ray SFR measures at high redshift measure the soft X-ray flux since at high redshift this corresponds to restframe hard X-ray flux.

The evidence that X-ray luminosity can be used to measure SFR is largely empirical. The first strong indication came when David et al. (1992) found a strong correlation between FIR and X-ray luminosity in a sample of normal and starburst galaxies drawn from the *IRAS* Bright Galaxy Sample (Soifer et al., 1986) that had measurements from the *Einstein X-ray satellite* (Giacconi et al., 1979). Their study found that $L_{x\text{-ray}}$ varied as $L_{60\mu\text{m}}^{0.7}$. A more recent study by Ranalli et al. (2003) found a tight linear relationship between $L_{x\text{-ray}}$ and $L_{1.4\text{GHz}}$ and L_{FIR} for local and low redshift star forming galaxies.

Grimm et al. (2003) related HMXB luminosity to the SFR by using $\text{H}\alpha$, UV, FIR and radio measurements, with a result in good agreement with that of Ranalli

et al. (2003). The dependence of the total X-ray luminosity of a galaxy due to HMXBs on SFR has been observed to have a break at an SFR of $\sim 4.5 M_{\odot} \text{yr}^{-1}$ for $M > 8 M_{\odot}$. Above this SFR there exists a linear L_X - SFR regime (see Eqn. 1.8), due to the existence of a cut-off in the luminosity function, below this SFR the L_X - SFR dependence is then non-linear (Eqn. 1.9). Hence these X-ray SFR relations which relate total X-ray luminosity to SFR may break down at low SFR (mainly due to contamination by LMXBs).

Perhaps the main limitation of X-ray SFR measures is the contamination from an AGN component. Recent surveys have shown that AGN probably account for most of the hard X-Ray background, but there have been many suggestions that SF galaxies could emerge at fainter fluxes and perhaps account for a significant fraction of the soft and hard X-ray energy density. The problem of AGN contamination is a large one, and really requires multi-wavelength data (such as radio morphologies etc) in order to identify AGN sources, though the X-rays themselves can be a good indicator of the AGN since bright or moderate AGN can be easily identified. Lower luminosity AGN are currently difficult to separate out.

Hence X-ray observations of non-AGN galaxies at high redshift will become increasingly important tracers of SFH.

$$M_{*,\text{all}} = \frac{L_X(2 - 10\text{Kev})}{6.7 \times 10^{39} \text{ergs}^{-1}}, \quad (1.8)$$

$$M_{*,\text{all}} = \left[\frac{L_X(2 - 10\text{Kev})}{6.7 \times 10^{39} \text{ergs}^{-1}} \right]^{0.6} \quad (1.9)$$

1.6.2 Creating a Madau Plot

The so-called ‘Madau Plot’ (Madau et al. 1996) shows the SFR/unit comoving volume as a function of redshift - the SFH of the Universe. In order to properly create one the following factors need to be considered:

1.6.2.1 Incompleteness corrections

Observational data will usually be flux-limited. This means that the absolute luminosities of the faintest objects in the survey will alter with redshift. This impacts on the true redshift dependence of the derived total luminosity density since the survey becomes more and more biased to the highest luminosity objects at high redshifts.

To account for this a functional form such as the Schechter (1976),

$$\Phi(L)dL/L^* = \Phi^* \left(\frac{L}{L^*} \right)^{-\alpha} e^{-L/L^*} dL/L^*, \quad (1.10)$$

is fit to the observed luminosity function $\Phi(L)$. The total luminosity density ρ_L is then

$$\rho_L = \int \Phi(L)LdL = \Phi^* L^* \Gamma(\alpha + 2) \quad (1.11)$$

The value of α is important since if it is > -1 then faint galaxies make an important contribution (and it is the faint galaxy population which is the hardest to observe and correspondingly least well constrained).

Luminosity functions for IR sources detected with the SWIRE survey carried out with the *SPITZER* space telescope (see Chapter 2 for information on this survey) will be calculated in Chapter 5. These calculations will make use of photometric redshifts and SED fitting in order to apply K-corrections and use the *accessible volume* method of Avni & Bahcall (1980) to determine luminosity functions for each *SPITZER* waveband.

1.6.2.2 Correction for dust

If the tracer of star formation is an optical or UV luminosity then the effects of dust extinction are often important, and need to be corrected for. For instance, the results of Steidel (1999) of Lyman Break galaxies at $z \sim 3$ showed a factor of 4.7 extinction at $\sim 1500\text{\AA}$ for LBGs brighter than R of 25.5 (or $0.4L_\odot$ at that redshift). This factor was derived from the observed $E(B-V)$ distribution and use of the Calzetti (1999) reddening law. Hence a conservative dust correction for UV samples would be to apply a factor 4.7 to all galaxies brighter than $0.4L_\odot$ (assuming similar dust extinctions at different redshifts). Even extinction corrected UV/ $H\alpha$ SFRs are discrepant with FIR/Radio estimators, hence an SFR (or luminosity) dependent extinction correction may be required. Such a correction works well for $H\alpha$, but not so well for UV (particularly at high redshift).

Devriendt et al. (1999)'s modeling of dusty SEDs from the UV to sub-mm attempted to incorporate dust self-consistently. This resulted in a correlation between SFR and luminosities, for a Salpeter IMF of mass range $0.1\text{--}120M_\odot$, at two UV wavelengths:

$$M_{*,\text{all}} = \left[\frac{\lambda L_\lambda(280\text{nm})}{7.7 \times 10^{34}\text{W}} \right]^{1.62} \quad (1.12)$$

and

$$M_{*,\text{all}} = \left[\frac{\lambda L_{\lambda}(160\text{nm})}{9.2 \times 10^{34}\text{W}} \right]^{1.72} \quad (1.13)$$

Although their model galaxies have a large scatter about these best-fit correlations, the non-linearity of the relationships they describe between SFR and UV luminosity is qualitatively expected since a more massive starburst is also dustier. This means that the effect of dust on the UV observations can be accounted for (albeit crudely).

1.6.3 Current views on SFH

Significant progress in understanding global galaxy evolution as a function of redshift has been made with the advent of large-scale spectroscopic surveys. The first study of SFR to $z \sim 1$ was made by Lilly et al. (1996) who studied the cosmic evolution of the field galaxy population using the CFRS. They showed that this population had evolved and that the evolution was strongly related to galaxy colour - there was an increase in SFR with look-back time.

Ellis et al. (1996) confirmed this with redshift survey data over a similar redshift range and concluded that the steepening of the luminosity function with look-back time was the result of the increasing space density of blue star-forming galaxies at moderate redshift.

These SFH studies were extended to higher redshift by deep optical surveys (e.g. the HDF North and South). Madau et al. (1996) used the UV surveys of Lilly et al. (1996) and UV dropout galaxies (the Lyman-break technique: Steidel et al. 1996a; Steidel et al. 1999) in the HDF-N to derive the SFH from $z \sim 0 - 4$ (also see Madau et al. 1998), with the $H\alpha$ surveys of Gallego et al. (1995) providing the local, $z \sim 0$ SFR. This first ‘Madau plot’ of SFH, for galaxies between $0 < z < 4$, indicated that the peak SFR occurred at $1.3 < z < 2.7$.

The first ‘complete’ pictures of SFH came with the combination of these findings with the mid-IR/optical HDF survey ($0.2 < z < 0.5$) of Connolly et al. (1997). The analysis revealed an increase in star formation with redshift, peaking at $z \sim 1 - 2$ (also see Pettini et al. 1998; Steidel 1999), and declining thereafter.

There have now been many more studies of SFH using a variety of methods (e.g. Rowan-Robinson 2001b; Cole et al. 2001; Baldry et al. 2002; Lanzetta et al. 2002; Rosa-González et al. 2002; Hippelein et al. 2003), though this is not to say that SFH derived from different methods have yet converged on an ‘answer’. Most recent SFH studies, observing young stars in distant galaxies at different epochs,

have indicated that SFR peaked at redshifts of $\sim 1 - 2$, and then declined by an order of magnitude to its present value.

It seems likely that the most robust route to a cosmic SFH is a combination of all the techniques mentioned: local SFH is well determined by local optical/UV surveys (Tresse & Maddox 1998; Treyer et al. 1998), medium redshifts are covered by spectroscopic near-IR surveys (such as Gronwall 1999) and high redshift SFR is determined by deep (photometric) FIR and sub-mm surveys (e.g. Hughes et al. 1998; Blain et al. 1999b).

Figure 1.8 shows the results of a variety of SFH studies, but see below.

1.6.4 Alternatives

In Heavens et al. (2004) a complementary approach was adopted, in which the fossil record of the stellar populations of 96,545 nearby galaxies, from the first release of the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2003), was studied by parameterizing their constituent stellar populations into a range of age bins. This method decouples the star formation from the mass assembly by taking into account all the stars which end up in normal galaxies today. The potential problem with this approach to the SFH is that the high redshift SFR is inferred from galaxies at low redshift, and it might be expected that this will be prone to its own set of biases.

Heavens et al's results broadly support those derived from high redshift galaxies (see Figure 1.8) but find, however, that the peak of star formation was more recent, at $z \sim 0.5$, in contrast to the so-called 'galactic downsizing' picture which predicts very modest recent star formation (Brinchmann & Ellis, 2000). In addition it also shows that the larger the stellar mass of the galaxy, the earlier the stars were formed (see Figure 1.9), implying a very different formation history for high- and low-mass formation. This then provides a natural explanation for why the most massive star-forming systems, such as luminous, sub-mm galaxies, should largely be found to lie at high redshifts, $z > 2$, and would support the hypothesis that bright sub-mm galaxies are the progenitors of today's massive ellipticals (e.g. Dunlop 2001).

Very recently, Hammer et al. (2004) presented direct observational evidence that supports the findings of Heavens et al., using a long term, multi-wavelength study of 195 $z > 0.4$ intermediate mass galaxies, mostly selected from the CFRS.

This found that IR observations revealed recent, efficient star formation to the extent that $\sim 14\%$ of the sample galaxies were LIRGs; sufficient to produce 38% of the stellar mass of intermediate mass galaxies and thereby accounting for the major-

ity of star formation since redshift 1. The study also showed that both morphological changes and episodic SFH in a hierarchical galaxy formation scenario could be explained by recent mergers and gas infall, such that $75\pm 25\%$ of intermediate mass spirals have recently (in the last 8 Gyr) experienced their last major merger.

The picture also accounts for, during this same period, the simultaneous decrease of the cosmic SFR, of the merger rate, and of the number densities of LIRGs, compact and irregular galaxies, whilst the densities of ellipticals and large spirals are essentially unchanged.

1.7 Continuation

As has been shown in this Chapter, the IR view of extragalactic astronomy is a key one. The next Chapter will deal with the latest space-based infrared observatory, the *SPITZER* space telescope, and the largest extragalactic survey being carried out with it; the SWIRE survey.

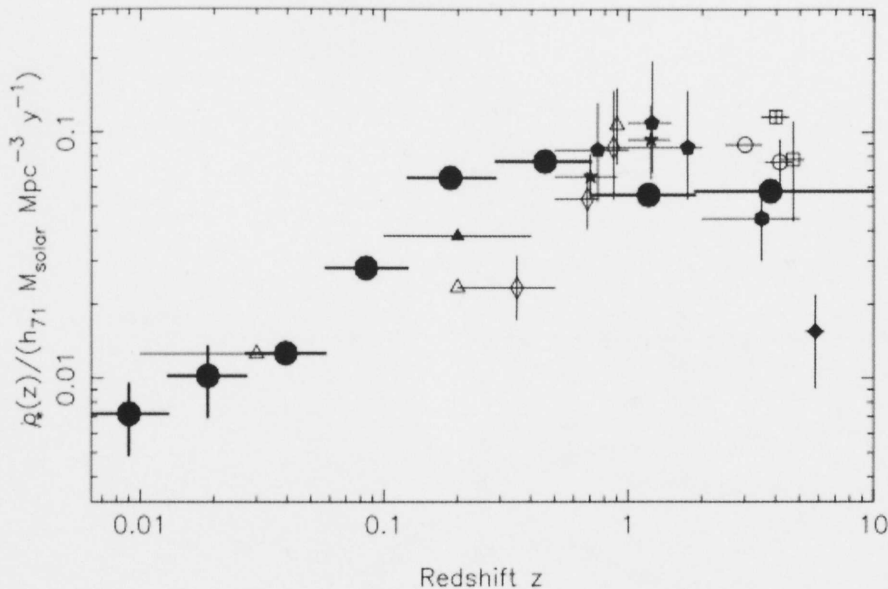


Figure 1.8: The star formation history of the Universe. Figure from Heavens et al. (2004). The star formation rate recovered from the ‘fossil record’ in the SDSS is shown by the eight large filled circles. The horizontal error bars represent the size of the bin in redshift. Vertical errors are bootstrap errors, and are invisibly small for most bins. The other symbols correspond to independent determinations using instantaneous measurements of the star formation rate, as follows; H α measurements are open triangles at $z \sim 0.03$ (Gallego et al., 1995), $z \sim 0.2$ (Tresse & Maddox, 1998), $z \sim 0.9$ (Glazebrook et al., 1999); UV from Subaru (Ouchi et al., 2004) are open squares, GOODS (Stanway et al., 2003) is a filled diamond, HST etc (Steidel et al., 1996b) are open circles, CFRS (Lilly et al., 1996) are open diamonds, HDF (Connolly et al., 1997) are filled pentagons, galaxies (Cowie et al., 1999) are star symbols, galaxies (Sullivan et al., 2000) is a filled triangle. The filled hexagon at $z = 3.5$ represents a new estimate of the star-formation density provided by sub-mm galaxies in the redshift range $2 < z < 5$. Heavens et al. derived this by integrating the sub-mm source number counts (Scott et al., 2002) down to $S_{850\mu\text{m}} = 1 \text{ mJy}$, and assuming that 75% of such sources lie at $z > 2$ (in line with recent redshift measurements - Chapman et al. 2003). In general the agreement is very good. However, there are two important results in Heavens et al. which result from the extremely small vertical error bars. First, Heavens et al. find that 26% of the mass of stars in the present-day Universe were formed at $z > 2$. Second, while they confirm the previous measurements of a generally high level of star-formation activity at $z \sim 1$, they find that global star-formation density peaked at significantly lower redshifts than previously claimed, in the bin spanning the redshift range $0.3 < z < 0.8$. The reason for this difference is clarified in Figure 1.9. h_{71} is the Hubble constant in units of $71 \text{ kms}^{-1} \text{ Mpc}^{-1}$.

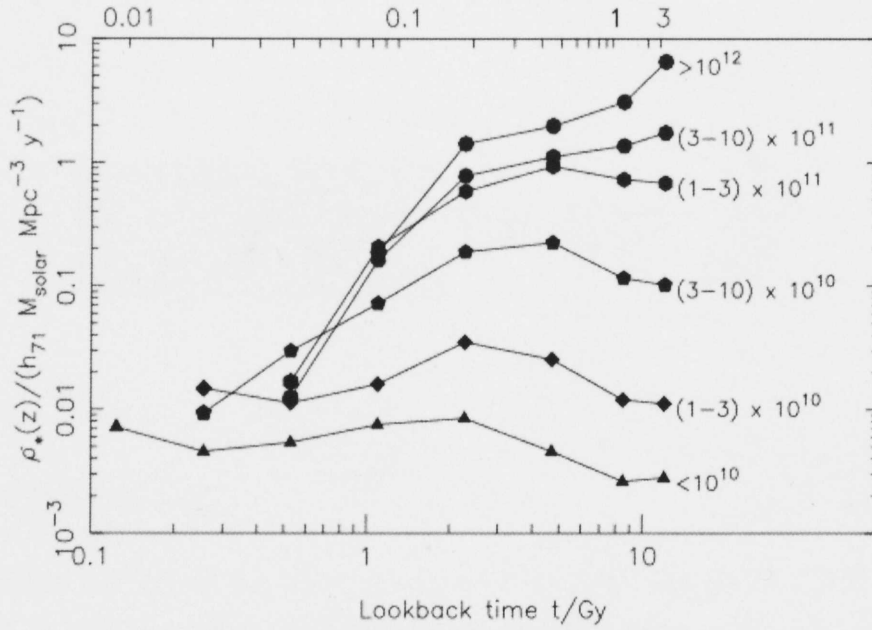


Figure 1.9: The star formation rate as a function of the observed stellar mass of the galaxy. Figure from Heavens et al. (2004). Labels are in Solar Masses. For clarity, the curves are offset vertically successively by 0.5 in the log, except for the most massive galaxies, which are offset by an additional 1.0. There is also a clear trend for galaxies with larger present-day stellar mass to have formed their stars earlier. The bulk of the star formation rate at $z \sim 0.5$ comes from galaxies with present-day stellar masses in the range $3\text{--}30 \times 10^{10} M_{\odot}$.

Chapter 2

SPITZER and SWIRE



2.1 Overview

This Chapter introduces the natural successor to *ISO*; the *SPITZER* space telescope (§2.2), and describes its instruments and the Legacy Programme projects being carried out with it (§2.3).

The SWIRE survey is the largest extragalactic Legacy project to be carried out by *SPITZER* and its unique role within the other surveys carried out by the satellite is expounded upon (§2.4). Science objectives, choice of fields and the extensive multi-wavelength data, either pre-existing or planned, are described. The data reduction procedures carried out as part of this Thesis on optical photometry taken for the SWIRE survey are detailed and the current status of the survey is summarised.

2.2 *SPITZER*

The *SPITZER* Space Telescope (Werner et al. 2004) is the fourth and final element of NASA's 'Great Observatories' (formerly *SIRTF*, the Space Infrared Telescope Facility) and was successfully launched in August 2003. *SPITZER* consists of a

0.85m telescope and 3 cryogenically-cooled instruments capable of imaging, photometry, and spectroscopy in the 3 - 180 μ m range. With a field of view of $5' \times 5'$ (in most bands), diffraction limited detectors down to $\sim 5.5\mu$ m, and sensitivities measured in μ Jys to mJys¹ it offers orders of magnitude improvements in capability over previous facilities.

2.2.1 IRAC: The Infrared Array Camera

IRAC (Fazio et al. 2004) is a camera with four channels, providing simultaneous $\sim 5.2' \times 5.2'$ images at 3.6, 4.5, 5.8, and 8 μ m (channels 1 to 4 respectively). Two adjacent fields of view are imaged in pairs (3.6 and 5.8 μ m; 4.5 and 8.0 μ m) using dichroic beamsplitters. All four detector arrays in the camera are 256 x 256 pixels in size, with a pixel scale of 1.2". Typically, the IR wavelengths covered by IRAC will be dominated by emission from evolved galaxies (from an extra - galactic viewpoint).

Table 2.1: IRAC Point-Source sensitivity (1σ , μ Jy) for low background

Frame Time (sec)	3.6 micron (μ Jy)	4.5 micron (μ Jy)	5.8 micron (μ Jy)	8.0 micron (μ Jy)
200	0.40	0.84	5.5	6.9
100	0.60	1.2	8.0	9.8
30	1.4	2.4	16	18
12	3.3	4.8	27	29

2.2.1.1 Post-Launch updates

Post-launch, IRAC was in fact found to perform better than forecast at the shortest wavelengths. The ratio of the actual point source detection threshold to the pre-launch value, for low background observations in 30 sec frames, is 0.69, 0.75, 1.60, and 1.31 in channels 1 to 4 (3.6 μ m to 8 μ m). Some issues were uncovered in flight by the *SPITZER* Science Centre (SSC), though none is at a level serious enough to require alteration of the SWIRE survey (but see §2.2.2.1 for issues at longer wavelengths that have required adaptation of the survey):

- **Persistent images in channel 1.** When a bright source ($K < 13$) is stared at for a long time (e.g. during downlink) a persistent image results in channel

¹ 5σ in 500 sec, including confusion.

1 that persists for several hours. Annealing the array after downlinks (briefly warming the arrays up from science operating temperatures) will erase the persistent images from the array, but does not protect against persistent images from bright object observations that can accumulate on the array before the next downlink. For SWIRE, the annealing following downlink should be sufficient, in concert with dithering between observations.

- **Persistent images in channel 4.** Here, a bright source leaves a persistent image that can last for more than a week (even through IRAC power cycles). However, the amplitude of the persistent images is rather low and annealing has been found to erase the channel 4 persistent images. Again, dithering helps to get rid of these spurious images.
- **Diffuse stray light.** All IRAC images contain a stray light pattern, seen as a ‘butterfly’ in channels 1 and 2, and a ‘chess board’ in channels 3 and 4. These are due to zodiacal light scattered onto the arrays. The stray light scales with zodiacal light which, being the light source for the flat fields, means that the stray pattern contaminates the flats and the zodiacal spectrum. Hence the flat fields aesthetically remove the stray light rather well from images but will induce systematic errors of around 5% in flux calibration for point sources that fall in the peak stray light location. Dithering will mitigate this effect as it is then unlikely that a source will remain within the stray light lobes.
- **Stray light from point sources.** If a bright star is located in certain regions, known as stray light avoidance zones, then a scattered light patch will appear on the array. A redundant observing strategy will help eliminate stray light problems. Bright sources can also cause ghost images due to internal reflections and also by illuminating an image of the telescope pupil. These ghost images are not yet well-characterised, but for the purposes of SWIRE are not thought to be an issue due to the nature of the fields observed.
- **Dark spots on pick-up mirror.** There is contamination on the mirror which causes a dark spot about 10 pixels wide in channels 2 & 4. This is a 15% effect which flat fields completely correct for.
- **Muxbleed.** This occurs when a bright star trails in the fast read direction (horizontal or x) for a large number of consecutive readouts, creating a dashed line. For bright sources, muxbleed does not scale linearly with source brightness, so even a sophisticated algorithm cannot accurately remove it. However

experiments at fitting the muxbleed for bright sources indicate that the decay pattern is always the same, and only the amplitude appears to be variable. Hence the affected areas can be flagged or masked; avoiding if not solving the problem.

- **Banding and column pulldown.** A bright source on the array will cause the flux values for that entire column to be reduced by a small amount. An algorithm to cosmetically correct the images for column pulldown has been developed and is being tested by the *SPITZER* Science Centre (SSC). An analogous effect for an extremely bright source is that the entire image appears to have a different dark current level from the preceding and following images. The physical origin of these effects and the probably related (and already known) banding effect is not yet understood. This work is in progress at SSC.

More information on the in-flight performance and calibration of IRAC can be found in Hora et al. (2004).

2.2.2 MIPS: Multiband Imaging Photometer for *SPITZER*

MIPS (Rieke et al. 2004) extends the *SPITZER* Space Telescope's capabilities for imaging and photometry to broad spectral bands centered nominally at 24, 70, and $160\mu\text{m}$, and is also capable of low-resolution spectroscopy between 51 and $106\mu\text{m}$. The instrument contains 3 separate detector arrays each of which resolves the telescope Airy disk with pixels of size $\lambda/2D$ or smaller (recall the Rayleigh criterion for resolution of a point source is $1.22\lambda/D$). All three arrays view the sky simultaneously: multiband imaging at a point is provided via telescope motions. The two shorter wavelength bands provide roughly $5'$ square fields of view (FOV); the $160\mu\text{m}$ array projects to the equivalent of a 0.5 by $5'$ FOV and fills in a $2 \times 5'$ image by multiple exposures. The $70\mu\text{m}$ array has a narrow FOV/higher magnification mode, and is also used in a spectroscopic mode.

2.2.2.1 Post-Launch updates

Following *SPITZER*'s successful launch, several divergences from predicted pre-launch capabilities have transpired. Although MIPS' $24\mu\text{m}$ array works exactly as anticipated (if not better), there are some issues at the longer wavelengths, as determined by the SSC:

- The $70\mu\text{m}$ array suffers from thermally-activated high resistance in a cable connection that is external to the instrument, but feeds it. This results in a

fixed-pattern noise on side B of the array, meaning that the signal-to-noise ratio and sensitivity are much better on side A than on side B. Hence half of the array is not as useful as had been hoped, and efforts are being focused on optimal use of side A. Also, one readout on side A is inoperative, resulting in a slightly reduced detector area.

- One block of 5 contiguous pixels in the $160\mu\text{m}$ array exhibits anomalous behavior due to a thermally-activated short in cabling external to MIPS. In data oriented as observers receive it, this block is located in the bottom row (the third group of 5 pixels in from the left). The most current analysis suggests that these pixels are $16''$ by $18''$.
- The SED slit was originally designed to be offset with respect to the array such that an 8×32 portion of the array is not illuminated in SED mode. This strip would then be able to provide a dark measurement for the $70\mu\text{m}$ array when taking measurements in Total Power (TP) mode; the other two arrays can be put in the dark by suitable positioning of the scan mirror. This special treatment for the $70\mu\text{m}$ array in TP mode is required because of the multiple $70\mu\text{m}$ optical paths which might allow light to contaminate the dark measurement. Unfortunately, this region falls on side B of the $70\mu\text{m}$ array, i.e., the noisier side. Further work on this issue is pending.
- Observations of K stars at $160\mu\text{m}$ were found to be $5\times$ stronger than expected. This has been determined to be due to a weakness in the stray light control resulting in a short-wavelength ($\sim 1 - 1.6\mu\text{m}$) light leak in this band.

The MIPS best-known sensitivity numbers are currently as follows:

The $24\mu\text{m}$ sensitivity for an unresolved point source is now estimated to be about $110\ \mu\text{Jy}$ in 500 seconds (5 sigma) on the darkest regions of sky, or about 1.5 times deeper than pre-launch predictions.

The good side of the $70\mu\text{m}$ array (default pixel scale) currently reaches a sensitivity level of about 6 mJy in 500 seconds (5 sigma) on dark sky for an unresolved point source, or about 3 times worse than pre-launch predictions.

The $160\mu\text{m}$ array currently reaches sensitivity levels of about $15 (\pm 5)$ mJy in 500 seconds (5 sigma, without confusion) for an unresolved point source on dark sky, about a factor of two worse than pre-launch predictions.

2.2.3 IRS

The Infrared Spectrograph (IRS) provides the *SPITZER* Space Telescope with low and moderate resolution spectroscopic capabilities from 5.2 to 38.0 μ m. The IRS is composed of four separate modules, with two of the modules providing $R \sim 64$ –128 spectral resolution over 5.2–38 μ m and two modules providing $R \sim 600$ spectral resolution over 9.9 to 37.2 μ m. Each module has its own entrance slit in the focal plane and there are no moving parts.

The IRS was designed to achieve high sensitivity at the expense of reduced dynamic range. Therefore, observers should take great care in interpreting weak spectral features. The low-resolution modules employ long slit designs that allow both spectral and one-dimensional spatial information to be acquired simultaneously on the same detector array. Two small imaging sub-arrays (‘Peak-up arrays’) in the short-low (SL) module allows objects to be placed accurately into any of the IRS entrance slits and will provide images of sources for photometric or structural information. The high-resolution modules use a cross-dispersed echelle design that allows broad spectral coverage in a single exposure.

2.3 The *SPITZER* Legacy Science Programme

NASA has sponsored the *SPITZER* Legacy Programme to undertake large projects of long-lasting and wide-ranging interest to the community. The six approved projects total over 3100 hours of *SPITZER* observing time, most of which is scheduled in the first year of the mission. The Legacy Programme projects typically mesh with substantial ancillary data from other space observatories and ground-based facilities and will provide catalogues, image mosaics and post-pipeline data analysis tools to the community. As such they will be invaluable to researchers who plan future *SPITZER* observations and follow-ups. The six Legacy projects are briefly described here:

- **From Molecular Cores to Planet-Forming Disks, P.I. Neal Evans II.**

Using IRAC, MIPS and IRS with 400 hours of observing time this aims to survey local molecular clouds and carry out follow-up spectroscopy of young and embedded stellar sources. Primary science drivers are the study of evolution of molecular cores into protostars and disks, and the early evolution of sub-stellar objects.

- **GLIMPSE: Galactic Legacy Infrared Mid-Plane Survey Extraordinaire, P.I Ed Churchwell.**

With the goal of studying the structure of the inner Galaxy and the statistics and physics of star formation this project will use 400 hours of IRAC imaging to image the inner Galaxy from 10 to 70 degrees on either side of the Galactic Centre, and also one degree above and below the plane - a total area of 240 deg².

- **GOODS: Great Observatories Origins Deep Survey, P.I Mark Dickinson.**

Designed to be a deep extragalactic survey, this will combine 647 hours of *SPITZER* time in $\sim 300''$ of the *Hubble* Deep Field North and the *Chandra* Deep Field South with deep observations from *Hubble*, *Chandra*, *XMM-Newton* and ground-based observatories in order to study galaxy formation and evolution out to early epochs.

- **SINGS: The *SPITZER* Nearby Galaxies Survey - Physics of the Star-Forming ISM and Galaxy Evolution, P.I. Robert Kennicutt.**

Designed to conduct a comprehensive imaging and spectroscopic survey of 75 nearby galaxies, using 512 hours of *SPITZER* time to explore their large-scale IR properties and thus understand the physical processes that link star formation to the ISM.

- **SWIRE: The *SPITZER* Wide-area InfraRed Extragalactic Survey, P.I. Carol Lonsdale.**

An extragalactic imaging survey in IRAC and MIPS across a wide area, with 851 hours of *SPITZER* time. The survey is designed to trace the evolution of spheroids, dusty star-forming galaxies and AGN out to redshifts of ~ 2 . SWIRE is described in more detail in §2.4.

- **The Formation and Evolution of Planetary Systems: Placing Our Solar System in Context, P.I. Michael Meyer.**

A project with 350 hours of *SPITZER* time to carry out imaging and spectroscopy of hundreds of young stars with accretion disks, both young and old. This will enable the evolution of planetary systems to be traced from stellar accretion through to the planetary debris disk phase.

2.4 The SWIRE survey

Two of the six approved Legacy Programmes are dedicated to complementary, deep IR cosmological surveys. Of the two, the *SPITZER* Wide-area Infrared Extragalactic Legacy Survey (SWIRE: P.I. Carol Lonsdale, Lonsdale et al. 2003) is the largest, with 851 hours to originally survey 67 square degrees of the most transparent, low-background extragalactic sky. SWIRE is a wide-area, high Galactic latitude imaging survey in 6 (originally 7) fields, in all 7 *SPITZER* imaging bands : IRAC 3.6, 4.5, 5.6, $8\mu\text{m}$ (dominated by evolved galaxies), and MIPS 24, 70, $160\mu\text{m}$ (dominated by Starbursts and LIRGs). These bandpasses are shown in Figure 2.1. It is intended to enable fundamental studies of cosmology and galaxy formation in the mid/far-IR, for the key redshift range $0.5 < z < 2.5$ where much of cosmic evolution has occurred. Building on ISO's heritage, SWIRE complements GOODS and smaller, deeper GTO (Guaranteed Time Observer) *SPITZER* surveys, and paves the way for *HERSCHEL* ($80 < \lambda < 670\mu\text{m}$; 2007 launch).

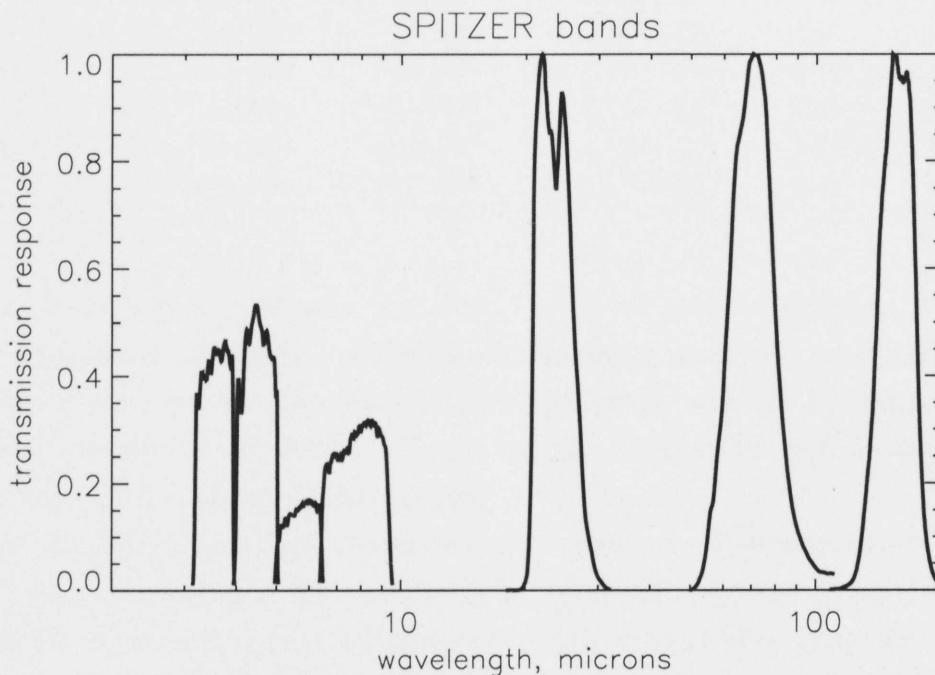


Figure 2.1: The seven *SPITZER* imaging bandpasses, as used in the **SWIRE** survey. The filter transmission curves include the relevant instrument efficiencies. IRAC responses are updated post-launch versions. MIPS responses are still pre-flight versions pending an update from the *SPITZER* Science Center.

2.4.1 Survey details

The SWIRE survey fields (see Table 2.2) were selected using the Schlegel et al. (1998) COBE-normalised IRAS $100\mu\text{m}$ maps (see Figure 2.2) to locate areas with $I(100\mu\text{m}) < 0.4 \text{ MJysr}^{-1}$; ecliptic latitudes $|\beta| > 40^\circ$; and contiguous area > 8 square degrees (Oliver, Lonsdale & Smith 2002). Prime areas were then chosen for the minimum contamination from bright stars/galaxies/radio sources, cirrus knots and nearby galaxy clusters. The availability of multi-wavelength supporting data was also a factor; for instance SWIRE also includes 9 square degrees in the XMM-LSS survey area (Pierre et al. 2001) due to its unique X-ray data set (even though $I(100\mu\text{m}) \sim 1.1 \text{ MJysr}^{-1}$).

Table 2.2: The 6 SWIRE fields, following the revision of the SWIRE observing strategy caused by the reduction in MIPS performance post-launch.

Field	RA centre (J2000)	DEC centre (J2000)	area (sq. deg.)	I100 μm (MJy/Sr)	E(B-V) (mag)
ELAIS-S1	00h 35m 00s	-43°40'00"	7.0 (2.34x3.0)	0.42	0.008
XMM-LSS	02h 21m 20s	-04°30'00"	9.18 (3.0x3.06)	1.3	0.027
CDF-S	03h 32m 00s	-28°16'00"	7.83 (3.0x2.61)	0.46	0.001
Lockman	10h 47m 00s	+58°02'00"	11.0 (3.66x3.0)	0.38	0.006
ELAIS-N1	16h 11m 00s	+55°00'00"	9.18 (3.0x3.06)	0.44	0.007
ELAIS-N2	16h 36m 48s	+41°01'45"	4.66 (1.87x2.5)	0.42	0.007

The area of each field was driven by the importance of studying AGN and galaxy evolution in the context of their environments; hierarchical models for galaxy formation predict earlier assembly of E/S0s in high density environments than in field (e.g. Benson et al. 2002). Thus a study of galaxy evolution needs to be undertaken in the context of environment.

The largest known local structures have volumes of perhaps $10^6 h^{-3} \text{ Mpc}^3$ ($100h^{-1} \text{ Mpc}$ linear size). This $100h^{-1} \text{ Mpc}$ comoving box size is essentially the scale on which you would expect to detect rich cluster(s) or their progenitors, so for sampling a variety of environments this field size is important. SWIRE will sample several hundred comoving volumes of length $> 100h^{-1} \text{ Mpc}$ for $0.5 < z < 2.5$, with noise due to cosmic variance addressed by the 6 (originally 7) separate target fields. Hence SWIRE allows complete, unbiased sampling of galaxy population clustering and can sample the linear regime of the power spectrum of density fluctuations.

The SWIRE fields are becoming the selected areas of the 21st century: they comprise the heart of the 100 square degree GALEX Deep Survey in the UV; will be partly covered by the UKIDSS Deep J & K Survey; one of the fields covers

the deepest pointings of the XMM-LSS survey; a major (possibly the deepest ever) VLA imaging survey at 20cm to $5\mu\text{Jy}$ *rms* has been conducted in a sub-field. An extensive optical/near-IR imaging program is underway from the ground. In the sub-mm the 0.5 square degree SHADES survey is being carried out at JCMT in two SWIRE fields and in the future *BLAST* and *HERSCHEL* will also cover these fields in the sub-mm. The available and projected ancillary data is summarised in Table 2.3 (non-optical) and Table 2.4 (optical and NIR).

Preliminary results and detailed modelling (Franceschini et al. 2001; Rowan-Robinson 2001a; Xu et al. 2002) suggest that the resulting Legacy Extragalactic Catalogue could contain in excess of 2 million IR-selected galaxies, dominated by LIRGs (as many as 40,000 at $z \geq 2$), $\sim 10^6$ early-type galaxies ($\sim 1/2$ at $z \geq 1.5$), $\sim 30,000$ classical AGN, and possibly as many as $1/4$ million dust-obscured QSO/AGN. See Table 2.5 for source densities and confusion limits.

SPITZER is extremely well suited to a shallow to moderate depth extragalactic survey of old stellar populations and dusty galaxies. The IRAC instrument was partly designed to detect red stellar populations at redshifts above 0.5 and the MIPS instrument was likewise designed to detect galaxies dominated by FIR emission from cool dust out to redshifts large enough to hopefully resolve the cosmic IR background.

2.4.1.1 ‘SWIRE II’

As mentioned in §2.2.2.1, *SPITZER*’s performance at the longer MIPS wavelengths is reduced from pre-launch estimates. This has impacted on the design of SWIRE as to reach the same sensitivity/depth at $70\mu\text{m}$ would require longer observations. In particular, since effectively half of the MIPS $70\mu\text{m}$ array is not useable due to pattern-noise, each MIPS observation needs to be repeated in order to re-observe with the good half of the array the strip of sky only observed by the bad half of the array. Due to time constraints, the question then arises whether it is more important to retain area-of-sky observed and observe to a shallower sensitivity with MIPS, or to retain depth of coverage at $70\mu\text{m}$ but sacrifice area, as it is not feasible to accomplish both.

We do not wish to make any of the observed fields significantly smaller than the others, since this then reduces the effectiveness of studies into large-scale structure - you are no longer sampling the same structuring scales in each field, and therefore your ability to overcome cosmic variance is reduced. On the other hand, if area is retained over $70\mu\text{m}$ depth, then this impacts on SWIRE science that relies on sensitivity and depth at the longer *SPITZER* wavelengths.

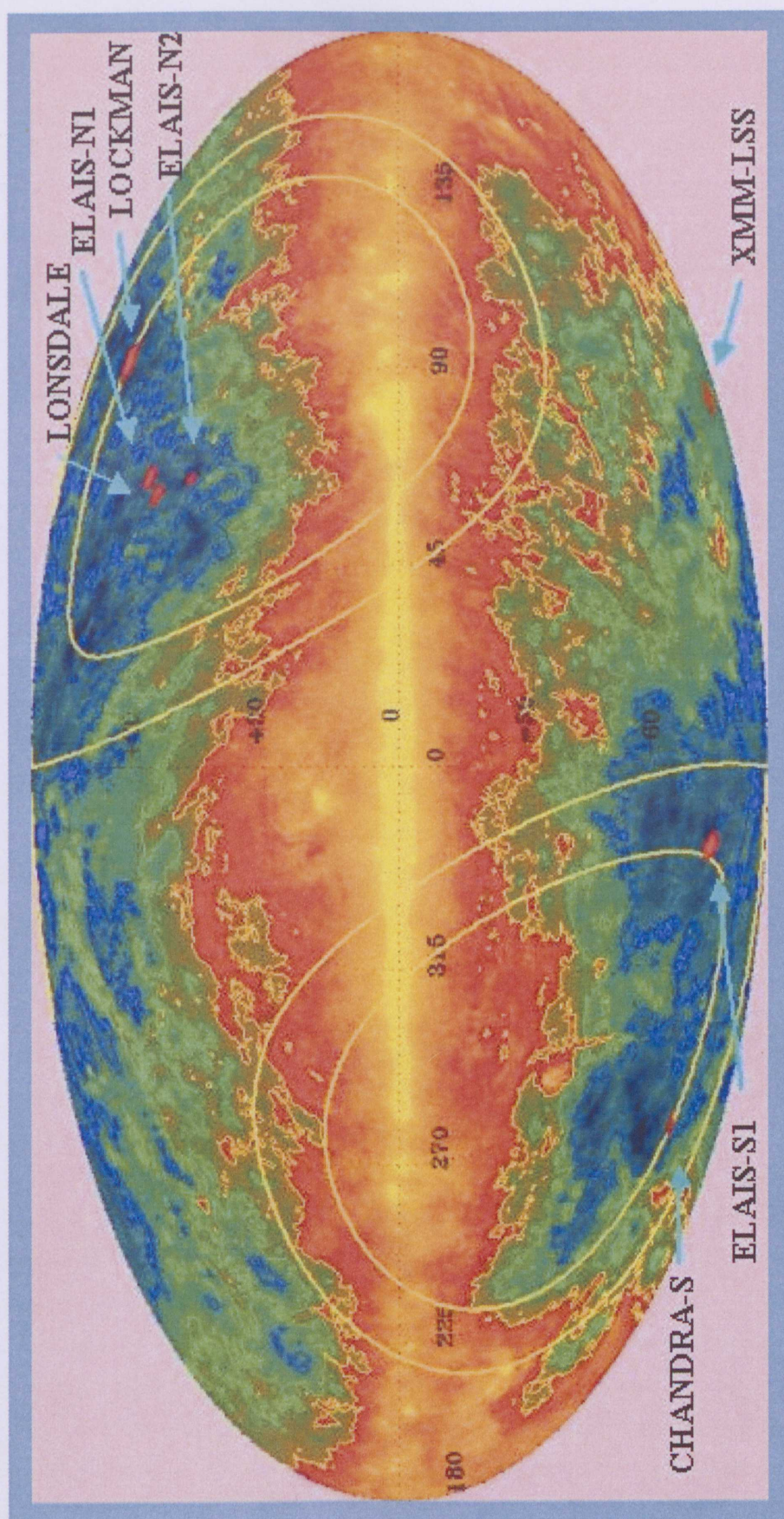


Figure 2.2: Schlegel et al. (1998) COBE-normalised IRAS $100\mu\text{m}$ map, showing original SWIRE fields. Blue areas have low $I(100\mu\text{m})$, yellow have large $I(100\mu\text{m})$. Image produced by Seb Oliver, Sussex.

SWIRE II has been designed as the best compromise of these conflicting issues. MIPS $70\mu\text{m}$ depth has been restored to the original sensitivities by doubling the amount of time that is spent on $70\mu\text{m}$ observations. This requires that the original SWIRE area of 66 square degrees is reduced to around 49 square degrees. The size of individual fields has accordingly been reduced, however in order to maximise the sampling of similar clustering and structure scales, the fields to be observed are still of comparable area. More large-scale structure information is retained by having six similar-sized fields than seven dis-similar fields. To this end, the Lonsdale field will no longer be included. This was one of the smallest fields, and also had very little supporting observations at other wavelengths. The reduced SWIRE II fields are given in Table 2.2 and the individual fields and complementary observations in the fields are shown in Figure 2.3. From now on, unless otherwise stated, reference to ‘SWIRE’ will be taken to mean the revised SWIRE II survey strategy.

2.4.2 Ancillary data

There are data taken with a variety of instruments, across a wide-range of wavelengths, that falls in the SWIRE fields; some pre-dating the SWIRE survey; some taken for the SWIRE survey; and some planned for the future. The available and projected ancillary data is summarised in Table 2.3 (non-optical) and Table 2.4 (optical and NIR). I will here restrict myself to discussing the ground-based optical photometry taken for SWIRE, as this has the most immediate relevance for photometric redshifts and resulting studies.

2.4.2.1 Ground-based data

Ground-based optical/NIR imaging data for the SWIRE fields will be essential for providing photometric redshifts. IRAC colours alone are powerful enough for stellar populations owing to the H^- opacity feature at $1.6\mu\text{m}$, but they are inaccurate at $z < 1.5$ due to the degeneracy of the stellar populations with age and confusion by the $2\mu\text{m}$ CO bandheads (Sawicki 2002). For star-forming galaxies MIPS colours are limited for photometric redshifts since there is a great variation in the SEDs of galaxies for $\lambda > 10\mu\text{m}$, where dust dominates. The use of three (or more) optical colours, coupled with the IRAC ($\lambda_{\text{rest}} < 5\mu\text{m}$) photometry will enable accurate photometric redshift determination.

The original aim was to obtain multi-colour optical imaging (SDSS g', r', i' or equivalent) down to the median optical magnitude ($r' \sim 25$) and galaxy redshift ($z \sim 1$) for the entire SWIRE Survey areas, along with complementary NIR (J, K')

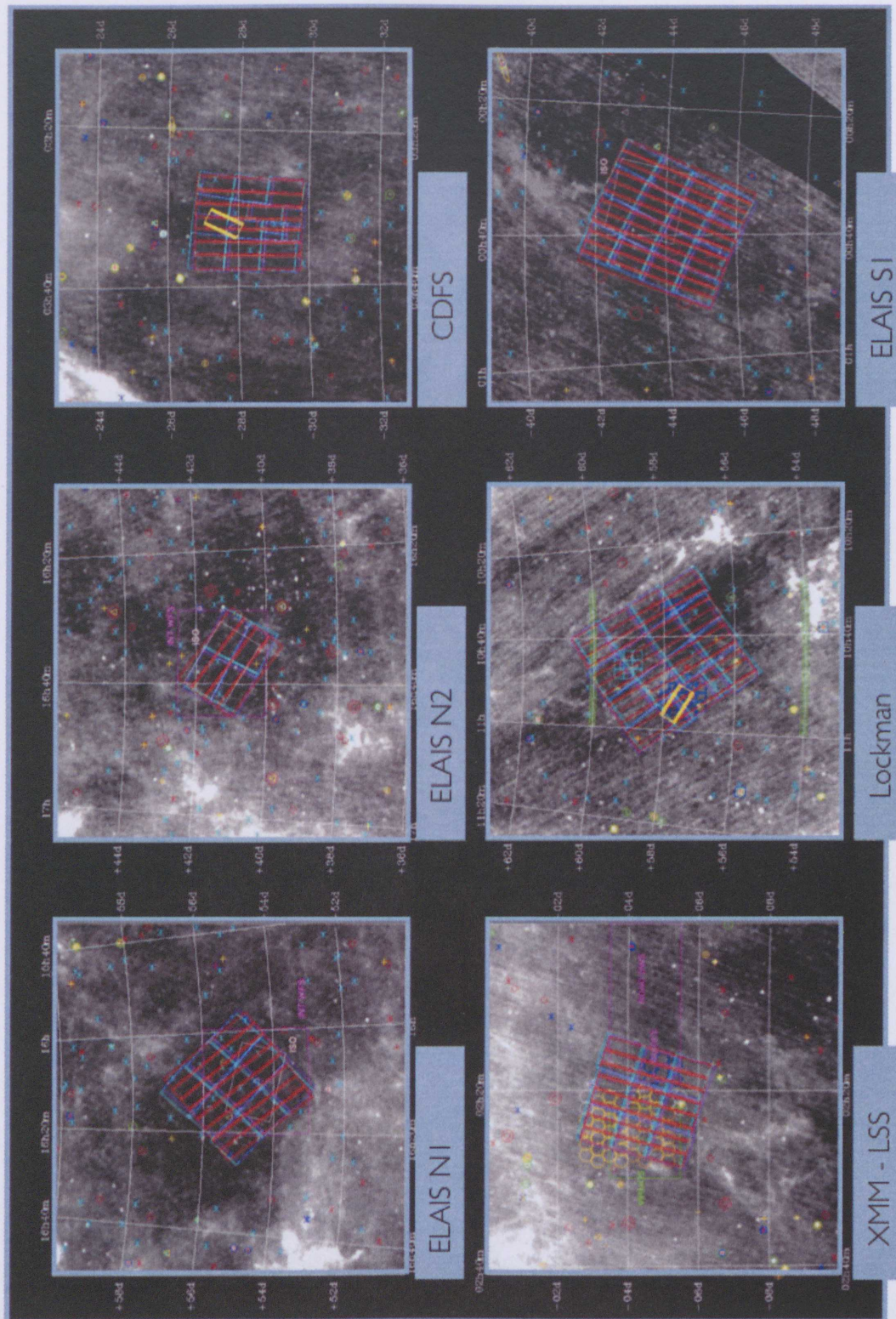


Figure 2.3: The six SWIRE II fields, following the revision of the SWIRE observing strategy caused by the reduction in MIPS performance post-launch. Background images are Galactic cirrus (IRAS $100\mu\text{m}$). Overlaid red strips are MIPS scan lines, light blue squares are IRAC fields of view (note that based on actual date of observations these may be rotated on the sky). Other ancillary data and surveys are selectively indicated. For a more in depth description please refer to Lonsdale et al. (2003). Images provided by Gene Smith, UCSD

data. This aim has proven difficult to meet. Moderate depth $R/r' \sim 24$ -25 data will be available for most of the 49 square degrees with a checkerboard of additional imaging available for other filters and to greater depths.

2.4.3 The data reduction pipeline

I have been responsible² for reducing optical survey data taken by the MOSAIC I camera on the Mayall 4m telescope at Kitt Peak National Observatory (KPNO) and the MOSAIC II on the Blanco 4m telescope at Cerro Tololo Inter-American Observatory (CTIO). Further data has been taken with the Large Format Camera (LFC) on the 5m Hale telescope at the Mount Palomar Observatory, however the quality of this data is not as good (based on preliminary reduction) and is not considered in this Thesis. Observations of a single pointing were typically made up of one (or more) sets of 5-point dithers, in an offset pattern designed to maximise uniform coverage and fill CCD-gaps. A coverage map is shown in Figure 2.4.

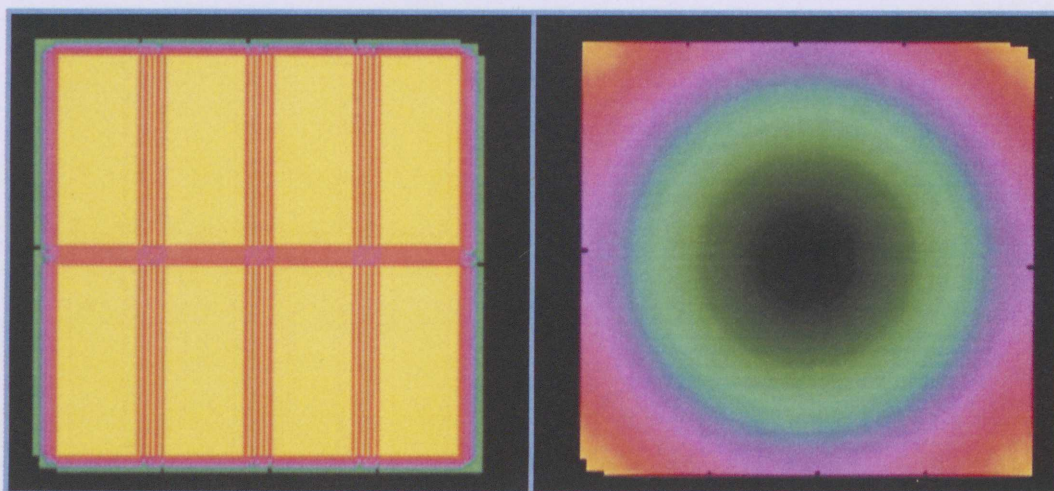


Figure 2.4: **Left figure:** The coverage map for a typical 8 chip CTIO pointing ie. 5 exposure dither with offsets (in arcseconds; ra,dec) of [0.0,0.0]; [43.2,-64.8]; [-43.2,64.8]; [21.6,32.4]; [-21.6,-32.4]. The colour coding for coverage is green 1; purple 2; mauve 3; red 4; yellow 5. **Right figure:** The photometry correction map for a typical CTIO pointing, due to mosaic distortion. 0% (black) in the middle; through green 1-2%; purple 3-5%; red 6-7% to yellow around the edges 8-9%. Maps generated by Mike Irwin.

Currently, the optical data taken in the Lockman Hole is the most complete, with 24 pointings, each of 0.33 sq. degrees, which (accounting for overlaps) gives

²Along with several others formerly at Imperial College London: Matt Fox, Simon Dye and Duncan Farrah, and more recently; Eduardo Gonzalez-Solares, Cambridge and Brian Siana, UCSD.

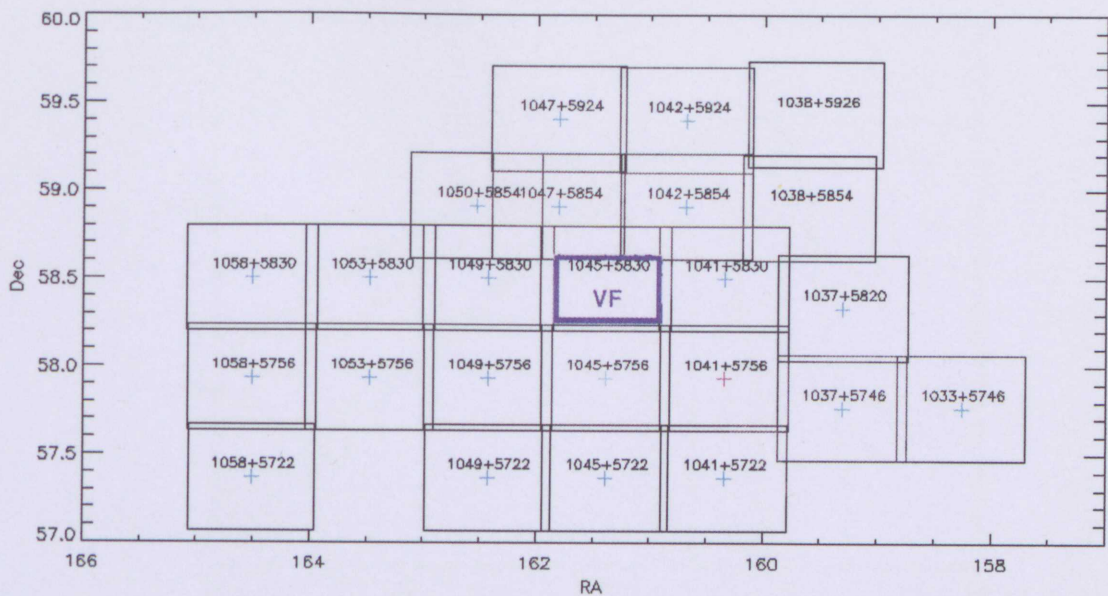


Figure 2.5: Optical pointings in the Lockman field (black rectangles). Each is 0.33 sq. degrees. The central deep optical pointing is the SWIRE Lockman VF; 1045+5830. The purple-outlined ‘hole’ is the deeper Lockman VF *SPITZER* pointing, which falls entirely within the deep optical pointing.

around 7 sq. degrees in total. All 24 pointings have r' and i' observations, 22 have g' and 4 (1.2 sq. degrees) have U . Additionally, one pointing goes deeper, covering the *SPITZER* SWIRE Validation Field (VF). Optical completeness limits are (Vega) $U \sim 25$, $g' \sim 25$, $r' \sim 24$, $i' \sim 23.3$ across the field and $U=25.0$, $g'=25.7$, $r'=25.0$, $i'=24.0$ in the deeper SWIRE VF pointing (5σ limits within a $2'$ aperture will go around 0.7 magnitudes fainter than these values). A plot of the pointings on the sky is shown in Fig. 2.5 and the optical magnitude distributions for the deeper Lockman VF are shown in Fig. 2.6.

The data reduction uses the Cambridge Astronomical Survey Unit (*CASU*) pipeline as described in Irwin & Lewis (2001). Currently, the pipeline is in a developmental stage (with full functionality), comprising a set of reduction algorithms coded in F77 and handled by Perl scripts. All procedures are therefore called as UNIX shell commands.

The pipeline adopts a standard approach. The usual steps of optical data reduction are taken; bias-correction, trimming, overscan correction, non-linearity correction, dark correction, flatfielding, CCD differential gain correction, and automatic removal of fringing. Object detection in each frame then enables photometry (where standards are available) and astrometry to be performed, using the digitised APM sky survey for reference (although any external reference catalogue can be

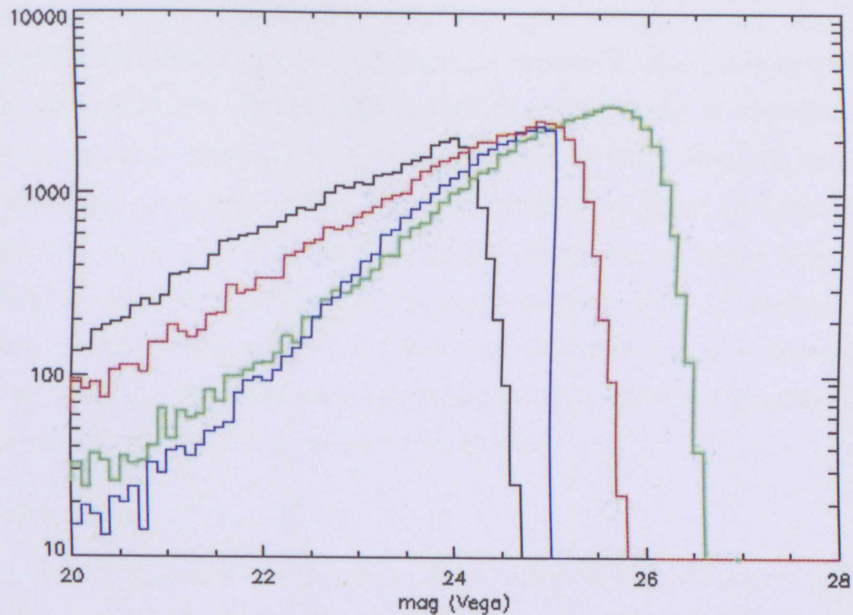


Figure 2.6: Distribution of optical source magnitudes (Vega) in the deeper pointing in the SWIRE VF located within the Lockman field. Green is U, red is g' , blue is r' , black is i' . Plot by Brian Siana, UC San Diego.

used in theory). Finally, the astrometric solutions are used for image stacking which carries out a full pixel re-binning of each frame and removes cosmics and bad/hot pixels/columns. A more detailed reduction breakdown of the procedures used in this Thesis is given in §2.4.3.2.

The philosophy behind the *CASU* pipeline is centred around the requirement of automation. Apart from some initial parameter input, almost all characteristics are derived from the data using robust statistics. This ensures minimal user input with only a small number of visual image checks being necessary at various stages throughout the pipeline.

2.4.3.1 Reduction subtleties

The *CASU* pipeline had not been used on CTIO or KPNO data before so some adaptations were necessary, in particular to handle the eight CCDs that the MOSAIC imagers use. Every instrument and telescope will have its own peculiarities and foibles and this was found to be the case with the CTIO and KPNO data. Some of these are detailed below:

- **Eight chip CCDs**

The MOSAIC cameras utilise eight CCDs. This results in eight extension FITS

images from KPNO and sixteen extension (two amplifiers per chip) FITS images for CTIO. The major complication is crosstalk, since not only do physical CCDs crosstalk; the two amplifier readouts also result in crosstalk from one CCD to the next. Furthermore, even within one CCD the two amplifier readouts generate crosstalk. This not only affects the ghost images but also the background level when stitching things together. Accordingly, appropriate 8x8 and 16x16 crosstalk matrices had to be developed. Note: Crosstalk correction for bias frames is *not* carried out since all the bias signal is generated in the ADC circuit, not the detector, and most of the pickup for crosstalk occurs in the dewar/wiring *before* it gets to the ADCs.

- **Drifting gain**

It was found that science frame images, after being bias-corrected and flat-fielded, tended to exhibit different brightness levels ($\sim 2.5\%$ effect) from chip to chip, image to image. This was found to be because the bias levels change from the zero frames taken earlier on in the evening to when the object frames are observed. This was resolved by subtracting off the overscan estimated bias from both object and zero frames before subtracting the zero frame.

- **Pupil image**

Typical reduced i' band images from CTIO were found to exhibit a ‘pupil’ type image (see Figure 2.7). The pupil max : min counts difference was about 2%. Both the CTIO (and KPNO) 4m prime-focus correctors produce pupil ghosts from light that reflects off the filters, off the back surface of the corrector, and returns through the filters to the science detectors. In the case of the CTIO 4m this added light is diffuse over the entire field. The reflected light is evident in a frame as an image of the telescope pupil. The amplitude of this ‘ghost-image’ is largest where the coating of the corrector is least effective (in this case the i' band). The pupil was removed by taking science frames from different fields (from different dither patterns)³ and combining them. Any remaining residual bright star images were removed by excluding the relevant bright frames and the resulting frame was used to characterise and remove the pupil images from the science frames. The pupil was found to be much smaller in areal extent and at a much lower level for KPNO images, to the extent that removal was not required.

- **Fringing**

³Each science field is observed five times using a ‘dithering’ co-ordinate offset.

Fringing is due to the interference patterns generated by incident light impinging on the CCD substrate and reflections between the CCDs and their supports or within the CCDs themselves. The fringing pattern in a given bandpass is a superposition of fringing from all wavelengths in the bandpass.

Typical z' band images from CTIO exhibited very obvious fringing patterns - see Figure 2.7. This problem is however easily corrected using a similar procedure as with pupil image removal.

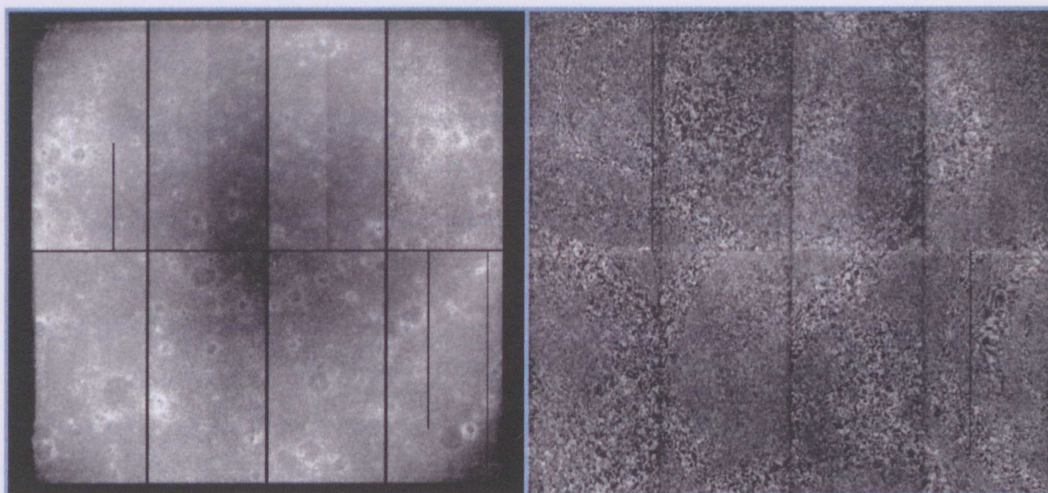


Figure 2.7: **Left figure:** Example of the pupil image removed from CTIO i' frames. The pupil is seen as a diffuse circular ring covering the entire frame, dark at the centre, and $\sim 2\%$ brighter at the edges. The smaller ‘spots’ are ghost residues of the brightest stars from the original science frames which were used to create the pupil frame. The count variation across them is too low to cause a problem ($\leq 0.5\%$). Note that the contrast has been exaggerated for presentation. **Right figure:** Example of the fringing pattern in CTIO z' frames.

2.4.3.2 Reduction procedure

The current pipeline recipe for MOSAIC camera-type data:

- 1) Stack bias frames to make master bias frame.
- 2) Trim and bias-correct (using the master bias) the flatfields.
- 3) Stack these processed flats to make a master flat.
- 4) Cross-talk correct the science frames using the 8×8 or 16×16 element cross-talk coefficient matrix.
- 5) Trim, bias-correct and flatten the science frames, using the master bias frame and master flat
- 6) Stitch 16 extension FITS files back to 8 extension FITS files if CTIO data

- 7) In order to eventually make a bad pixel mask a gain-corrected flatfield is created.
- 8) Stitch this gain corrected flat to 8 extension FITS if CTIO data.
- 9) Create bad pixel mask, using a routine that generates confidence maps for each filter, and utilises the disk files of bad pixel masks for the CCDs.
- 10) Generate catalogue of objects in all frames using an object detection routine and utilising the bad pixel mask.
- 11) Refine the astrometry using associated object catalogues now generated, hopefully producing $\sim 0.2''$ residuals.
- 12) Check if any astrometric solutions need further refinement. This may require manual astrometry correction for problem frames.
- 13) re-run step 11) since stacking critically dependent on good astrometric solution.
- 14) Morphological classification and aperture corrections, using the usual star, galaxy, noise classes.
- 15) With all astrometry OK, now need to update the headers of each CCD image with this refined pointing information.
- 16) Stack all science frames, using the bad pixel mask and the refined astrometric solutions. A confidence map of the resulting stacked image is also produced.
- 17) Produce catalogue of objects in the stacked frame, using the confidence map to weight values.
- 18) Classify objects in the stacked image as in step 14).
- 19) CCD gain normalisation is based on flats (dome or twilight). These differ from the dark sky - for example a twilight flat is bluer than most astronomical sources, and also the dark sky - and this means differences in the colour equations between the CCDs will cause the apparent *dark sky* to differ slightly. Hence the chip-by-chip dark sky percentage correction can be calculated, based on the catalogue files. A typical correction might be of order 0.3%, say.
- 20) Use the observations of standard stars throughout the night(s) to generate photometric zeropoints.
- 21) For some nights where there were few observations of standard stars, or photometric conditions were thought to be poor, the catalogues were calibrated against the SDSS photometry in that field. There are typically several hundred/thousand sources in common, allowing a well-defined stellar sequence to be created and compared as a final check of photometry. *Comparison to the SDSS was possible in ELAIS N1 and LOCKMAN.*

We now have final, flattened, stacked and photometrically calibrated images

(still 8 extension) which can be used for source extraction. For SWIRE (as recommended by *CASU*) the source-extraction was carried out on the stacked, dithered individual images.

- **Mosaicing**

It is also possible to mosaic the stacked eight extension images into a single mosaiced image. These will be used in the SWIRE survey to provide thumbnails of regions of interest etc. Accordingly, mosaicing has been carried out for all pointings. The caveat to mosaicing is that for such large-area cameras there is significant field distortion resulting in varying pixel scale across the F.O.V - the pixels on the edges of the mosaic (CTIO and KPNO) sample a smaller piece of sky than the pixels in the centre - around 13% in area. This means that they get less background light per pixel than those in the centre, so when we flatten the field to make the background uniform, we are artificially multiplying the pixels toward the edge. It makes the background uniform, but causes a problem for sources - consider the following:

The flux from an object (before flattening) will be the same on any part of the mosaic (it is just distributed over a larger number of pixels if it is near the edge of the mosaic). Therefore, the artificial flattening of the background will also artificially increase the flux towards the edges. Thus, when the image is resampled onto an image with a uniform pixel scale (when we mosaic), surface brightness conservation rather than flux conservation needs to be used.

The simplest solution is to take a simple model for the mosaic distortion (see Figure 2.4) and use the WCS information directly in the image headers to compute an accurate (ie. to better than 0.5%) correction.

2.4.4 Current status of the survey

Some early results from the SWIRE survey have been published; in Lonsdale et al. (2004) and Oliver et al. (2004):

In Lonsdale et al. (2004) the SWIRE galaxy populations were characterised for the SWIRE VF in the Lockman Hole, based on the 3.6 to $24\mu\text{m}$ *SPITZER* data and deep U, g' , r' , and i' optical imaging reduced as set out in §2.4.3. The colours of the sources covered a broad range but were generally well represented by redshifted SEDs of known galaxy populations. However, there existed significant samples of unusually blue objects in the [3.6]-[4.5] colour, as well as many objects that were red in the 3.6 to $24\mu\text{m}$ region.

In Oliver et al. (2004) a first analysis of large-scale clustering was presented. The angular correlation function of galaxies selected as bright at $3.6\mu\text{m}$ was computed, with clustering detected with a high level of significance. The results were consistent with existing clustering measurements in K-band surveys and with stable clustering models.

At time of writing (October 2004) five of the six SWIRE fields have had *SPITZER* observations completed, with the remaining field, ELAIS-S1, scheduled to be completed by the end of the year. IRAC data for ELAIS N1 and LOCKMAN has been fully reduced and bandmerged, with preliminary cross-identifications with available optical data carried out. Progress with MIPS is almost as well advanced - $24\mu\text{m}$ data is also reduced in these fields, and 70 and $160\mu\text{m}$ catalogues have also been produced. This excludes the 5 of 32 MIPS scans lost in the original observing of ELAIS N1 (now taken), and some GTO embargoed areas in the fields. Many of the artefacts found early on in the IRAC data, such as drifting bias, banding, latents and column pull-down, have now been fixed in the reduction process. The more complicated issues of muxbleed and ghosting or scattered light near bright stars are still to be fully characterised but to first order are corrected.

The SWIRE Version 1.0 data products public release (October 2004) includes an image atlas and source lists from the ELAIS-N1 field. The release includes both *SPITZER* IRAC and MIPS mid-IR data products and also U, g' , r' , i' and Z optical data covering the same regions of the sky from the Isaac Newton Telescope (INT) Wide-Field Survey (WFS) (more information on the INT WFS is given in Chapter 5). The contents and nature of the release are as follows:

The Version 1.0 SWIRE ELAIS-N1 *SPITZER* Image Atlas consists of a set of 16 1×1 degree IRAC mosaiced FITS images of the ~ 9 square degree *SPITZER* field, and three ~ 2 square degree mosaiced MIPS images, one per band. For IRAC there is one image per IRAC band per 1×1 'tile'. In addition, for each band and each IRAC tile a noise image, a coverage image and a mask image are provided, for a total of 256 IRAC FITS images.

The Version 1.0 SWIRE ELAIS-N1 Optical Image Atlas consists of a set of 16 1×1 degree optical FITS images of the ~ 9 square degree *SPITZER* field on the same tile system as the SWIRE ELAIS N1 *SPITZER* Image Atlas. There is one image per optical band per tile, for a total of 80 FITS images. The INT WFS survey images have been re-projected onto the same pixel scale and projection scheme as the *SPITZER* images so that optical and infrared data can be easily convolved.

The Version 1.0 SWIRE ELAIS-N1 Source Lists have three parts:

(1) a list including IRAC and MIPS $24\mu\text{m}$ sources which have been bandmerged together. The *SPITZER* source list has been positionally matched to the optical source list and the optical position and 5-band magnitude data are reported for each successful match. This list contains only sources lying within a region of ~ 6 square degrees which has full coverage in all four IRAC bands;

(2) a $70\mu\text{m}$ source list; and

(3) a $160\mu\text{m}$ source list.

The longer wavelength lists have not been bandmerged with the IRAC+ $24\mu\text{m}$ list or the optical source list at this time due to complex source confusion issues. These lists cover the full area scanned by each MIPS-array (except for areas of low coverage near edges) and so not restricted to the IRAC full coverage area.

It is important to note that this public release catalogue has had several cuts applied in order to ensure high reliability in these early source lists. More information on the exact criteria applied in order for a *SPITZER* source to be present in the public release are given in the SWIRE Delivery Document (Surace et al. 2004a, in prep.) and can be broadly summarised as requiring a $\text{SNR} > 20$ in one band, and $\text{SNR} > 10$ in at least one additional band, with a weighting based on coverage.

Further information on bandmerging, optical-IR associations and reliability is given in Chapter 5, where optical and IR data is used to derive photometric redshifts and construct luminosity functions. Here the full catalogue is considered and less severe cuts are imposed.

Table 2.3: Imaging Surveys (not optical/NIR) within SWIRE Fields. Adapted from Lonsdale et al. 2003.

Field	Survey	Instrument	RA h m	Dec d m	Bands	Size □°	Depth ¹
ELAIS-S1	ELAIS	ISO	0 35	-43 28	7,15,90 μ m	4	1 mJy ²
		BeppoSAX/MECS	0 35	-4 28	2-10 keV	1.7	36 ks
		ATCA	0 35	-43 28	1.4 GHz	4	80 μ Jy
XMM-LSS	XMM/Moderate Survey Subaru/XMM-Newton Deep Survey	XMM	2 24	-5	0.5-10 keV	2	20 ks
		XMM	2 18	-5 00	R	1	50&100 ks
		Subaru				1.3	28 ³
		SCUBA/SHADES			450&850 μ m	0.25	60,3 mJy
		VLA			1.4 GHz	~ 1	12 μ Jy
CDF-S	XMM/LSS VLA Survey CDF-S	VLA	2 24	-4 30	1.4 GHz	5.6	4 mJy
		Chandra	3 32	-27 48	0.5-8 keV	0.1	1 Ms
		HST-WFPC			VI	17 □	28.2
Lockman	LH-E	HST-ACS			BViz	0.25	V ~ 28
		SIRTF/GOODS			3.6-24 μ m	300,50 □	4.0,02 μ Jy ⁴
		SIRTF/GTO			3.6-160 μ m	0.4	0.11 mJy ⁵
		ROSAT-HRI	10 53	57 29	0.5-2 keV	0.13	1.2 Ms
		ROSAT-PSPC	10 52	57 21	0.5-2 keV	0.3	200 ks
		XMM	10 53	57 29	0.5-10 keV	0.2	190 ks
		Chandra	10 53	57 29	0.5-8 keV	1.35	5 ks
		ISO	10 52	57 21	7,15,90,175 μ m	0.1-0.5	3 mJy ²
		VLA	10 52	57 29	6.20 cm	0.35,0.09	11,30 μ Jy
		SIRTF/GTO			3.6-160 μ m	0.4	0.11 mJy ⁵
ELAIS-N1	LH-W	SCUBA 8mJy	10 52	57 22	450&850 μ m	130 □	8 mJy
		VLA			20cm	100 □	5 μ Jy
		SCUBA/SHADES			450&850 μ m	0.25	60,3 mJy
		ISO	10 34	58	90,175 μ m	0.5	15 mJy
		Chandra	10 34	57 40	0.5-8 keV	0.4	40,70 ks
		ISO	16 10	15 31	15,90,175 μ m	2.6	1 mJy ²
		ISOPHOT	16 11	54 25	170 μ m	1.98	50 mJy
		Chandra	16 10	54 33	0.5-8 keV	300 □	75 ks
		XMM			0.5-10 keV	0.2	150 ks
		ISO	16 37	41 16	7,15,90,175 μ m	2.6	1 mJy ²
ELAIS-N2	ELAIS FIRBACK SCUBA 8mJy	ISOPHOT	16 36	41 05	170 μ m	0.96	50 mJy
		SCUBA	16 37	41 02	450&850 μ m	130 □	8 mJy
		VLA			20 cm	100 □	9 μ Jy
		Chandra	16 36	41 01	0.5-8 keV	300 □	75 ks
		XMM			0.5-10 keV	0.2	150 ks

¹ exp. time for X-ray, limiting mag. for optical/NIR, $\sim 1 \sigma$ flux density for IR-radio; ² 15 μ m; ³ R/r/r' band; ⁴ 24 μ m; ⁵ 3.6 μ m.

Table 2.4: Imaging Surveys (optical/NIR) within SWIRE Fields; filters & magnitudes (Vega, 5 σ , 3''). Adapted from Lonsdale et al. 2003.

Field	Telescope or Instrument	u' U*	g' B*	V*	r' R*	i' I*	z' Z*	J H*	K K _s	Area [Future] ^a (Sq.deg)
ELAIS-S1	ESO 2.2m/WFI	...	26*	25.5*	25.5*	...	...	...	...	[6.25]
XMM-LSS	ESO VLT/VIMOS	...	...	...	...	25*	24*	...	...	[6.25]
	CFHT/Megacam ^b	25.6	...	25.7	25.5	24.0	...	...	...	[64]
CDF-S	VLT/NIRMOS	...	...	...	...	...	...	22.5*	23	[2.0]
	CTIO4m/MosaicII	24	25.7	...	25	24	23.5	...	...	1.6
	CTIO4m/MosaicII	27*	27*	...	26.5	25.8	...	...	...	0.36
	LasCampanas/WRC	...	...	...	...	...	...	...	K'20.5	0.6[1.0]
Lockman	KPNO4m/Mosaic I	24(1.3□')	25.7	...	25	24	...	...	...	6.5
	KPNO4m/Mosaic I	25.7	26.7	...	26	25	...	...	...	0.36
	KPNO2.5/Flamigos	...	...	...	...	...	...	...	TBD	TBD
	Palomar 5m/LFC	...	25.7	...	25	24	...	...	...	1.0[4.0]
	UKIRT/WFCAM ^c	...	...	...	...	...	...	22.5	21	[10]
ELAIS-N1	INT/WFC (ISLES)	...	...	...	23.8	...	...	...	...	9.2
	Palomar 5m/WIRC	...	...	...	...	...	...	22	21*	[1.0]
	INT WFS	23.3*	24.7	...	23.8	23.0	21.7*	...	...	9.0 ^d
ELAIS-N2	UKIRT/WFCAM	...	...	...	...	...	...	22.5	21	[10]
	INT WFS	23.3*	24.7	...	23.8	23.0	21.7*	...	...	4.5 ^d

^a Based on time allocated or programme already approved.

^b The CFH Legacy Survey, AB magnitudes.

^c UKIDSS.

^d Overlap between SWIRE and INT fields is less than this due to field orientation.

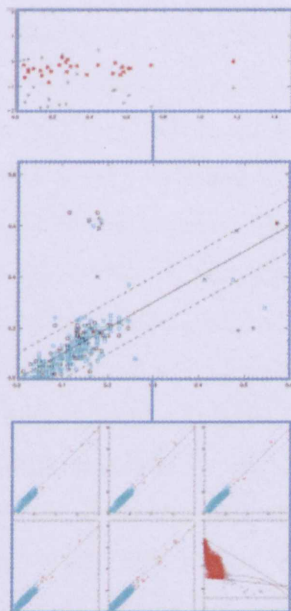
Table 2.5: SWIRE photometric sensitivity, cirrus & confusion noise levels and detection statistics (taken from Lonsdale et al. 2004).

Band ($\lambda/\mu\text{m}$)	3.6 (μJy)	4.5 (μJy)	5.8 (μJy)	8.0 (μJy)	24 (μJy)	70 (mJy)	160 (mJy)
5 σ limit	3.7	5.3	48	37.7	130	12	80
Cirrus noise 5 σ							
$I_{100}=0.5\text{MJy/sr}$	4.7e-7	4.7e-6	7.0e-5	1.2e-3	0.1	0.12	2.6
$I_{100}=1.0\text{MJy/sr}$	1.3e-6	1.3e-5	2.0e-4	3.3e-4	0.29	0.33	7.5
$I_{100}=2.0\text{MJy/sr}$	3.8e-6	3.8e-5	5.6e-4	9.2e-3	0.82	0.95	21
Confusion limit							
Xu et al. (2003) ^a	0.12	0.21	0.43	1.02	65	6.15	81.5
Rowan-Robinson (2001) ^b	...	...	...	0.68	135	4.7	59
Dole et al. (2002) ^c	...	...	...	0.05	50	3.2	36
Detection statistics							
Detections ^d	15,767	12,283	1,302	1,362	1,005	–	–
Galaxies ^e	14,350	11,050	925	1,025	1,000	–	–
Predicted galaxies (full survey, x10 ⁶)	2.39	1.84	0.15	0.17	0.28	–	–

^a Model S1+E2, using a photometric criterion and confusion limit=3 $\times$ confusion noise.
^b Using a source density criterion of 40 beams per source.
^c Using a source density criterion with the probability that two sources will be too close to separate of 10%.
^d Detections in the 0.3 sq. deg. SWIRE survey validation field in Lockman.
^e In the 0.3 sq. deg. SWIRE survey validation field in Lockman after statistical removal of stars (Surace et al. 2004).

Chapter 3

ImpZ: a new photometric redshift code for galaxies and quasars



3.1 Overview

In this Chapter a combined galaxy-quasar approach to template-fitting photometric redshift techniques is presented and shown to be a powerful one.

The code, ImpZ, is presented, developed and applied to two spectroscopic redshift catalogues, namely the Isaac Newton Telescope Wide Angle Survey ELAIS N1 and N2 fields and the *Chandra* Deep Field North. In particular, optical size information is used to improve the redshift determination. The success of the code

is shown to be very good with $\Delta z/(1+z)$ constrained to within 0.1 for 92 per cent of the galaxies in our sample.

The extension of template-fitting to quasars is found to be reasonable with $\Delta z/(1+z)$ constrained to within 0.25 for 68 per cent of the quasars in our sample. Various template extensions into the far-UV are also tested.

This Chapter presents work originally published as Babbedge et al. (2004). Any results not the work of T. Babbedge are indicated in §3.11.

3.2 Introduction

Photometric redshifts are a powerful statistical tool for studies of the evolutionary properties of galaxies, in particular of faint galaxies, for which spectroscopic data is hard, or impossible, to obtain.

Photometric redshifts are faster to measure than spectroscopic redshifts and can be applied to much fainter magnitudes since the bin sizes are larger ($\approx 1000\text{\AA}$ vs. $1\text{--}2\text{\AA}$). There is, however, a trade-off with redshift precision – Hogg et al. (1998) found that photometric redshifts were predicted with an accuracy of $\Delta z \approx 0.1$ (0.3) in z for 66 per cent (99 per cent) of the sources examined.

The bulk of the photometric redshift identification is carried out using the broadband continuum shape and presence and/or absence of spectral breaks (like the $4000\text{\AA}$ Balmer Break) or the onset of the $\text{Ly}\alpha$ forest and Lyman limit which enter optical wavebands at high redshift (the $\text{Ly}\alpha$ forest effect, e.g. Steidel & Sargent 1987 and Madau 1995). Although methods based on training sets such as polynomial fitting (e.g. Wang, Bahcall & Turner 1998) and artificial neural networks (e.g. Tagliaferri et al. 2002 and Ball et al. 2004) have had some success in determining photometric redshifts, here the template-fitting procedure is used (but with an element of training in that the templates have been adapted to improve fits). This is because there is a relative paucity of galaxies with both spectroscopic redshifts and photometry in the bandpasses used in the catalogues under study here, particularly at higher redshifts, making the construction of a training set unfeasible. Empirical methods are also hard to apply outside of the boundaries in which they were defined – such as the redshift distribution of the training set or the photometric bands use.

In the template-fitting method (e.g. Sawicki, Lin & Yee 1997; Giallongo et al. 1998) the observed galaxy fluxes, f_i^{obs} in the i^{th} band, are compared to a library of reference fluxes, $f_i^{templ}(z, T)$, where T is a set of parameters that account for the template galaxy's morphological type, age, metallicity and dust. We then fit the

observed fluxes to the library fluxes using χ^2 minimisation. As well as deriving redshifts, the procedure produces information on spectral (template) type, although this is less robust due to the degeneracies in the parameter space (see §3.7.3.1). A way of breaking these degeneracies is to use Bayesian probability (e.g. Jaynes 2000) to weight the solutions based on a prior knowledge of the expected population distributions. Application of Bayesian methods to photometric redshifts has been presented in, for example, Kodama et al. (1999) and Benítez (2000). Usually such applications use priors such as the expected redshift distribution of the sample but this naturally suppresses unbiased information on the true redshift distribution. Here Bayesian methods are implemented using absolute magnitude limits and extinction distributions which it is hoped retain the power of Bayesian methods without unduly influencing the underlying science (see §3.3.2).

One important refinement is the consideration of extinction for galaxies. Madau (1999) used a single dust absorption correction of $A_{1500}=1.2$ mag, except for galaxies in the redshift range 0.75–1.75 where the equivalent extinction at $2800\text{\AA}$ was used. Galaxy evolution models such as those of Le Borgne & Rocca-Volmerange (2002) include evolution of dust extinction with time. In order to allow for variation in extinction from galaxy to galaxy, extinction needs to be solved as an additional free parameter to redshift. In Steidel et al. (1999) dust absorption was corrected for by assuming that colour deviations in their sample galaxies were entirely due to dust absorption, based on the empirical relation between far-infrared emission and the observed UV spectrum slope, as derived by Meurer et al. (1999). More recently, Thompson, Weymann & Storrie-Lombardi (2001) used Spectral Energy Distribution (SED) template-fitting photometric redshift techniques in the deep NICMOS northern HDF, fitting extinction as a parameter ranging from $E(B - V)=0$ to 1.0. The study of Bolzonella, Miralles & Pelló (2000) found that the inclusion of A_v as a free parameter caused significant increases in aliasing. In a similar technique developed in Rowan-Robinson (2003a), hereafter RR03, these aliasing problems were reduced by setting several A_v priors (see §3.3.2).

In this Chapter the SED template-fitting set out in RR03 is refined and applied to two spectroscopic redshift galaxy samples from the European Large-Area *ISO* Survey (ELAIS; Oliver et al. 2000) N1 and N2 fields of the Isaac Newton Telescope Wide-Angle Survey (INT WAS; McMahon et al. 2001), a part of the INT Wide-Field Survey (INT WFS), and also the *Chandra* Deep Field North, CDFN) for validation purposes. The effect of non-zero A_v , different SED templates and various template

extensions into the far-UV are explored, as is the inclusion of several different quasar templates and the applicability of template-fitting techniques to quasar-like sources. In §3.3 the photometric redshift technique is set out. In §3.4 the various templates and extensions to the UV are discussed. The ImpZ code is then applied to two spectroscopic redshift galaxy samples in §3.5. The results of this validation are given in §3.6. Error analysis is discussed in §3.7. Discussions and conclusions are presented in §3.8 and §3.9.

An investigation into the accuracy and reliability of extinction measures derived by photometric redshift codes will be carried out in Chapter 4, and the application of photometric redshifts to the first tranche of data from the SWIRE survey (described in Chapter 2) will be carried out in Chapter 5, in order to determine luminosity functions. Note that for these investigations the flat, $\Omega_\Lambda=0.7$ cosmological model with $H_0=65\text{km s}^{-1}\text{Mpc}^{-1}$ is used.

3.3 Method

3.3.1 χ^2 analysis

The template-fitting procedure is as follows: the observed galaxy magnitudes are converted for each i^{th} photometric band into an apparent flux, f_i^{obs} . Equivalently, this reconstructs the target galaxy's SED at a very low spectral resolution by sampling the luminosity at the effective wavelength of each photometric band. The observed fluxes can then be compared to the template fluxes, $f_i^{\text{templ}}(z, T)$, computing the reduced χ^2 , χ_{red}^2 as

$$\chi_{\text{red}}^2 = 1/D \sum_{i=1}^N \frac{[f_i^{\text{obs}} - s f_i^{\text{templ}}(z, T)]^2}{\sigma_i^2} \quad (3.1)$$

where N is the number of photometric bands, D is the number of degrees of freedom, σ_i is the observational uncertainty in the i^{th} band (hence the solution is weighted by the flux errors, however to avoid excessively high weighting by very high signal-to-noise observations, a minimum flux error is set, typically 0.5 per cent) and s is a normalisation factor to minimize χ^2 for each template.

$$s = \frac{\sum_{i=1}^N f_i^{\text{obs}} f_i^{\text{templ}}(z, T) / \sigma_i^2}{\sum_{i=1}^N f_i^{\text{templ}}(z, T)^2 / \sigma_i^2} \quad (3.2)$$

Note that if there is a detection in just one band then fitting is not attempted.

Table 3.1: Common spectral lines and breaks in SEDs, and the redshifts where they enter and leave the filters used in this study, where transition is defined by the points where filter transmission drops below 50 per cent of the maximum filter transmission. Redshifts greater than seven are not considered.

<i>INT WAS filters</i>											
<i>Filter</i>	Lyman Limit (912Å)		Lyα (1216Å)		Balmer Break (4000Å)		0[III] doublet (4983Å)		Hα (6563Å)		
	enters	leaves	enters	leaves	enters	leaves	enters	leaves	enters	leaves	
<i>U</i>	2.5	3.3	1.6	2.2	–	–	–	–	–	–	
<i>g'</i>	3.5	4.9	2.4	3.4	0.03	0.35	0	0.08	–	–	
<i>r'</i>	5.0	6.6	3.5	4.7	0.38	0.73	0.10	0.38	0.05	0.07	
<i>i'</i>	6.7	NA	4.8	6.0	0.75	1.1	0.40	0.71	0.07	0.30	
<i>Z</i>	NA	NA	6.0	6.9	1.1	1.4	0.71	0.93	0.30	0.46	

<i>Barger et al. (2000) filters</i>											
<i>Filter</i>	Lyman Limit (912Å)		Lyα (1216Å)		Balmer Break (4000Å)		0[III] doublet (4983Å)		Hα (6563Å)		
	enters	leaves	enters	leaves	enters	leaves	enters	leaves	enters	leaves	
<i>B</i>	3.3	4.5	2.2	3.1	0	0.25	0	0.003	–	–	
<i>V</i>	4.5	5.6	3.1	3.9	0.25	0.50	0.003	0.20	–	–	
<i>R</i>	5.6	6.7	3.9	4.8	0.50	0.75	0.20	0.40	0	0.07	
<i>I</i>	6.9	NA	4.9	6.1	0.80	1.2	0.44	0.73	0.10	0.31	
<i>Z</i>	NA	NA	5.5	NA	1.1	1.5	0.69	1.0	0.28	0.52	
<i>HK', (H)</i>	NA	NA	NA	NA	2.7	3.5	2.0	2.6	1.2	1.7	
<i>HK', (K')</i>	NA	NA	NA	NA	3.9	4.8	2.9	3.6	2.0	2.5	

3.3.2 The ImpZ code

This code builds on the technique presented in RR03, extending it to include the correct treatment of CCD response, filter transmission characteristics and the statistical effect of Inter-Galactic Medium (IGM) absorption ($\text{Ly}\alpha$, $\text{Ly}\beta$, $\text{Ly}\gamma$, $\text{Ly}\delta$, and Lyman continuum), as set out in Madau et al. (1996) (see Fig. 3.1). Correct treatment of the effects of the IGM is needed because it is possible to mis-interpret the $\text{Ly}\alpha$ forest effect as the intrinsic Lyman break and because, particularly at high redshifts, it will imprint its own recognisable feature onto the SED. Although the treatment of IGM absorption is only based on the average accumulated absorption, the *rms* fluctuations away from the mean can be expected to be small once integrated through a broad bandpass (Press, Rybicki & Schneider, 1993). At high redshift, Massarotti, Iovino & Buzzoni (2001) have shown that correct treatment of internal dust reddening (the Interstellar Medium) and IGM attenuation are the main factors in photometric redshift success.

The effect of internal dust reddening for each galaxy is already incorporated in the templates (Table 3.2) and alterable via fitting for A_v , using the reddening curve of Savage & Mathis (1979). Observed fluxes are compared to template fluxes for $0.01 \leq \log_{10}(1+z) \leq 0.90$, equivalent to $0.02 < z \leq 6.94$.

The following parameters and cuts were used:

- (i) In order to reject unphysical fits only those that give absolute B -band AB magnitudes (M_B , 4400Å) in the range $[-22.5 - 2\log_{10}(1+z)] < M_B < -13.5$ are considered for the 6 galaxy templates. Having an upper envelope dependent on redshift was found to be the best way to suppress luminous outliers at low redshift whilst allowing more luminous galaxies at higher redshifts, and this luminosity–redshift dependence agrees with the natural consequence of known strong luminosity evolution for galaxies (e.g. Lin et al. 1999). For the AGN templates a range from $-27 < M_B < -17.5$ was allowed. These restrictions cut out excessive numbers of aliases at the minimum and maximum redshift. A number of different limits have been investigated but these were found to be the most effective. Originally, limits were applied to the I band but this failed to constrain the UV luminosity. Shifting the limits to the B band allows both the young and old star components of the SED to be constrained for the redshifts considered.
- (ii) Sources are defined as *stellar* or *non-stellar*, where this is a purely morphological property differentiating between point-like and more extended sources. Those defined as *stellar* will have Active Galactic Nuclei (AGN) templates

considered in addition to the galaxy templates, whereas *non-stellar* sources will only be fit by galaxy templates. This reduces the increased degeneracy introduced by including AGN templates. The procedure for splitting sources into *stellar/non-stellar* sub-groups is different for the INT WAS ELAIS spectroscopic sample and the CDFN sample, and is described for each in §3.5.1 and §3.5.2 respectively.

- (iii) sources that were saturated were removed since their photometry is poor. This reduces z_{phot} outliers.
- (iv) A prior expectation that a *stellar* source is more likely to be a QSO is introduced by minimising $\chi^2_{red} + \alpha F(T)$ rather than χ^2 ($\alpha=4$ here) for *stellar* sources. $F(T)$ is a delta function such that $F(T) = 0$ if the template, T , is an AGN template, and $F(T) = 1$ if the template is a galaxy template. Essentially it is a prior to prefer AGN solutions due to the morphology information contained in the class flags – a weak Bayesian (e.g. Jaynes 2000) formulation – and was reached based on the results in §3.6.1.4 and §3.6.2.3.

For the ‘free’ A_v fitting option the following restrictions were used:

- (v) for the elliptical and AGN templates, A_v can take the value 0 only. The reason that A_v is set to zero for AGN is that since AGN are essentially a power-law, the additional inclusion of A_v gives too much freedom to the shape of the AGN template, and it was found that resulting degeneracies reduce the effectiveness of the photometric redshift technique.
- (vi) for other templates, A_v can take the values 0.0 to 1.0, in steps of 0.1. The maximum A_v was chosen to be approximately twice that of the typical A_v of galaxies at $z \approx 4$ found by Steidel et al. (1999) who derived a typical $E(B-V)$ of 0.15. Note that the templates already include some extinction (see Table 3.2) so that the A_v of the solution is technically the difference between the actual value and the template’s inherent value.
- (vii) no solution for A_v is sought if the reduced χ^2 , χ^2_{red} , of the $A_v=0$ solution is <1 , or if there are less than 4 bands.
- (viii) a prior expectation that the probability of a given value of A_v declines as $|A_v|$ moves away from 0 is introduced by minimising $\chi^2_{red} + \beta A_v^2$ rather than χ^2 ($\beta=2$ here). This can again be viewed as a weak implementation of Bayesian methods.

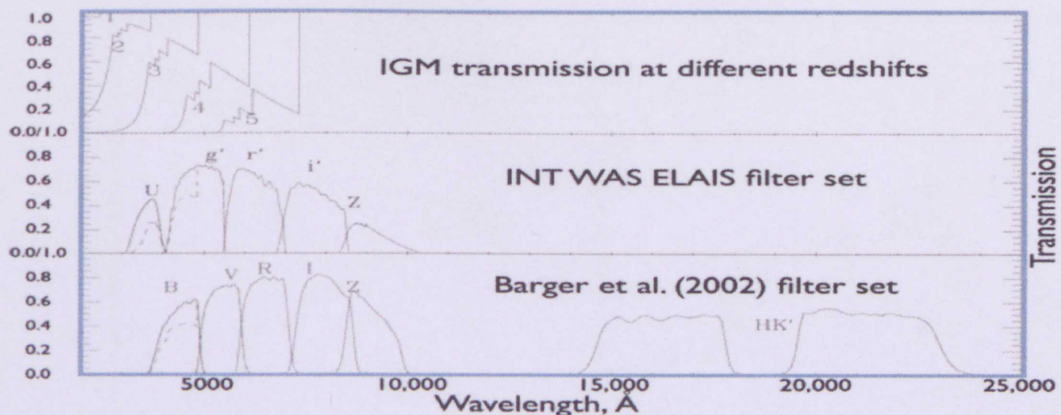


Figure 3.1: IGM transmission effect at redshift 1, 2, 3, 4 and 5 on the observed flux from a source. Also shown the INT WAS filters (solid lines), combined with the CCD response of the WFS camera, and also the filters (solid lines) used in the Barger et al. (2002) CDFN catalogue, combined with the relevant CCD (Suprime-Cam and QUIRC) responses. The additional effect of including IGM absorption is illustrated for the redshift 3 case by over-plotting the filter response when combined with the redshift 3 IGM transmission curve. It can be seen to effect U and g' in the INT WAS filter set, and the B filter in the CDFN filter set (over-plotted as dashed lines).

3.4 Template SEDs

The choice of how many templates to use in fitting is a crucial one. The choice of too many leaves the code with too much freedom, leading to large numbers of aliases and degeneracy. Similarly, too few and the code will be unable to find accurate redshifts for real objects, something Bolzonella et al. (2000) termed ‘catastrophic’ failures.

As in Mobasher et al. (1996) and RR03 the code uses six galaxy templates; E, Sab, Sbc, Scd, Sdm and starburst galaxies. These six templates (or similar versions) have been found to provide a good low-resolution representation of observed galaxy SEDs (Mobasher et al. 1996, RR03), and are used in preference to a large array of evolving galaxy templates, as generated by evolutionary codes such as that of Bruzual & Charlot (1993), since too much freedom is then available in fitting. The empirical templates used in RR03 were based on observations (starburst template adapted from Calzetti & Kinney 1992) and on observations and colour synthesis (the remainders adapted from Yoshii & Takahara 1988). In a method reminiscent of empirical techniques, these templates were adapted to improve photometric redshift results.

The templates used in this work were generated by reproducing these original

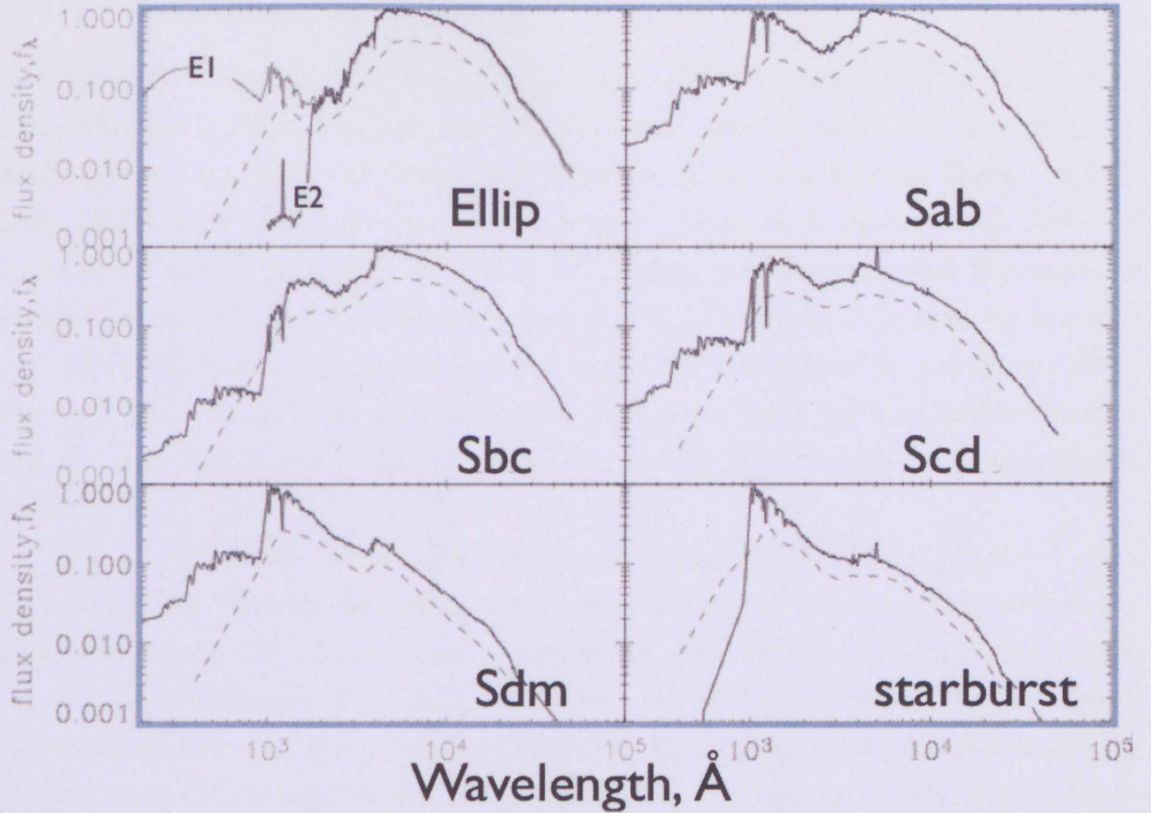


Figure 3.2: The 6 galaxy templates used. Dashed lines show the original RR03 templates (offset for clarity), solid lines shows the SSP generated versions, along with extension into the Far-UV (Sub-1000Å) as set out in section 3.4.3. For the elliptical template two SSP generated fits are shown, which diverge below around 2000Å. Line E1. fits the UV bump that is due to planetary nebulae, whereas Line E2. does not. This is discussed in section 3.4.1.

templates via spectrophotometric synthesis, in order to strengthen their physical basis. The original templates were convolved with filter transmission curves in order to create virtual datapoints. These datapoints were then fit using a code which combines a given number of single stellar populations (SSPs), each weighted by a different SFR and extinguished by a different amount of dust. The procedure is based on the synthesis code of Poggianti, Bressan & Franceschini (2001) and has been previously applied to spectra in Berta et al. (2003). The code minimizes the χ^2 obtained from comparing the new template to the datapoints. Minimization is based on the Adaptive Simulated Annealing algorithm. Details on this algorithm and on the fitting technique are given in Berta et al. (2004). The templates are plotted in Fig. 3.2, and have been extended further into the UV regime as set out in §3.4.3.

3.4.1 SSP Populations

The spectra of the SSPs have been computed with a Salpeter IMF between 0.15 and 120 solar masses, adopting the Pickles (1998) spectral atlas and extending its atmospheres outside its original range of wavelengths with Kurucz (1993) models from 1000Å to 50,000Å, as described in Bressan, Granato & Silva (1998). Nebular emission is added by means of case B HII region models computed through the ionization code CLOUDY of Ferland et al. (1998). The adopted metallicity is solar.

When generating the new templates, each SSP is weighted by a different SFR. For each SSP a uniform screen attenuation is adopted, using the standard extinction law ($R_v = A_v / (E(B - V)) = 3.1$, Cardelli, Clayton & Mathis 1989) and adopting a different $E(B - V)$.

With 10 SSPs, there are a total of 20 free parameters (SFR and $E(B - V)$ for each SSP), but the code automatically discards those populations which contribute less than one per cent to the total spectrum, at each wavelength. As a result each template is constructed from only few SSPs. The $E(B - V)$ values for the oldest populations (9th and 10th) are constrained to be less than 0.2 (the characteristic extinction of the older quiescent stellar population in a sample of nearby galaxies is $E(B - V) \approx 0.1$; Rowan-Robinson 2003b). The total $E(B - V)$ for each template is obtained by comparing the non-extincted final spectrum (S_n) to the extincted version (S_e) since in the V band the following relation holds: $S_e = 10^{-0.4A_v} S_n$. For details of the populations and their contribution to each template see Table 3.2.

Two fits were generated for the elliptical template – E1 and E2. E1 fits the small UV bump present in ellipticals from approximately 1000–2000Å, a feature that is due to emission from planetary nebulae (Yoshii & Takahara 1988). In order to prevent this UV bump being fit by young stellar populations, the SFR of the 3 youngest SSPs was set to zero. E2 consists only of the two oldest SSPs and fails to fit this UV bump. For this reason, E2 was not used as a template, but is plotted in Fig. 3.2 for interest.

The template–extension into the UV is described in 3.4.3.

3.4.2 AGN Templates

As well as galaxy templates, the inclusion of a number of different AGN templates has been investigated (see Fig. 3.3) to allow the ImpZ code to identify quasar-type objects as well as normal galaxies. This is of particular interest for application of ImpZ to the SWIRE ELAIS-N1 field in Chapter 5 since many of these sources are expected to be AGN (Oliver et al. 2000). Fitting with AGN templates is only carried

Table 3.2: The six galaxy templates and the SSPs that were used to create them. SFR is given in $M_{\odot} yr^{-1}$ and normalised so that each template has a total mass of $10^{10} M_{\odot}$.

SSP			SED Template													
#	Age (yr)	Δt (yr)	Elliptical(E1)		Sab		Sbc		Scd		Sdm		Sbrst			
			SFR	E(B-V)	SFR	E(B-V)	SFR	E(B-V)	SFR	E(B-V)	SFR	E(B-V)	SFR	E(B-V)		
1	10^6	$2 \cdot 10^6$	—	—	—	—	—	—	—	—	—	—	—	—		
2	$3 \cdot 10^6$	$4 \cdot 10^6$	—	—	0.100	0.04	—	—	—	—	4.097	0.001	41.17	0.9465		
3	$8 \cdot 10^6$	$3 \cdot 10^6$	—	—	—	—	—	—	—	—	—	—	35.67	0.024		
4	10^7	$4 \cdot 10^6$	0.099	—	—	—	1.461	0.18	—	—	—	—	—	—		
5	$5 \cdot 10^7$	$6.2 \cdot 10^7$	—	—	0.332	0.015	—	—	2.576	0.03475	13.54	0.004	—	—		
6	10^8	$1.25 \cdot 10^8$	—	—	—	—	—	—	—	—	13.62	4.685	—	—		
7	$3 \cdot 10^8$	$2 \cdot 10^8$	—	—	0.484	0.12	1.647	—	1.692	0.12	9.995	—	—	—		
8	$5 \cdot 10^8$	$3.5 \cdot 10^8$	—	—	—	—	0.896	0.003	2.80	0.032	11.58	0.0616	—	—		
9	10^9	$1.25 \cdot 10^9$	0.396	—	1.074	0.017	1.509	0.137	0.771	0.1838	1.111	0.0818	7.78	0.0015		
10	$1.2 \cdot 10^{10}$	10^{10}	0.950	—	0.854	0.134	0.747	0.186	0.756	0.138	—	—	—	—		
A_v (young - 1st 3 SSPs)			0.0		0.12205		0.0		0.0		0.0031		1.38			
A_v (total)			0.0		0.2344		0.3308		0.271		0.4303		0.736			

out for sources that have been defined as *stellar*, as described in §3.3.2.

The last decade has seen a large rise in the number of optically selected high-redshift quasars and the existence of large samples of quasars (e.g the Sloan Digital Sky Survey – SDDS – York et al. 2000) means that the derivation of photometric redshifts for quasars is gaining popularity as well as reliability. For galaxies the technique relies on the identification of continuum features such as the 4000Å break – see Table 3.1 for examples.

For a featureless spectra a photometric redshift is far harder to determine, if at all. The majority of quasars can be characterised in the UV–optical region as a featureless continuum. Overlaid on this continuum however are a series of (mostly) broad emission line features which contain a significant amount of flux (Francis et al. 1991; Richards et al. 2001). Also, at higher redshifts the result of Ly α forest absorption will imprint an additional redshift-dependent feature onto the continuum. Empirical redshift–colour relationships have been applied to quasars, but such polynomial fitting is limited due to the nature of quasar colours, which can change rapidly across a small redshift range as an emission line passes in and out of a passband, or remain constant with redshift due to the featureless continuum – a relationship which is poorly reproduced by polynomial functions that vary slowly with redshift. An extension of this technique which implements a nearest neighbour (NN) estimator with the reference points derived from colours averaged over redshift bins was presented in Richards et al. (2001), with around 70 per cent of predicted redshifts matching reasonably well with the spectroscopic values ($\Delta z < 0.1$ for 55 per cent and $\Delta z < 0.2$ for 70 per cent of their sample).

The alternative approach is a template-fitting procedure as used in several quasar studies (e.g. Hatziminaoglou, Mathez & Pelló 2000) and adopted in this work. This approach requires a template or templates that can cover the observed range of spectral types, across a large enough wavelength span to be applicable for low and high redshift objects. Unlike galaxies, quasars have SEDs with similar power-law continua so the use of the mean spectrum of a sample of quasars is feasible. Budavári et al. (2001) used the SDSS composite spectrum of Vanden Berk et al. (2001), resulting in a slightly greater *rms* than that found in the empirical NN method of Richards et al. (2001). They suggested that the use of a single quasar template is not sufficient – perhaps one corresponding to broad absorption lines or FeII is also needed. A similar study by Wu, Zhang & Zhou (2004) with the SDDS composite achieved $\Delta z < 0.1$ for 47 per cent and $\Delta z < 0.2$ for 68 per cent of their sample. Budavári et al. (2001) went on to reconstruct 4 discrete templates in an

iterative manner, gaining better results than with the empirical NN method. However, this is beyond the scope of this Chapter and is left as a future direction.

In this study, several AGN templates were constructed. The optical–IR basis of these templates is outlined below, and extension to UV in §3.4.3:

- (i) the SDSS median composite quasar spectrum (Vanden Berk et al. 2001) covers a rest-wavelength range from 800 to 8555Å and is constructed from 2204 quasars spanning $0.044 \leq z \leq 4.789$. For wavelengths longward of Ly α to optical wavelengths the continuum is well-fitted by a power law ($f(\lambda) \propto \lambda^{\alpha_\lambda}$) with a wavelength power-law index, α_λ ($\alpha_\lambda = -(\alpha_\nu + 2)$), of -1.56 . This is consistent with a number of other works based on optical and/or radio-selected samples that have found power-law continuum indexes, as average values from spectra, from photometry, or using composite spectra, of $-2 \leq \alpha_\lambda \leq -1$ (e.g. Schneider et al. 2001, Brotherton et al. 2001, Carballo et al. 1999, Natali et al. 1998, Zheng et al. 1997, Francis 1996, Francis et al. 1991 and Cristiani & Vio 1990). The continuum blueward of the Ly α emission line is heavily absorbed (the median redshift is 1.253) due to Ly α forest absorption. Since this effect is strongly effected by redshift however and the median composite uses spectra across a broad range of redshift, little can be drawn from the absorption in that region of the SED. Instead, the UV part of the SED will be treated separately – see §3.4.3. The template has been extended to wavelengths longer than 8555Å by utilising the IR part of the average optical quasar spectrum of Rowan-Robinson (1995), slightly modified as set out in Rowan-Robinson et al. (2004a). This extends the template out to 25 μ m with what is essentially a continuation of the continuum power-law. See the ‘SDSS’ line in Fig. 3.3.
- (ii) in addition to the SDSS composite template, two simpler AGN templates were included. These are based on the mean optical quasar spectrum of Rowan-Robinson (1995), spanning 400Å to 25 μ m. For wavelengths longer than Ly α the templates are essentially $\alpha_\lambda \approx -1.5$ power-laws, with slight variations included to take account of observed SEDs of ELAIS AGN (Rowan-Robinson et al., 2004a). These two AGN templates are referred to as RR1 and RR2, and are very similar to those used in Rowan-Robinson et al. (2004a). They differ from one another at wavelengths longer than 1 μ m where RR2 contains more flux. For wavelengths shorter than the Lyman limit, several UV behaviours were again considered – see §3.4.3. These templates can be seen as ‘RR1’ and ‘RR2’ in Fig. 3.3.

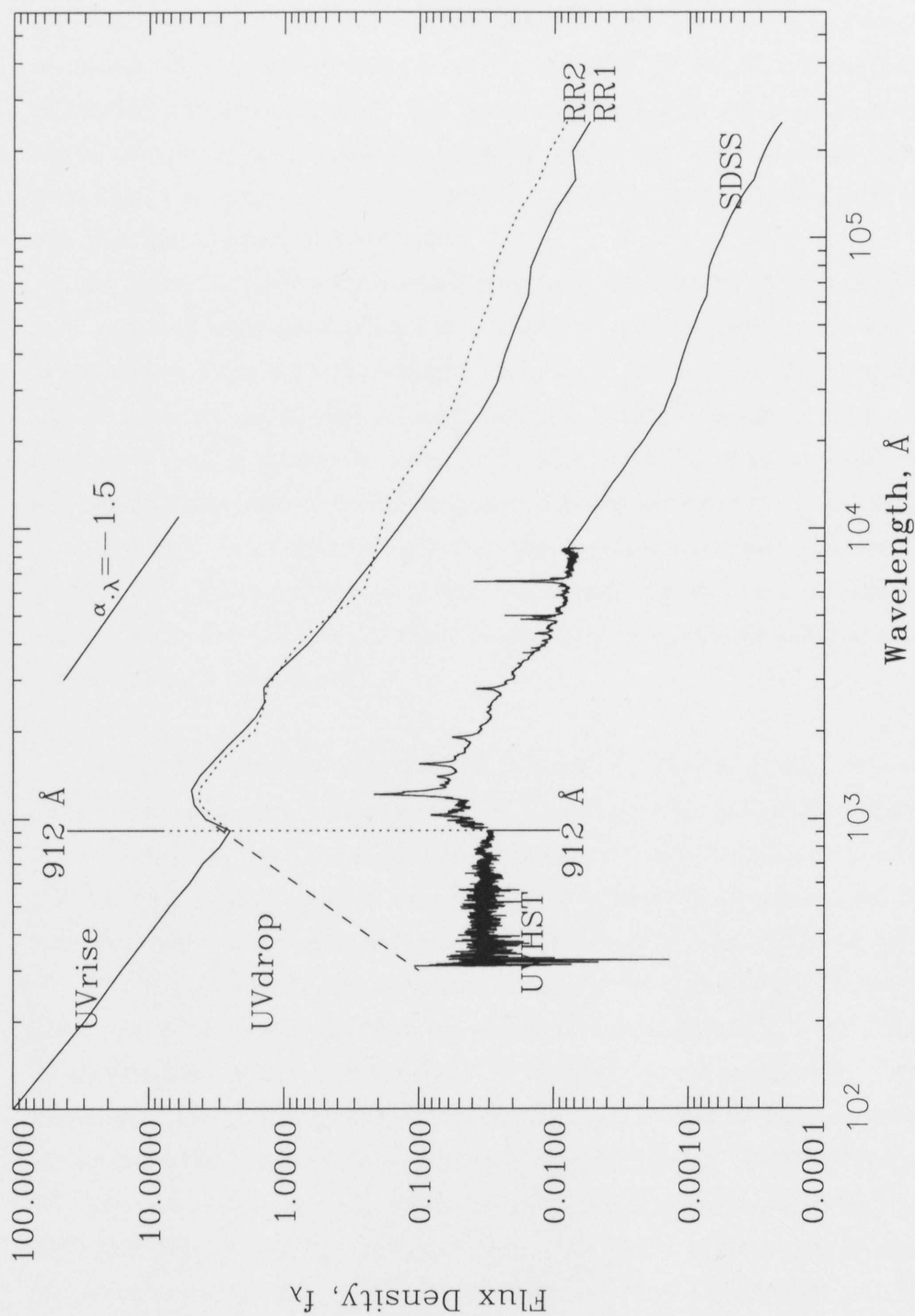


Figure 3.3: The various AGN templates that were investigated. The solid line 'SDSS' is the mean SDSS quasar spectra (Vanden Berk et al. 2001), shown here with the Zheng et al. (1997) UV behaviour, 'UVHST', and extended into the IR as set out in §3.4.2. The solid line 'RR1' and dotted line 'RR2' are the empirical AGN templates based on Rowan-Robinson (1995), shown with either a drop-off in the UV ('UVdrop', dashed) or a rise in the UV ('UVrise', solid). The 912Å Lyman limit has been indicated, as is the slope of a power-law continuum with $\alpha_\lambda = -1.5$. Discussion of these AGN is covered in §3.4.2, with UV treatment discussed in §3.4.3.

3.4.3 Far UV treatment

The Milky Way becomes virtually opaque at wavelengths between 100 – 912Å due to absorption by neutral hydrogen. Hence it is difficult to be certain of the far-UV rest-frame emission of galaxies or quasars. Ground-based observations can only start revealing the sub-1200Å regime for objects at $z \gtrsim 2$ due to atmospheric absorption of shorter wavelengths. Escaping our own atmosphere with space-based telescopes has allowed the far-UV and extreme-UV region to be explored in more detail, but even then the action of the IGM and of neutral hydrogen in our own Galaxy makes the SED determination uncertain.

In order to apply a template-fitting technique out to large redshifts it is important that the templates extend to sufficiently short wavelengths. For galaxies this is perhaps a more straight-forward task, since the emitted electromagnetic energy can be assumed to be due to stars and dust heated by those stars. There exist a number of stellar synthesis codes that, when coupled with spectral evolution, can self-consistently reproduce the emission of galaxies across many orders of magnitude in wavelength. The SSPs adopted by the spectral synthesis code and used to generate the 6 galaxy templates in this work were not detailed enough below 1000Å; hence for the far-UV part of these templates the results of other spectral evolution codes has been considered.

Both the isochrone synthesis of Bruzual & Charlot (1993) and the PEGASE code of Fioc & Rocca-Volmerange (1997) show that for old stellar populations (older than several Gyr) such as those that characterise ellipticals, there is a rise in the far-UV due to low-mass stars in their post-AGB evolution. Furthermore, hot post-AGB stars decrease the amplitude of the 912Å break once their envelopes have dissipated.

In order to extend the elliptical template into the far-UV, therefore, the sub-912Å part of the spectrum from the elliptical template in HYPERZ (Bolzonella et al. 2000) was used, who had extended it from the elliptical template of Coleman, Wu & Weedman (1980), hereafter CWW. The flux was scaled in order to give a slight rise across the 912Å discontinuity. The four template set of CWW (elliptical, Sbc, Scd, Im) has been used in many photometric redshift studies (e.g Gwyn 1999, Benítez 1999 and Brodwin et al. 1999) and has been found to be a robust and reasonably complete template set. The extension into the far-UV carried out by Bolzonella et al. (2000) was by means of Bruzual & Charlot (1993) spectra with parameters (SFR and age) selected to match the observed spectra at zero redshift. They in fact use the IMF of Miller & Scalo (1979), however this choice has a negligible impact on the final results, as they discuss in their §4.6.

The Sab, Sbc, Scd and Sdm templates were extended in a similar manner, using the sub-912Å part of the spectrum (suitably scaled to give a factor 10 rise in flux across the 912Å discontinuity) from the Scd template of CWW, extended by Bolzonella et al. (2000). They were all given the same UV behaviour because the difference in UV spectrum between these galaxy types is expected to be less than the uncertainty in their actual UV behaviour. Indeed at redshifts where this region enters the optical filters, the dominant effect is due to IGM absorption.

The starburst template was extended following the results of Bruzual & Charlot (1993) and Fioc & Rocca-Volmerange (1997) which show that within 10 Myr the UV light drops sharply due to the evolution of massive stars off the Main Sequence. Below 912Å the starburst was assumed to be optically thick, an assumption that has been verified for nearby starburst galaxies by Leitherer et al. (1995a).

It is noted here that as well as the UV behaviours used above for the 6 galaxy templates, other forms were tested, such as sharp cut-offs at 912Å – essentially assuming that the galaxies are optically thick to ionizing radiation below the Lyman limit – or simply taking the flux at 1000Å and setting this value for sub-1000Å wavelengths. Such approaches were not found to be as successful.

Determining the exact shape of the UV spectra of AGN is problematic for the same reasons as for galaxies. Additionally, the observed broad continuum feature in the optical-UV, the ‘big blue bump’ (E.g. Shang et al. 2004), is confused by many broad and blended lines, which are thought to be due to fast moving ionised clouds near the centre of the AGN. Contamination from the host galaxy also has an effect for low luminosity AGN, particularly in the case of a nuclear starburst. Hence several far-UV trends have been investigated to see how they effect the accuracy of quasar photometric redshifts:

- (i) although observations of the continuum blueward of the Lyman edge are rare, Zheng et al. (1997) constructed a composite spectrum from 284 *Hubble Space Telescope* (HST) Faint Object Spectrograph (FOS) spectra of 101 quasars at $z \approx 1$. Around 90 per cent of the sample were at redshifts < 1.5 so the region blueward of Ly α could be studied without large effects from the Ly α forest. The shortest wavelength data, 350–600Å, were drawn from higher redshift quasars for which significant corrections for the Ly α forest and continuum absorption were made. There appears to be a break in the continuum slope at around 1050Å with $\alpha_\lambda \approx -0.2$ in the far UV. This composite spectra was used

as one possible UV extension to the sub-912Å SEDs of the ‘SDSS’, ‘RR1’ and ‘RR2’ AGN templates and can be seen in Fig. 3.3 as the line labelled ‘UVHST’.

- (ii) the ‘UVHST’ is approximately a flat continuum in f_λ . In order to explore the two alternatives, the sub-912Å SEDs of the ‘SDSS’, ‘RR1’ and ‘RR2’ AGN templates were also modelled as: a ‘UVrise’ with $\alpha_\lambda = -1.5$; a ‘UVdrop’ with $\alpha_\lambda = +3$. These can also be seen in Fig. 3.3.

3.5 Spectroscopic comparisons

An important stage in the development of any photometric redshift code is to run it on a catalogue of objects for which the redshifts are already known from spectroscopic observations. A version of the ImpZ code has already been used to study the evolution of the UV radiation density, the dust opacity, and hence the SFH for galaxies in the HDF North and South (RR03). As part of this, a comparison was made between the photometric output and the spectroscopic redshifts of 152 HDF North galaxies. For galaxies with at least 4 photometric bands (U,B,V,I) it was found that the spectroscopic redshifts were successfully matched to an accuracy of around 10 per cent in $(1+z)$. Around 2.5 per cent (defined where there was one or more secondary minima with χ^2 less than 1.0 above the global minimum and $(1+z)$ differing by more than 20 per cent) of galaxies were found to have a ‘significant’ redshift alias.

The version of ImpZ in RR03 has also been used to generate photometric redshifts for the final band-merged ELAIS catalogue (6.7, 15, 90 and 175 μm , and U , g' , r' , i' , Z , J , H , K and 20cm; Rowan-Robinson et al. 2004a), fitting both galaxies and quasars by using their U , g' , r' , i' , Z , J , H , and K data. Again the photometric redshifts were accurate to around 10 per cent in $(1+z)$, with a greater dispersion in Δz for AGN fits.

In order to extend the applicability of ImpZ, this investigation explores ImpZ’s application to two further sets of photometric data with spectroscopic redshifts.

3.5.1 ELAIS spectroscopic redshifts

The spectroscopic data in the ELAIS N1 and N2 fields (Pérez-Fournon et al. 2004; in prep.) is comprised of two samples:

- (i) objects observed with the William Herschel Telescope and the fibre-fed WYF-FOS/Autofib2 spectrograph at the Observatorio del Roque de Los Muchachos,

La Palma, as part of an International Time Project approved by the Comité Científico Internacional of the Observatories of the Instituto de Astrofísica de Canarias for the year 2000 (PI I. Pérez-Fournon), and

- (ii) objects from the SDSS First Data Release (Abazajian et al. 2003).

These data comprise 172 extragalactic sources, with spectroscopic redshifts ranging from a 0.0264 to 2.9426, and detections in 0 to 5 of the INT WAS bands. The mean limiting magnitudes (Vega, 5σ in 600 seconds) in each filter across these two areas are 23.40(U), 24.94(g'), 24.04(r'), 23.18(i'), and 21.90(Z). More information on the photometric data can be found in Chapter 5; §5.3.2.

The spectroscopic redshift information also includes a ‘QSO’/‘GALAXY’ flag (26/146 objects). These data are reduced to 163 by removing objects flagged as saturated via the INT WAS class flags (1 source), objects that have no WAS detections (4 sources), objects with only one detection (3 sources), and objects flagged as being contaminated by a bright star (1 source), leaving 157 objects with detections in 5 bands, and 6 with detections in 4 bands, sub-divided into 25 ‘QSO’ and 138 ‘GALAXY’ sources. The ‘QSO’/‘GALAXY’ information for INT WAS data enables us to decide on the best combination of the INT WAS class flags for defining possible AGN’s that should be included in AGN template-fitting, and additionally gives a direct measure of how well the galaxy and AGN templates manage to separate out these two populations. Hence a choice can then be made of which AGN templates to use, and what treatment in the UV is most successful.

Sources are defined as *stellar* (and so AGN templates are considered in addition to the galaxy templates) based on class flags. The INT WAS sources are classed in each band as either -1 : point-like, 0 : noise, 1 : non-stellar, -9 : saturated, -2 : could be stellar, -3 : might just be stellar. The best bands to define stellarity are g' , r' and i' so if the flag is -1 in any of these bands then the source is defined as *stellar*. The choice of this definition of *stellar* was reached after extensive tests with the spectroscopic INT WAS ELAIS catalogue which found that this identified the most number of actual quasars whilst keeping galaxy contamination to a minimum.

This *stellar* definition splits the sample into 24 *stellar* and 139 *non-stellar* sources.

Galactic extinction in ELAIS N1 and N2 is low (they were after all selected for their low $100\mu\text{m}$ intensity). Both have extinctions of $E(B-V) = 0.007$, which using the extinction-wavelength relation in Cardelli et al. (1989) equates to $A_v \approx 0.022$ for $R_v=3.1$. One can also use the same relation to find the extinction in each of

the WAS bandpasses and correct for it (see Table 3.3). The effect of varying R_v on the shape of the extinction curve is most apparent at the shorter wavelengths, and along with uncertainties in the actual form of the average R_v -dependent extinction law, the accuracy of these corrections is around 0.002 in magnitude (less than errors in the actual photometry).

3.5.2 CDFN spectroscopic redshifts

The Barger et al. (2002) catalogue in the CDFN was also used. This comprises an X-ray selected catalogue (from the 1Ms *Chandra* observation of the HDF North; Brandt et al. 2001) of 169 objects with spectroscopic redshifts and broad band photometry (B , V , R , I , z' from Subaru/Suprime Cam and a notched HK' filter with a central wavelength of $1.8\mu\text{m}$ from the University of Hawaii 2.2m telescope/QUIRC – see Fig. 3.1 for filter transmissions combined with the CCD responses). The resolution of the X-ray and optical/near-IR observations are similar (around $1''$) with nearly all true counterparts expected to lie within the $2''$ (5σ) radii of the X-ray source for sources within $6.5'$ of the approximate X-ray image centre and $3.6''$ radii (4σ) for sources beyond this radius.

The 1σ limiting magnitudes are (AB magnitudes): $B(29.0)$, $V(28.5)$, $R(29.2)$, $I(27.6)$, $z'(27.0)$ and $HK'(23.3, \text{Vega})$. As no errors are provided with these measurements, photometric errors of 0.05 in the Subaru bands and 0.15 in HK' have been assumed. The catalogue is reduced to 161 sources after removal of those flagged as saturated (7 sources) or contaminated (1 source). In addition, HK' detections were only used if they were brighter than magnitude 20.0 for data quality reasons. This means there are 105 sources with detections in 6 bands, 52 with 5 bands and 4 with four bands. Dropout treatment was applied to the two shortest wavebands – B and V .

Since this sample is X-ray selected, a larger proportion can be expected to be AGN, or AGN-dominated. Hence although this sample does not have an exactly analogous set of filters to the INT WAS, it is another excellent test-bed for the AGN template-fitting. It also has a larger sample of high-redshift galaxies which test the ImpZ application to galaxies across a broader redshift range. In place of the *stellar* definition in the application to the INT WAS survey, AGN template-fitting was carried out in addition to the usual galaxy template-fitting for objects that are flagged as being optically compact [C – 23 sources], having broad-line features [B – 6 sources], or having both [BC – 23 sources]. Hence 52 of 161 sources have AGN template-fitting applied. Barger et al. (2002) used HYPERZ on this sample but only

Table 3.3: ELAIS N1 and N2 Galactic extinction corrections for the INT WAS filters and CDFN Galactic extinction corrections for the Barger et al. (2002) filter set, derived using Cardelli et al. (1989) with $R_v=3.1$.

<i>INT WAS filters</i>						
<i>filter</i>	<i>U</i>	<i>g'</i>	<i>r'</i>	<i>i'</i>	<i>Z</i>	
A _λ	0.034	0.025	0.019	0.013	0.010	
<i>Barger et al. filters</i>						
<i>filter</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>	<i>z'</i>	<i>HK'</i>
A _λ	0.049	0.037	0.031	0.022	0.018	0.005

managed to get about 1/3 of their broad-line sources' photometric redshifts within 25 per cent of the spectroscopic values.

Galactic extinction in CDFN is again low, with extinction $E(B - V)=0.012$, which using the extinction–wavelength relation in Cardelli et al. (1989) equates to $A_v \approx 0.037$ for $R_v=3.1$. Again, this can be used to find the extinction in each of the bandpasses and correct for it (see Table 3.3).

3.5.3 Comparison to HYPERZ

In order to see how the popular template-fitting photometric code HYPERZ compares, it has been run on the same two catalogues by Mari Polletta at University of California, San Diego, using as similar parameters as possible. The set of 6 galaxy templates was used, with RR1UVrise and RR2UVrise used for AGN-fitting. One difference between the HYPERZ and ImpZ codes is that the A_v prior that increases the χ^2_{red} for increasing $|A_v|$ is not implementable in HYPERZ. Similarly the prior that makes AGN fits more preferable than galaxy fits for *stellar* sources is not available in HYPERZ (these priors were set out in §3.3.2). HYPERZ was run with the same redshift range, but a redshift step in $(1+z)$, rather than in $\log_{10}(1+z)$. The same absolute magnitude limits as in ImpZ were used (but in g' band) for the galaxy and AGN fits, with an A_v range of 0.0 to 1.0 for galaxy fits and $A_v=0$ for AGN and elliptical fits. Two reddening laws were tried – Calzetti et al. (2000) and Seaton (1979) (fit by Fitzpatrick 1989 for the Milky Way), with galaxies getting the (marginally) best results with the Seaton (1979) law. Allowing A_v to vary for AGN fits gave very similar results to setting $A_v=0$, with the best results shown in Fig. 3.4 and Fig. 3.6. The results of this comparison to HYPERZ are in §3.6.4.

3.6 Spectroscopic redshift results

We measure the reliability and accuracy of the photometric redshifts via the fractional error $\Delta z/(1+z)$ for each source, examining the mean error $\overline{\Delta z}/(1+z)$, the *rms* scatter σ_z and the rate of ‘catastrophic’ outliers η , defined as the fraction of the full sample that has $|\Delta z/(1+z)| > 0.2$.

$\Delta z/(1+z)$, $\overline{\Delta z}/(1+z)$ and σ_z are calculated as follows:

$$\Delta z/(1+z) = \left(\frac{z_{\text{phot}} - z_{\text{spec}}}{1 + z_{\text{spec}}} \right) \quad (3.3)$$

and

$$\overline{\Delta z}/(1+z) = \sum \left(\frac{z_{\text{phot}} - z_{\text{spec}}}{1 + z_{\text{spec}}} \right) / N. \quad (3.4)$$

and

$$\sigma_z^2 = \sum \left(\frac{z_{\text{phot}} - z_{\text{spec}}}{1 + z_{\text{spec}}} \right)^2 / N. \quad (3.5)$$

with N being the number of sources with both spectroscopic redshifts and photometric redshifts.

For both spectroscopic samples, the outlier-clipped *rms*, σ_{red} , calculated from sources with $|\Delta z/(1+z)| < 0.2$ was around 0.07 and the outlier fraction was 4.9 per cent for the INT WAS ELAIS and 12.4 per cent for the CDFN sample.

3.6.1 Results of ELAIS spectroscopic study

The code parameters and templates that gave the best results are described in §3.6.5. Fig. 3.4 shows the results of running ImpZ on the INT WAS ELAIS spectroscopic redshift sample with this ‘optimum’ set of parameters and templates, with Fig. 3.5 showing in close-up the behaviour at low redshift. As well as plotting $\log_{10}(1+z_{\text{spec}})$ versus $\log_{10}(1+z_{\text{phot}})$ for the whole sample, the results for just those with a spectroscopic ‘QSO’ flag are shown, as is the ‘GALAXY’ sub-sample. This better illustrates the varying success of the code on these different groups of sources, and the template-types that were best-fitting. In particular, it can be seen that 20 of the 25 ‘QSO’ objects were best-fitted by AGN templates. Four of the five that weren’t were defined as *non-stellar* following the definition set out in §3.3.2 (so AGN-fitting was not applied to them) and all five are at low redshift ($z < 0.3$).

ImpZ found solutions for all but one of the 162 sources. The failed source is discussed in §3.6.1.5.

For the sample as a whole, the total *rms* scatter, σ_{tot} , was 0.12, with $\overline{\Delta z}/(1+z) = -0.02$. The outlier-clipped *rms*, σ_{red} was 0.067 and the rate of ‘catastrophic’

outliers, η was 4.9 per cent.

The code was successful in identifying and fitting AGN templates to nearly all of the ‘QSO’ objects, and was quite successful at returning an accurate z_{phot} . The total *rms* scatter, σ_{tot} , was 0.28 for this sub-sample, with $\overline{\Delta z}/(1+z) = -0.11$. The outlier-clipped *rms*, σ_{red} was 0.11 and the rate of ‘catastrophic’ outliers, η , was 32 per cent, higher than for the spectroscopic sample as a whole. It can be seen from Fig. 3.4 however that in fact the agreement with z_{spec} is reasonable (all but one are within the $3\sigma_{\text{red}}$ limits), especially considering the infancy of applying photometric redshifts to quasars. Nine of the 25 ‘QSO’ sources were fit within 25 per cent of their z_{spec} values.

The code was even better on the ‘GALAXY’ sources, with $\sigma_{\text{tot}}=0.059$, $\overline{\Delta z}/(1+z) = -0.004$, $\sigma_{\text{red}}=0.059$ and no ‘catastrophic’ outliers. Although these ‘GALAXY’ sources were all relatively low redshift ($z < 0.2$), the success is encouraging.

Statistical results for both the ‘best-case’ setup and also for other ImpZ setups can be found in Table 3.4.

3.6.1.1 *Stellar definition*

It is important to restrict which sources the AGN templates are fit to. If the AGN templates are fit to all sources, instead of only fitting to those defined as *stellar*, then the overall accuracy of the ImpZ code on the INT WAS spectroscopic sample drops to $\sigma_{\text{tot}}=0.16$ and η rises to 6.8 per cent. This is because the inclusion of AGN templates introduces more degeneracies into the color-redshift space and we therefore wish to use further information, in this case the class flags, to break some of these degeneracies.

Similarly, although the *stellar* sources are more likely to be quasars, if we restrict the fitting of galaxy templates to *non-stellar* objects only, then the accuracy of ImpZ results for *stellar* objects is reduced because not all of them will be quasars. If galaxy templates are only fit to *non-stellar* sources then $\sigma_{\text{tot}}=0.16$, $\overline{\Delta z}/(1+z) = 0.01$, $\sigma_{\text{red}}=0.07$ and $\eta=7.5$ per cent. Instead, galaxy templates are fit to *stellar* objects, but AGN template-fits are made preferable through the prior set out in §3.3.2. The alteration of this prior is discussed in §3.6.1.4.

Bearing in mind that the code is designed to be applied to large surveys, we wish to make the criteria for a *stellar* definition and ensuing AGN-fitting as tight as possible in order to minimize galaxy contamination (and improve efficiency). The best combination of class flags for identifying quasars without undue contamination from galaxies was found to be *stellar* if the class flag is -1 in g' , r' , or i' band. This defines 21/25 ‘QSO’ sources and 3/138 ‘GALAXY’ sources as *stellar*.

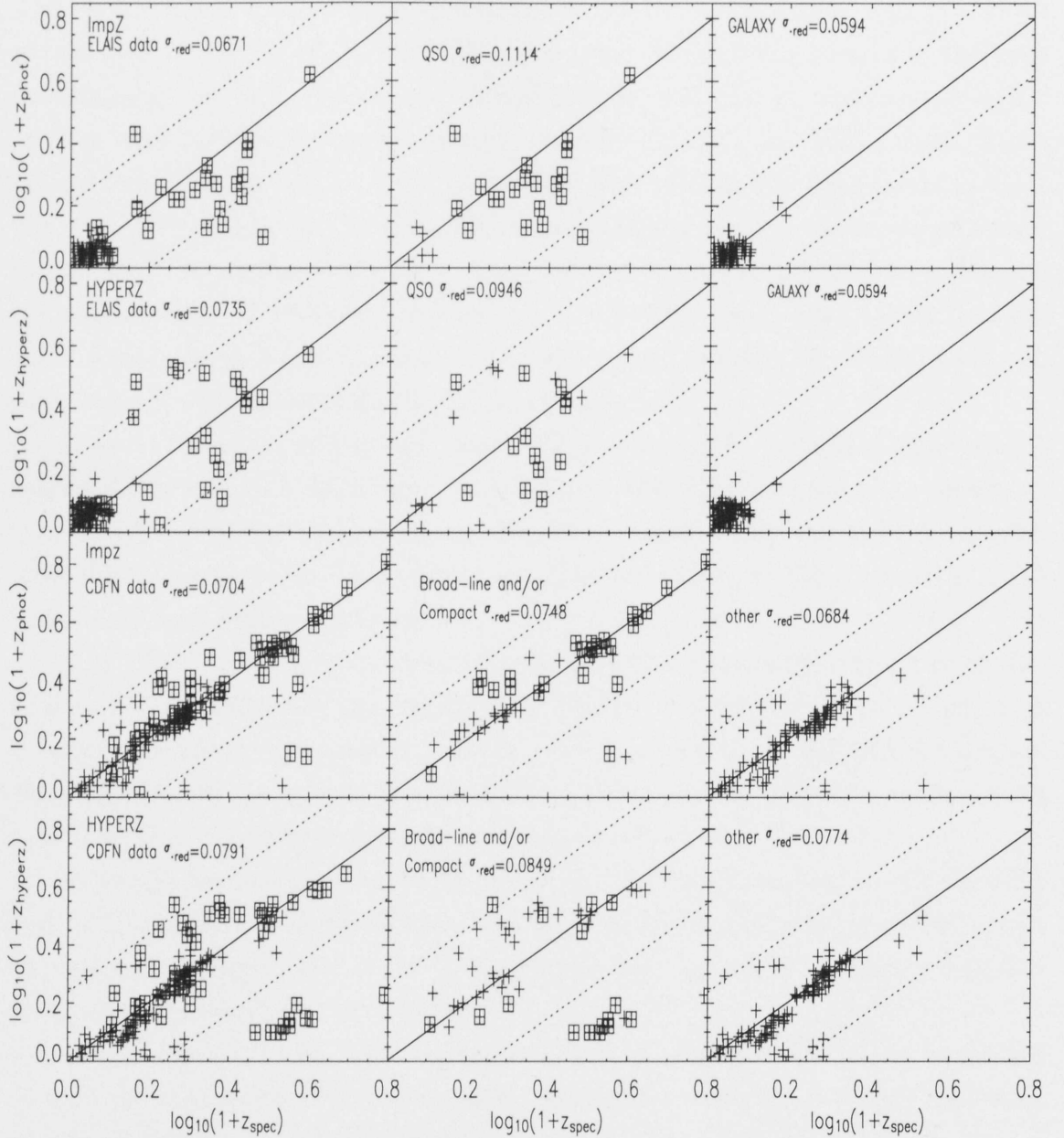


Figure 3.4: Spectroscopic validation results for the INT WAS ELAIS and CDFN spectroscopic samples. The rms values shown are the outlier-clipped rms values, σ_{red} . Top two rows shows INT WAS results (first row is ImpZ results, second row is HYPERZ results), set out as follows: first plot is all the data (crosses) with those flagged as ‘QSO’ outlined with a square. The dotted lines are the $3\sigma_{red}$ limits; second plot is only ‘QSO’ objects (crosses) with those fit as AGN outlined with a square. Dotted lines are again $3\sigma_{red}$; fourth plot are ‘GALAXY’ objects (crosses) with those fit as AGN outlined by a square. Dotted lines are $3\sigma_{red}$ limits. The third and fourth rows shows results from the CDFN sample with a similar format as to the first row: first plot is all the data (crosses) with those flagged as ‘B’, ‘C’ or ‘BC’ outlined with a blue square. The dotted lines are the $3\sigma_{red}$ limits; third plot is only ‘B’, ‘C’ or ‘BC’ objects (crosses) with those fit as AGN outlined with a square. Dotted lines are again $3\sigma_{red}$; fourth plot shows remaining objects (crosses) with dotted lines the $3\sigma_{red}$ limits (third row is ImpZ results, fourth row is HYPERZ results).

3.6.1.2 AGN fitting

The choice of which AGN templates to include in the template-set, and to a lesser extent how to treat them in the UV, had a large effect on the success of the code in obtaining accurate redshifts for *stellar* objects, and also in whether the ‘QSO’ sources were correctly identified as such and best-fitted by an AGN rather than a galaxy template. At high enough redshifts for the different UV treatments to enter the INT WAS bandpasses ($z \gtrsim 2.5$) there are relatively few sources available to test the different behaviours – the CDFN sample is more useful (see §3.6.2.1). For the highest redshift INT WAS source (‘QSO’ at $z = 2.94$) it was found however that the AGN templates were not the best-fitting when the ‘UVHST’ behaviour was used, with instead a low redshift Sbc template being fit.

The ‘UVdrop’ behaviour was found to be reasonable, with the high-redshift source being fit as an AGN at $z = 3.4$ whilst the ‘UVrise’ gave the redshift as $z = 3.1$. The ‘UVrise’ behaviour was therefore chosen to be the more successful, although the main reason for its choice was determined by the CDFN results (§3.6.2) which had more high-redshift sources.

The ‘SDSS’ AGN template was found to best-fit a reasonable number of *stellar* sources but unfortunately the resulting photometric redshifts were inaccurate, with a larger number of catastrophic outliers. For example, using the SDSS template with the ‘UVrise’ behaviour best-fit 19/25 ‘QSO’ sources, but with an increased $\sigma_{tot}=0.30$ and an outlier fraction of more than half.

It was found that the best combination of AGN templates was to use the RR1 and RR2 templates with the UVrise behaviour. Using just one or the other tended to increase the *rms* scatter of the ‘QSO’ objects from $\sigma_{tot}=0.28$ to roughly 0.40 and to increase the number of outliers.

It is noted that if no AGN templates are used – only the 6 galaxy templates – then the outlier fraction for the ‘QSO’ sources increases to $\eta=80$ per cent with $\sigma_{tot}=0.48$. Indeed, no source with $z_{spec} > 0.6$ is fit within $3\sigma_{tot}$ of z_{spec} .

3.6.1.3 High redshift sources

Since the main power of photometric redshifts is in their application to higher redshifts, it is informative to examine the higher redshift sources as a separate sample. Taking our redshift cut as $z_{spec} > 0.3$ (sources below this redshift are plotted in close-up in Fig. 3.5) means that there are 22 sources in the high redshift sample, comprising 2 ‘GALAXY’ and 20 ‘QSO’ sources. Hence the statistics for this sample are similar to that for the QSO sources alone, with $\sigma_{tot}=0.34$, $\overline{\Delta z}/(1+z) = 0.12$

and $\sigma_{red}=0.11$ with an outlier rate of 36 per cent. As would be expected, then, the accuracy for higher redshift sources is less than for lower redshift sources, but is still good. A better grasp of high redshift performance is provided by the CDFN sample, which has more objects at $z_{spec} > 0.3$ – see §3.6.2.2.

3.6.1.4 Relaxation of parameters

A_v If A_v fitting is completely turned off, so that only $A_v=0$ solutions are allowed then the majority of the increase in *rms* comes from increased scatter in the ‘GALAXY’ sub-sample. Hence the inclusion of A_v as a parameter improves the accuracy of the redshifts, whilst presumably giving some information about the extinction of each source. Several different A_v limits were tried for the galaxy templates. For example, since the ELAIS fields were originally IR-selected we might expect some sources to have high extinction so a range of $A_v = 0 - 3$ was used, with $\beta = 3$ instead of 2 in the A_v prior that minimises $\chi_{red}^2 + \beta A_v^2$. This did not alter the results. However, extending A_v freedom to AGN templates increases the outlier-rate for ‘QSO’s to $\eta = 40\%$.

AGN prior If the prior that a galaxy-fit to a *stellar* source must have $\chi_{red}^{2, galaxy} < (\chi_{red}^{2, AGN} - 4)$ is removed then only 17 of 25 ‘QSO’ sources are fit as AGN and the highest redshift source (‘QSO’ at $z = 2.94$) is instead fit as a low-redshift Sbc galaxy, with an overall increase in the *rms* and outlier fraction. If the prior is reduced in strength, to $\chi_{red}^{2, galaxy} < (\chi_{red}^{2, AGN} - 2)$ then although the overall statistics are almost as good, the highest redshift source is again fit as a low-redshift Sbc galaxy.

Absolute Magnitude limits The choice of the absolute *B*-band magnitude, M_B , limits of the photometric solutions is important for removing physically unlikely low-redshift low-luminosity and high-redshift high-luminosity solutions which greatly increase the number of catastrophic outliers. For example, allowing brighter AGN limits of $-29 < M_B < -17$ instead of $-27 < M_B < -17$ resulted in a number of high photometric redshift ($z > 5$) fits to low redshift sources. Similarly, increasing the galaxy limits to $-25.5 < M_B < -13$ replaced a number of correct faint low-redshift fits with incorrect brighter high-redshift fits. Incorrect low-redshift solutions for high-redshift sources were found to increase if the opposite action was taken and brighter galaxy and AGN fits were not allowed. The use of an upper M_B envelope that increased with redshift was found to be more successful than using a fixed value for galaxies, as might be expected from the known strong evolution in galaxy luminosities. The

selected redshift dependence used here was $[-22.5 - 2\log_{10}(1+z)] < M_B < -13.5$, though $[-22.5 - z/3] < M_B < -13.5$ worked equally well.

The final absolute magnitude limits were chosen in order to give the best agreement with the spectroscopic data whilst taking into consideration that large photometric surveys as a whole will have a greater diversity of sources.

3.6.1.5 Outliers

ImpZ fails to find a solution for one INT WAS ELAIS source, a ‘GALAXY’ at redshift 0.1454 with a *non-stellar* flag. This source is not detected in g' , but is relatively bright in other bands (19.42, 18.05, 17.18, 16.75 in U , r' , i' and Z). It was flagged as having multiple counterparts so this might imply that the photometry is incorrect. HYPERZ manages to find a solution at $z_{hyp}=0.19$ as an Sab with $A_v=0.4$.

The remaining most conspicuous outliers are a group of three sources with high spectroscopic redshifts and lower photometric redshift solutions, falling below the $3\sigma_{red}$ boundaries. It is noted that two of these sources are at redshifts where the 4000Å break has left the longest INT WAS waveband (at $z \approx 1.4$) but the 912Å Lyman limit has still not entered the shortest waveband ($z \approx 2.5$). Sources in this redshift range are harder to successfully derive redshifts for since the primary SED features on which photometric redshift-fitting relies are not available. Table 3.1 details the redshifts where common spectral features enter and leave the bandpasses used in the INT WAS and CDFN catalogues. For five other sources that fall into this redshift range, ImpZ is still successful in deriving the correct redshift, implying a success-rate in this redshift region of 71 per cent.

The other outlier (a ‘QSO’) lies above the $3\sigma_{red}$ boundaries, with a low z_{spec} and a high z_{phot} solution as an AGN. A solution near the correct redshift is found if the SDSS AGN template is used, however including this template degrades the performance of the code for the rest of the sample.

3.6.2 Results of CDFN spectroscopic study

Fig. 3.4 shows the results of running ImpZ on the CDFN spectroscopic redshift sample with the same ‘optimum’ set of parameters and templates as plotted for the INT WAS sample. As expected, since there is less available information on which to base the *stellar* and *non-stellar* definition and no actual ‘QSO’ or ‘GALAXY’ flag, the resulting analysis can be less clearly separated into results for galaxies and quasars.

ImpZ found solutions for all 161 sources. The total *rms* scatter, σ_{tot} , was 0.17,

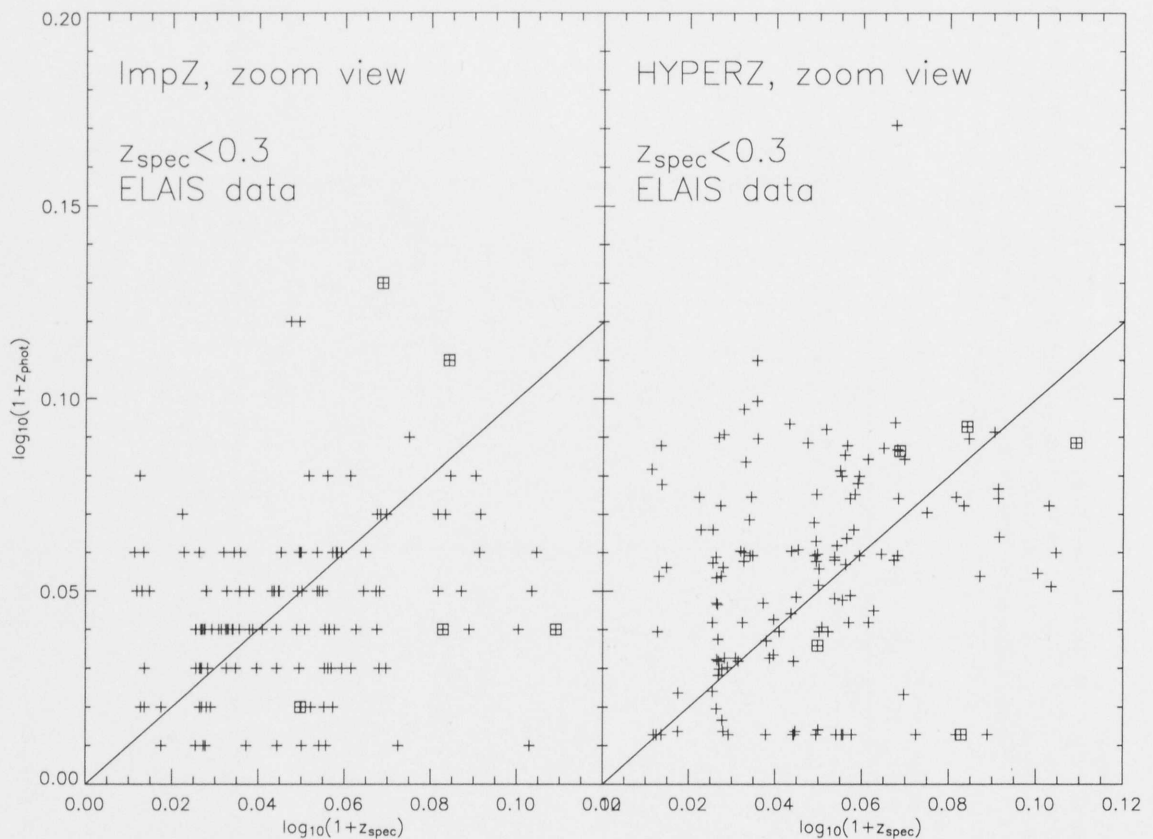


Figure 3.5: Zoomed view of spectroscopic validation results for the INT WAS ELAIS spectroscopic sample. First plot shows all ImpZ data for $z_{\text{spec}} < 0.3$ (crosses) with those flagged as ‘QSO’ outlined with a square; second plot is the same plot for the HYPERZ results. For both plots the scatter appears large since the photometric redshift method is accurate to perhaps 0.05 in $(1+z)$ – of order of $(1+z)$ for low redshifts.

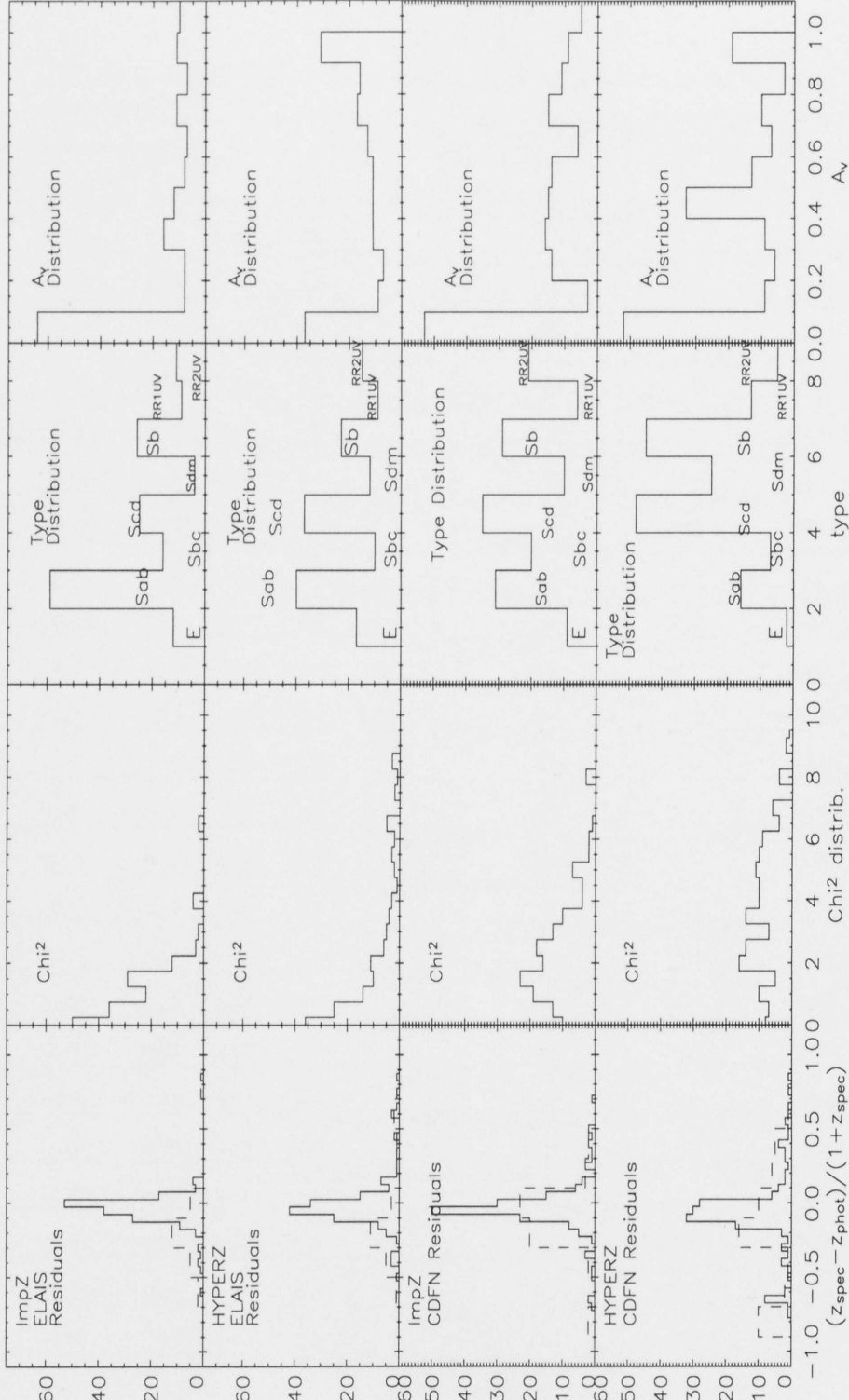


Figure 3.6: Spectroscopic validation results for the INT WAS ELAIS and CDFN spectroscopic samples. Top two rows show INT WAS results (first row shows ImpZ results, second row shows HYPERZ results), set out as follows: first plot is the distribution of residuals between z_{spec} and z_{phot} , normalised to $(1+z_{\text{spec}})$. Solid histogram is for the whole sample, dashed histogram is that of QSO objects only; second plot shows the reduced χ^2 distribution of the fits; third plot is the type distribution of the fits where 1=E, 2=Sab, 3=Sbc, 4=Scd, 5=Sdm, 6=Sb, 7=RR1UVrise and 8=RR2UVrise; fourth plot is the A_v distribution. The third and fourth rows show results from the CDFN sample with the same format as the first two rows except that the dashed histogram is now that of broad-line and/or compact sources only (third row shows ImpZ results, fourth row shows HYPERZ results).

Table 3.4: Statistical results for application of the ImpZ code to the INT WAS ELAIS catalogue, for different ImpZ setups.

INT WAS ELAIS Statistics for different ImpZ setups											
All sources				'QSO' sources				'GALAXY' sources			
$\bar{\Delta}z/(1+z)$	σ_{tot}	σ_{red}	$\eta(\%)$	$\bar{\Delta}z/(1+z)$	σ_{tot}	σ_{red}	$\eta(\%)$	$\bar{\Delta}z/(1+z)$	σ_{tot}	σ_{red}	$\eta(\%)$
'Best-case' ImpZ setup as in §5.1											
-0.02	0.12	0.067	4.9	-0.11	0.28	0.11	32.0	-0.004	0.059	0.059	0.0
AGN fit to all sources as in §5.1.1											
-0.01	0.16	0.07	6.8	-0.05	0.36	0.11	40.0	-0.002	0.07	0.06	0.7
Galaxies only fit to <i>non-stellar</i> sources as in §5.1.1											
0.01	0.16	0.07	7.5	-0.08	0.32	0.11	36.0	0.03	0.11	0.06	2.2
SDSS template with UVrise as the only AGN template, as in §5.1.2											
-0.04	0.13	0.07	8.0	-0.21	0.30	0.11	52.0	-0.004	0.06	0.06	0.0
RR1 template with UVrise as the only AGN template, as in §5.1.2											
-0.01	0.16	0.06	6.2	-0.07	0.39	0.10	40.0	-0.004	0.06	0.06	0.0
RR2 template with UVrise as the only AGN template, as in §5.1.2											
-0.03	0.15	0.07	8.0	-0.17	0.36	0.12	52.0	-0.004	0.06	0.06	0.0
UV drop behaviour in place of UVrise, as in §5.1.2											
-0.02	0.12	0.07	4.9	-0.11	0.29	0.12	32.0	-0.004	0.06	0.06	0.0
The 4 CWW templates in place of the E, Sab, Sbc, Scd, and Sdm templates, as in §6.2											
-0.02	0.13	0.07	5.6	-0.12	0.28	0.12	32.0	-0.01	0.07	0.07	0.7
Sab, R1UVrise and RR2UVrise as the only templates, as in §6.2											
-0.05	0.14	0.07	8.6	-0.19	0.30	0.12	48.0	-0.03	0.07	0.06	1.5
No AGN templates, as in §5.1.2											
-0.07	0.20	0.06	12.3	-0.42	0.48	0.11	80.0	-0.004	0.06	0.06	0.0
A_v free for AGN templates											
-0.03	0.13	0.07	6.8	-0.17	0.30	0.11	44.0	-0.004	0.06	0.06	0.0
$A_v=0$ to 3, with $\beta=3$ in A_v prior (see §3.3.2)											
-0.02	0.12	0.07	4.9	-0.11	0.28	0.11	32.0	-0.01	0.06	0.06	0.0
$A_v = -0.4$ to 1.0											
-0.02	0.13	0.07	6.2	-0.11	0.29	0.12	36.0	-0.004	0.06	0.06	0.7
A_v set to zero for all templates, as in §5.1.3											
0.01	0.13	0.08	5.6	-0.10	0.28	0.10	32.0	0.02	0.08	0.07	0.7
AGN prior removed, as in §5.1.3											
-0.01	0.15	0.07	7.4	-0.17	0.34	0.12	44.0	0.02	0.07	0.06	0.7
AGN prior set to 2 instead of 4, as in §5.1.3											
-0.01	0.14	0.07	6.2	-0.14	0.32	0.11	36.0	0.02	0.07	0.06	0.7
AGN prior set to 25 instead of 4, as in §5.1.3											
0.003	0.14	0.07	6.2	-0.08	0.32	0.11	36.0	0.02	0.07	0.06	0.7
Without U band information, as in §6.2											
0.01	0.43	0.06	13.0	-0.11	0.43	0.11	60.0	0.03	0.43	0.06	4.4
Without Z band information, as in §6.2											
-0.03	0.13	0.07	7.4	-0.13	0.30	0.10	48.0	-0.01	0.06	0.06	0.0
Brighter AGN limits of $-29 < M_B < -17.5$, as in §6.3											
0.01	0.25	0.07	6.2	0.10	0.64	0.12	40.0	-0.004	0.06	0.06	0.0
Reducing faint AGN limits to $-27.0 < M_B < -15$, as in §5.1.3											
-0.02	0.12	0.07	4.9	-0.11	0.28	0.11	32.0	-0.01	0.06	0.06	0.0
Brighter galaxy limits to $-23.5 < M_B < -13.5$, as in §5.1.3											
-0.02	0.13	0.07	6.2	-0.11	0.28	0.11	32.0	-0.003	0.06	0.06	1.5
Brighter galaxy limits to $-25.5 < M_B < -13.5$, as in §5.1.3											
0.01	0.33	0.06	7.4	-0.10	0.29	0.12	36.0	0.03	0.34	0.05	2.2
Reducing faint galaxy limits to $-23 < M_B < -17.5$, as in §5.1.3											
-0.02	0.12	0.06	4.9	-0.11	0.28	0.11	32.0	0.001	0.06	0.06	0.0

with $\overline{\Delta z}/(1+z) = -0.01$. The outlier-clipped *rms*, σ_{red} was 0.11 and the rate of ‘catastrophic’ outliers, η was 12.4 per cent.

The code was successful in identifying and fitting AGN templates to 27/52 of the broad-line or compact objects, and overall was successful at returning an accurate photometric redshift. The total *rms* scatter, σ_{tot} , was 0.19 for this sub-sample, with $\overline{\Delta z}/(1+z) = -0.01$. The outlier-clipped *rms*, σ_{red} was 0.07 and the rate of ‘catastrophic’ outliers, η , was 17.3 per cent. From Fig. 3.4 it can be seen that the code really only went badly wrong for 3 sources.

The code is also successful for the remaining sources (not B and/or C sources), with $\sigma_{tot}=0.16$, $\overline{\Delta z}/(1+z) = -0.01$ and $\sigma_{red}=0.07$. The rate of ‘catastrophic’ outliers, η , was 10.1 per cent.

Statistical results for both the ‘best-case’ setup and also for other ImpZ setups can be found in Table 3.5.

3.6.2.1 AGN fitting

Nineteen of 29 (66 per cent) broad-line (B or BC) source redshifts were within 25 per cent of their spectroscopic values. As a comparison, Barger et al. (2002) got 1/3 of the sample within this tolerance.

If just the BC (broad-line and compact), or just the C (compact) flags are used as the *stellar* definition (in place of B, C, BC) then the broad-line source numbered 174 in Barger et al. (2002) (with the highest spectroscopic redshift, $z = 5.19$) is incorrectly fit as a low-redshift galaxy. The reason why the B flag should perhaps not be used in the *stellar* definition is that this is a spectroscopically rather than photometrically derived property, and so would not be available to a photometric survey in general.

As with the INT WAS ELAIS spectroscopic sample, the most successful AGN templates were found to be the RR1 and RR2 templates and due to the greater number of high-redshift sources in the CDFN sample, the best UV treatment could be investigated more clearly. It was found that using the UVdrop or UVHST behaviours was less successful than UVrise. The UVHST behaviour increased the population of low-redshift sources incorrectly fit as high-redshift, although the overall success was good, with the main result being a slight increase in the outlier fraction for the *stellar* sources. The UVdrop treatment had a similar effect, making the UVrise behaviour the most effective.

It is noted that if no AGN templates are included in the template-set then the outlier-rate for *stellar* sources increases to 58 per cent, with a large population of high-redshift *stellar* sources incorrectly placed at lower redshifts. If AGN templates

along with galaxy templates to *non-stellar* sources then the outlier-rate for *non-stellar* sources increases to 28 per cent and σ_{tot} rises to 0.88. If, conversely, galaxy templates are only fit to *non-stellar* sources then the *rms* scatter of the *stellar* sources becomes much larger, with $\sigma_{tot}=1.42$.

3.6.2.2 High redshift sources

Again, the higher redshift sources are examined as a separate sample. Taking our redshift cut as $z_{spec} > 0.3$ (sources below this redshift are plotted in close-up in Fig. 3.5) means that there are 143 sources in the high redshift sample, comprising 92 *non-stellar* and 51 *stellar* sources. The statistics for this sample are $\sigma_{tot}=0.18$, $\overline{\Delta z}/(1+z) = 0.01$ and $\sigma_{red}=0.07$ with an outlier rate of 13 per cent. The accuracy for higher redshift sources is therefore still good. The performance is better than for the high-redshift sample in the INT WAS ELAIS catalogue since in that case 90 per cent of the sources were ‘QSO’, for which photometric redshift-fitting is less accurate.

3.6.2.3 Relaxation of parameters

A_v If A_v fitting is completely turned off, so that only $A_v=0$ solutions are allowed then η increases to 17.4 per cent. Again, the inclusion of A_v as a parameter improves the accuracy of the redshifts, though analysis of a sample with known A_v would be required to quantify how the resulting A_v of the solution compares to actual A_v .

AGN prior If the prior that a successful galaxy-fit to a *stellar* source must have $\chi_{red}^{2, galaxy} < (\chi_{red}^{2, AGN} - 4)$ is removed then only 13 of the 52 *stellar* sources are fit by AGN and many of those that are then fit as galaxies are placed at much lower z_{phot} . Using a reduced prior of $\chi_{red}^{2, galaxy} < (\chi_{red}^{2, AGN} - 2)$ causes the highest z_{spec} source to again be fit as a low redshift galaxy, and increasing the prior to $\chi_{red}^{2, galaxy} < (\chi_{red}^{2, AGN} - 25)$ creates a number of false high- z_{phot} AGN solutions.

Absolute Magnitude limits As with the INT WAS sample, allowing brighter AGN limits of $-29 < M_B < -17.5$ instead of $-27 < M_B < -17.5$ resulted in a number of high photometric redshift ($z > 5$) fits to low redshift sources. Similarly, increasing the luminous galaxy limits to $-25.5 < M_B < -13.5$ replaced a number of correct faint low-redshift fits with incorrect luminous high-redshift fits. Incorrect low-redshift solutions for high-redshift sources were found to increase if the opposite action was taken and brighter galaxy and AGN fits were not allowed. Again, allowing an

increase in the upper galaxy M_B envelope with redshift was found to be the best solution (i.e $-22.5 - 2\log_{10}(1+z)$).

3.6.2.4 Outliers

There are a group of three high spectroscopic redshift sources whose photometric solutions are significantly lower than their spectroscopic redshifts (there are a total of five sources below the $3\sigma_{red}$ boundary, and one above, but the others are close to the boundaries). It is noted that this group of three are at redshifts where the 4000Å break has left the Z waveband (at $z \approx 1.5$) but the 912Å Lyman limit has still not entered the shortest waveband ($z \approx 3.3$). Sources in this redshift are harder to successfully derive redshifts for since the primary SED features on which photometric redshift-fitting relies are not available. For 20 other sources that fall into this redshift range, ImpZ is still successful in deriving the correct redshift, implying a success-rate in this redshift region of 87 per cent. The slightly better performance than for the INT WAS ELAIS sample (71 per cent) for the corresponding ‘feature desert’ is likely to be due to the inclusion of HK’ information (which 4000Å enters at $z \approx 2.7$) and partly due to the poor-number statistics for the INT WAS ELAIS sample (only 6 sources in that redshift range).

3.6.3 Statistical properties

The distribution of residuals of the ImpZ solutions in Fig. 3.6 is quite strongly peaked around zero, with a Gaussian-like distribution and a slightly non-Gaussian extension to larger values. The distributions show that the ImpZ code is successful to an accuracy of perhaps 0.1 to 0.2 in $(1+z)$ for nearly all sources. The distributions of ImpZ solutions (dashed line in 3.6) for the ‘QSO’ sub-sample is also Gaussian-like, but these distributions are wider and shallower. For the INT WAS ELAIS ‘QSO’s the distribution is peaked at around -0.2 rather than zero, implying that the redshift solutions tend to be slightly larger than the true values. This could be because A_v is set to zero for AGN so a QSO reddened by some extinction is fit as unreddened, but at a slightly higher redshift. However, this is not seen in the larger CDFN sample.

The χ^2_{red} distributions of the ImpZ solutions shows that the majority of solutions are good, with χ^2_{red} peaking below 2. There is no large population of poor- χ^2_{red} solutions. From the ImpZ type distributions it can be seen that Sab solutions dominate, with a sizeable fraction of Scd and starbursts and very few Sdm solutions.

The A_v distributions are strongly peaked at zero with an even spread of higher

values (but no clustering at the highest value of $A_v = 1$ which would imply that the A_v range was insufficient).

3.6.4 HYPERZ results

From Fig. 3.4 and Fig. 3.6 it can be seen that for both the INT WAS and CDFN spectroscopic samples, the ImpZ code manages to do better. The strongest cause of these differences are probably the AGN and A_v priors that are used in the ImpZ code. In particular, HYPERZ is not as successful for the broad-line and/or compact sources in the CDFN sample, with a larger population of high-redshift sources incorrectly placed at low-redshift (see Fig. 3.4).

Overall, HYPERZ has, for the INT WAS sample, $\sigma_{tot}=0.17$, $\overline{\Delta z}/(1+z) = 0.02$, $\sigma_{red}=0.073$ and $\eta=8.0$ per cent. For the CDFN sample the statistics were $\sigma_{tot}=0.26$, $\overline{\Delta z}/(1+z) = -0.04$, $\sigma_{red}=0.08$ and $\eta=24.2$ per cent. Only 9/29 broad-line source redshifts were within 25 per cent of their spectroscopic values.

From Fig. 3.6 it can be seen that the non-Gaussian tails of the redshift residuals are more pronounced, particularly for the CDFN sample, and the χ^2_{red} of the solutions are only weakly peaked to low values.

A consideration of the ‘feature desert’ in redshift space where the 4000Å break has left the optical wavebands, and the 912Å Lyman limit has not yet entered shows a marked difference from the ImpZ results for the CDFN, indeed it is this region where HYPERZ most strongly diverges from ImpZ in its outlier-rate: for the CDFN sample, ImpZ had a 87 per cent success-rate with the 23 sources in this range, whereas HYPERZ fails for 10 (57 per cent success).

3.6.5 ImpZ summary parameters

Based on these results, the final best-case setup for application of ImpZ to the surveys such as the INT WAS is as follows:

Templates – 6 galaxy templates (E1, Sab, Sbc, Scd, Sdm and Starburst) and 2 AGN templates (RR1UVrise and RR2UVrise), with IGM and Galactic extinction corrections.

Fitting – AGN templates fit to *stellar* sources only and galaxy templates fit to all sources, with the prior that a successful galaxy fit must have $\chi^2_{red, galaxy} < (\chi^2_{red, AGN} - 4)$ if the source is *stellar*. A_v freedom is allowed for Sab, Sbc, Scd, Sdm and Starburst templates, with a prior that makes low A_v fits preferable.

Limits – A_v limits of 0.0 to 1.0 and absolute magnitude limits of $[-22.5 - 2\log_{10}(1+z)] < M_B < -13.5$ for galaxies and $-27.0 < M_B < -17.5$ for AGN.

Table 3.5: Statistical results for application of the ImpZ code to the CDFN catalogue, for different ImpZ setups.

CDFN Statistics for different ImpZ setups											
All sources				Broad-line and/or Compact sources				Other sources			
$\bar{\Delta}z/(1+z)$	σ_{tot}	σ_{red}	$\eta(\%)$	$\bar{\Delta}z/(1+z)$	σ_{tot}	σ_{red}	$\eta(\%)$	$\bar{\Delta}z/(1+z)$	σ_{tot}	σ_{red}	$\eta(\%)$
'Best-case' ImpZ setup as in §5.2											
-0.01	0.17	0.07	12.4	0.01	0.19	0.07	17.3	-0.01	0.16	0.07	10.1
AGN fit to all sources as in §5.2.1											
0.17	0.70	0.07	18.6	0.01	0.19	0.07	17.3	0.24	0.84	0.07	17.3
Galaxies only fit to <i>non-stellar</i> sources as in §5.2.1											
0.25	0.80	0.07	24.8	0.86	1.42	0.07	56.3	-0.01	0.16	0.07	11.0
SDSS template with UVrise as the only AGN template, as in §5.2.1											
-0.07	0.23	0.07	22.4	-0.19	0.34	0.08	48.1	-0.01	0.16	0.07	10.1
RR1 template with UVrise as the only AGN template, as in §5.2.1											
-0.01	0.18	0.07	13.7	0.004	0.21	0.07	21.2	-0.01	0.16	0.07	10.1
RR2 template with UVrise as the only AGN template, as in §5.2.1											
-0.01	0.17	0.07	12.4	0.01	0.19	0.08	17.3	-0.01	0.16	0.07	10.1
UV drop behaviour in place of UVrise, as in §5.2.1											
0.06	0.52	0.07	14.3	0.21	0.88	0.08	23.1	-0.01	0.16	0.07	10.1
The 4 CWW templates replacing E, Sab, Sbc, Scd, and Sdm templates, as in §6.2											
0.01	0.36	0.07	14.3	-0.05	0.20	0.08	21.1	0.04	0.42	0.06	11.0
Sab, R1UVrise and RR2UVrise as the only templates, as in §6.2											
0.08	0.57	0.07	36.6	0.39	0.96	0.06	59.6	-0.07	0.21	0.08	25.7
No AGN templates, as in §5.2.1											
-0.07	0.31	0.07	21.1	-0.18	0.49	0.08	44.2	-0.01	0.16	0.07	10.1
A_v free for AGN templates, as in §5.2.2											
0.08	0.50	0.06	23.0	0.25	0.86	0.05	50.0	-0.01	0.16	0.07	10.1
$A_v=0$ to 3, with $\beta=3$ in A_v prior (see §3.3.2)											
-0.02	0.18	0.08	13.7	0.01	0.20	0.08	17.3	-0.03	0.16	0.07	11.9
$A_v = -0.4$ to 1.0											
0.03	0.37	0.07	13.7	-0.01	0.20	0.07	17.3	0.05	0.43	0.07	11.9
A_v set to zero for all templates, as in §5.2.2											
0.08	0.43	0.08	17.4	0.22	0.72	0.09	26.9	0.01	0.16	0.08	12.8
AGN prior removed, as in §5.2.2											
-0.03	0.19	0.07	13.7	-0.08	0.23	0.09	19.2	-0.01	0.16	0.07	11.0
AGN prior set to 2 instead of 4, as in §5.1.3											
-0.02	0.19	0.07	14.3	-0.03	0.23	0.08	21.1	-0.01	0.16	0.07	11.0
AGN prior set to 25 instead of 4, as in §5.1.3											
0.06	0.45	0.07	16.8	0.21	0.76	0.08	28.8	-0.01	0.16	0.07	11.0
Brighter AGN limits of $-29 < M_B < -17.5$, as in §5.2.2											
0.13	0.68	0.07	14.9	0.43	1.17	0.07	25.0	-0.01	0.16	0.07	10.1
Reducing faint AGN limits to $-27.0 < M_B < -15$, as in §5.2.2											
-0.01	0.19	0.07	13.7	-0.02	0.24	0.08	21.2	-0.01	0.16	0.07	10.1
Brighter galaxy limits to $-23.5 < M_B < -13.5$, as in §5.2.2											
0.04	0.37	0.07	13.0	0.02	0.17	0.07	15.4	0.04	0.44	0.07	15.4
Brighter galaxy limits to $-25.5 < M_B < -13.5$, as in §5.2.2											
0.12	0.53	0.07	18.6	0.05	0.20	0.07	19.2	0.16	0.63	0.07	18.3
Reducing faint galaxy limits to $-23 < M_B < -17.5$, as in §5.2.2											
0.04	0.35	0.07	12.4	0.02	0.19	0.08	15.4	0.15	0.41	0.07	11.0

3.7 Error analysis

Errors in the derived photometric redshifts arise from several causes. The first is the inherent error in the measured flux of sources, which is expected to be increasingly important for fainter sources. The template-fitting technique adds further error due to fitting the continuum of observed galaxy SEDs with a set of standard templates which can only sample this continuum. This is known as cosmic variance.

Catastrophic errors are usually due to degeneracies in the colour–redshift–extinction space. For example, a late-type, heavily extinguished galaxy may appear similar to an early-type unreddened galaxy, but have a very different redshift. The relative magnitude of these sources of error needs to be more properly quantified.

3.7.1 Photometry

In order to remove the effect of cosmic variance from the analysis, a synthetic catalogue of fluxes (U , g' , r' , i' and Z) was generated 5 times, for 7,000 hypothetical *sources*. These *sources* were created by redshifting the templates (equal numbers of each type) and calculating their fluxes in each band. The redshift distribution was chosen to resemble that of ‘main’ galaxies in the SDSS First Data Release, with a simple Gaussian distribution peaked at -20 with a σ of 7 to model the absolute magnitude (r') distribution of the *sources* (additionally, *sources* were prevented from having extreme absolute magnitudes). The fluxes were randomly altered in a Gaussian distribution of errors of width determined by the 1σ values of the photometric errors in the INT WAS ELAIS catalogue plus 1 per cent of the flux. This Monte Carlo simulation generates 35,000 different *sources*. The photometric redshift code is then used to predict, for $A_v=0$, the redshifts and spectral types of the *sources*. Since the synthetic catalogue is constructed from the same set of templates as those used in the ImpZ code, cosmic variance is eliminated, leaving only the effect of photometric error.

Fig. 3.7 shows the result of this procedure. The first plot (both rows) shows the distribution of residuals between z_{in} and z_{out} , with the first row showing results for low-redshift input sources ($z_{in} < 1$) and the second row showing results for high-redshift input sources ($z_{in} > 1$). The distribution of error in redshift for the low- z_{in} sample is very strongly peaked at zero and is relatively symmetric about this, but the low lying extension to larger errors is not that of a purely Gaussian distribution. These large shifts in the redshift occur when a secondary minimum in the χ^2_{red} distribution for the *source* fluxes becomes the primary minimum when the *source* fluxes are perturbed. Hence for the low- z_{in} sample it can be seen that for

the large majority of *sources*, the redshift solution is close to the correct value, with only a low-level Gaussian spread due to photometric error.

For the high- z_{in} sample the distribution is also quite symmetrical about zero, but is less strongly peaked. This is to be expected due to the poorer signal-to-noise photometry of these more distant sources. For the high- z_{in} sample, then, the dominant effect is the error in the photometry, causing the general broadening in the residual distribution.

The spectral types of the simulated galaxies are compared with the predicted types in Table 3.6. This gives the percentage of galaxies for which their spectral type in the synthetic catalogue was successfully reproduced for each template. From this analysis it is concluded that without A_v freedom, the simulated *sources'* redshifts are well reproduced within 0.1 in $(z_{in}-z_{out})$ for $0 < z < 1$ and roughly 0.4 in $(z_{in}-z_{out})$ for $z > 1$. Also, for low redshift *sources*, photometric errors have a reduced effect on the results, whereas for high redshift *sources* the precision of the photometry has the major influence on the redshift accuracy.

3.7.2 Templates

In order to investigate the effect of the choice of template-set on the photometric redshifts the 4 UV-extended CWW templates (E, Sbc, Scd, Im) are used in place of 5 galaxy templates in the ImpZ code (E1, Sab, Sbc, Scd, Sdm), retaining the starburst template and the two AGN templates, RR1UVrise and RR2UVrise. The code is then applied to INT WAS ELAIS and CDFN spectroscopic catalogues. The resulting photometric redshifts are compared to the output when the original templates were used. The results are almost as good with $\sigma_{tot}=0.13$, $\sigma_{red}=0.07$ and $\eta=5.6$ per cent for the INT WAS sample and $\sigma_{tot}=0.36$, $\sigma_{red}=0.07$ and $\eta=14.3$ per cent for the CDFN. The 6 galaxy templates were also replaced with just the Sab template, in order to represent an undersampling of SED space. It was found that even in this rather extreme example, $\sigma_{tot}=0.14$, $\sigma_{red}=0.07$ and $\eta=8.6$ per cent for the INT WAS sample and $\sigma_{tot}=0.57$, $\sigma_{red}=0.07$ and $\eta=36.6$ per cent for the CDFN.

It is clear that the template-fitting procedure is largely unaffected by the specific choice of templates to use, provided that the main SED features of normal galaxies (such as the Balmer break) are represented.

Table 3.6 shows the comparison between the input *source's* template and the template that was fit for it for the 35,000 *sources* generated in §3.7.1. It is immediately clear that the majority (75 per cent) of the input template types are recovered, and that there is almost no degeneracy between early and late-type tem-

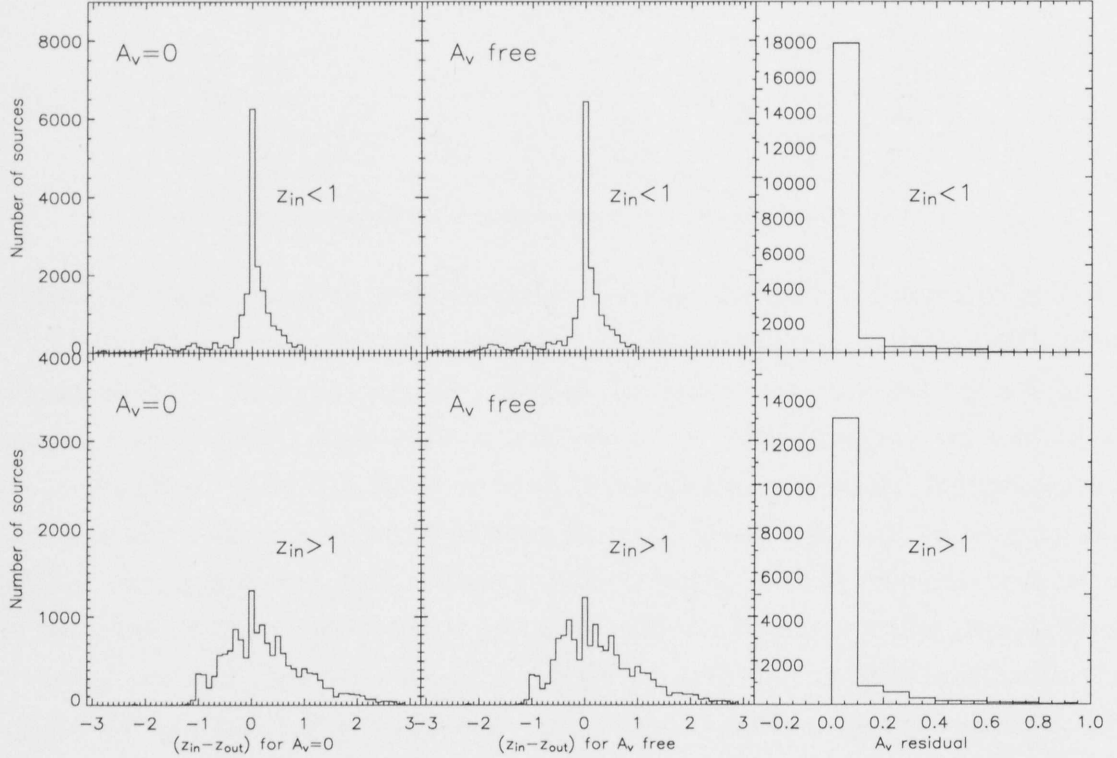


Figure 3.7: Results of Monte Carlo synthetic catalogue investigations with 35,000 sources (Section 3.7. Top row shows results for ‘low’ input redshift sources (those with $z_{in} < 1$), set out as follows: first plot is the distribution of residuals between z_{in} and z_{out}), for template-fitting by ImpZ with A_v freedom turned off; second plot is the same, but for solutions with A_v freedom allowed in ImpZ fitting, as described in 3.6.5; third plot shows the A_v residual from fitting with A_v freedom turned on. This is simply the A_v of the fit since the input synthetic catalogue was generated without A_v . The second rows displays the same information for the ‘high’ input redshift sources (those with $z_{in} > 1$).

Table 3.6: Comparison between the input model template types and the best-fitting templates when ImpZ was run on the Monte-Carol generated model catalogues. Values are given as the percentage for each input template that was fit by each output template. Ideally only the diagonal region (bold) would be populated.

Out	Input SED type							
	E	Sab	Sbc	Scd	Sdm	Sbrst	RR1	RR2
E	88	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sab	8.0	71.7	18.6	0.0	2.9	0.0	0.1	0.3
Sbc	2.0	8.3	71.2	0.0	0.0	0.0	0.0	0.0
Scd	2.0	8.3	10.2	84.8	4.3	7.4	0.0	0.0
Sdm	0.0	10.0	0.0	3.0	87	25.0	0.0	0.0
Sbrst	0.0	1.7	0.0	12.2	5.8	67.6	3.9	4.7
RR1	0.0	0.0	0.0	0.0	0.0	0.0	64.3	30.3
RR2	0.0	0.0	0.0	0.0	0.0	0.0	31.7	64.7

plates. There is also a clear demarcation between the galaxy templates and the AGN templates – very few AGN templates are fit as galaxy templates (with some overlap with the starburst template). Recall that the reverse does not occur (galaxy template fit by AGN) since *sources* with an input AGN template are treated as *stellar* by ImpZ. Although there are some degeneracies between the templates, this does not effect the photometric redshift accuracy greatly (as can be seen by the redshift residuals in Fig. 3.7). Hence the photometric redshift of a galaxy is more certain than its exact spectral type, as expected if the bulk of redshift identification is due to common features such as the Balmer break and in agreement with the results of fitting the INT WAS ELAIS catalogue with only one galaxy template, and also from the study of Bolzonella et al. (2000).

3.7.3 Filters

What are the relative importance of different filters? In order to successfully derive redshifts for different sources, the filter set in use needs to have sufficient wavelength coverage to encompass the main template features for a broad range of redshifts. As seen in §3.6.1.5 and §3.6.2.4, most outliers were sources whose spectroscopic redshifts meant that the main template features (Balmer break and Lyman limit) did not fall within filter bandpasses. It is of interest to see how results change when a filter is not included in the template-fitting. To this end, ImpZ was run on the INT WAS ELAIS catalogue without *U* band information. The statistical results of this can be found in Table 3.4 but the main effect was that without *U* band photometry, all z_{phot} values were below 1.5, although 7 sources lie at $z_{\text{spec}} > 1.5$. This is because information on the position of the Ly α line has been lost, and at these z_{spec} redshifts

no other main template feature falls into the INT WAS bands.

Additionally, a synthetic catalogue of 5000 *sources* was generated as in §3.7.1 but without U band photometry. For the $z_{in} < 1$ sample, the $(z_{in} - z_{out})$ residual distribution was strongly peaked at zero, in a similar fashion to the first plot in Fig. 3.7, but with a population of outliers with $(z_{in} - z_{out}) \approx -2.6$. This suggests that without the use of the *U* band to decide if the Lyman break feature is present or not, the Balmer break can be mistaken to be Ly α in the g' band. Hence the low- z_{in} *source* is then placed at a high- z_{out} . As a whole, though, the loss of *U* band information does not adversely effect the $z_{in} < 1$ sample. In contrast, the $z_{in} > 1$ sample is highly dependent on it for a reasonable z_{out} value. The $(z_{in} - z_{out})$ residual distribution is almost flat – the z_{out} accuracy is very poor. Thus the *U* band is central to good photometric redshift accuracy for $z \gtrsim 1.5$. This is clear from Table 3.1 – without *U* band none of the template features listed is present in the remaining INT WAS filters until $z > 2.4$ when Ly α enters the g' band.

3.7.3.1 Degeneracies in parameter space

As seen in §3.7.1 and §3.7.2 there do exist degeneracies in the parameter space and this is a cause of outliers in the photometric error analysis of the simulated catalogues. Common degeneracies include confusion between the main template features (when either the redshift or the lack of bands means most features don't fall into the filter bandpasses) and confusion between different galaxy templates. Often, however, the spectral types can be degenerate without altering z_{phot} greatly (compare Table 3.6 with Fig. §3.7).

It is also of interest to see if A_v introduces its own degeneracies. Such degeneracies will be inherent even if A_v is not explicitly fit, since real galaxies will have different A_v . In order to quantify this, the same synthetic catalogue procedure as in §3.7.1 is carried out, but the ImpZ code is allowed to fit for free A_v . Since the input catalogue is created with $A_v=0$ we can see how fitting for free A_v alters the findings.

Fig. 3.7 shows the result of this procedure as the second and third plots on each row (again the first row is for the $z_{in} < 1$ sample and the second row is for the $z_{in} > 1$ sample). The distribution of residuals between z_{in} and z_{out} are very similar to those for the $A_v=0$ case, with both the low- z_{in} and high- z_{in} samples being strongly peaked at zero. The low- z_{in} sample has a noticeable but low-level tail to higher residuals, whilst the high- z_{in} sample can be well represented by a broad Gaussian. The high- z_{in} sample has a slight secondary bump at $(z_{in} - z_{out}) \approx -0.4$, which is likely to be due to confusion between the Balmer break and O[III] doublet, since,

as can be seen in Table 3.1, these features enter and leave the i' and Z band with a separation of around 0.4 in redshift.

The A_v residual is also shown. This is simply the A_v of the fit since the input synthetic catalogue was generated without A_v . The low- z_{in} sample is very strongly peaked at zero, and the high- z_{in} sample is also strongly peaked at zero, with slightly more $A_v > 0$ solutions. This means that the increasing photometric error for more distant/faint *sources* causes a few *sources* to be fit as redder *sources* than they really are. This however does not necessarily cause an increase in the redshift error, as can be seen from the redshift residual plots for the A_v -free fitting. It is clear that the addition of A_v freedom introduces little degeneracy, and the fact that the redshift solutions tend to improve lends weight to the argument that the A_v thus determined reflects the physical A_v of the galaxy.

Running the Monte Carlo simulations with larger photometric errors tended to increase the width of the residual distributions.

3.7.4 Overall errors

The main sources of error are due to photometry, cosmic variance and degeneracies in colour–redshift–extinction space. The relative effect of each depends on the signal-to-noise of the source with photometric errors dominating those with low signal-to-noise. Splitting into low ($z < 1.5$) and high redshift ($z > 1.5$), one can broadly say that the error for low-redshifts is 0.1 or less in $(1+z)$ whereas for the high-redshifts the error can be as large as 0.3 or more.

3.8 Discussion

A comparison can be made to the photometric accuracies of other recent works: photometric redshifts for galaxies in the Great Observatories Origins Deep Survey (GOODS; Dickinson et al. 2001) were estimated for 434 galaxies by Mobasher et al. (2004) where in total there were as many as 18 independent photometric measurements for each galaxy. Using the Bayesian method (Benítez 1999) they obtained a total *rms* scatter, σ_{tot} , of 0.11, with an outlier-clipped *rms*, σ_{red} , of 0.047 and an outlier fraction, η , of roughly 10 per cent. This is very similar to the success of the ImpZ code on the INT WAS ELAIS sample, which had a maximum of only 5 photometric bands. In Richards et al. (2001), using statistics based on $\Delta_z = (z_{phot} - z_{spec})$, redshifts were estimated for 2625 quasars in the SDSS filter system with an overall *rms*, σ_z of 0.676 and σ_{red} of 0.1 for sources with $|\Delta_z| < 0.3$.

The success of the ImpZ code can also be directly compared for quasars to the results of Barger et al. (2002) who got one third of broad-line sources within 25 per cent of z_{spec} . ImpZ fit two thirds of the same CDFN broad-line sample within 25 per cent. More recently, Kitsionas et al. (2003) estimated photometric redshifts for a sample of X-ray selected QSOs in the SDSS bands (up to 5 filters), obtaining z_{phot} within $|\Delta z| < 0.3$ for 20 of the 30 QSOs at $z > 0.4$. The same statistic can be calculated for INT WAS ELAIS ‘QSO’ $z > 0.4$ sub-sample, where 10 of 20 sources are within the same Δz tolerance, and for the broad-line and/or compact CDFN sources at $z > 0.4$, where 36 of 50 (72 per cent) of sources are within $|\Delta z| < 0.3$. The ImpZ quasar redshift results are clearly highly successful and show that reliable redshift estimates for quasars can be achieved.

It is important to note that the intrinsic variability of quasars offsets the magnitudes measured in various bands depending on the actual epoch of observation (e.g. Hook et al. 1994). This is certainly an issue for the INT WAS survey which was completed over several years. The variability scrambles the real spectrophotometric data taken over an extended period whereas the template fits assume that the photometry in each band is taken at the same time (or that there is no variability) and is therefore sampling the same underlying SED. This problem was noted in Wolf et al. (2001) who found around half their quasar sample had completely incorrect photometric redshifts, presumably mainly due to this problem. Afonso-Luis et al. (2004)’s study of $15\mu\text{m}$ quasars in ELAIS found a similar variability when comparing the INT data to SDSS data in common (SDSS data was taken at a different epoch), in contrast to other sources such as main sequence stars. Clearly future surveys need to be scheduled with this effect in mind.

3.9 Conclusions

In this Chapter, photometric redshifts have been studied using SED template-fitting on two spectroscopic redshift catalogues (INT WAS ELAIS and CDFN). The overall accuracy of the redshift code, ImpZ, is found to be very good, with $\Delta z/(1+z) < 0.1$ for 92 per cent of galaxies (where this statistic is calculated from the 138 ‘GALAXY’ sources in the INT WAS ELAIS catalogue). The addition of A_v freedom in the fitting improves the redshift solution, suggesting that some information about the true A_v of the source is also returned. Application to sources with known A_v will help to quantify the quality of this information (Chapter 4). The template-fitting method is also extended to quasars via the inclusion of AGN templates and is found to be reasonable, with $\Delta z/(1+z) < 0.25$ for 68 per cent of quasars (based on the 25

‘QSO’ sources in the INT WAS ELAIS catalogue). It is noted that the inherent time-variability of quasars reduces the effectiveness of the technique for surveys where the photometry is collected over an extended period.

A combined galaxy–quasar approach to template-fitting photometric redshift techniques has been presented and the results and analysis presented in this work clearly show that photometric redshifts can be calculated with good success for *both* galaxies and quasars, as long as certain considerations are taken into account: it is important to limit the absolute magnitude of the solutions to prevent unphysical results; use available optical morphology/stellarity information in order to pre-select sources that are more likely to be quasars than galaxies (since we expect quasars to be point-like whereas most galaxies will be extended in some way). Although the application of template-fitting to a single source in order to derive its redshift can never be completely relied on, due to the inherent degeneracies and limitations of a method reliant on perhaps four or five data-points, the statistical information drawn from application to a large catalogue of objects is extremely powerful and can be used for many different investigations.

Further investigation of extinction as derived by photometric redshift codes will be explored in Chapter 4, and incorporation of near-IR data and application to the SWIRE survey will be covered in Chapter 5.

3.10 Addendum

Since this work was carried out Shang et al. (2004) have combined data from the Far Ultraviolet Explorer (*FUSE*), the *Hubble* Space Telescope (*HST*) and the 2.1m telescope at KPNO in order to investigate the UV to optical SEDs of 17 AGN. Their results suggest that most of these types of object exhibit a spectral break at around 1100Å and do not rise significantly to shorter wavelengths (though Scott et al. 2004 do not see a spectral break in their composite FUSE spectra for low-redshift AGN). This suggests that the ‘UVrise’ power-law extension adopted in this Chapter for the AGN templates (since it gave, marginally, the best results) is probably not the best description, and that the peak of AGN energy generation does not lie in the Extreme-UV ($\sim 100 - 912\text{\AA}$) as had been suggested by Mathews & Ferland (1987). The fact that in this Chapter the ‘UVrise’ was found to be, marginally, the best treatment is attributed to the fact that at the redshifts where this spectral region is shifted into the optical wavebands, the dominant effect is, by far, that of intervening IGM absorption. When this is coupled with the small number statistics of

high redshift AGN in the samples explored here, the ability to correctly differentiate between the various UV treatments is strongly suppressed.

As a final note and to illustrate that the debate is by no means settled, modelling in Shang et al. (2004) also suggests that for AGN with luminosities approaching the Eddington limit the spectral break becomes progressively weaker - for L/L_{Edd} of 0.289 the SED still rises shortward of $1000\text{\AA}$.

3.11 Acknowledgements

Application of HYPERZ to the samples was carried out by Mari Polletta, UC San Diego. The SSP generation of the galaxy SEDs from the lower-resolution versions was carried out by Stefano Berta, Padova.

Chapter 4

Can a photometric redshift code reliably determine dust extinction?



Figure 4.1: NASA/HST/R.Thompson (Univ. Arizona)

4.1 Overview

As demonstrated in Chapter 3, photometric redshifts can be routinely obtained to accuracies of better than 0.1 in $\Delta z/(1+z)$. However, the issue of dust extinction is one that has still not been well quantified. In this Chapter the success of two template-fitting photometric redshift codes (ImpZ and HYPERZ) at reliably returning A_v in *addition* to redshift is explored using sources in the CNOC2 survey that have both spectroscopic redshifts and A_v values derived from their Balmer decrements. It is also investigated whether the empirical value of $\gamma = 0.44$, the

ratio between gas- and star- derived extinction, as determined by Calzetti (2001b), is necessarily the best value for this sample.

By directly comparing the extinction values from the two codes it is found that the agreement between them is reasonable, with $\sim 70\%$ of values agreeing within $|\Delta A_v|$ of 0.3. Hence, using five band photometry, the A_v can only be determined to an accuracy of around 0.3, say, via photometric redshift methods.

When comparing the two codes to the Balmer-derived A_v , Balmer- A_v , the correlation between the photometrically derived A_v , Phot- A_v , and the Balmer- A_v is not so good. The correlation is improved when the empirical value of $\gamma = 0.44$, the ratio between gas- and star- derived extinction, as determined by Calzetti (2001b), is allowed to vary. From least-squares-fitting the minimum in the reduced χ^2 distribution is found for $\gamma = 0.33 \pm \sim 0.2$.

For the sample of galaxies in this Chapter, this factor two difference in covering factor implied by the Calzetti ratio is found to be consistent, within the errors of the method. The sample has a some preference for an increased covering factor which would imply they are undergoing more rapid, ‘bursty’ star formation than the galaxies Calzetti used in her derivation. Perhaps more importantly, the results demonstrate the pitfalls of assuming that star- and gas-based extinction measures will give the same dust extinction given some conversion factor. Thus, correlation to Balmer-derived values are modulo the uncertainty in comparing star- and gas-based extinction measures.

This Chapter presents work to be published in Babbedge, Whitaker & Morris (2004, in prep.). Any results not the work of T. Babbedge are indicated in §4.8.

4.2 Introduction

As was discussed in Chapter 1, star formation rates (SFRs) and their global history (SFH) form the backbone of a slew of methods (observational, numerical, and analytical) to investigate the processes of galaxy formation and evolution over cosmic time. SFH is important in indicating likely eras of dominant activity and in providing a self-consistent picture of chemical enrichment. This can then be compared to the predictions from semi-analytical models of galaxy formation and with inter-galactic medium (IGM) absorption line diagnostics. However, SFRs can be imprecise due to complications arising from dust reddening.

COBE measurements of the cosmic far-IR/sub-mm background energy density (Puget et al. 1996) showed it to be equal or greater to the UV/optical background (e.g. Hauser et al. 1998), implying that a large fraction of the energy from stars over the history of the Universe is hidden from the optical due to dust. The role of dust in high redshift galaxies therefore an important one). For example, star forming galaxies detected via the Lyman break technique at $z \sim 2 - 4$ are highly extinguished in the rest-frame UV, meaning star formation rates are $\sim 3 - 10$ times higher than if dust is ignored (e.g. Meurer, Heckman & Calzetti 1999). Correction factors found for other high redshift star forming galaxies are of a similar order. The exact form of this extinction correction remains uncertain and in particular its evolution with epoch.

Hence an important improvement to optical-based SFH studies is the determination of the extinction of galaxies, in addition to their redshifts. In order to fully allow for variation from galaxy to galaxy, extinction needs to be solved as an additional free parameter to redshift, however the study of Bolzonella, Miralles & Pelló (2000) found that the inclusion of A_v as a free parameter caused significant increases in aliasing. In a similar technique developed in Rowan-Robinson (2003b), hereafter RR03, and extended in Chapter 3, these aliasing problems were reduced by setting several A_v priors.

In this Chapter a sample of galaxies from the Canadian Network for Observational Cosmology (CNOC2) Field Galaxy Redshift Survey (Yee et al. 2000) are used to investigate the reliability of A_v values as determined by two SED template fitting photometric redshift codes – HYPERZ (Bolzonella et al. 2000) and ImpZ (see Chapter 3) – by comparing the returned $[z_{phot}, A_v]$ to the spectroscopically derived redshifts and Balmer-derived A_v 's.

In §4.3 the CNOC2 galaxy sample and spectroscopic data are set out. In §4.4 the link between the Balmer decrement, extinction and photometry is discussed. The photometric redshift method is briefly outlined in §4.5 and the results of applying the two redshift codes to the CNOC2 sample are presented in §4.6. Overall discussions and conclusions are presented in §4.7.

Note that for these investigations the flat, $\Omega_\Lambda=0.70$ cosmological model with $H_0=72\text{km s}^{-1}\text{Mpc}^{-1}$ is used.

Table 4.1: 5-sigma limits (Vega) for the four CNOC2 areas, and the Galactic extinction $E(B - V)$ in each area. This can be converted to a correction in each band via Cardelli et al. (1989) with $R_v=3.1$.

Area	I_c	R_c	V	B	U	$E(B - V)$
0223	22.97	24.02	23.95	24.55	22.98	0.036
1447	23.52	23.72	24.35	24.76	23.27	0.029
0920	22.85	24.03	23.94	24.55	23.18	0.012
2148	22.69	23.88	23.70	24.48	23.08	0.035

4.3 The CNOC2 catalogue

The CNOC2 survey (Yee et al. 2000) was a spectroscopic/photometric survey of faint galaxies over 1.5 square degrees of sky, comprising four widely separated patches on the sky. The survey was carried out at the CFHT 3.6m telescope over a total of seven runs from February 1995 to May 1998. There are over 6000 spectra with redshifts to a nominal spectroscopic limit of $R_c \sim 21.5$ and five-band photometry (I_c , R_c , V , B , U)¹ for a complete sample of approximately 40,000 galaxies to $R_c \sim 23$. The mean limiting magnitudes (Vega, 5σ) in each filter for the four areas are given in Table 4.1 and the filter response curves are shown in Figure 4.2.

Use of band-limiting filters restricted the spectral window in the survey to 4400 – 6300Å. This includes the [OII] emission line doublet at restframe 3727Å (3726 and 3729Å) for redshifts between 0.18 and 0.69. The survey’s results on galaxy clustering over this range have been published (Carlberg et al., 2000) whilst an analysis of cosmic star formation history is in preparation (Whitaker et al, in prep.).

4.3.1 Extension of the CNOC2 Survey

In Babbedge, Whitaker & Morris (2004; in prep.) follow-up observations of a subset of the CNOC2 sample of galaxies are presented. The nature of these follow-up observations is briefly outlined here in order to provide a clear picture of the sample used for the extinction studies in this Chapter:

The goal of the additional observations was to observe wavelength ranges including $H\alpha$ (at restframe 6563Å) and $H\beta$ (at restframe 4861Å) so that limits on

¹ V photometry is in actuality g -band data calibrated to the V system based on Landolt standards

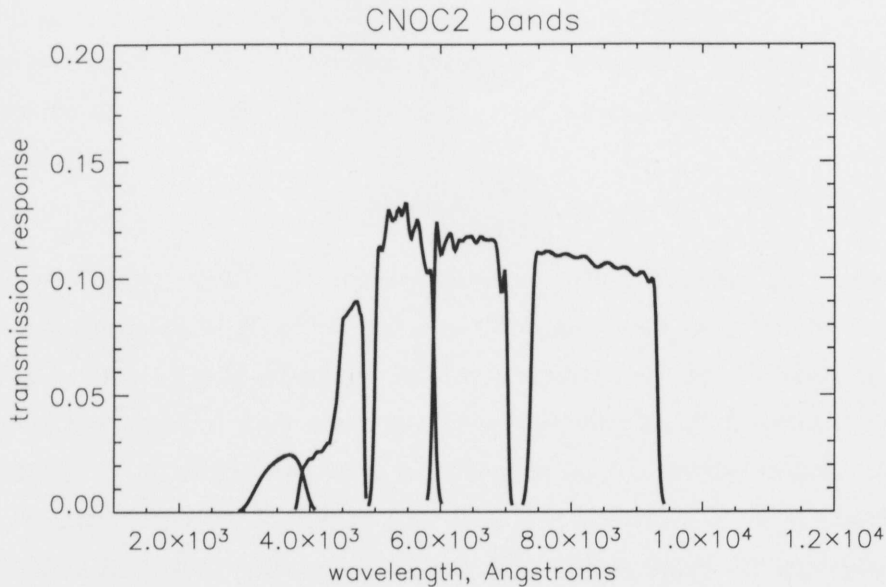


Figure 4.2: CNOC2 passbands combined with CCD response. From short to long wavelength they are U, B, V, R_c , I_c .

the reddening of the objects could be set. In this Chapter, these Balmer-decrement measures of the extinction will be compared to extinction measures derived from redshift codes. In future work (Whitaker et al. in prep.) they will be used to estimate the unreddened star formation rates for this subsample.

Data was taken with the CFHT MOS spectrograph (Crampton et al., 1992). 17 masks containing a total of 719 slits were observed, spread across 3 of the CNOC2 ‘patches’. The R300 grism was used, giving a potential wavelength coverage from 4000-10,000Å (depending on slit location), with a dispersion of 5Å per CCD pixel. A slit width of 1.5'' was used giving a nominal spectral line FWHM of 3.4 pixels or 17Å.

The data were reduced in IRAF (Tody, 1993) by Richard Whitaker. The reduction was based on a slightly modified version of the CNOC2 standard reductions of Yee et al. (2000). The steps included object finding, tracing and extraction, wavelength calibration, flux calibration, and interpolation over bad sky subtraction and zero order residuals. Error vectors were carried through the same procedure.

4.3.2 Measurement of the Balmer Decrement from CNOC2

A purpose written code (Whitaker et al, in prep) was used to measure the fluxes and equivalent widths of the Balmer lines in each spectrum. In brief the code measures the flux and equivalent width over pre-defined spectral windows, set for each line.

Each window includes two continua regions and a line region.

Error estimates on the equivalent widths are computed using the formulae set out by Bohlin et al. (1983). For the error on the flux measurement the following relation was used:

$$\sigma_F = F \frac{\sigma_{eqw}}{eqw} \quad (4.1)$$

where the equivalent width errors have already scaled in order to make the error distribution a gaussian of $\mu = 0$, $\sigma = 1$ (see Whitaker et al, in prep. for full details).

Of the ~ 600 objects observed in the extension to the CNOC2 dataset the intensities of $H\alpha$ and $H\beta$ were measured (at above 3σ) in 29 of them. The Calzetti curve (Calzetti et al. 1993) was used to compute A_v 's from the Balmer decrement, with the lowest measured A_v being 0.01 and the highest 6.6. The distribution of Balmer-derived A_v values is shown in Figure 4.3. These values are typically accurate to 30%; the mean of the ratio ($A_v/\sigma A_v$) is 0.31.

The choice of extinction curve is one of the sources of uncertainty. From Figure 4.4 it can be seen that the extinction curves of local galaxies do differ. The largest differences are due to the strength of the feature at $\sim 2175\text{\AA}$, thought to result from graphite grains, amorphous carbon or PAH. However, for the Balmer lines, this feature is not a factor: The Balmer lines are sampling the longer wavelength region where the extinction curves have a more constant slope, so that differences are reduced. The main difference between the curves here can be parameterized by the chosen value of the ratio R_v , which is the total-to-selective extinction ratio at V band (Calzetti et al. 1993). In these investigations the 'standard' Milky Way value of $R_v=3.1$ is used.

4.3.3 Correction For [NII] Emission and Stellar Absorption

The window employed in the spectral measurement code covers both the $H\alpha$ and [NII] lines. These two lines cannot be separated in the data, nor can they be de-blended using gaussian fitting tools (e.g. SPLOT in IRAF) since the data is not of high enough resolution. Instead, to correct for the overmeasurement of $H\alpha$ flux, an $H\alpha$ to [NII] ratio of 0.5 (as per Kennicutt 1992) is assumed.

The Balmer emission lines suffer from stellar absorption and so any measurement of their fluxes must take this into account – this is particularly true for $H\beta$ where one often finds an emission line sitting in an absorption trough. However, the resolution of the data means one cannot fit the emission and absorption components within each line separately, so instead the average corrections found by Kewley et al. (2002) from the Nearby Field Galaxy survey are applied. They report average cor-

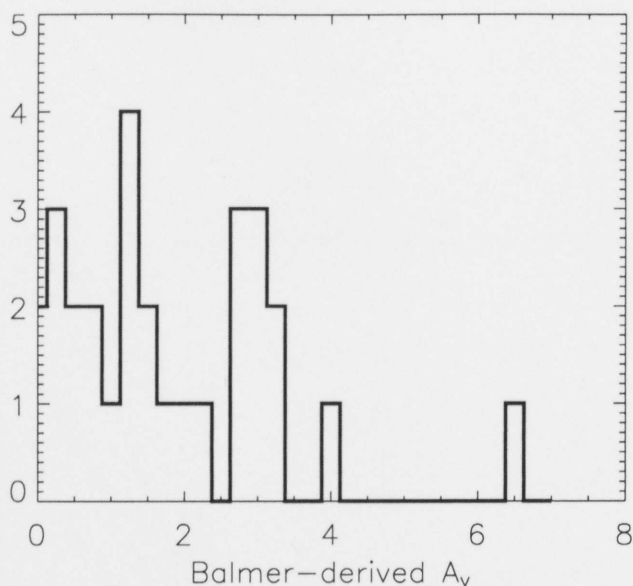


Figure 4.3: The distribution of Balmer-derived A_v values for the 29 sources in the sample.

rections (in equivalent width) of $1.5\text{\AA}$ for $H\alpha$ and a $1.0\text{\AA}$ for $H\beta$. The corresponding flux is therefore added to the measurements.

4.4 The Balmer Decrement and its Relation to Dust

The passage of light through dust results in the light becoming dimmed and also being selectively removed (Calzetti, 1997a). This second process is strongly wavelength dependent and is more severe for bluer regions of the spectrum than for redder ones.

The wavelength dependent nature of extinction due to dust can be used to quantify how much dust the radiation has passed through en route. One might envisage two spectral features with a known intensity ratio - by measuring the *observed* intensity ratio and comparing this to the theoretical (dust-free) case one may determine the amount of dust along the line of sight (the bluer feature is more strongly extinguished than the red and so the ratio is altered from the dust-free case).

The $H\alpha$ and $H\beta$ Balmer lines provide such a tool for the optical region of the spectrum - their intensity ratio is well known from atomic physics (Osterbrock, 1989) and is 2.86 in typical nebula conditions ($T=10,000\text{K}$, $n_e = 10^2 - 10^4\text{cm}^{-3}$). Their ratio thus leads to the Balmer optical depth, τ_B^l , and can therefore provide a measure of the dust content due to the internal reddening along the line of sight

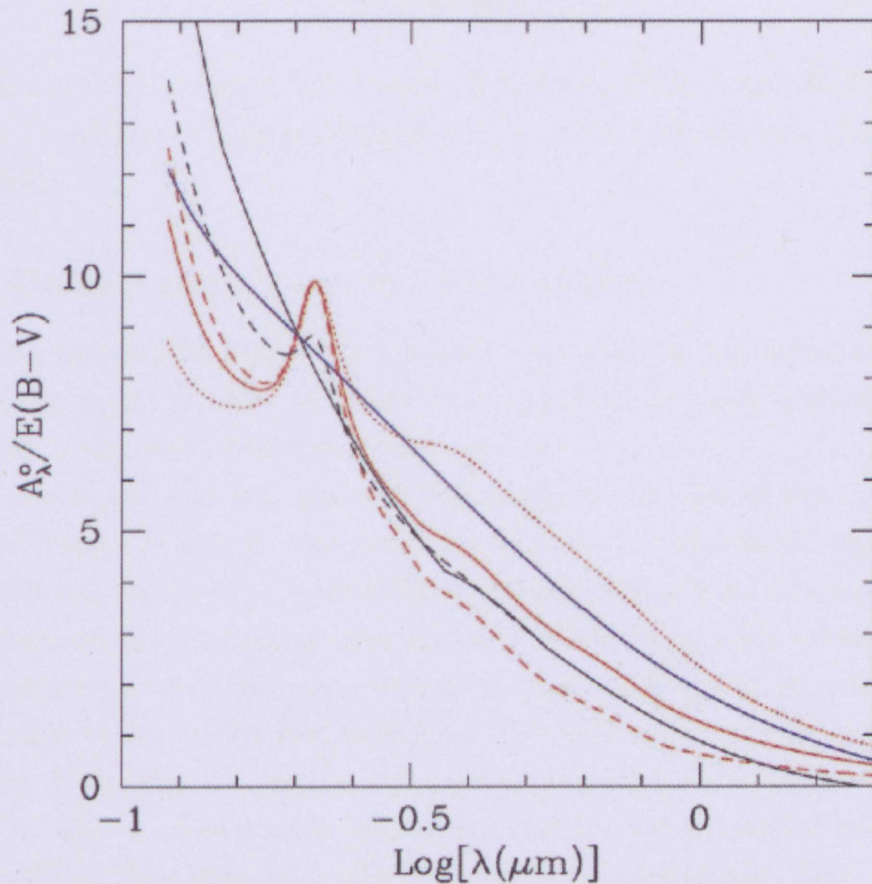


Figure 4.4: Examples of extinction curves in local galaxies. Plot from the review by Calzetti (2001a). The extinction curve of the Milky Way is shown for three different values of R_v ; 3.1 (solid red line), 5.0 (dashed red line), and 2.0 (dotted red line) (from Cardelli et al. 1989; Fitzpatrick 1989). The extinction curves of the Large Magellanic Clouds 30 Doradus region (dashed black line) and of the Small Magellanic Clouds bar (solid black line) are also indicated for $R_v=2.7$ (Gordon & Clayton 1998; Misselt et al. 1999). The starburst obscuration curve (blue line) is shown here for a purely illustrative comparison. A direct comparison is incorrect since, as discussed in §4.4.1, the dust obscuration of galaxies is conceptually different from the dust extinction of stars.

(e.g Calzetti et al. 1994), down to an optical depth of $\tau = 1$.

The observed ratio, R_{obs} , of $H\alpha/H\beta$ can be shown to be related to the reddening, $E(B-V)$, according to the following equation (E.g Calzetti et al. 1996):

$$E(B - V) = \frac{2.5[\log(R_{obs}) - \log(R_{int})]}{k(H\beta) - k(H\alpha)} \quad (4.2)$$

Where R_{int} is the intrinsic $H\alpha/H\beta$ ratio of 2.86 and $k(H\alpha)$ and $k(H\beta)$ are the extinction co-efficients at the wavelengths of $H\alpha$ and $H\beta$ respectively (from Calzetti et al. (1993)).

4.4.1 Balmer extinction vs. photometry

Are we able to compare photometry-derived extinction values, hereafter Phot- A_v , to Balmer- A_v values in order to better understand the accuracy and/or reliability of photometry-derived extinction measurements?

The crucial point here is that the Balmer decrement probes the extinction of the ionised gas in the source – the extinction of molecular clouds/HII regions (star-forming regions), $E(B-V)_g$. In the SED template-fitting method where photometry in a number of bands is compared to a library of templates with variable internal A_v , the resulting best-fit returns a template type, redshift and A_v . In this case the extinction is due to the ISM acting on the stellar continua within the galaxy as a whole. Thus Phot- A_v probes the dust obscuration of the stellar continuum, $E(B-V)_s$. This is more complicated than just the total amount of dust between the observer and the source, as would be the case for a single star, since folded into this is information on scattering and the geometrical distribution of dust within the galaxy.

As the Balmer and photometry methods are probing different regimes of the galaxy extinction, they might well be expected to give differing results. In a galaxy such as starburst where there is a significant amount of heavily-obscured star formation the two regimes will be linked - the galaxy's overall emission is dominated by the young star formation. At the opposite end of the scale an elliptical galaxy will have little dust or ongoing SFR. In this case the two measures are un-correlated (though both measures are likely to be low and so comparison between the two is not an issue). For intermediate-type galaxies the relationship falls somewhere between these two regimes.

The following relationship between the colour excess of the stellar continuum and of the nebular emission lines is given in Calzetti (2001b) and Calzetti (1997b)

and is as follows:

$$E(B - V)_s = (0.44 \pm 0.03)E(B - V)_g \quad (4.3)$$

This follows on from Calzetti et al. (1994) where 39 starburst and blue compact galaxies were used to derive an *effective* extinction law. From this, it was found that the difference between the optical depth to the Balmer lines, and to the underlying stellar continuum at the lines was approximately a factor two. Calzetti's relationship is a purely empirical one but it has often, in the past, been assumed to yield the most appropriate reddening corrections for the integrated light of extended star-forming regions or galaxies (e.g Calzetti et al. 2000; Westera et al. 2004). Here we start with this ratio of 0.44 but then consider other possible values in order to see how the results are affected.

4.5 Methodology

The main outcome of applying a redshift code is the best-fitting redshift, extinction and SED of each galaxy. In the template-fitting procedure, the observed galaxy magnitudes are converted for each i^{th} photometric band into an apparent flux, f_i^{obs} . The observed fluxes can then be compared to a library of template fluxes, $f_i^{templ}(z, T)$, computing the reduced χ^2 ; χ_{red}^2 , and selecting the best-fitting solution.

4.5.1 The ImpZ code

This code was presented in Chapter 3. Observed fluxes are compared to template fluxes for $0.01 \leq \log_{10}(1+z) \leq 0.90$, equivalent to $0.02 < z \leq 6.94$.

Galactic extinction in the CNOC2 regions is low; using the extinction-wavelength relation in Cardelli et al. (1989) one can calculate Galactic extinction in each of the CNOC2 bandpasses and correct for it (see Table 4.1).

For the CNOC2 sample survey the following parameters were used, adapted from investigations presented in Chapter 3:

Templates – the 6 galaxy templates (E1, Sab, Sbc, Scd, Sdm and Starburst), with IGM treatment and Galactic extinction corrections. In addition to the galaxy templates, 2 AGN templates can be considered. However, for the CNOC2 sample used here it was found that the AGN templates did not provide the best fit to any of the sources, (as expected based on their spectra) so in this Chapter only the 6 galaxy templates are considered.

Internal extinction – A_v limits of -0.3 to 3.0 in the A_v freedom. Slight negative A_v was allowed since the inherent A_v of the templates is non-zero. For the elliptical

template A_v can take the value 0 only, since ellipticals are not expected to have significant internal extinction (note that in fact none of the sources are fit as ellipticals by ImpZ).

Magnitude limits – Chapter 3 found it necessary to apply redshift-dependent absolute magnitude limits to exclude unphysical solutions (such as super-luminous sources at high redshift). Here, the same limits are used: Absolute magnitude limits of $[-22.5 - 2\log_{10}(1+z)] < M_B < -13.5$ for galaxies.

Prior – ImpZ usually applies a prior expectation that the probability of a given value of A_v declines as $|A_v|$ moves away from 0 by minimising $\chi_{red}^2 + \alpha A_v^2$ rather than χ^2 ($\alpha=2$ here). This can be viewed as a weak implementation of Bayesian methods and was reached at based on degeneracy studies in Chapter 3. For this investigation it was of interest to turn this prior off. This is because the Balmer A_v values of the sample range from 0 to 6.6, or (multiplying by 0.44) 0 to 2.9. Hence applying an A_v prior would naturally tend to limit the A_v solutions to values in a similar range, regardless of the input A_v limits, and so a correlation could be achieved simply because the sample all have Balmer A_v values that equate to the lower end of the A_v parameter space.

4.5.2 HYPERZ

Richard
Richard Whitaker of Durham University has applied the popular public code of Bolzonella et al. (2000), HYPERZ, to the sample, using the same set of galaxy templates and as optimal input parameters as possible.

HYPERZ was allowed the same A_v limits as ImpZ. Any non-detections in a given band were replaced with a flux of zero, the error being the limiting flux in the band (see Table 4.1 for 5σ limits) and the HYPERZ code was run in its standard form.

4.6 Results

4.6.1 ImpZ

ImpZ was highly successful at deriving photometric redshifts in very close agreement with the spectroscopic values for *all* of the sources (note that redshift solutions are considered in the range [0:7]). The accuracy of the photometric redshifts is measured

via the *rms* scatter σ_z , calculated as follows:

$$\sigma_z^2 = \sum \left(\frac{z_{phot} - z_{spec}}{1 + z_{spec}} \right)^2 / N. \quad (4.4)$$

with N being the number of sources with both spectroscopic redshifts and photometric redshifts. For this data, $\sigma_z=0.04$. The redshift residual; $[\log_{10}(1+z_{spec}) - \log_{10}(1+z_{phot})]$, is plotted in Figure 4.5.

ImpZ is therefore successful at returning accurate redshifts. However, can it simultaneously provide a measure of the extinction compatible with that implied by the Balmer decrement?

The distribution of A_v residuals for ImpZ is plotted in Figure 4.6. It can be seen that there is quite a spread to the distribution.

Figure 4.7 plots (purple squares) the ImpZ A_v values and residuals as a function of Balmer- A_v (multiplied by the Calzetti 2001b factor of 0.44). From the residuals it can be seen that the residuals increase with Balmer- A_v . There is also one source with a much larger residual. This is the source with the largest Balmer- A_v , of 6.6 ± 0.8 . It is likely that this object is quite extreme, so disagreement between the star- and gas-derived extinction measures is to be expected.

Calculating the following statistics:

$$\overline{\Delta A_v} = \sum (Balmer[A_v] - Phot[A_v]) / N. \quad (4.5)$$

and

$$\sigma_{A_v}^2 = \sum (Balmer[A_v] - Phot[A_v])^2 / N. \quad (4.6)$$

and outliers are defined by

$$|\Delta A_v| > 0.5 \quad (4.7)$$

gives $\overline{\Delta A_v} = -0.14$, $\sigma A_v = 0.72$ and an outlier fraction, η , of 34 per cent.

Note that the statistics and plots for the ImpZ A_v results refer to output *without* the A_v prior discussed in §4.5.1 in order to test the raw ability of the code. Including the A_v prior does not particularly effect the results - statistics become $\overline{\Delta A_v} = -0.21$ and $\sigma A_v = 0.78$, with an outlier fraction, η , of 45 per cent. Thus there is an overall slight shift to lower solutions.

4.6.2 HYPERZ

HYPERZ was unable to match the spectroscopic redshift reliably when run with redshift as a free parameter (for either the original or ImpZ template sets), in con-

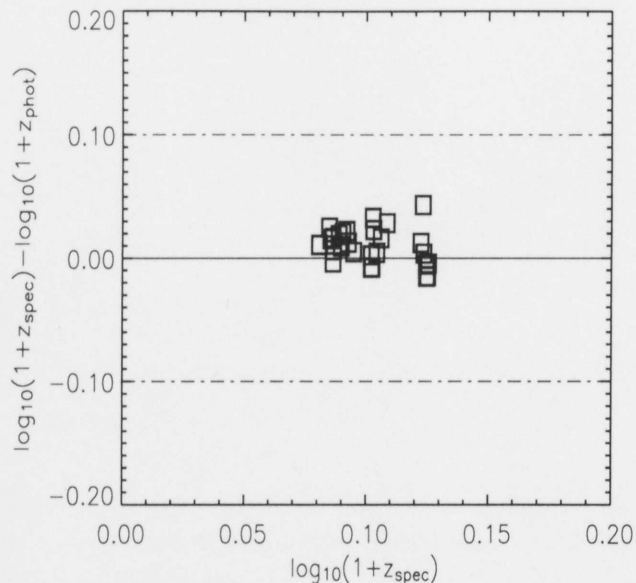


Figure 4.5: Photometric redshift residuals for ImpZ. Dotted lines denote ten percent accuracy in $(1+z)$. All the sources are fit to a high accuracy and precision ($\sigma_z=0.06$) (recall we are exploring a full redshift space of $z[0:7]$).

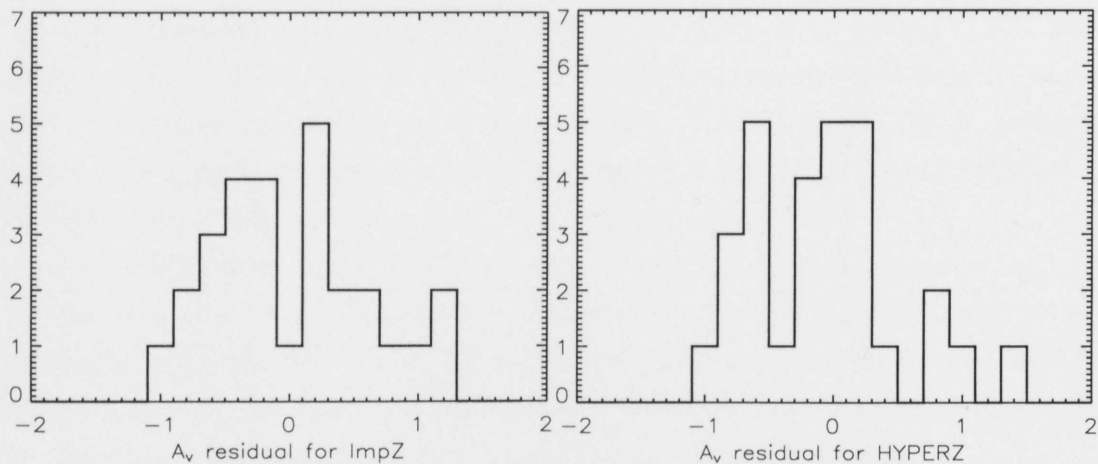


Figure 4.6: A_v residuals for ImpZ (left) and HYPERZ (right). Plot is $\text{Balmer}[A_v]$ (multiplied by the Calzetti 2001 factor of 0.44) versus the residual $(0.44 \cdot \text{Balmer}[A_v] - \text{Phot}[A_v])$.

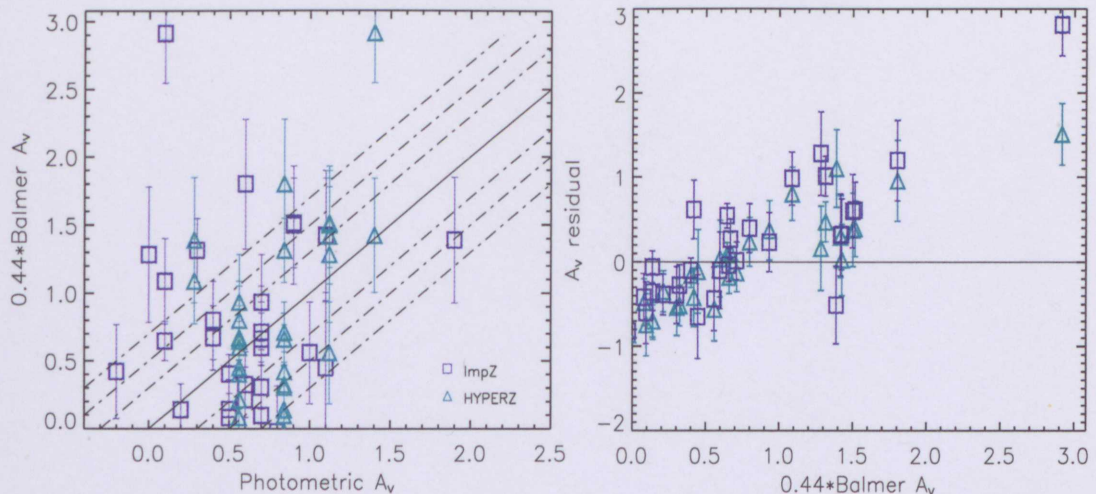


Figure 4.7: **Left:** A_v results for HYPERZ (red triangles) and ImpZ (purple squares). Plot is the photometrically-derived A_v versus the Balmer[A_v] (multiplied by the Calzetti (2001) factor of 0.44). Dot-dashed lines denote residuals of 0.3, 0.5 and 0.7 in A_v . Errors are not defined for the Phot- A_v values. **Right:** A_v residuals for HYPERZ (light blue triangles) and ImpZ (purple squares). Plot is Balmer- A_v (multiplied by the Calzetti 2001 factor of 0.44) versus the residual ($0.44 \times \text{Balmer}[A_v] - \text{Phot}[A_v]$).

trast to ImpZ, and the resulting A_v values do not correlate well with the Balmer- A_v values. Although a number of different HYPERZ input parameters were also considered, this poor correlation was not improved. In an attempt to produce better A_v results, the parameter space was eventually constrained by setting HYPERZ to a very small ($z/100$) margin either side of the known spectroscopic redshift of each source (i.e. removing redshift as a free parameter). This decreased the A_v problems, though this is perhaps against the spirit of the endeavor since we wish to test the ability to derive *both* redshift and A_v from a photometric code.

An additional problem was that when the elliptical template was included, the vast majority ($> 80\%$) of the sources were then fit as elliptical galaxies with essentially zero extinction. From the spectroscopic data this is known to be incorrect. The work-around was to exclude the elliptical template and only consider Sab, Sbc, Scd, Sdm and starburst templates. Again, this is not an ideal situation.

So, constraining the HYPERZ redshift solutions to the spectroscopic values and excluding the elliptical template, gives $\overline{\Delta A_v} = 0.02$, $\sigma A_v = 0.78$ and an outlier fraction, η , of 45 per cent. The distribution of A_v residuals for HYPERZ is plotted in Figure 4.6. Figure 4.7 plots (light blue triangles) the HYPERZ A_v values and residuals as a function of Balmer- A_v (multiplied by the Calzetti 2001b factor of

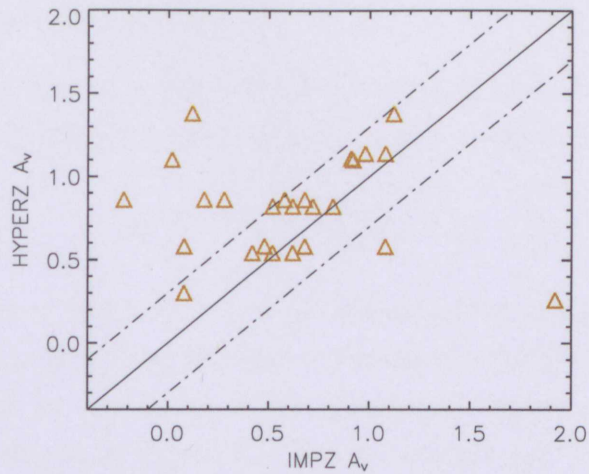


Figure 4.8: Comparison between ImpZ and HYPERZ: A_v results for Impz versus those from HYPERZ. Solid line is exact agreement, dot-dashed lines are residuals of 0.4 in A_v .

0.44). The source with the largest Balmer- A_v is again an outlier, though not to such an extent. The residuals are again correlated with the Balmer- A_v .

4.6.3 Comparison of ImpZ and HYPERZ

As well as comparing the two photometric redshift code's extinction outputs to the Balmer-derived values, it is instructive to compare them to one another to see if they tend to agree on a similar extinction value for a given source. A plot of ImpZ- A_v versus HYPERZ- A_v is given on Figure 4.8.

This shows that the two codes are in reasonable agreement about the extinction of a given source. Twenty of the twenty-nine sources (70%) agree within < 0.3 in A_v . The main difference appears to be where ImpZ gives a low value of $A_v < 0.2$ for a source - HYPERZ tends to return a larger A_v estimate. The source with the highest HYPERZ- A_v , of 1.4, but low ImpZ- A_v , of 0.1, is the source with the largest Balmer- A_v . The fact that the two codes fail to agree, and both also fail to agree with the Balmer-derived value could indicate that this source is not well represented by the templates available.

Calculating similar statistics as when comparing to the Balmer- A_v , comparison between the two codes' A_v values gives $\overline{\Delta A_v} = -0.03$, $\sigma A_v = 0.52$ and an outlier fraction, η , of 38 per cent.

4.6.4 The Calzetti ratio

We now consider the empirical ratio of 0.44 introduced by Calzetti (1997b) and set out in Eqn. 4.3. We consider a range of other ratios, γ , so that

$$E(B - V)_s = \gamma E(B - V)_g \quad (4.8)$$

Varying this ratio from $0.05 < \gamma < 1$, a χ^2 minimisation analysis is carried out in order to find the ratio that gives the best correlation between the Phot- A_v and the Balmer- A_v , weighted by the errors in the Balmer- A_v measurements. The results of this analysis are shown in Figure 4.9. For both ImpZ and HYPERZ, the lowest reduced χ^2 is reached for $\gamma = 0.33$. Based on the change in γ that increases the reduced χ^2 by one, the 1σ error on this value is $\gamma = 0.33 \pm 0.25$ for ImpZ and $\gamma = 0.33^{+0.2}_{-0.1}$ for HYPERZ.

The resulting statistical measures, σA_v and the outlier fraction, η , are also plotted as a function of γ for the ImpZ and HYPERZ results (Figure 4.10).

Figure 4.10 A shows how the *rms* in the residual, σA_v , varies with γ . A clear minimum is seen at $\gamma \sim 0.2$ to 0.35 for ImpZ results, and at around 0.2 to 0.4 for HYPERZ.

A similar minimum is seen in the range $\gamma \sim 0.15$ to 0.4 for ImpZ results when the outlier fraction, η , is plotted against γ in Fig. 4.10 B. For HYPERZ, the minimum is at around $\gamma \sim 0.25$ to 0.5 .

This analysis suggests that for this sample, the Calzetti ratio of 0.44 is a reasonable choice for γ within the accuracy of the method, though a value of ~ 0.33 is preferred. A choice of $\gamma=0.33$ gives the following statistics:

For ImpZ; $\overline{\Delta A_v} = -0.07$, $\sigma A_v = 0.58$ and an outlier fraction, η , of 31 per cent.

For HYPERZ; $\overline{\Delta A_v} = -0.19$, $\sigma A_v = 0.48$, η , of 45 per cent.

As before, the distribution of A_v residuals is plotted (Figure 4.11). It can be seen that the distribution is more peaked, though offset from zero.

Figure 4.12 plots the Phot- A_v values and residuals as a function of Balmer- A_v (multiplied by $\gamma=0.33$). It can be seen that for lower Balmer- A_v , the Balmer- A_v tends to underestimate the extinction in comparison to the Phot- A_v value. Again, the source with the largest Balmer- A_v , of 6.6 ± 0.8 (multiplied by $\gamma = 0.33$ in the plot) has poor agreement between its Balmer- A_v and Phot- A_v . If this source is excluded, the remaining sources do follow the line denoting agreement, albeit with large scatter.

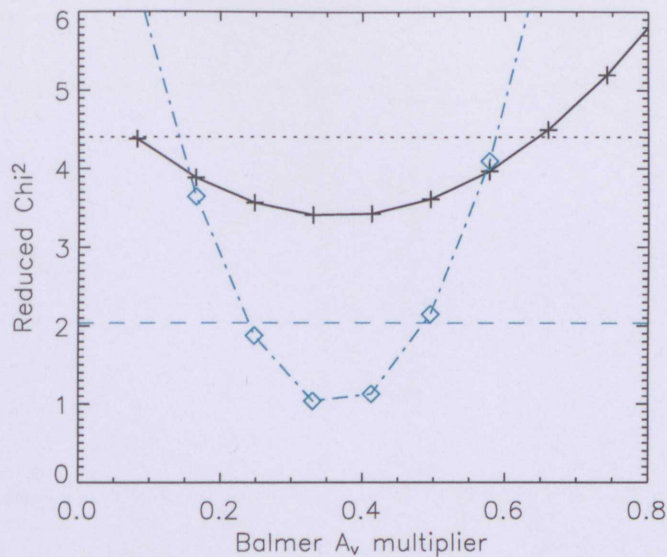


Figure 4.9: χ^2 analysis. The reduced χ^2 for ImpZ (solid line with crosses) and HYPERZ (dot-dashed line, diamonds) as a function of γ , the chosen ratio between photometrically-derived and Balmer ratio-derived extinction measures. The χ^2 values that are 1 above the minimum in the two distributions are indicated by horizontal lines (ImpZ, dotted; HYPERZ, dashed).

4.6.5 Inherent A_v

The results discussed in Section 4.6.1, 4.6.2 and 4.6.4 refer to the Phot- A_v values of the best-fitting solutions. However, these values are those of the variable A_v which has been *added* to the template in question. In *addition* to this it is also necessary to consider the *inherent* A_v of the templates. This is problematic in that the templates originate from empirical templates drawn from observations, along with alterations found to optimise redshift solutions in previous studies. Their re-generation via spectrophotometric synthesis where the overall template is re-produced using a small number of simple stellar populations (SSPs) is designed to give some insight into the underlying physics of each template. Hence an overall A_v can be defined, based on the A_v 's of the contributing SSPs.

In Chapter 3 these inherent A_v values were given (ranging from 0 for the elliptical to 0.74 for the starburst). However it is possible to reproduce the same² overall template using different proportions of SSPs with differing A_v contributions. For example, the starburst template can be generated from young SSPs to give the 'same' overall template, but with a total A_v of either 0.05 or 0.74. Similarly, the Scd can be generated with an A_v of 1.6 or 0.27. Clearly, then, we should not take the

²here, 'same' means from the point of view of flux through a broad-band filter

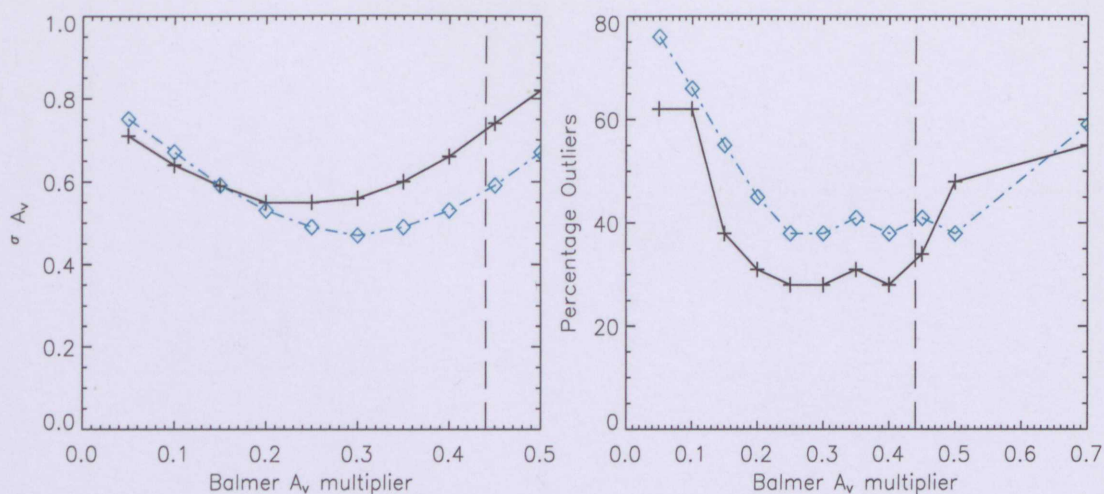


Figure 4.10: A: σA_v for ImpZ (solid line with crosses) and HYPERZ (dot-dashed blue line, diamonds) as a function of γ , the chosen ratio between photometrically-derived and Balmer ratio-derived extinction measures. The Calzetti value of $\gamma = 0.44$ is indicated as a long-dashed line. **B:** Percentage outliers for ImpZ (solid line with crosses) and HYPERZ (dot-dashed blue line, diamonds) as a function of γ , the chosen ratio between photometrically-derived and Balmer ratio-derived extinction measures. The Calzetti value of $\gamma = 0.44$ is indicated as a long-dashed line.

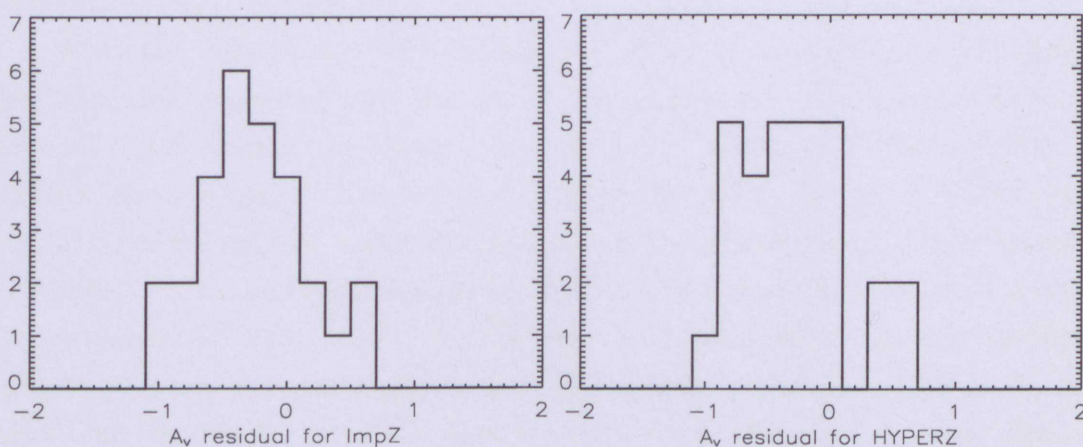


Figure 4.11: A_v residuals for ImpZ (left) and HYPERZ (right). Plot is $\text{Balmer}[A_v]$ (multiplied by $\gamma = 0.33$) versus the residual ($0.33 \cdot \text{Balmer}[A_v] - \text{Phot}[A_v]$).

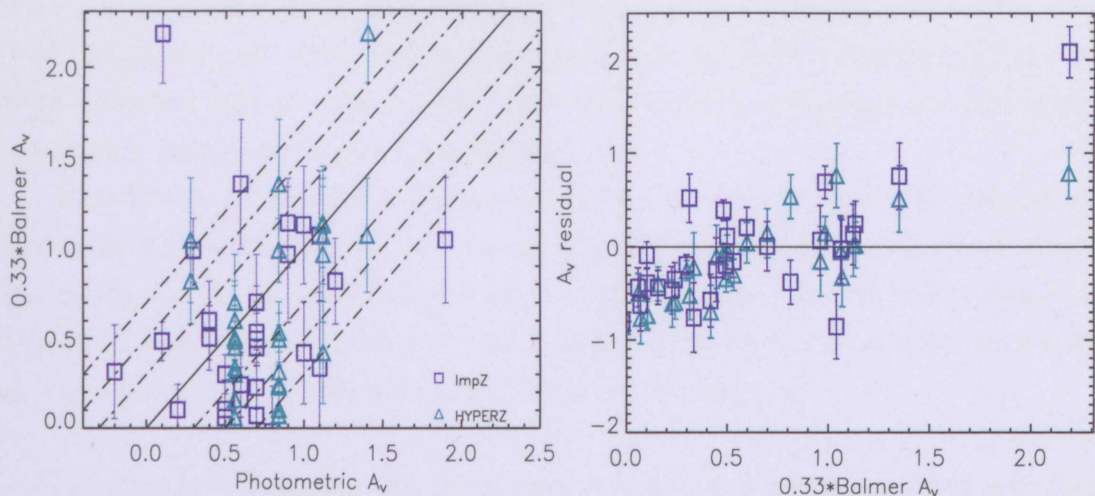


Figure 4.12: **Left:** A_v results for HYPERZ (light blue triangles) and ImpZ (purple squares). Plot is the photometrically-derived A_v versus the Balmer[A_v] (multiplied by $\gamma = 0.33$). Dot-dashed lines denote residuals of 0.3, 0.5 and 0.7 in A_v . **Right:** A_v residuals for HYPERZ (light blue triangles) and ImpZ (purple squares). Plot is Balmer- A_v (multiplied by $\gamma = 0.33$) versus the residual ($0.33 \times \text{Balmer}[A_v] - \text{Phot}[A_v]$).

inherent A_v 's of the SSP solutions at face value (note that in the case of fitting SSPs to spectroscopic data most of these degeneracies can be expected to be broken). However, empirically, we would expect the inherent A_v of the late-type templates (Sab, Sbc, Scd, Sdm) to have low extinction, perhaps $A_v \sim 0.2$, and the starburst to be dusty ($A_v > 0.5$, say).

When the Calzetti ratio of 0.44 was used, it was clear (e.g Figure 4.7) that the residuals were correlated with Balmer- A_v . Decreasing the ratio γ from 0.44 to 0.33 reduced this tendency (e.g Figure 4.12). However, at higher Phot- A_v (>0.5), the Balmer estimate tended to be lower, with either value of γ . Inclusion of some inherent A_v for each template type will act to increase this discrepancy. Since the details of inherent A_v are undetermined, inclusion in the analysis would introduce a second free parameter in addition to γ . For this relatively small sample there is insufficient data to properly constrain both so here it is merely noted that inherent A_v is an additional complication and that it will act to increase the Phot- A_v estimates.

4.7 Discussions and conclusions

A number of redshift codes routinely output an A_v value in addition to redshift, but little has been done to investigate the reliability and/or accuracy of such extinc-

tion measures. The main reason for this lies in the aim of such codes - they have been developed and optimised in order to derive *redshifts*. However, as the field of photometric redshift methods matures, it is useful to consider some of the other parameters that redshift solutions output.

This Chapter has asked the question ‘Can a photometric redshift code reliably determine dust extinction?’. Using a sample with extinctions derived from Balmer flux-ratios the A_v values produced by two photometric redshift codes, ImpZ and HYPERZ, have been compared. It was found that ImpZ was successful in returning good photometric redshifts and that HYPERZ was less so.

By directly comparing the extinction values from the two codes it was found that the agreement between the two was reasonable, with $\sim 70\%$ of values agreeing within $|\Delta A_v|$ of 0.3. Hence, using five band photometry, the A_v can only be determined to an accuracy of around 0.3, say, via photometric redshift methods. It is expected that the ability of photometric redshift codes to determine extinction will improve with the availability of more photometric bands (here, there are five wide band filters between 3000-9000Å). A sample with a combination of wide and narrow-band filters, with good wavelength coverage and range (in particular, extension to near-IR) will break many of the degeneracies and allow the codes to accurately differentiate between different possible fits.

When comparing the two codes to the Balmer-derived A_v , the correlation between the Phot- A_v and the Balmer- A_v was not as good:

For ImpZ, $\overline{\Delta A_v} = -0.34$, $\sigma A_v = 0.56$; for HYPERZ, $\overline{\Delta A_v} = -0.46$, $\sigma A_v = 0.54$.

It is also noted that there was one galaxy, fit as a starburst, with very high Balmer extinction (of $A_v = 6.6 \pm 0.8$). Neither code was able to reach agreement with this measure, ^{or} with one another. Clearly this source is of interest and could be quite extreme. Further observations will be of interest.

The correlation improved between the Phot- A_v and the Balmer- A_v when the empirical value of $\gamma = 0.44$, the ratio between gas- and star- derived extinction, as determined by Calzetti (2001b), was allowed to vary. From least-squares-fitting the minimum in the reduced χ^2 distribution was found for $\gamma = 0.33 \pm \sim 0.2$. For $\gamma = 0.33$, the statistics were as follows:

For ImpZ, $\overline{\Delta A_v} = -0.07$, $\sigma A_v = 0.58$; for HYPERZ, $\overline{\Delta A_v} = -0.19$, $\sigma A_v = 0.48$.

The Calzetti ratio of 0.44 means that there is around a factor two difference in

reddening such that the ionised gas (as measured by the Balmer decrement) is twice as reddened as the stellar continua (as measured by the photometry) (e.g. Fanelli et al. 1988; Calzetti et al. 1994). This implies that the covering factor of the dust is larger for the gas than for the stars, which can be explained by the fact that the ionising stars are short-lived and so for their lifetime remain relatively close to their (dusty) birthplace, whilst the majority of stars, contributing to the galaxy's overall optical luminosity are longer-lived and can migrate away from their dusty origins.

For the sample of galaxies in this Chapter, this factor two difference in covering factor implied by the Calzetti ratio is found to be consistent, within the errors of the method. The sample has a some preference for an increased covering factor which would imply they are undergoing more rapid, 'bursty' star formation than the galaxies Calzetti used in her derivation. Perhaps more importantly, the results demonstrate the pitfalls of assuming that star- and gas-based extinction measures will give the same dust extinction given some conversion factor. Thus, correlation to Balmer-derived values are modulo the uncertainty in comparing star- and gas-based extinction measures.

It is important to note that for the HYPERZ results, this level of correlation was only obtained by removing redshift as a free parameter, and excluding elliptical templates. This reduces the number of situations in which HYPERZ might be applied to a sample in order to derive extinction measures.

However the results presented here show that, given certain considerations, there is potential in the application of photometric codes to reliably derive an extinction measure, though this has a precision of only 0.3 in A_v , say. The results also show that it is important to note that this will be a measure of the star-based extinction, and will not necessarily be well correlated with the extinction to the ionised regions of a galaxy.

4.8 Acknowledgements

The Balmer A_v and HYPERZ results used here were calculated by Richard Whitaker, Physics Dept., Durham. I am grateful for the use of these data prior to publication in Babbedge, Whitaker & Morris (2004; in prep.).

Chapter 5

Application to SWIRE



5.1 Overview

In this Chapter, ImpZ, the photometric redshift code presented in Chapter 3, is extended to incorporate near-IR data (sub $5\mu\text{m}$), using a sample which has both spectroscopic redshifts, optical photometry *and* SPITZER data.

The emission of a galaxy at optical to near-IR and at mid-IR wavelengths will not typically be well correlated - that is, the optical to near-IR emission will tend to be dominated by emission from stars, whereas at longer wavelengths the re-processed emission from dust is the dominant contribution. Hence the optical to mid-IR SED of a galaxy cannot be allocated to one of a set of generic templates. Here, the analysis is separated into optical/near-IR, and mid-IR, using optical and IRAC $3.6\mu\text{m}$, $4.5\mu\text{m}$ detections in the photometric redshift fitting procedure. Including the 3.6 and $4.5\mu\text{m}$ data from *SPITZER* enables several solution degeneracies to be broken, since this then provides data on the underlying SED across a much wider

observed wavelength range (3000Å to 50,000Å).

It is concluded that the inclusion of the first two IRAC bands in the photometric solution reduces the *rms* error in $\log_{10}(1+z)$ and enables the rejection of the majority of catastrophic outliers that result from only using optical data in the fitting procedure.

Luminosity functions (LFs) are then investigated at 3.6, 4.5, 5.8, 8 and 24 μ m for the SWIRE survey in the ELAIS-N1 field, comprising band-merged optical, IRAC and MIPS 24 μ m data in a common overlap area of 6 square degrees. Issues of star/galaxy separation, reliability, completeness and the resulting selection functions are discussed.

The 3.6 and 4.5 μ m galaxy LFs are found to be similar to other near-IR studies, where the LF is probing the stellar mass. There is evidence for positive evolution in the galaxy LF such that the bright-end of the LF increases to higher luminosities for higher redshifts. In the highest redshift bin (redshift 1.5 to 2) there is then a drop in space density, possibly indicative of the redshift at which the bulk of stellar mass formed and favouring the predictions of hierarchical galaxy formation over monolithic scenarios. The 24 μ m galaxy LF, more indicative of star formation rate, is in agreement with previous *IRAS* and *ISO* results in the mid- and far-IR, with evidence of strong luminosity evolution with redshift.

The quasar LFs, calculated in the IRAC bands, show similar high redshift behaviour to radio-selected quasars and optical quasar studies (excluding the very faint and the very luminous), and the steep drop in space density in the redshift bin $3 < z < 4$ implies a similar cosmic history and evolution. The drop in space density is found to be less pronounced for the 24 μ m sample, which could imply a more common heritage with the most luminous quasars, and the X-ray-selected quasar population.

This Chapter presents work to be published in Babbedge et al. (2004, in prep.). Any results not the work of T. Babbedge are indicated in §5.10.

5.2 Introduction

IR based-surveys indicate that far-IR populations of luminous galaxies have undergone strong evolution, with a radical increase in their luminosities and contribution to the comoving SFR to higher redshifts - studies of the extragalactic background suggest at least half the luminous energy generated by stars has been reprocessed

into the IR by dust (e.g. Puget et al. 1996, Lagache et al. 1999). Contrast this with the fact that, locally, luminous IR galaxies are negligible contributors to overall SFR and energy output. The evolution that is required by such studies is in agreement with suggestions from longer wavelengths - the luminous sub-mm galaxies have been shown to have median redshifts > 2 (Chapman et al. 2003; Simpson et al. 2004), indicating that significant evolution has occurred. The links between IR and sub-mm have been further strengthened by early results from *SPITZER* - Serjeant et al. (2004a) found that the populations dominating the 5.8 and $8\mu\text{m}$ extragalactic background light also contribute around a quarter of the $850\mu\text{m}$ background and the majority of the $450\mu\text{m}$ background.

One powerful tool in the study of galaxy populations is the construction of Luminosity functions (LFs) at a variety of wavelengths. These have long been used to constrain galaxy formation models and to quantify SFR and evolution (both of luminosity and number density). IR-based LFs have been constructed at a variety of wavelengths:

Some of the earliest IR LFs were constructed from the *IRAS* satellite mission (e.g. Rowan-Robinson et al. (1987) derived 25 , 60 and $100\mu\text{m}$ LFs). Saunders et al. (1990) used *IRAS* data to derive the $60\mu\text{m}$ and 40 - $120\mu\text{m}$ LFs, which were found to be indicative of strong evolution such that luminosity increases with redshift, perhaps $\text{luminosity} \propto (1+z)^{3\pm1}$.

The *ISO* mission also enabled IR LFs to be constructed; Clements et al. (2001) used deep $12\mu\text{m}$ *ISO* data with follow-up optical imaging and spectroscopy to determine the mJy $12\mu\text{m}$ LF, finding that the excess (in comparison to the low-redshift *IRAS* results) at high luminosities (higher redshift) was compatible with rapid luminosity evolution $(1+z)^{4.5}$. This had also been claimed by Xu (2000) and suggested by Elbaz et al. (1999) based on number counts.

More recently, Serjeant et al. (2004b) used the optical-IR band-merged ELAIS Final Analysis catalogue of Rowan-Robinson et al. (2004a) to calculate the ELAIS $90\mu\text{m}$ LF, finding that for consistency with source counts a luminosity evolution of $(1+z)^{3.4\pm1}$ was required - consistent with the evolution in comoving volume averaged SFR at $z < \sim 1$ derived from rest-frame optical and UV surveys (e.g. SLOAN; Glazebrook et al. 2003).

In this Chapter, ImpZ is extended to incorporate near-IR data, using a sample which has both spectroscopic redshifts, optical photometry and *SPITZER* data.

Band-merged 3.6 : $24\mu\text{m}$ *SPITZER* data and associated optical photometry (U,

g' , r' , i' and Z) from one SWIRE field (ELAIS-N1) is then used to derive photometric redshifts, study the luminosity functions of SWIRE galaxies and quasars at several IR wavelengths and to investigate evolution with redshift.

In §5.3 the IR and optical catalogues, data calibration and band-merging are set out. The photometric redshift method, IR SED fitting and luminosity function calculations are outlined in §5.4, §5.5 and §5.6 respectively. Luminosity functions with redshift are presented at 3.6, 4.5, 5.8, 8 and $24\mu\text{m}$ for galaxies and quasars in §5.7 and these are compared to other studies in §5.8. Overall discussions and conclusions are presented in §5.9.

For this work the flat, $\Omega_{\Lambda}=0.70$ cosmological model with $H_0=72\text{km s}^{-1}\text{Mpc}^{-1}$ is used.

5.3 The data

5.3.1 Infrared data

In this Chapter one field observed in the first stage of the SWIRE survey is considered; the 9.2 deg^2 ELAIS-N1 field, centred on $16h11m+54d55m$. For this field there are band-merged catalogues from 3.6:24 micron inclusive, though this excludes the 5 of 32 MIPS scans lost in the original observing of ELAIS-N1 due to a spacecraft ‘safing’ event (these have now been re-observed and are undergoing reduction). A plot of the IRAC and MIPS coverage of ELAIS-N1 shown in Figure 5.1.

5.3.1.1 Processing at SSC

Prior to delivery to the SWIRE Team, *SPITZER* data undergoes initial processing at the *SPITZER* Science Center (SSC).

IRAC data was processed using the SSC S9.10 software revision in February 2003. The individual images were linearised, flat-fielded, dark-subtracted and flux calibrated. Standard calibration products were used, specifically contemporaneous darks and flats taken in the same campaign.

MIPS data was processed by the SSC software version S10. The pipeline follows algorithms developed by the MIPS Instrument Team from extensive pre-launch laboratory testing (Gordon et al., 2004).

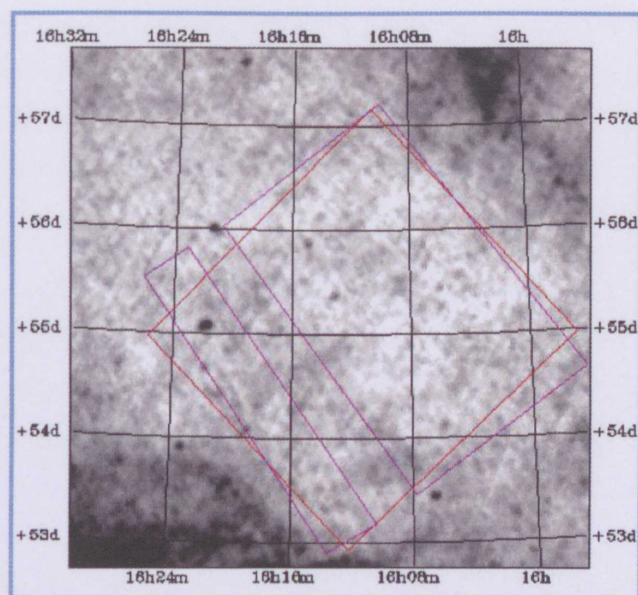


Figure 5.1: *SPITZER* coverage in ELAIS-N1. IRAC (red box) data and MIPS (purple boxes) data indicated. Note the gap in MIPS coverage due to a spacecraft safing event (now re-taken).

5.3.1.2 Processing by SWIRE

Post-SSC processing carried out by the SWIRE Team is designed to address a number of the in-flight behaviours and artefacts that transpired post-launch, as were detailed in Chapter 2. It is noted that some bright star artefacts still remain, though nearly all can be excluded by specifying multi-band detection. Specific treatments are:

For IRAC

- **Latents.** Fast timescale (minutes) latents are common in SWIRE. Targets likely to cause image latents at $3.6\mu\text{m}$ are detected via a threshold level and affected pixels are then tracked as a function of time so they can be masked during co-addition.
- **Muxbleed.** Due to bright stars trails. An additional mask is set based on a thresholding scheme prior to co-addition. The small rotation between individual IRAC epochs, combined with the half-offsets between epochs, is effective in minimising this effect in most cases.
- **Banding.** Appears as broad uniform bands to either side of bright sources. This is again detected via a thresholding scheme and masked prior to co-addition.

- **Column pulldown.** Due to a bright source reducing the flux in an entire column. This is detected via statistical fluctuations in the columns and corrected by applying an additive constant to the affected column in order to match the background level in the rest of the frame.

After individual processing, the data are mosaiced and co-added to create ‘tiles’ of one square degree with a sub-sampled pixel size of $0.6''$ (half a native IRAC pixel). Resampling to a finer grid is chosen since the SWIRE dithers provide some degree of multiple pixel phasing, so the resolution is improved slightly. Coverage maps, uncertainty images and mask files are also produced.

For MIPS $24\mu\text{m}$

Prior to mosaicing, saturating latents (appearing as dark blotches) were removed by medianing sequences of time-ordered images and dividing these into the observations. Where the background varied appreciably across the field (due to varying zodiacal background for different epochs of observation) the median background was calculated and removed. At mosaicing, all images were re-projected onto a common tangent plane and interpolated to a pixel scale of $1.2''$. Coaddition with outlier rejection was carried out the MOPEX developed by SSC.

Further information on the IRAC and MIPS data processing can be found in Surace et al. (2004b:in prep.), Shupe et al. (2004:in prep.) and in the SWIRE Delivery Document (Surace et al. 2004a: in prep.).

Source extraction and photometry

The depths (5 sigma) are approximately 3.7, 5.4, 48 and $37.8 \mu\text{Jy}$ in the IRAC bands (3.6 to $8\mu\text{m}$) and $130\mu\text{Jy}$ at $24\mu\text{m}$ for ELAIS-N1. Source extraction was carried out using SExtractor (Bertin & Arnouts 1996), with aperture fluxes for IRAC extracted within a $2.9''$ radius and within a $12''$ radius for MIPS. Aperture corrections derived from stars in the mosaic images were applied and are as follows: $0.87(3.6\mu\text{m})$; $0.81(4.5\mu\text{m})$; $0.80(5.8\mu\text{m})$; $0.70(8\mu\text{m})$ and $0.58(24\mu\text{m})$.

Additionally, for those sources (a small fraction) determined to be *extended* from their flux, stellarity index and isophotal area, the Kron fluxes were selected as the ‘best’ flux measures. The Kron fluxes were extracted with a minimum Kron radius (IRAC) of $2''$ and a Kron factor of 2.5.

Absolute IRAC photometric zeropoints are accurate to 3% for stars (Reach et al. 2004) but additional effects add a random scatter to the measured fluxes, with the dominant error being a colour-dependency in the flat field. Resultant fluxes are

hence subject to calibrational error of $\sim 10\%$.

The GOODS Validation Field (Chary et al. 2004), taken as part of the Extragalactic First Look Survey (FLS) program, is a deep observation of the same part of the ELASI N1 field and comparison shows a good agreement in fluxes, with a 10–15% scatter for the brightest IRAC sources and good agreement for MIPS down to 0.2–0.3 mJy. The non-reducing scatter at bright IRAC fluxes is believed to be due to the IRAC flat-fielding, which is carried out using the zodiacal background. This has a very different spectral shape to the stars used to calibrate IRAC and hence the flat-field is incorrect for sources whose SEDs significantly differ from that of the zodiacal background (e.g. stars). This would manifest itself as a scatter at bright fluxes where stars become prevalent (as seen).

The IRAC data is astrometrically accurate to $< 0.5''$ and the MIPS data to $< 1''$ and IRAC and MIPS $24\mu\text{m}$ sources were merged into multi-band IR catalogues using positional matching. For the χ^2 positional match a maximum 36 mosaic pixels ($0.6''$ pixel scale) criterion was used, within which the best candidate is selected. Although the smallest χ^2 is the best candidate after the initial selection, it may not turn out to be the best match after the multi-band confusion processing.

In the full coverage area (both IRAC and MIPS observations), there are a total of $\sim 410,000$ *SPITZER* sources (reliable or otherwise).

5.3.1.3 Reliability and completeness

Reliability

One of the most important sources of unreliability are bright star artefacts. The majority of artifacts associated with bright stars were eliminated from the basic SWIRE source lists by tuning SExtractor to avoid their close vicinity.

The other major cause of unreliability is then source confusion, combined with the limited performance of aperture photometry methods (as opposed to PSF-fitting methods) in highly confused regions. Outside of bright-star avoidance zones, a robust rejection of such effects can be implemented effectively, for example, by using multi-band catalogues; in general every reliable source in a given band was also detected at $3.6\mu\text{m}$; in the case of a $3.6\mu\text{m}$ source a detection at $4.5\mu\text{m}$ is an effective way of excluding spurious sources.

Based on studies with the multi-band IR catalogues, and also with the band-merged optical-IR catalogues, a *reliable* source is here considered to be one that has a detection with $S:N > 4$ in the band in question *and* have a detection in another

optical or IR band. Hence in order for a source to be considered, for example in the $3.6\mu\text{m}$ luminosity function calculation, it must first have a good S:N detection at $3.6\mu\text{m}$ and be detected at some other optical or IR band. Although this approach will conceivably exclude real sources which are only detected in a single band this is not, in practice, a significant population. This is because the chosen flux limit for the LF in a given band is relatively bright, so the likely source SED would then mean that detection in an adjacent band is expected.

In order to estimate the reliability of the MIPS $24\mu\text{m}$ detections, Shupe et al. (2004; in prep.) ran source extraction on a ‘negative’ of the mosaic by multiplying the original by -1 and adding a constant equal to twice the mean background, a technique used by Papovich et al. (2004). The resulting number counts were compared to actual extracted $24\mu\text{m}$ sources which also had $3.6\mu\text{m}$ detections (for reliability). Above the minimum $24\mu\text{m}$ flux level that will be considered in this Chapter, the contamination was $< 0.5\%$, dropping steeply with flux.

In the area in common with the optical data (see §5.3.2) 301,021 *SPITZER* sources are defined as *reliable* (all with a $3.6\mu\text{m}$ detection). Of these; 101,139 (34%) are detected at $4.5\mu\text{m}$; 27,554 (9%) are detected at $5.8\mu\text{m}$; 27,074 (9%) are detected at $8\mu\text{m}$ and 38,601 (13%) are detected at $24\mu\text{m}$ (Numbers from table 2 of Rowan-Robinson et al. 2004b).

Completeness

The completeness of the IRAC data was evaluated using a deeper field within the ELAIS-N1 field. This deeper observation was taken as part of the Extragalactic First Look Survey (FLS) program and consists of two non-overlapping IRAC pointings. These FLS data are much deeper than the SWIRE data, so that faint SWIRE sources are detected to a very high confidence in the FLS. Thus the FLS data act as a ‘truth’ set to which the SWIRE data can be compared.

FLS and SWIRE data were compared in a 25 square arcminute area. Integral completeness curves resulting from this are shown in Figure 5.2. The 95% confidence level occurs at $18\mu\text{Jy}$, $10\mu\text{Jy}$, $43\mu\text{Jy}$, and $42\mu\text{Jy}$ for IRAC $3.6\mu\text{m}$, $4.5\mu\text{m}$, $5.8\mu\text{m}$, and $8\mu\text{m}$ respectively. These values compare well to completeness functions derived by adding simulated sources to the central high-coverage portion of the ELAIS-N1 mosaics (M. Vaccari, Imperial College; priv. comm).

In order to derive the MIPS $24\mu\text{m}$ completeness function, simulated sources were added to the central high-coverage portion of the ELAIS-N1 mosaics. The number of simulated sources corresponds to 200 beams per source, with a flux distribution that

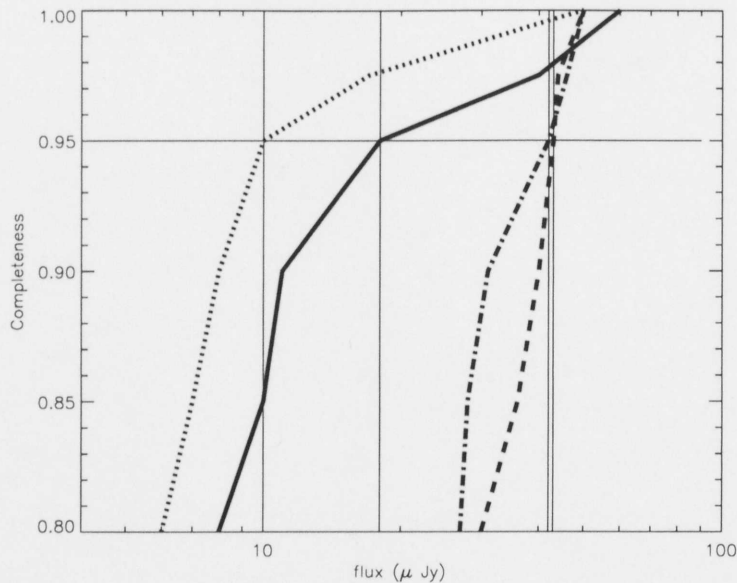


Figure 5.2: IRAC selection functions, based on comparison to the deeper FLS observations. 95% completeness is indicated by a solid intersecting line. $3.6\mu\text{m}$ is solid curve, $4.5\mu\text{m}$ is dotted curve, $5.8\mu\text{m}$ is dashed curve, $8\mu\text{m}$ is dot-dashed curve. Flux is in μJy . 95% completeness corresponds to a fluxes of, respectively, $18\mu\text{Jy}$, $10\mu\text{Jy}$, $43\mu\text{Jy}$ and $42\mu\text{Jy}$.

was logarithmic (so each logarithmic bin has the same number of sources). These sources were then SExtracted using gaussian filtering and cross-correlated with the input (simulated) catalogue, allowing completeness versus flux to be calculated. The resulting MIPS $24\mu\text{m}$ completeness function is shown in Fig. 5.3.

For the investigations in this Chapter, based on these completeness functions and the limiting depths of the observations, the following lower flux limits are chosen, below which a source is not considered for a given LF calculation:

For IRAC LFs, sources are cut at the 95% confidence level; so for the $3.6\mu\text{m}$ LF this is at $18\mu\text{Jy}$; for $4.5\mu\text{m}$ LF this is at $10\mu\text{Jy}$; $5.8\mu\text{m}$ at $43\mu\text{Jy}$; $8\mu\text{m}$ at $42\mu\text{Jy}$.

For MIPS $24\mu\text{m}$ sources are cut at the 70% completeness level; that is $250\mu\text{Jy}$. The decision to cut at a lower completeness level for the $24\mu\text{m}$ LF is taken after factoring in the additional selection functions, described in Section 5.6.1, of requiring enough bands to calculate a redshift and of the source then obtaining a good redshift solution. For the $24\mu\text{m}$ sources these additional selection functions are not as severe as in other bands, so the flux cut can be taken down to a lower value for the same overall selection function.

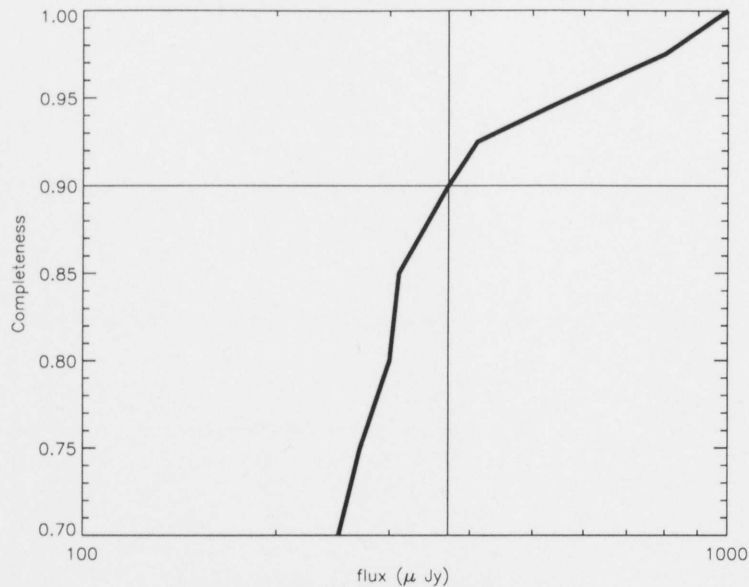


Figure 5.3: MIPS 24 μm selection function, based on simulated sources with 200 beams per source. 90% completeness is indicated by a solid intersecting line. Flux is in μJy . 90% completeness corresponds to a flux of $370\mu\text{Jy}$, 70% completeness to $250\mu\text{Jy}$.

5.3.2 ELAIS-N1 optical data

This Chapter makes use of optical photometry available in the ELAIS-N1 field (U, g', r', i' and Z). The source of the data and basic reduction, photometry and catalogue information is outlined below:

The INT Wide-Field Survey consists of several projects mapping areas of the sky in multiple colours with the INT Wide Field Camera (WFC - Ives et al. 1996) on the Observatorio del Roque de Los Muchachos (La Palma, Spain). For more information on the survey and its goals see McMahon et al. (2001).

The WFC is formed by four 4k x 2k CCDs. The arrays have $13.5\mu\text{m}$ pixels corresponding to $0.33''/\text{pixel}$ at the telescope prime focus and each one covers an area on the sky of $22.8' \times 11.4'$. The total sky coverage per exposure for the array is therefore 0.29 square degrees. Gaps between detectors are typically $20''$ and optical observations are carried out allowing for a 10% overlap between adjacent pointings for photometric purposes. The CCD layout of the camera is shown in Fig. 5.4 and the filters are shown in Fig. 5.5.

The ELAIS-N1 (16h10m+54d30m) field is approximately 9 deg^2 in U, g', r', i' and Z bands and comprises 1,185,418 sources. There is a 6 deg^2 overlap with the *SPITZER* observations, giving 750,994 optical sources in this full coverage

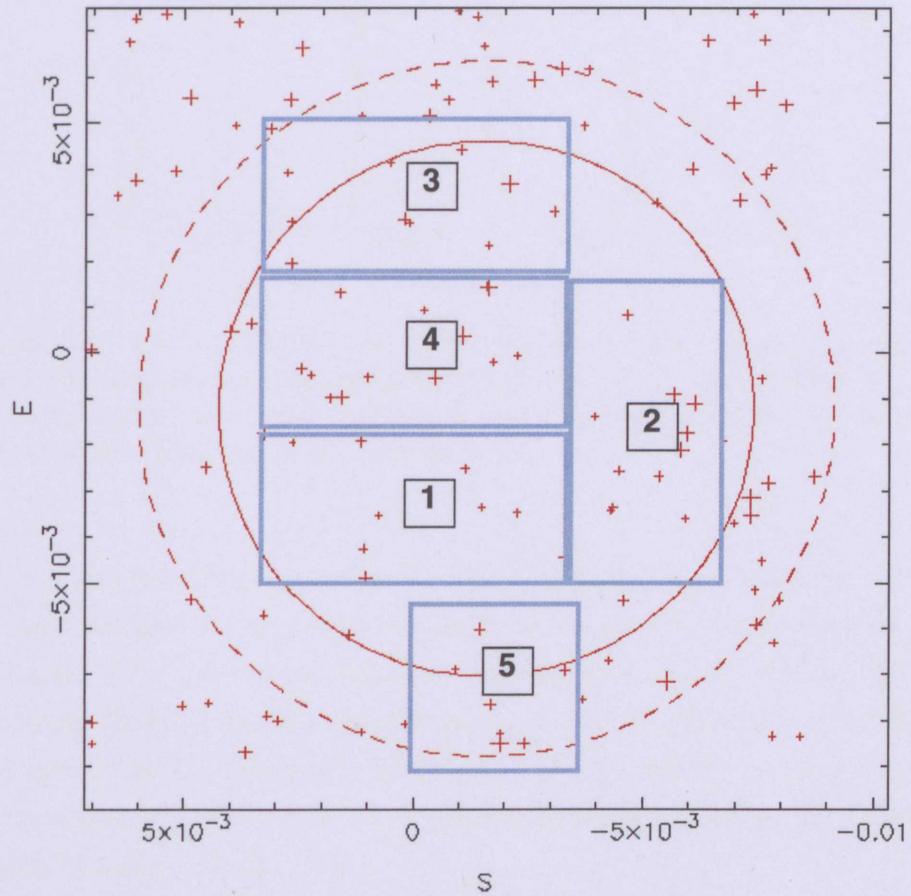


Figure 5.4: INT WFC CCD layout. The 4 science CCD's are numbered 1 to 4, along with the star-guider (chip 5). Red-solid line denotes the unvignetted central field of view ($40'$), red-dotted line denoted the 50% vignetted region ($52'$). The CCDs cover an area of $22.8' \times 11.4'$ on sky. The plot here is scaled in radians. Adapted from McMahon et al. (2001).

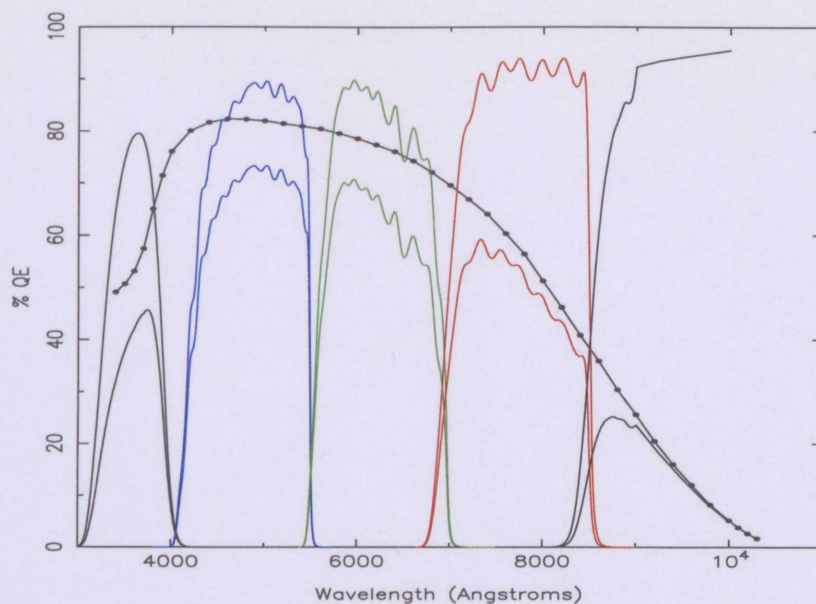


Figure 5.5: INT WFC filters. Solid line with points shows the quantum efficiency of the detector. Transmission curves of U, g' , r' , i' and Z filters are solid lines, with re-plotted versions showing the total throughput of the system in the different filters (from the *CASU* website).

area. These data have been processed at the Cambridge Astronomical Survey Unit (*CASU*) as described in Irwin & Lewis (2001) using a similar procedure to that laid out in Chapter 2 for the optical data that was reduced as part of this Thesis.

The mean limiting magnitudes (Vega, 5σ in 600 seconds) in each filter across this area are 23.40(U), 24.94(g'), 24.04(r'), 23.18(i'), and 21.90(Z), however the completeness falls off before this, as is demonstrated by a plot of the r' magnitude distribution of sources in Fig. 5.6.

The core flux was calculated using aperture integration over a radius of $r_{\text{core}}=3.5$ pixels ($\sim 1.16''$, note that the mean seeing was $\sim 1.17''$ in N1), modified to simultaneously fit ‘cores’ in cases of overlapping images. Curve-of-growth analysis shows that this core flux is the most robust single number for representing the flux for all sources, although it will underestimate the fluxes of large extended sources.

5.3.2.1 Photometric calibration and merging

Calibration was carried out at *CASU* and is summarised here, along with some additional steps taken for this Thesis in order to merge and clean the individual pointings:

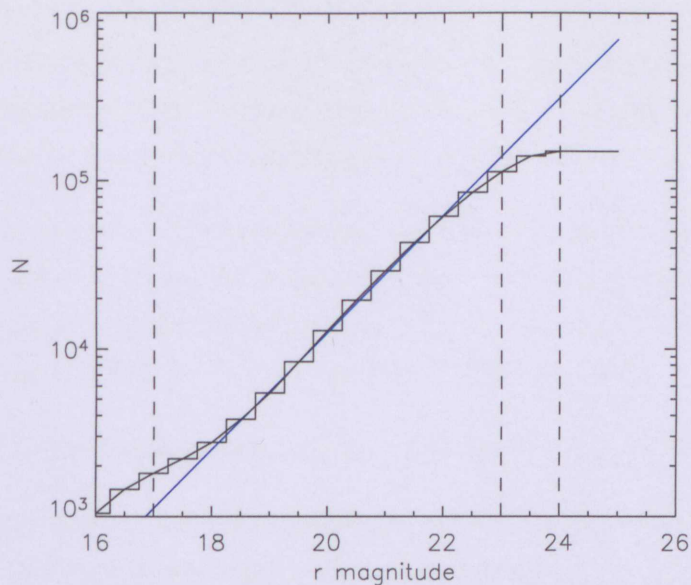


Figure 5.6: Histogram of r' band magnitudes (integrated counts) in ELAIS-N1, with the nominal 5σ limit of 24.04 and the magnitude cut at $r'=23$ in order to retain completeness (based on deviation from a power-law distribution - blue line). At the bright end, sources brighter than r' of 17 are also cut due to the large contamination from stars, and the loss of photometric accuracy due to saturation.

Calibration

Standard star observations were made throughout each observing night of selected Landolt (1992) standard fields. These give zeropoint calibrations for the whole mosaic to an accuracy of $\sim 1\text{-}2\%$ for photometric nights. However, on non-photometric nights the derived zeropoint systematic errors been found to be up to $\sim 10\%$ so further photometry correction was required in order to correctly track the varying extinction on such nights.

Adjacent camera pointings overlap by several square arcminutes so sources in these overlapping regions can be used as magnitude reference points. However, a systematic error is introduced due to the uncorrected sensitivity differences between the CCDs in the cameras (for example, in their colour equations). Overcoming this involves three stages:

- (i) Firstly, each CCD is gain-corrected onto a common system by using the twilight flats;
- (ii) Since the twilight sky is significantly bluer than the majority of astronomical objects, the measured dark sky levels in each chip are then used as a secondary

correction. Such corrections are negligible in the flat region of the generic CCD response curves (g' and r') but are around 1-2% for i' and Z. U band dark sky values were also consistent with zero correction, although due to the low sky levels in the U band this is to a lower accuracy;

- (iii) The CCDs are then checked for any residual offsets for each filter by using the mean offset between adjacent pointings on photometric nights. The only filters requiring significant adjustments to the individual CCD zero points at this stage are CCD3 for U (-3%) and CCD1 for Z (+3%).

Non-photometric observations can now be calibrated in one of two ways:

- (i) The overlap regions between pointings can be used to directly tie in all the frames onto a common system, with extra weighting given to data taken from photometric nights;
- (ii) The stellar locus in various 2-colour diagrams (in regions of low unchanging extinction like these) can be used to compare colours from all the passbands by cross-correlating the loci between any of the pointings. The colour-colour loci cross-correlations (actually made from a smoothed version of the diagrams) give results accurate to better than $\pm 3\%$ and can be used in conjunction with the overlap results to give overall photometry for the survey to the level of 2%.

The final products include astrometrically calibrated multi-extension FITS (MEF) images as well as morphologically classified merged multicolour catalogues. These, as well as further information on the images and catalogues, are publically available from the WFS web page (<http://www.ast.cam.ac.uk/~wfcsur/index.php>).

Additional steps - merging

The original INT WAS five band catalogues in N1 were for each individual pointing (54 pointings in N1). There is overlap between the pointings (which was how the photometric calibration was carried out). In order to merge the catalogues from the individual pointings an association radius of $0.9''$ was used (based on the seeing, $1.17''$, and a nearest-neighbour separation histogram - see Fig. 5.7). For sources that had duplicates, the one with the lowest photometric error was retained.

A comparison of the r' band magnitudes of sources that were within $0.9''$ of one another and therefore merged into one source shows that except for very bright sources (mainly star spikes, artefacts or large galaxies) and very faint sources (where

noise is naturally an issue) the matching is good - see Fig. 5.8 for a comparison of r' magnitudes in two overlapping pointings of sources that were merged to one source. Except for very bright sources (mainly star spikes, artefacts or large galaxies) and very faint sources (where noise is naturally an issue) the matching is good. Note that most outliers are where the source falls on a chip edge in one pointing, and the flux is under-estimated. The merging process, in which the source with the lowest photometric error was retained, will prefer the source entry where the source did not fall near a chip edge.

In addition to merging pointings it was also found necessary to mask out CCD3. This chip is partially vignetted over $\sim 1/3$ of its area. While this is corrected to some degree by flat-fielding, the noise is higher in the affected region and the photometry becomes more unreliable (particularly in the NW corner). This gives rise to large (>0.5 mag) offsets for some sources when compared to their entries in overlapping pointings. Issues arising from the vignetting are most easily overcome by rejecting data from CCD3 - the number of non-overlapping sources (i.e. only observed in CCD3) rejected by doing this is negligible (essentially only along one part of a chip separation gap in the overlapping pointing).

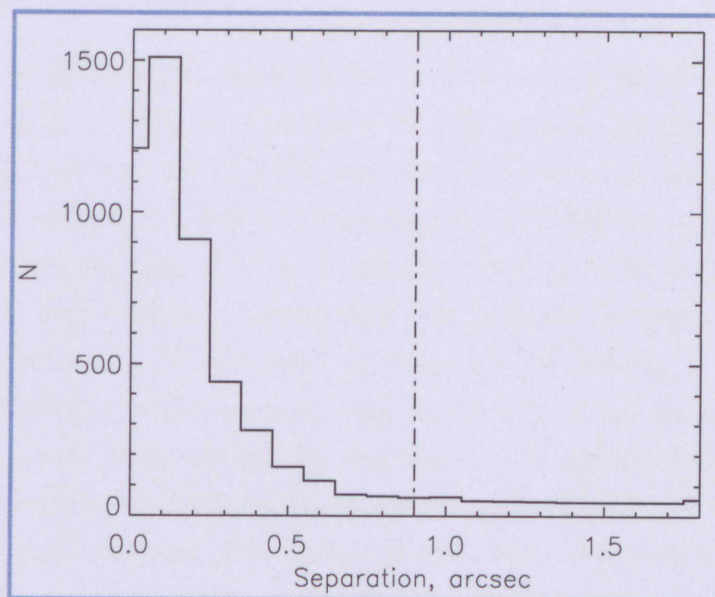


Figure 5.7: Histogram of nearest-neighbour separations in the ELAIS-N1 optical catalogues, here generated for the overlap region between two individual pointings. The dot-dashed line marks the chosen merging radius of $0.9''$.

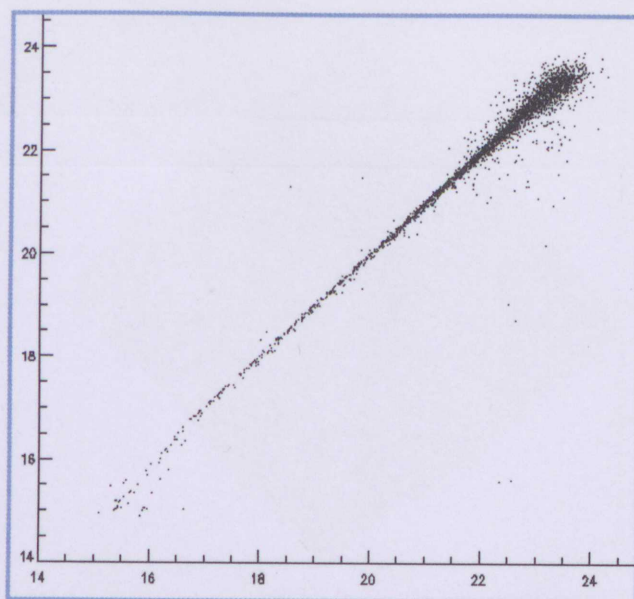


Figure 5.8: Optical source merging: Optical sources falling within an overlap area between two pointings in the ELAIS-N1 field and which were merged (separation $< 0.9''$). Axes are the r' band magnitude of the merged source in the two over-lapping pointings.

5.3.2.2 Optical associations

The *SPITZER* and optical observations do not have a 100% overlap. In fact, the area overlap is $\sim 70\%$, as illustrated in Figure 5.9. In the area in common there are 301,021 reliable *SPITZER* sources (all detected at $3.6\mu\text{m}$). The optical catalogues were associated with the band-merged SWIRE 3.6 to $24\mu\text{m}$ catalogues using the Webcmp package of IPAC's Infrared Science Archive (IRSA). Webcmp is optimized for very fast cross-correlations, by position, between extremely large datasets. A radius of $1.5''$ was used for cross-identifications, a value chosen to maintain completeness whilst keeping false matches to a minimum. Where an IR source picks up more than one optical association, the association with detections in the most optical bands is selected first (this cuts down spurious one band optical source associations), and then the nearest if more than one have the same number of optical bands.

A measure of the number of spurious matches was determined by artificially shifting the optical catalogue by $5'$ and associating with the IR catalogue to give 'false' matches. The number of false matches begins to match the number of real matches at optical-IR separation radii above $\sim 1''$, however, the proportion of associated sources which have optical-IR separations larger than $1''$ is a small fraction of

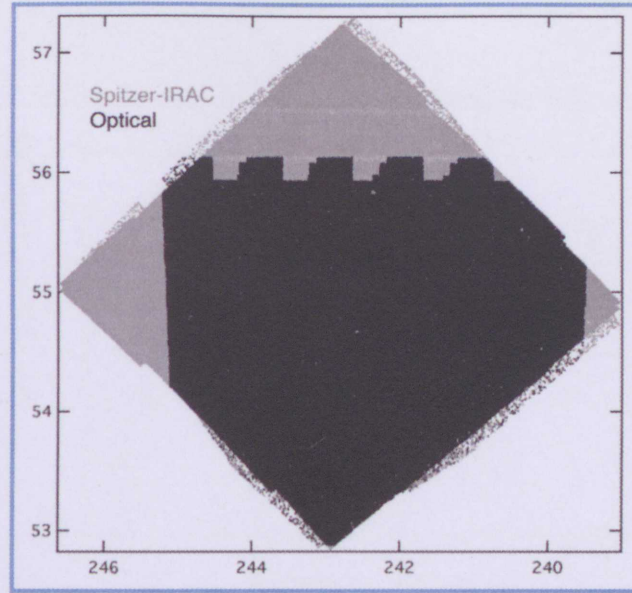


Figure 5.9: The *SPITZER* IRAC data (grey) and the overlap area with optical data (black). The ‘crenellations’ are due to the layout of the WFC CCDs. The MIPS observations are indicated by the grey dotted region, almost entirely obscured by the IRAC area. Image from Surace et al. (2004a; in prep).

the total number of associated sources so the number of spurious sources is in fact a small contaminant - the spurious match percentage, defined by the total number of ‘real’ matches divided by the total number of ‘false’ matches (out to the maximum association radius of $1.5''$) is less than 5% - see Fig. 5.10. Additionally, it is less likely that such spurious matches would survive photometric redshift SED-fitting and IR-fitting procedures as they would need to have a sensible SED. An in-depth discussion of the completeness and reliability of the optical-*SPITZER* cross-ID’s is given in Surace et al. (2004a: in prep.), with analysis based on the Likelihood Ratio (LR) goodness-of-match parameter, as described in Rutledge et al. (1999). Essentially, the cross-ID’s can be considered 100% complete (excepting a possible few bright true matches at large separations) but not 100% reliable. The analyses suggest the reliability is $\sim 95\%$.

Of the $\sim 301,000$ *SPITZER* sources in the overlap area, just over 96,000 are optically blank (including a small fraction in INT WFS coverage gaps), meaning that there are 204,866 band-merged (IRAC+MIPS24) sources in the 6 deg^2 ELAIS-N1 optical overlap with optical associations. This represents 68% of the *SPITZER* sources in the overlap area.

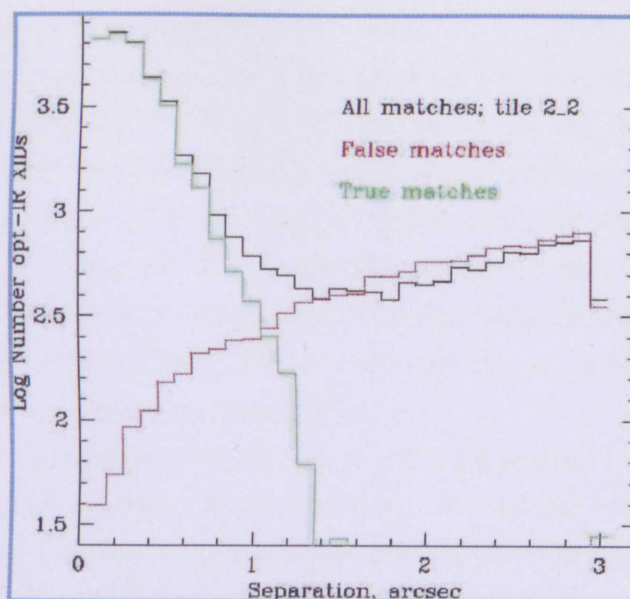


Figure 5.10: Cross-ID statistics for a sub-tile in N1. Black histogram is total number of optical:infrared cross-ID's, green is true matches, red is false matches, obtained by shifting optical catalogue by $5'$ prior to matching. Plot by Carol Lonsdale, IPAC, Caltech.

5.3.3 Star/galaxy separation

Star/galaxy separation is an important but complex issue, even with the luxury of multi-wavelength data. The SExtractor parameter CLASS_STAR gives a measure of the compactness of a source³, however this measure is not an infallible star identifier - at faint fluxes the measure breaks down since one can then no longer reliably differentiate between extended and point-like sources. Additionally, although a nearby galaxy will be clearly extended, distant galaxies and quasars will also appear point-like. Imposing a simple stellarity cut would therefore exclude many interesting extragalactic sources, as can be seen from colour-colour plots of point-like sources - many are clearly not on the stellar locus. Even at brighter fluxes, a star may not be classed as point-like in all bands so a consideration of class flags, magnitudes and saturation flags is required.

For the optical-IR catalogue in question, it is clear that almost all sources with $r' < 17$ are stars and hence for the analyses in this Chapter it is assumed that all sources brighter than this are stars and removed. In addition, all sources that are flagged as saturated in one of more optical bands are removed, since in addition to almost certainly being stars, their photometry and CLASS_STAR designations are unreliable. For the identification of stars at fainter magnitudes it is worthwhile to

note that at wavelengths covered by IRAC we are well into the Rayleigh-Jeans tail of stellar black-body curves and that stars have all have essentially the same slope in their SEDs. This means that they will be colourless in the IRAC bands (in Vega magnitudes). As such, the stellar locus is well-defined in colour-colour space and can be used in conjunction with stellar flags to define a robust star/galaxy separator. Here, the $(3.6\mu\text{m}/r')$ versus $(r'-i')$ diagram in conjunction with stellarity is used as the basic method to identify stars and remove them from the catalogue, as detailed in Rowan-Robinson et al. (2004b). From these definitions, 38,500 of the $\sim 205,000$ optical-IR sources are classed as stars (19%).

The resulting *extragalactic* catalogue of 166,366 sources can now be split into extended and point-like sources, where point-like sources will be either faint galaxies or quasars. Sources are defined as point-like (and so AGN templates are considered in addition to the galaxy SEDs in photometric redshift fitting as was described in Chapter 3) based on the class flags. The optical sources are classed in each band as either -1: Point-like, 0: Noise, 1: non-stellar, -9: saturated, -2: could be stellar, -3: might just be stellar. The best bands, as found in Chapter 3, to define stellarity are g' , r' and i' so if the flag is -1 in any of these bands then the source is defined as point-like.

5.4 Photometric Redshifts and extension to IR bands

In order to calculate LFs the redshifts of the sources are required. The multi-wavelength nature of the catalogue is ideal for the derivation of photometric redshifts. As was shown in Chapter 3, the photometric redshift method is reliable when using five or more optical bands. Here the redshift code presented in Chapter 3, ImpZ, is extended to utilise some of the IR bands from *SPITZER* and tested on a dataset that includes spectroscopic redshifts.

The emission of a galaxy at optical to near-IR and at mid-IR wavelengths will not typically be well correlated - that is, the optical to near-IR emission will often be dominated by emission from stars, whereas at longer wavelengths re-processed emission from dust is the dominant contribution. Hence the optical to mid-IR SED of a galaxy cannot be allocated to one of a set of generic templates. Here, the analysis is separated into optical/near-IR, and mid-IR, using optical and IRAC $3.6\mu\text{m}$, $4.5\mu\text{m}$ detections in the photometric redshift fitting procedure¹, and using

¹use of the longer *SPITZER* wavelengths was not found to improve the redshift technique,

the longer wavelengths to fit IR templates to those sources defined as having an IR-excess (see Section 5.5).

An important requirement for photometric redshift fitting is that the photometry in each band is equivalent - different aperture sizes will sample the galaxy out to different radii, and possibly in different locations. When only using optical data, use of fixed aperture fluxes is sufficient, however if we wish to include IRAC near-IR fluxes it is important to be comparing like with like, and these fluxes are intended to be integrated fluxes. Hence here, for the optical bands, the aperture magnitudes corrected to the integrated magnitudes via curve-of-growth analysis are used. This procedure could introduce errors for galaxies whose integrated SEDs differ largely from their central regions, but in practice the results are good, as found in §5.4.2.

5.4.1 The WIYN dataset

In the 0.3 deg² LOCKMAN Validation Field of the SWIRE survey there is U, g', r' and i' band photometry taken with the MOSAIC I camera on the Mayall 4m telescope at Kitt Peak National Observatory (KPNO). The reduction of this data was described in Chapter 2. This has been band-merged with the *SPITZER* 3.6 to 24μm data to produce a multi-wavelength catalogue. For the brighter sources in this catalogue the SWIRE Team has a set of 360 spectroscopic redshifts from the WIYN survey (Owen et al., in preparation). This provides an excellent test bed for the extension of the photometric redshift method to longer wavelengths. ImpZ has been applied to this dataset, first using *only* the optical data in the redshift-fitting, and then also utilising the 3.6 and 4.5μm data in the fits. In order to achieve good results with the inclusion of near-IR bands, it was found necessary to adapt the IR behaviour of the galaxy SEDs used by the code which were set out in Chapter 3. The original behaviour was essentially a simple power-law drop-off to longer wavelengths. Adaptations described in Rowan-Robinson et al. (2004b) have been incorporated, based on studies carried out by Rowan-Robinson et al. (2004b), Polletta et al. (2004) and this Thesis which found that the original galaxy SEDs tended to under-estimated the IR flux required. A plot illustrating the necessary alterations is shown in Figure 5.11.

though it is anticipated that in the future, longer wavebands could be considered for sufficiently high redshift sources (so that we are still probing optical to near-IR restframe wavelengths)

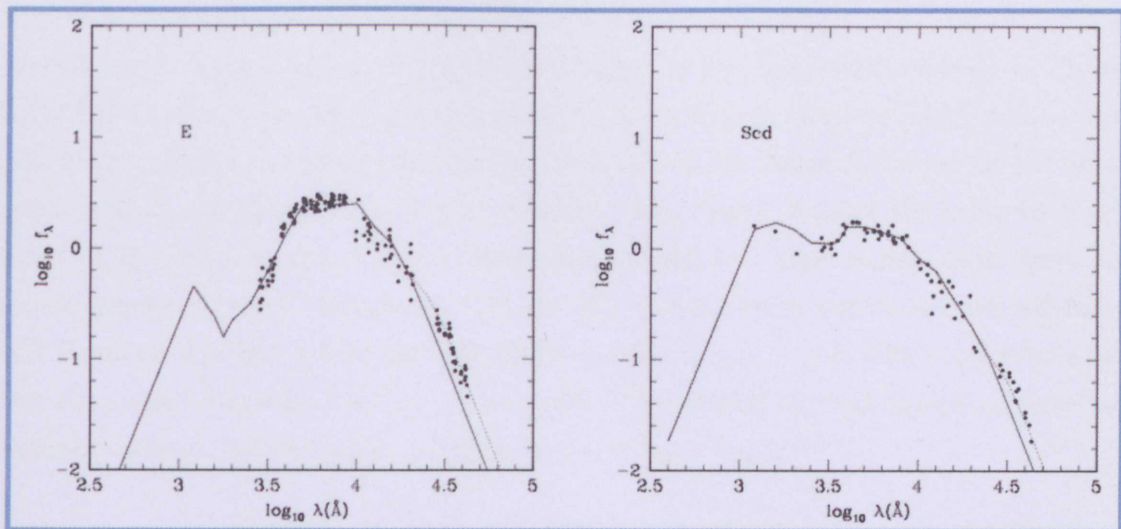


Figure 5.11: Comparison of photometric data for SWIRE-ELAIS galaxies with spectroscopic redshifts, showing optical template fits for E and Scd galaxies, illustrating the need to refine the templates at wavelengths $> 2\mu\text{m}$ (dotted line). Figure taken from Rowan-Robinson et al. (2004b) which uses the galaxy templates of Rowan-Robinson (2003a) from which the SSP-generated galaxy templates used in Chapter 3 were derived.

5.4.2 WIYN results

It was found that using *only* the four optical wavebands produced satisfactory agreement with the spectroscopic values, but there were a reasonable number of outliers. This is because with just four (or fewer) bands, only spanning observed wavelengths from 3000 to 9000Å, there is not really sufficient information to break the various possible degeneracies (e.g. confusing the Lyman and Balmer breaks). Of the 360 sources with spectroscopic redshifts, 320 received a photometric redshift solution with a $\chi_{red} < 10$. This value of χ_{red} is chosen as a threshold based on the results in Chapter 3, and the results from the WIYN sample, since most fits above this value are incorrect.

The total *rms* scatter, σ_{tot} , was 0.28, with $\overline{\Delta z}/(1+z) = -0.02$. The outlier-clipped *rms*, σ_{red} was 0.1 and the rate of ‘catastrophic’ outliers, η was 6.3 per cent. The comparison between spectroscopic and photometric redshifts using only optical bands is plotted in Figure 5.12(A) as $\log_{10}(1+z_{spec})$ versus $\log_{10}(1+z_{phot})$.

Including the 3.6 and 4.5 μm data from *SPITZER* enables several solution degeneracies to be broken, since then data is provided on the underlying SED across a much wider observed wavelength range (3000Å to 50,000Å). As can be seen in

Figure 5.12(B), this additional near-IR information has reduced the dispersion and the IR bands have enabled the rejection of most of the large outliers seen in Figure 5.12(A). This is an important improvement - even though the two IRAC bands may not have enabled a correct photometric redshift to be found for some of the large outliers that are apparent in Figure 5.12(A), they have enabled the code to reject most of the original optical-only catastrophic outliers. This means that there are fewer spurious redshift solutions. Of the 360 sources with spectroscopic redshifts, 331 received a photometric redshift solution with a $\chi_{red} < 10$. The total *rms* scatter, σ_{tot} , was 0.18, with $\overline{\Delta z}/(1+z) = -0.02$. The outlier-clipped *rms*, σ_{red} was 0.06 and the rate of ‘catastrophic’ outliers, η was 3.8 per cent.

It is concluded that the inclusion of the first two IRAC bands in the photometric solution reduces the *rms* error in $\log_{10}(1+z)$ and enables the rejection of the majority of catastrophic outliers. This has also been found by studies carried out in Rowan-Robinson et al. (2004b) which studied the WIYN dataset and also a sample of spectroscopic redshifts in ELAIS-N1. In both cases the inclusion of the first two IRAC bands in the solution was found to improve the *rms*. Further information on the photometric redshifts and their extension to IR wavelengths for the SWIRE survey can be found in Rowan-Robinson et al. (2004b) and Polletta et al. (2004).

5.4.3 Fitting procedure

Based on the photometric redshift investigations presented in Chapter 3 and §5.4.2 and on work by Rowan-Robinson et al. (2004b) and Polletta et al. (2004) the photometric redshifts of the optical-*SPITZER extragalactic* sources are derived from their optical and IRAC 3.6, 4.5 μ m detections.

In order to obtain reliable photometric redshifts a source needs to be detected in the r' band, at 3.6 μ m, and in at least two additional bands (in the optical, or IRAC 3.6, 4.5 μ m). This reduces the total number of *extragalactic* sources to 133,645 (80%); of which 101,139 (76%) have a detection at 4.5 μ m; 27,554 (21%) have 5.8 μ m; 27,072 (20%) have 8 μ m and 38,601 (29%) have 24 μ m. For these, the code only fails to produce a photometric redshift solution below the χ_{red}^2 maximum for 7,452 (6%) of the sources.

Templates – the six galaxy templates (E1, Sab, Sbc, Scd, Sdm and Starburst) and two (type 1) AGN templates are used in the template fitting, with AGN templates only included for sources defined as *point-like* rather than *extended*. The distribution of template solutions is as follows:

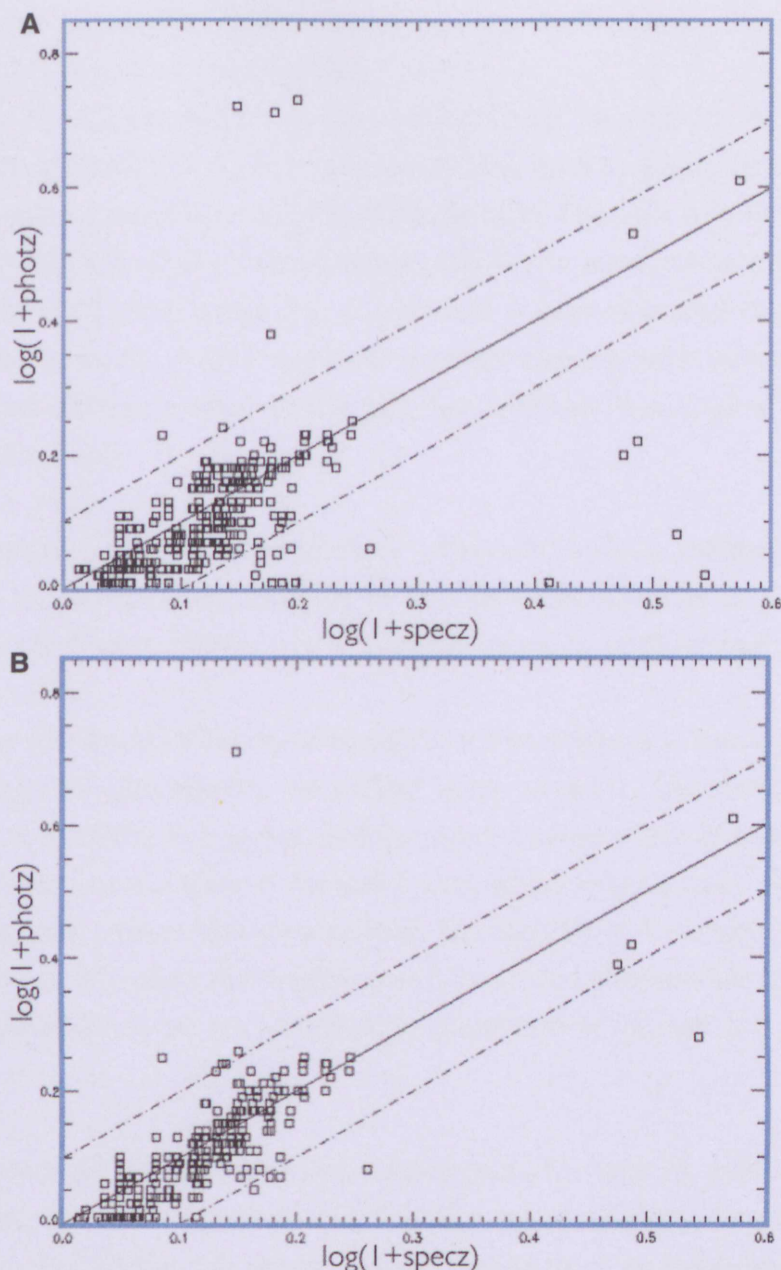


Figure 5.12: A: Comparison between spectroscopic redshifts and ImpZ redshifts for the WIYN sample (Owen et al. 2004, in prep.), using *only* the four optical bands in the photometric redshift solution. Solutions with $\chi_{red} > 10$ have been rejected. The outlier-clipped rms , σ_{red} is 0.1 and the rate of ‘catastrophic’ outliers, η is 6.3 per cent.

B: Comparison between spectroscopic redshifts and ImpZ redshifts for the WIYN sample (Owen et al. 2004, in prep.), using the four optical bands *and* the SPITZER 3.6 and 4.5 μm data in the photometric redshift solution. It can be seen that as well as reducing the dispersion, the IR bands enable the rejection of most of the large outliers seen in part A. Solutions with $\chi_{red} > 10$ have been rejected. The outlier-clipped rms , σ_{red} is 0.06 and the rate of ‘catastrophic’ outliers, η is 3.8 per cent.

29,383 ellipticals (23%), 19,326 Sab (15%), 13,483 Sbc (11%), 29,235 Scd (23%), 9,512 Sdm (7%), and 6,169 AGN (5%).

Fitting – variable extinction is allowed in the fits via variable A_v . As found in Chapter 3, the inclusion of A_v as a parameter does have an important improvement on the accuracy of resulting redshifts, though from Chapter 4 it is also apparent that the derived extinction of the source is subject to some uncertainty. With the inclusion of near-IR data in the fits, A_v freedom is now extended to the AGN fits, though restricted to $A_v \leq 0.3$ in order to prevent aliasing with normal galaxies (it was found that otherwise low redshift galaxies could be fit as higher redshift AGN with high extinction).

The resulting photometric redshifts are expected to be accurate to *at least* 0.1 in $\log_{10}(1+z)$, based on comparison to spectroscopic samples in Chapter 3 and §5.4.2, Rowan-Robinson (2003a), Rowan-Robinson et al. (2004b) and Polletta et al. (2004).

Accuracy for the AGN tends to be a little lower, perhaps 0.2 in $\log_{10}(1+z)$, due to the aliasing and photometric variability issues noted in Chapter 3. In Rowan-Robinson et al. (2004b) it is noted that for some quasars there is a significant dust torus contribution to emission at 3.6 and 4.5 μm which acts to make the redshift determination poorer. Hence for sources with $S(3.6)/S(r') > 4$ the two shorter IRAC bands are not considered in the redshift solution. In the photometric redshift fitting, only 5% of SWIRE sources are identified by photometric redshift fitting as (type 1) AGN.

We plot redshift distributions (black histogram) for each IR population (3.6 μm , 4.5 μm , 5.8 μm , 8 μm and 24 μm sources) in Fig. 5.13. Galaxy template solutions (E, Sab, Sbc, Scd, Sdm and starburst) are overplotted as light blue dot-dashed histogram, ellipticals are overplotted as purple dashed histogram, AGN solutions are overplotted as red solid histogram, **multiplied by 5** for clarity. The mean redshift of each population is indicated by a vertical line; light-blue dot-dash line (all galaxies), purple-dashed (ellipticals), red triple-dot-dashed (AGN).

From these histograms it can be seen that, below a redshift of $z \sim 0.5$, around a third of galaxies are ellipticals, except for the 24 μm population where they make up less than twenty per cent of the galaxy population. This is expected since although the old stellar populations in an elliptical galaxy will contribute to emission in the IRAC bands, their contribution to 24 μm is negligible. Coupled with the expectation that an elliptical galaxy has little dust or ongoing star formation this means that

ellipticals make up only a fraction of the $24\mu\text{m}$ population. Some of the elliptical template fits to $24\mu\text{m}$ sources will in fact be Arp220-like objects which, in the optical, have SEDs similar to ellipticals due to the heavy obscuration of young stars.

In the IRAC channels, the elliptical population can be seen to extend out to a redshift of around unity. Above this redshift the number of sources drops away. The mean redshift of the elliptical population in each band is as follows: $\langle z_{3.6} \rangle = 0.50$; $\langle z_{4.5} \rangle = 0.50$; $\langle z_{5.8} \rangle = 0.45$; $\langle z_8 \rangle = 0.34$; $\langle z_{24} \rangle = 0.40$.

The remainder of the galaxies are spirals and starbursts. These extend out to redshifts of around 1.5 before they start to drop below the sensitivities of the optical survey. The mean redshift of the spiral and starburst population in each band is as follows: $\langle z_{3.6} \rangle = 0.59$; $\langle z_{4.5} \rangle = 0.61$; $\langle z_{5.8} \rangle = 0.51$; $\langle z_8 \rangle = 0.42$; $\langle z_{24} \rangle = 0.58$. A comparison of the galaxy redshift distributions to the models of Rowan-Robinson (2001b), Xu et al. (2003) and Pozzi et al. (2004) is given in Rowan-Robinson et al. (2004b) and indicates that the models manage to broadly reproduce the observed galaxy distribution, although the Pozzi et al. (2004) model predicts the peak to be at a higher redshift, of $z \sim 1$.

The AGN are seen to be a population that extends across the full redshift range, with indication of a slight peak in their distribution at a redshift of around two, and a tail to high redshift. This slight rise to redshift two, and decline thereafter, is as predicted by the new version of Xu et al. (2003)'s models when including a new evolutionary model for dusty galaxies and the SWIRE limits. This predicted AGN distribution was given in Hatziminaoglou et al. (2004).

Above a redshift of around two the AGN solutions dominate over the galaxy counts, though this is mainly due to SWIRE's ability to detect them to higher redshift. As a relative fraction, the AGN population is largest for the $24\mu\text{m}$ sources. The mean redshift of the optical AGN population in each band is as follows: $\langle z_{3.6} \rangle = 2.2$; $\langle z_{4.5} \rangle = 2.4$; $\langle z_{5.8} \rangle = 1.9$; $\langle z_8 \rangle = 1.9$; $\langle z_{24} \rangle = 1.9$.

It is important to note that the requirement of a good photometric solution before a source can be included in the LF calculation acts as an additional selection function. These are calculated in Section 5.6.1.

5.4.4 Extinction with redshift

The photometric redshift fitting returns a measure of the extinction, A_v , as well as the redshift for source. Hence it is possible to see how the extinction of galaxies changes with redshift. Chapters 3 and 4 showed that four band photometry (the

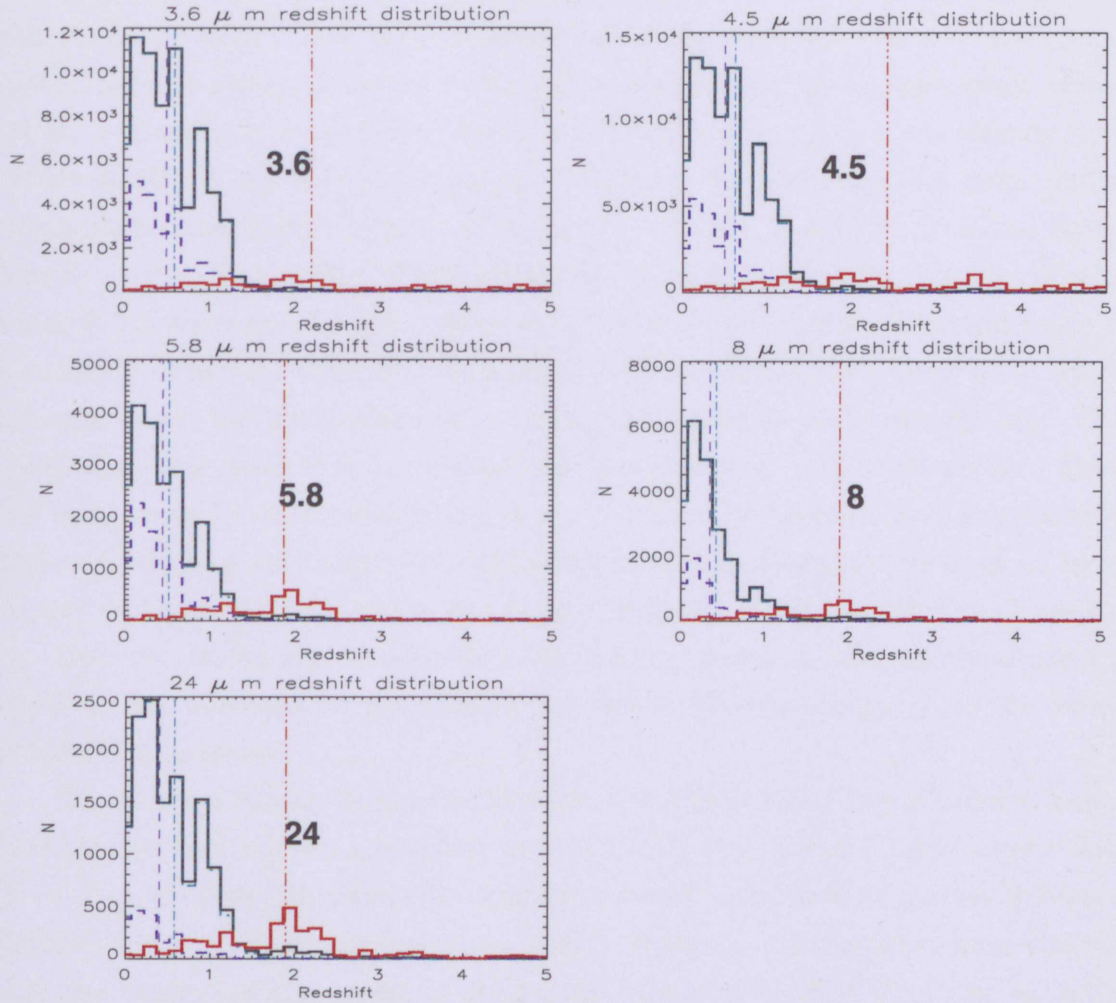


Figure 5.13: Photometric redshift distributions by *SPITZER* band (black histogram). Galaxy template solutions (E, Sab, Sbc, Scd, Sdm and starburst) are overplotted as light blue dot-dashed histogram, ellipticals are overplotted as purple dashed histogram, AGN solutions are overplotted as red solid histogram, **multiplied by 5** for clarity. The mean redshift of each population is indicated by a vertical line; light-blue dot-dash line (all galaxies), purple-dashed (ellipticals), red triple-dot-dashed (AGN).

minimum number used in this Chapter to derive a redshift) was sufficient for reliable photometric redshifts but the reliability of the A_v value was lower. Here, the evolution of A_v is explored using sources with at least six detections at U, g', r', i', Z, 3.6 μ m and 4.5 μ m in order to improve the reliability of the estimate.

A factor that needs to be taken into consideration is that a large fraction of sources are fit with $A_v=0$. This is partly due to the approach taken by the photometric redshift fitting procedure - in order to reduce redshift- A_v degeneracy issues, an $A_v > 0$ solution is not considered if a solution with $\chi^2_{red} < 1$ has already been achieved with $A_v=0$ (as was described in Chapter 3). Although this helps reduce degeneracies and improve the accuracy of the redshifts, it acts to skew the A_v solutions to the $A_v=0$ value. This would impact on the mean A_v , $\langle A_v \rangle$, of each redshift bin since the $A_v=0$ solutions would swamp the results. A second route to illustrating how A_v varies with redshift is therefore shown in Figure 5.14. Here, for each band, the distribution of A_v values is plotted for each redshift bin. This avoids the large number of $A_v=0$ solutions dominating an $\langle A_v \rangle$ calculation. From the histograms for each redshift bin, it is clear that the proportion of sources with higher A_v drops significantly as redshift increases. The distributions drop off more steeply at higher redshift and in the highest redshift bin all the solutions have low A_v . However, it can also be seen that the number of sources with intermediate A_v , of 0.1 to 0.4, increases for the redshift bin [0.5 to 1] when compared to the lowest redshift bin [0 to 0.5].

The study of Rowan-Robinson (2003a) in the *Hubble* Deep Fields found evidence that galaxies had higher A_v values than seen locally at $z=0.5$ to 1.5 and lower values at $z > 2$, as predicted by closed-box star formation models such as Rowan-Robinson (2001b) and King & Rowan-Robinson (2003). However, other studies have claimed that the extinction of galaxies at $z \sim 3$ is substantial with $E(B-V)=0.15$; $A_v > 0.4$ (Steidel 1999; Adelberger & Steidel 2000; Vijh et al. 2003), though these were based on a single colour; (G-R). Erb et al. (2003) found that a mean extinction of $E(B-V)$ of 0.1 was needed to get agreement between UV continuum and $H\alpha$ derived SFR for galaxies at $2 < z < 2.6$. It is therefore possible that some of the drop in extinction seen here in the largest redshift bins is due to degeneracy between reddening due to redshift and reddening due to dust, though the use of IRAC channels 1 and 2 in the solution should act to reduce this problem.

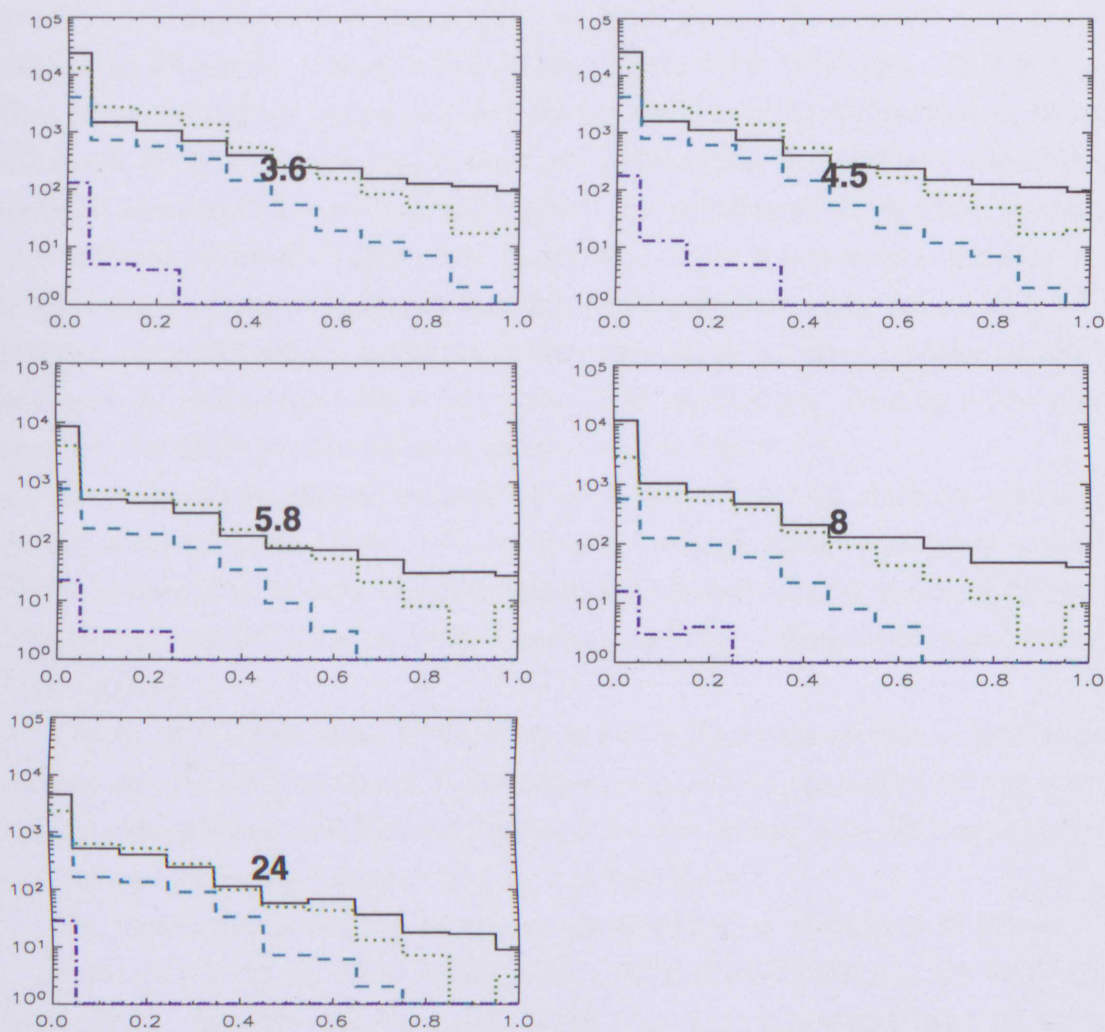


Figure 5.14: A_v distributions for each *SPITZER* band. Histograms for each redshift bin; [0 to 0.5] (black solid); [0.5 to 1] (green dotted); [1 to 1.5] (blue dashed); [1.5 to 2] (purple dot-dashed).

x-axis is A_v , y-axis is Number

5.5 Mid IR SED fitting

Mid-IR template fitting is carried out in a technique described in Rowan-Robinson (2003a) and Rowan-Robinson et al. (2004b). A source that has been fit with an optical to near-IR galaxy template, based on its U band to $4.5\mu\text{m}$ detections as set out in §5.4, now has its IR excess calculated by subtracting the galaxy model fit prediction from the 4.5 to $24\mu\text{m}$ data. At least two of these bands then need to exhibit an IR excess (one of which is required to be 8 or $24\mu\text{m}$). This excess is then characterised by finding the best-fitting out of a cirrus (Efstathiou & Rowan-Robinson, 2003), M82 and Arp220 starbursts (Efstathiou et al., 2000b) or AGN dust torus IR template (Rowan-Robinson, 1995). More information on these templates can be found in Rowan-Robinson et al. (2004b). Here, it is merely noted that each template is the result of radiative transfer models and that although for *individual* galaxies one could obtain better *individual* fits using radiative transfer codes, we here wish to characterise the broad types of IR population. Barring a few minor updates, the SEDs are the same as those shown in Figure 1.3.

Sources are also allowed to be fit by a mixture of an M82 starburst and cirrus since it was found that, often, both components were required to properly represent the IR excess. This mirrors the conclusions of Rowan-Robinson & Crawford (1989) from fitting mid-IR SEDs to *IRAS* sources, and the findings of Rowan-Robinson et al. (2004b).

For an IR SED fit, then, there needs to be an IR excess. If this is not the case then an mid-IR template-based K-correction, K_{IR} , is not calculated for the source and the extrapolated mid-IR contribution from the optical/near-IR template fit is used instead for in the calculation of $z_{max,IR}$ (see §5.6).

For those sources with an IR excess, the distribution of types is as follows:

8,091 cirrus (31%), 7,595 M82 (29%), 2,624 Arp220 (10%), 7,598 AGN dust torus (29%). Additionally, there are 20,793 sources with a single band IR excess, and 79,492 with no IR excess.

Now that the optical/near-IR and mid-IR SEDs of each source have been characterised and their photometric redshifts determined, this information can be used in Section 5.6 in order to calculate LFs, and to include K-corrections derived from the model templates.

5.6 Luminosity function procedure

Provided a selection function can be defined, a luminosity function is calculable so long as there is no significant population of objects which remain undetected at *any* redshift. Assuming that we have a sufficiently detailed selection function (see §5.6.1) and that no such *invisible* population exists - a reasonable assumption given that local galaxies can all be expected to be detected in some of the multi-variate wavelengths under consideration - we can use the *accessible volume* method of Avni & Bahcall (1980) to determine LF's for each *SPITZER* waveband.

In this, the LF, $\Phi(L)$, is calculated using the $1/V_{max}$ method (Schmidt 1968) where V_{max} is the volume corresponding to the maximum redshift at which a source could be detected by the survey. Due to the multi-variate flux limits of the catalogue, this maximum redshift may be set by either the optical limits, or the IR limits, as determined by using K-corrections calculated from the optical/near-IR and mid-IR template fits.

Thus:

$$\Phi(L)dL = \sum_i \frac{1}{V_{max,i}} \quad (5.1)$$

where $\Phi(L)$ is the number of objects per Mpc in the luminosity range L to $(L+dL)$ and

$$V_{max,i} = \min(V_{optical,i}, V_{IR,i}) \quad (5.2)$$

So for the case of the $3.6\mu\text{m}$ LF, $V_{IR,i}$ would correspond to the maximum redshift out to which the source in question would be detectable at $3.6\mu\text{m}$, down to the chosen limit of $18\mu\text{Jy}$ (as set in §5.3.1.3 to minimise incompleteness and maintain reliability). $V_{optical,i}$ corresponds to the maximum redshift out to which the same source would be detectable, down to the chosen magnitude limit of $r'=23$ (in order to minimise incompleteness and photometric inaccuracy; see Fig. 5.6).

The associated *rms* error, from Poisson statistics², is given by

$$\Delta\Phi(L) = \sqrt{\sum_i \frac{1}{V_{max,i}^2}} \quad (5.3)$$

To find $V_{optical,i}$ we find the redshift, $z_{max,optical}$, at which the optical apparent magnitude, $m(z)$, of a source of absolute magnitude M , when redshifted to a redshift, z , becomes fainter than the chosen limiting magnitude of the survey, where $m(z)$ is

²bins containing only one galaxy have a 1σ range of $(0.18-3.3)V_{max}^{-1}$ rather than $\pm V_{max}^{-1}$, based on an underlying Poisson distribution with one detection (Gehrels 1986)

given by;

$$m(z) = M + 5\log_{10}\left(\frac{D_L}{10pc}\right) + 2.5\log_{10}K_{opt} \quad (5.4)$$

Here, D_L is the luminosity distance to redshift z , and K_{opt} is the K-correction. K_{opt} also includes the increased effect of IGM absorption at higher redshifts as proscribed in Chapter 3. K_{opt} is defined as:

$$K_{opt}(z) = (1+z) \frac{\int F(\lambda)S(\lambda)\delta\lambda}{\int F(\frac{\lambda}{1+z})S(\lambda)IGM(\lambda, z)\delta\lambda} \quad (5.5)$$

where $F(\lambda)$ is the optical SED template at source, $S(\lambda)$ is the combined filter transmission and CCD response curve, and $IGM(\lambda, z)$ is the redshift dependent IGM transmission.

To find $V_{IR,i}$ we find the redshift, $z_{max,IR}$ at which the IR flux in the IR band in question, $S_{IR}(z)$, of a source of absolute monochromatic luminosity, L_{IR} , when redshifted to an arbitrary redshift, z , becomes fainter than the chosen limiting flux of the survey, where $S_{IR}(z)$ is given by;

$$S_{IR}(z) = \frac{L_{IR}}{4\pi\left(\frac{D_L}{10pc}\right)^2 K_{IR}} \quad (5.6)$$

where D_L is the luminosity distance to redshift z , L_{IR} is the luminosity in the IR band in question as calculated from the photometric redshift and the observed flux and K_{IR} is the K-correction. K_{IR} is defined as follows:

$$K_{IR}(z) = (1+z) \frac{\int F(\lambda)S(\lambda)\delta\lambda}{\int F(\frac{\lambda}{1+z})S(\lambda)\delta\lambda} \quad (5.7)$$

where $F(\lambda)$ is the IR SED template at source and $S(\lambda)$ is the chosen IR filter transmission. For IR K-corrections we do not need to incorporate IGM transmission effects.

In order to calculate the LFs correctly, however, we need to use a weighting function on the volume elements in order to correct for the various selection biases that are inherent in the catalogue. This is set out in §5.6.1.

As well as calculating an overall LF, we can split it into different redshift bins in order to look for evolution in the LF with redshift. For redshift bins the LF calculation is then slightly modified, in that the minimum redshift of the redshift bin in question needs to be subtracted from the $V_{max,i}$ in Eqn. 5.2. The sources are split into galaxies and quasars based on their best-fitting optical/near-IR template

and for these two samples LFs are constructed in the following redshift bins:

- (i) For galaxies, LFs are constructed in the redshift bins [0 to 0.25]; [0.25 to 0.5]; [0.5 to 1]; [1 to 1.5]; [1.5 to 2]. Galaxies with redshifts above two are cut since the reliability of their photometric redshifts is lower and they can have a large effect on the bright end of the LF, particularly given the low number of sources above this redshift. This typically excludes $\sim 1\%$ of the sample.
- (ii) For quasars (smaller number statistics and broader redshift range), LFs are constructed in the redshift bins [0 to 1]; [1 to 2]; [2 to 3]; [3 to 4]. Quasars with redshifts above four are cut since, again, the reliability of their photometric redshifts is lower and they can have a large effect on the bright end of the LF. Due to photometric variability and the reduced accuracy of photometric redshift techniques when applied to quasars this cut is prudent at this early stage in the analysis of the SWIRE data. For 3.6 and $4.5\mu\text{m}$ this excludes $\sim 50\%$ of the sources fit in the optical by AGN templates. For the longer wavebands it excludes $\sim 10\%$ of the AGN sample.

5.6.1 Incompleteness and selection functions

The data set used to calculate the luminosity function in each IR band is a biased sample. This is due to the multivariate flux limits imposed in order for a source to be included in the calculation and the requirements that it has enough information to be passed to the redshift and IR SED fitting codes *and* obtain a solution. The general procedure for deriving an overall selection function is the same regardless of the IR band in question. Here the $3.6\mu\text{m}$ LF will be used as an example:

With the assumption that we have already removed stars; the source needs to have a $3.6\mu\text{m}$ detection (unsurprisingly) and we require that the source is *reliable*, as set out in §5.3.1.3. This is dependent on the $3.6\mu\text{m}$ selection function, $\eta_{\text{detec}}(S_{3.6})$, shown in Fig. 5.2. Then, in order to be passed to the photometric redshift code it needs to have detections in at least four of the bands used to calculate redshift (optical, $3.6\mu\text{m}$ and $4.5\mu\text{m}$), two of which need to be $3.6\mu\text{m}$ and r' . This is characterised by $\eta_{\text{pz,in}}(S_{3.6})$. The source then needs to obtain a solution with a χ^2_{red} value less than 10 (for reliability), as characterised by $\eta_{\text{pz,out}}(S_{3.6})$. We do not characterise the selection effect from fitting the mid-IR emission with mid-IR templates since this does not exclude any additional sources from the LF calculation (it merely means we can not apply a mid-IR template-based K-correction in calculating $V_{\text{IR},i}$).

Hence we need to be able to characterise the probability of a $3.6\mu\text{m}$ source of flux $S_{3.6}$ passing each of these criteria and thus construct a combined selection function as a function of $3.6\mu\text{m}$ flux, $\eta(S_{3.6})$, using this to weight the contribution of each source to the $3.6\mu\text{m}$ luminosity function.

The probability that a given $3.6\mu\text{m}$ source has sufficient information to be passed to the photometric redshift code, $\eta_{pz,in}(S_{3.6})$, is calculated in the following manner:

We take all *reliable* $3.6\mu\text{m}$ sources and construct a source count distribution, $N_{all}(S)$. We then find all those sources which are eligible for photometric redshift calculation and construct a similar source count distribution, $N_{pz,in}(S)$. Dividing one by the other gives the selection bias, as a function of $3.6\mu\text{m}$ flux, that is introduced by attempting to calculate redshifts;

$$\eta_{pz,in}(S) = \frac{N_{pz,in}(S)}{N_{all}(S)} \quad (5.8)$$

Similarly, we can calculate the selection bias, $\eta_{pz,out}(S_{3.6})$, introduced by requiring a source to receive a redshift solution and that this solution have $\chi^2 < 10$, by constructing the source count distribution, $N_{pz,out}(S)$, of all sources which did obtain a good redshift solution, and obtain the resulting selection bias via;

$$\eta_{pz,out}(S) = \frac{N_{pz,out}(S)}{N_{pz,in}(S)} \quad (5.9)$$

An overall selection bias, $\eta(S_{3.6})$, as a function of $3.6\mu\text{m}$ flux is then the combination of these functions, namely;

$$\eta(S) = \eta_{detec}(S)\eta_{pz,in}(S)\eta_{pz,out}(S) \quad (5.10)$$

The resulting selection functions for each IR band are given for IRAC in Fig. 5.15 and for MIPS $24\mu\text{m}$ in Fig. 5.16. These selection functions are used to weight the contribution of each source to the volume element integral in the LF calculation by modifying Eqn. 5.11 to become;

$$\Phi(L)dL = \sum_i \frac{\eta(S_i)}{V_{max,i}} \quad (5.11)$$

After implementation of the lower flux cut (given for each band in §5.3.1.3), removal of $r' < 17$ ‘stars’ and specifying a photometric redshift solution with $\chi^2 < 10$ the number of sources remaining for LF calculation is as follows:

For 3.6 μ m LF calculation - 67,261 sources (of which 1,194 optical AGN).

For 4.5 μ m LF calculation - 80,635 sources. (of which 2,219 optical AGN)

For 5.8 μ m LF calculation - 20,665 sources (of which 680 optical AGN).

For 8 μ m LF calculation - 22,857 sources (of which 816 optical AGN).

For 24 μ m LF calculation - 13,219 sources (of which 592 optical AGN).

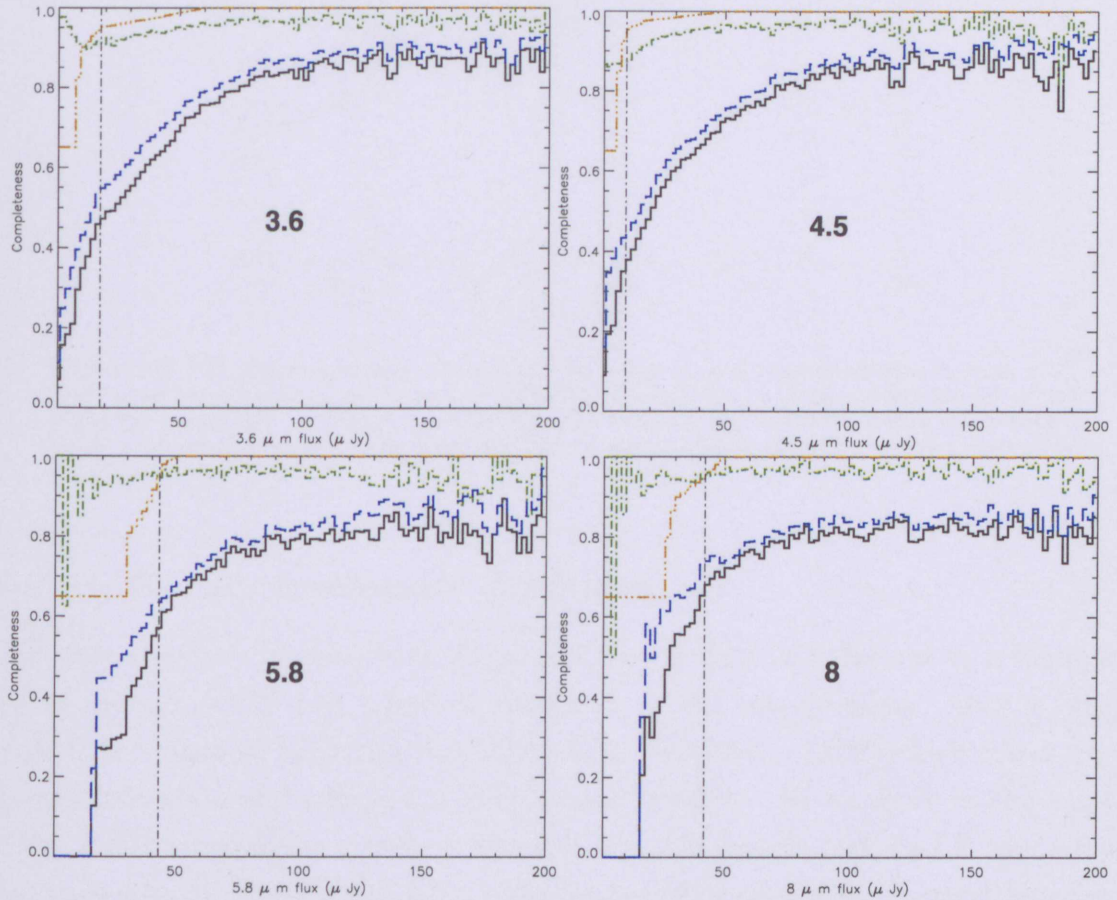


Figure 5.15: IRAC selection functions. Solid histogram is the overall selection function $\eta(S)$, blue dashed histogram is $\eta_{pz,in}(S)$, green dot-dashed histogram is $\eta_{pz,out}(S)$, brown dot-dot-dot-dashed histogram is $\eta_{detec}(S)$. It can be seen that the largest effect is due to the number of bands needed before a photometric redshift can be calculated. The chosen flux limit for the IRAC band, from §5.3.1.3, is shown as a vertical dot-dashed line.

5.7 Results

LFs have been calculated for each IR band - 3.6, 4.5, 5.8, 8 and 24 μ m. These are plotted in Figs. 5.17 to 5.21. In each Figure, the overall galaxy and quasar LFs are shown, and the LFs are then broken down into each redshift bin.

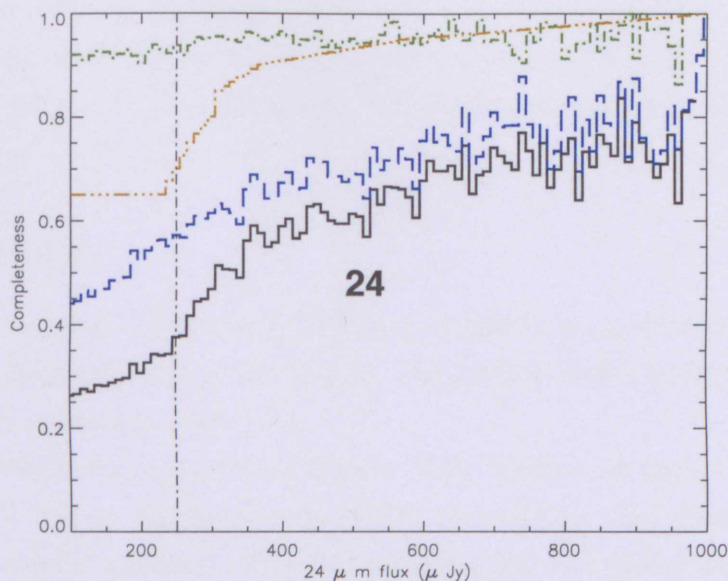


Figure 5.16: $24\mu\text{m}$ selection functions. Solid histogram is the overall selection function $\eta(S)$, blue dashed histogram is $\eta_{pz,in}(S)$, green dot-dashed histogram is $\eta_{pz,out}(S)$, brown dot-dot-dot-dashed histogram is $\eta_{detec}(S)$. It can be seen that the largest effect is due to the number of bands needed before a photometric redshift can be calculated. The chosen flux limit from §5.3.1.3 is shown as a vertical dot-dashed line.

5.7.1 Galaxy luminosity functions

The overall galaxy luminosity function at $3.6\mu\text{m}$ is relatively flat out to a luminosity of around $4 \times 10^{10} L_{\odot}$, where it exhibits a ‘knee’ and steepens - that is, they exhibit the classical Schechter functional form (Schechter, 1976) which arises from galaxy formation and reflects the galaxy mass function. As we move to the longer *SPITZER* wavelengths this knee becomes less of a feature and the LF as a whole becomes steeper. The 3.6 and $4.5\mu\text{m}$ LFs are sampling the stellar mass of the galaxies, since the bulk of emission at these wavelengths arises from the older stellar populations. As the most massive galaxies are rare this imposes the ‘knee’ seen in the LF. The relative flatness of their LFs is also seen in optical and K band LF studies which also sample the stellar mass. At the longer *SPITZER* wavelengths the LF as a whole steepens, since it is then essentially sampling the star formation rate via dust emission, and the characteristic ‘knee’ seen at shorter wavelengths is less prominent (since we are now probing SF rather than stellar mass).

5.7.2 Quasar luminosity functions

The quasar LF shows that the space density of quasars is roughly constant with luminosity, but at the bright end the space density drops away. For $3.6\mu\text{m}$ this

turnover occurs above a luminosity of $\sim 10^{11} L_{\odot}$. The turnover becomes less pronounced, and moves to higher luminosities as the longer *SPITZER* wavebands are considered. By $24\mu\text{m}$ the overall quasar LF has become steeper, and the turnover has moved to $\sim 6 \times 10^{11} L_{\odot}$.

5.7.3 Evolution

Exploring the luminosity function at different redshifts is a powerful probe of evolution, both in luminosity and space density. For both galaxies and quasars the signs of evolution are evident in their LFs.

There is evidence for positive evolution of the galaxy LF from the first redshift bin ($0 < z < 0.25$) out to the third redshift bin ($0.5 < z < 1$). For these three redshift bins there are similar numbers of fainter galaxies, but increasing numbers of bright galaxies as redshift increases. This implies that the bright end of the LF has evolved. The fourth redshift bin ($1 < z < 1.5$) does not show a strong continuation of this trend, so the bulk of bright galaxies are found at intermediate redshifts, of $0.5 < z < 1$.

In the highest galaxy redshift bin ($1.5 < z < 2$) there is then a clear drop in the space density of galaxies, by a factor of at least five. One interpretation of this would be that the epoch of the peak formation of the brightest galaxies has been reached (see §5.8 for further discussion of this).

The quasar LFs also show positive evolution out to the third redshift bin ($2 < z < 3$), with increasing numbers of bright quasars at higher redshift. Again, this is the behaviour predicted by curved luminosity-evolution models in which only the bright end evolves.

The highest quasar redshift bin ($3 < z < 4$) exhibits a drop in the space density of quasars, of up to a factor ten. One interpretation of this would again be that the epoch of the peak formation of the brightest quasars has been reached.

5.8 Other studies

Galaxies

The IRAC 3.6 and $4.5\mu\text{m}$ galaxy luminosity functions can be compared to near-IR luminosity functions in the J ($1.25\mu\text{m}$) and K_s ($2.2\mu\text{m}$) bands which, similarly, probe the stellar mass in galaxies (particularly as the mean redshift of the IRAC galaxies is $z \sim 0.6$ - equating to a restframe wavelength of 2.25 and $2.8\mu\text{m}$ for channels 1 and 2). The J and K_s luminosity functions of Pozzetti et al. (2003) found no

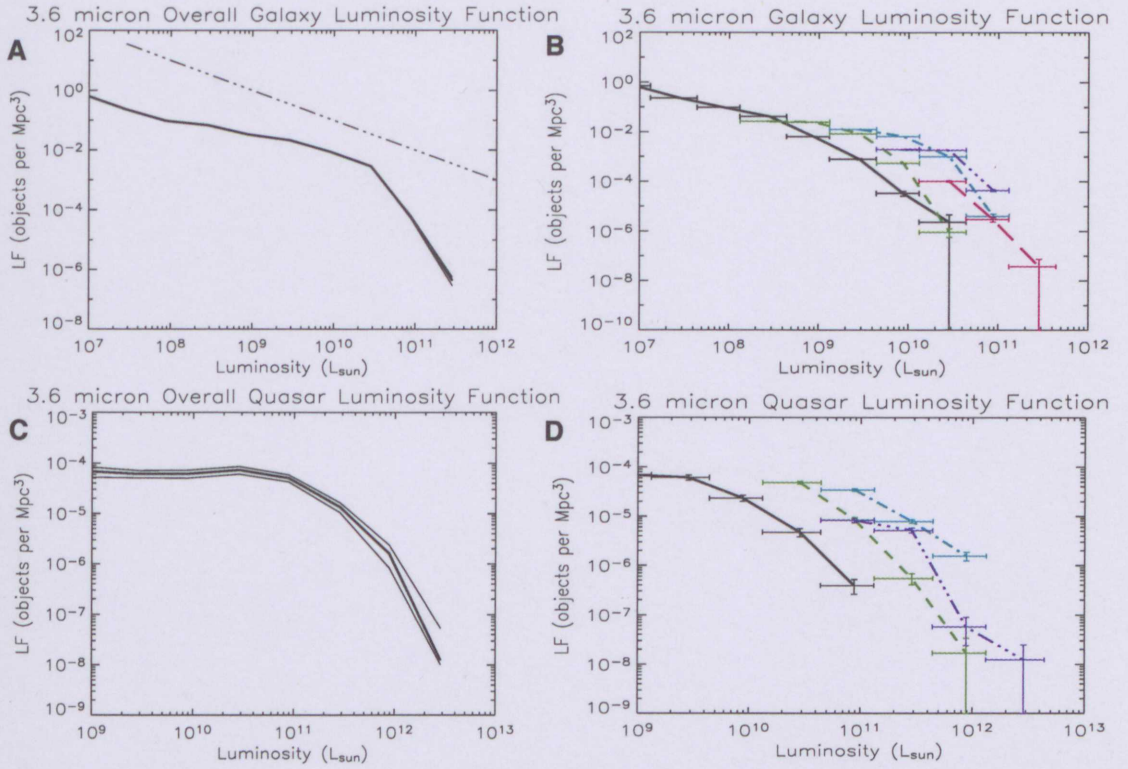


Figure 5.17: 3.6 μm luminosity functions. **A** and **B** are for galaxies; first the overall luminosity function (with overplotted power-law of slope -1 for comparison), and then split into redshift bins of [0 to 0.25] (black solid); [0.25 to 0.5] (green dashed); [0.5 to 1] (light blue dot-dash); [1 to 1.5] (purple triple-dot-dash); [1.5 to 2] (pink long-dash). **C** and **D** are for quasars; first the overall luminosity function, and then split into redshift bins of [0 to 1] (black solid); [1 to 2] (green dashed); [2 to 3] (light blue dot-dash); [3 to 4] (purple triple-dot-dash).

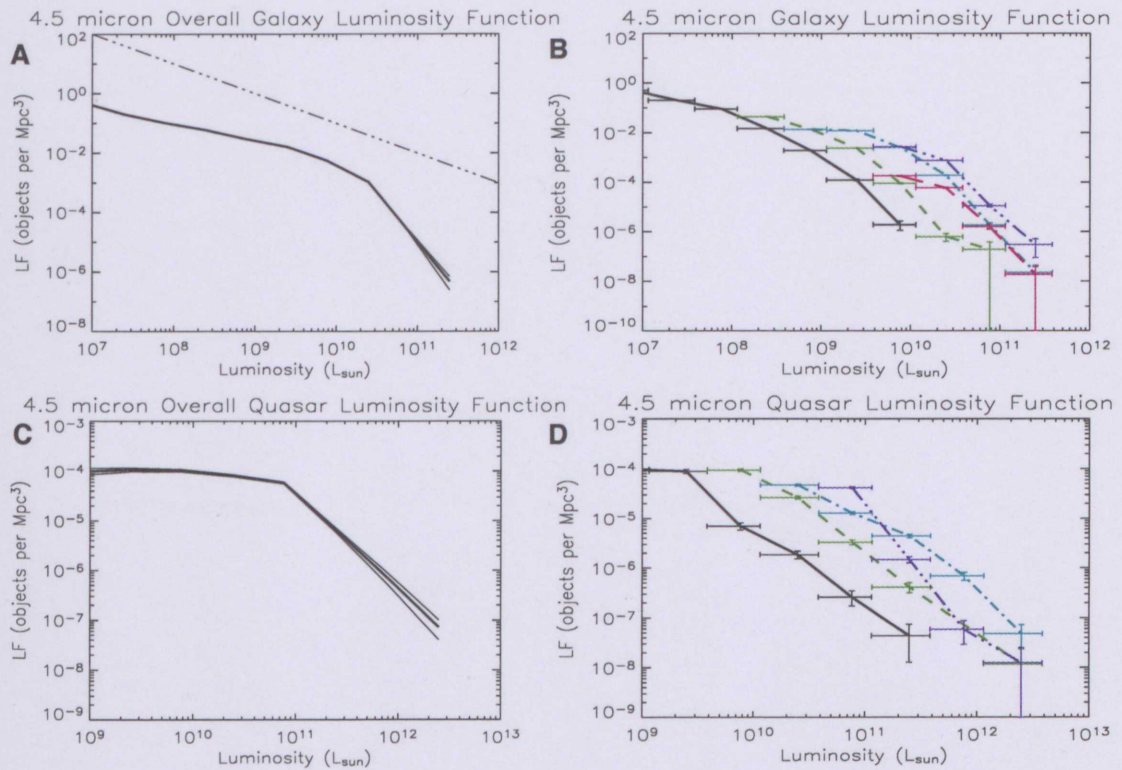


Figure 5.18: 4.5 μm luminosity functions. A and B are for galaxies; first the overall luminosity function (with overplotted power-law of slope -1 for comparison), and then split into redshift bins of [0 to 0.25] (black solid); [0.25 to 0.5] (green dashed); [0.5 to 1] (light blue dot-dash); [1 to 1.5] (purple triple-dot-dash); [1.5 to 2] (pink long-dash). C and D are for quasars; first the overall luminosity function, and then split into redshift bins of [0 to 1] (black solid); [1 to 2] (green dashed); [2 to 3] (light blue dot-dash); [3 to 4] (purple triple-dot-dash).

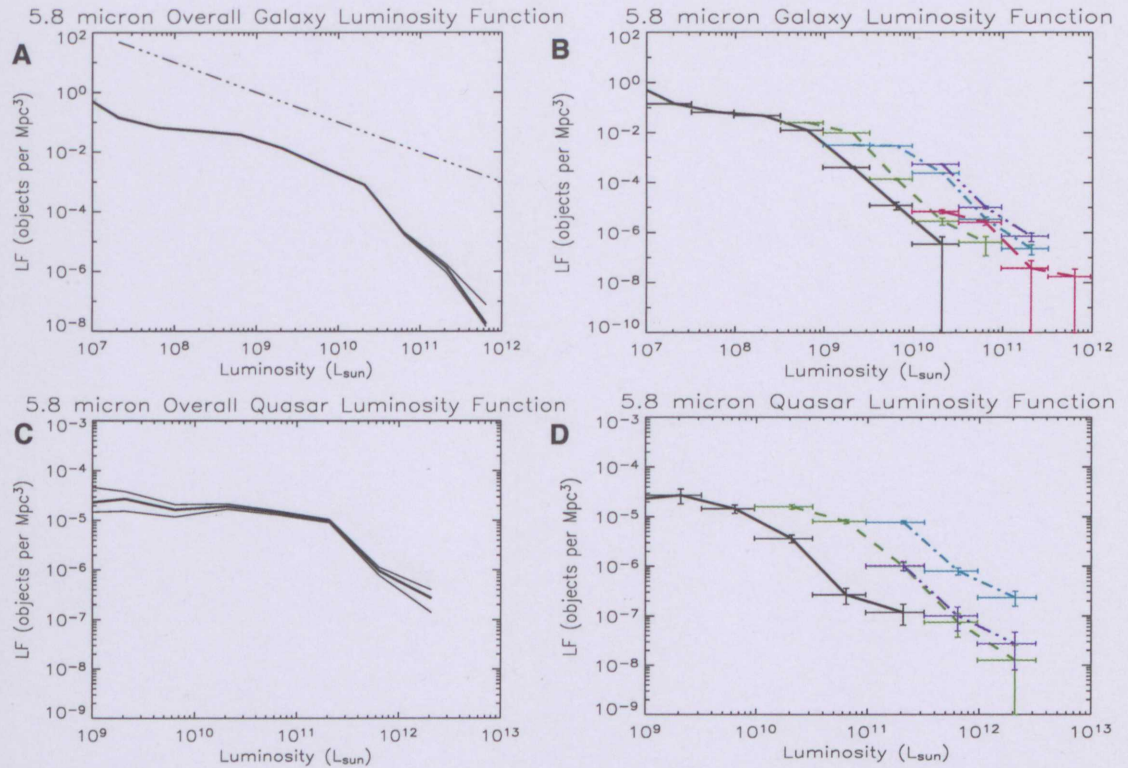


Figure 5.19: 5.8 μm luminosity functions. A and B are for galaxies; first the overall luminosity function (with overplotted power-law of slope -1 for comparison), and then split into redshift bins of [0 to 0.25] (black solid); [0.25 to 0.5] (green dashed); [0.5 to 1] (light blue dot-dash); [1 to 1.5] (purple triple-dot-dash); [1.5 to 2] (pink long-dash). C and D are for quasars; first the overall luminosity function, and then split into redshift bins of [0 to 1] (black solid); [1 to 2] (green dashed); [2 to 3] (light blue dot-dash); [3 to 4] (purple triple-dot-dash).

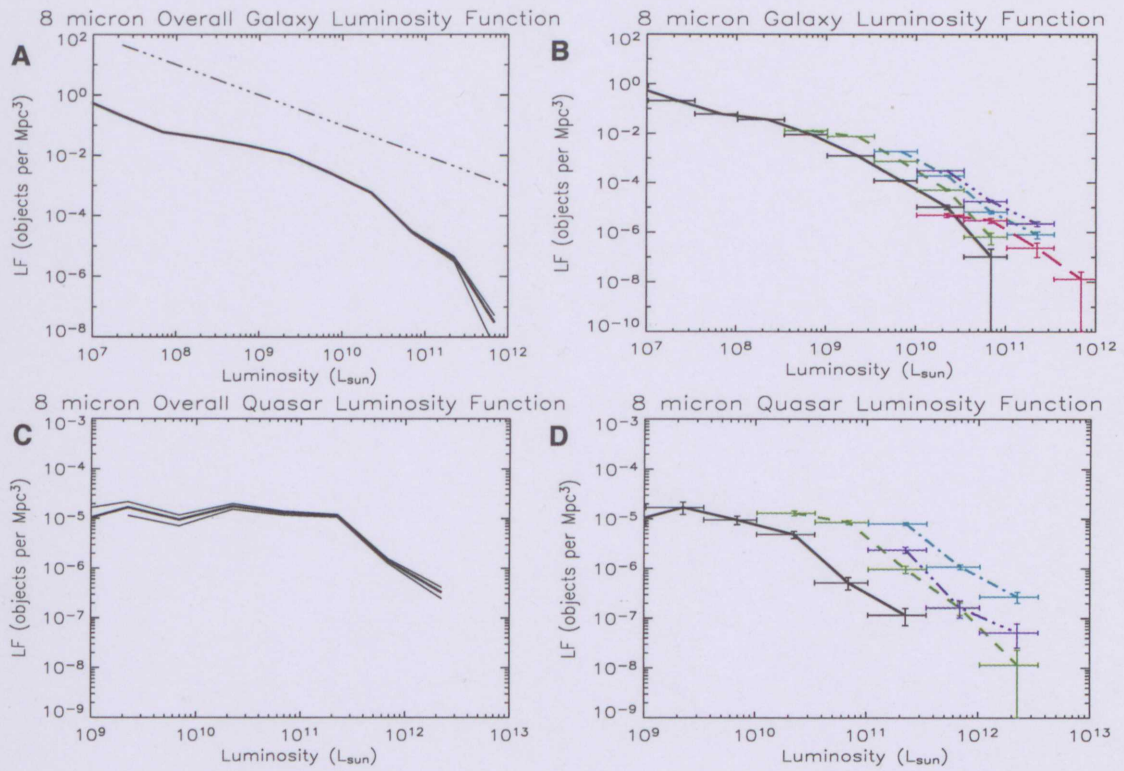


Figure 5.20: $8\mu\text{m}$ luminosity functions. A and B are for galaxies; first the overall luminosity function (with overplotted power-law of slope -1 for comparison), and then split into redshift bins of [0 to 0.25] (black solid); [0.25 to 0.5] (green dashed); [0.5 to 1] (light blue dot-dash); [1 to 1.5] (purple triple-dot-dash); [1.5 to 2] (pink long-dash). C and D are for quasars; first the overall luminosity function, and then split into redshift bins of [0 to 1] (black solid); [1 to 2] (green dashed); [2 to 3] (light blue dot-dash); [3 to 4] (purple triple-dot-dash).

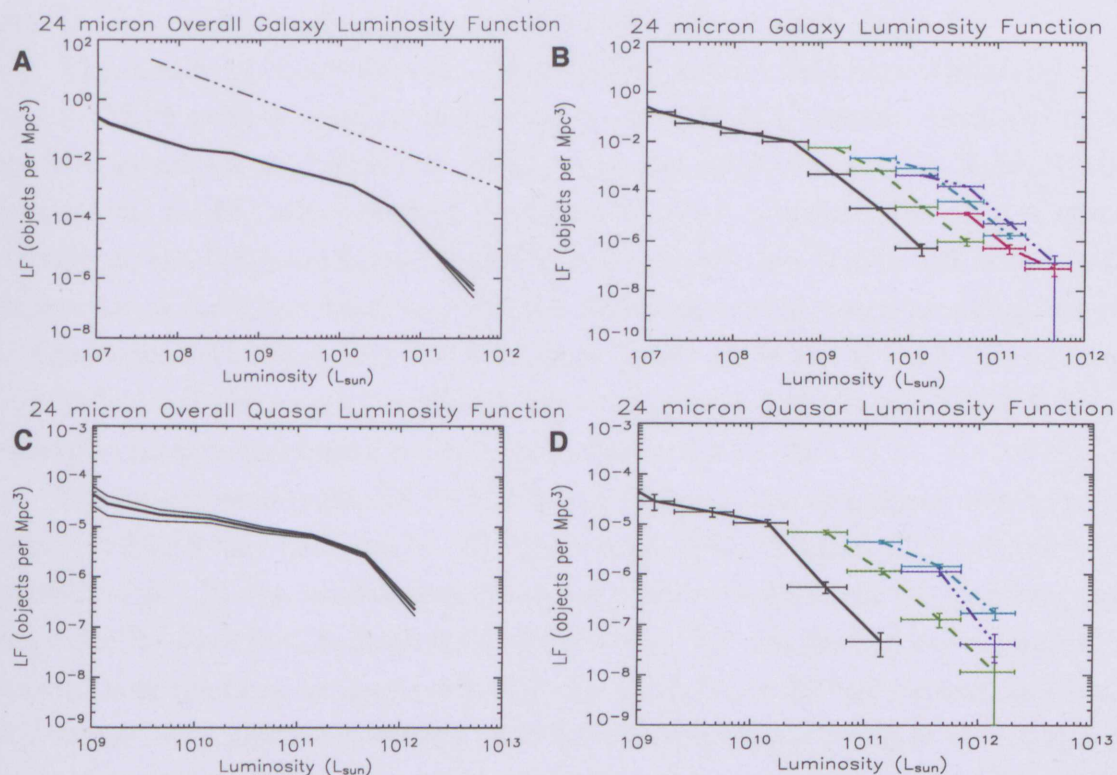


Figure 5.21: 24 μm luminosity functions. A and B are for galaxies; first the overall luminosity function (with overplotted power-law of slope -1 for comparison), and then split into redshift bins of [0 to 0.25] (black solid); [0.25 to 0.5] (green dashed); [0.5 to 1] (light blue dot-dash); [1 to 1.5] (purple triple-dot-dash); [1.5 to 2] (pink long-dash). C and D are for quasars; first the overall luminosity function, and then split into redshift bins of [0 to 1] (black solid); [1 to 2] (green dashed); [2 to 3] (light blue dot-dash); [3 to 4] (purple triple-dot-dash).

evidence of steepening of the faint end of the LFs up to a redshift of ~ 1.3 and no evolution of the faint end, in agreement with the trend seen in this study. The positive luminosity evolution displayed at the bright end of the LFs in §5.7.3 was also seen in the Pozzetti et al. study. Their mild evolution to $z \sim 1.5$ is in agreement with previous indications (Cowie et al. 1996; Cole et al. 2001; Cohen 2002; Feulner et al. 2003). The NIR LF and its evolution are a powerful test of galaxy formation scenarios (Kauffmann & Charlot 1998) and hierarchical vs. monolithic formation models show a sharp difference in predicted NIR LFs at redshifts $z > 1$.

The models of Kauffmann & Charlot (1998) predict that pure luminosity evolution (PLE) gives a constant bright-end to the LF with redshift, since the most massive galaxies formed at high redshift in the monolithic scenario. In contrast, the hierarchical model foresees ongoing formation at lower redshifts. The drop in space density at the bright-end seen in the highest redshift bin ($1.5 < z < 2$) is therefore supportive of the hierarchical over the monolithic galaxy formation model. It is also in agreement with the study of Ellis & Jones (2004) where the K band LFs of three high redshift clusters were considered, which suggested that the redshift of K-band galaxy formation had been reached at a redshift $z \sim 1.5 - 2$.

The longer wavelength *SPITZER* bands ($5.8\mu\text{m}$, $8\mu\text{m}$ and $24\mu\text{m}$) can be compared to *IRAS* and *ISO* results. Clements et al. (2001)'s $12\mu\text{m}$ *ISO* LF (out to a redshift of $z=1.2$) was compatible with strong positive evolution at the high luminosity/redshift end of the LF. Both the Clements et al. LF and the 5.8 , 8 and $24\mu\text{m}$ LFs derived here are in good agreement with the older *IRAS* LF determination (Rush & Malkan 1994) and lower redshift *ISO* LF determinations (Fang et al. 1998) but show higher space densities at high luminosities, indicative of the contribution from higher redshift sources.

A more direct comparison is possible between the $24\mu\text{m}$ LF and the local luminosity function at $25\mu\text{m}$ constructed by Shupe et al. (1998) from *IRAS* data. At the faint end (10^7 to $10^9 L_\odot$) they found a lower source density with the LF flattening off. The trend found here is more similar to the $25\mu\text{m}$ results of Soifer & Neugebauer (1991) which continues the rise in space density to fainter luminosities. However, the Soifer & Neugebauer (1991) LF was shown by Shupe et al. (1998) to suffer from contamination from the Local Supercluster. It is important to note that the $24\mu\text{m}$ LF here goes a factor 10^3 deeper in flux compared to the depth of 250mJy used in the LF of Shupe et al. (1998). At the bright end, the local LF derived by Shupe et al. (1998) is lower than the $24\mu\text{m}$ LF derived here, as would be expected from the evidence of positive luminosity evolution with redshift found here.

Rowan-Robinson et al. (1987)'s studies of 25 , 60 and $100\mu\text{m}$ LFs found they

could be broadly represented by broken power-laws, steepening at higher luminosities. For the $25\mu\text{m}$ LF the break was at $\sim 3 \times 10^{10} L_{\odot}$, in good agreement with the observed steepening seen to occur at a luminosity of $\sim 4 \times 10^{10} L_{\odot}$ in the $24\mu\text{m}$ LF. The 60, and 40- $120\mu\text{m}$ LFs of Saunders et al. (1990) also exhibit strong luminosity evolution at the bright end, as have the more recent ELAIS results at $90\mu\text{m}$ of Serjeant et al. (2001) and Serjeant et al. (2004b).

Quasars

The evolution of quasars is well established. Most studies agree that the space density of quasars above a given luminosity increases by a large factor (~ 50) out to $z \sim 2$, that it then levels out, and then decreases to $z \sim 5$ (e.g. Hook, Shaver & McMahon 1998). The decrease from redshift $z \sim 2$ to the present day can be interpreted as due to; a reduction in the merger rate; a decrease in the cold gas available for fueling; and an increase in the timescale of gas accretion (Kauffmann & Haehnelt, 2000).

The quasar LF can usually be characterised by a Schechter or double power-law (Boyle et al., 1988). Pei (1995) used a double power-law model where the bright and faint ends were independent of redshift, with the break occurring at a luminosity that was dependent on redshift. This pure luminosity evolution model gives good agreement out to $z < 2.3$ (Boyle et al. 1988; Boyle et al. 2000) but at higher redshift it is not sufficient. Studies of higher redshift quasars show that better agreement is reached when the bright end of the LF evolves (e.g. Warren et al. 1994).

In addition, there is a significant drop in the space density at redshifts above ~ 3.5 , a situation long suspected but not strongly confirmed until the early '80's (e.g. Osmer 1982). This drop by around a factor ten in space density has been seen in numerous quasar studies since (e.g. Warren et al. 1994; Schmidt et al. 1995; Kennefick et al. 1995) and was convincingly measured by Fan et al. (2001a). They found that the decline was fit well by the model of Schmidt et al. (1995). Fan and co-workers later extended the analysis to higher redshifts, finding that the space density at redshift $z=6$ was in good agreement with the decline seen at $3 < z < 5$ (Fan et al., 2001b). This dramatic drop can be interpreted as marking the epoch of peak formation of quasars, at around ten per cent of the current age of the Universe. As such, it has strong implications for models of black hole formation, fuelling and evolution (e.g. Haehnelt & Rees 1993; Granato et al. 2001; Schirber & Bullock 2003).

Some studies, however, do not find evidence for such a strong drop in quasar space density between redshifts of two to four. The COMBO-17 faint AGN results

of Wolf et al. (2003) found a broad plateau-like maximum in quasar activity at $z \sim 2$ with a smooth turnover rather than a break to higher redshifts. It is important to note that this was for *faint* AGN though, which suggests that faint AGN have a different cosmological history to the brighter AGN. At the other end of the scale, Vigotti et al. (2003) found that the very brightest quasars also exhibited only a slight decrease in space density from redshift two to four, such that the space density of the most luminous quasars peaked at an earlier epoch than the quasar population as a whole. This lack of decline was also found by the earlier study of McMahon et al. (1992) of bright optical quasars at $z > 4$.

Studies of X-ray-selected and radio-selected quasars are not strongly affected by dust. Wall et al. (2004) recently used the Parkes quarter-Jansky flat-spectrum sample of quasars and were able to demonstrate a drop in space density at redshift $z > 3$ at a significance level of 3.5σ . This is similar to the results of Shaver et al. (1996), also for radio quasars. X-ray selected quasars from *Chandra* have been shown to decrease in number density, or to at least remain constant, with redshift, out to redshift $z=3$ (Cowie et al., 2003). However, Miyaji et al. (2000) failed to find evidence of a decrease for *ROSAT*-selected X-ray quasars, though with marginal statistics.

The quasar LFs calculated here show similar high redshift behaviour as radio quasars and optical studies of quasars (excluding the very faint and the very luminous), with a steep drop in space density in the redshift bin $3 < z < 4$ implying a similar cosmic history and evolution. Also, the space density of quasars in the redshift bin $1 < z < 2$ as compared to the $3 < z < 4$ bin are seen to be similar, in all the IRAC bands, as was found by optical studies such as Warren et al. (1994). This agreement supports the argument that the observed drop seen in optical studies is not the effect of intervening dust obscuration causing an apparent drop in space density at high redshift (e.g Wright 1981; Fall & Pei 1993) since the quasar LFs calculated here will be less effected by this. Indeed the selection functions calculated in §5.6.1 should correct for the loss of sources from the optical part of the multi-band catalogue.

It is noted that the drop is less pronounced for the $24\mu\text{m}$ sample, which could imply a more common heritage to the more luminous quasars, and the X-ray-selected quasar population.

5.8.1 Bias

Bias in LF calculation is an issue that cannot be ignored. LFs are the result of complex selection functions and large corrections for incompleteness required to correct for all the biases and limits introduced by observational selection effects.

The global LFs calculated here are the sum of the LFs of each galaxy type (Binggeli et al. 1988). As such, there will be bias if certain galaxy types are not visible in a given redshift bin. However, even when they are, there will still be a potential bias if they are observable in different absolute magnitude ranges (Lilly et al. 1996; Brown et al. 2001). There are several different LF estimators, each with their own advantages and drawbacks (e.g Willmer 1997; Takeuchi et al. 2000). The different biases each method can introduce to the LF were explored in an admirable paper by Ilbert et al. (2004) who considered the dependancy of limiting absolute magnitudes and the intrinsic bias introduced by the differing LFs of different galaxy populations. The various LF estimators will be described below, along with their up and downsides:

- (i) *1/V_{max} estimator.* The classical estimator (Schmidt 1968), as used in this Chapter, accounts for the apparent magnitude limit of a survey by assuming a homogeneous galaxy distribution. It has been shown that this assumption is not robust to clusters or voids (Takeuchi et al. 2000) but this should be less of an issue for the 6 square degree field used here, and even less-so for the SWIRE survey as a whole. An advantage is the simplicity of the method and that it is able to give the shape and normalisation of the LF at the same time.
- (ii) *The C⁻ method.* The C⁻ method of Lynden-Bell (1971), updated to the C⁺ method (Zucca et al., 1997) makes no assumption of the spatial distribution of galaxies but information on the LF normalisation is lost (needs to be derived via Davis & Huchra 1982 or similar).
- (iii) *Maximum-likelihood statistical measures.* Method such as STY (Sandage et al., 1979) and the step-wise maximum likelihood (SWML; Efstathiou et al. 1988) are based on the likelihood of obtaining a sample equal to the one observed given the depth of the survey. As there is no binning, all the information available is used. Again, there is no assumption of the galaxy distribution but the LF normalisation is lost. Additionally, STY assumes a parametric form for the luminosity distribution (such as Yahil et al. 1991).

Ilbert et al. (2004) found that the 1/V_{max} and C⁺ methods act to underestimate the LF at the faintest luminosity bins, biasing the global LF faint-end slope. This

was because beyond the absolute magnitude where a certain galaxy population is not observable, the methods recover the LF slope of the remaining populations. The situation for the STY and SWML estimators was more complicated. Consider the case of two galaxy populations, SED_1 and SED_2 . Beyond a certain absolute magnitude the first population is not observed. In this case, there are three outcomes for the faint-end of the LF: If the LFs of the two galaxy populations is the same then the global LF is recovered; if the LF of SED_2 is flatter at the faint-end, then the global LF is underestimated; if the LF of SED_2 is steeper, then the global LF will be overestimated.

So, the different methods have different inherent biases, which manifest at higher redshift where the k-corrections for different populations will be large and potentially different. However, when the different estimators give the same global LF, then this implies that there is no bias present. For the $1/V_{max}$ LF calculated here, there is therefore a potential that the faint-end of the LFs has been underestimated. In general, however, if the selection function as a function of flux and redshift is accurate, the $1/V_{max}$ will give an unbiased estimate.

The second consideration for the LFs calculated here is that they are based on photometric redshifts. Here, the photometric redshift has been assumed to be true for each source (as in other studies, such as Gwyn & Hartwick 1996; Sawicki et al. 1997; Mobasher et al. 1996; Takeuchi et al. 2000). This approach has the shortcoming that the photometric redshift is only an estimate of the true redshift. This leads to potential problems with the derived LF, which have been minimised to some extent by excluding poor χ^2_{red} solutions, only calculating the LFs in the redshift range where the photometric method has been tested to a reasonable extent (z of 0-2 for galaxies and z of 0-4 for quasars), and by using generous redshift bin widths.

A future extension to this work will be to carry out Monte Carlo simulations where each photometric redshift is assumed to be sampled from an underlying Gaussian distribution. This will enable the effect of photometric redshift uncertainty to be quantified in the LF bins.

A more extended method, as used by Bolzonella et al. (2002), would be to adopt a Monte Carlo approach that accounts for the non-Gaussianity of the photometric redshift errors, since the probability distribution of the redshift solution, $P(z)$, is not always a Gaussian centred on the true redshift, but can have several distinct peaks.. This is beyond the scope of the analyses carried out here, but it is believed that the inclusion of the IRAC channels 1 and 2 in the redshift solution has improved the reliability of the results, and reduced the incidence of secondary solutions that lead

to degeneracies. The error in the quasar LFs will be larger since the photometric redshift technique is less accurate for quasars, due to their photometric variability over the timescale of the optical survey.

5.9 Discussion and conclusions

This Chapter has extended the photometric redshift method to incorporate near-IR data (sub $5\mu\text{m}$) in the solution. This was found to improve both the accuracy and reliability of the solutions and is anticipated to be extremely effective for future multi-wavelength studies that combine optical photometry with data from the *SPITZER* space telescope. Application of the extended photometric redshift technique to a six square degree area in the ELAIS N1 field of the SWIRE survey has shown that the majority of the SWIRE population can be characterised as star-forming galaxies with a mean redshift of $\langle z \rangle \sim 0.6$, with a tail extending out to redshifts of $z \sim 1.5$. Ellipticals make up around a third of the population, with a mean redshift of $\langle z \rangle \sim 0.5$ and a tail to a redshift of around unity. The proportion of $24\mu\text{m}$ sources that are ellipticals is seen to be lower than that of the shorter wavelength *SPITZER* sources. In addition to the galaxies, there is a population of AGN ($\sim 5\%$ of the total) that extends across the full redshift range, with indication of a slight rise in their distribution to redshift two, and a decline thereafter.

The distribution of A_v values with redshift was found to drop off more steeply at higher redshift and in the highest redshift bin all the solutions have low A_v . However, it was found that the number of sources with intermediate A_v , of 0.1 to 0.4, increases for the redshift bin [0.5 to 1] when compared to the lowest redshift bin [0 to 0.5], as predicted by closed-box star-formation models (Rowan-Robinson 2001b; King & Rowan-Robinson 2003).

Using the photometric redshift solutions, along with selection functions designed to account for the bias in the multi-wavelength catalogue, allowed luminosity functions to be calculated in each *SPITZER* band. This was done using the $1/V_{\text{max}}$ estimator, for both galaxies and quasars. The relevant K-corrections in the optical and IR were derived using the optical/near-IR template solutions of the redshift fitting procedure, and separate mid-IR template fitting solutions applied to the longer *SPITZER* wavebands.

The 3.6 and $4.5\mu\text{m}$ galaxy LFs were found to be similar to other near-IR studies, where the LF is probing the stellar mass. There was evidence for positive evolution

in the galaxy LFs such that the bright-end of the LF increases to higher luminosities for higher redshifts. In the highest redshift bin (redshift 1.5 to 2) there was a drop in space density, possibly indicative of the redshift at which the bulk of stellar mass formed and favouring the predictions of hierarchical galaxy formation over monolithic scenarios. The $24\mu\text{m}$ galaxy LF, more indicative of star formation rate, was in agreement with previous *IRAS* and *ISO* results in the mid- and far-IR, with evidence of strong luminosity evolution with redshift. In addition, these LFs are extended to a much fainter flux level.

The quasar LFs, calculated in the IRAC bands, showed a similar high redshift behaviour as optical studies of quasars (excluding the very faint and the very luminous), and of radio quasar studies. The steep drop in space density seen in common in the redshift bin $3 < z < 4$ implies a similar cosmic history and evolution. The drop in space density was less pronounced for the $24\mu\text{m}$ sample, which could imply a more common heritage with the most luminous quasars, and the X-ray-selected quasar population.

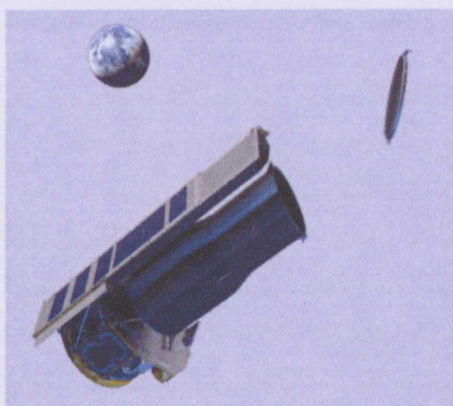
The LFs calculated in this Chapter have demonstrated the evolution of both galaxies and quasars. A future step will be to model these LFs using Schechter Functions and power-law fits in order to derive star formation rates, and hence star formation histories.

5.10 Acknowledgements

The production of the SWIRE catalogues has been a big team effort. Work that directly relates to this Chapter is as follows: False cross-ID match statistics were calculated by Carol Lonsdale, UC San Diego; The IRAC to deep FLS observation comparison and resulting selection functions shown in Fig. 5.2 were calculated by Jason Surace, IPAC, CALTECH; the MIPS $24\mu\text{m}$ simulated source extraction and resulting selection function shown in Fig. 5.3 were calculated by Mattia Vaccari, Imperial College London; The FIR SED fitting was developed and applied by Michael Rowan-Robinson, Imperial College London.

Chapter 6

Overall Discussion and Conclusions



In this Thesis a study of galaxies and quasars from the viewpoint of their optical and infrared properties has been presented. Rather than focussing in on individual objects, the general characteristics of extragalactic sources have been explored by classifying them as one of a small set of generic ‘types’. This template-fitting approach opens up a wealth of possible applications, from deriving redshifts, to the tracing the distribution and evolution of different galaxy populations in both space and time.

The investigations carried out by this Thesis have been conducted in the context of, and building on, the field of infrared astronomy and the most important phenomenological and physical properties of galaxies at these wavelengths, in concert with their perhaps more familiar optical properties.

More precisely, this Thesis presented and developed a photometric redshift technique for both galaxies and quasars which derives redshifts and dust extinction. This

was first applied to optical data (Chapter 3) and then extended to incorporate infrared data as well (Chapter 5), with a separate treatment of mid- to far-infrared emission allowing the construction of K-corrected infrared luminosity functions for both galaxies and quasars. Issues of degeneracy, optical morphology and the reliability of dust extinction measures have been investigated (Chapters 3 and 4) and it is concluded that they are not insurmountable issues.

Space-based extragalactic surveys in the infrared have played an important role in this Thesis:

The reduction of data from infrared observatories such as *ISO* has proved to be complex and this Thesis has investigated data products from the most ambitious extragalactic survey carried out with this satellite (ELAIS) by comparing early results with those produced by more sophisticated techniques developed at a later date (see Appendix A), finding that the preliminary reduction techniques were broadly robust.

Following on from the recent successful launch and ongoing operation of the *SPITZER* infrared space observatory, this Thesis has made use of data from the SWIRE extragalactic survey which combines *SPITZER* and ground-based observations in six extragalactic fields. As well as reducing ground-based optical photometry to produce band-merged source catalogues (Chapter 2), this Thesis has used optical-infrared catalogues to derive redshifts and to then apply an infrared template fitting technique to the mid- to far-infrared emission of these sources in order to derive luminosities (Chapter 5). The large-scale nature of the SWIRE survey then allowed luminosity functions to be constructed in a number of *SPITZER* wavebands, which are an important probe of galaxy evolution and star formation.

The work in this Thesis can be summarised as follows:

- **Chapter 1**

In this Chapter the field of infrared astronomy was outlined from a historical perspective and the most important phenomenological properties of galaxies at these wavelengths were detailed. The infrared spectral range and issues of atmospheric emission and absorption were introduced. The origin of infrared emission in galaxies, its relation to the underlying physical processes, the phenomenon of starburst and Active Galactic Nuclei and the properties of Luminous Infrared Galaxies were also discussed and recent, key space-based IR missions were detailed.

Finally, the measurement of star formation rates at different wavelengths, their

importance, and the use of luminosity functions in order to derive star formation rates and star formation history have been explained.

- **Chapter 2**

This Chapter introduced the natural successor to *ISO*; the *SPITZER* space telescope, and described its instruments and the Legacy Programme projects being carried out with it.

The SWIRE survey is the largest extragalactic Legacy project to be carried out by *SPITZER* and its unique role within the other surveys carried out by the satellite was expounded upon. Science objectives, choice of fields and the extensive multi-wavelength data, either pre-existing or planned, have been described. The data reduction procedures carried out as part of this Thesis on optical photometry taken for the SWIRE survey were detailed and the current status of the survey was summarised.

- **Chapter 3**

In this Chapter a combined galaxy-quasar approach to template-fitting photometric redshift techniques was presented and shown to be a powerful one.

The code, ImpZ, was presented, developed and applied to two spectroscopic redshift catalogues, namely the Isaac Newton Telescope Wide Angle Survey ELAIS N1 and N2 fields and the Chandra Deep Field North. In particular, optical size information has been used to improve the redshift determination. The success of the code was shown to be very good with $\Delta z/(1+z)$ constrained to within 0.1 for 92 per cent of the galaxies in the sample.

The extension of template-fitting to quasars was also found to be reasonable with $\Delta z/(1+z)$ constrained to within 0.25 for 68 per cent of the quasars in the sample. Various template extensions into the far-UV were also tested, though firm conclusions on the far-UV behaviour of quasars could not be made.

- **Chapter 4**

As demonstrated in Chapter 3, photometric redshifts can be routinely obtained to accuracies of better than 0.1 in $\Delta z/(1+z)$. However, the issue of dust extinction is one that has still not been well quantified. In this Chapter the success of two template-fitting photometric redshift codes (ImpZ and HYPERZ) at reliably returning A_v in *addition* to redshift was explored using sources in the CNOC2 survey that have both spectroscopic redshifts and A_v values derived

from their Balmer decrements. It was also investigated whether the empirical value of $\gamma = 0.44$, the ratio between gas- and star- derived extinction, as determined by Calzetti (2001b), was necessarily the best value for this sample.

By directly comparing the extinction values from the two codes it was found that the agreement between them is reasonable, with $\sim 70\%$ of values agreeing within $|\Delta A_v|$ of 0.3. Hence, using five band photometry, the A_v can only be determined to an accuracy of around 0.3, say, via photometric redshift methods.

When comparing the two codes to the Balmer-derived A_v , the correlation between the photometrically derived A_v , Phot- A_v , and the Balmer- A_v was not so good. The correlation improved when the empirical value of $\gamma = 0.44$, the ratio between gas- and star- derived extinction, as determined by Calzetti (2001b), was allowed to vary. From least-squares-fitting the minimum in the reduced χ^2 distribution was found for $\gamma = 1/3 \pm \sim 0.2$.

For the sample of galaxies in this Chapter, then, the factor two difference in covering factor implied by the Calzetti ratio was found to be consistent, within the errors of the method. The sample had a some preference for an increased covering factor which would imply they are undergoing more rapid, ‘bursty’ star formation than the galaxies Calzetti used in her derivation. Perhaps more importantly, the results demonstrate the pitfalls of assuming that star- and gas-based extinction measures will give the same dust extinction given some conversion factor. Thus, correlation to Balmer-derived values are modulo the uncertainty in comparing star- and gas-based extinction measures.

• Chapter 5

This Chapter extended the photometric redshift method to incorporate near-IR data (sub $5\mu\text{m}$) in the solution. This was found to improve both the accuracy and reliability of the solutions and is anticipated to be extremely effective for future multi-wavelength studies that combine optical photometry with data from the *SPITZER* space telescope. Application of the extended photometric redshift technique to a six square degree area in the ELAIS N1 field of the SWIRE survey showed that the majority of the SWIRE population can be characterised as star-forming galaxies with a mean redshift of $\langle z \rangle \sim 0.6$, with a tail extending out to redshifts of $z \sim 1.5$. Ellipticals make up around a third of the population, with a mean redshift of $\langle z \rangle \sim 0.5$ and a tail to a

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a more common heritage with the most luminous quasars, and the X-ray-selected quasar population.

Continuations and future prospects

The next step in these studies will be to extend the analyses to the 70 and 160 μ m data from *SPITZER*. The reduction and reliability of this data is now at a level where it can be used with confidence, with the majority of early problems now solved, or at least understood and flagged. Preliminary band-merging with the other *SPITZER* wavebands and optical data is in the process of being completed at IPAC by the SWIRE Team. Completion of this will allow inclusion of MIPS 70 and 160 μ m data in the mid- and far-IR SED fitting and, although the subset of sources with detections at 70 and 160 μ m is smaller, the mid- and far-IR SED of these sources can be constrained far more accurately. The natural progression will be to then calculate LFs at 70 and 160 μ m, where these LFs are then able to probe the nature of dusty IR galaxies.

Schechter functions (or double power-laws) can then be fit to the LFs, in order to explore the evolution of the luminosity density, the contribution to the IR background of the SWIRE sources at 3.6 to 160 μ m, and to derive the star formation history as seen by *SPITZER*.

With the completion of *SPITZER* observations of the SWIRE fields in December 2004, and the full reduction of the data, the analyses carried out in this Thesis can be extended to the full 49 square degrees of the SWIRE survey, enabling more robust statistics, and reducing cosmic variance issues. The same large area will allow the dependence of the galaxy LF on environment to be explored, thus probing the differing evolution of cluster and field galaxies. The availability of catalogues covering a larger area will be of most importance at 70 and 160 μ m where the number of sources is lower.

With the completed SWIRE survey, the predicted photometric redshift distributions of the SWIRE galaxies can be tested (or used to test) various source-count models and extend large-scale structure studies to three dimensions across a cosmologically significant volume. The photometric redshifts can also be used to identify cluster members.

Moving to other wavelengths, the *SPITZER* sources can be compared to X-ray surveys, and this has been carried out by Franceschini et al. (2004) in the ELAIS-N1 field for *Chandra* sources from the ELAIS deep X-ray survey (Manners et al. 2003). This found that the majority of the *Chandra* sources were at redshifts $0.5 < z < 2$ and

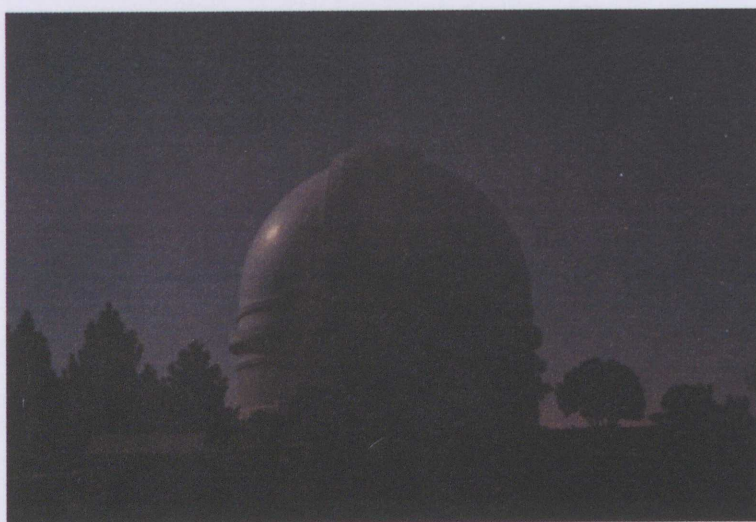
also that up to $\sim 50\%$ of the X-ray background could be attributed to starbursts or normal galaxies with moderate, hidden AGN. Interestingly, around 6% of MIPS $24\mu\text{m}$ sources were type 1 AGN based on their X-ray, IR and optical characteristics; similar to the 4% fraction found by the optical/near-IR template fitting carried out here. The similarities in the behaviour of the $24\mu\text{m}$ quasar luminosity function at high redshift and of X-ray-selected quasars that was suggested by the work in Chapter 5 is therefore mirrored by Franceschini et al.'s study. Further comparison to X-ray samples will allow continued exploration of the incidence of type 2 AGN, dust-shrouded quasars, and the links between their IR and X-ray properties, and also allow studies of galaxy clusters. For SWIRE, there are several further X-ray surveys; in addition to the *Chandra* survey in ELAIS-N1 there are *Chandra* surveys in Lockman (e.g. Yang et al. 2004) and in the CDFS, and *XMM* surveys in ELAIS-N1 (Mann et al. 2001), ELAIS-N2 (Manners et al. 2003) and in the XMM-LSS field (Pierre et al., 2004).

A similar analysis can be carried out for sub-mm sources, in particular in the Lockman and XMM-LSS fields where SCUBA data from JCMT exists, or is in the process of being taken (The Scuba Half-degree Extragalactic Survey; SHADES, see Mortier et al. 2004). The nature of the sub-mm population is still uncertain and correlation with SWIRE will allow many questions to be answered. For example, the contribution of sub-mm sources to the cosmic IR background, which peaks at $\sim 100\mu\text{m}$ is still uncertain. Also, although many high redshift sub-mm sources show hard X-ray emission, the majority of the bolometric flux does not appear to come from AGN (Alexander et al. 2004). Hence combining the sub-mm, IR, optical, and X-ray data available in SWIRE fields promises to allow proper characterisation of these sub-mm sources for the first time.

In conclusion, then, the template-fitting techniques developed in this Thesis have been shown to be a powerful tool for the extragalactic astronomer, and to yield a wealth of information on galaxy and quasar populations, particularly when applied to large-area multi-band surveys such as SWIRE. Future work will make full use of the opportunities demonstrated here.

A P P E N D I X A

Appendix



A.1 An investigation into the PA and FA ELAIS catalogues

As described in Chapter 1, the ELAIS survey was the largest open-time scientific programme on *ISO*. In order to allow follow-up targeting at an early stage in the campaign, it was decided that an initial data reduction would be carried out, to produce a Preliminary Analysis (PA). This was begun before a good understanding of the instrumental systematics and responses had been quantified. PA results have now been superseded by the Final Analysis (FA), which has involved recalibration of $6.7\mu\text{m}$ catalogues and re-reduction of $15\mu\text{m}$ (Vaccari et al. 2004) and $90\mu\text{m}$ (Heraudeau et al., 2004) observations via new methods optimised for the *ISO* instruments.

There is clearly a need to investigate more fully the exact relationship between the FA products and the PA products. This need is driven, firstly, by the wish to validate, or refute, the findings presented from PA products, and, secondly, to identify where the two techniques differ.

A final band-merged ELAIS catalogue has now been collated, incorporating data at multiple wavelengths (published in Rowan-Robinson et al. 2004a - note that this applies the 1.96 ADU/Gain/s/mJy conversion at 15 μ m but does not include the correction found by Vaccari et al. (2004) of 1/1.098 required to be consistent with *IRAS*). The 15 and 90 μ m observations are incorporated into this release. Accordingly, a comparison between the 15 μ m PA and FA, and 90 μ m PA and FA catalogues has been carried out in this Thesis. A summary of some of the results of these comparisons was presented in Rowan-Robinson et al. (2004a). Results are laid out in more detail here.

A.1.1 A 15 micron comparison

Notes on the PA catalogues used - there are essentially two versions of the 15 μ m PA catalogue: both the publicly available v1.4.¹ catalogue and the somewhat deeper consortium - only v1.3. version, which, barring depth, is otherwise equivalent (the former is a subset of v1.3, but cut at 4mJy). However, there exists a flux calibrational difference between the two versions - the v1.4 applies the additional factor 1.75 from Serjeant et al. (2000) which was later found to be incorrect. In this analysis the v1.3 catalogue has been used and for flux comparisons between the PA and FA catalogues only the PA sources denoted 'secure' (REL=2) are considered (we denote a PA flux as S(PA) and an FA flux as S(FA)). There are 1924 PA sources, of which 878 are REL=2, of which 415 are REL=2 and have fluxes brighter than 2.86mJy (an early suggestion for the completeness level).

Notes on the FA catalogues used - these are the latest versions, incorporating Lari et. al's latest simulations for flux calibration. The number of sources in each field is 490 (N1), 566 (N2), 131 (N3), 462 (S1). Of these, there are 349 with fluxes brighter than 3mJy.

Accordingly, the consortium-only v1.3 PA sources have been matched to FA sources via a 6'' association radius - these are 'pairs'. An association radius of 6'' was used as this is the pixel field of view of ISOCAM. This association yields 674 pairs, of which 388 are a 'bright' PA source with S(PA)>2.86mJy. This means that

¹Available at <http://athena.ph.ic.ac.uk/elais/data>

77% of the PA REL=2 sources are confirmed by the FA analysis. More importantly, when excluding those towards the faint limit, with $S(\text{PA}) < 2.86 \text{ mJy}$, we find that 93% of the brighter PA REL=2 sources are confirmed by the FA analysis.

Fig. A.1 plots the $S(\text{PA})$ vs. $S(\text{FA})$ fluxes of the pairs (where the PA source is REL=2 - 'secure') that were found. It can be seen that a flux ratio $S(\text{PA})/S(\text{FA})$ of around unity is a reasonable trendline. In fact, the mean $S(\text{PA})/S(\text{FA})$ of these 674 pairs is 1.08.

For direct flux comparison it is preferable to consider stars (or point-like objects) since for extended objects the measurement of a flux is more dependent on the specific procedure, for example 'what aperture should we consider?' and 'where do we define the centre of the source?'.

There are 76 pairs whose FA source is labelled 'STAR' (this flag is currently only available in the S1 field). Three of these pairs have $S(\text{PA}) < 1 \text{ mJy}$ (at this faint level they should be excluded since this is well below a level where noise dominates), giving a mean $S(\text{PA})/S(\text{FA})$ for the remaining 73 STAR pairs of 1.04 ± 0.05 . This shows that the PA flux estimates for point sources are consistent with the FA flux values, modulo the incorrect factor of 1.75 from Serjeant et al. (2000) which was used in some PA analyses.

As well as the pairs, the unmatched FA sources (UMFs) without *any* PA match (neither REL=2 nor REL=3, where REL=3 denotes a less secure PA source) are plotted, with the $S(\text{PA})$ set to 1.91 mJy . This $S(\text{PA})$ value has been chosen since the likely completeness level found by Väisänen et al. (2002) for PAv1.3 was 2 mJy (with 1.05 conversion factor). Since the PAv1.3 N1_3 raster was not reduced, and the S1.6 raster was only part-reduced, UMFs from these areas are not included.

The brighter UMFs (23 are $> 3 \text{ mJy}$, of which 3 are $> 10 \text{ mJy}$) and UMPs (7 are $> 4 \text{ mJy}$, though none are above 6 mJy) have been investigated in the NASA Extragalactic Database (NED) with a $0.5'$ search radius, as have low $S(\text{PA})/S(\text{FA}) < 0.6$ pairs (33 outliers lying well above the general $x=y$ trendline):

70 per cent of the low $S(\text{PA})/S(\text{FA})$ outliers are extended galaxies/mergers in NED, and 24 per cent are stars/star-like. Only 2 have no NED association. This supports the belief that the PA analysis underestimates the flux of extended sources. Thumbnails of some of these sources are shown in Fig. A.2.

Around 74 per cent (17 of 23) of the UMFs have NED associations (including the 3 with $S(\text{FA}) > 10 \text{ mJy}$), of which $\sim$ half (8 of 17) are clearly extended galaxies/mergers, and $\sim$ 35 per cent are stars/star-like (6 of 17). The six remaining

UMFs that do not have NED associations or any bright PA sources near them are all faint (below 8mJy) and any reasonable S/N cut would immediately reject them as unreliable. This supports the claim that the UMFs are in general new sources not picked up by the original PA analysis.

Unmatched PA (REL=2) sources are also overplotted, with S(FA) set at 1mJy - a likely completeness level for the S1 final catalogue presented in Lari et al. (2001).

Of the seven UMPs, only two have clear NED associations - one is a 2MASS source, the other has an ELAIS radio source 0.2' away. This supports the supposition that generally the UMPs are not reliable sources. Thumbnails of the four brightest UMFs and the two UMPs with NED associations are shown in Fig. A.3.

Clearly the FA analysis has validated the majority of PA sources and identified a number of new, real sources.

A.1.2 A 90 micron comparison

Notes on the PA catalogues used - again, for flux comparisons between the PA and FA catalogues only the PA sources denoted 'secure' (REL=2) are considered. There are 334 PA sources, of which 141 are REL=2.

Notes on the FA catalogues used - there are 163 FA sources.

The PA REL=2 sources have been matched to the FA catalogue sources with a 40'' search radius (the resolution of the ISOPHOT pixels is from 43'' to 89''). Recall that source-extraction is carried out in a circular aperture of 6 pixels (i.e. 180'') using SEXTRACTOR (Bertin & Arnouts 1996). This association yields 117 pairs, meaning that 83% of the PA REL=2 sources are confirmed by the FA analysis.

Fig.A.4 plots the S(PA) vs. S(FA) fluxes of the pairs (where the PA source is REL=2) that were found. It can be seen that a flux ratio S(PA)/S(FA) of around unity is a reasonable trendline. In fact, the mean S(PA)/S(FA) of these 117 pairs is 1.3. The substantial scatter can be mainly attributed to the limitations of the PA processing.

As well as the pairs, the unmatched FA sources (UMFs) without PA matches (neither REL=2 or REL=3) are plotted, with the S(PA) set to 60mJy (an optimistic completeness level). There are several that have quite bright fluxes. The one source which has S(PA)/S(FA)>4 has also been indicated, by a box, on the plot. This source has been followed up in NED and appears to be a merger. In this case the

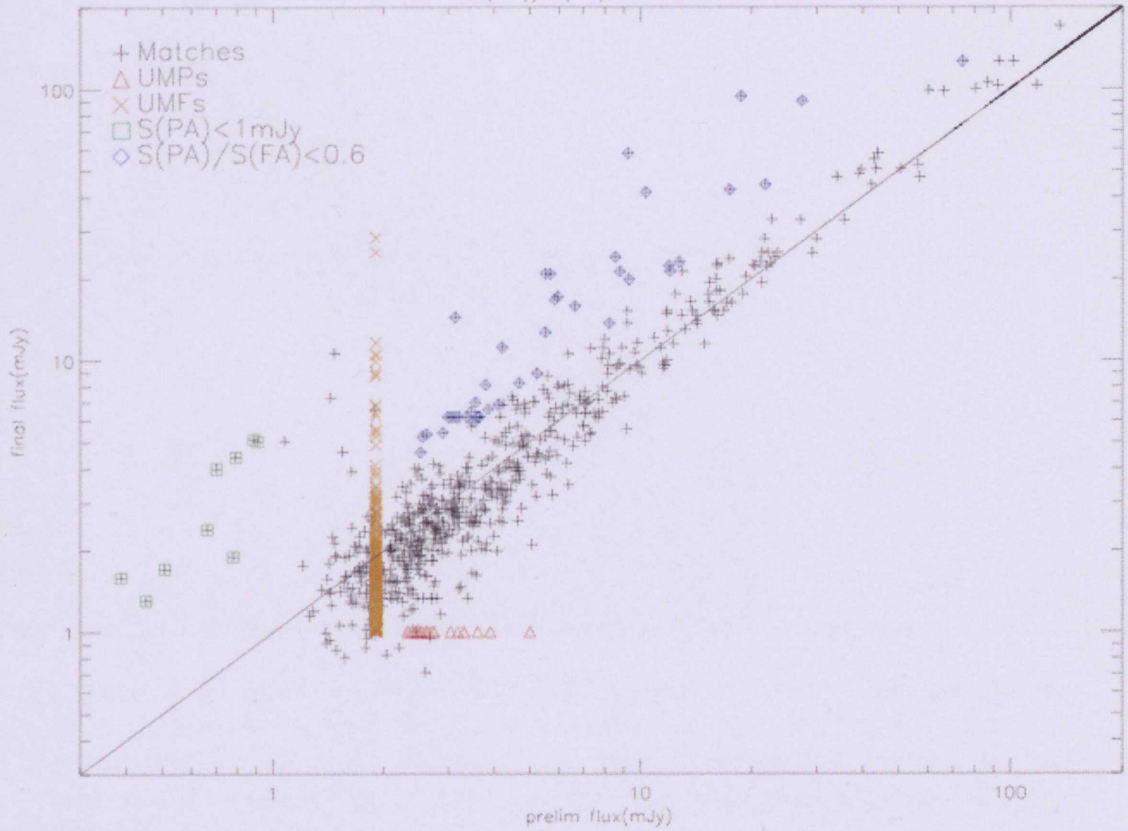


Figure A.1: 15 μ m PA to FA comparison. + are matched PA(REL=2):FA pairs (within 6"). Red triangles are REL=2 UMPs, orange crosses are UMFs. Those pairs with $S(\text{PA}) < 1\text{mJy}$ have been highlighted as unreliable (green square over +). Those pairs with $S(\text{PA})/S(\text{FA}) < 0.6$ have been highlighted (blue diamond over +). The line $S(\text{PA}) = S(\text{FA})$ has been overplotted. At low fluxes the trend appears to drop below the line of unity, which is attributable to the treatment of noise in the PA analysis which tended to overestimate faint source fluxes slightly.

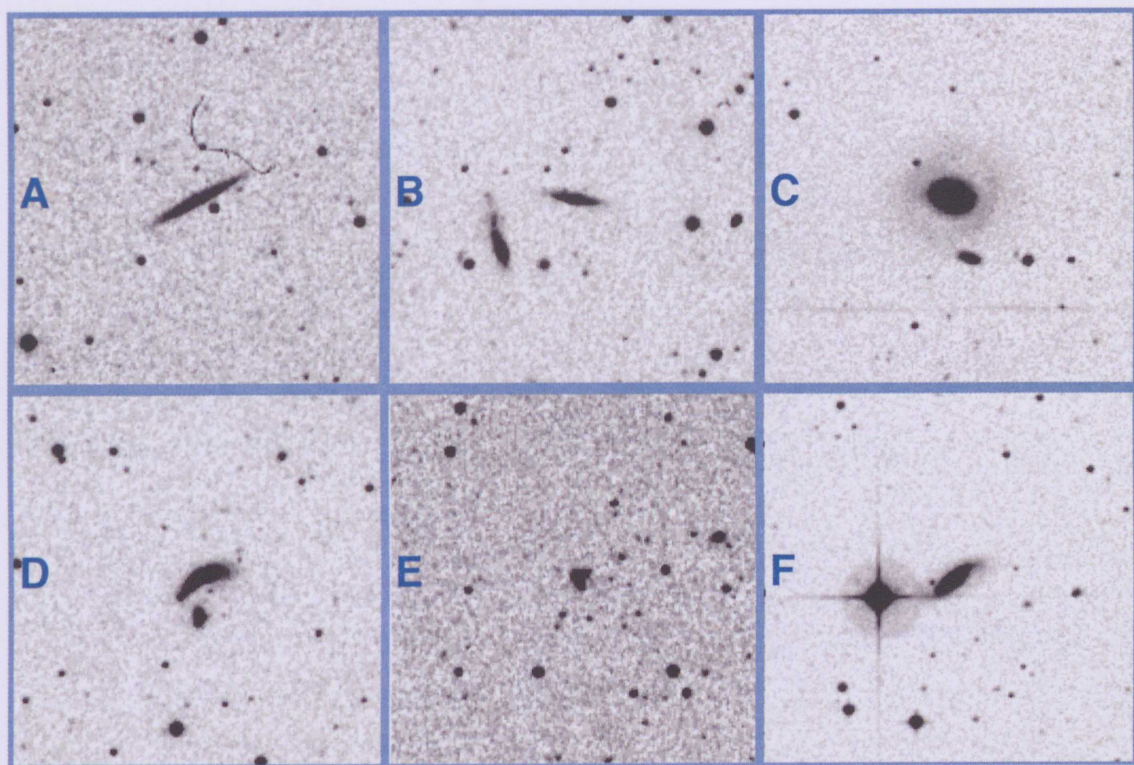


Figure A.2: Examples of low $S(\text{PA})/S(\text{FA})$ outliers in the $15\mu\text{m}$ comparison. Each thumbnail is a $5'\times 5'$ thumbnail from the Digitized Sky Survey, centred on the source position in the FA catalogue. They illustrate that majority of these outliers are extended sources, for which the PA method underestimated the flux. Thumbnails A to F are as follows:

A: ELAISC15_J163508+405918, 5.7mJy. Also UGC, FGC, RFGC, ELAISR20, 2MASX, FN2, PGC source (ignoring the ‘cosmic string’ in this thumbnail!).

B: ELAISC15_J163728+405253, 8.2mJy. Also SN 2002aw, 2MASXi, FIRST source.

C: ELAISC15_J003432-433914, 2.9mJy. Also ESO, MCG, 2MASX, PGC, APM-BGC source.

D: ELAISC15_J163813+415615, 10.4mJy. Also UGC, ARP, VV, LZw, CGCG, UZG, MCG, 2MASX, PGC source.

E: ELAISC15_J163820+404916, 4.2mJy. Also 2MASXi, ELAISR20 source.

F: ELAISC15_J003511-435915, 5.5mJy. Also ESO, MCG, LCRS, 2MASX, PGC, ELAISP90 source.

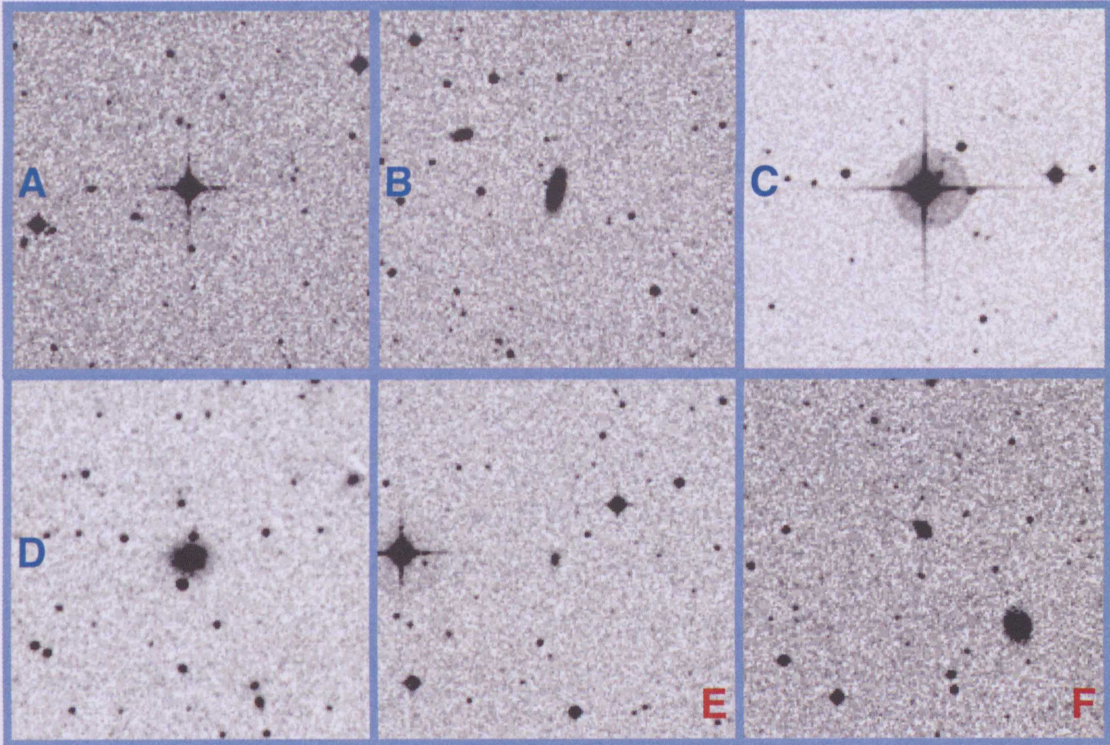


Figure A.3: The four brightest (A, B, C, D) UMFs in the $15\mu\text{m}$ comparison. Each thumbnail is a $5'\times 5'$ thumbnail from the Digitized Sky Survey, centred on the source position in the FA catalogue. E and F are the 2 UMPs with NED entries. They illustrate that majority of the UMFs are real sources, whereas most of the UMPs are not (see text for details). Thumbnails A to F are as follows:

A: ELAISC15_J003244-433346, 6.8mJy. Most likely a star.

B: ELAISC15_J003731-440812, 10.4mJy. Also LCRS, 2MASX, APMBGC, ELAISP90 source.

C: ELAISC15_J003836-440029, 25.1mJy. Most likely a star.

D: ELAISC15_J163137.82+412936.01, 9.1mJy. Also KUG, MCG, CGCG, 2MASX, PGC source.

E: ELAISC15_J003005-423729, 3.1mJy. Also a 2MASX source.

F: ELAISC15_J003637-423709, 5.0mJy. ELAIS radio source $0.2'$ away.

two different methods have treated the source(s) differently when calculating the flux.

The 26 brighter UMFs ($>200\text{mJy}$) have been investigated in NED, initially with a $0.5'$ search radius, then with $1.5'$ if none were found:

The brightest ($S(\text{FA})=682\text{mJy}$) is an extended galaxy (2MASS, *IRAS*, ELAISJ15, ELAISR20 source). 12 of 26 have NED associations within $0.5'$ (20 of 26 within $1.5'$) and of these five have ELAIS $15\mu\text{m}$ detections and at least eight are extended galaxies. Thus a number of the bright UMFs are galaxies and the majority are new, real sources. Thumbnails of four example UMFs and also the outlier with $S(\text{PA})/S(\text{FA})>4$ are shown in Fig. A.3.

Unmatched PA ($\text{REL}=2$) sources are also overplotted, with $S(\text{FA})$ also nominally set at 60mJy , however none of these sources are particularly bright and follow-up checks by the reduction team have shown them to be spurious - arising from limitations in the PA pipeline.

The $90\mu\text{m}$ FA reduction has verified that the majority of the PA sources were reliable and that their fluxes were reasonable. At the same time the FA reduction has identified a number of new, real sources.

A.1.3 PA - FA conclusions

The comparisons made by this Thesis at 15 and $90\mu\text{m}$ validate the PA products and confirm the majority of PA sources - around 80% of PA 'secure' sources are retained. Additionally, the FA products are able to deal more successfully with extended sources and go significantly deeper than the PA products.

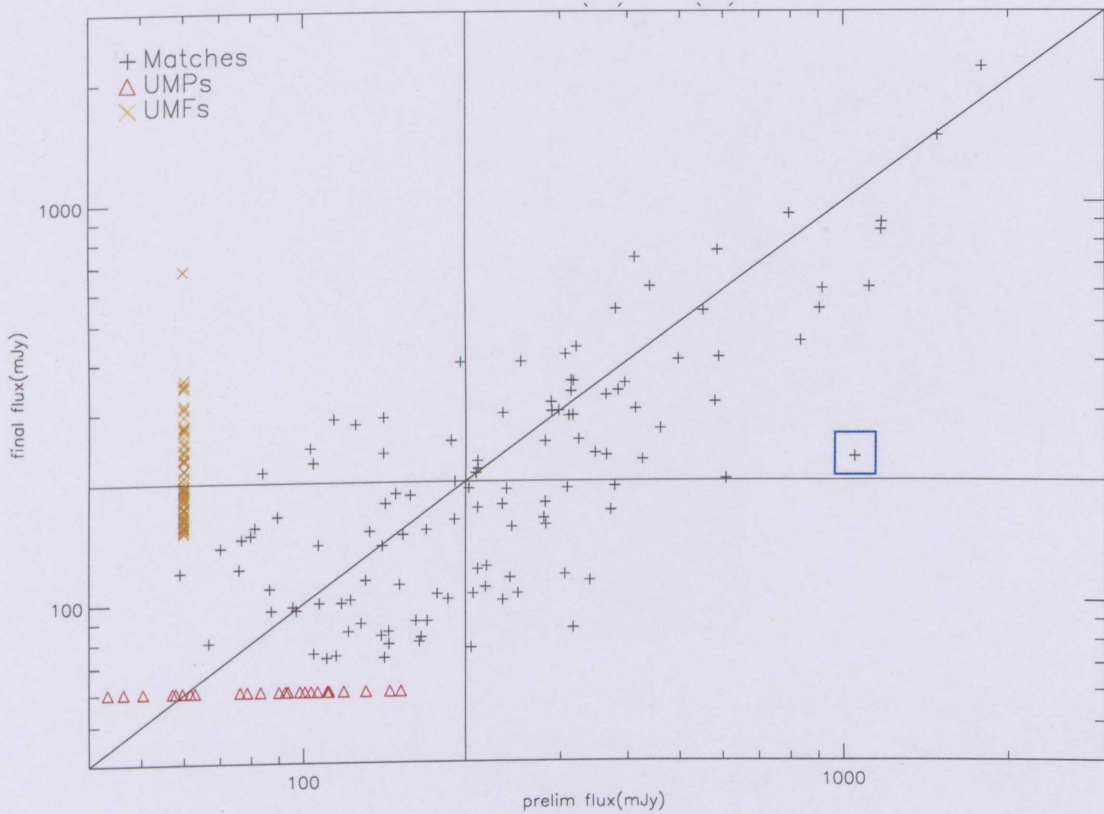


Figure A.4: $90\mu\text{m}$ PA to FA comparison. + are matched PA(REL=2):FA pairs (within $40''$). Red triangles are REL=2 UMPs, orange crosses are UMFs. The source outlined by a blue box is the match with $S(\text{PA})/S(\text{FA}) > 4$. The line $S(\text{PA}) = S(\text{FA})$ has been overplotted, as have the lines $S(\text{PA}) = 200 \text{ mJy}$ and $S(\text{FA}) = 200 \text{ mJy}$.

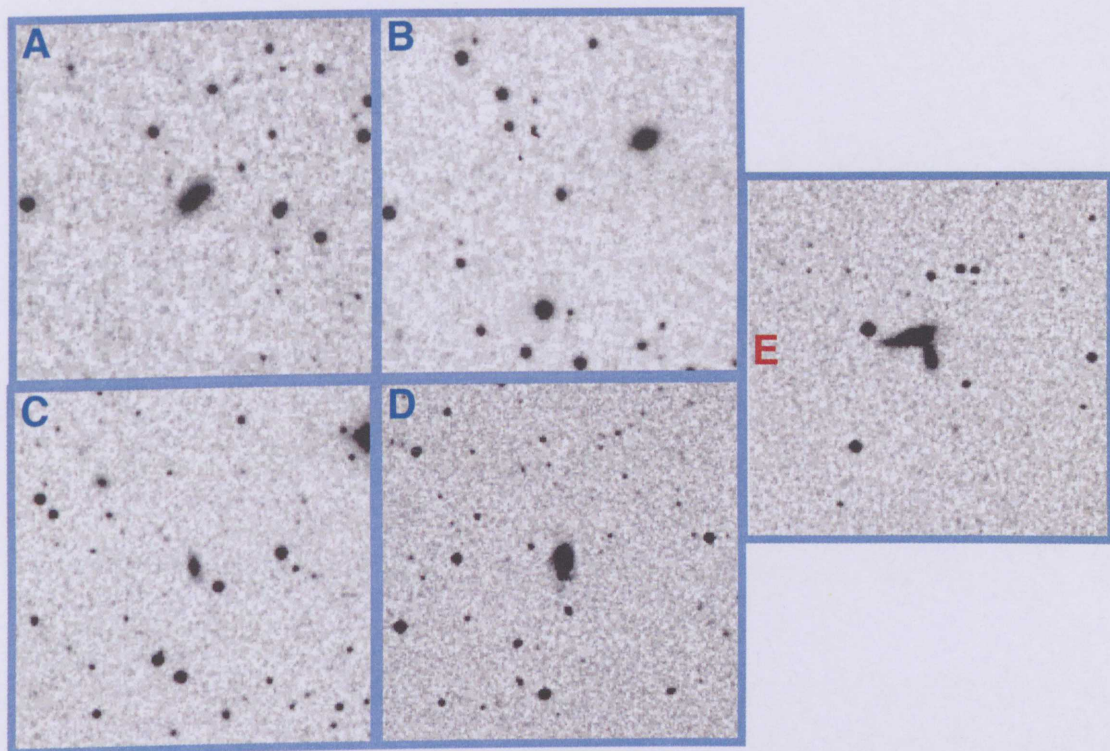


Figure A.5: Four example (A, B, C, D) UMFs in the $90\mu\text{m}$ comparison. Each thumbnail is a $5'\times 5'$ thumbnail from the Digitized Sky Survey, centred on the source position in the FA catalogue. They illustrate that majority of the UMFs are real sources. E is the outlier with $S(\text{PA})/S(\text{FA}) > 4$. It can be seen that it is most likely to be a merger so the discrepancy in the flux values is due to differences in defining the source. Thumbnails A to E are as follows:

A: ELAISP90_J160737+535736, 230mJy. Also CGCG, MCG, 2MASX, IRAS_F, FN1, PGC source.

B: ELAISP90_J161045+543536, 275mJy. Also an ELAISR20 source.

C: ELAISP90_J164014+421624, 308mJy. Also a 2MASXi source.

D: ELAISP90_J003827-433843, 682mJy. Also ESO, 2MASX, IRAS_F, ESO-LV, ELAISR20, ELAISC15 source.

E: ELAISP90_J143156+333745, is 1027mJy in the PA and 229mJy in the FA.

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*[Pliny] always said that there was no book
so bad that some good could not be got out of it.*

Pliny the Elder, in Pliny the Younger Letters Book 3, Number 5.