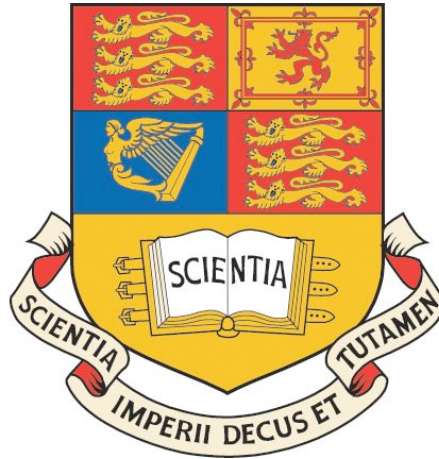


Multi-Wavelength Surveys of Extreme Infrared Populations

Markos Trichas
Astrophysics Group

Department of Physics
Imperial College London



Abstract of Thesis

Author Markos Trichas

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This Thesis presents a study of galaxies and quasars from the viewpoint of their optical, infrared and X-ray properties by combining optical data from Gemini and WIYN with near to far-IR and optical data from the SWIRE survey and X-ray data from Chandra. This work represents the largest existing optical spectroscopic survey in ELAIS-N1 with ~ 300 reliable spectroscopic redshifts and the largest X-ray survey, in the same field, which has extended the previous X-ray coverage in ELAIS-N1 by a factor of 12 and has detected more than 600 X-ray sources. Optical spectroscopy is used both to calibrate photometric redshift techniques and distinguish between star forming galaxies and quasars. The merged X-ray, optical and infrared catalogue is used to determine spectral energy distributions and correctly identify and characterize AGN, star forming galaxies and the link between black hole growth and star formation in the host galaxy.

to my beloved Sophia

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Markos Trichas

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When you set out on your journey to Ithaca,
pray that the road is long,
full of adventure, full of knowledge.
The Lestrygonians and the Cyclops,
the angry Poseidon do not fear them:
You will never find such as these on your path,
if your thoughts remain lofty, if a fine
emotion touches your spirit and your body.
The Lestrygonians and the Cyclops,
the fierce Poseidon you will never encounter,
if you do not carry them within your soul,
if your soul does not set them up before you.

Always keep Ithaca in your mind.
To arrive there is your ultimate goal.
But do not hurry the voyage at all.
It is better to let it last for many years;
and to anchor at the island when you are old,
rich with all you have gained on the way,
not expecting that Ithaca will offer you riches.

Ithaca has given you the beautiful voyage.
Without her you would have never set out on the road.
She has nothing more to give you.

And if you find her poor, Ithaca has not deceived you.
Wise as you have become, with so much experience,
you must already have understood what Ithacas mean.

Konstantinos Kavafis (1863-1933)

Chapter 1

Introduction

The beginning is the most important part of the work

Plato (428-347 BC)

1.1 Overview

This chapter gives an overview and a literature review of the main topics and meanings related to the work in this thesis. Its main goal is to introduce the concept of infrared extragalactic astrophysics and describe the most important phenomenological properties of galaxies when observed at these wavelengths. I begin by summarizing the latest cosmological results from WMAP in order to set the environment variables in which galaxies form and evolve. The infrared spectral range, its division into near-, mid- and far-infrared and the issues of atmospheric emission and absorption at these wavelengths are introduced. The need of space-borne infrared telescopes in order to be able to observe the entire infrared region is highlighted. This is followed by a brief description of IRAS, ISO, AKARI and Herschel, the overall mission designs, instrumentation and key surveys performed or planned with them. In addition, an overview of the main results obtained with IRAS and ISO is given, focusing on the findings associated with the work in this thesis. The origin of infrared emission in galaxies, its relation with their underlying physical properties, the phenomenon of cirrus, starburst, AGN, the connection between star formation and AGN activity and the properties of Luminous Infrared Galaxies are discussed. Finally, a description of classic star formation indicators and various methods of modelling star formation history are presented.

1.2 A Broad Picture of the Universe

Cosmology is the study of the Cosmos. This means that Cosmology attempts to understand the origin, evolution and fate of the Universe as a whole. Early cosmological models were based on the ancient Greek concept of a geocentric Universe which remained in use for more than two thousand years until its replacement by Copernicus' heliocentric system. Until well into the twentieth century the Cosmos consisted entirely of the Milky Way and the existence of other galaxies, or "island universes" as they came to be known, was only discussed by philosophers such as Kant. It was not until the first quarter of the 20th century that Hubble showed that some of the observed objects not only lie outside our galaxy but also move away from each other with speeds proportional to their distances.

The picture of the Cosmos today is best described by the standard big bang model of an evolving, expanding Universe consisting of around 100 billion galaxies within our current observable horizon, distributed in great clusters, sheets and filamentary structures. All this arose from a single event 13.7 ± 0.2 Gyr ago [326], and has been expanding ever since. According to this Friedmann–Lemaître–Robertson–Walker cosmological model which is defined by relatively few parameters, we live in an isotropic, homogeneous, spatially flat universe which emerged in a state of extremely high density and temperature and has been expanding adiabatically since then.

The current best set of cosmological parameters, as defined from the third year WMAP results, describe a Universe which is flat with $\Omega_{tot} = 1.02 \pm 0.02$ [35], with a baryon density of $\Omega_b h^2 = 0.0223^{+0.00075}_{-0.00073}$, a matter density of $\Omega_m = 0.237 \pm 0.034$ and a dark energy density of $\Omega_\Lambda = 0.763 \pm 0.034$ [325] (Ω_X being defined as the ratio of the density of species X to the critical density of the Universe). The dark energy equation of state implies it has a negative pressure, $w \equiv p/\rho < -0.78$ with 95% confidence limit [326] (where p and ρ are the pressure and density of dark energy respectively), causing accelerating expansion with a present expansion parameter, given by the Hubble constant, of 73.5 ± 3.2 km/sec/Mpc [325]; the Hubble constant is the present value of the Hubble parameter, the ratio of the comoving distance of a galaxy from the observer to its recession velocity. The current age of the Universe is estimated to be in the range of 13.7 ± 0.2 Gyr [326] and the temperature of the Cosmic Microwave Background is 2.725 ± 0.002 K [227]. Table 1.1 provides a list of the most important cosmological parameters based on the third year WMAP data.

Parameter	Symbol	Value	Uncertainty	
CMB Temperature (K)	T_{CMB}	2.725	± 0.002	
Total density	Ω_0	1.02	± 0.02	
Hubble constant (km/sec/Mpc)	H_0	73.5	± 3.2	
Matter density	Ω_m	0.237	± 0.034	
Baryon density	$\Omega_b h^2$	0.02230	+ 0.00075	- 0.00073
Dark energy density	Ω_Λ	0.763	± 0.034	
Dark energy eq. of state	w	< -0.78	95 C.L.	
Spectral index	n	0.951	± 0.016	
Amplitude of fluctuations	σ_8	0.742	± 0.051	
Optical depth to reionisation	τ	0.088	+ 0.028	- 0.034
Age of Universe at decoupling (kyr)	t_{dec}	379	+ 8	- 7
Age of Universe (Gyr)	t_0	13.7	± 0.2	

Table 1.1: Basic cosmological parameters for the best-fit Λ CDM model based on the third year WMAP data [325].

The major successes of the Hot Big Bang Model which established it as the dominant model over rival theories, such as Hoyle's steady state model, was the prediction of the Cosmic Microwave Background Radiation, the predictions of light-element abundances produced during the epoch of cosmological nucleosynthesis, the provision of a relatively clear framework within which the formation of cosmic structures can be understood and the qualitatively explanation of nucleosynthesis.

There remain, however, certain problems such as the Horizon problem, Monopole problem, Flatness problem, Cosmological Constant problem, the origin of the baryon asymmetry, the origin of the primordial spectrum of density fluctuations and the nature of the dark matter. The introduction of the inflationary paradigm [130] offered some answers to these problems but without being able to provide a definite answer for itself, since it is still unclear not only which of the various proposed inflationary models best describes our observations but also what the origin of the scalar fields generating inflation is. Although alternative approaches tried to establish cosmological models based on the Concordance Model but without the presence either of dark energy [37] or dark matter [234], the Big Bang Model still remains the dominant cosmological model accepted by almost everyone.

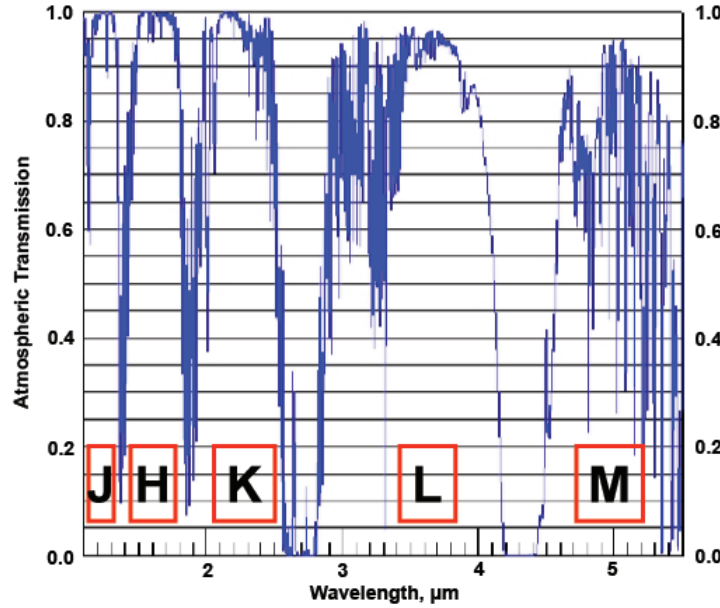


Figure 1.1: Atmospheric transmission for Mauna Kea in the near-infrared spectral region [5]. Common wide-band filters in each spectral window are labelled in red boxes.

1.3 The Infrared Region

Even though the first infrared detection of a celestial body can be traced back to 1800 when Herschel first detected the Sun in infrared, it was not until the 1960s that extragalactic infrared observations became possible with the development of lead sulphide detectors which allowed Johnson to define the first infrared magnitude system and the invention of germanium bolometers which enabled Low and Kleinmann to observe individual extragalactic sources in the infrared region for the first time [213]. The latter can be divided into three subregions, near-infrared (NIR), mid-infrared (MIR) and far-infrared (FIR) which span roughly between $1\text{--}5\mu\text{m}$, $5\text{--}30\mu\text{m}$ and $30\text{--}300\mu\text{m}$ respectively with longer wavelengths ranging from $300\mu\text{m}$ to beyond 1mm known as the submillimetre and millimetre regions.

Only a small part of the infrared region can be observed from the ground since the atmosphere is almost opaque over large wavelength ranges from almost all ground-based observing sites. This is mainly due to the fact that H_2O and CO_2 which can be both found in large quantities in Earth's atmosphere are significant absorbers of the infrared radiation. The existence of other absorbers such as ozone and other aerosols in the Earth's atmosphere plays an important role in the absorption of infrared emis-

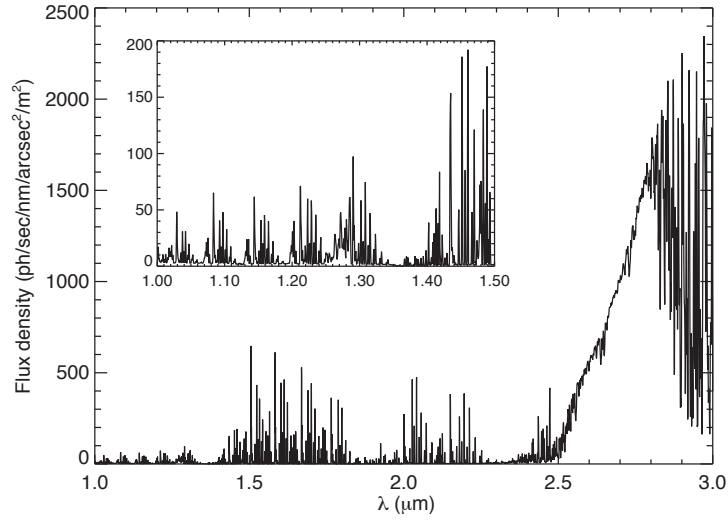


Figure 1.2: Atmospheric OH emission lines in the near-infrared region [6].

sion since it gives rise to Rayleigh scattering [13]. In addition, the atmosphere emits molecular lines and a very broad thermal continuum. Finally thermal emission from the observer's instrument contributes significantly to the thermal continuum emission at wavelengths longer than a few μm [13]. Figures 1.1, 1.3 and 1.4 shows the transmission of Earth's atmosphere at near and mid-ir wavelengths.

1.3.1 The Near-Infrared Region

There are several windows in the Earth's atmosphere where we can make observations in the near-IR region. These windows are described by a set of filters as seen in Figure 1.1: J($1.25\mu\text{m}$), H($1.65\mu\text{m}$), K($2.2\mu\text{m}$), L($3.6\mu\text{m}$) and M($4.8\mu\text{m}$). The large gap seen in atmospheric transmission between 5 and 8 μm is due entirely to absorption by water vapour which partly accounts for the treatment of the near-infrared as a distinct spectral region.

Besides absorption by the atmosphere, a significant problem associated with near-IR observations is the blackbody thermal continuum emission which becomes important at $\lambda \geq 3\mu\text{m}$. This means that the radiation emitted by the telescope and water vapours is a strong background against which celestial bodies must be detected. As long as the detector noise is small, it is the photon shot noise associated with this background that is the principal source of noise in infrared observations; such observations are said to be background limited and one always wants the detectors to be so good that it is the background shot noise, rather than the approximately

constant detector noise, that dominates the observational noise. The infrared spectral region beyond $3\mu\text{m}$ where the background emission becomes so important is called thermal infrared. Because of the large thermal background and therefore the large associated photon shot noise, observations at thermal infrared wavelengths are generally much less sensitive than those at the wavelength range between 1 and $3\mu\text{m}$. It is partly for this reason that most of the near infrared observations are made in the J, H and K bands. Even though thermal infrared emission is rather weak in these three bands, OH lines emission produced by the atmosphere's interaction with the sunlight create a strong background against ground near infrared observations in the range between $1\mu\text{m}$ and $3\mu\text{m}$ (Figure 1.2).

1.3.2 The Mid-Infrared Region

As mentioned in §1.3, the mid-infrared region extends from 5 to $30\mu\text{m}$ which is the longest infrared wavelength observable from the ground. There are two bands in the mid-IR region where ground observations are feasible, the N and Q band filters, seen in Figures 1.3 and 1.4, spanning from $8\mu\text{m}$ to $14\mu\text{m}$ and $16\mu\text{m}$ to $25\mu\text{m}$ respectively. At higher and drier ground based observing sites, the atmosphere is somewhat transparent even out to $30\mu\text{m}$, as it can be seen in Figure 1.4 for the case of Mauna Kea.

Absorption in mid-IR is mainly attributed to CO_2 which causes a deep absorption in the $15\mu\text{m}$ while water vapour is responsible for the deep absorption near the $8\mu\text{m}$. Scale height for air and water is 8 and 3 km respectively. As a result the effect of the atmosphere can be reduced as much as possible by siting telescopes at high altitudes. On the other hand, OH lines which affect the $1\text{--}3\mu\text{m}$ observations originate at an altitude of 90 km and thus their influence cannot be reduced from even the highest ground based sites.

Just as in the case of the near-IR region, one of the major problems associated with ground observations in the mid-IR is the background-limiting problem. If the observations take place in the N band filter, the background noise is dominated by the telescope's thermal emission, while in the Q band filter it is dominated by the atmosphere's thermal emission.

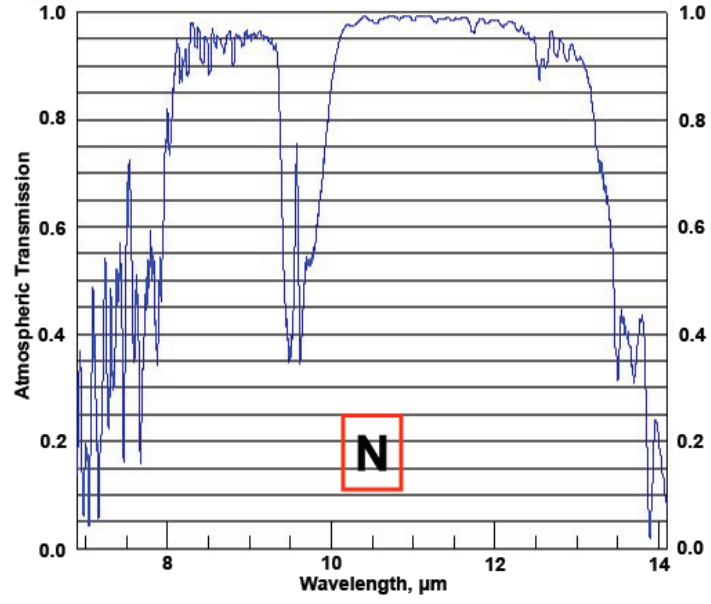


Figure 1.3: Atmospheric transmission for Mauna Kea in the mid-infrared spectral region between 7 and 14 μm [5]. N-band filter is labelled in the red box.

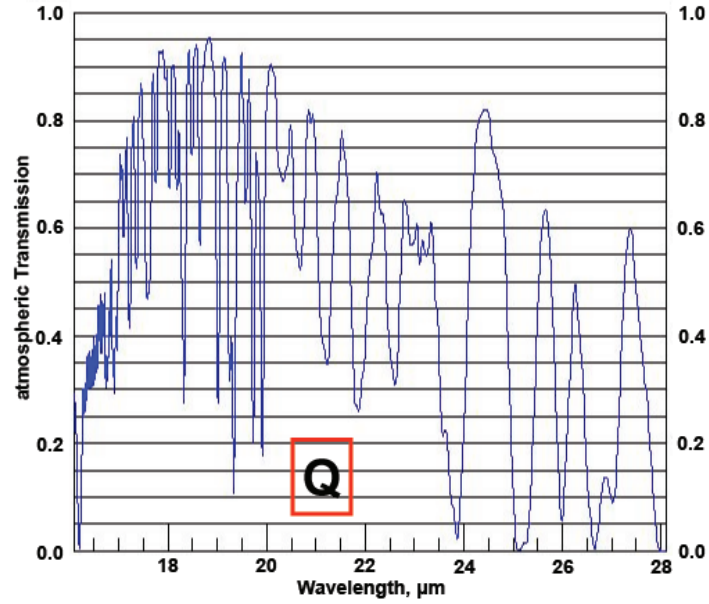


Figure 1.4: Atmospheric transmission for Mauna Kea in the mid-infrared spectral region between 15 and 28 μm [5]. Q-band filter is labelled in the red box.

1.3.3 The Far-Infrared Region

As mentioned before, the Earth's atmosphere is almost opaque over large wavelengths up to about $300\mu\text{m}$ and partially transparent in the submillimeter region. This means that in order to observe celestial sources in the far-IR, astronomers must get above as much of Earth's atmosphere as possible, using airplanes, balloons or space telescopes. The great advantage of the satellite missions is that they can be used in altitudes above the atmosphere's emission and absorption. In addition it is much easier to cool the instrument and, as a result, minimize the telescope's thermal emission. The sensitivity achieved in this way is much higher than any other ground observation in detecting infrared emission.

1.3.4 The Submillimeter Region

The primary source of millimeter-submillimeter opacity in the Earth's atmosphere is water. As a result, observations at submillimeter wavelengths are possible only in a number of atmospheric windows between 0.3mm and 2mm [205]. Under less favorable conditions with higher atmospheric water vapor content, transmission decreases and the high frequency windows effectively close. The deep absorptions are caused by highly pressure-broadened transitions of H_2O and CO_2 . The many small absorption features are primarily due to O_3 , although a few $O^{18}O$ lines are also present. The amount of atmospheric water vapor determines which transmission windows can be used profitably for observations. It is therefore very useful to monitor changing weather conditions in order to make appropriate decisions on filter selection and integration times.

1.4 Space-based Infrared Telescopes

Infrared instruments are concerned with achieving maximum sensitivity for the detection of faint signals such as distant galaxies. One of the major problems is how to exclude extraneous radiation so that only radiation of the desired wavelength and from the smallest possible area of the sky be collected by the detector. In addition, the latter has to be cooled to a low enough temperature so that its own thermal radiation is negligible. Finally in order for large-scale infrared surveys to be conducted efficiently, the atmosphere's absorption and thermal emission have to be absent. All of these handicaps can be solved with the use of space infrared telescope facilities. The ability to launch a small aperture telescope which could be cooled to very low temperatures provides us with the ability to observe the entire infrared region with-

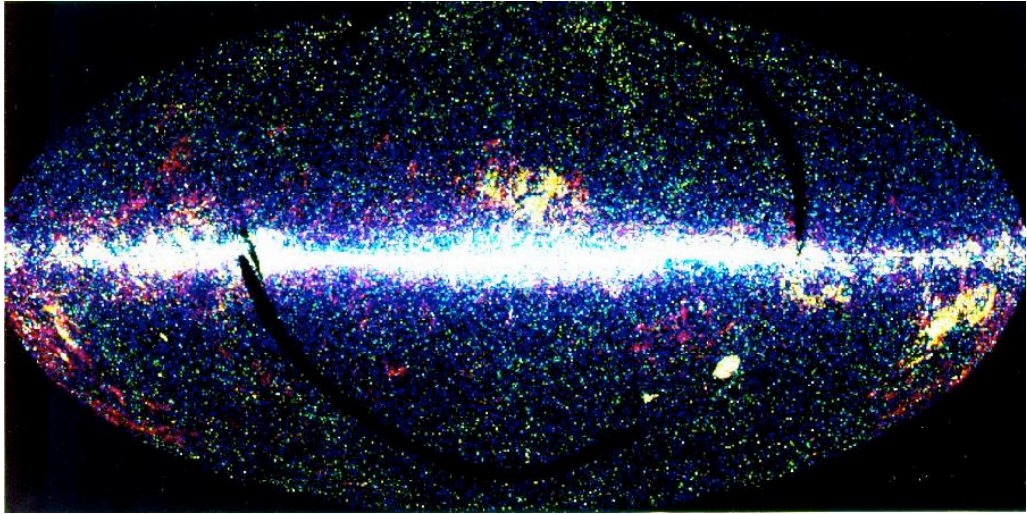


Figure 1.5: An image of infrared point sources in the entire sky as seen by the Infrared Astronomical Satellite (IRAS). The plane of our Galaxy runs horizontally across the image. Sources are color coded by their infrared colors. Blue sources are cool stars within our Galaxy, which show an obvious concentration to the galactic plane and center. Yellow-green sources are galaxies which are basically uniformly distributed across the sky, but show an enhancement along a great circle above the galactic plane. Reddish sources are cirrus sources. Image and caption from [4].

out having to face background noise problems. The most important space infrared telescopes missions IRAS, ISO, Akari, Herschel and their key results are outlined below while Spitzer which has played a central role in this thesis is described in more detail in Chapter 2.

1.4.1 IRAS

IRAS [242] was the first space-based cryogenically cooled long life Infrared telescope. It was launched on the 26th January 1983 on a NASA Delta 3910 launch vehicle into a 900km near-polar orbit. After launch IRAS surveyed over 96% of the sky with a completeness limit of 0.5Jy at 12, 25 and 60 μ m and 1.5Jy at 100 μ m until its Helium supplies were exhausted on 21st November 1983. IRAS was equipped with a 0.57m Ritchey-Chretien telescope cooled to less than 10K. The telescope focused radiation onto three instruments; the main IRAS survey instrument [39][16]; the Low Resolution Spectrometer [355][356] and the Chopped Photometric Channel [355][356]. LRS was a slitless spectrometer with a wavelength range from 7.5 to 23 μ m. CPC was operated during selected pointed observations between 50 and 100 μ m. The IRAS all sky survey catalogued around 350,000 infrared sources (Figure 1.5) and resulted in

the recognition of entirely new phenomena not only in our Galaxy and Solar System [30] but also on larger scales [319].

IRAS features that made it useful for cosmological studies were the uniformity in completeness, reliability, calibration and lack of extinction. Rowan–Robinson et al [295] found a 20% excess in the differential number counts for $60\mu\text{m}$ sources in the northern cap over the southern cap. This anisotropy was used to identify the material responsible for the acceleration of the Local Group with respect to the microwave background [358][231]. From these results an estimate of $0.5 < \Omega_{tot} < 1$ was made. Efforts were made to determine the magnitude of a uniform $100\mu\text{m}$ background by Hauser et al [140] and Rowan–Robinson [277]. If this background was due to starburst galaxies and not due to the instrument itself it would imply a significant evolution in the luminosity function for the starbursts. Hacking et al [132] found an excess of sources at the lowest flux levels which could only be fitted by a model with pure luminosity evolution. Helou et al [144] predicted that more than 10% of the radio counts in the range of $100\mu\text{Jy}$ are due to starburst galaxies. Finally Weedman & Williams [350] speculated that the fall off in the optical source counts at redshifts greater than three is due to the extinction produced by the dust in galaxies.

IRAS surveys opened the realm of the Infrared Extragalactic Astrophysics. Almost 25,000 galaxies were detected, about half of which had never been observed before [302]. The vast majority of these sources are late type spiral galaxies and quasars [300], Seyfert galaxies [70] and early type galaxies [182]. Elliptical and SO galaxies were rarely detected [131]. De Jong et al [71] reported that the vast majority of these objects were modest infrared emitters since no object with $L_{IR} > 10^{11} L_{\odot}$ was found. Extreme infrared properties were revealed by Soifer et al [320] who found that a complete flux-limited sample of 86 galaxies from the mini-survey [287] had $L_{IR} > 10^{10} L_{\odot}$. This new class of galaxies, which was going to be known as Luminous Infrared Galaxies (LIRG), was soon superseded by another class of infrared galaxies known as Ultraluminous Infrared Galaxies [299]. IRAS 09104 + 4109 was observed at a redshift of 0.442 and it was estimated that it emitted almost $6 \times 10^{11} L_{\odot}$ in Infrared. A few years later an even more luminous Infrared galaxy was observed. Rowan–Robinson et al ([286]) found a new class of Infrared galaxies that emitted the enormous far-IR luminosity of $3 \times 10^{14} L_{\odot}$ at a redshift of 2.286 which were named Hyperluminous Infrared galaxies ([280]).

In order to understand the properties of infrared galaxies, the determination of

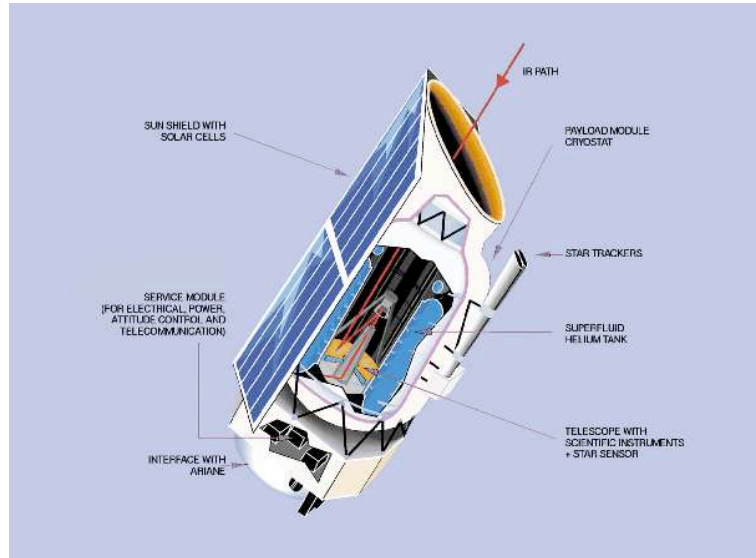


Figure 1.6: ISO spacecraft [174].

redshifts for large unbiased samples of infrared sources is required. For this reason a great number of full sky and small area surveys took place [345][296][107][177][304]. These surveys revealed that even though the majority of optically selected objects are weak far-IR emitters [158] ULIRGs are almost two times more numerous than optically selected QSOs [178]. In addition it became clear that strong interactions and mergers of gas rich spirals are responsible for luminous infrared galaxies and that starbursts generated a substantial fraction of the infrared luminosity during the early phases of the interaction [190] while AGN contribute almost 30% of the total luminosity. It was also shown that 30% of the infrared luminosity between 8 and $1000\mu\text{m}$ is generated by late type stars and that emission between 8 and $40\mu\text{m}$ is dominated by emission from small grains [318]. IRAS changed the way the extragalactic sky was studied, from the study of a small number of sources to the study of large samples, but most importantly demonstrated the significance of the Infrared spectral region in understanding galaxy evolution and star formation history and was instrumental in driving more recent infrared space astronomy missions such as ISO, Spitzer, AKARI and Herschel.

1.4.2 ISO

The Infrared Space Observatory [173] was developed by ESA in collaboration with NASA and ISAS. ISO, which was first proposed to ESA in 1979, was launched with ESA's Ariane-44P launch vehicle on 16th November 1995 into a highly eccentric

orbit with an apogee height of 70600km and a perigee height of 1000km. After a three-month verification and calibration phase, ISO took 26450 observations until its on board helium was completely consumed on April 1998 after 28 months of continuous operation. ISO's design resembles that of IRAS, consisting of a 60cm diameter aplanatic Ritchey–Chretien system cooled by superfluid liquid helium to temperatures of 2–4K.

1.4.2.1 Instruments

ISO, seen in Figure 1.6, was equipped with four instruments: two spectrometers, one camera and a spectrophotopolarimeter. Although the four instruments were developed separately they were designed to form a complete, complementary and versatile common-user package. This package provided photometry and imaging in the range between 2.5 and $240\mu\text{m}$ and full spectroscopy between 2.5 and $200\mu\text{m}$. The four instruments were:

ISOPHOT [202] was a spectrophotopolarimeter equipped with two cameras, a polarimeter and a spectrometer which allowed it to cover the largest wavelength range on ISO from 2.5 to $240\mu\text{m}$. More specifically it was able to perform low-resolution spectrometry between 2.5 and $12\mu\text{m}$, multi-wavelength and multi-aperture polarimetry between 3 and $120\mu\text{m}$ and imaging between 50 and $240\mu\text{m}$. Particular strengths of the instrument included the detectability of very cold sources, high resolution mapping and fast spectrophotometry.

ISOCAM [51] was a near-IR and mid-IR camera which took images of the sky in the wavelength range 2.5 to $18\mu\text{m}$. It featured two independent channels: the short wavelength channel, 2.5 to $5.5\mu\text{m}$, and the long wavelength channel, 4 to $18\mu\text{m}$. Compared to IRAS, the space resolution was improved by a factor of 50 and sensitivity by a factor of 1000. These new capabilities revealed the prevalence of hidden star formation in nearby and, even more, in distant regions of the universe.

SWS [68] was a short wavelength spectrometer which covered the wavelength range of 2.38– $45.2\mu\text{m}$ with a spectral resolution ranging from 1000-2500. By inserting Fabry-Perot filters the resolution was enhanced by a factor 10 to 20, for the wavelength range from 11.4- $44.5\mu\text{m}$.

LWS [58] was a long wavelength spectrometer which operated over the wavelength range 43– $196.9\mu\text{m}$ at either medium (about 150 to 200) or high (8000 to 10000)

spectral resolving power.

1.4.2.2 ISO Extragalactic Surveys

The ISOCAM Guaranteed Time (GTO) Extragalactic Surveys: Five extragalactic surveys were performed with two of the most sensitive ISOCAM filters, LW2 ($5\text{--}8.5\mu\text{m}$) and LW3 ($12\text{--}18\mu\text{m}$) including large area shallow surveys and small area deep field integrations. In order to reduce the effect of large scale structures two of them were carried out in the Lockman Hole and three in the southern field which covered a total of 1.5 square degrees and detected over 1000 sources [335][168][264][89]. These regions were selected for their low zodiacal and cirrus emission and because of the existence of data at other wavelengths.

The two Hubble Fields Observations by ISOCAM: These surveys of almost 50 square arcmin at $6.7\mu\text{m}$ and $15\mu\text{m}$ of the North and South Hubble Deep Fields aimed at characterizing the SEDs of distant and high-redshift galaxies. They achieved a completeness to a limiting flux of $100\mu\text{Jy}$ at $15\mu\text{m}$. These surveys allowed to discover luminous infrared galaxies up to redshift of $z = 1.5$ [292], provided detailed morphological information for the galaxies observed by ISO at any redshift, allowed a detailed characterization of distant IR sources [60] and concluded that more than half sources at $z > 0.4$ are either irregular or mergers.

The ISOCAM survey of the two CFRS fields: Two fields in the Canada-France redshift survey [206] were observed to intermediate depths at 6.7 and $15\mu\text{m}$ and twice as deep at $15\mu\text{m}$. This survey provided an insight into the nature of the galaxies detected by ISOCAM [108].

FIRBACK survey: ISOPHOT FIRBACK survey [264] aimed at detecting at $175\mu\text{m}$ far-IR background sources in the Marano field and also in the ELAIS-N1 and N2 fields. FIRBACK detected 300 sources which were later studied by SCUBA and IRAM in an effort to provide constraints on the redshifts of these sources which would otherwise be difficult to measure in the optical.

Lensing Cluster surveys: This was an ultradeep ISOCAM survey [12] through three lensing galaxy clusters at 7 and $15\mu\text{m}$ which revealed a large number of luminous Mid-Infrared sources and showed that about half of the $7\mu\text{m}$ sources are cluster galaxies and the rest are lensed distant galaxies.

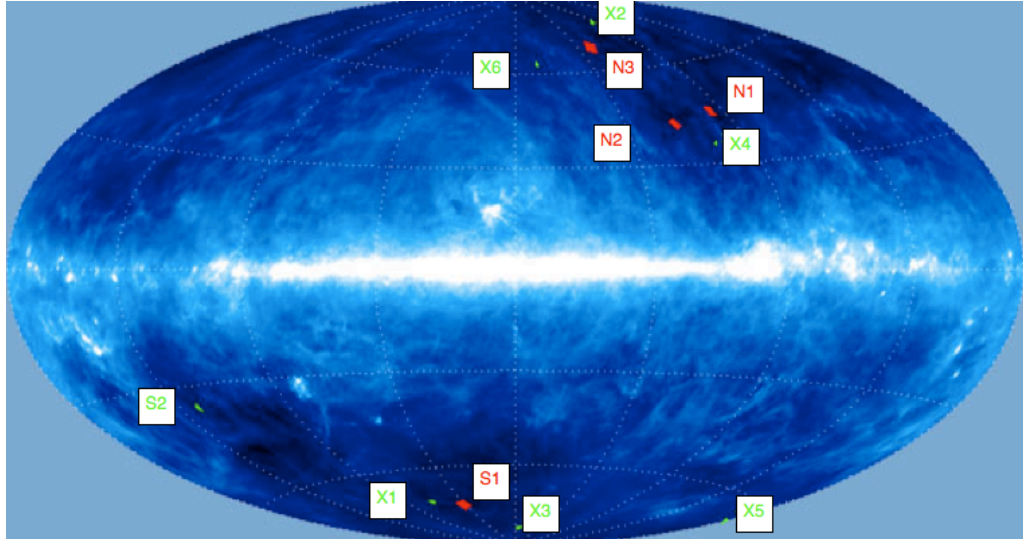


Figure 1.7: The location of the ELAIS survey fields overlaid on a Hammer-Aitoff equal projection of the COBE normalized IRAS maps [308]. Image and caption from [245].

The Japanese Guaranteed Time survey: This ultra deep Lockman survey revealed heavily reddened populations and galaxies at intermediate redshifts [335].

PHOT Serendipitous Survey: The Serendipity Survey [329] filled the time between ISO's fine pointings with measurements near $200\mu\text{m}$. A total of 21 IRAS point sources were detected. 19 of these objects are galaxies, one is a planetary nebula and one is an empty field without a bright optical counterpart. Almost 15% of the sky was observed with a 50% completeness for sources brighter than 1.5Jy.

CAM Parallel Survey: The CAM survey [313] was performed at $6.7\mu\text{m}$ using the ISOCAM infrared camera in its parallel mode at $\sim 6''$ resolution down to a limiting flux of 5mJy and detected a total of 287 objects covering a total of 33 square degrees.

ELAIS: ELAIS [291] was the most important program in the ISO open time proposals, with 377 hours awarded [294]. ELAIS covered almost 12 square degrees of the sky at $15\mu\text{m}$ and $90\mu\text{m}$, 7 square degrees at $6.7\mu\text{m}$ and 1 square degree at $175\mu\text{m}$. To reduce the effects of cosmic variance, the survey area was split into three main fields in the north, one main field in the south and six smaller fields. Preliminary analysis of the ELAIS source lists found more than 1000 sources at 15 and $90\mu\text{m}$. Both $90\mu\text{m}$ source count models [81] and integrated number count models implied strong luminosity and density evolution in both bright normal spirals and

starburst galaxies with varying AGN contributions. This analysis was performed using the CAM Interactive Analysis [247] for the 15 μm sample. The 90 μm data were reduced by using the PHOT Interactive Analysis [114]. This extensive multi-wavelength coverage provided the best studied sky areas of their size and natural targets for future surveys. ELAIS survey revealed that although the largest single population is relatively nearby cirrus galaxies, a large percentage ($\sim 15\%$) of the 15 μm population are ULIRG ($\log_{10}$ of 1–1000 μm luminosity $L_{IR} > 12.2$), many of them highly obscured Arp220-like starbursts. This implies very strong evolution in the star formation rates in $z < 1$. In addition ELAIS revealed that a significant population of galaxies are luminous cool galaxies ($\log_{10}$ of 1–1000 μm luminosity $L_{IR} > 11.5$), consistent with the idea that the quiescent component of star formation in galaxies undergoes the same evolution as the starburst component. The small proportion of optically blank fields to $r'=24$ are identified as high luminosity dusty starbursts or Type 2 AGN since they appear to have high infrared-to-optical ratios, high infrared luminosities and are located at higher redshifts ($z > 0.6$). The survey revealed the existence of nine hyperluminous infrared galaxies ($\log_{10}$ of 1–1000 μm luminosity $L_{IR} > 13.22$) and nine extremely red objects interpreted as ultraluminous dusty infrared galaxies that lie at $z \sim 1$.

1.4.3 AKARI

1.4.3.1 Science Mission and Objectives

AKARI [251], previously known as ASTRO-F and Infra-Red Imaging Surveyor (IRIS), was launched on February 21, 2006 with ISAS's (Japanese Institute of Space and Astronautical Science) M-V launch vehicle, into a sun-synchronous polar orbit with an altitude of 750 km. AKARI will perform the first survey of the entire sky at infrared wavelengths since the IRAS mission. The AKARI project is run by the ISAS in collaboration with other Japanese institutions, Seoul National University in Korea, Imperial College London, University of Kent, Sussex University in the United Kingdom and the Space Research Organization of the Netherlands (SRON) with the Kapteyn Astronomical Institute and the ESA.

AKARI's infrared telescope is a 67cm diameter silicon carbide Ritchey-Chretien telescope. The telescope is cooled to 5.8K by liquid Helium in order to reduce the instrumental thermal emission [165]. The mission's lifetime is estimated to be more than 550 days. This is achieved by maintaining the temperature of the cryostat's outer wall below 200K which will double the lifetime of the Helium.

The key scientific goals of AKARI are:

- To investigate the galaxy formation history in the distant Universe. Several millions of galaxies will be detected in more than two far-IR bands. Their dust temperature and mass will be derived by using already known redshift values. Dust temperature determines in the best way the strength of the radiation field of a galaxy while dust mass is the best measure of heavy element contents of a galaxy. The strength and compactness of a starburst region can be derived by using the total far-IR luminosity and dust temperature respectively. In addition the complete near-IR and mid-IR SEDs that will be obtained for a great number of galaxies using the nine wide-band channels will detect highly reddened galaxies and highly-redshifted galaxies.
- To investigate the history of proto-planetary disks by searching for weak-line T-Tauri stars not only in Taurus molecular cloud but also in more distant clouds. The circumstellar disk evolution of pre-main sequence stars of medium mass will be investigated as well as a large number of minor bodies of our solar system such as asteroids, comets and Kuiper belt objects.
- To detect faint far-IR sources powered by pre-main sequence stars in dense molecular clouds. Many of these objects are associated with molecular cores containing high density gas. IRAS detected such point sources which indicate newly-born stars in their parental molecular cores but ASTRO-F will be able to detect much fainter far-IR sources. These results will be able to reveal the true timing of firing the stars.
- To obtain photometric maps in all bands and low-resolution spectroscopic data of both ecliptic pole regions which will allow us to monitor the variability of AGNs in these regions.
- To obtain complete NIR, MIR and FIR maps of almost 20 square degrees of both the Large and Small Magellanic Clouds. This surveys will reveal the nature of star formation, cluster formation and galaxy evolution in this galaxy with rather low heavy-element abundance.

1.4.3.2 Focal Plane Instruments

AKARI incorporates two focal plane instruments, the Far-Infrared Surveyor (FIS) and the Infrared Camera (IRC), which will cover a wide range of the Infrared Spectral region spanning from $2\mu\text{m}$ to $200\mu\text{m}$.

FIS uses two high sensitivity detector arrays which will survey the entire sky in four far-IR bands from $50\mu\text{m}$ to $200\mu\text{m}$ and with angular resolutions of 30–50 arc-sec [334]. FIS also incorporates a Fourier-transform spectrometer mode that will allow imaging spectroscopy of selected sources with a resolution of almost 0.2cm^{-1} .

IRC is equipped with three cameras each with three filters. IRC employs large format detector arrays which will take deep images of selected sky regions at near-IR and mid-IR. Typical angular resolutions of $\sim 10''$ are expected.

In comparison with previous space-borne telescopes, AKARI has more than 1000 times higher sensitivity in mid-IR wavelengths. In addition it offers four times the resolution of ISO over a much wider area even when compared to SPITZER.

1.4.4 HERSCHEL

1.4.4.1 Science Mission and Objectives

The Herschel Space Observatory [257], formerly known as FIRST, is the fourth cornerstone mission in ESA's longterm science program plan, "Horizon 2000". Herschel is a multi user observatory type mission intended to open the far-IR and submillimeter part of the spectral region by being able to cover approximately the 57 to $670\mu\text{m}$ range. Herschel is scheduled to be launched with ESA's Ariane-5 launch vehicle which will carry Herschel into a transfer trajectory towards the second Lagrangian point in the Sun-Earth system, located 1.5×10^6 km beyond Earth's orbit around the Sun. From there it will carry out observations with its 3.5m silicon carbide Cassegrain telescope which will have a wavefront error of less than $6\mu\text{m}$ and which will be passively cooled to a temperature as low as 80K. The mission will have a predicted operational lifetime of 3 to 4.5 years.

The science objectives of the mission have been discussed in several major symposia. Herschel's ability to perform unbiased photometric surveys and medium and high resolution spectroscopic follow-up observations of selected objects will provide a deeper understanding in the following areas:

- Deep galactic and extragalactic broadband photometric surveys in the 100– $600\mu\text{m}$ Herschel prime wavelength band and related research. The main goals will be detailed investigations of the formation and evolution of galaxy bulges

and elliptical galaxies in the first third of the present age of the Universe and star formation in the galaxy.

- Follow-up spectroscopy of especially interesting objects discovered in the surveys. The far-IR/submillimeter band contains the brightest cooling lines of interstellar gas, which give very important information on the physical processes and energy production mechanisms such as AGN and star formation in galaxies.
- Detailed studies of the physics and chemistry of the interstellar medium, both locally in our own galaxy as well as in external galaxies, by means of photometric and spectroscopic surveys and detailed observations. This includes implicitly the important question of how stars form out of molecular clouds in various environments.
- Observational astrochemistry of gas and dust as a quantitative tool for understanding the stellar and interstellar lifecycle and investigating the physical and chemical processes involved in star formation and early stellar evolution in our own galaxy. Herschel will provide information on most phases of this lifecycle.
- High resolution spectroscopy of a number of comets and the atmospheres of the cool outer planets and their satellites.

1.4.4.2 Scientific Instruments

Herschel is equipped with three instruments; the Heterodyne Instrument for the Far Infrared (HIFI), the Spectral and Photometric Imaging Receiver (SPIRE) and the Photodetector Array Camera and Spectrometer (PACS).

HIFI [69] is a single-pixel, high-resolution heterodyne spectrometer. The instrument comprises of 5 frequency bands covering 480-150 GHz and a sixth dual-band for the 1410-1910 GHz range. The instantaneous frequency coverage is 4 GHz. One frequency band is operated at a time. The noise performance of the instrument is near-quantum noise limited. Because of its high spectral resolution and wide frequency coverage, HIFI is expected to help us investigate comets, planetary-satellite atmospheres, star formation and galactic nuclei.

SPIRE [128] contains a three-band imaging photometer operating at 250, 360

and $520\mu\text{m}$, and an imaging Fourier Transform Spectrometer (FTS) covering $200\text{--}670\mu\text{m}$. The photometer field of view of SPIRE is $4'\times 8'$, observed simultaneously in all the three bands. A beam steering mirror allows spatial modulation of the telescope beam and will be used to produce fully-sampled images. Observations can also be made by scanning the telescope without chopping. The spectral resolution can be adjusted between 0.04 and 2 cm^{-1} . SPIRE will be of great help in investigating the far-Infrared components of star-formation history in high redshifts, infrared luminous objects, obscured AGNs at high redshifts and the large-scale structure and environments of star-forming galaxies.

PACS [259] employs two Ge:Ga photoconductor arrays with 16×25 pixels, each, and two filled Si bolometer arrays with 16×32 and 32×64 pixels, respectively, to perform imaging line spectroscopy and imaging photometry in the $57\text{--}210\mu\text{m}$ wavelength band. In photometry mode, it will simultaneously image two bands, $60\text{--}85\mu\text{m}$ or $85\text{--}130\mu\text{m}$ and $130\text{--}210\mu\text{m}$, over a field of view of about $1.75'\times 3.5'$, with full beam sampling in each band. In spectroscopy mode, it will image a field of about $50''\times 50''$, resolved into 5×5 pixels, with an instantaneous spectral coverage of almost $600\text{--}2500\text{ km/s}$ and a spectral resolution of approximately $75\text{--}300\text{ km/s}$. In both modes background noise is expected to be limited.

1.5 Origin of Extragalactic Infrared Emission

Infrared continuum emission can either be free–free, bound–free from low density gas or from stellar photospheres, synchrotron (non–thermal) which originates in more exotic objects such as Active Galactic Nuclei (AGN) or thermal emission from dust. As it can be seen from Figure 1.8 from Telesco [337], which shows the spectral energy distribution of the galaxy continuum emission, stars, especially red ones are bright at wavelengths shorter than $5\mu\text{m}$ while dust emission is characterized by a broad bump with the maximum flux density occurring somewhere between 10 and $250\mu\text{m}$. Hot dust is often detected in K but is usually weak in J and H. For most infrared sources, the broad bump emission resembles a blackbody emission modified by a wavelength–dependent emission efficiency of the form λ^n where n usually varies between -1 and -2 . Infrared emission in excess of this blackbody on the short wavelength side of the bump is usually present and indicates that there is dust at temperatures higher than that characterizing most of the bump. Dust components and major infrared emission and absorption mechanisms are described in more detail below.

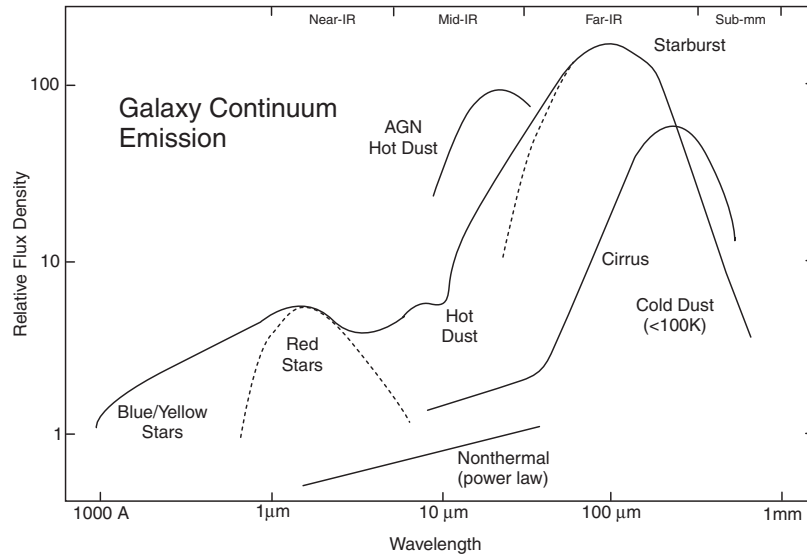


Figure 1.8: SED of a galaxy showing the different infrared emission generators in different types of extragalactic sources such as cirrus, starburst and AGN [337].

Dust: One of the most important results of the IRAS maps at 60 and 100 μm was the discovery that the sky at high galactic latitudes is covered by structures that look like Earth's cirrus clouds. Infrared cirrus which is more evident at 60 and 100 μm but also at 12 and 25 μm is believed to be due to dust grains in the otherwise cool (15–30 K), diffuse atomic hydrogen clouds that have been warmed slightly by ultraviolet light from nearby stars. Emission from dust in external galaxies is quite cool and its emission is only observable in the far-IR. Normal spiral galaxies show evidence for a cool dust which peaks around 150 μm . Towards the bulges of spiral galaxies there is an enhancement of emission between 40 and 120 μm similar to the enhancement in emission observed in the disks of this class of galaxies. The difference is that enhancement in the emission in the disks originates from a warm dust component, while in the bulges it is due to interstellar radiation arising from the greater density of stars. Starburst galaxies [235] show an enhancement in mid-IR emission due to the heating from HII regions populated by early type stars. Finally AGN show excess radiation in the near-IR and mid-IR. Near-IR component is usually variable and its origin is believed to originate from synchrotron radiation and the existence of dust with temperature near 1500 K .

PAH: Polycyclic Aromatic Hydrocarbons are large molecules containing more than fifty atoms [265]. CC and CH stretching and bending of PAHs have been the

favourite explanation for a family of infrared bands centered at 3.3, 6.2, 7.7, 8.6 and 11.3 μm which contribute to the diffuse emission from the disk of the galaxy [228] and which are observed in planetary nebulae, HII regions, nebulae around early type stars and in galaxies. Duley & Williams [77] pointed out that these infrared bands might also be originated by hydrogenated amorphous graphitic particles. PAH spectra are only seen in emission and it is believed that they are excited by the absorption of single energetic photons [117].

Silicon Compounds: SiO stretching and OSiO bending can be seen at 9.7 μm and 18.5 μm respectively, in M stars, planetary nebulae and in absorption in the interstellar medium. SiC can be seen at 11.2 μm in emission in red giants. Amorphous silicate material can also be seen at 9.7 μm and 18 μm [353] while crystalline silicates give rise to features seen between 20 and 45 μm [338].

Interstellar Medium: Interstellar medium is characterised according to its density. According to Whittet [354] interstellar medium is classified to hot, warm, cool and cold. Hot interstellar medium which occupies most space in galaxies is hot ionized matter at very low densities ($n \sim 5 \times 10^{-3} \text{ cm}^{-3}$) that is heated to very high temperatures ($\sim 5 \times 10^5 \text{ K}$) by the interstellar radiation field. Hot interstellar medium causes little extinction and allows ionizing radiation, such as far-UV and X-ray, to pass through with little extinction. The highest density regions of the hot interstellar medium ($n \sim 3 \times 10^{-1} \text{ cm}^{-3}$) with temperatures of order 10^5 K are known as the warm interstellar medium. These regions remain transparent enough for the interior to be heated by photons from the hot ISM. When density reaches to $10^{-1} - 10^{-2} \text{ cm}^{-3}$ the center of the cool ISM cloud, that now has a characteristic temperature of 80K, may contain unionized atomic H and dust but molecules will have short lifetimes against dissociation. Substances that survive easily are silicates with strong signatures at 9.7 and 18.8 μm , H_2O and CH- compounds with signatures at 3 and 3.4 μm . At higher densities ($n > 10^2 \text{ cm}^{-3}$), the cloud cores are shielded from all high energy radiation and molecules are abundant. The temperature of these dense clouds, which are called cold ISM, are typically 15K. Strong spectral features of cold ISM are absorption lines arising from H_2O , CO_2 and CO .

Stellar Atmospheres: Stars cooler than AO exhibit a broad bump around 1.6 μm . A number of atomic absorption lines in late type stars and dwarf stars can be seen in the range between 2 and 2.5 μm [10]. K and later type stars are affected strongly by CO_2 in 1.65, 2.3 and 4.7 μm [33] while in M type stars, H_2O absorption

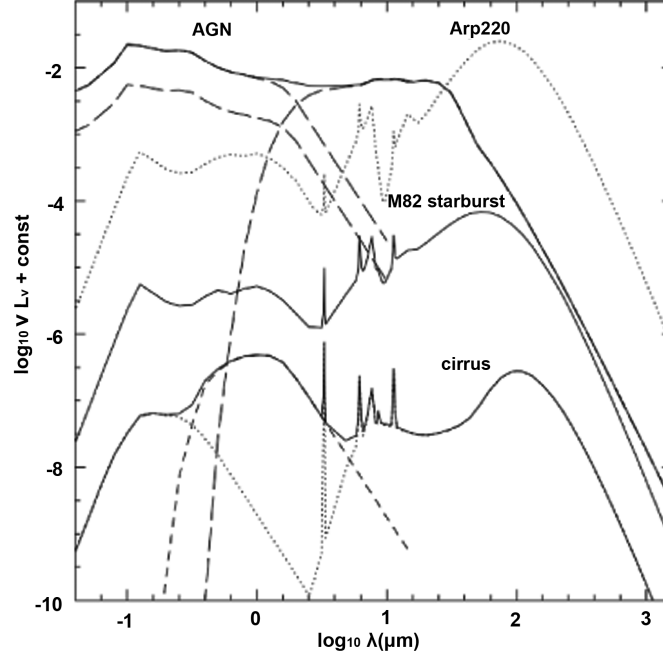


Figure 1.9: Adopted spectral energy distributions from Rowan Robinson [281]. Cirrus, with optical emission split into low-mass (dashed curve) and high mass (dotted curve) stars, M82 starburst, Arp220 starburst and AGN dust torus.

dominates the near-IR region [164]. Features due to SiO are observed at 4.1 and 7.9 μm and affect strongly G, K and M type stars. In the case of red and brown dwarfs, H_2 collision induced absorption takes place between 0.7 and 40 μm [203]. Near-IR spectrum of brown dwarfs is dominated by deep methane and water vapour absorption. Cool carbon stars exhibit absorption bands around 3.1 and 5 μm while at longer wavelengths there is a SiC feature at 11.2 and 30 μm and an absorption band at 13.7 μm due to CH bending.

Zodiacal Light: The dominant source of diffuse background in the near and mid-ir regions is the so called zodiacal light. This arises from interplanetary dust which scatters sunlight in the optical and near-ir, but which emits thermally in the near infrared. The spectrum of the zodiacal light in the mid-ir is featureless and corresponds to a temperature of 261 ± 1.5 K. The zodiacal light consists of slowly varying diffuse emission which is brightest in the plane of the ecliptic.

1.5.1 Infrared Source Components

Infrared emission from an extragalactic source is usually modelled by using various key ingredients in order to recreate the observed SED of each source, such as interstellar dust grains [79], an assumed density distribution for the dust [84], spherical symmetry of the dust [316], spherically symmetric radiative transfer codes [82] and source components. Rowan–Robinson & Crawford [288] utilised a cirrus SED, a starburst and an AGN dust torus and later on Rowan–Robinson [281] extended this model to include four spectral components: an infrared cirrus, an M82–like starburst, an Arp 220–like starburst and an AGN dust torus while Efstathiou et al [84] extended earlier models by Rowan–Robinson & Efstathiou [289] and Siebenmorgen & Krugel model [315] by including a full treatment of the evolution of star-forming regions as well as a detailed model for PAHs. Each of these components, shown in Figure 1.9 [281], is described below. An emphasis is given to their infrared, X-ray and optical properties where applicable.

1.5.1.1 Infrared Cirrus

Low et al [212] found that the infrared sky as seen by IRAS exhibits thermal emission from dust both within our solar system and the Galaxy. He characterised these highly structured extended sources observed predominantly, but not exclusively, at 60 and 100 μm , as infrared cirrus.

Infrared cirrus originates from the absorption of the general starlight of a galaxy by interstellar dust in neutral hydrogen clouds and then re-emitted in the infrared region. Rowan–Robinson [278] presented models for the interstellar grains and cirrus which gave good fit to the interstellar extinction curve and to the far-IR emission from dust clouds at high Galactic latitudes. The deficiency of these models was that very small grains, which are responsible for the excess in mid-IR [196], were not included. Their tiny size and low heat capacity produces temperature fluctuations which result in colour temperatures much higher than the time averaged temperature of the grain material.

Siebenmorgen, Krugel & Laureijs [314] presented models that include a cirrus component and which take into account the distribution of stars and dust in galaxies, changes in metallicity during the lifetime of galaxies and incorporated population synthesis models. Efstathiou & Rowan–Robinson [83] presented a model that represents precisely the observed SEDs of nearby normal galaxies. In order to produce a

cirrus model the ingredients needed are the input stellar radiation field, characterised by its spectrum and intensity, an interstellar dust model with an assumption about its distribution and opacity and a radiative transfer treatment of the interaction between the two to generate the SED.

1.5.1.2 Starbursts

One of the major discoveries of IRAS was galaxies undergoing massive bursts of star formation. Starbursts, which are usually irregulars or spirals, emit mainly in the infrared due to the fact that UV light from young stars is absorbed by dust and re-radiated at infrared wavelengths. There are two proposed explanations for the gas inflow that can cause star formation: interactions or mergers of gas rich galaxies [146] and bar-driven inflow of gas in spiral galaxies [149]. Even though there is no exact quantitative definition of what constitutes a starburst galaxy the definition given by Larson & Tinsley [186], which characterizes as a starburst a galaxy that undergoes a massive burst in star-formation of duration $\sim 10^{7-8}$ years, involving as much as 5% of the total stellar mass, is widely accepted.

Even though starbursts last $\sim 10^7$ years [270] they constitute a very important class of objects locally, since ~ 25 % of the mass formation within $10\ Mpc$ takes place in four galaxies [143]. ISO surveys were a great contributor in increasing our understanding of starbursts. They made possible to distinguish, both qualitatively and quantitatively, starburst galaxies and dust-enshrouded AGNs and confirmed that infrared luminous starbursts have low nebular excitation due to episodic and rapid aging [120]. In addition ISOCAM surveys confirmed that starbursts can be driven by mergers, interactions and bar-driven inflow of gas [53]. Two archetypal starbursts are M82 and Arp220.

The near-infrared continuum of starburst galaxies is dominated by photospheric radiation from red giant stars, with smaller detectable contributions often arising from ionised gas, very hot dust and blue stars. Moving to the medium infrared, the continuum begins to rise with increasing wavelength, as the reradiated emission from hot dust becomes more important. The slope of the rise depends on the star-formation intensity. As it can be seen in Figure 1.8, the flux density of a pure starburst reaches maximum at $\sim 80\ \mu m$ and falls rapidly after $100\ \mu m$.

X-ray emission in pure star-forming galaxies can be described by a soft thermal component with temperatures lower than 2 keV dominating below 1 keV and a hard

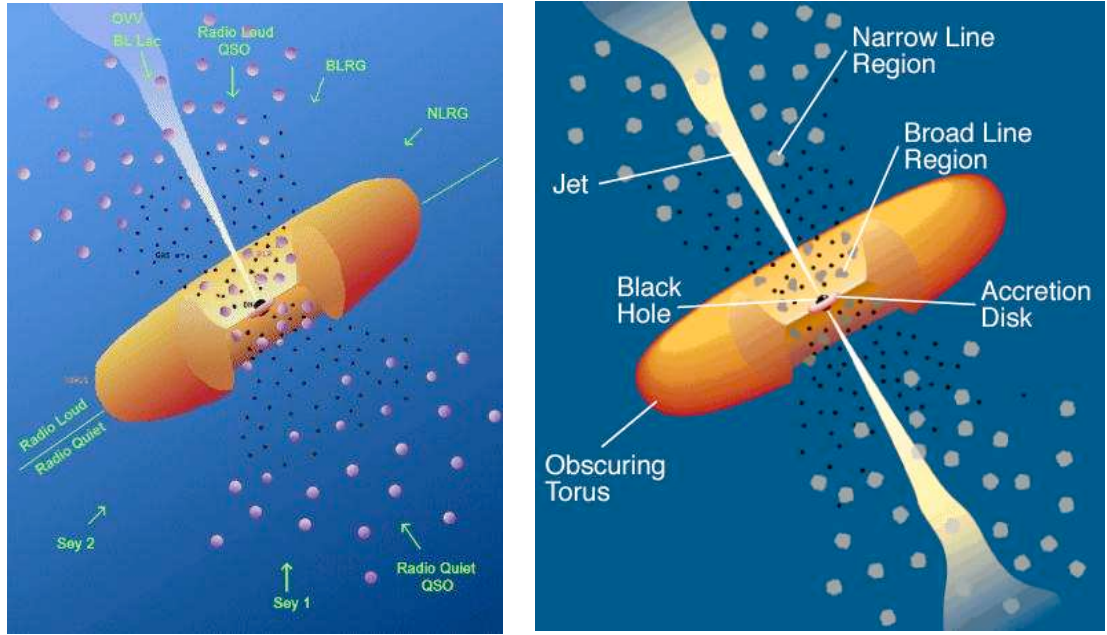


Figure 1.10: AGN classification according to the viewing angle (left) and AGN's main constituents (right) [344].

component which dominates between 2 and 10 keV and is described by a power law with photon index $\Gamma \sim 1.2$ or a characteristic temperature $kT > 5$ keV [253]. Soft emission is associated with the boundary region between the fast supernovae and stellar wind driven outflows and the cooler, denser interstellar medium not with the wind itself [330]. This is because kinetic energy from supernovae and stars contribute to the heating of interstellar medium causing soft thermal x-ray emission from the diffuse gas at temperatures between 0.5 and 2 keV. This emission is extended and can show plumes or outflows from the central starburst. Hard component luminosity is consistent with emission produced from high mass x-ray binaries [208].

A large fraction of starbursts appear to belong to the intriguing population of ultra luminous X-ray sources (ULX) with X-ray luminosities, $L_X > 10^{39} \text{ erg s}^{-1}$ [332], associated with young stellar populations. These sources, which can dominate the emission from galaxies, are usually compact, point sources that are seen offset from the nucleus in starbursts and ellipticals.

1.5.1.3 AGN

The term AGN (Active Galactic Nuclei) refers to galaxies in which a significant fraction of the energy output is not emitted by normal components such as stars, dust

and interstellar gas [255]. It is believed that they are all powered by the accretion of matter onto a supermassive black hole [267] and the differences between classes of AGN are due to the different orientation relative to the line of sight [276][14] (Figure 1.10). AGN can be divided into many subclasses such as Seyferts, quasars, radio-loud, radio-quiet, Type 1, Type 2 etc [324]. According to the AGN unification models (Figure 1.10), these subclasses arise due to the viewing angle and the AGN is modelled as a central black hole surrounded by an accretion disk which is in turn surrounded by a dust torus. Accretion of matter onto the black hole causes emission of radiation across the spectral region which is absorbed by the dust torus (especially the UV and X-rays) and re-radiated in the infrared. Both broad and narrow optical-UV emission lines can be observed in AGN. Broad lines are due to the existence of relativistic gas clouds between the accretion disk and the torus (e.g. Type 1s) while narrow lines are due to gas clouds beyond the dust torus that move with low velocities (e.g. Type 2s). The strongest observed broad lines are the hydrogen Balmer lines, $H\alpha$, $H\beta$, H, Lyman- α and abundant ion lines such as MgII [255]. Prominent narrow lines in Type-2 AGN are OII, OIII and CIV [255]. Emission from AGN-heated thick tori dominate the mid-IR emission of quasars, radio and Seyfert galaxies while the far-IR emission of many Seyfert galaxies can be due to star formation. In the case of low luminosity AGN (LLAGN) X-ray observations with Chandra have revealed the presence of nuclear, compact, point like X-ray sources with $L_X > 10^{38} - 10^{41} \text{ erg s}^{-1}$ in 60% of the sources that show evidence of AGN from optical spectroscopy [148]. However Ranalli et al [266] found that only one third of these LLAGN the nucleus dominates the X-ray emission concluding that LLAGN X-ray emission is comparable to the emission due to star formation.

AGN are strong X-ray emitters with almost 10% of their bolometric luminosity emitted in X-ray. The typical shape of a high energy spectrum between 0.1 and 100 keV is well described by a power law continuum with varying amount of absorption by neutral material given by

$$P(E) \propto E^{-\Gamma} \quad (1.1)$$

where P is measured in photons $\text{s}^{-1} \text{ keV}^{-1}$ and Γ is the photon spectral index related to the frequency spectrum by

$$F(\nu) \propto \nu^{\Gamma-1} \propto \nu^{-\alpha} \quad (1.2)$$

where α is the energy index related to the photon index by

$$\Gamma = \alpha + 1 \quad (1.3)$$

Other prominent X-ray spectral features found in AGN are the Fe K α line at 6.4 keV and a Compton reflection component at energy ranges greater than 10 keV [121]. Nandra & Pounds [241] found that a photon index with value $\Gamma = 1.95$ corrected for absorption describes accurately the X-ray continuum while Rissaliti et al [272] showed that Type 2 AGN are obscured at soft (2 keV) X-ray consistent with the unification models described before.

Until the rather recent developments in X-ray astronomy, AGN were detected using methods based either on their optical or UV emission. Optical methods utilized optical colour selection in order to identify AGN candidates based on their broad spectral energy distribution which is significantly different from starlight in normal galaxies. These methods then required extensive optical spectroscopy to securely identify AGN [268]. The other method is using UV/optical emission lines obtained from low resolution optical spectroscopy in order to identify AGN [64]. Even though these methods are still used today (SDSS, 2dF) very successfully they both suffer from selection effects and especially a bias against Type 2 AGN where the AGN activity can be obscured by dust.

Since the launch of ROSAT it has become evident that the X-ray surveys are by far the most efficient way of finding AGN [138] at a given optical magnitude than any other technique. Soft X-ray bands suffer from the same selection effects against absorbed objects as the optical and UV surveys do, when a hard bandpass is available, as for example with Chandra > 2 keV, these effects are minimised and one can detect highly obscured AGN that might otherwise be completely missed in other surveys [183]. X-ray observations therefore bring us a step closer to the true AGN population since even AGN with column densities of up to $5 \times 10^{23} \text{ cm}^{-2}$ have been identified from deep Chandra surveys [328].

One of the key finding of X-ray surveys is the discovery that luminous AGN were far more numerous at $z \sim 1 - 3$ than they are today [25]. Strong evolution with redshift suggests that galaxy formation and the creation of AGN may have been related. The apparent local correlation between the mass of the central black hole and the stellar mass of the host galaxy bulge, known as the $M_{BH-\sigma}$ relation [220],

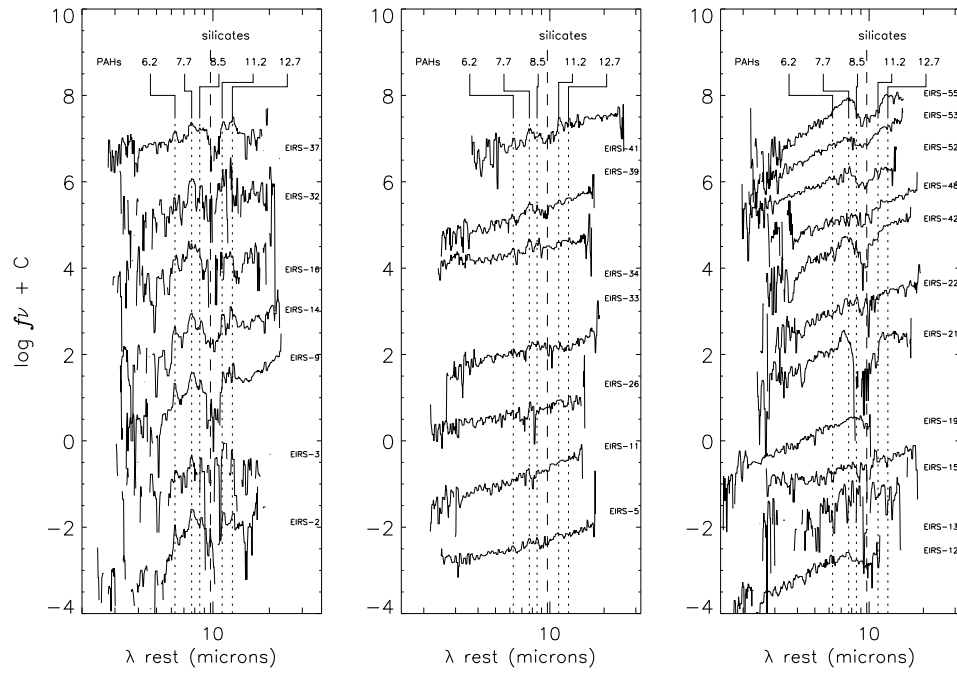


Figure 1.11: IRS spectra of $15\mu\text{m}$ ULIRGs from the ELAIS survey showing different types of mid-infrared SEDs, including strong PAH, star-forming dominated SEDs (left), power-law continua with or without PAH features (center) and silicate absorption (right) [145].

suggest that the formation and evolution of galaxies and the build-up of the super-massive black holes at their centers are interconnected. Connection between AGN and star-formation activity can be further strengthened by the presence of starbursts in many local AGN [204] and from evidence from X-ray and submm surveys which suggest that black hole growth and spheroid formation coevolve in the early Universe [248]. During this phase obscuration in Type-2 AGN is caused by starburst regions [9]. AGN/starburst connection will be discussed in detail in Chapter 6.

1.5.1.4 Quiescent Galaxies

With the term quiescent we indicate those galaxies in which current and/or recent star-formation and AGN activity contribute an insignificant fraction of bolometric luminosity. Ellipticals and lenticulars are regarded as the most quiescent among galaxies. They have relatively small amounts of interstellar matter and therefore little fuel to feed either star formation or AGN activity. However, not only they are not devoid of circumstellar and interstellar gas and dust but a significant fraction of them show evidence of star formation [67] as infrared observations indicate.

X-ray emission in elliptical galaxies, which is dominated by the diffuse thermal emission, is associated with the gravitationally heated gas and the heating procedure from supernovae similar to that of the star forming galaxies [49] but considerably softer. Nonetheless, ellipticals exhibit a less pronounced harder tail with temperatures higher than 2 keV attributed to the integrated emission from low mass X-ray binaries [93].

1.5.2 Luminous Infrared Galaxies

Among the most important cosmological results of the last few decades was the discovery by COBE of a substantial level of background radiation at FIR wavelengths [263]. This background is at least comparable in intensity to the integrated light from galaxies in the Hubble Deep Field [141], implying that the total star formation was shrouded in gas and dust. Later surveys at IR [292][291][17][74] and sub-mm wavelengths [155][27] resolved the bulk of this background into a huge population of distant luminous infrared galaxies ($L_{IR} \geq 10^{11} L_{\odot}$) with a comoving density at least 40 times greater at $z \sim 1$ than the local universe [88]. From being a bolometric irrelevance locally, LIRG sources seemed to be a major, perhaps even dominant contributor to the extragalactic background at $z \geq 1$, with sub-mm surveys finding several hundred LIRGs per square degree at $z \geq 1$ [312]. Other studies, primarily

using HST and Spitzer , have shown that the universe at $z \geq 1$ may also have harboured the bulk of the formation of galaxy morphologies. The Hubble sequence as we see it today was largely in place by $z \sim 0.5$ and a substantial fraction of the formation of morphologies and stellar mass buildup happened in the redshift range $1 < z < 2$ [63]. The bulk of galaxy formation and evolution appeared to occur approximately in the redshift range $1 < z < 3$ and that much of the activity was obscured. The higher luminosity classes of this intriguing population of LIRGs, namely ULIRG and HLIRG are described below.

1.5.2.1 ULIRG

Since IRAS surveys, our understanding of ULIRGs has increased dramatically. A great number of these objects have been observed in the local Universe which makes this class of galaxies the dominant population in $z \leq 0.3$. The first ones detected seemed to lack optical counterparts [287] and no AGN. It seems that strong interactions and mergers of gas-rich spirals are the engine that powers the majority of ULIRGs [301]. According to this scenario, interactions and mergers between gas rich spirals funnel dust to the central regions and in the later stages of merging this fuels an AGN which then dominates the infrared luminosity of the ULIRG. At the final stages, ULIRG becomes an optical QSO as the dust shrouding the AGN is dispersed leaving behind a large elliptical galaxy with a massive quiescent central black hole [184]. However Rigopoulou et al [271] using PAH emission features from ISO data found that most of the ULIRGs were starburst rather than AGN powered and that AGN activity does not increase with the merger advancement. Other authors also found indications of star formation [59], [98] and even both star formation and AGN [96][145] (Figure 1.11). The closest ULIRG to us appears to be a pure starburst [214]. It seems that interactions and mergers of gas-rich spirals result in gas-inflow which can generate both a starburst and fuel the central black hole. Farrah et al [96], by examining the power source of 41 local ULIRGs, found that all of the sample contains a luminous starburst , whereas only half contains an AGN. In 90% of the sample, the starburst provides over half the IR emission, with a mean fractional luminosity of 82%. In addition they found that a common factor governs both luminosities, plausibly the gas masses in the nuclear regions. No trend for increasing fractional AGN luminosity with increasing total luminosity was found, contrary to previous claims. Most ULIRGs undergo multiple starbursts during their lifetime with a mean starburst age range of $1-4 \cdot 10^7$ years.

Recent years have seen new theoretical motivations for the observed sharp rise in

the number of ULIRGs over $0 < z < 1$, in part from large scale structure models that invoke biased hierarchical buildup to assemble galaxies [127]. These models are however not yet at the stage where they can make detailed predictions of the astrophysical properties of ULIRGs, hence we must turn to observations to explain this rise. Observationally, followup of ULIRGs spanning $0 < z < 1$ has revealed some intriguing differences compared to local ULIRGs. They seem to undergo strong positive luminosity evolution, of the form $(1 + z)^{\sim 4}$ [262]. Many distant ULIRGs are powered by obscured starbursts and/or AGN, but AGN are often unexpectedly weak in the X-ray, implying extremely high obscuration levels [159]. Many distant ULIRGs appear to be mergers [52] as seen locally, but some of the more luminous ones appear to be optical QSOs with massive undisturbed elliptical hosts [99]. Distant ULIRGs also appear to have a lower average metallicity than those seen locally [110]. Finally there may be an increased fraction of cool dust emission in distant ULIRGs, especially among samples selected at far-IR wavelengths. This emission could arise from a compact dusty starburst with colder than average dust, but could also arise from cirrus emission, where dust spread throughout the disk of a galaxy is heated to a few tens of K by ambient starlight, rather than the same mass of dust heated by a compact starburst. Cirrus emission has been noted as a potentially important factor in distant ULIRGs by several authors [167][83][97] and would result in substantially lower star formation rates for the same given infrared luminosity.

1.5.2.2 HLIRG

Following the discovery of IRAS F10214+4724 by Rowan–Robinson et al [290] an entirely new class of infrared galaxies emerged, the HLIRGs. The detection of a huge mass of CO [45], the detection of a wealth of molecular lines [322] and of sub-mm emission in the range between $450\text{--}1250\mu\text{m}$ [289] implied that this object incorporated a huge mass of dust. Early models implied that this might be a giant elliptical galaxy undergoing formation [87] and which exhibits Seyfert 2 emission line spectrum [289]. Farrah et al [97] suggested that some HLIRGs may reside inside cluster analogues of the ULIRGs which would explain the formation mechanisms for cluster ellipticals [184]. Hubble spectra of 9 HLIRGs [101] found that 2 were starburst-dominated and 5 were AGN-dominated. Subsequent work on a sample of 11 HLIRGs [99] found that all exhibit both starburst and AGN contributions. More recent studies of 4 HLIRGs [100] found an active galactic nucleus (AGN) in at least three and probably all four in their sample. Three objects of the sample also harbor a starburst. It is still under dispute whether HLIRGs are primaeval star-forming galaxies [280] or just an extrapolation of ULIRGs and not primeval [154]. In the

former, studies of a sample of 39 HLIRGs concluded that for about half of them the AGN dust torus is the dominant contributor to the total IR luminosity, while in half of cases a starburst seems to be the dominant contributor. Both an AGN and a starburst component are needed to understand the SEDs of HLIRGs. Even though it becomes clearer that there is a physical link between these two components [336] we are not yet able to fully understand the nature of HLIRGs and establish whether they undergo a major burst of star formation or multiple epochs of starbursts.

1.6 Star Formation History

Understanding how structure in the Universe forms and evolves is one of the primary goals of modern cosmology. Star formation rates and their global history contain some of the most important tracers of the evolving large scale structure such as the production of elements, structure formation and the energy budget of the Universe. An important realisation of observational cosmology is that SFH can be derived by a number of observational, numerical and analytical methods that can help to constrain and investigate galaxy formation and evolution scenarios.

Up to now two alternative scenarios of galaxy formation have been proposed, the Classical model and the Hierarchical model [41]. The Classical model has its roots in the monolithic low collapse models of Larson [187]. According to Arimoto & Yoshii [15], the collapse of a proto gas cloud may be initially fragmented and at this stage star formation can only continue if the dark matter halo is sufficiently massive to retain the gas against the pressure of the supernovae ejecta. In the case of more massive systems, the star formation can last for longer but eventually the gas will be driven away by supernovae winds which will result in a spheroidal star system. In this scenario the subsequent evolution depends entirely on the galaxy environment so that galaxies in dense environments lose their wind material to the intra-cluster medium while galaxies in low density environments regain their gas in the form of a gas disk. On the contrary, in the Hierarchical model all galaxies are viewed as similar star forming systems which exhibit no intrinsic difference between star formation occurring at different epochs. The major difference between these two scenarios is that while morphology is set in an early epoch in the Classical model, in the case of the Hierarchical model it can change in both directions since it is viewed as a fluid quantity.

Even though systematic investigations of the young stellar content of galaxies were

carried out by Hubble and Baade, the first quantitative star formation rates were derived by Tinsley [339] using evolutionary synthesis models of galaxy colours. The provision of absolute SFRs of a large sample of nearby galaxies came some years later with the use for the first time of integrated emission-line fluxes [61], near-UV continuum fluxes [75] and IR continuum fluxes [136]. The first direct measurement of the global SFH was made by Lilly et al [207] who used photometric measurements in U, B and Z bands to determine the SFR to a redshift of ~ 1 . They concluded that the luminous energy density of the Universe increases to $z \sim 1$ with the SFR at this redshift being almost ten times higher than it is today. Madau et al [218] made use of the Lyman Break Technique to determine the SFR in a sample of galaxies in the Hubble Deep Field with redshift range between 2 and 4. They found a drop-off to the SFR with increasing redshift with the lower value occurring at redshift 4. Subsequent studies [293][155][109] in infrared and submillimetre doubted Madau's results and supported a more shallow decline of the SFR at $z > 1$. The reason for this difference was that the SFRs from UV were not corrected for the effects of dust extinction. Since young stars are unresolved in all but the closest galaxies, information on the young stellar populations of galaxies needs to be obtained indirectly. The tracers that are used to measure SFRs are based on spectral synthesis modelling of broadband colours.

1.6.1 Population Synthesis Modeling

Population synthesis models is an approach that requires four rather uncertain ingredients [274]:

- A stellar evolutionary model grid which is used to derive the effective temperatures and bolometric luminosities for various stellar masses as a function of time.
- A stellar atmospheres grid that assigns a spectrum to each star for a given luminosity and effective temperature.
- An initial mass function that is used to sum together the individual stellar templates in order to synthesise the luminosities, colours or spectra of single-age populations as functions of age.
- The isochrones of the previous step are added in linear combination to synthesise the colours or spectrum of a galaxy with an arbitrary star formation history usually parametrised as an exponential function of time.

Synthesis models provide a relationship between SFR per unit mass or luminosity and the integrated colour of the population. Widely used population synthesis models are those from Bruzual & Charlot [46] and Leitherer [201]. Extensive libraries of models have been compiled by Leitherer & Heckman [200] and Leitherer [199]. The fact that the redshift evolution of the SFR is constructed using different estimators in addition with the fact that the SFR may be derived using an incorrect initial mass function (IMF), age or metallicity of star formation history plus the fact that there may be systematic errors from reddening makes these models relatively imprecise. This means that these methods should be avoided in populations where the dust content, abundances or IMFs can change systematically. In practise depending on the redshift of a galaxy a different estimator is used. If the galaxy lies in redshift up to 0.4, then $H\alpha$ luminosity is used to estimate SFR, if the galaxy is situated at a redshift between 0.4 and 1, then $[OII] \lambda 3727 \text{ \AA}$ is used and finally if the galaxy is at redshift greater than 2 then UV continuum luminosity is used.

In order to calibrate an SFR indicator, a relation between the observed luminosity and SFR is needed. In principle, the SFR, is derived using a model of the duration and time behavior of the starburst and of stellar evolution, with an assumed initial mass function where stars are formed over the lower and higher mass range. The result is subject to imprecision, however, since folded into this are assumptions about the position of the stars in the Hertzsprung-Russell diagram, the evolution of the stars on the latter and of metallicity and its evolution. The model IMF plays a key role since it is used to extrapolate from the stellar populations 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 cut off will dramatically alter the model predictions). For example, there are indications that the IMF in the early universe may have been top-heavy -there were proportionally more massive stars in comparison to the standard IMF - with stars preferentially forming in top-heavy IMF with characteristic masses of a few hundreds solar masses when the gas metallicity is below a critical value. The conversion to a SFR from a chosen band involves uncertainty since each band only traces a minor portion of the total energy output of stars with a possible additional contamination from AGN. The different estimators used to measure SFRs are reviewed in the following sections.

1.6.2 Ultraviolet

In order to avoid the problems associated with the population synthesis models, observations should be made in the wavelength range between 1250 and 2500 Å where the SFR scales linearly with luminosity. The conversion between UV flux over a given wavelength interval and the SFR can be derived using the method described earlier. Madau et al [219] published calibrations for wavelengths in the range 1500–2800 Å which can be converted to Salpeter’s [297] IMF with mass limits 0.1 and $100M_{\odot}$ and give [170]

$$SFR (M_{\odot} \text{ year}^{-1}) = 1.4 \times 10^{-28} L_v (\text{ergs sec}^{-1} \text{ Hz}^{-1}). \quad (1.4)$$

The main advantage of this method is that it is directly related to the photospheric emission of the young stellar populations and it can be applied to star forming galaxies with continuous star formation over timescales of 10^8 years or longer, over a wide range of redshifts [90]. Its main drawback is that it is sensitive to extinction and the form of IMF [47].

1.6.3 Recombination Lines

Another way of estimating the SFR is to use rest frame optical observations of the nebular emission lines including $H\alpha$, $H\beta$, $P\alpha$, $P\beta$, $\text{Br}\alpha$ and $\text{Br}\gamma$ with the $H\alpha$ being the most commonly used. The nebular lines effectively re-emit the integrated stellar luminosity of galaxies shortward of the Lyman limit, providing a direct probe of young stellar populations. The conversion between ionizing flux and the SFR is also derived using evolutionary synthesis models. Due to the fact that ionizing flux originates from stars with masses $>10M_{\odot}$ and ages $<20\text{Myr}$, the SFR measured in this way provides an instantaneous estimator of the SFR. Using the same calibrations as for the UV and the same Salpeter IMF we get [170]:

$$SFR (M_{\odot} \text{ year}^{-1}) = 7.9 \times 10^{-42} L(H\alpha) (\text{ergs sec}^{-1}) \quad (1.5)$$

$$SFR (M_{\odot} \text{ year}^{-1}) = 8.2 \times 10^{-40} L(\text{Br}\gamma) (\text{ergs sec}^{-1}). \quad (1.6)$$

This method offers high sensitivity and the direct coupling between the nebular emission and the massive SFR but with uncertainties in extinction, in the IMF and in the assumption that all star formation is traced by the ionised gas. Ferguson et al [104] pointed out that it is highly important to include the diffuse $H\alpha$ emission in the SFR measurement when using this method. The biggest problem associated

with SFR estimations using $H\alpha$ luminosity is extinction. It can be measured by comparing $H\alpha$ fluxes with those of IR recombination lines or the thermal radio continuum or via $H\alpha/H\beta$. Higher extinction is encountered in dense HII regions in circumnuclear starbursts. In this case the use of near-IR Paschen or Brackett recombination lines are needed in order to estimate the SFR. These lines are usually 1–2 orders of magnitude weaker than $H\alpha$. This means that it can be used only to HII regions and with many restrictions to galaxies as a whole. The same method is used for higher order recombination lines and the thermal continuum emission at submillimeter and radio wavelengths [244].

1.6.4 Forbidden Lines

Due to the fact that for redshifts greater than 0.5, $H\alpha$ emission is redshifted out of the visible, it is helpful to use bluer emission lines as SFR estimators. The strongest emission feature in the blue is the forbidden line doublet $[OII]\lambda 3727$. Even though the excitation of forbidden lines is sensitive to abundance and the ionization state of the gas, $[OII]\lambda 3727$ excitation is very well defined and can be used as an SFR tracer especially for distant galaxies, as it is visible up to redshift of 1.6. Kennicutt [169] published calibrations which can be converted to Salpeter’s [297] IMF with mass limits 0.1 and $100M_{\odot}$ and give [170]:

$$SFR (M_{\odot} \text{ year}^{-1}) = (1.4 \pm 0.4) \times 10^{-41} L[OII] (\text{ergs sec}^{-1}) \quad (1.7)$$

In Equation 4 the uncertainty depicts the range between blue emission line galaxies and more luminous spiral or irregular galaxies. Similar to all the previous methods luminosities derived from $[OII]$ fluxes have to be corrected for extinction.

1.6.5 Infrared and Submillimetre

The IR emission ($1\text{--}1000 \mu m$) in normal star forming galaxies may be originated from three processes:

- (i) Emission from dust heated by young OB stars [72].
- (ii) Emission from the photospheres or circumstellar envelopes of evolved stars such as red giants undergoing mass loss [229].
- (iii) Cirrus emission from dust distributed throughout the optically thin neutral interstellar medium, heated by the general stellar radiation field composed of a combination of unabsorbed radiation from young OB stars inside the star

forming regions [363] and an A, F, G dwarfs and K and M giants population [211].

The calibration of infrared luminosity as an SFR estimator is based on two assumptions, that young stars dominate the radiation field throughout the UV to the visible and that dust opacity is infinite throughout a galaxy. If these two assumptions are true, then the IR luminosity is a very good approximation of the bolometric luminosity and as a result IR is a very reliable SFR estimator. In the case of bright infrared dusty galaxies the two assumptions hold and infrared luminosity is a direct indicator of the true SFR [258]. Rosa-Gonzalez et al [274] showed that in the case of merging infrared starburst galaxies, low metallicity late type spirals and blue compact dwarfs, there is an agreement between SFR(IR) and SFR($H\alpha$) if the $H\alpha$ luminosity has been corrected for reddening. The young star forming populations dominate the IR emission in late type spirals. On the other hand, the origin of the IR emission in early type spiral galaxies is still under dispute which makes the use of SFR(IR) controversial. Kennicutt & Kent [171] demonstrated that early type galaxies are deficient in young stars which was later supported by additional evidence by Sauvage & Thuan [305]. Furthermore, modelling of IR SEDs require a cooler component, often attributed to the general stellar radiation field. Finally Inoue [156] proposed that the SFR(IR) can be used in a wide range of galaxies by suggesting that small dust opacity and a large cirrus contribution offset each other. Kennicutt [170] by applying the models of Leitherer & Heckman [200] for continuous bursts of age 10–100 *Myr* and adopting Salpeter’s IMF, derived the conversion between far-IR flux and SFR:

$$SFR (M_{\odot} \text{ year}^{-1}) = 4.5 \times 10^{-44} L_{FIR}(\text{ergs sec}^{-1}). \quad (1.8)$$

1.6.6 Radio and X-ray

Radio emission is a highly indirect indicator because it relies on the little understood physics of the cosmic ray generation and confinement [62]. One of the main reasons that radio luminosity is considered a good SFR estimator is the close FIR–Radio correlation, which only deviates by less than a factor of two over five orders of magnitude [31]. When compared with FIR and sub-mm, radio has better positional accuracy which makes more reliable identifications of objects possible. The major handicap of radio is that it is hard to account for the contamination of the radio flux by AGNs.

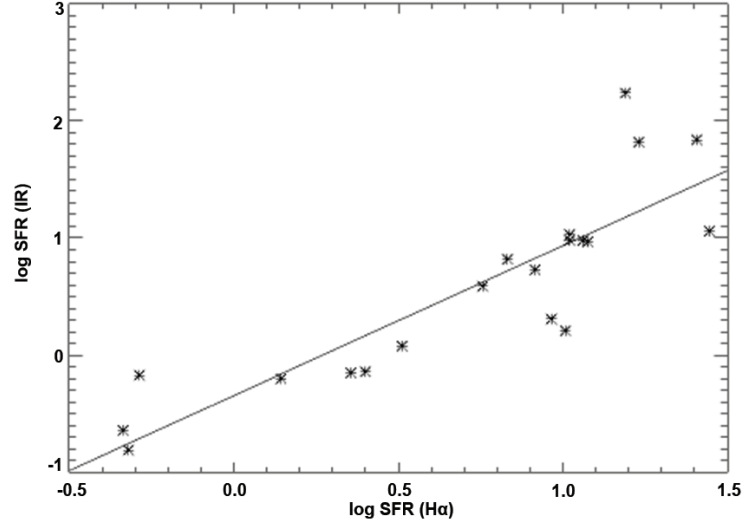


Figure 1.12: Comparison of the SFRs derived using the infrared and the $H\alpha$ luminosities. The straight line is the best fit for the data.

Star-forming galaxies are also luminous in X-ray, mainly due to the existence of high mass X-ray binaries, supernovae remnants and hot plasmas [93]. David et al [66] first proposed that X-ray can be used as an SFR estimator and found a strong correlation between FIR and X-ray in a sample of normal and starburst galaxies. Ranalli et al [266] found a very tight relation between luminosities from X-ray, 1.4GHz and FIR for local and low redshift galaxies described by the following equation:

$$SFR (M_{\odot} year^{-1}) = 2.0 \times 10^{-40} L_{2-10 \text{ keV}} (ergs \text{ sec}^{-1}). \quad (1.9)$$

Subsequent studies [240] related the number of, and total luminosity from, high mass X-ray binaries to the star formation rates supported Ranalli's correlation. For galaxies with $SFR \geq 4.5 M_{\odot} year^{-1}$ a similar correlation to that given in equation 1.9 was found [129]

$$SFR (M_{\odot} year^{-1}) = 1.5 \times 10^{-40} L_{2-10 \text{ keV}} (ergs \text{ sec}^{-1}). \quad (1.10)$$

Although expressions utilizing the soft X-ray luminosity (0.5-2 keV) have been derived by Ranalli et al [266] the hard X-ray relation is considered more robust due to the dependence of the soft X-ray luminosity on the intrinsic absorption which becomes highly significant in dusty starbursts.

1.6.7 Comparison of Star Formation Rates

We have performed a comparison of SFR estimates using $H\alpha$, bolometric infrared and 2800 Å luminosities using the 38 common sources found between Pascual's sample [250] and SWIRE N1 catalogue. In order to compare the infrared and $H\alpha$ star formation rates we used the relations:

$$SFR (M_{\odot}year^{-1}) = 4.5 \times 10^{-44} L_{IR} (erg sec^{-1}) \quad (1.11)$$

$$SFR (M_{\odot}year^{-1}) = 7.9 \times 10^{-42} L(H\alpha) (erg sec^{-1}). \quad (1.12)$$

Equation 1.11 depends on the total infrared luminosity and assumes that young stars dominate the radiation field throughout the UV–visible regimes and that the optical depth is large. The total infrared luminosity is then a good representation of the bolometric luminosity of the galaxy. Although this situation may hold for LIRGs, it does not apply for normal galaxies where the emission may be dominated by a cirrus component [211]. To estimate the SFR(IR) we used the bolometric infrared luminosities (1–1000 μm) given in the SWIRE catalogue, which was compared with Pascual's catalogue.

Equation 1.12 comes from evolutionary synthesis models, assuming solar metallicity and no dust. In this case the total integrated stellar luminosity shiftward of the Lyman limit is reemitted in the nebular emission lines. In order to measure the $H\alpha$ luminosity and correct the $H\alpha$ flux, we follow Pascual's procedure [250] which was based on a given magnitude scale [115]:

$$m_{H\alpha} = -17.0 - 2.5 \log f_{H\alpha} \quad (1.13)$$

$H\alpha$ flux was corrected for the presence of $[N_{II}]\lambda\lambda 6548, 6584$ lines. In addition a mean internal extinction correction was applied to the objects and an 8 % statistical correction to the measured flux. The corrected flux is given by:

$$f_0(H\alpha) = f(H\alpha) \times 10^{0.4A_{H\alpha}} \times (1 + (H\alpha/[N_{II}]\lambda\lambda 6548, 6584)^{-1})^{-1} \times 1.08 \quad (1.14)$$

where $H\alpha/[N_{II}]\lambda\lambda 6548, 6584 = 2.33$ and $A_{H\alpha} = 1$. The contamination from other emission lines such as $[O_{II}]\lambda 3727$, $H\beta$ and $[O_{III}]\lambda\lambda 4959, 5007$ found to be negligible at the flux limits of the sample.

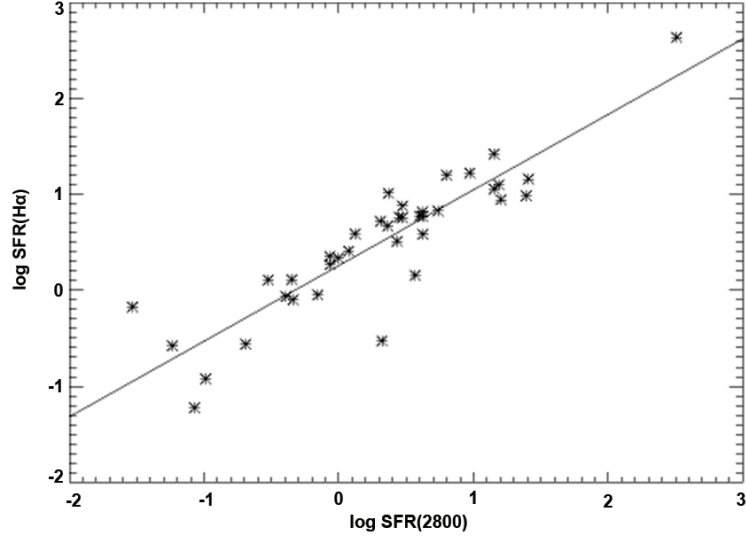


Figure 1.13: Comparison of the SFRs derived using the 2800 Å and the H α luminosities. The straight line is the best fit for the data.

H α luminosity is derived from the corrected flux using:

$$L(H\alpha) = 4\pi D_L^2 f_0(H\alpha) \quad (1.15)$$

where D_L is the luminosity distance related to the transverse comoving distance by:

$$D_L = (1 + z) D_M. \quad (1.16)$$

For a universe with a cosmological constant the transverse comoving distance D_M does not have an analytical solution. In order to calculate the luminosity distance we used the numerical recipe LUMDIST routine in IDL. This routine calculates D_L of an object given its redshift, the Hubble parameter and the deceleration parameter. In this case each object's redshift is retrieved from the SWIRE N1 catalogue. The Hubble parameter was set to 72 km/sec/Mpc and the deceleration parameter was set to default. All sources that exhibit $SFR(IR) < 10^{-9}$, mainly due to misidentifications, were removed from our sample. Our calculation agreed totally with the results produced by Pascual [250] since the faintest object in our sample had exactly the same H α flux and luminosity as those measured by Pascual, namely $7.22 \times 10^{-16} \text{ erg sec}^{-1} \text{ cm}^{-2}$ and $3.78 \times 10^{41} \text{ erg sec}^{-1}$.

Figure 1.12 shows the SFRs derived using the infrared and H α luminosities. The straight line was fitted by using the numerical recipe LINFIT routine in IDL. This

function fits the paired data to the simple linear model

$$y = A + Bx \quad (1.17)$$

by minimising the chi-square error statistic. In this case y is the SFR(IR) and x is the SFR($H\alpha$). A , B are estimated automatically by LINFIT. As a result it produces a least squares fit to the data with a straight line. Finally we performed a Spearman rank correlation test for both SFRs which produced a correlation coefficient of 0.95 confirming the strong correlation between the infrared and $H\alpha$ SFR estimators.

A similar procedure was performed in order to compare SFRs derived from $H\alpha$ and 2800 Å luminosities. The 2800 Å SFR is derived from the relation:

$$SFR (M_{\odot} \text{ year}^{-1}) = 1.4 \times 10^{-28} L_v(\text{ergs sec}^{-1} H z^{-1}). \quad (1.18)$$

The 2800 Å luminosity is used as an SFR tracer in objects at redshifts $z > 2$ where all strong emission lines except $Ly\alpha$ are shifted outside the optical range. As mentioned before this equation is derived from evolutionary synthesis models and is valid between 1500 and 2800 Å, a region not affected by the $Ly\alpha$ forest and the contribution from old populations.

To calculate the $L(2800 \text{ Å})$ we used the absolute magnitudes at 2800 Å given at our SWIRE catalogue which was compared with Pascual's catalogue. The relation between the flux and the absolute magnitudes at 2800 Å was taken from Hayes & Latham [142]:

$$m(2800 \text{ Å}) = -48.6 - 2.5 \log f(2800 \text{ Å}). \quad (1.19)$$

$L(2800 \text{ Å})$ is derived from the $f(2800 \text{ Å})$ using:

$$L(2800 \text{ Å}) = 4\pi D_L^2 f(2800 \text{ Å}) \quad (1.20)$$

where D_L in this case is equal to $10pc$ since these are absolute magnitudes. The comparison of the 2800 Å and the $H\alpha$ SFRs is given in Figure 1.13. The straight line was fitted by using the same numerical recipe LINFIT routine in IDL. In this case y is the SFR($H\alpha$) and x is the SFR(2800 Å). The Spearman rank correlation test for these two SFRs produced a correlation coefficient of 0.92. The agreement of the different star formation rate estimators implies that the infrared emission results from the same young stellar population that produces the $H\alpha$ emission and suggests that the dust is heated in close proximity to the young star-forming regions.

Figure 1.12 demonstrates that there is good agreement between the $\text{SFR}(H\alpha)$ and $\text{SFR}(\text{IR})$ for sources at $z < 0.3$ while for the higher redshifts, and as a result higher luminosities, the agreement becomes poorer. Assuming that both are valid measures of the true star formation rate it is obvious that the $\text{SFR}(H\alpha)$ traces almost all the SFR as derived from the infrared luminosity. However, this is not true for the more luminous objects which becomes obvious for the 3 brightest infrared sources in this sample where the $\text{SFR}(\text{IR})$ estimate exceeds the one from $\text{SFR}(H\alpha)$ by a factor of > 2 . This is indicative of the presence of highly obscured dust-enshrouded star-forming regions within these galaxies which means that more precise extinction correction has to be applied to high- z sources and that there should be a reddening correction taken into account. The comparison between $\text{SFR}(\text{UV})$ and $\text{SFR}(H\alpha)$ (Fig. 1.13) shows that for most of the galaxies the $\text{SFR}(H\alpha)$ values are above the 1 : 1 relation. All these sources lie at $z > 0.3$ while the remaining sources, below the 1 : 1 relation are sources at $z < 0.242$. The latter implies that the UV extinction correction might be underestimated and the actual UV flux be slightly higher. These results imply that $\text{UV}/H\alpha$ decreases with increasing SFR for galaxies at $0 < z < 0.5$ whereas for low star formation rate objects the UV luminosities lead to higher star formation rates than $H\alpha$. In the case of the high redshift objects it is obvious that the UV flux underestimates the SFR which can be either attributed to variations in the star formation history due to starburst events or an increasing attenuation of the UV emission relative to $H\alpha$ for higher luminosity galaxies.

1.6.8 Chemical Evolution Models

Pei et al [252] attempted to reproduce the observed evolution of interstellar gas column density and metallicity from assumptions about stellar evolution, gas flows and metal enrichment. They used data from quasar absorption-line surveys, optical imaging and redshift surveys to obtain solutions for the cosmic histories of stars, interstellar gas, heavy elements, dust, and radiation from stars and dust in galaxies out to a redshift of 5. They found a UV correction factor of 2.5, 3–4 and 2–8 for the current epoch, $z = 1$ and $z = 3$ respectively. They concluded that the process of galaxy formation appears to have undergone an early period of substantial inflow to assemble interstellar gas at $z \geq 3$, a subsequent period of intense star formation and chemical enrichment at $1 \leq z \leq 3$, and a recent period of decline in the gas content, star formation rate, optical stellar emissivity, and infrared dust emissivity at $z \leq 1$.

1.6.9 Source Count Models

There are two types of source count models: the so-called forwards and backwards models. The first statistically follows the growth of dark matter halos forward in time by accretion and mergers and then assumes a semi-analytic galaxy formation paradigm and evolutionary framework [323]. On the other hand, in backwards models, a local luminosity function is evolved backwards in time assuming some form of evolution. The major advantage of backwards models is that they are closely tied to observation and they only have few parameters, though they essentially ignore what is known about galaxy evolution, using functional forms only. In order to construct a backwards model, four basic ingredients are needed:

- (i) A Cosmology.
- (ii) A Luminosity Function which is defined as the number of galaxies per unit volume, Φ , having luminosities in the range L to $L + dL$. There are many forms of luminosity function used which they all depend on the wavelength at which the observations are taken. A number of analytical forms can be fitted to the data taken such as: a power law + exponential [307], a double power law [191] and a power law + exponential Gaussian [303].
- (iii) A form of galactic density or luminosity evolution. Density evolution which is a change in the number of galaxies that can be observed at the present epoch as a result of interactions or mergers. Luminosity evolution is an indication of a change in the star formation rate which results in a change in the distance where the galaxy can be observed.
- (iv) A Spectral Energy Distribution and the way it is redshifted.

Rowan-Robinson [281] presented a source count model who followed a different approach than all the other authors. Instead of assuming that normal galaxies trace the total star formation and starbursts the instantaneous star formation, he splitted the SED of normal galaxies into a young and an old component. This means that the young component along with the starburst and AGN component trace the SFR. King & Rowan-Robinson [179] improved this model by introducing density evolution and a variation of optical depth with redshift.

1.7 Continuation

The next Chapter will deal with the Spitzer Space Telescope, its Legacy Science Programme and will focus in describing in great detail the SWIRE survey, the

largest program performed so far with Spitzer, which has played a central role in this thesis.

Chapter 2

Spitzer and SWIRE

I know that I am mortal and the creature of a day; but when I search out the massed wheeling circles of the stars, my feet no longer touch the earth, but, side by side with Zeus himself, I take my fill of ambrosia, the food of the gods.

Ptolemy (83-161 AD)

2.1 Overview

This chapter reviews the main characteristics and science program of the Spitzer Space Telescope. The mission and instrumentation of ISO's successor are reviewed and all the Legacy Programme projects carried out with it so far are briefly summarised. This Chapter focuses in describing the largest program performed with Spitzer, the Spitzer Wide-area Infra-Red Extragalactic (SWIRE) survey, which has played a central role in the work presented in this thesis. SWIRE resembles ELAIS both conceptually, being the most ambitious and largest-area extragalactic survey carried out with Spitzer, and practically, observing three of four ELAIS main fields. Science objectives, selection of fields, extensive multi-wavelength data obtained and key results so far, are described. Thanks to such an extensive multi-wavelength coverage, the SWIRE fields have now become among the best studied sky areas of their size and natural targets of on-going or planned large-area surveys both with ground and space-based facilities such as the HERMES survey which will be performed with Herschel.

Telescope Aperture	85cm
Orbit	Solar (Earth trailing)
Cryogenic Lifetime	> 5 years
Angular Resolution	$\sim 1.5''$ at $6.5\mu\text{m}$
Wavelength Range	3-180 μm (Imaging)
	5-40 μm (Spectroscopy)
	50-95 μm (S.E.D.)
Field of View	$5' \times 5'$
Telescope Temperature	< 5.5 K

Table 2.1: Spitzer's main properties

2.2 Spitzer

The Spitzer Space Telescope (SST, or simply Spitzer) [352], formerly known as the Space Infrared Telescope Facility (SIRTF), was launched into an Earth trailing solar orbit on 25th August 2003 from Florida's Cape Canaveral aboard a Delta II launcher in order to study the creation of the universe, the formation and evolution of primeval galaxies, the genesis of stars and planets and the chemical evolution of the universe at wavelengths between 3 and 180 μm . The unique orbit that Spitzer was put on, allowed the telescope to cool rapidly without having to carry large amounts of coolant. Spitzer, which can be characterized as ISO's successor, was the first infrared telescope to be successfully orbited by the US after IRAS. It is the final mission of NASA's ambitious program to observe the Universe in a broad range of wavelengths spanning from optical to gamma-rays, X-rays and Infrared as part of NASA's Great Observatories Program including three other space telescopes, Hubble, Compton and Chandra.

Spitzer (Figure 2.1) incorporates an 85cm diameter telescope cooled as low as 5.5K. The projected cryogenic lifetime of the observatory systems is in excess of 5 years. Spitzer is equipped with three observing instruments capable of photometry, imaging and spectroscopy in the range between 3 and 180 μm with a field of view of $5' \times 5'$ and diffraction limited detectors down to $\sim 5.5\mu\text{m}$. Table 2.1 summarizes the main properties of Spitzer.

2.2.1 Observing Modes

Observations with Spitzer are designed selecting an Astronomical Observation Template (AOT) and choosing its parameters. Seven of these AOTs or observing modes were available at the time of writing of this document all of which are described in

greater extent in the Spitzer Science Planning Database.

- **Infrared Array Camera (IRAC)**
 - **Mapping and Photometry:** Simultaneous images at 3.6, 4.5, 5.8 and 8 μm , with 25% bandwidth over $5.1' \times 5.1'$ field of view.
- **Multiband Imaging Photometer for Spitzer (MIPS)**
 - **Photometry and Super Resolution Imaging:** Imaging photometry and high resolution imaging at 24, 70 and 160 μm .
 - **Freeze – Frame Scan Mapping:** Telescope scanning at 24, 70 and 160 μm for large field maps. The maps are constructed by using slow telescope tracks, combined with image stabilization using a motion compensating cryogenic scan mirror. Maps are built up of $5.1'$ wide strips and are between 0.6 and 6 degrees in length.
 - **Spectrophotometry (SED):** R=10-20 spectroscopy mode covering 50-95 μm using the MIPS 70 μm Ge:Ga array.
 - **Total Power Measurement:** Zero level reference observations for absolute brightness of very extended sources.
- **Infrared Spectrograph (IRS)**
 - **Staring – Mode Spectroscopy:** Low resolution spectra ($R > 50$) from 5 to 40 μm . High resolution spectra ($R=600$) from 10 to 38 μm . Photometry at 15 μm , with an one square arcmin field of view.
 - **Spectral Mapping:** Slit scanning spectroscopy of fields up to a few arcmin in extent.

The three focal plane instruments on the Spitzer Space Telescope, IRAC, MIPS and IRS are described in more detail below.

2.2.2 IRAC

The Infrared Array Camera [102] is a four channel camera that obtains simultaneous broadband images at 3.6, 4.5, 5.8, and 8.0 μm . Two nearly adjacent $5.2' \times 5.2'$ fields of view in the focal plane are viewed by the four channels in pairs. All four detector arrays in the camera are 256×256 pixels in size, with a pixel size $1.22'' \times 1.22''$, with the two shorter wavelength channels using InSb and the two longer wavelength channels using Si:As IBC detectors. IRAC is designed to study the early universe and in particular the evolution of normal galaxies to $z > 3$ by means of deep, large area surveys. Its sensitivity requirements were driven by the goal to achieve a signal to noise of 10 on a galaxy at $z=3$ in all four wavelength bands [317]. The wavelength

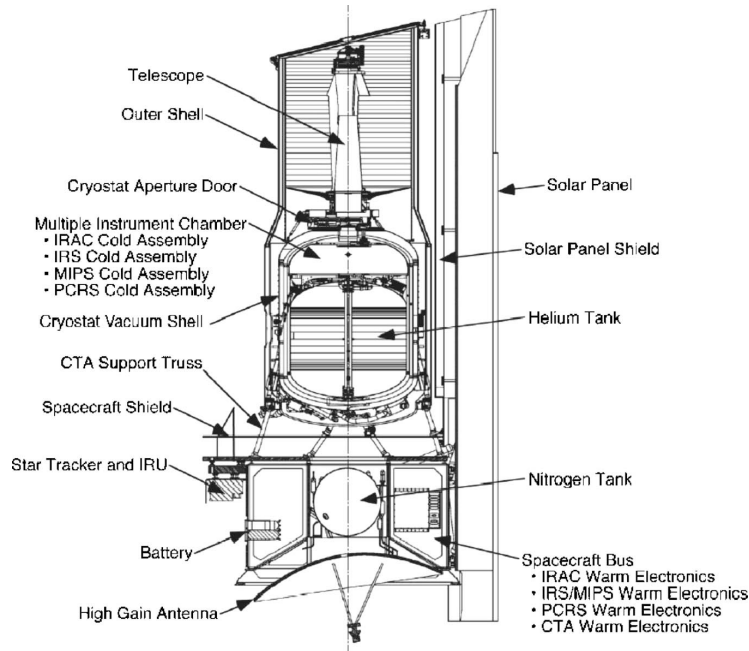


Figure 2.1: Side elevation of Spitzer's launch configuration [352].

range that IRAC operates in is where stars have a peak emission at a wavelength of $1.6\mu\text{m}$ at the minimum of H^- opacity [163]. This emission can be used to determine photometric redshifts for $1 < z < 5$ [357]. IRAC's point source sensitivities and instrumentation summary are given in Table 2.2.

Post launch performance not only met all of the science requirements but in many cases the performance was better than expected. In channel 1, IRAC can reach the same point source sensitivity as the Keck interferometer at the L band in 1/100 the exposure time and does so with a far larger field of view [119]. Noise measurements in channels 3 and 4 scale as the inverse square root of time for integration times as long as 24 hours [102]. In the case of channel 1 and 2 there is a deviation from the rule by 2000 sec, indicating that these channels are approaching the source completeness limit [102]. IRAC can reach a limit of 0.1 mJy in 23.4 hours making feasible the detection of galaxies at $z=6$ [359].

There are however several instrumental artifacts such as persistent images in 3.6 and $8.0\mu\text{m}$ arrays, point source and diffuse stray light and more complex effects related to instrumental design and adopted observing strategy, which are known as muxbleed, banding and column pulldown.

Wavelength (μm)	3.6	4.5	5.8	8.0
$\lambda/\delta\lambda$	4.7	4.4	4.0	2.7
Field of View	$5.2' \times 5.2'$	$5.2' \times 5.2'$	$5.2' \times 5.2'$	$5.2' \times 5.2'$
Pixel Size (arcsec)	1.22	1.21	1.22	1.22
Sensitivity (5σ in 500 sec)	$1.3 \mu\text{Jy}$	$2.7 \mu\text{Jy}$	$18 \mu\text{Jy}$	$22 \mu\text{Jy}$
Array Type	InSb	InSb	Si:As (IBC)	Si:As (IBC)

Table 2.2: IRAC main properties [102]. Sensitivities are indicative in low background sky. Confusion is not included.

2.2.3 MIPS

The Multiband Imaging Photometer [269] provides long-wavelength capability with imaging bands at 24, 70 and $160\mu\text{m}$ with bandwidths of ~ 5 , 19 and $35\mu\text{m}$ respectively. It is also capable of very low resolution SED spectroscopy from 52 to $100\mu\text{m}$. The instrument achieves telescope limited resolution of $6''$, $18''$ and $40''$ at 24, 70 and $160\mu\text{m}$ respectively. MIPS uses three detector arrays each of which resolves the telescope airy disk with pixels of size $\lambda/2D$ or smaller: 128×128 pixels at $24\mu\text{m}$, 32×32 pixels at $70\mu\text{m}$ and 2×20 pixels at $160\mu\text{m}$. MIPS can achieve simultaneously high sensitivity, large imaging fields and large angular resolution which enables it to study source structure and penetrate confusion limits.

The on orbit performance of the instrument is generally in agreement with pre-launch expectations. In fact the point source sensitivity of the $24 \mu\text{m}$ array is about $110 \mu\text{Jy}$ (500 seconds, 5σ , dark sky) or about 1.5 times deeper than pre-launch predictions. Nonetheless, several divergences have transpired for the longer wavelength arrays, namely the 70 and $160 \mu\text{m}$ channels.

The $70 \mu\text{m}$ channel is three to four times less sensitive than anticipated. Much of the shortfall arises from a high cosmic ray showering near or within the instrument with a hit rate of roughly 1 hit per 11 sec with many hits occurring simultaneously on widely separated pixels. However, the photometric repeatability with this array is within 5% [126] verifying the effectiveness of the measures taken to tame poor unexpected performance. In addition one side of the $70 \mu\text{m}$ array suffers from fixed pattern noise due to a thermally activated high resistance cable connection external to the instrument. The sensitivity of the non affected side of the $70 \mu\text{m}$ array is about 6mJy in 500 seconds (5σ , no confusion), about 3 times worse than pre-launch predictions. In the case of the affected side the sensitivity is worse by a factor of 2-3 compared with the good side.

Wavelength (μm)	24	70	55-95	160
$\lambda/\delta\lambda$	4.0	3.5	14-24	4
Field of View	$5.4' \times 5.4'$	$5.25' \times 2.6' / 2.6' \times 1.3'$	$0.32' \times 3.8'$	$0.53' \times 5.3'$
Pixel Size (arcsec)	2.5	9.8/5.0	9.8	16
Sensitivity (5σ in 500 sec)	110 μJy	7.2 / 14.4 μJy	200 μJy	24 μJy
Array Type	Si:As (IBC)	Ga:Ga/Ge:Ga	Ge:Ga	Ge:Ga

Table 2.3: MIPS main properties [269]. Sensitivities are indicative in low background sky. Confusion is not included.

Problems associated with the 160 μm channel are also associated with this unexpectedly high cosmic ray shower which results in lower sensitivities than those planned. In addition, the optical train allows a small amount of near infrared radiation onto the array, compromising measurements of stars with Rayleigh-Jeans SED. Other problems associated with the 160 μm array is the faulty block of 5 pixels and the 1.0-1.6 μm spectral leak. MIPS sensitivities and main instrumentation are given in table 2.3.

2.2.4 IRS

The Infrared Spectrograph [153] comprises four separate spectrograph modules covering the wavelength range from 5.3 to $38\mu\text{m}$ with spectral resolutions, $R=\lambda/\Delta\lambda \sim 90$ and 600, and it was optimized to take full advantage of the very low background in the space environment. In addition to its spectrographs, IRS contains two peak-up imaging fields with their bandpasses centered at $16\mu\text{m}$ and $22\mu\text{m}$. IRS was designed for optimum sensitivity to dust features in the local and distant universe and to achieve the highest possible resolution for the given array dimensions effectively limited in sensitivity by the zodiacal and Galactic backgrounds.

Post launch performance of the IRS is working as anticipated. All four spectrograph modules and the IRS peak-up arrays are performing well with all the arrays been more sensitive than pre-launch estimates. Slit and peak-up field of view dimensions as well as wavelength ranges that can be calibrated for each sub-slit have been changed slightly to reflect in-orbit measurements. Finally the pointing accuracy is very good. Low accuracy IRS peak-ups may not be necessary if target coordinates are well known or if peak up images are not required. Table 2.4 summarizes the main properties of the IRS.

λ (μm)	Array Type	$\lambda/\Delta\lambda$	FOV	Pixel (arcsec)	Sensitivity (μJy)
5.2-14.5	Si:As (IBC)	60-127	$3.6'' \times 5.7''$	1.8	400
13-18.5	Si:As (IBC)	3	$1' \times 1.2'$	1.8	75
9.9-19.6	Si:As (IBC)	600	$4.7'' \times 11.3''$	2.4	$1.5 \times 10^{-18} \text{ W m}^{-2}$
14-38	Si:Sb (IBC)	57-126	$10.6'' \times 168''$	5.1	1.7
18.7-37.2	Si:Sb (IBC)	600	$11.1'' \times 22.3''$	4.5	$3 \times 10^{-18} \text{ W m}^{-2}$

Table 2.4: IRS main properties [153]. Sensitivities are indicative in low background sky. Confusion is not included.

2.3 Spitzer Science Program

Nearly 80% of Spitzer’s observing time is available to the scientific community through invitations for General Observing (GO) programs. The remaining 20% includes GTO time for instrument teams as well the First Look survey and the Spitzer Legacy Science Programs described below. The first science program executed after the commissioning of the observing modes was the First Look Survey.

FLS: The First Look Survey was a 112 hour survey which covered about 5 square degrees centered on (J2000.0) $\alpha=17^h 18^m$, $\delta=59^\circ 30'$ in order to characterize the mid-IR sky with high sensitivity that is ~ 100 times deeper than previous systematic large-area surveys. The FLS was composed of extragalactic, galactic, and ecliptic components. More specifically FLS aimed to characterize the dominant source populations with both MIPS and IRAC data, plus ancillary data at optical, near-infrared and radio wavelengths, exploring the cirrus foreground at moderately high galactic latitudes, and its effect on point-source detectability, characterizing the cirrus and background source counts at low galactic latitudes, characterizing the extent and brightness of the extended and point source emission from a representative, nearby molecular cloud complex in the IRAC and MIPS bandpasses, deriving number counts and scale heights for main belt asteroids of diameters smaller than 1Km and characterizing the zodiacal light as a function of distance from the ecliptic plane.

The original Spitzer Legacy Science Program was comprised of six Legacy Science projects selected by the Spitzer Science Center in November 2000 following a solicitation of proposals and competitive peer review. The program was motivated by a desire to enable major science observing projects early in the Spitzer mission, with the goal of creating a substantial and coherent database of archived observations that could be utilized by subsequent Spitzer researchers, including General Observers (GO).

Band	3.6 μm	4.5 μm	5.8 μm	8 μm	24 μm	70 μm	160 μm
Sensitivities	7.3 μJy	9.7 μJy	27.5 μJy	32.5 μJy	0.45mJy	2.75mJy	17.5mJy
Limit	10 μJy	10 μJy	43 μJy	40 μJy	450 μJy	30mJy	200mJy

Table 2.5: SWIRE Sensitivities (5σ) and lower flux limits for inclusion in the SWIRE catalogues [331]. Sources were required to be detected at 3.6 and 4.5 μm .

The six projects of the original Legacy Program utilized a total of 3160 hours of the telescope’s observing time, primarily in the first year of the mission, and integrated substantial ancillary data from ground-based observatories and other space-borne telescopes. During Cycle-2 five additional programs were selected that met the Legacy selection criteria, in Cycle-3 eight more legacy programs were selected and in Cycle 4 seven additional programs were chosen. All legacy programs of the four cycles are described briefly below except for the SWIRE survey which is described in more detail in §2.4.

Original Legacy Program

GLIMPSE: The Galactic Legacy Infrared Mid-Plane Survey Extraordinaire [54] used ~ 400 hours of IRAC imaging in all bands in an effort to study the inner Galaxy from 10 to 70 degrees on either side of the galactic center and one degree above and below the galactic plane. The scientific aims of GLIMPSE are to produce a complete census of star formation in the inner galaxy, measure the stellar disk scale length, delineate the stellar structure of the molecular ring, inner spiral arms and bar as traced by the distributions of stars and star formation regions, determine the luminosity and initial mass functions of all nearby star formation regions and clusters down to the stellar limit or below, detect all young O and B stars still embedded in their natal clouds, detect and identify young stellar objects in nearby star forming regions, determine the mid-IR interstellar extinction law in dense regions and detect a host of other types of stars and nebulae.

GOODS: The Great Observatories Origins Deep Survey [73] is a multi-observatory program which is collecting the deep, extensive multiwavelength data for two fields, the Hubble Deep Field North and the Chandra Deep Field South totalling 320 square arcmin. The survey utilized a total of 647 hours of Spitzer observing time in an effort to study galaxy formation and evolution over a wide range of redshifts.

Field	RA h m s	DEC d m	Area deg ²	Background MJy/sr	E(B – V) mag
ELAIS-N1	16 11 00	+55 00 00	9.18	0.44	0.007
ELAIS-N2	12 36 48	+41 01 45	4.66	0.42	0.007
ELAIS-S1	00 38 30	-44 00 00	7	0.42	0.008
CDF-S	03 32 00	-28 16 00	7.83	0.46	0.001
Lockman	10 45 00	58 00 00	11	0.38	0.006
XMM-LSS	02 21 00	-05 00 00	9.18	1.3	0.027

Table 2.6: The final six SWIRE Fields [210].

SINGS: The Spitzer Infrared Nearby Galaxies Survey [172] is a comprehensive infrared imaging and spectroscopic survey of 75 nearby galaxies using 512 hours of Spitzer observing time. Its primary goal is to characterize the infrared emission of galaxies and their principle infrared emitting components, across the entire range of galaxy properties and star formation environments, including regions that until now have been inaccessible at infrared wavelengths. SINGS will provide new insights into the physical processes connecting star formation to the ISM properties of galaxies, and provide a vital foundation for understanding infrared observations of the distant universe and ultraluminous and active galaxies.

From Molecular Cores to Planet Forming Disks: This program used 400 hours of the observing time of all three Spitzer instruments to observe sources from molecular cores to protoplanetary disks, with a wide range of cloud masses, stellar masses, and star-forming environments [92]

The Formation and Evolution of Planetary Systems: This survey made use of 350 hours of Spitzer observing time in order to trace the evolution of planetary systems from stellar accretion and provide new numerical tools for simulating the dynamical history of forming solar systems [233]..

Cycle – 2

SCOSMOS: This is a deep uniform imaging survey with 220 hours of Spitzer time using both the IRAC and MIPS detectors to observe the HST-COSMOS 2 deg^2 field [298]. COSMOS is an HST Treasury program (Cy12-13) that is specifically designed to probe the coupled formation and evolution of galaxies and large-scale structure during the formative era of galaxy, AGN, and clusters ($z \sim 0.5-3$). The COSMOS survey also includes extensive multi-wavelength imaging from X-ray to

radio (XMM, GALEX, Subaru, NOAO, VLA and CSO) and spectroscopic surveys (VLT and Magellan).

SIMPLE: The Public Deep IRAC Survey in the Extended Chandra Deep field South (PI: van Dokkum) is a 122.9 hour survey covering a total of 0.5×0.5 degree area surrounding the Chandra Deep Field South. The main science goals are to select massive galaxies at high redshift, to disentangle contributions from age, dust, and AGNs to their broad band SEDs, and to study the host galaxies of AGNs.

SAGE: The Spitzer Survey of the Large Magellanic Cloud: Surveying the Agents of a Galaxy's Evolution [232] is a 511 hours uniform, unbiased imaging survey of the Large Magellanic Cloud using IRAC and MIPS aiming in understanding the recycling of matter between the interstellar medium (ISM) and stars which is the driving force behind the evolution of a galaxy's visible matter.

GLIMPSE II: GLIMPSE II (PI: Churchwell) is a 148.8 hours IRAC survey aiming in determining the content and distribution of stars in the inner Galaxy; the extent, stellar population, and interaction of the strong nuclear wind with the ambient interstellar medium above and below the nucleus of our Galaxy; and determine the rate and location of current star formation in the inner Galaxy.

MIPSGAL: This program (PI: Carey) will survey 220 deg^2 of the inner galactic plane using 417 hours of the 24 and $70 \mu\text{m}$ MIPS channels. The survey data will be used to examine the early phases of high mass star formation, complete the census of star formation in the inner Galactic disk and provide a snapshot of the current Galactic star formation rate, measure the distribution and heating of very small grains in the ISM.

Cycle – 3

SCOSMOS: This is a complimentary 396.2 hours survey of SCOSMOS Cycle-2 which uses MIPS to fully observe the HST-COSMOS 2 deg^2 field. The MIPS-deep data are critical for deriving star formation rates, and AGN activity of galaxies and their dependence on morphological properties and clustering environment over the last 90% of the cosmic history.

GOALS: The Great Observatory All-sky LIRG Survey (PI: Armus) is an 160 hour

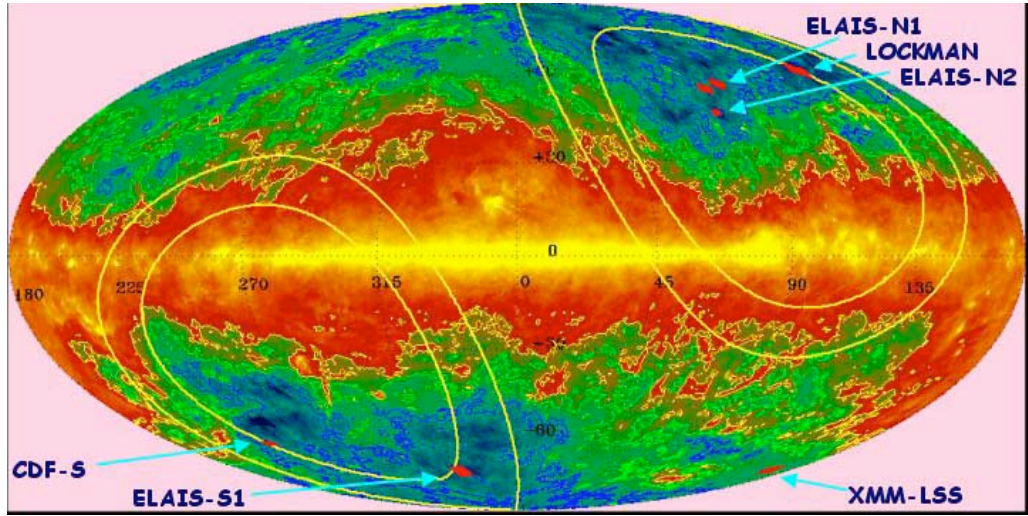


Figure 2.2: SWIRE survey fields are superimposed on a cirrus background Schlegel map [4].

low and high resolution IRS spectroscopic survey of a total of 158 LIRGs selected from the IRAS Revised Bright Galaxy Sample. The primary goals are to search for buried AGN and determine their contribution to the bolometric luminosity, determine the star-formation rates and ages, characterize the state of the ionized and molecular gas, and study the properties of the small and large dust grains and determine if all of these properties are a function of luminosity and/or merger stage.

FIDEL: The Deep-Wide Far-Infrared Survey of Cosmological Star Formation and AGN Activity (PI: Dickinson) is a 397 hours very deep MIPS imaging geared towards 70 micron detection of 1000 normal IR-luminous galaxies at $0.5 < z < 2.5$ at wavelengths which trace thermal dust emission which more directly correlates with physical properties of interest such as star formation rates. It will survey a total of 2200 arcmin^2 in three premier deep survey fields using far-infrared, radio and submillimeter data to measure bolometric luminosities, dust temperatures and masses, to quantify the population of Compton-obscured AGN, and to calibrate the use of $24 \mu\text{m}$ data for studying high redshift galaxy evolution.

SSGSS: The Spitzer SDSS GALEX Spectroscopic Survey (PI: Schiminovich) is a 121.1 hours IRS mid-ir spectroscopic survey of a sample of 100 galaxies selected from the SDSS main spectroscopic survey in the Lockman Hole field, and have been observed by GALEX in the UV and SWIRE in the IR. The main goal of this survey is to study the global properties of SDSS galaxies using atomic and molecular

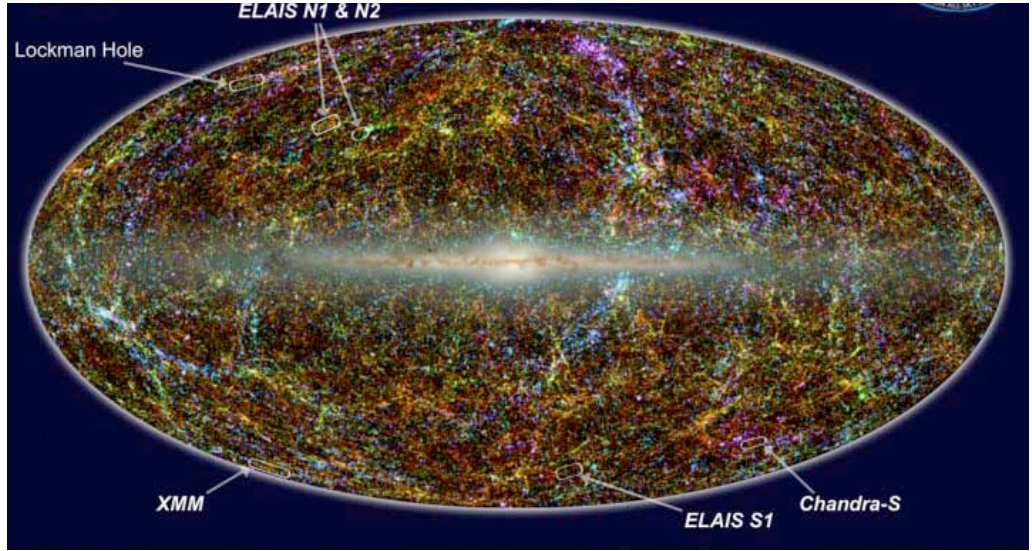


Figure 2.3: SWIRE survey fields superimposed on a 2MASS all-sky image colour-coded by photometric redshift [4].

nebular diagnostics measured from IR to UV which will result in new diagnostics for the study of the physical state of the ISM and the star formation history of each galaxy and will derive new global physical properties for the latter.

GLIMPSE 3D: This 254.5 hours IRAC program is going to map 112 square degrees in a series of latitude strips above and below the Galactic plane in all four IRAC bands. The resulting dataset will be used to determine the scaleheight of the Galactic bulge, the Galactic bar(s), the thin stellar disk, the Galactic ring, and the inner spiral arms, with a variety of different stellar tracers. In addition it will enable studies of diffuse IR cirrus, and the vertical scaleheights of different stellar populations.

MIPSGAL II: This is a 72 deg^2 , 158 hours MIPS survey at 24 and $70 \mu\text{m}$. These observations will connect the two fields observed by MIPSGAL and are complementary to the GLIMPSE II and GLIMPSE 3D surveys. This data will finish the census of massive star formation inside the molecular ring, provide detailed information on the distribution and energetics of small dust grains toward the nucleus of our Galaxy, and identify all massive evolved stars in the surveyed portion of the Galactic bulge.

GouldsBelt: This is a 285 hours program (PI: Allen) with IRAC and MIPS targeting molecular clouds in Gould's Belt. Together with the clouds surveyed by the

Cores to Disks Spitzer Legacy program and clouds studied by GTO/GO programs, these observations will complete the census of star formation regions within 500 pc. The large sample will be used to control for effects of environment on star formation, assess the fraction of star formation in distributed and clustered modes, including the number in groups of various sizes and study the physical conditions in extended structures with a goal of understanding the formation of dense cores.

Taurus – 2: This 60 hour survey (PI: Padgett) aims in compiling a comprehensive, unbiased and spatially contiguous map of the Taurus Main Cloud using MIPS and IRAC, adding an area of 24 square degrees and restoring full coverage of L1495 and L1536 which will reveal the lowest luminosity members of the young stellar population in western Taurus: collapsing protostars, young substellar objects, and edge-on disks and will allow the characterization of the circumstellar environment of each object, and construct a complete luminosity function for the cloud members that will place constraints on the initial mass function.

Cycle – 4

UKIDSS: This is a 292 hours imaging survey (PI: Dunlop) with IRAC and MIPS of the 1 deg^2 UKIDSS survey. The main goal is to provide robust measurements of both stellar mass and star-formation rates, and allow the first statistical study of the evolution of the high-mass end of the galaxy mass function out to $z=6$. Moreover, Spitzer imaging will allow the evolution of starforming and passive galaxies to be studied separately, and help delineate the link between stellar mass assembly and starformation at high redshift.

SAGE – Spectroscopy: This 224.4 hours IRS and MIPS-SED spectroscopy survey (PI: Tielens) aims in determining the composition, origin, evolution, and observational characteristics of interstellar dust and its role in the LMC.

LVLS: The Local Volume Legacy Survey (PI: Kennicutt) is a 280.5 IRAC and MIPS survey of a volume-complete sample of 258 galaxies within the 11 Mpc local volume. Its broad goal is to provide critical insight into two of the primary processes that shape the growth of galaxies: star formation and its interaction with the interstellar medium. It will also provide an infrared and multi-wavelength census of the Galactic neighborhood, exploiting the highest spatial resolution and absolute depth achievable with Spitzer.

SAGE – SMC: This 285 hours survey (PI: Gordon) aims in extending the SAGE analysis to the whole SMC (Bar, Wing, and high-density portion of the Magellanic Bridge), a galaxy whose properties are uniquely similar to those of star-forming galaxies at high redshift.

The 5 mJy Extragalactic Spectroscopic Survey: This is a 200 hours spectroscopic survey (PI: Helou) with IRS of a flux limited sample of galaxies.

SDWFS: The Spitzer Deep Wide-Field Survey also known as the IRAC Shallow survey [86] is a 201-hour program to remap a total of 8.5 square degrees in the NOAO Deep Wide-Field Survey in Bootes. A major scientific driver for this program is the detection of galaxy clusters at redshifts greater than one via the redshifted $1.6\mu\text{m}$ peak in galaxy SEDs. It is also aimed at identifying and estimating the sizes of high ecliptic latitude asteroids from $8\mu\text{m}$ thermal emission and detecting fluctuations in the $1\text{--}3\mu\text{m}$ cosmic background due to $\text{Ly}\alpha$ from Population III objects at $z\sim 15$ (Cooray et al, 2004).

Spitzer Legacy Survey of the Cygnus – X Complex: This is a uniform, unbiased survey (PI: Hora) of the Cygnus-X complex with 120 hours of IRAC and MIPS time which will analyze the evolution of high mass protostars with a large and statistically robust sample at a single distance, study the role of clustering in high mass star formation, study low mass star formation, assess what fraction of all young low mass stars in the nearest 2 kpc are forming in this one massive complex, and provide an unbiased survey of the region and produce a legacy data set which can be used in conjunction with future studies of this region (e.g., with Herschel and JWST).

2.4 SWIRE

The largest project performed with Spitzer so far is the Spitzer Wide-area Infrared Extragalactic Survey, commonly known as SWIRE [210]. SWIRE resembles ELAIS in many ways not only because it observed three of the ELAIS main fields (S1, N1, N2) but also because it carried out the largest area extragalactic survey among the Spitzer science program. SWIRE used 851 hours of the available Spitzer observing time. The original plan was to survey 7 high-latitude fields covering 67 square degrees in total in all 7 Spitzer imaging bands down to the sensitivities shown in

Field	Instrument	RA h m	DEC d m	Bands	Size deg^2	Depth
ELAIS-S1	ISO	0 35	-43 28	7,15,90 μm	4	1mJy
	BeppoSax/MECS	0 35	-43 28	2-10keV	1.7	36ks
	ATCA	0 35	-43 28	1.4GHz	4	80 μJy
XMM-LSS	XMM	2 24	-5	0.5-10keV	2	20ks
	XMM	2 18	-5	0.5-10keV	1	50-100ks
	Subaru			R	1.3	28
	SCUBA			450/850 μm	0.25	60,3mJy
	VLA			1.4GHz	~ 1	12 μJy
	VLA	2 24	-4 30	1.4GHz	5.6	4mJy
CDF-S	Chandra	3 32	-27 48	0.5-8keV	0.1	1Ms
	HST-WFPC			V I	17arcmin	28.2
	HST-ACS			B V i z	0.25	V $\sim$ 28
	Spitzer			3.6-24 μm	300arcmin	4,0.02 μJy
	Spitzer			3.6-160 μm	0.4	0.11mJy
Lockman	ROSAT-HRI	10 53	57 29	0.5-2keV	0.13	1.2Ms
	ROSAT-PSPC	10 52	57 21	0.5-2keV	0.3	200ks
	XMM	10 53	57 29	0.5-10keV	0.2	190ks
	Chandra	10 53	57 29	0.5-8keV	1.35	5ks
	ISO	10 52	57 21	7,15,90,175 μm	0.1-0.5	3mJy
	VLA	10 52	57 29	6,20cm	0.35,0.09	11,30 μJy
	Spitzer			3.6-160 μm	0.4	0.11mJy
	SCUBA	10 52	57 22	450/850 μm	130arcmin	8mJy
	VLA			20cm	100arcmin	5 μJy
	SCUBA			450/850 μm	0.25	60,3mJy
	ISO	10 34	58	90,175 μm	0.5	15mJy
	Chandra	10 34	57 40	0.5-8keV	0.4	40,70ks
ELAIS-N1	ISO	16 10	54 33	15,90,175 μm	2.6	1mJy
	ISOPHOT	16 11	54 25	170 μm	1.98	50mJy
	Chandra	16 10	54 33	0.5-8keV	300arcmin	75ks
	XMM			0.5-10keV	0.2	150ks
ELAIS-N2	ISO	16 37	41 16	7,15,90,175 μm	2.6	1mJy
	ISOPHOT	16 36	41 05	170 μm	0.96	50mJy
	SCUBA	16 37	41 02	450-850 μm	130arcmin	8mJy
	VLA			20cm	100arcmin	9 μJy
	Chandra	16 36	41 01	0.5-8keV	300arcmin	75ks
	XMM			0.5-10keV	0.2	150ks

Table 2.7: Imaging Surveys within SWIRE Fields [210].

Table 2.5. The area has been reduced to almost 49 square degrees in six fields in order to maintain two high quality coverage of each field with MIPS due to the post launch MIPS problems described in § 2.2.3. Building on ISO's and ELAIS' heritage, SWIRE complemented smaller, deeper, GTOs Spitzer surveys showing the way for future surveys to be carried out by Herschel.

The key scientific goals of SWIRE are to enable fundamental studies of cosmology and galaxy formation in the mid-infrared and far-infrared, for the key redshift range $0.5 < z < 3$ where much of the cosmic evolution has occurred. SWIRE used the 4 IRAC and 3 MIPS bands which are dominated by evolved and starburst galaxies respectively in order to understand the evolution of active star-forming galaxies and passively evolving systems in volumes large enough to place this evolution in the context of structure formation and galaxy environment [209][139][284][348]. In addition, the large volume of the SWIRE survey enabled studies of the spatial dis-

tribution and clustering of starburst, evolved galaxies and AGN and the evolution of their clustering [246] and finally it allowed to derive evolutionary relationships between galaxies and AGN as a function of redshift, environment and luminosity [20]. SWIRE has detected more than 1.5 million extragalactic sources [209] at $3.6\mu\text{m}$ and around 350 thousand at $24\mu\text{m}$ and has provided the community with more than one million photometric redshifts of unprecedented reliability and accuracy [283].

2.4.1 Selection of SWIRE Fields

To maximize the survey's sensitivity the SWIRE team performed a detailed analysis to find appropriate high latitude fields with low background. SWIRE fields represent, in many respects, the largest, lowest infrared background regions in the sky. The selection criteria were:

- Low galactic cirrus emission ($I_{100} < 0.5 \text{ MJy/sr}$) from Schlegel maps [309] shown in Figure 2.2. This is a reprocessed composite of the COBE/DIRBE and IRAS/ISSA maps with the zodiacal foreground and confirmed point sources removed in order to minimize the confusion and noise.
- High galactic latitude in order to ensure maximum visibility from the satellite and to minimize zodiacal foreground.
- A large contiguous area ($> 8 \text{ deg}^2$) in $\beta > 40$ was chosen in order to maximize the satellite's visibility and manage to perform large scale structure studies.
- The areas were chosen to have minimum contamination by bright stars, galaxies, radio sources and galaxy clusters.
- Availability of multi-wavelength data in other wavebands.

The final six fields selected for SWIRE include the ELAIS-N1, ELAIS-N2, ELAIS-S1, Lockman Hole, Chandra Deep Field South (CDFS) and the XMM Large Scale Structure Survey field (XMM-LSS). The latter is the only field that exceeded the cirrus threshold selection criterion, but the wealth of survey data over a large area, and especially the available XMM data, that this field provided outweighed the risk of compromising the longer wavelength data. Table 2.6 summarizes the six observed SWIRE fields and Figure 2.3 shows the SWIRE fields superimposed on the 2MASS full sky image.

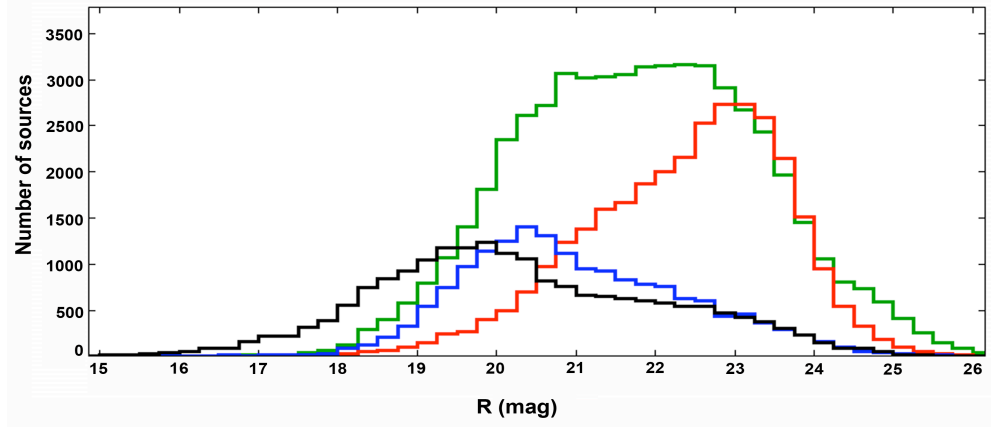


Figure 2.4: Distribution of R magnitudes in SWIRE. Different colour coding denotes different infrared populations according to SED fitting. Black line is cirrus, blue is Arp220, green is M82 and red is dust torus.

2.4.2 Observations

Spitzer observations of the SWIRE fields were designed to return data with high sensitivity and a reasonable number of samples, while still covering large areas with both IRAC and MIPS. The longest Spitzer Astronomical Observing Requests (AOR) are limited to few hours in durations. As a result SWIRE’s observing strategy was to combine together dozens of AOR to map each field, a total of 182 AORs all of which can be retrieved via SPOT, and the frame-level data can be retrieved via LEOPARD. Both tools can be obtained from the Spitzer Science Center.

Each field was mapped with IRAC using a large grid of AOR’s with grid spacing of 280 arcsec, which is 90% of the detector’s width. Each point was covered with 30 sec exposures. The exposure time was chosen as the best trade between sensitivity at the shorter wavelengths and obtaining enough overlapping images. Between frames a small cycling dither pattern was employed. The AOR’S were arranged on a 4×4 grid while the entire grid was repeated in two epochs, each one offset by the other by an 150 arcsec width and follow one another with a temporal spacing of 2.5 hours. Thus for any point on the sky there are a minimum of four independent images on widely spaced parts of the detector array in order to minimize the instrumental signatures arising in the detectors. The entire survey has a minimum of 120 seconds exposure time with some areas having coverages of up to 480 seconds exposure time. Because different IRAC channels share a different field of view the coverage is not the same between bands.

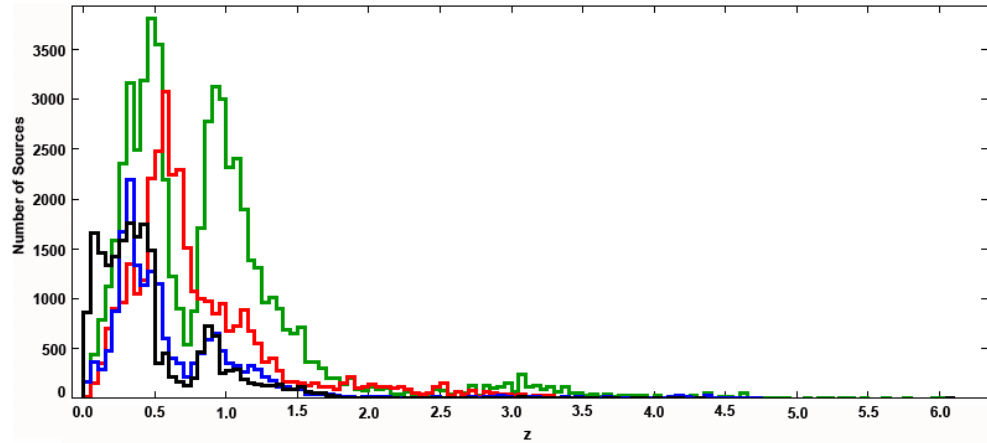


Figure 2.5: Redshift distribution for all SWIRE sources with optical associations. Colours from Figure 2.4.

MIPS observations were performed using the Scan Mode with medium scan rate and a spacing of 148 arcsec. The AORs were arranged into two coverages with the second coverages offset by 150 arcsec in the cross-scan direction. Adjacent AORs were overlapped by 239 arcsec to ensure overlap with the good 70 μm array. This layout provided approximately 40 Basic Calibrated Data images in the 24 μm channel, 20 BCD for the 70 μm band and 4 BCD for the 160 μm channel. Each BCD represents 4 sec exposure time yielding a total integration time per point of 160, 80 and 16 sec for the 24, 70 and 160 μm bands respectively. Due to the rotation of Spitzer’s field of view and the resulting overlap of some regions the latter have slightly higher coverage.

2.4.3 Multi-Wavelength Supporting Observations

Ground based multi-wavelength data were essential for SWIRE in order to allow the team to obtain optical identifications of the huge number of infrared sources observed, accurate well calibrated photometric redshifts in a reasonable amount of time, colours and morphologies for source classification and the study of the effects of environment on morphology, optimize the discovery of high redshift and other rare sources and finally provide independent optical samples for comparisons with infrared selected samples.

The first SWIRE field observed was ELAIS-N1, which is one of the 5 fields observed by ISO as part of the 11 deg^2 ISO ELAIS survey [291]. As a result, extensive supporting data have been obtained. Radio data were obtained with VLA for 1.5

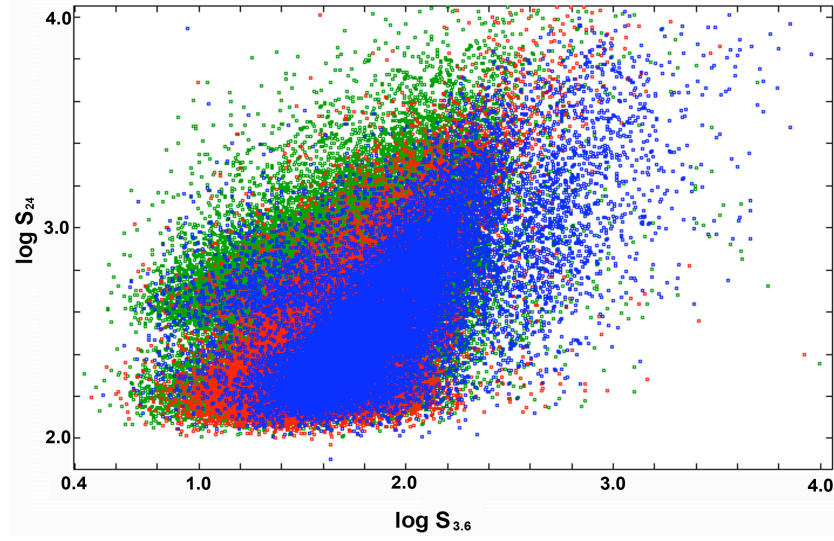


Figure 2.6: Values of $\log S_{3,6}$ versus $\log S_{24}$ for all SWIRE sources with optical identifications. Different colours for different infrared template types: Green dots are sources fitted with one of the two starburst templates, Arp220 or M82, blue dots are sources fitted with a cirrus template and red dots are sources fitted with a torus template.

deg^2 from the 20 cm radio survey down to 0.135-1.15mJy flux limit [56]. Existing X-ray data consisted of only a single moderate depth (75 ks) ACIS-I Chandra pointing [222] which we have extended by a factor of 12 covering a total of more than 1.5 deg^2 [341], described in Chapter 5. Current work has also provided the largest spectroscopic follow up of ELAIS-N1 with almost 300 high quality spectra from GMOS and WIYN [342], described in Chapters 3 and 4. Previous spectroscopic follow ups consisted of a sample of 70 sources observed with IRS [145] and 233 sources observed with Keck in all three northern fields ELAIS-N1, N2 and Lockman [36]. ELAIS-N1 also contains a deep HST-ACS pointing [34]. Other follow-ups include an approved program to survey 9 deg^2 with J, H, K coverage from UKIDSS at limiting magnitudes up to 22.5, 22 and 21 Vega magnitudes respectively and an ongoing GALEX program to survey a total of 10 deg^2 .

Spitzer observations of the XMM-LSS were performed in July 2004 covering a total of 9.1 deg^2 . In addition to the Spitzer and XMM observations, the field is covered also by VLA, GALEX, UKIDSS and CFHTLS as well as by the VIMOS Very Deep Survey [195]. The latter has provided SWIRE with more than 1000 accurate spectroscopic redshifts which along with the 300 spectroscopic redshifts from ELAIS-N1 [342] they were used for calibrating the ImpZ code [283].

	Cirrus	M82	Arp220	Torus	Excess	No Excess
QSO	219	1313	302	2766	2001	11868
Ellipticals	3475	5250	7276	7383	16971	178546
Spirals	17134	47986	13891	22979	108656	542336

Table 2.8: Number of infrared populations according to SED fitting of all SWIRE sources with optical associations [283].

Spitzer observations of the Lockman Hole were carried out in April/May 2004 over a region of 11 deg^2 making it the largest SWIRE field. Since it was originally noted [160], Lockman has been the target for numerous extragalactic surveys in many wavebands. A deep 2MASS survey with $J < 17.8$, $H < 16.5$, $K < 16$ [29] covers the entire SWIRE field. ISO surveys [335][168][95][273] have surveyed various parts of this field from 7 to $175 \mu\text{m}$ while Ciliegi et al [57] have covered the field with radio surveys at 6 and 20 cm. In addition there is extensive millimeter/submillimeter coverage from the Bolocam 1 mm survey [188] and various SCUBA surveys [312][78]. Lockman Hole has been observed with all available X-ray telescopes such as the previous generation ROSAT [138] and ASCA [157] and the latest XMM-Newton [137] and Chandra [360][261].

2.4.4 Optical Data

Optical imaging for the ELAIS SWIRE fields have been obtained with the Wide Field Survey on the 2.5m Isaac Newton Telescope and using the Wide Field Camera [230]. The survey consists of single 600 sec exposures in five bands: U, g, r, i, Z to magnitude limits of 23.4, 24.9, 24, 23.2, 21.9 respectively (Vega, 5σ for a point like object) which is about one magnitude deeper than SDSS. A total of 54 pointings were done in ELAIS-N1 covering a total area of 9 deg^2 . Approximately 70% of the SWIRE ELAIS-N1 is covered by optical data. Optical associations of ELAIS sources using the INT-WFS survey were described by Gonzalez-Solares et al [125]. The same layout was used for ELAIS-N2 with 100% overlap between SWIRE ELAIS-N2 and optical data obtained from WFS.

Deep imaging of Lockman hole has been carried out with the KPNO Mosaic Camera on the 4m Mayall telescope. The survey consists of 5×360 sec exposures in g, r, i to magnitude limits of approximately 25.1, 24.4, 23.7 respectively but vary significantly between pointings. 25 pointings were observed in these 3 filters covering a total of 7 deg^2 . There are also 4 additional pointings which cover the SWIRE-Chandra field

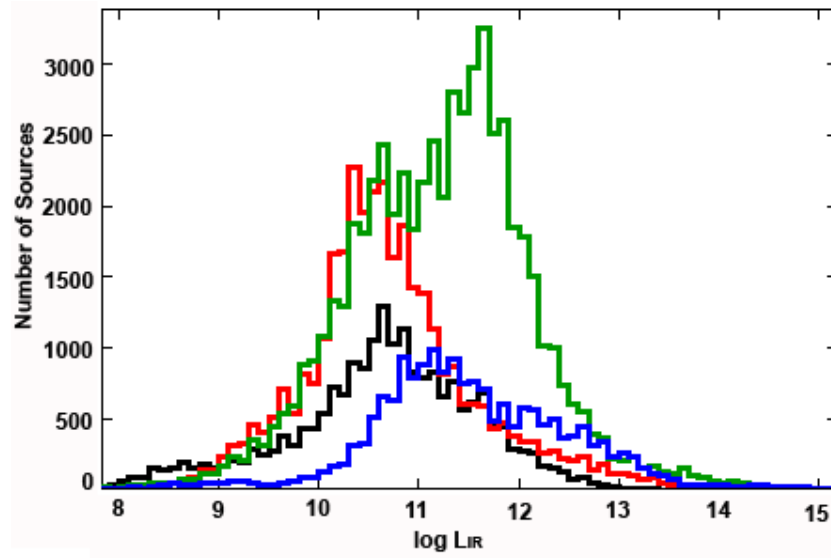


Figure 2.7: Distribution of bolometric infrared luminosities of SWIRE sources. Colours are from Figure 2.4.

which have deep U band imaging with 5×720 sec exposures to a magnitude limit of 24.1.

For the case of XMM-LSS, CFHTLS optical identifications for all SWIRE sources have been provided in the latest SWIRE data release: u, g, r, i, z magnitudes are available, and indication whether they are pointlike in the optical. Table 2.7 summarizes the wealth of imaging surveys conducted within SWIRE fields at all wavelengths. Figure 2.4 shows the R magnitude distribution of all SWIRE sources with available redshifts, fitted with one of the four infrared templates described in §1.5.1.

2.4.5 Status and Results

At the time of writing (December 2007) all of SWIRE fields have had Spitzer observations completed and all of the IRAC and MIPS data have been fully reduced and bandmerged. The latest products public release, SWIRE Version 5.0 includes the final versions of IRAC and MIPS images which consist of the coadded mosaic images for all for all seven imaging bands used. In addition optical images are included for all five optical bands (UgriZ) where available. At the moment there are four primary SWIRE catalogs, a bandmerged catalog consisting of optical, IRAC and MIPS 24 μm fluxes associated with each other and three separate catalogs for 24, 70 and 160 μm . The new version of the catalogs which is anticipated in the following months

will include a bandmerged catalogue which will include also 70 and 160 μm data as long as an asteroid catalogue for the XMM-LSS field.

As mentioned before SWIRE has detected more than 1.5 million galaxies with more than 1 million having highly reliable redshifts [283]. 10% of these have $z > 2$ with 5.6% lying in even higher redshifts of $z > 3$. Figure 2.5 shows the redshift distribution of all SWIRE sources with available redshifts, spectroscopic or photometric, colour coded according to SED fitting. 23.8% of the sources have detections in 24 μm and 1.4% in 70 or 160 μm . Figure 2.6 shows a plot of $\log_{10}S_{3.6}$ versus $\log_{10}S_{24}$ for all SWIRE sources. Sources that have $\log_{10}S_{3.6} < 1.7$ and $\log_{10}S_{24} > 2.5$ are likely to be obscured high redshift type-2 quasars [226]. From Figure 2.6 it is obvious that there are thousands of these candidates, most of which are fitted with a starburst template.

One of SWIRE's key findings is that 4% of the 24 μm sources appear to be HLIRGs. Figure 2.7 shows the distribution of bolometric infrared luminosities for SWIRE sources with available redshifts. Most of the U/HLIRG appears to be sources fitted with a starburst template consistent with existence of large columns of dust. There is also a significant population of ULIRGs fitted with a cirrus template which will be discussed further in Chapter 5.

75% of the sources are fitted with one of the galaxy templates, 22% with an elliptical template and the remaining 3% are fitted with a QSO template. Table 2.8 gives the number of the different populations found by SWIRE for all sources with optical associations.

The latest results from SWIRE are described in Rowan Robinson et al [283] who have demonstrated that when at least 6 photometric bands are used, which only a survey like SWIRE can provide in such an extent, the agreement between spectroscopy and photometry is excellent with less than 1% outliers. Demanding more photometric bands discriminates against high redshift objects, which will start to drop out in short wavelength bands and against quasars. Comparisons with spectroscopy is described in more detail in Chapter 5, especially for the case of ELAIS-N1.

2.5 Future

SWIRE fields are among the best studied sky areas combining multi-wavelength observations of large areas at sufficient depth. As a result, SWIRE fields are natural targets for both current and future follow-ups. The most important among them is the Herschel Multi-Tiered Extragalactic Survey (HerMES) (PI: Oliver) which will make use of 1600 hours of Herschel's time, divided between SPIRE (950 hours) and PACS (650 hours) in order to chart the formation and evolution of infrared galaxies throughout cosmic history. Herschel's sensitivity combined with the ability to fully probe the far-infrared to sub-mm region of high redshift sources, will enable us to measure the bolometric emission of infrared galaxies, study the evolution of the luminosity function, measure galaxies' clustering properties, and probe populations of galaxies below the confusion limit through lensing and statistical techniques. SWIRE has addressed the same questions for sources at $z < 1$ and as a result provides an excellent target sample in order to fully understand the complex processes of galaxy formation up to $z \sim 3$. HerMES planned observations are shown in Figure 2.8.

2.6 Continuation

SWIRE data has been used extensively for the remaining part of this thesis. In the following Chapters I will present three different follow-ups which constitute the largest optical spectroscopic and X-ray surveys performed in SWIRE ELAIS-N1.

Level	Fields	Area RA		Dec	Number of SCANS in each mode						5-sigma sensitivity (ignoring confusion)					Donut Area
					PACS-MED	PACS-SLO W 25"	PACS-SLO W 50"	PARA-LLEL	SPIR-E-FAST	SPIR-E-NOM	110	160	250	350	500	
Clusters Deep	Various	0.01	Various	Various		72				400	2.0	3.0	3.4	4.7	4.0	0.01
Cluster Shallow	Various	0.04	Various	Various		30				240	3.1	4.7	4.4	6.0	5.1	0.04
Level-1	GOODS-S	0.11	03h32m30s	-27d48m17s		112		4	20	240	1.6	1.7	4.2	5.7	4.9	0.11
Clusters Highz	Various	0.03	Various	Various		24				120	3.5	5.2	6.2	8.5	7.2	0.03
Level-2	GOODS-N	0.11	12h36m55s	+62d14m19s		30				60	3.1	4.7	8.8	12.0	10.2	0.11
	ECDFS	0.25	03h32m25s	-27d48m50s			16	4	20	38	5.9	8.3	8.7	11.9	10.1	0.14
Level 3	Lockman-ROSAT	0.25	10h52m43s	+57d28m48s		24		4	20	14	4.8	6.8	11.1	15.2	12.9	0.25
	UDS	0.25	02h17m48s	-05d05m45s		21		7		14	5.1	7.2	11.1	15.2	12.9	0.25
	Groth	0.25	14h19m17s	+52d49m34s		20		7		14	5.2	7.4	11.1	15.2	12.9	0.25
	Lockman-OWEN	0.25	10h46m00s	+59d01m00s		18		4	20	14	5.5	7.8	11.1	15.2	12.9	0.25
	HDFN	0.25	12h36m49s	+62d12m58s						30			12.4	17.0	14.4	0.14
Level-4	COSMOS	2	10h00m28s	+02d12m21s	52					40	6.2	8.7	10.8	14.7	12.5	2.0
	UDS	0.7	02h17m48s	-05d05m45s			7	7		14	8.3	11.8	11.1	15.2	12.9	0.5
	VVDS	0.7	02h26m00s	-04d30m00s			7	7		14	8.3	11.8	11.1	15.2	12.9	0.7
Level-5	XMM	5	02h21m36s	-04d39m00s				7			20.4	29.3	14.0	19.3	16.3	3.6
	ELAIS-N1-SCUBA	2	16h10m00s	+54d30m00s				7			20.4	29.3	14.0	19.3	16.3	2.0
	Bootes-SCUBA2	2	14h32m06s	+34d16m48s				7			20.4	29.3	14.0	19.3	16.3	2.0
	EGS-SCUBA2	1.3	14h19m12s	+52d48m00s				7			20.4	29.3	14.0	19.3	16.3	1.1
	CDFS	8	03h32m00s	-28d16m00s				4	20		27.0	38.8	14.0	19.3	16.3	7.8
	Lockman	11	10h45m00s	+58d00m00s				4	20		27.0	38.8	14.0	19.3	16.3	10.5
Level-6	XMM	9.3	02h21m20s	-04d30m00s				2			38.2	54.8	26.2	36.1	30.4	4.3
	ELAIS S1 SWIRE	7	00h38m30s	-44d00m00s				2			38.2	54.8	26.2	36.1	30.4	7.0
	ELAIS N1 SWIRE	9.3	16h11m00s	+55d00m00s				2			38.2	54.8	26.2	36.1	30.4	7.3
	ELAIS N2 SWIRE	4.8	16h36m48s	+41d01m45s				2			38.2	54.8	26.2	36.1	30.4	4.8
	NDWFS/Bootes	8	14h32m06s	+34d16m48s				2			38.2	54.8	26.2	36.1	30.4	6.0
	FLS	4.7	17h18m00s	+59d30m00s				2			38.2	54.8	26.2	36.1	30.4	4.7
	0444 Akari	7	04h41m24s	-53d22m12s				2			38.2	54.8	26.2	36.1	30.4	7.0
Notes:																
1 Number of scans include the observations from overlapping but shallower AORS																
2 "Area" is the area in this field at this depth																
"Donut Area" is the area excluding deeper cores																
"Cumulative Area" is the total area in the survey above deeper than this																
3 PEP team observations																

Figure 2.8: Summary of fields, areas and depths of HerMES [2].

Chapter 3

Multi-Object Spectroscopy of SWIRE ELAIS-N1 Populations

Above the cloud with its shadow is the star with its light.

Pythagoras (572-490 BC)

3.1 Overview

Multi-object spectroscopy (MOS) is an efficient way of obtaining spectra for several objects at the same time. There are three different ways of doing this technically: with masks having slits cut into them at the place of the objects, with moving 'slit-lets', or with optical fibers. All spectra presented in this chapter have been retrieved by using either mask spectroscopy (GMOS-N) or fiber spectroscopy (WIYN). Extracting one-dimensional spectra from this kind of data faces several problems. Firstly, the large number of spectra which have to be extracted from the two-dimensional frame. Secondly, the slits in MOS spectra are usually much shorter than in 'long-slit' spectroscopy, so special care has to be taken to ensure accurate subtraction of the night-sky emission. Thirdly, the optics of the spectrograph bends the spectra, resulting in curved object spectra on the detector. Some of the reduction steps can be done in an automatic manner, but many require interactive control, making the whole MOS data reduction process, rather time-consuming.

This chapter will briefly summarize the two instruments used and describe the sample selection criteria, the observations and data reduction of MOS data taken with GMOS and WIYN as part of the SWIRE survey. The reduction pipeline is based on the Image Reduction and Analysis Facility (IRAF) [340] and makes use of standard

Grating	Ruling Density	Blaze Wavelength	R	Coverage	nm/pixel
	lines/mm	nm		nm	
B1200	1200	463	3744	143	0.023
R831	831	757	4396	207	0.034
B600	600	461	1688	276	0.045
R600	600	926	3744	286	0.047
R400	400	764	1918	416	0.067
R150	150	717	631	1071	0.174

Table 3.1: GMOS-N Gratings [3].

IRAF reduction tools developed within the IRAF command language environment. In the case of the GMOS data the specialized Gemini IRAF package was used while for the WIYN data the specialized DOHYDRA reduction task was incorporated. Since only few detailed descriptions of MOS data reduction are available, this chapter is intended to serve as a technical guide to MOS data reduction. All work presented in this chapter was a collaborative effort by the author, Dr Duncan Farrah and Dr Antonis Georgakakis for the GMOS spectroscopic follow-up and by the author and Dr Ivan Valtchanov for the WIYN spectroscopic follow-up.

3.2 The Gemini Multi-Object Spectrograph North

3.2.1 General Characteristics

GMOS-N is a multi-object spectrograph on the 8 m Gemini North telescope which was built by a collaboration between UK and Canada, was delivered in July 2001 and entered regular science service in late 2001. Three 2048×4608 CCD with $13.5 \mu\text{m}$ pixel, optimised for the red end of the optical length region, are used to provide $0.36\text{--}1.1 \mu\text{m}$ long-slit, multi-slit spectroscopy broad and narrow-band imaging over a 5.5 arcmin field of view [150]. Spectral resolution varies with different gratings (Table 3.1). A summary of the main instrument specifications is given in Table 3.2 and a schematic of the detector array is shown in Figure 3.1.

3.2.2 MOS

In multi-slit mode GMOS-N is able to locate several hundred slits in a single mask. A total of 18 masks can be loaded into GMOS at any given time with up to six hundred slitlets over a 5.5×5.5 arcmin² field of view.

Characteristic	Specification
Wavelength Range	0.36-1.1 μm
Field of view	$5.5 \times 5.5 \text{ arcmin}^2$
Image scale at detector	0.072'' per 13.5 μm pixel
Minimum slit width	0.2''
Spectral resolution	$R = 5000$ to $R = 500$ with 0.2'' slit
Integral field Capability	Remotely deployable, 0.2'' pixels with 52 arcsec^2 field
Detector	6144 $\times$ 4608, 13.5 μm pixel 3×1 EEV CCD array

Table 3.2: Specifications of the GMOS-N instrument [150].

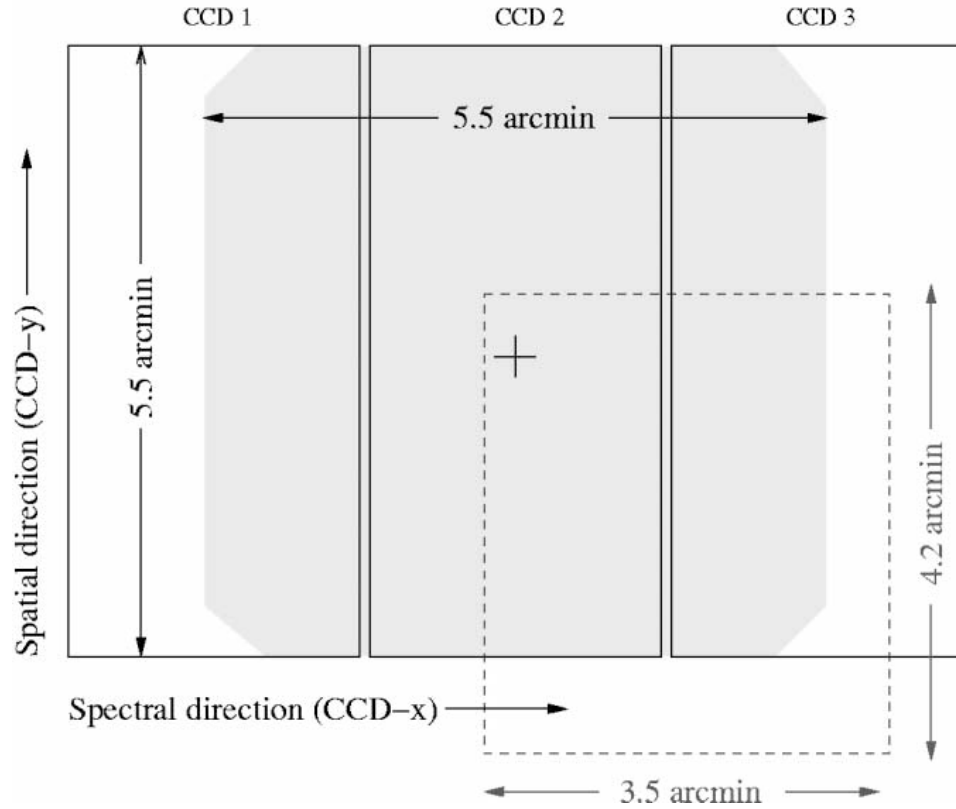


Figure 3.1: Schematic diagram showing the layout of the three GMOS-N detectors. The small gaps between the detectors of about 0.5 mm correspond to about 37 pixels. The shaded region represents the imaging field of view while the dotted line shows the on-instrument wave-front sensor patrol field, projected onto the detector plane [150].

Full Unignetted Field Size	60 arc-minutes diameter
Minimum Fiber to Fiber Separation	37 arc-seconds
Positioning Accuracy	0.3 arc-seconds rms
Configuration Time (100 Fibers)	20-25 minutes
Total Number of Fiber Slots	288
Number of Guide Fibers	10
Number of Available Science Cables	2
Number of Active Fibers per Cable	90 Red, 83 Blue
Fiber Cable Length	25 meters
Blue Cable Spectral Window	3000-7000 Angstrom
Blue Cable Fiber Diameter	3.1 arc-seconds
Red Cable Spectral Window	4000 Angstrom- $1.8\mu\text{m}$
Red Cable Fiber Diameter	2.0 arc-seconds

Table 3.3: Hydra Positioner Characteristics

3.2.3 IFU

GMOS-N is also equipped with an Integral Field Unit (IFU) [11] making it possible to obtain spectra simultaneously of an area of about 35 arcsec^2 with a sampling of 0.2 arcsec . This mode is based upon using a 1500 element array in the pre-slit environment to slice the focal plane into a multitude of small components which allows to reconstruct an image at a particular wavelength, or extract a spectrum from any point in the field of view. The science field of view is 35 arcsec^2 and is sampled by 1000 elements. The sky is sampled with 500 elements which are located $\sim 1 \text{ arcmin}$ away from science field of view.

3.2.4 Nod & Shuffle

One of the most interesting modes on GMOS is Nod & Shuffle [124] which provides superior sky subtraction and increases the density of the slits. Its main handicaps are the increased observing time required and the smaller field of view. The basic concept of this method, which is adapted from the near-infrared astronomy nodding or beam-switching, is that unilluminated portions of the CCD can be used for storage. In this mode the telescope is frequently nodded between an object and a sky position while at the same time it shuffles the charge on the CCD detectors between science and unilluminated regions. This technique provides the observer with images that contain two spectra, one of the object and one of the sky. Even though these two spectra are stored in different regions of the CCD, they were imaged with exactly the same pixels through identical optical paths. As a result when one subtracts the sky spectrum from the object spectrum one will be able to achieve

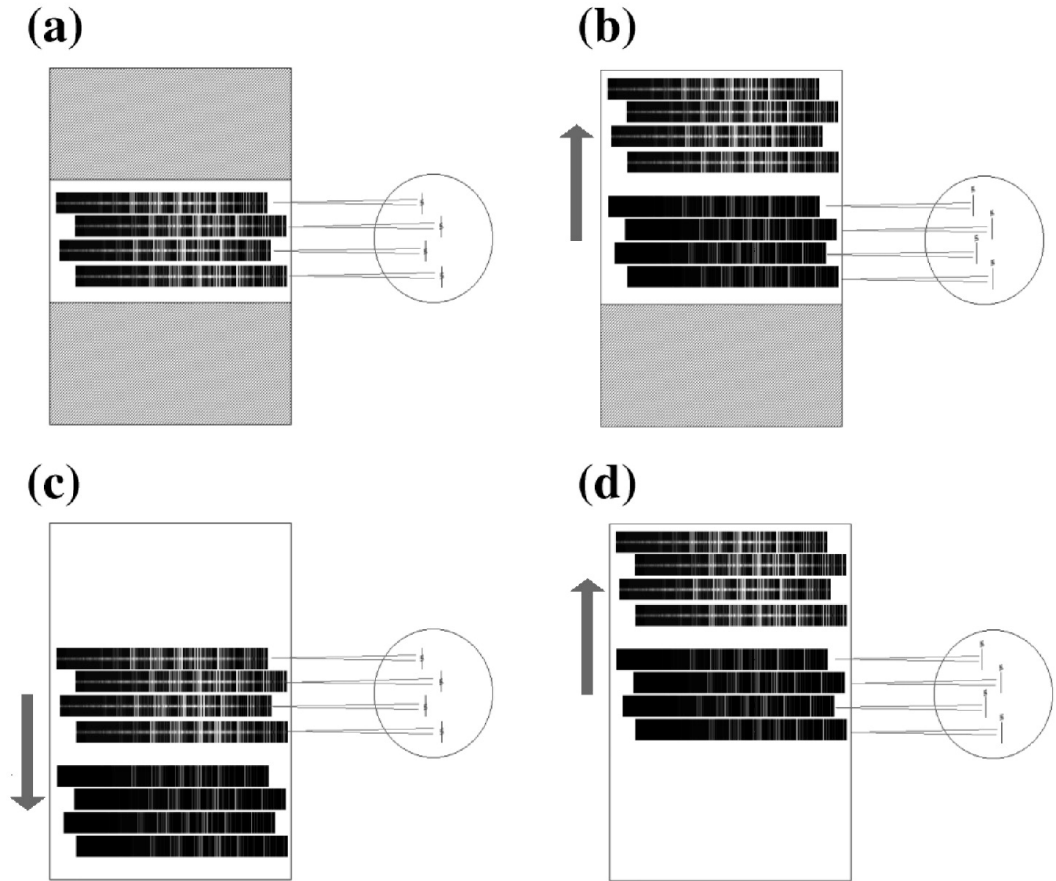


Figure 3.2: Illustration of the nod-shuffle procedure implemented in the LDSS spectrograph showing progressive stages of image formation. (a) The spectra of the objects through the slits is imaged onto the central portion of an oversized CCD. (b) The first image is shuffled up into a storage region (with the shutter closed), and the telescope is offset to adjacent sky which is then imaged onto the now empty central region of the detector. (c) The object image is shuffled back and additional object photons are imaged. (d) Sky is shuffled back and imaged. Steps (c) and (d) are cycled continuously until the integration is complete. Figure and caption from [124].

Available Gratings	7
Minimum Fiber to Fiber Separation	37 arc-seconds
Cameras	Simmons (f.i. 381 mm, 3000 Å-1.5 μ m)
	Bench (f.i. 285 mm, 3800 Å-1.5 μ m)
Total Number of Fiber Slots	288
Collimator	6 inch f/6.7 Paraboloid
Camera Collimator Angle	Variable between 11 and 45 degrees
Detector	2048 (24 μ m-pixels) CCD
Typical Resolution Element	2 to 4 pixels
Spectral Coverage	100 Å to 1 octave

Table 3.4: Bench Spectrograph Characteristics

sky subtraction accuracies as good as 0.04% [124] with the trade-off of almost a factor $\sqrt{2}$ higher noise in the sky-subtracted spectrum. Due to the fact that the sky spectrum is derived from regions adjacent to the object much shorter slits can be used. This results in an increase of the number of slits in MOS mode of up to a factor of 10. However since a part of the detector is used for storage and remains unilluminated the field of view is reduced by up to 50%. An example of how Nod & Shuffle works is given in Figure 3.2.

3.3 WIYN Hydra

Hydra is a multi-object spectrometer that utilizes fiber optics on the 3.5 meter WIYN Consortium (University of Wisconsin, Indiana University, Yale University and National Optical Astronomy Observatory) telescope.

Two science fiber cables are available on Hydra but only one can be used for a particular configuration. The red cable has a constant transmission between 5000-10000 angstroms while the blue one is shortward of 4000. The larger diameter fibers of the blue cable can provide larger capabilities below 7000 angstroms. The spectrograph used with Hydra is a bench stable spectrograph that permits easy changes of configuration between high and low dispersion and between various spectral regions. There are four filter slots available but currently only three are used. One slot can hold thick filters up to 0.35 inch for Echelle grating and the other two available slots can hold thinner glass filters of up to 0.25 inch. The main characteristics of the fiber positioner and the spectrograph are shown in Tables 3.3 and 3.4 respectively [24].

3.4 Selection and Observations

3.4.1 GMOS

We observed the SWIRE-EN1 field with the Gemini Multi-Object Spectrograph on the 8.1-m Gemini North telescope. The observations were carried out in queue-scheduled mode during 2005 April 03 to 2005 May 15. GMOS provides multi-slit optical spectroscopy over a 5.5-arcmin field of view. We used the 400-lines/mm red grating (R400_G5305) at a central wavelength of 7500 Å. Nod-and-shuffle mode was used, with a 3.0 arcsec nod along a 5-arcsec slit and a charge shuffle of 5.1 arcsec. A single integration consisted of fifteen cycles, each cycle being a sequence of four nods in a BAAB configuration (where A & B represent the different nod positions), each of 30 s duration, giving an integration time of 1800 s. This was then repeated with the central wavelength offset by 50 Å, to give full wavelength coverage across the gaps between different CCDs. Thus each source was observed with a total integration time of 3600 s. Thirteen masks were observed, with an average of 18 slits per mask, giving ~ 230 objects in total.

Within the SWIRE-EN1 field, we have X-ray observations taken as part of the ELAIS Deep X-ray Survey [222]. These consist of a single 71.5-ks pointing with the *Chandra* X-ray observatory's Advanced CCD Imaging Spectrometer, covering an area of 17×17 square arcmin. There are 102 sources in common between *Chandra* and SWIRE, with X-ray fluxes brighter than 2.3×10^{-15} ergs s $^{-1}$ cm $^{-2}$ in the 0.5–8 keV band [112]. We covered this area with six pointings of GMOS, each pointing having a field of view of 5.5×5.5 square arcmin, observing a total of 14 X-ray AGN from the ELAIS N1 Deep X-ray survey. Figure 3.3 shows an image of the central region of this area retrieved from SAO-DSS. Sources with extracted spectra are shown as green circles.

There is a single deep *Hubble* Space Telescope observation within the SWIRE-EN1 field [34], taken as part of the early release observations of the Advanced Camera for Surveys (ACS). The ACS field is centred on the Tadpole galaxy (also known as UGC 10214, VV 29 and Arp 188), a bright spiral at $z = 0.032$ with an extended tidal tail [161]. This 14 square arcmin image includes 156 galaxies detected by both ACS and SWIRE [139]. We observed this field with one GMOS pointing.

Our choice of GMOS pointings was a balance between exploiting our deep X-ray data and sparse sampling the SWIRE field to allow for cosmic variance. In addition

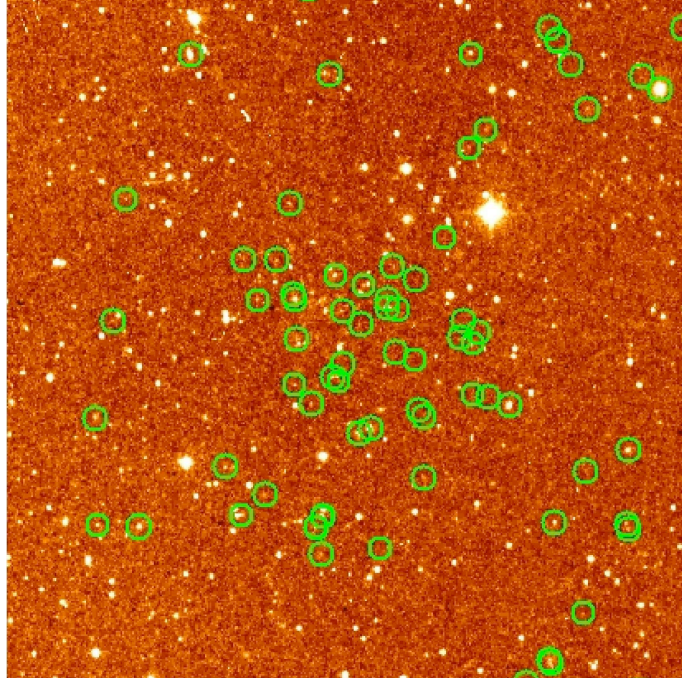


Figure 3.3: SAO-DSS $20' \times 20'$ image of the ELAIS-N1 Deep X-ray Survey central region. Green circles indicate sources with extracted spectra from our GMOS and WIYN spectroscopic follow-up. The radius of each circle is $20''$.

to the ACS field, we selected a further six GMOS pointings, randomly scattered across the SWIRE field, in order to reduce the possibility of observing sources in the same large-scale structure.

A target list for each field was prepared from the photometric redshift catalogue, selecting sources with $21.5 < r < 23.5$ mag. These sources were then distributed between three prioritized groups, with top priority given to X-ray sources in the *Chandra* fields. Next priority were sources with either (i) optical or infrared SEDs identified as AGN in the catalogue, or (ii) photometric redshifts $z > 1$. Finally, all other SWIRE sources with $21.5 < r < 23.5$ were assigned to the lowest priority group. The mask preparation software used these priorities in automatically assigning slits to objects in the target list and we were able to place 15–20 slits on each of the thirteen masks (excluding acquisition/guide stars).

3.4.2 WIYN

A selected number of sources from an area of approximately one square degree was included for spectroscopic observations on the NOAO WIYN 3.5m telescope using

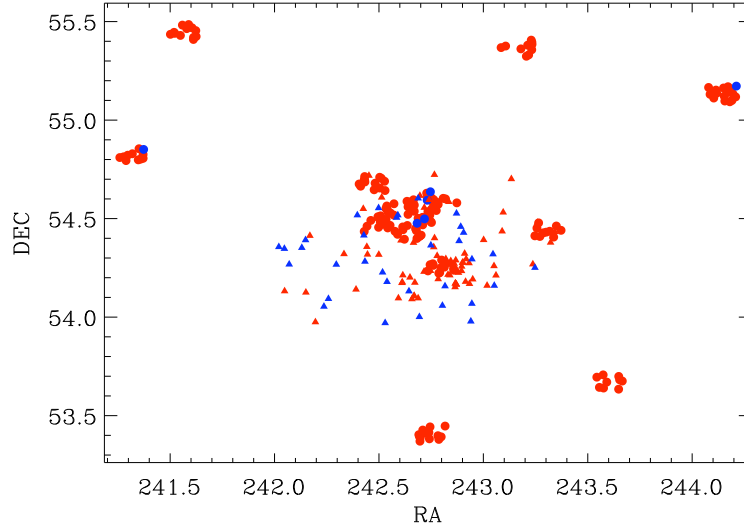


Figure 3.4: RA, DEC positions of all extragalactic sources observed with GMOS (circles) and WIYN (triangles). Different symbols represent different optical SED fits. Blue sources are sources fitted with a QSO template while red denotes the sources fitted with a galaxy template.

HYDRA multi-object bench spectrograph. The observations were performed with the red and blue wing of the camera on two different runs: the red run took place on 12-14 April 2005 and the blue run on 2-4 July 2005. Both runs were half nights and there were quite significant weather changes which complicated the subsequent redshift measurements.

The object selection included sources detected in the Chandra and XMM fields, SWIRE infrared selected sources classified as dust torii, $24\mu m$ sources, as well as galaxies from the two clusters and the region between them. The objects had to be brighter than 21mag in R-band. The candidate targets were ordered by the following priority: brightest cluster galaxies, X-ray detected sources (from both Chandra and XMM), sources fitted with a dust torus template, galaxies from the region between the two clusters, $24\mu m$ sources. This selection was used by the automated procedure which allocated the fibers in the field. In a couple of cases an optimization by hand was possible. For the second run (using the blue wing of the spectrograph) the priority was given to those objects already observed with the red spectrograph and the new objects were concatenated at the end of the list. Figure 3.4 shows the positions of all sources with extracted spectra.

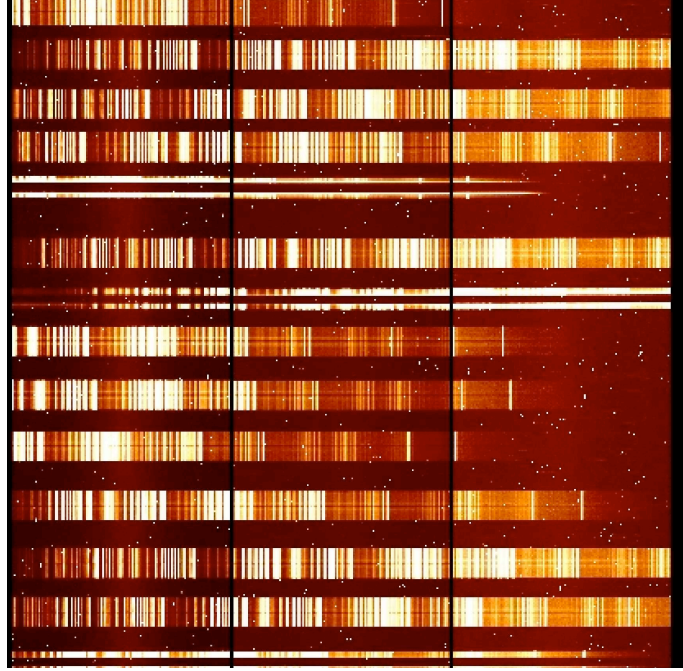


Figure 3.5: Raw GMOS image from the ACS field using the ds9 application. GMOS users have to set ds9 in order to be able to display multi-extension fits images by using the command `stdimage=imtgmos4`.

3.5 Data Reduction

3.5.1 GMOS

Data reduction was carried out with the then recently updated v1.8 GMOS package within IRAF within the v2.12.2a Gemini IRAF package. The reduction pipeline recipe I used for this set of data is detailed below. Since there is no standard GMOS reduction pipeline available, this method may need to be changed significantly for other sets of data.

- (i) The first thing to do is to prepare raw GMOS images (Figure 3.5) for reduction using GPREPARE which is used to generate and attach the variance,

$$var = (readnoise/gain)^2 + (data/gain), \quad (3.1)$$

data quality extensions and the Mask Definition Files (MDF) to GMOS spectra where read noise is given in terms of the number of electrons introduced per pixel into the final signal upon readout of the device and gain is the number of received photons needed to produce one count. It is highly recommended that when using this command not to attach both variance and data quality

extensions since not all tasks in the GMOS package are tested with this option. Input raw images should be multi-extension FITS files. After being processed with GPREPARE, data extensions will be named as defined by the parameters and several additional header keywords will be added. In order to display the newly prepared GMOS data using the ds9 application the GDISPLAY task is used. GDISPLAY is available with four different display buffer sizes. The one used for the remaining of the reduction was the full size display of full frame images from GMOS. GPREPARE has to run on all files in order for the other tasks to run properly.

- (ii) In the second step we create a combined bias image with GBIAS. In the case of GMOS-N data bias and dark frames are essentially identical as it has very little dark current. Before using GBIAS all the input biases must be prepared using GPREPARE (step 1). Then the prepared bias images are averaged and combined.
- (iii) In the third step we make the coadded flatfield using GSFLAT. We have trimmed the image and subtracted the combined bias image. In this way we generate a normalized lamp spectroscopic flatfield. The main function of GSFLAT is to remove both this normalized flatfield, the GMOS spectral response and the uneven illumination from the flatfield image and leave only the pixel to pixel variations and the fringing. It is important to set properly the offset in the spatial direction between the theoretically predicted position of the spectra and the actual position. The default is 6.0. This means that if we set it to 5.0 we will have a 1 pixel shift downwards, and so on. In the case of this sample 22.0 proved adequate. After testing various functions we found the optimum to be a cubic spline fit of order 5 on CCD1, an 11th order on CCD2 and a 13th order in CCD3. Each of these fits has to be tested for at least two slits. We have fitted the function to one detector at a time so that the output flatfield to have three science extensions, one for each detector. This will subtract the large scale structure but not every individual distortion.
- (iv) In the next step we mask out the leaked emission line in the flatfield files. This is done by using IMREPLACE to replace the bad region with values of 1.0. This leak emission originates from the fact that the filter has a leak which appears as an emission line in the flats from the halogen lamp.
- (v) We then remove the cosmic rays contamination using the GSCRREJ task. This task identifies cosmic rays by comparing with a high order model. Pixels

that are found to be affected are replaced by the model values.

- (vi) By now we have a dark frame which also has the bias response and flatfields with the bias response removed. The raw science data has bias, dark and flat contaminant that need removing. In order to remove them we run GSREDUCE for each data frame which have the same wavelength grating as the coadded flatfield to perform a basic reduction of the images. In this step the images are trimmed, the combined biases subtracted and a flatfield correction is applied using the coadded flatfield from step 3.
- (vii) In the next step we combine the nod and shuffle frames and do the sky subtraction by using the GNSSKYSUB [7]. In this case the input image is self-subtracted by a shifted version of itself, so that a spectrum at a given nod position has a spectrum of the sky, obtained through exactly the same light path, removed. The final output of this task is a set of positive and negative object spectrum pairs, both of which are sandwiched between a pair of positive and negative sky spectra. To create the final one-dimensional spectrum the positive and negative sky-subtracted object spectrum pairs need to be separately extracted and co-added.
- (viii) Then we use GSREDUCE again to mosaic and cut into slitlets. This is achieved by providing an initial wavelength calibration based on the grating and central wavelength, interpolating across the detector gaps and then cutting the images into slitlets with one slitlet per science extension (Figure 3.6).
- (ix) The next act is to use GSTRANSFORM to make the wavelength calibration for each frame. In order to this task to run properly the database directory with the appropriate wavelength transformations needs to be defined. This is achieved by running GSWAVELENGTH on the appropriately reduced arcs.
- (x) We then use SCOMBINE to combine all the data frames into a single file. In this dataset we had 6 files in total per mask. Three per central wavelength.
- (xi) The final step is to copy out the file with IMCOPY, negative it, by using IMARITH, shift it up by using IMSHIFT and finally add everything together by using COMBINE. Remaining files used in the intermediate steps are deleted with IMDEL.
- (xii) In the final step we determine redshifts. Redshifts were determined by visual inspection of the one dimensional spectra extracted with the APALL task



Figure 3.6: Image of a GMOS mask after been mosaiced.

(Figure 3.7), through the identification of emission and absorption features using the RVIDL task which measures radial velocities from spectra by determining the wavelength shift in spectral lines relative to specified rest wavelengths. The presence of strong emission and absorption features such as CIV , $[CIII]\lambda 1909$, $MgII$, NeV , $[OII]\lambda 3727$, $H\beta$, $[OIII]\lambda 4959$, $[OIII]\lambda 5007$, $H\alpha$, $[NII]\lambda 6583$ directly indicated the redshift, especially in the cases where at least two of these lines were present. We successfully derived 192 redshifts. A quality flag was assigned to each redshift similar to that adopted in the CFRS survey [193]. Out of the 192 extracted redshifts 162 are secure ones while the remaining 30 are either single emission line objects usually fitted with OII or $H\alpha$ lines or very noisy spectra with very weak features which didn't allow us to make a safe estimation of their redshifts. Examples of GMOS spectra are given in Figures 3.8 and 3.9.

3.5.2 WIYN

The observations were reduced following the standard procedure for HYDRA. For most of the sources we had both blue and red parts, the blue covering the wavelength range 3500–6500 Å. and the red one 5000–10000 Å. We successfully derived redshifts for 137 from 146 objects from which some 40 objects were identified at redshift 0

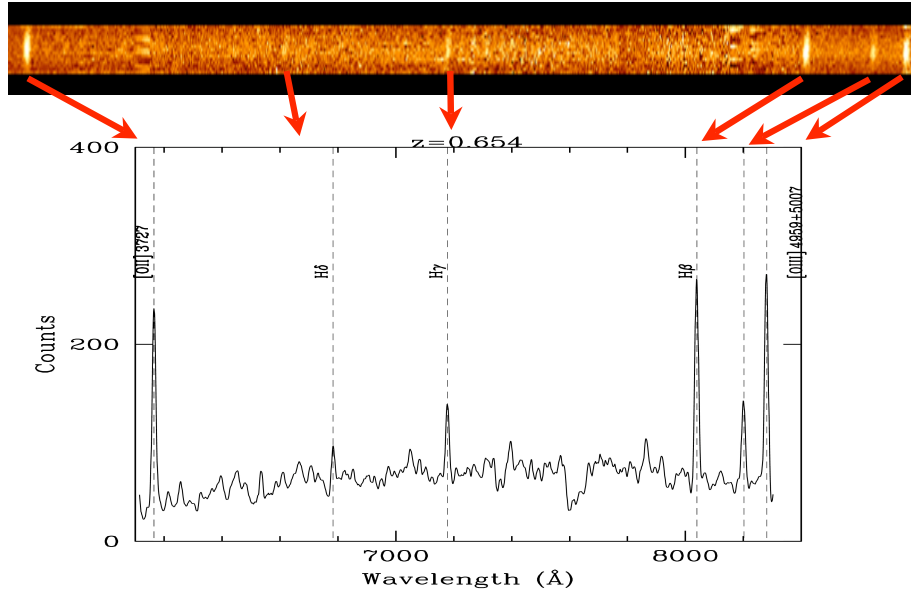


Figure 3.7: An image of an individual slitlet with prominent emission lines and the resulting one dimensional spectrum.

(stars), mostly from the $24\mu\text{m}$ selection, but some XMM and AGN classified sources also have redshift 0. The reason for such a high number of stars is that the selection was based on an older version of the SWIRE catalogue at the early stages of the survey containing a large number of stars not properly removed.

3.5.2.1 Preliminary Steps

Data Reduction was performed using IRAF. Since the data were obtained using CCDs as detectors, the standard CCD reduction was performed with the IRAF CCDRED package [346].

- (i) The first step was to list the different files with their identification using the CCDLIST task, which helps us to identify zero files, flats, comparison lamp exposures, spectrophotometer standard and the objects. For our convenience, three different lists containing only the flat-fields, zero exposures and object exposures were created for subsequent use.
- (ii) Our next act was to create one zero level file to be used for all images. This task was performed with ZEROCOMBINE which combines all bias frames into an average frame but with the highest value being ignored when forming the average for any given frame.

- (iii) The next task is to set up the translation table between the header information and things that CCDRED would like to know. The task used for setting up this translation file is the SETINSTRUMENT task. In Hydra's case the translation file was set for fibers.
- (iv) Using the CCDPROC task we apply bias, trim, overscan and zero level corrections to all files.
- (v) Then by using the FLATCOMBINE task we combine all flats by using an averaged sigma clipping algorithm to reject pixels.
- (vi) Object frames are combined with the IMCOMBINE task. For this step the pixels were combined by computing a weighted average while in this step pixels are rejected using the CRREJECT algorithm which rejects pixels above the average. In order for this algorithm to work properly all images should be obtained using CCDs with known read out noise, gain and sensitivity parameters which in this case they were read directly from the image header.

3.5.2.2 Hydra Reduction

In the Hydra manual [24] each object observation is reduced (flat-fielded, aperture extraction, and wavelength calibrated) independently and the calibrated files are then combined with scombine. This is the best strategy when an absolute flux calibration is needed, because each observation (including the spectrophotometric standard) is corrected for airmass and exposure independently. We have followed a rather different approach which is briefly summarized in first combining the files and then do the reduction. With exposures of up to 30 min the shifts in pixel coordinates between the subsequent observations are not significant. In this way the benefit is that the sky spectra will not be affected by cosmic hits. In this case, the flux calibration will only be relative. For this part of the reduction we have used the specialised HYDRA package included in the IMRED package. The steps followed are the following:

- (i) The command language script used for the remaining of the reduction was the DOHYDRA reduction task. When running it the user has to define the list of object spectra to be processed, an aperture reference spectrum, which typically is a flat field spectrum, a flat field spectrum and a list of primary arc spectra.

- (ii) When all of these are defined and DOHYDRA has ran properly, the user enters in the interactive part of the process which allows him to resize and edit apertures.
- (iii) Then the user will need to reorder the apertures.
- (iv) Then the task asks the user to fit the traced positions interactively and fit the curve to aperture.
- (v) The user can delete points on the fitted curve of the trace of the aperture and refit if there are deviant ones.
- (vi) Once done, the flat fields will be extracted and a response function will be created for all fibers that includes the throughput. It is then renormalised and applied to all fibers. Then the task will extract the comparison lamp. At least 3, 4 lines will have to be identified and then fitted. It is preferable to use chebyshev polynomials of order 4 for the fit.
- (vii) The procedure then extracts the apertures, assigns the arcs and dispersion and corrects the objects spectra. In the next step the pipeline enters in the sky subtraction phase. In this case we have used the average sigma clipping for sky rejection which should be able to delete most of the deviant spectra. In case there are some left, they can be deleted interactively.
- (viii) The spectra are then flux calibrated using spectro-photometric standard stars observed during each night. In this step DOHYDRA task is used again in order to find the aperture with the standard star. This is then copied to an one-dimensional spectrum. In order to extract the calibration data of the standards and interpolate between the desired starting and ending wavelengths the task LALIB was used. Finally the observed calibration star is divided to the one with the flux.
- (ix) Redshifts were determined using the RV package within IRAF. Prominent absorption and emission lines were identified in the spectra in order to determine the redshifts using RVIDLINES task. An alternative method used, where feasible, was by using a cross-correlation technique. There are two packages IRAF/rv with fxcor and IRAF/rvsao with xcsao. The procedure consists of cross-correlating a template spectrum with known redshift and the object spectrum. The maximum correlation coefficient corresponds to a shift of the template that matches the objects. This shift determines the redshift.

The obstacles are the atmospheric absorption bands which must be masked, otherwise they can give a false signal or noisy correlation coefficient. Examples of WIYN spectra are given in Figures 3.8 and 3.9.

3.6 Cross-Correlation with SWIRE

Since GMOS and WIYN sources were selected from SWIRE, it is expected all of the sources to have a SWIRE counterpart and that the number of random associations is very low. In order to identify the objects with spectra in SWIRE we have used a simple cross-correlation algorithm that looks for associations/counterparts between the two catalogues. For each source in the spectroscopic catalogue it looks for sources in the SWIRE catalogue that fall within a given search radius, r , from each GMOS/WIYN source. When it picks up more than one optical association, the nearest association is selected. This algorithm implements a nearest-neighbour cross correlation method based on minimizing

$$D = \sqrt{(RA_2 - RA_1) \times \cos(DEC_1)^2 + (DEC_2 - DEC_1)^2} \quad (3.2)$$

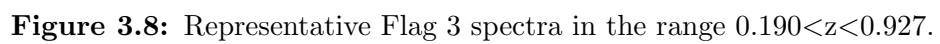
and calling this an association when $D < r$. We have applied a search radius of 1 arcsec. For all 289 spectroscopically identified extragalactic sources a SWIRE counterpart was found within the applied search radius. 95% of the sources have an association within 0.5 arcsec.

The way to quantify the expected rate of random associations when using a simple nearest-neighbour algorithm is to randomize the source catalogue (SWIRE) but keep its source density constant. This is achieved by applying various coordinate shifts greater than the search radius

$$RA_{Shifted} = RA \pm R \quad (3.3)$$

$$DEC_{Shifted} = DEC \pm R \quad (3.4)$$

and carry out the association process with the object catalogue (GMOS/WIYN) in exactly the same way. The obtained rate of identifications is the expected number of random associations, which sets an upper limit to the rate of spurious associations. The average number of random associations was found to be only 1/289 sources (0.3%), as expected. Number of associations and cumulative percentage of associations are shown in Figure 3.10.



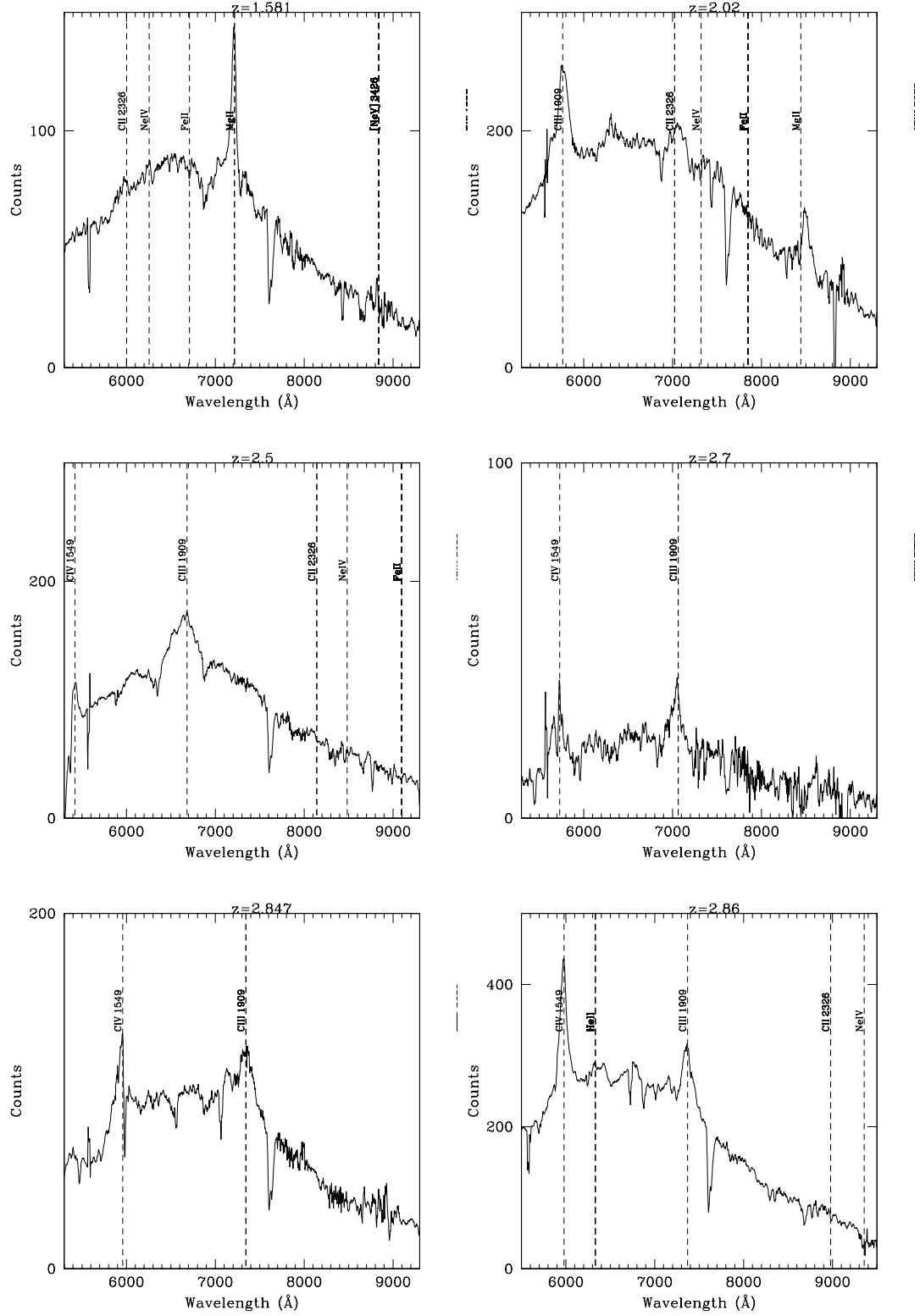


Figure 3.9: Representative Flag 3 spectra in the range $1.581 < z < 2.86$ all of which are spectroscopically identified broad line AGN.

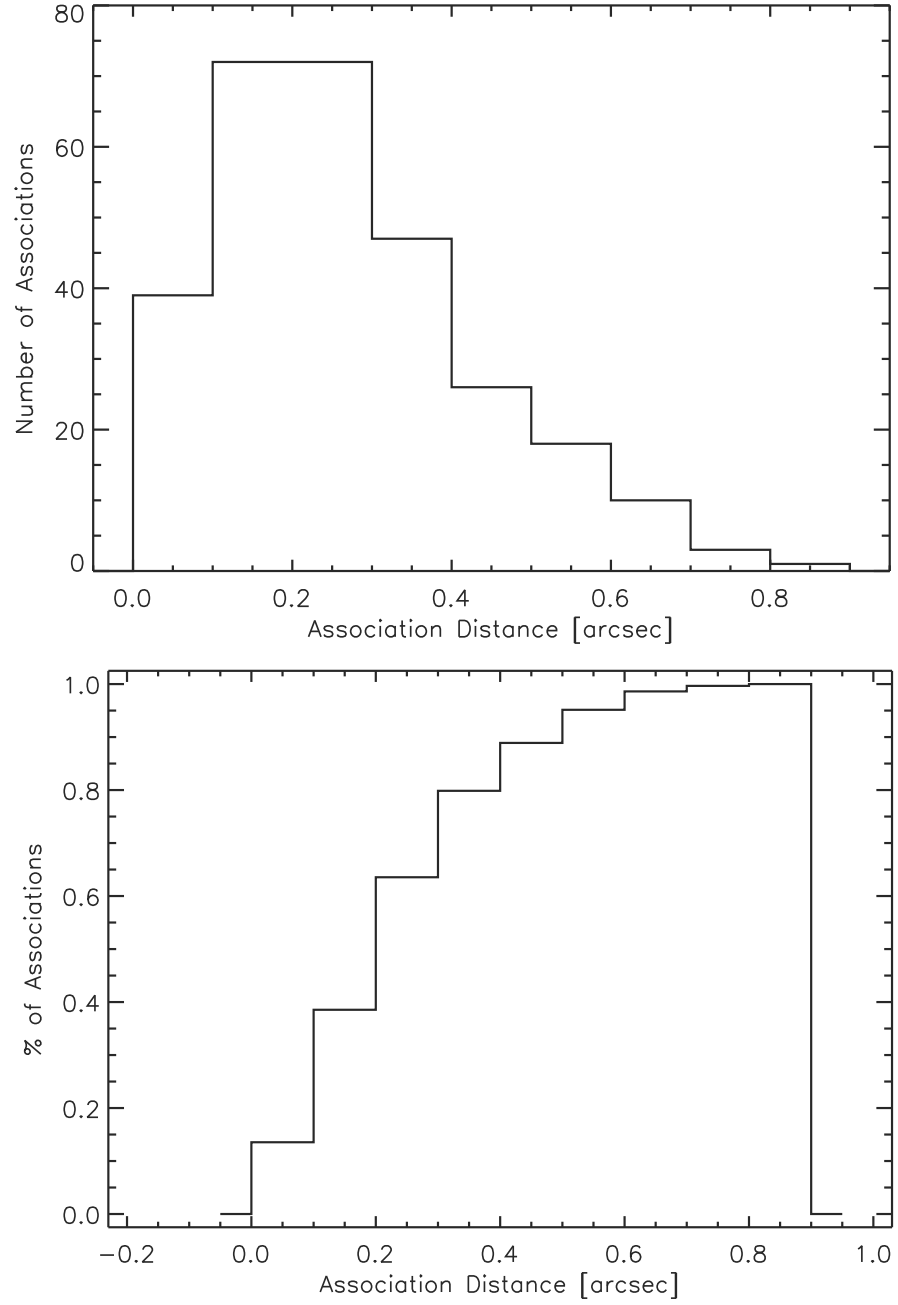


Figure 3.10: Astrometric accuracy. Positional difference between spectroscopically identified sources and SWIRE.

3.7 Number of Spectra and Object Classes

GMOS/WIYN spectroscopic follow-up represents the largest optical spectroscopic sample obtained in ELAIS-N1 with a total of 376 objects observed. We were able to successfully determine redshifts for 329 sources, a success rate of 88%. For the remaining 47 sources a redshift could not be determined due to the bad quality of the spectra or the lack of prominent spectral features in the wavelength range covered. Out of the 329 successfully identified objects, 40 (12%) were found to have redshift 0 (stars) mostly from the $24\mu\text{m}$ selection, but some XMM and AGN classified sources also found to have redshift 0. For the remaining of this work only the 289 objects identified as extragalactic sources will be used. From this sample 244 (84%) found to be star-forming galaxies or not specified, 13 (5%) were spectroscopically identified as narrow line AGN and 32 (11%) were recognized as broad line QSO.

The extragalactic catalogue contains 110 (38%) LIRG ($L_{IR} > 10^{11}$ solar luminosities). Among them there are 6 HLIRG and 41 ULIRG with $L_{IR} > 10^{13}$ and $L_{IR} > 10^{12}$ solar luminosities respectively. From the 289 sources, 19 (7%) are fitted with a Cirrus infrared template, 32 (11%) are fitted with a starburst infrared template, 64 (22%) are fitted with a dust torus template and the remaining are either single band infrared excesses or sources that appear to be bulge dominated. According to the optical templates best fit 61 (21%) are ellipticals, 189 (66%) are spirals and 39 (13%) are fitted with a QSO template. All but two sources have $3.6\mu\text{m}$ detections, 172 (57 %) have $24\mu\text{m}$ and 15 (5%) have $70\mu\text{m}$.

3.8 Confidence Classes

The number of objects in the confidence classes are given in Table 3.5. The objects with high quality spectra are the second and third confidence classes which contain 209 (72%) sources. For the latter the redshift estimation is considered highly secure. For Flag 1 objects the redshift should be considered as an educated guess. Nonetheless, the fact that the estimated redshifts for Flag 1 objects is very close to the photometric redshifts of the same objects (see Chapter 4) has allowed us to include them in the final spectroscopic catalogue. All objects with prominent single emission lines are to be found in Flag 9 which contains only about 5% of all extragalactic sources and as a result they do not contribute significantly to our database. All of these sources were fitted with an $[OII]\lambda 3727$ line in accordance with the analysis presented for the CFRS survey [193].

Flag	Notes	Number	%
1	Weak spectral features. Insecure	63	22
2	Two or more matching lines. Highly secure	71	25
3	Three or more strong spectral features. Certain	138	48
9	Single emission line object. Assigned to OII	15	5
Total		289	100

Table 3.5: Distribution of extragalactic objects into the confidence classes used in the final spectroscopic catalogue.

3.9 Redshift Distribution

The redshift distribution of the spectroscopic sample is shown in Figure 3.11. The WIYN distribution starts to cut-off at redshift of 0.4, because many of the sources observed during this run were targeted between the regular, north-eastern and the irregular, south-western cluster and as result lied at lower redshifts. In addition most of the 24 μm sources targeted were also at $z < 0.5$. The lack of objects with redshifts from WIYN spectroscopy in the range $0.6 < z < 0.7$ is most likely due to the limits of the instruments spectral range. Objects with these redshifts have their OII and $\text{H}\alpha$ lines shifted around the upper end of the spectral range. A small secondary peak appears for galaxies at redshift $z \sim 1.2$. All of these sources have prominent MgII lines and are sources which were classified as dust torii by the photometric redshift code [283] .

In the case of the GMOS run there is a peak at $z \sim 0.9$ due to the fact that most of the sources selected for this sample were selected to have photometric redshifts of ~ 1 . In addition all of the single strong emission line objects which were fitted with an OII line would appear to lie at a redshift range of $0.8 < z < 1.0$ which even though they consist only 5% of the sample they contribute to the primary peak. A secondary peak which appears at very low redshifts are sources with very strong $\text{H}\alpha$ lines selected from the 24 μm SWIRE sample. The much lower number of high redshift sources found with GMOS is due to the restricted wavelength coverage of the instrument and the lack of usage of a blue grating which resulted that most of the lines downwards MgII were outside the observable range.

Figure 3.11 (bottom) shows the R-band distribution for the extragalactic sources. Cut-offs are due to the limitations of the 3.5 and 8 meter telescopes to obtain spectroscopy of sources up to 21.5 and 23 magnitude respectively, in a reasonable amount of time.

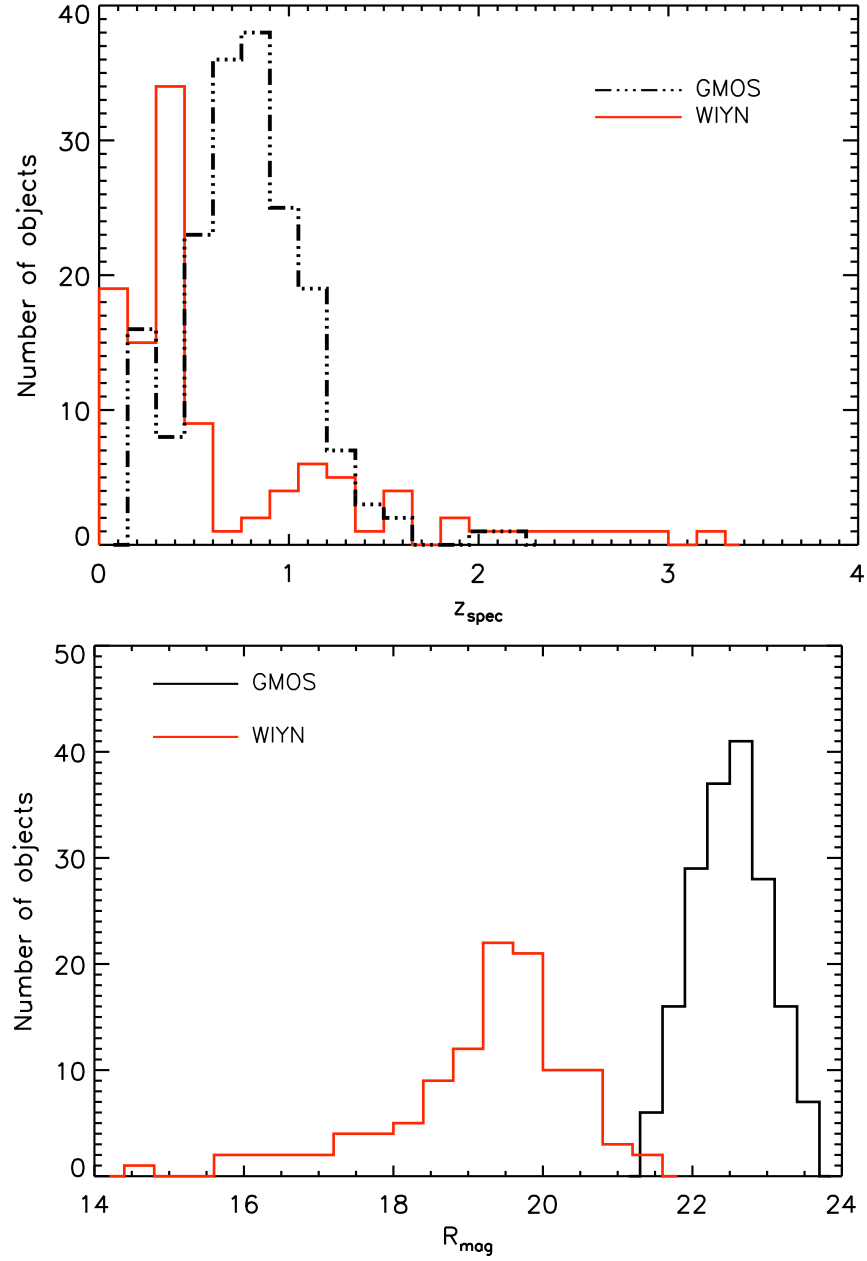


Figure 3.11: Top : The overall redshift distribution of all extragalactic sources in the final spectroscopic catalogue, divided into objects with spectroscopy from Gemini GMOS (dashed black line) and from WIYN Hydra (solid red line). **Bottom :** R-band distribution for the extragalactic sources. Lines and colours same as top.

ID	RA	DEC	z^a	R	S_{24}^b	$\log(L_{IR})^c$	J1 ^d	J2 ^e	TC ^f	SC ^g
HLIRG-1	242.9055	54.4291	1.392	20.83	5004	13.26	QSO	Torus	1.0	0.0
HLIRG-2	242.9449	54.0686	0.690	20.75	1563	13.22	QSO	Torus	0.9	0.1
HLIRG-3	242.8916	54.4591	2.860	18.99	1106	13.16	QSO	Torus	0.9	0.1
HLIRG-4	242.6961	54.6165	2.700	21.37	0	13.09	QSO	Torus	1.0	0.0
HLIRG-5	242.5173	54.2274	1.070	20.00	1906	13.31	QSO	Torus	1.0	0.0
HLIRG-6	242.7487	54.3648	1.100	20.44	1123	13.00	QSO	Torus	0.6	0.4

^aSpectroscopic Redshift

^bObserved 24 μ m fluxes in mJy

^cBolometric Infrared Luminosity(1 – 1000 μ m) ($H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\lambda = 0.7$)

^dOptical SED best fit

^eInfrared SED best fit

^fFraction of AGN contribution at 8 μ m

^gFraction of Starburst contribution at 8 μ m

Table 3.6: Properties of the 6 Hyper Luminous Infrared Galaxies with available spectra from GMOS/WIYN.

3.10 Ultra/Hyper Luminous Infrared Galaxies

As mentioned in § 3.7, the spectroscopic catalogue contains 110 sources with $L_{IR} > 10^{11} \odot$, 41 of which belong to the extreme population of ULIRG with $L_{IR} > 10^{12} \odot$. There are 6 additional sources with even more extreme infrared luminosities ($L_{IR} > 10^{13} \odot$). Tables 3.6 and 3.7 summarize the main properties of the 6 HLIRG and 41 ULIRG respectively found in our sample. The majority of the sample (29/47) were observed with WIYN and as a result they are all brighter than 21.5 R magnitudes. From the 18 ULIRG observed with GMOS, 7 have $R < 21.5$, one has $R > 23$ and the remaining have $22 < R < 23$.

39 of the sources show at least 2 strong emission lines and strong continuum. 4 are single emission line objects fitted with an [OII] line and 4 are very noisy spectra and their redshift estimation should be taken as an educated guess which might result in lower estimation of their bolometric infrared luminosity. Nonetheless, we have included them in our sample because the value of their spectroscopic redshifts seem to agree with the photometric ones (see § 4.2.6). 14 of the sources have been classified as broad line objects. From the remaining 33 there were only two sources that we were able to perform emission line diagnostics and they were both classified as composite from the [NII]/ $H\alpha$ versus [OIII]/ $H\beta$ diagnostic diagram and as star forming in the [SII]/ $H\alpha$ versus [OIII]/ $H\beta$ (see §4.4). For the remaining 31 we have used optical/IR SED fitting to draw conclusions.

Most of the U/HLIRG (31/47) are fitted with a QSO optical template, with one

source fitted with a young elliptical template, 2 with a starburst template and the remaining with different spiral templates. The infrared emission of 29 sources is dominated by a dust torus, one source appears to be cirrus dominated and the remaining sources are starburst dominated. 9 of the sources, including 3 HLIRG, seem to be powered both by a starburst and an AGN and from the remaining more than half of them (19) seem to contain a very powerful AGN. It is important to note here that 15/19 AGN dominated ULIRGs lie at high redshifts ($1 < z < 3.17$) in agreement with previous studies which used mid-IR spectroscopy [42][348]. In the following two subsections we discuss the individual sources.

3.10.1 HLIRG

HLIRG – 1 : This source, which is one of the brightest of our sample, was observed with WIYN because of its bright R-band magnitude ($R=20.83$). As it can be seen by its spectra in Figure 3.13 it exhibits a broad MgII line at a redshift of 1.392 confirming the prediction of both optical and ir SED fitting that it is dominated by an AGN. Our observations show a marginal detection of OII and FeII lines. The line that is matched with CII was very difficult to be found in the slit so it is considered as an ambiguous matching. It has detections in all IRAC bands with very strong $24\ \mu\text{m}$ emission. The fact that this object has very reliable redshift estimation in addition to the very strong $24\ \mu\text{m}$ detection implies that the bolometric infrared luminosity estimation is very reliable.

HLIRG – 2 : This is also one of the bright ($R=20.75$) sources observed with WIYN. It is a Flag 3 sources with clear detections of more than 3 lines. All the balmers ($H\gamma$, $H\beta$) found from spectroscopy are quite broad with a possible detection of MgII at the edge of the wavelength coverage. Very strong [OIII] doublet, OII and NeIII are clearly visible indicating also the presence of a strong starburst present at the same time with the AGN activity verified also by SED fitting. This source lies at intermediate redshift (0.69) and is also a very strong $24\ \mu\text{m}$ emitter. Both optical and ir SED fitting imply the presence of a strong AGN, as confirmed by the broad lines, but with significant starburst contribution as also seen from its spectrum. Precise redshift and $24\ \mu\text{m}$ measurements make it an additional very strong candidate for HLIRG status.

HLIRG – 3 : This is the brightest example ($R=18.99$) in the sample of HLIRG at very high redshift ($z=2.86$). It is as well a Flag 3 object with the detection of

at least 2 broad lines CIII and CIV, the possible detections of two more SiIV and HeII and the detection of $\text{Ly}\alpha$ in the blue. The clear presence of these lines makes it almost certain the presence of a very strong AGN which is also identified by optical and IR SED fitting. The latter though implies the presence of rather strong starburst at this early stage of evolution.

HLIRG – 4 : This source exhibits three broad lines CII, CIII and CIV. The clear detection of these lines indicates the presence of a QSO in agreement with SED fitting. It is the only source that lacks $24\mu\text{m}$ detection.

HLIRG – 5 : This Flag-2 object at intermediate redshift exhibits a very broad MgII line and marginal detections of CII and CIII. The clear presence of the MgII broad line in the slit makes the redshift estimation almost certain. It is a very strong $24\mu\text{m}$ emitter with detections in all IRAC and MIPS bands, except $160\mu\text{m}$. Its SED shows an AGN powered source with no evidence of on-going star-formation.

HLIRG – 6 : This object exhibits four strong lines, a broad MgII line accompanied by the presence of NeV, OII and NeIII. Spectroscopy and photometry agree to the fact that this is a composite object with clear presence of both an AGN and a star-formation component.

3.10.2 ULIRG

Examples of ULIRG spectra found in the catalogue are given in Figure 3.14. ULIRG found belong to all confidence classes. There are 4 Flag 9 sources, ULIRG 1, 2, 3, and 4, with estimated infrared bolometric luminosities lying in the ULIRG class. All of the sources are fitted with an OII line which spans their redshifts in a range between 1.01 and 1.486. Their comparison with photometric redshifts is rather good which make the assignment of the OII lines rather logical. In addition all of them have rather strong $24\mu\text{m}$ detections which also enhances our confidence in their ULIRG class. If we assume that matching the strong single emission line with OII is correct then we would expect that these sources would be strong star forming systems. This seems to be supported by SED fitting which best fits them with a starburst template in all cases with also some contribution from cirrus in the case of ULIRG-1. In case these sources belong to the ULIRG class then their star formation rates range from $200 < SFR(IR) < 800 M_{\odot} \text{ year}^{-1}$.

From the remaining 37 ULIRG there are 4 sources with ambiguous redshift determinations. These are objects ULIRG 12, 13, 14 and 15. All of the objects are faint ($22.5 < R < 23.4$) very strong $24\ \mu\text{m}$ emitters with detections in all IRAC bands except ULIRG-7 which lacks 5.8 and $8\ \mu\text{m}$ detections. The fact that they are very faint can explain their noisy spectra. An example of this confidence class ULIRG is shown in Figure 4.15 where the redshift estimation was based on H+K absorption features which due to the noisy nature of the specific spectrum was not feasible to determine in the slit whether they are real features or not. There is also a possible OII line but again as it was mentioned before, redshifts estimations for these objects should be taken as educated guesses based on the fact that they seem to have a good agreement with photometric redshifts. ULIRG-8 also show evidence of H+K absorption features while in ULIRG 6 and 7 we can marginally detect OII and MgII.

There are 33 objects in the sample of ULIRG for which the available spectra were of very good quality enabling us to accurately identify spectral features and derive redshifts. All 5 sources with broad lines and $z > 2$ belong to the upper class of ULIRG with $\log_{10}(L_{IR}) > 12.5$. Two of them were targeted x-ray sources from Chandra and XMM and the remaining three were identified as high redshift QSO from the photoz code. All 5 of them show very strong broad CIV, 4 have very prominent broad CIII, 2 of them have Ly α breaks and one has broad MgII. Agreement of their QSO status between optical spectroscopy and optical/ir SED fitting is excellent in 4 out of 5, while one object appears to be fitted with a dusty Arp220 like starburst. Optical imaging supports the idea of a high redshift QSO rather than a spiral like dusty starburst.

One of the Flag 3 objects observed with GMOS has an infrared SED dominated by cirrus. Its spectrum can be seen in Figure 3.14. It is an intermediate redshift object at $z = 0.818$. There is a clear detection of a very strong narrow OII line, a broad H line and marginal detections of H+K absorption features and NeIII emission line with a possible identification of an H δ absorption line, indicating the presence of both an AGN surrounded by a dust cloud originating from star-formation. The lack of other objects with similar SED fits in our spectroscopic sample does not allow us to draw conclusions from just one spectrum. We have already been awarded time and observed 60 of these objects with EFOSC-2 which will allow us to fully understand these objects but at the time of writing spectra were not available.

3.11 Summary

We have carried out the largest spectroscopic survey of ELAIS-N1 field so far which has provided us with almost 300 redshifts. The data reduction methods used for the two different instruments had a very high success rate in extracting spectra and measuring redshifts. From the total 376 objects observed we were able to successfully determine a redshift for 88% of them. There are 289 extragalactic sources contained in the final catalogue all of which have a SWIRE counterpart within 1 arcsec. Almost half of the extragalactic sources are Luminous Infrared galaxies which has provided us with a sample of 47 U/HLIRG sources. Spectral analysis of their spectra has found that all HLIRGs are AGN dominated with half of them at lower redshifts showing evidence of a star-formation component. Optical/IR SED fitting is in complete agreement with this picture. In the case of ULIRG sources all high-redshift objects appear to be QSO with evidence of broad lines while at intermediate redshifts both broad and narrow lines are present, indicating the presence of composite objects. One of the ULIRGs found in our sample has an infrared SED dominated by a cirrus component. Its spectrum show evidence of both a broad and a narrow region suggesting that it is a composite object. Given that these sources are luminous infrared galaxies we would expect that the AGN should be hosted in a large galaxy which is actively forming stars. However both spectroscopy and SED fitting show that this is the case for only $\sim 50\%$ of the cases. This can either mean that either most of these sources are highly obscured AGN or it might show that U/HLIRG undergo several burst events during their lifetime.

3.12 Continuation

The entire extragalactic spectroscopic catalogue is presented in Appendix A. The data obtained, combined with the large set of X-ray data acquired from the same area, have been used extensively in order to calibrate photometric redshifts, perform emission line diagnostics and search for AGN/starburst connection evidence, all of which are discussed in the following chapters.

<i>ID</i>	RA	DEC	<i>z</i>	$\log(L_{IR})$	J1	J2	TC	SC
ULIRG1	242.5534	54.4655	1.387	12.67	Sbc	M82	0	0.55
ULIRG2	241.2385	54.8435	1.486	12.54	sb	Arp220	0	1
ULIRG3	242.5546	54.5288	1.115	12.09	Sdm	Arp220	0	1
ULIRG4	243.6318	53.7101	1.010	12.07	Sdm	Arp220	0	1
ULIRG5	243.3587	54.8020	0.818	12.31	Scd	Cirrus	0	0
ULIRG6	242.4048	54.6756	0.875	12.22	Scd	Arp220	0	1
ULIRG7	242.7308	54.5932	0.883	12.95	QSO	Torus	0.6	0.4
ULIRG8	241.3705	54.8254	1.214	12.22	Sbc	Torus	0.8	0.2
ULIRG9	242.5035	54.6552	1.088	12.19	Ell	M82	0.35	0.65
ULIRG10	244.1795	55.1601	0.908	12.07	Scd	Arp220	0	1
ULIRG11	242.8132	54.2536	0.789	12.00	sb	Arp220	0	1
ULIRG12	242.4294	54.6975	0.872	12.56	Sbc	Arp220	0	1
ULIRG13	242.6501	54.5786	1.322	12.47	Scd	Arp220	0	1
ULIRG14	242.6152	54.4435	1.200	12.35	Scd	Arp220	0	1
ULIRG15	242.5335	54.5519	1.100	12.02	QSO	M82	0.4	0.6
ULIRG16	242.6878	54.6034	0.560	12.92	QSO	Torus	1	0
ULIRG17	242.7487	54.3648	1.100	12.92	QSO	Torus	0.55	0.45
ULIRG18	242.6960	54.6165	2.700	12.91	Sdm	Arp220	0	1
ULIRG19	242.5296	53.9706	2.015	12.77	QSO	Torus	1	0
ULIRG20	243.0523	54.1602	1.060	12.76	QSO	Torus	1	0
ULIRG21	242.2580	54.0934	0.904	12.75	QSO	Torus	1	0
ULIRG22	242.0471	54.0934	1.320	12.72	QSO	Torus	0.75	0.25
ULIRG23	242.2364	54.0538	1.900	12.70	QSO	Torus	1	0
ULIRG24	242.8837	54.3866	3.170	12.69	QSO	Torus	1	0
ULIRG25	242.8163	54.3866	1.924	12.61	QSO	Torus	1	0
ULIRG26	242.4330	54.2823	2.847	12.59	QSO	Torus	1	0
ULIRG27	242.3964	54.5177	0.572	12.52	QSO	M82	0	1
ULIRG28	242.1485	54.3916	1.300	12.52	QSO	Torus	1	0
ULIRG29	242.4275	54.4153	2.383	12.5	QSO	Torus	1	0
ULIRG30	242.8038	54.0585	0.970	12.5	QSO	Torus	1	0
ULIRG31	242.2956	54.2672	0.010	12.38	QSO	Torus	1	0
ULIRG32	242.6436	54.1318	1.235	12.36	QSO	Torus	1	0
ULIRG33	242.4983	54.5540	1.571	12.35	QSO	Torus	1	0
ULIRG34	242.6935	54.0014	0.752	12.34	QSO	Torus	1	0
ULIRG35	242.5172	54.2275	1.000	12.3	QSO	Torus	0.65	0.35
ULIRG36	242.5904	54.5178	1.010	12.23	QSO	Torus	1	0
ULIRG37	242.0702	54.2680	1.310	12.22	QSO	Torus	1	0
ULIRG38	242.5385	54.1796	0.336	12.19	QSO	M82	0	1
ULIRG39	242.6720	54.1756	0.227	12.13	Scd	Arp220	0	0.7
ULIRG40	242.1305	54.3524	1.200	12.09	QSO	Torus	1	0
ULIRG41	243.2496	54.2510	1.180	12.02	QSO	Torus	1	0

Table 3.7: Properties of the 41 Ultra Luminous Infrared Galaxies with available spectra from GMOS/WIYN. Columns are similar to Table 3.6.

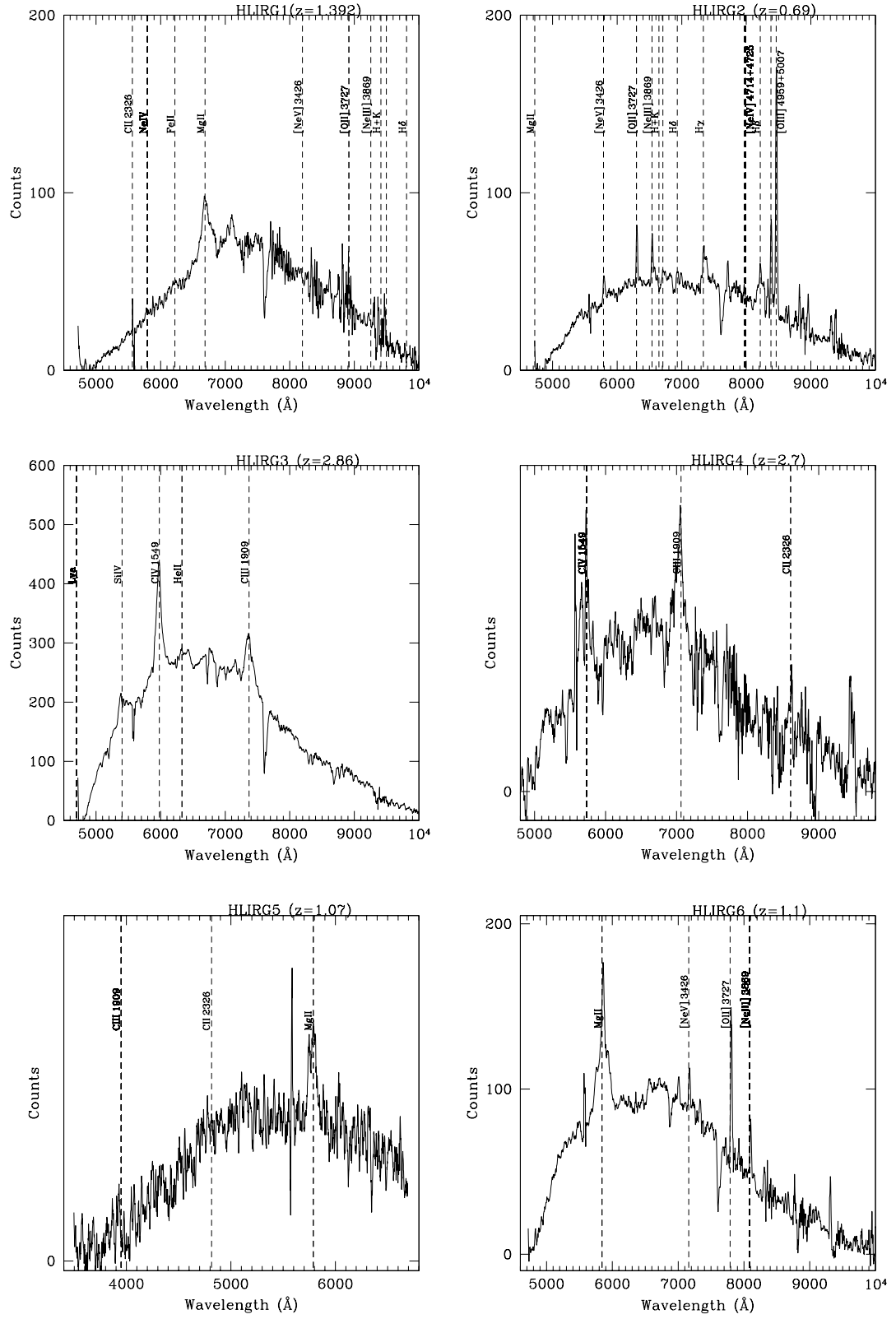


Figure 3.12: Optical spectra of the six hyper luminous infrared sources found in our sample. HLIRG 2, 3, 4, 6 are Flag 3 objects and HLIRG 1, 5 are Flag 2 sources.

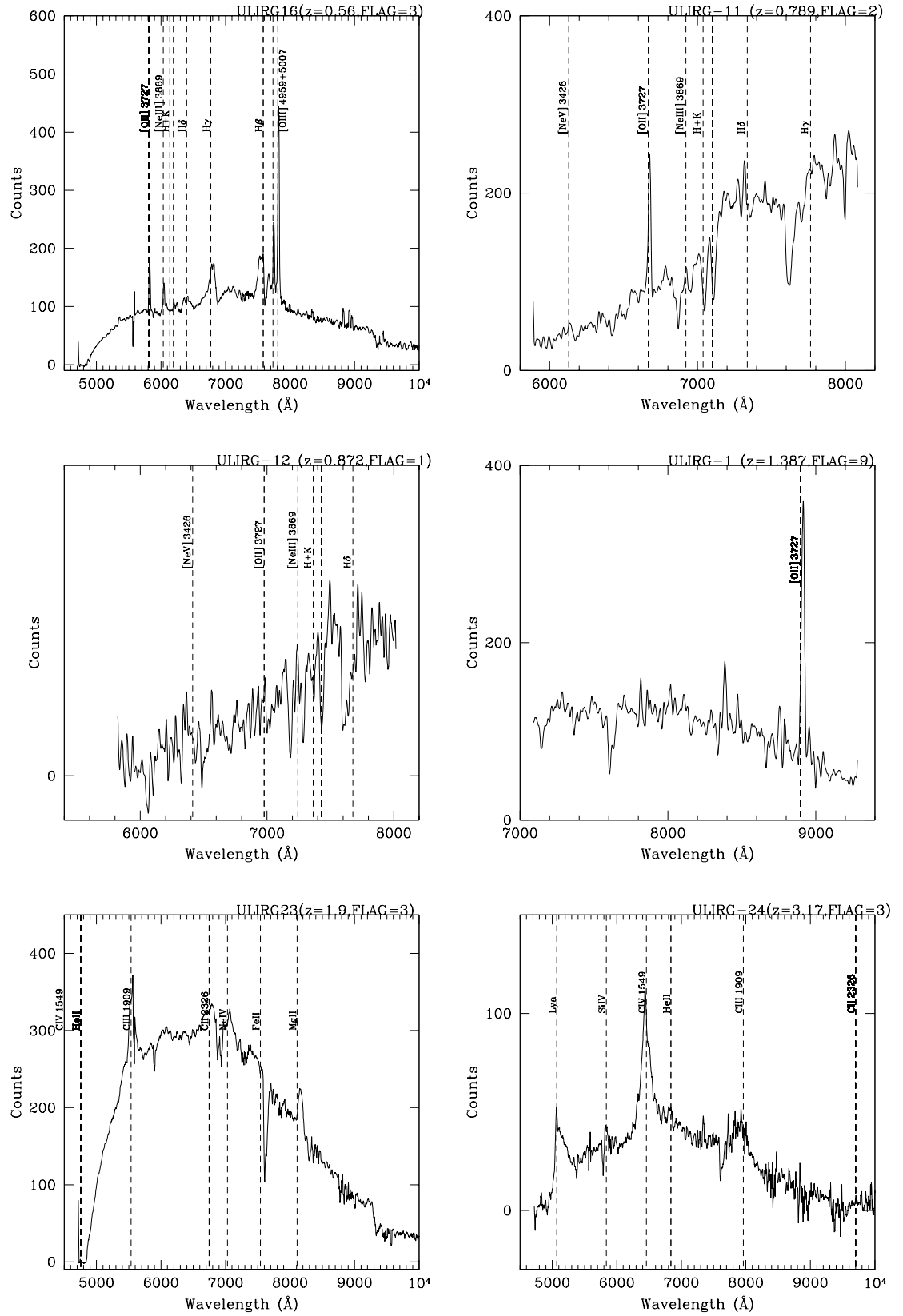


Figure 3.13: Examples of ULIRG spectra of different confidence classes found in the spectroscopic sample.

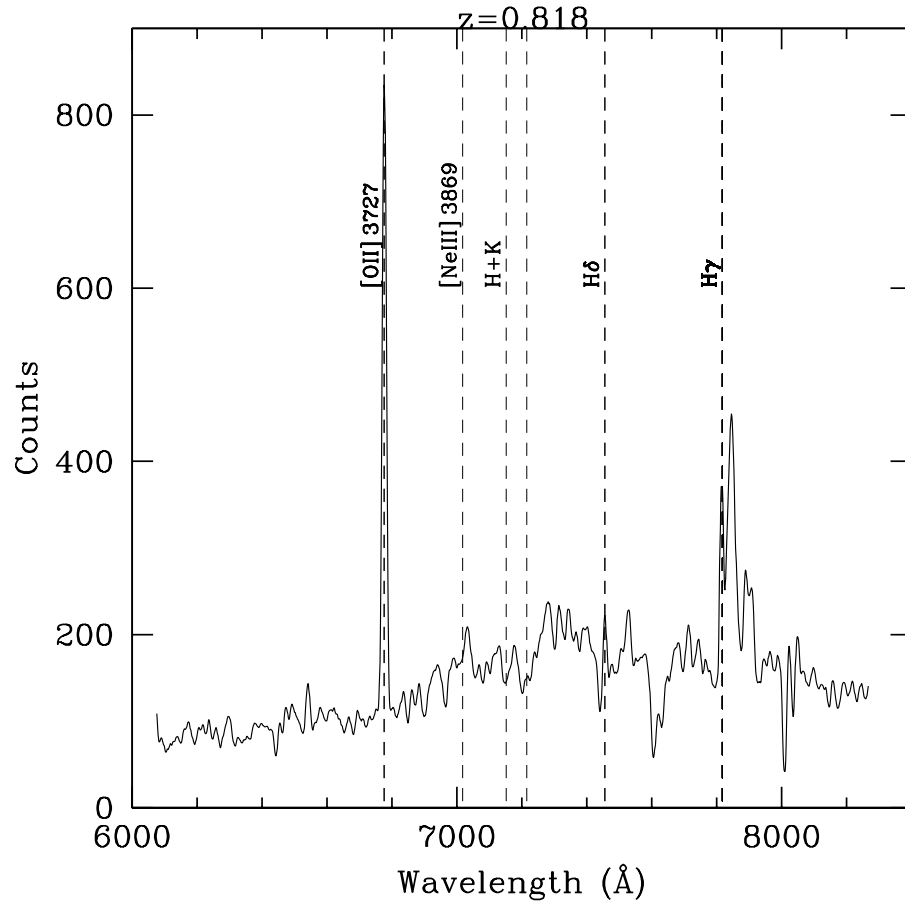


Figure 3.14: GMOS Flag 3 spectrum of the only ULIRG cirrus found in the sample.

Chapter 4

Comparison with SWIRE Photometry

But Aristarchus of Samos brought out a book consisting of certain hypotheses, in which the premises lead to the conclusion that the universe is many times greater than that now so called. His hypotheses are that the fixed stars and the sun remain motionless, that the earth revolves about the sun in the circumference of a circle, the sun lying in the middle of the orbit, and that the sphere of the fixed stars, situated about the same center as the sun, is so great that the circle in which he supposes the earth to revolve bears such a proportion to the distance of the fixed stars as the center of the sphere bears to its surface.

Archimedes (287-212 BC)

4.1 Overview

In this Chapter I analyze the performance of the latest version [283] of the ImpZ code [19] by comparing the values of spectroscopic redshifts from GMOS and WIYN with the estimated values of photometric redshifts for the same sources. The set used here is the entire extragalactic spectroscopic catalogue which contains 289 redshifts. The accuracy of the code is very good with less than 4.5% catastrophic outliers when good quality spectra are used. We also present luminosities comparisons for the various infrared populations in our sample and report here the identification of two very interesting populations: a population of U/LIRG cirrus galaxies and a large population of elliptical-like galaxies with very strong ongoing starbursts. Emission line diagnostics of 30 sources within the GMOS/WIYN sample reveal the

high accuracy of Rowan-Robinson’s template fitting method in isolating AGN from star-forming sources and its success in identifying composite. In comparison with other infrared diagnostics that utilize IRAC and MIPS colours, SED fitting performs better achieving the same level of success rate as optical spectroscopy. Finally we report here the identification of a new parameter space in IRAC color-color plots where narrow line AGN lie, completely missed by previous studies.

4.2 Introduction

In recent years, extragalactic surveys have revolutionized our view of the high-redshift Universe, showing that the redshift range between $0.5 < z < 3.0$ witnessed an extraordinary transformation in the demographics of starburst and AGN activity in galaxies. The factors that drove these changes are however unclear. Consequently, the properties of large samples of sources are the current driving force behind modern extragalactic surveys [243][181][361][210]. However, either most of the sources in these surveys are too faint for spectroscopic observations or it is not cost and time effective to acquire large spectroscopic redshift samples using the current facilities. Photometric techniques provide an excellent tool for estimating redshifts, essential for statistical studies of the galaxies’ properties and evolution with only a fraction of the observing time required by spectroscopic surveys. These techniques are faster and can estimate redshifts beyond the spectroscopic limit with the main handicap of possessing larger errors than spectroscopic techniques.

4.2.1 Photometric Redshift Codes

In photoz codes, identification is carried out either by using the broadband continuum shape and spectral breaks, like the Balmer Break, or the onset of the Ly α forest and Lyman limit which enter optical wavebands at high redshift [216]. Although methods based on polynomial fitting [347] and artificial neural networks [23] have had some success in determining photometric redshifts, in the remaining of this work we utilise the template-fitting procedure developed by Rowan-Robinson [282] and Babbedge et al [18]. In the template-fitting methods [306] the observed galaxy fluxes are compared to a library of reference fluxes and a set of parameters that account for the template galaxy’s morphological type, age, metallicity and dust. The observed fluxes are then fitted to the library fluxes using χ^2 minimisation. As well as deriving redshifts, the procedure produces information on spectral types.

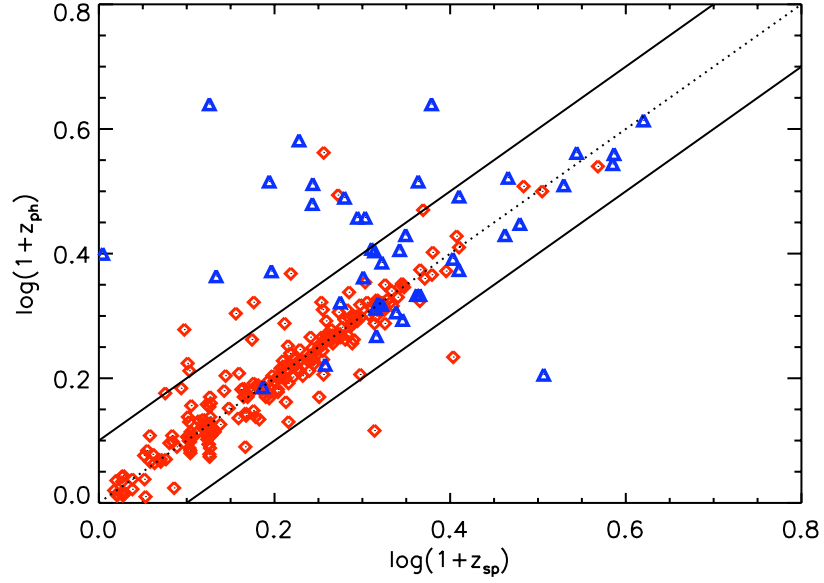


Figure 4.1: Photometric versus spectroscopic redshift for all sources with available spectroscopic redshifts from GMOS/WIYN. The straight lines represent a 10% accuracy in $\log(1+z)$. Blue triangles are sources fitted with a QSO template from the photometric optical fitting method.

An important refinement of the photoz codes is to estimate extinction. Madau [217] 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 include evolution of dust extinction with time [192]. In order to allow for variation in extinction from galaxy to galaxy, extinction needs to be solved as an additional free parameter to redshift. Dust absorption is 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 [327]. The study of Bolzonella [40] found that the inclusion of A_v as a free parameter caused significant increases in aliasing. In a similar technique these aliasing problems were reduced by setting several A_v priors [282].

4.2.2 Photometric Redshifts from SWIRE

SWIRE catalogues were analysed by using six optical and three AGN templates based on empirical SEDs. Each source in the catalogue selects the best solution from these 9 templates but quasar templates are allowed only when a source is flagged as stellar. In addition a further condition was introduced: that each source should be detected in $3.6\text{ }\mu\text{m}$, r-band and at least two other bands. SPITZER not

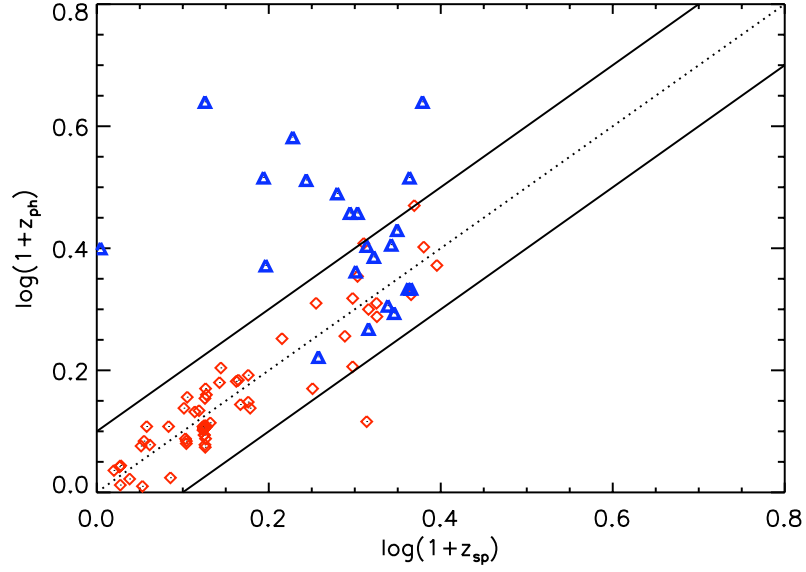


Figure 4.2: Photometric versus spectroscopic redshift for all sources belonging either to Flag 1 or Flag 9 confidence classes (see §3.8). Colours and symbols are the same as Figure 4.1.

only made the last condition applicable by being able to measure $3.6 \mu m$ fluxes but also provided a great improvement in the rms deviation of $\log_{10}(1+z)$ when using UgrIZJHK data and SWIRE 3.6 and $4.5 \mu m$ fluxes.

Babbedge et al [19] presented an updated version of Rowan -Robinson’s [282] photometric redshift code that derived redshifts for both galaxies and quasars. Their code is extended to include the statistical effect of intergalactic absorption. This code uses the same six templates but reproduced to high resolution using spectrophotometric synthesis to strengthen their physical basis. In order to derive photometric redshifts for quasars, they used a method identical as for galaxies but exploited optical morphology information. This means that if a source appeared to be point-like, then QSO templates were considered in addition to galaxy templates. The overall accuracy of this code is very good with $\Delta z/(1+z) < 0.1$ for 92 % of the 138 sources studied. The inclusion of AGN templates has extended the template fitting method to quasars also, with $\Delta z/(1+z) < 0.25$ for 68 % of the 25 quasars in the INT WFS ELAIS catalogue.

The latest version of the ImpZ code [283] has incorporated some additional changes taking into account the large spectroscopic samples obtained with GMOS, WIYN and VLT. First of all the galaxy templates used for SED fitting have been fitted with

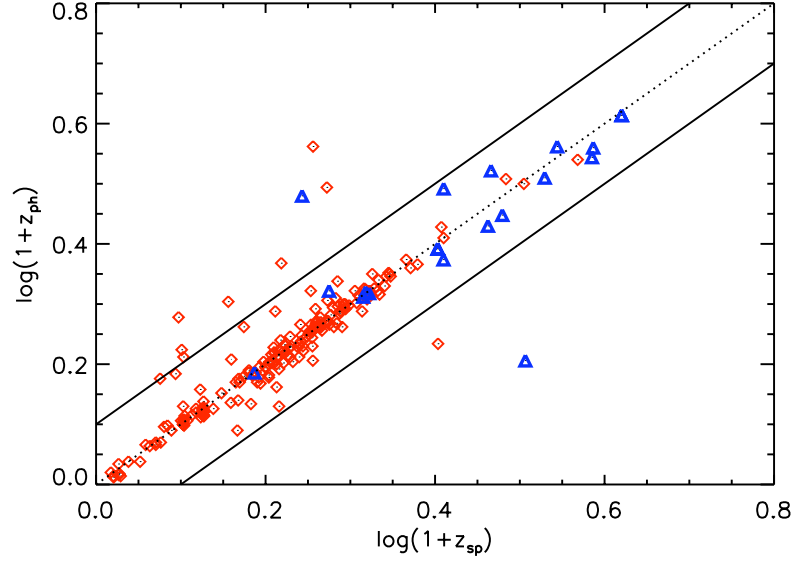


Figure 4.3: Photometric versus spectroscopic redshift for all sources belonging to the secure spectroscopic confidence classes 2 and 3 (see §3.8) . Colours and symbols are the same as Figure 4.1.

star formation histories. In addition, torii are identified after two passes through the data and extinction is allowed as free parameter [283]. All photometric redshifts used in the remaining of this work are derived with the updated version of ImpZ.

4.2.3 Template SEDs

The number of templates used in the SED fitting method is crucial. The choice of a large number of templates can result in a significant number of aliases and degeneracies while on the other hand a restricted number of templates will prevent the photometric redshift code from finding accurate redshifts for real objects. The latest version of the ImpZ code utilizes a total of 10 templates. Seven of them are galaxy templates, E, Sab, Sbc, Scd, Sdm, starburst and an additional young elliptical galaxy template and three are AGN templates.

The original galaxy templates were adapted by Yoshii & Takahara [362] apart from the starburst template [48] and the young elliptical template [223]. The latter is a 1Gyr old simple stellar populations template for which the UV behaviour of the old elliptical template has replaced the template shortward of $2100\text{\AA}$ in order to include the UV emission observed in high redshift ellipticals. The same has been adopted in order to extend the original Maraston template longward of $3\text{ }\mu\text{m}$. The

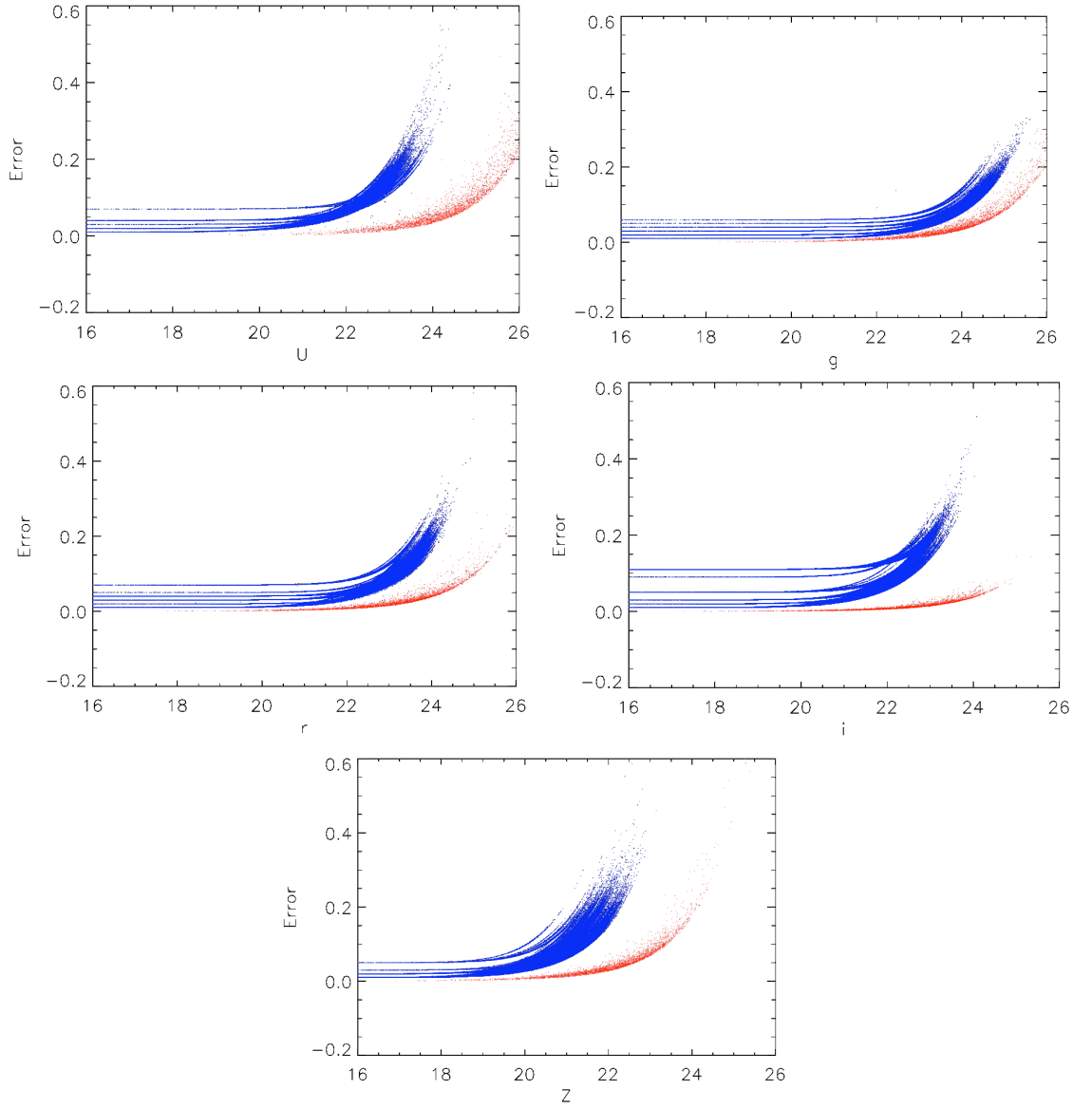


Figure 4.4: Comparison of photometric accuracies between the VVDS (red lines) and SWIRE ELAIS-N1 (blue lines) surveys for U, g, r, i, Z filters. The strange appearance of the error lines for the case of SWIRE data is because the different lines have an offset and do not converge to zero because there is also the zero point error which is different for each pointing and dominates the error at bright levels.

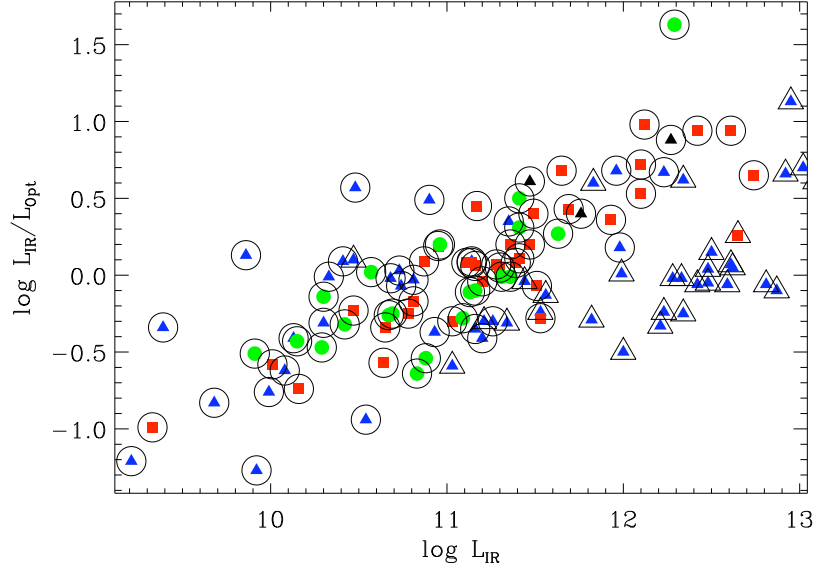


Figure 4.5: Ratio of bolometric infrared to optical luminosity versus bolometric infrared luminosity of all 112 sources detected at $24\ \mu\text{m}$ in our spectroscopic sample which are fitted with one of the four available infrared templates (see §1.5.1). Blue triangles are torii; green dots are cirrus; black triangles are Arp220 and red squares are M82. Open black triangles are sources fitted with a QSO template and black open circles are sources fitted a galaxy template.

rest of the galaxy templates were reprocessed [19], each weighted by a different star formation rate and extinguished by a different amount of dust. This higher resolution regeneration gave the templates physical validity. All of the templates are further improved by using the wealth of spectroscopic data obtained with VIRMOS as part of the VVDS survey [194].

4.2.4 Template Fitting

In a method previously used [20], the photometric analysis is separated into optical/near-IR and mid-IR, and template-fitting is carried out in a two-stage approach [285]: Optical and IRAC 3.6, 4.5 detections are used for the photometric redshift fitting procedure; the longer wavelengths are then used to fit IR templates to those sources defined as having an IR-excess. Variable extinction is allowed in the fits via variable A_v added to the templates. A_v limits of 0 to 2 in the A_v freedom are used for the galaxy templates whilst for the AGN fits A_v is restricted to $A_v \leq 0.3$ in order to prevent aliasing with normal galaxies [283]. It is noted that the inclusion of A_v freedom gives an important improvement in the accuracy of the resulting redshifts, though it is also apparent that the derived extinction of

the source is imprecise [21]. A prior against large A_V is introduced by minimising $\chi_{red}^2 + \alpha A_V^2$ rather than χ^2 , with $\alpha=1.5$ here [283].

4.2.5 Mid IR SED fitting

A source that has been fit with an optical to near-IR galaxy template, based on its U band to 4.5, now has its IR excess calculated by subtracting the galaxy model fit prediction from the 4.5 to 24 data [285]. At least two of these bands then need to exhibit an IR excess (one of which is required to be 8 or 24). This excess is then best-fit as either cirrus [83], M82 and Arp220 starbursts [84] or an AGN dust torus IR template [279]. This approach is highly effective and blind comparisons of predicted $70\mu\text{m}$ flux derived from the mid-IR SED fitting to the observed $70\mu\text{m}$ fluxes of SWIRE sources gives impressive agreement for all four mid-IR templates, across almost 2 orders of magnitude in 70 flux [283]. Sources can also 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 [20]. This mirrors the conclusions of from fitting mid-IR SEDs to *IRAS* sources [288][285].

4.3 Spectroscopic Comparisons

We have compared the spectroscopic redshifts obtained with GMOS/WIYN with photometric redshifts calculated using the latest version of the ImpZ code [283]. Reliability and accuracy of the photometric redshifts are measured 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 $|\Delta z/(1+z)| > 0.15$. $\Delta z/(1+z)$, $\overline{\Delta z}/(1+z)$ and σ_z are calculated as follows:

$$\Delta z/(1+z) = \left(\frac{z_{phot} - z_{spec}}{1 + z_{spec}} \right) \quad (4.1)$$

and

$$\overline{\Delta z}/(1+z) = \sum \left(\frac{z_{phot} - z_{spec}}{1 + z_{spec}} \right) / N. \quad (4.2)$$

and

$$\sigma_z^2 = \sum \left(\frac{z_{phot} - z_{spec}}{1 + z_{spec}} \right)^2 / N. \quad (4.3)$$

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

Figure 4.1 shows a comparison of $\log_{10}(1 + z_{phot})$ versus $\log_{10}(1 + z_{spec})$ for the entire sample of SWIRE ELAIS-N1 sources with available spectroscopy from GMOS/WIYN, where red diamonds are galaxies and blue triangles are QSOs, as reported by the photometric optical template fitting. For galaxies with confidence class flagged as 1, where there are ambiguous redshift solutions due to noisy spectra, we tried to use the information from the optical photometry to select between the aliases, where possible. ImpZ code found solutions for all sources. For the sample as a whole, the total *rms* scatter, σ_{tot} , was 0.12, with $\overline{\Delta z}/(1 + z) = -0.02$ and the rate of 'catastrophic' outliers was 7.6% (23 sources).

Figure 4.2 shows the corresponding $\log_{10}(1 + z_{phot})$ versus $\log_{10}(1 + z_{spec})$ comparisons for sources having ambiguous redshift determination (Flags 1 and 9) and Figure 4.3 shows the same comparison for sources with secure redshift extraction (Flags 2 and 3). In the latter the photometric code was quite successful at returning an accurate z_{phot} with $\sigma_{tot}=0.09$, $\overline{\Delta z}/(1 + z) = -0.008$ and only 4.4% (10 sources) catastrophic outliers. It has to be mentioned here that one of the key results here is the excellent performance of the photometric code for both sources identified as QSOs from the optical fitting and high redshift sources with good quality of spectra. From the 19 sources with spectroscopic redshift $z > 1.5$ there are only two catastrophic outliers and if we allow $|\Delta z/(1 + z)| > 0.2$ then there is only one catastrophic outlier. In addition from the 18 sources which were fitted with a QSO optical template the number of outliers was two. Taking into consideration the problems that photometric codes face with high redshift sources and QSOs and bringing in mind that the main power of photometric redshifts is their application in both these populations and especially in high redshift sources then this success is more than encouraging. In terms of outliers, possible reasons for these are either photometric redshift aliasing or poorer optical photometry for the case of the GMOS fainter sample. The photometric code outputs the χ^2 distribution as a function of redshift and from this we can assess whether photometric redshift aliases are likely. This suggested that only for one of the 10 sources with $|\log_{10}((1 + z_{phot})/(1 + z_{spec}))| > 0.10$ is there an obvious photometric alias. The main cause for the remaining outliers in this sample is the worsening photometric accuracy at the fainter optical magnitudes samples here. Figure 4.4 presents a comparison of photometric accuracies for the present sample (blue lines) and the VVDS sample (red line) where it is obvious that the errors especially in the R-band (where this sample was selected) become significant at magnitudes fainter than 22 where most of our sources lie. The strange appearance of SWIRE's error lines arose from the fact that the error in the flux is basically

proportional to $\sqrt{flux}$ with gain and sky variance also factored in. The error in the magnitude is proportional to the flux error divided by the flux. The different lines have an offset and do not converge to zero because there is also the zero point error which is different for each pointing and dominates the error at bright levels.

For the case of sources flagged as having rather ambiguous spectroscopic redshift estimations the agreement is broadly good, but it is noticeable that both in terms of the rms accuracy and in the number of serious outliers the results look worse than those presented for Flags 2 and 3. The percentage of catastrophic outliers is 15.4%, 92% of which are sources fitted with an optical QSO template. For sources with $z_{photo} < 0.6$ we used the information from the optical photometry to select between aliases with relative success. The parameter space between $0.7 < z_{photo} < 1.5$ is occupied mainly by the sources given a confidence class of 9. These are the very strong single emission line objects fitted with an OII line. In literature people tend to assign these objects either to OII or H lines. In our case assignment to OII lines provides a good agreement with the photoz values with no catastrophic outliers. Significant disagreement occurs at $z_{phot} > 1.5$ where most of our outliers occur. In this redshift range most of the prominent narrow line spectral features would be redshifted outside the wavelength coverage of both instruments. Redshift estimation in this case would have to rely on broad line features and emission lines such as Mg II. Nonetheless the bad quality of all these spectra with very low S/N ratios and almost featureless continua resulted in assigning lower redshifts either due to the problematic identification of spectral features or to the assigning of OII lines to the single emission line objects (Flag 9). This has caused an apparent overestimation of photozs.

4.4 Infrared Populations

Using infrared template fits (§4.2.3-4.2.5), we are able to estimate bolometric infrared luminosity, L_{ir} , which in the case where there is no contribution from an AGN dust torus, can be a measure of the total star formation rate in a galaxy. One of the things that someone should bear in mind when trying to estimate bolometric infrared luminosities is that this estimate is highly uncertain if far-infrared data are not available [283]. As a result in this section we have included an estimate of bolometric infrared luminosities only from sources which have significant $24\ \mu\text{m}$ detections ($S_{24} > 150\ \mu\text{Jy}$) and for which we were able to estimate their bolometric optical luminosity resulting to a sample of a total of 172 GMOS/WIYN extragalac-

tic sources. It is recommended to use sources that have longer wavelength detections which not only provide more accurate luminosities measurements but also preciser SED fittings.

Figure 4.5 shows the ratio L_{ir}/L_{opt} versus L_{ir} for a sample of 112 sources with $24\mu\text{m}$ detections which were fitted with one of the four available infrared templates. The remaining 60 $24\mu\text{m}$ sources are either single band infrared excess or have no excess. Different colours represent sources dominated by cirrus, M82-like starburst, Arp 220-like starburst or AGN dust tori templates. From the 112 sources, 19 (17%) are fitted with a cirrus template, 26 (23%) with an M82 starburst template, 5 (4%) with an Arp220 starburst template or single band infrared excess and 62 (56%) with a dust torus template. Among this sample there are 42 (38%) Luminous Infrared Galaxies ($L_{IR} > 10^{11} L_{\odot}$), 25 (22%) of which have $L_{IR} > 10^{12} L_{\odot}$ most of them fitted with a dust torus template.

Since the optical bolometric luminosity of a galaxy, corrected for extinction, is a measure of the stellar mass, the ratio $L_{IR}/L_{optical}$ can be interpreted as the specific star formation rate which is basically the inverse of the timescale in years to accumulate the present stellar mass, forming stars at the current rate. For galaxies with $L_{IR} < 10^{10} L_{\odot}$ the ratio $L_{IR}/L_{optical}$ should be interpreted as the optical depth of the interstellar dust since most of the infrared emission is reemission of the general starlight absorbed by interstellar dust. 64 sources are found to have $L_{IR}/L_{optical} < 0.2$. These should be interpreted as very low star-forming galaxies. There is a sloping cutoff to the right part of Figure 4.5. This could be explained as a limit on the optical bolometric luminosity and stellar mass. As it can be seen to the right of the limit there are AGN and some starbursts. In the case that these AGN were Type 1 we would expect them to lie on $L_{IR} = L_{optical}$ but since they appear to have $L_{IR} > L_{optical}$ that means that they are probably Type 2.

We now look more closely at each infrared template type in turn. In the case of cirrus dominated sources infrared emission is due to interstellar dust heated by the general stellar radiation field. As a result, the ratio $L_{IR}/L_{optical}$ is a measure of the dust opacity of the interstellar medium. From the 19 cirrus dominated sources, 4 are fitted with a starburst optical template, 14 with a spiral template and 1 with an elliptical template. We also notice a very interesting population of luminous cirrus galaxies. 10 (53 %) of which have $L_{IR} > 10^{11} L_{\odot}$ and one of them $L_{IR} > 10^{12} L_{\odot}$ (see Figure 3.14). The luminosity of the latter is substantially greater than the

optical bolometric luminosity, suggesting that the optical depth of the interstellar medium in these galaxies is 1. Cirrus galaxies with $L_{IR} < 10^{11} L_{\odot}$ have values of $\log_{10}(L_{IR}/L_{optical})$ of -0.2. This can be explained if the quiescent phase of star formation was significantly more luminous in the past and that dust of interstellar medium is much more opaque in galaxies at $z \sim 1$.

Although M82-like galaxies lie in the same luminosity range as cirrus, a much higher proportion (70%) lie at the LIRG range. Most of the M82 starbursts are fitted with a spiral optical SED with very high dust opacities. One very interesting finding is the presence of 2 ULIRG elliptical which would result in very high star formation rate. In the case of Arp 220 dominated sources the higher values of L_{ir} result in higher values of L_{ir}/L_{opt} consistent with the idea that Arp 220 are very dusty. Highly extinguished starbursts like Arp220 look like ellipticals in the optical because the light from the young stars is almost extinguished which explains the large percentage of Arp220 fitted with an elliptical template.

Due to selection effects (see §3.4.2) the $24\mu\text{m}$ population is dominated by torus sources. L_{ir}/L_{opt} in this case can be interpreted as $f_{tor}k_{opt}$ where f_{tor} is the covering factor of the torus and k_{opt} is the bolometric correction that needs to be applied to the optical luminosity to account for emission shortward of the Lyman limit [283].

Among the ULIRGs found in our sample there are seven galaxies that would be classified as early-type red galaxies but which are all fitted with starburst SEDs, 4 Arp220 and 3 by a combination of M82 with significant contribution (20-60%) from a torus template. As mentioned before, the 4 sources fitted with an Arp220 template are most likely highly extinguished starbursts, which are probably the product of a merger event, that look like ellipticals in the optical because the optical light from the young stars is almost completely extinguished. In addition the very high values of L_{ir} , reaching up to $L_{IR} = 10^{13.3} L_{\odot}$, results to such high values of star formation rates that is not feasible to be generated by a single starburst event but rather from significant accretion of gas through a galaxy merger. The broad band SEDs of the remaining three elliptical-like galaxies with composite infrared SEDs (both an AGN and an M82 starburst) points to the presence of Type-2 QSOs, with the central engine hidden behind large columns of obscuring dust. The presence of a strong star-formation component imply that there is either an obscured starburst or that the star-formation event is causing the obscuration of the central engine. In both cases there seems to be a strong underlying relation between the supermassive

z^a	J1 ^b	J2 ^c	SC ^d	TC ^e	S1 ^f	S2 ^g	S3 ^h	D1 ⁱ	D2 ^j
0.066	sb	Cirrus	0.2	0	-0.45	-0.72	-0.06	SF	SF
0.13	sb	M82	1	0	-0.68	-0.74	0.20	SF	SF
0.063	Sab	Cirrus	0.4	0	-0.29	-0.54	0.07	COM	SF
0.126	Scd	Cirrus	0.4	0	-0.71	-0.97	0.01	SF	SF
0.315	Scd	Cirrus	0.25	0	-0.55	-0.71	-0.20	SF	SF
0.266	E	Torus	0.45	0.55	-0.17	0.22	0.18	COM	AGN
0.453	Sdm	Torus	0.1	0.9	-0.69	-0.44	1.14	AGN	AGN
0.263	Scd	Cirrus	0.4	0	-0.64	-0.68	-0.30	SF	SF
0.127	E	M82	0.55	0.45	-0.07	-0.41	-0.04	COM	SF
0.268	Sdm	M82	0.65	0.35	-0.29	-0.46	0.56	AGN	AGN
0.336	QSO	M82	0.55	0.45	-0.37	-0.59	1.14	AGN	AGN
0.339	Scd	M82	1	0	-0.53	-0.85	-0.12	SF	SF
0.143	Sbc	Cirrus	0.45	0	-0.91	-0.15	-0.13	SF	AGN
0.041	sb	M82	0.55	0.45	-1.38	-0.35	0.81	COM	AGN
0.092	sb	M82	0.55	0.45	-1.34	-0.59	1.35	AGN	AGN
0.048	Sdm	M82	1	0	-0.71	-0.49	0.23	SF	SF
0.212	Scd	Cirrus	0.2	0	-0.91	-0.97	-0.52	SF	SF
0.338	Sdm	Cirrus	0.4	0	-0.69	-0.58	0.15	SF	SF
0.300	Sdm	M82	0.65	0.35	-0.52	-0.43	-0.26	SF	SF
0.227	Scd	M82	0.6	0.4	-0.31	-0.29	-0.16	COM	SF
0.063	Sab	Cirrus	0	0	-0.27	-0.81	0.85	AGN	AGN
0.069	Sab	Cirrus	0	0	-0.11	-0.82	0.60	AGN	SF
0.144	E	Cirrus	0.25	0	-0.62	-0.51	0.03	SF	SF
0.299	Scd	M82	0.8	0.2	0.15	0.22	0.09	COM	AGN
0.157	Scd	M82	0.5	0.5	0.18	-0.38	-0.39	COM	SF
0.214	Scd	M82	1	0	-0.77	-0.87	0.53	SF	SF
0.281	E	Torus	0.25	0.75	-1.28	-0.66	0.87	AGN	AGN
0.26	Sbc	M82	1	0	-0.36	-0.24	0.29	SF	AGN
0.19	Scd	Cirrus	0.5	0	-0.31	-0.27	0.14	COM	AGN
0.176	E	M82	0.6	0.4	-0.27	-0.47	-0.37	COM	SF

^aSpectroscopic Redshift^bOptical SED best fit^cInfrared SED best fit^dFraction of Starburst contribution at 8 μm ^eFraction of Torus contribution at 8 μm ^f $\log([\text{NII}]/\text{H}\alpha)$ ^g $\log([\text{SII}]/\text{H}\alpha)$ ^h $\log([\text{OIII}]/\text{H}\beta)$ ⁱSpectroscopic Classification according to the $[\text{NII}]/\text{H}\alpha$ versus $[\text{OIII}]/\text{H}\beta$ diagnostic.^jSpectroscopic Classification according to the $[\text{SII}]/\text{H}\alpha$ versus $[\text{OIII}]/\text{H}\beta$ diagnostic.**Table 4.1:** Measured emission line ratios and SED fitting results.

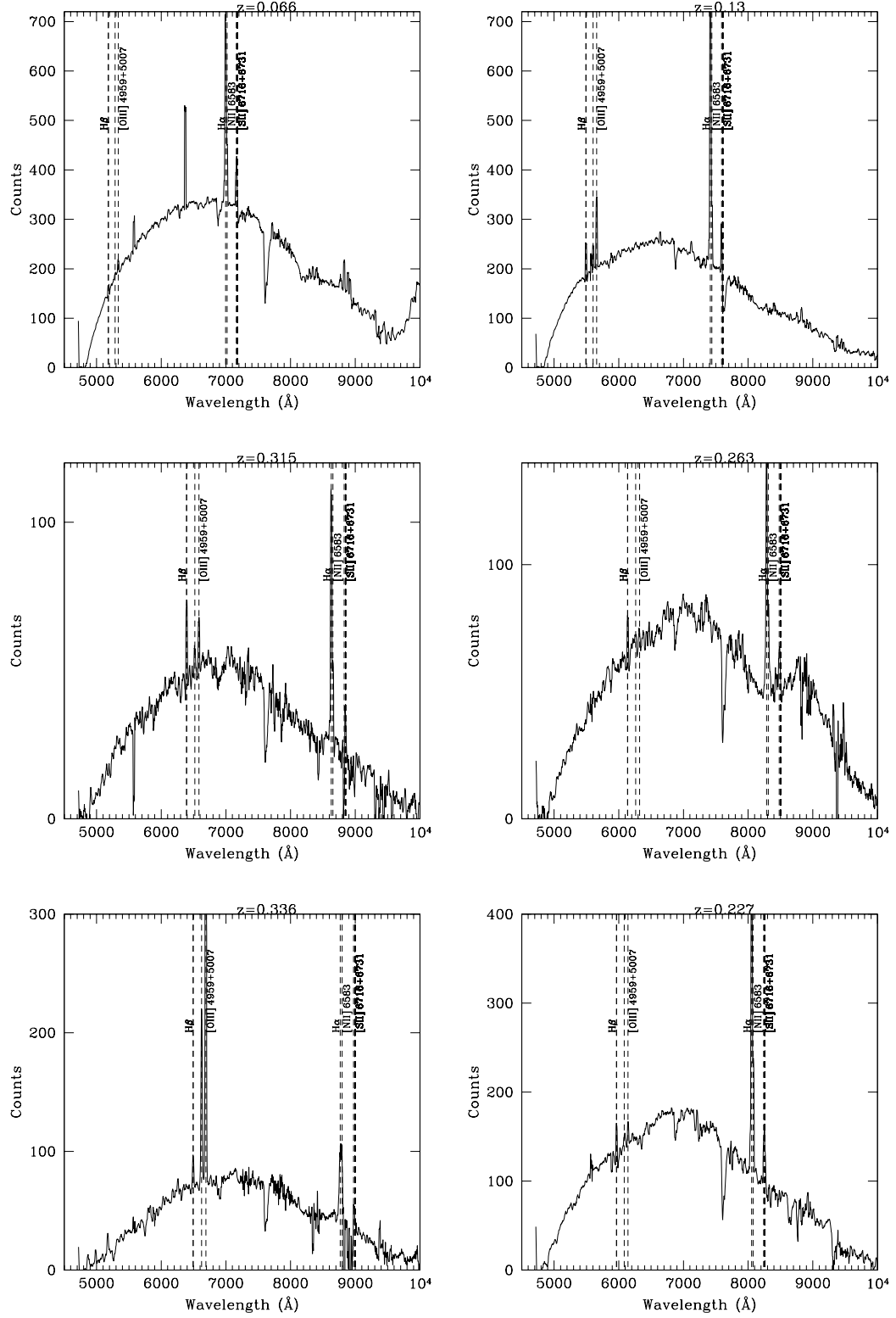


Figure 4.6: Representative Flag 3 spectra of the spectra with available [SII], H α , [OIII], H β , [NII] lines, used to estimate line ratios.

central black hole and the star-formation event either by the presence of gas that both feeds the SMBH and the starburst, as a result of a major merger event or points to the fact that these ULIRG ellipticals belong to the proposed green-valley transition objects between blue star-forming galaxies and red QSO remnants.

4.5 Emission Line Diagnostics

A suite of three emission line diagnostic diagrams has been used to classify the dominant energy source in narrow emission line galaxies [22]. These diagrams are based on the four optical line ratios: $[OIII]/H\beta$, $[NII]/H\alpha$, $[SII]/H\alpha$ and $[OI]/H\alpha$. Although other ratios, such as $[OII]/[OIII]$, offer cleaner separation between planetaries and H_{II} regions [22], combinations such as $[NII]/H\alpha$ versus $[OIII]/H\beta$ and $[SII]/H\alpha$ versus $[OIII]/H\beta$ not only are very accurate in distinguishing the dominant component of narrow line galaxies but are also very insensitive to reddening and do not require the samples to be flux calibrated. This is due to the fact that the lines in these pairs are chosen to be close in wavelength and as a result the line ratios are accurately determined even for uncalibrated spectra. This is extremely useful in the case of our sample which is not flux calibrated due to problems associated with the set up of flats during some observations which prevented us from flux calibrating the entire sample.

We have identified a total of 30 sources with very secure detections of all 5 lines, $[OIII]$, $H\beta$, $[NII]$, $H\alpha$, $[SII]$. The flux in each emission line is measured using IRAF's SPLIT routine, by interactively fitting a Gaussian function to each emission feature line profile and then integrating. A table of the resulting fluxes measurements and examples of spectra used are given in Table 4.1 and Figure 4.6 respectively.

Figure 4.7 shows the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagnostic diagram for our sample of 30 sources. The red line represents the most conservative AGN rejection criterion and they are the sources with very low contribution to $H\alpha$ from AGN [43]. This line is similar to Kauffmann's [166] pure starburst line which has included this line to distinguish between pure star-forming sources and composite objects whose spectra contain significant contributions from both AGN and star formation. Everything below this line are classed as HII region like galaxies. The blue line is the line developed by Kewley [175]. This line uses a combination of stellar population synthesis models and detailed self consistent photoionization models to create

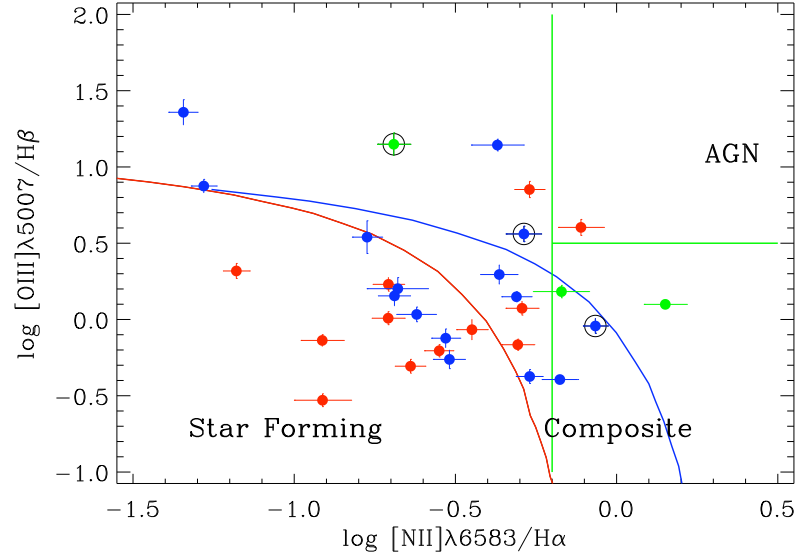


Figure 4.7: The $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagnostic diagram for all 30 sources with available lines. The red line is the pure star formation line [166]. Blue line is the extreme starburst line [175]. The green lines is the Seyfert/LINER line [147]. Open black circles are sources with X-ray detections from the ELAIS-N1 Deep X-ray survey [222]. Red, blue and green colors represent sources fitted with a cirrus, starburst or dust torus template respectively.

a theoretical maximum starburst line. Everything that lies above this line should be AGN dominated. All sources that lie between these two lines are classed as composites and their spectra can be either due to a combination of star formation and a Seyfert nucleus or due to a combination of star formation and LINER emission. The green solid lines represents Ho's classification scheme [147] where everything below the Kewley line and left from the green line is classified as H_{II} nuclei, upper left represents the Seyfert nuclei sources, upper right box are LINER and low right box are the transition objects. Figure 4.8 shows the $[SII]/H\alpha$ versus $[OIII]/H\beta$ diagnostic diagram for the same sample as before. The black line separates between AGN and star forming galaxies while the red line provides an empirical division between LINER and Seyfert sources [176]. Green lines are the same as Figure 4.7.

According to the above classifications we have five different categories of sources in these two diagrams:

- (i) **Star forming galaxies** : Those sources that lie below the pure starburst line in the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagram and below the AGN/Starburst line in the $[SII]/H\alpha$ versus $[OIII]/H\beta$.

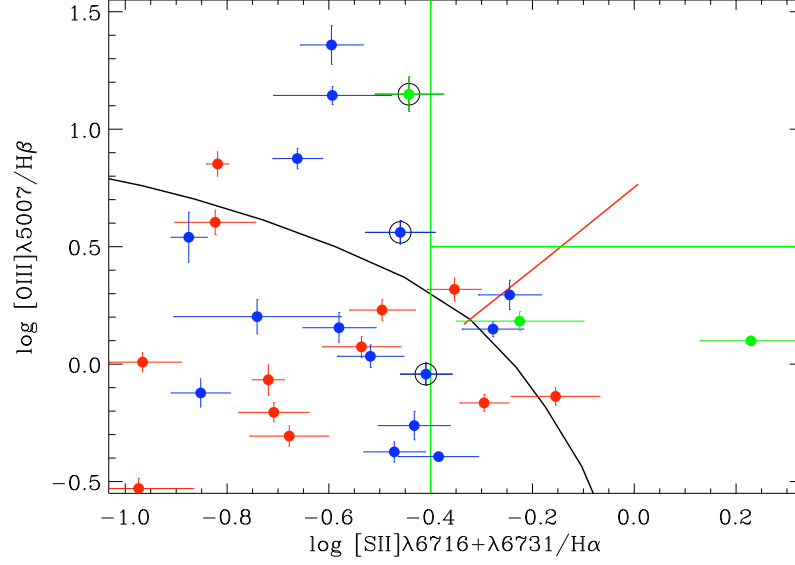


Figure 4.8: The $[SII]/H\alpha$ versus $[OIII]/H\beta$ diagnostic diagram for all 30 sources with available lines. The red line is the Seyfert/LINER line [176] and the black line is the AGN/starburst line [22]. Green lines and different colors and symbols same as Figure 4.7.

- (ii) **Seyfert** : Those sources that lie above the extreme starburst line in the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagram, above the the AGN/Starburst line in the $[SII]/H\alpha$ versus $[OIII]/H\beta$ diagram and above the Seyfert/LINER line in the same diagram.
- (iii) **Composite Objects** : Sources that lie between the pure starburst and extreme starburst lines in the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagram.
- (iv) **LINER** : Objects that lie above the extreme starburst line in the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagram and below the Seyfert/LINER separation line in the $[SII]/H\alpha$ versus $[OIII]/H\beta$ diagram.
- (v) **Ambiguous objects** : Those objects which in the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagram appear to be composite and lie above or below the starburst/AGN separation line in the $[SII]/H\alpha$ versus $[OIII]/H\beta$ diagram.

Based on the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagram from the 30 sources in our sample we have found 14 pure starforming sources, 9 composite objects, 3 of which appear to be LINERs and 7 narrow line AGN of which 1 appears to be a LINER. In the same plot we are using different colour coding for the different infrared SED types. Sources with X-ray detections from the ELAIS-N1 Deep X-ray Survey [222]

are plotted as open black circles. According to the $[SII]/H\alpha$ versus $[OIII]/H\beta$ diagnostic 6 sources are Seyferts, 6 are LINERs and the rest appear to be star-forming galaxies. In general there is good agreement between the two diagnostics. From the 21 sources that were classified as pure star-forming or AGN dominated in the $[NII]/H\alpha$ versus $[OIII]/H\beta$ diagram there are only three cases which are classified differently in the $[SII]/H\alpha$ versus $[OIII]/H\beta$ diagnostic.

There are twelve sources in our sample best fitted with a cirrus infrared template. Ten of them are fitted with a galaxy optical template and two are fitted with a starburst template. According to both emission line diagnostics seven of them are pure star-forming sources and one is AGN dominated. For the remaining four, emission line diagnostics are not clear whether they are star-forming, AGN or composites. For all 10 sources that are classified as star-forming or composites, SED fitting identifies a strong starburst component that contributes between 20-40% to the $8\mu\text{m}$ emission which may mean that this contribution can be much higher in mid and far-infrared wavelengths. For the two cirrus sources that appear to be narrow-line AGN, infrared show no evidence of the presence of a torus.

Fifteen sources are best fitted with a starburst infrared template. Agreement between SED fitting and spectroscopy for these sources is very good. For the 5 sources that were identified as star-forming from spectroscopy, template fitting finds a dominant star-formation component that contributes up to 65-100% to the infrared emission. All six composites have composites SEDs with AGN contributing between 20 and 50% to the $8\mu\text{m}$ emission. In the case of all three narrow line AGN infrared has identified a strong torus component contributing between 35-45%. Finally, for the remaining spectroscopically ambiguous sources, SED fitting finds no evidence of a torus component.

In the case of the three sources fitted with a torus template there is an excellent agreement between spectroscopy and ImpZ code. All sources appear to be composite in the infrared with AGN dominating in all three cases consistent with emission line diagnostics.

If we assume that the different spectroscopic diagnostics used here provide us with a 90% accuracy, taking into account that 3 out of 30 sources have been classified differently from the two diagrams, then X-ray achieve less than 70% since from the three luminous AGN in X-ray one appears to be either a pure star-forming galaxy

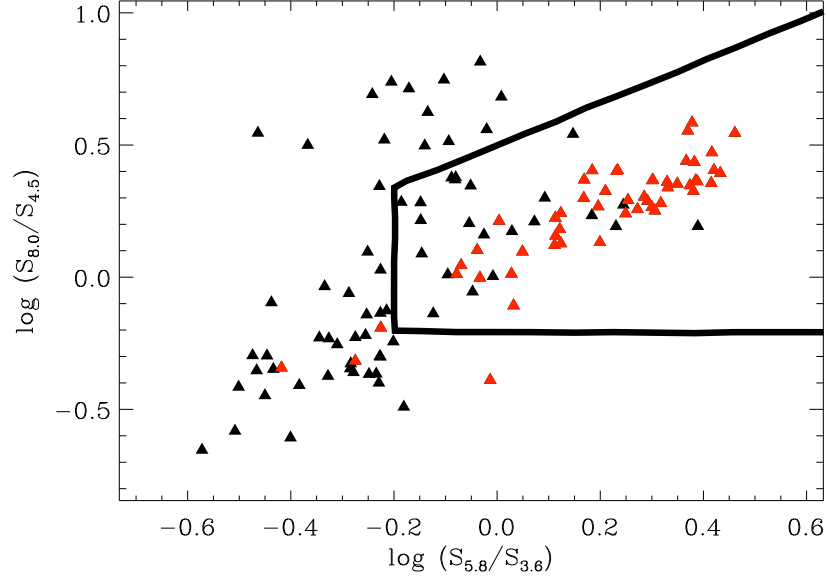


Figure 4.9: IRAC color-color plot using available data from SWIRE. Triangles represent the 123 sources with spectroscopic redshifts from GMOS/WIYN and significant detections in all IRAC bands. Red triangles represent the sources which are fitted with a QSO optical template. Solid line is the AGN area as defined by Lacy [185] .

or a composite object. On the other hand infrared/optical SED fitting is doing very well in isolating star forming galaxies from narrow line AGN and identifying composite objects and it reaches the same accuracy with spectroscopic diagnostics.

Although there are differences between different diagnostics it is essential to combine information from different wavelengths to be able to get a full picture of the wide range of properties of AGN and galaxies at different wavebands.

4.6 Comparison with Colour-Colour Diagrams

Previous studies with ISO have shown that mid-ir continuum associated with AGN provides a powerful tool in distinguishing AGN from starbursts. The origin of this continuum arises mainly from three sources: emission from very small dust grains in H_{II} regions, polycyclic aromatic hydrocarbon (PAH) emission and AGN. In this section we utilize SWIRE infrared data and GMOS/WIYN spectroscopic data to perform Lacy's [185] infrared diagnostics for our spectroscopic sample in order to distinguish between AGN and starbursts. In this way we will be able to compare with the performance of our template SED fitting.

For the Lacy diagnostic we require sources that have detections in all four IRAC bands, $3.6\mu\text{m}$, $4.5\mu\text{m}$, $5.8\mu\text{m}$, $8\mu\text{m}$, resulting in a sample of 123 sources with available spectra from GMOS/WIYN. For the IRAC-MIPS diagnostic, sources are required to have detections in IRAC's Channels 1 and 3, $3.6\mu\text{m}$, $5.8\mu\text{m}$, and MIPS's $24\mu\text{m}$ band. This requirement limited the number of our sources to 109.

Figure 4.9 shows the Lacy diagnostic for the above sample. Sources that lie within the black line are those expected to be AGN dominated from the infrared colours. Sources that are plotted in red are the 52 out of 123 sources which were fitted with a QSO optical template [283]. From the 52 sources only 4 lie outside Lacy's box. In Figure 4.10 I have plotted the same sources using the IRAC-MIPS color-color plot. The larger wavelength difference between 8 and $24\mu\text{m}$ makes the interpretation of the MIPS/IRAC colors more complicated but as it can be seen again only 3 of the QSO fitted sources lie outside the AGN selected area right of the solid black line. Almost 30% of the sources that were not fitted with a QSO template lie within the AGN area in the IRAC colour-colour plot. Inclusion of the $24\mu\text{m}$, increases the number of outliers by almost 20%.

In Figure 4.11 I am using the IRAC colour-colour plot combined with information obtained from the spectroscopic diagnostics. In this case sources which were spectroscopically identified as either narrow or broad line AGN are plotted with the general population shown in Figure 4.9. As before all of the sources used here satisfy the requirement of having detections in all 4 IRAC bands. This resulted in a sample of 18 broad line AGN and 13 narrow line AGN.

As it can be seen all broad line objects lie within the AGN wedge and almost all of them (16/18) have been detected also in X-ray. In addition 16/18 broad line AGN (88.9 %) of the sources are fitted with a QSO template. The remaining two which were fitted with a starburst template are the only ones in this broad line sample which have broad Balmer lines and evidence of star formation. Indeed the SEDs of these two objects are composite and show both an AGN and a starburst component with the starburst dominating in $8\mu\text{m}$.

11 out of 13 narrow line AGN lie outside the defined AGN area. As it can be seen in Table 4.1 all of these objects, except the cirrus dominated sources, are either starburst dominated or composite objects with significant contributions from

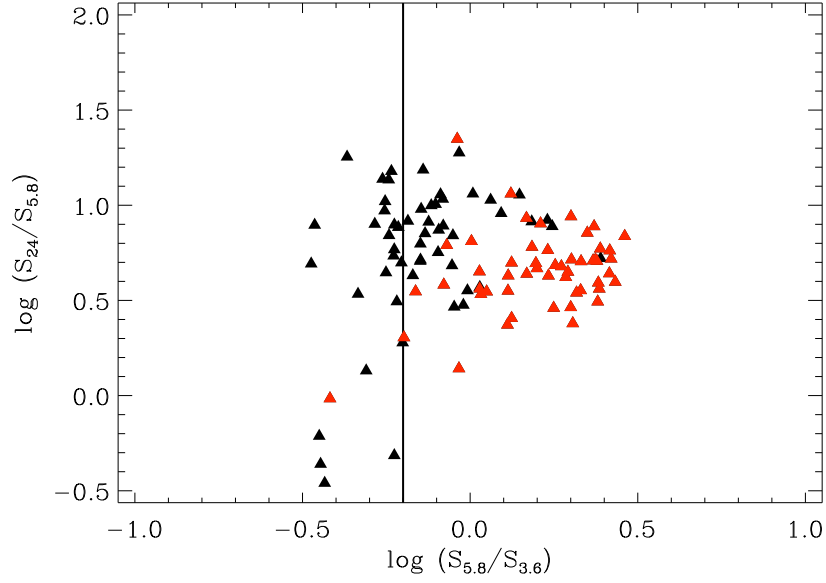


Figure 4.10: IRAC-MIPS color-color plot using available data from SWIRE. Triangles represent the 109 sources with spectroscopic redshifts from GMOS/WIYN and significant detections in 3.6, 4.5 and 24 μm . Solid line distinguishes between AGN and star-forming galaxies [185][28].

a torus template, reaching up to 45% of infrared emission in 8 μm . Except two of them, the remaining twelve are missed by X-rays. This tentatively suggests that the central engine is obscured by high columns of dust. These missing sources could be associated with Compton-thick or low-luminosity AGN. The fact that all these narrow line AGN are low-redshift objects that lie in the same parameter space, on the top left corner above the AGN wedge, and that the vast majority (12/13) is fitted with an early type galaxy template suggest that the galaxy contamination is significant and these are probably low-luminosity AGN completely missed by both X-rays and infrared color diagnostics. At low redshifts, most of the obscured AGN are associated with early type galaxies rather than systems in formation [275] in agreement with the SED fitting used here.

4.7 Summary

In this Chapter a comparison between spectroscopic and photometric redshifts in ELAIS-N1 is presented. The overall accuracy of the redshift code is found to be very good with a total *rms* scatter, $\sigma_{tot} = 0.12$, $\overline{\Delta z}/(1+z) = -0.02$ and the rate of 'catastrophic' outliers is equal to 7.6% (23 sources). The same comparison for sources with high quality spectra found to be even better with $\sigma_{tot}=0.09$,

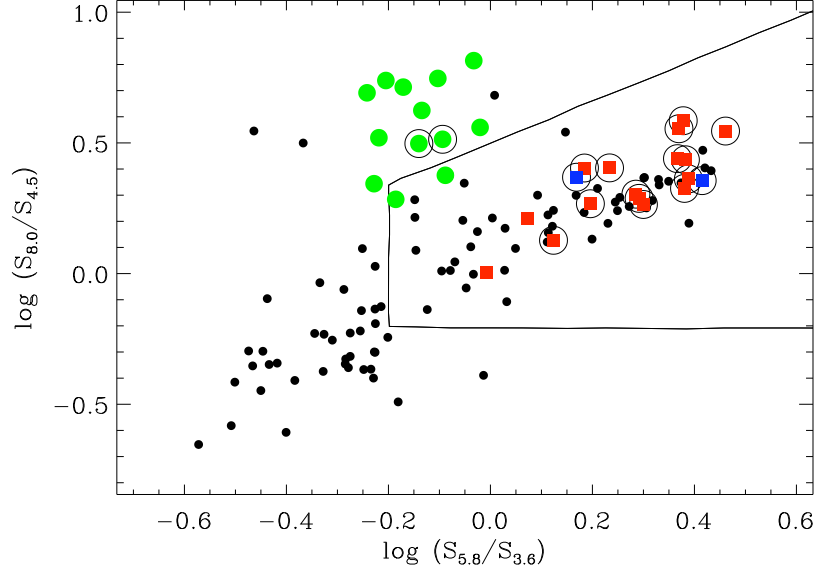


Figure 4.11: IRAC color-color plot similar to that of Figure 4.9. Open black circles are sources with X-ray detections, large green filled circles are sources classified as narrow line AGN from emission line diagnostics, red squares are spectroscopically identified broad line QSO fitted with a QSO optical template and blue squares are spectroscopically identified broad line QSO fitted with a non-QSO optical template.

$\overline{\Delta z}/(1+z) = -0.008$ and only 4.4% (10 sources) catastrophic outliers. In addition the latest developments incorporated to the ImpZ code has reduced the number of catastrophic outliers for high-redshift QSOs to less than 2%.

Comparisons of bolometric infrared and optical luminosities have shown that more than half of the sources fitted with a cirrus template are LIRGs. In addition, we have identified a population of elliptical galaxies with very strong ongoing starbursts.

Emission line diagnostics and comparison with the SED fitting method used throughout this thesis has demonstrated the accuracy and validity of the later. Although X-ray and IRAC/MIPS colour-colour plots have been proven useful in isolating AGN or star-forming dominated sources, only the template fitting method could match optical spectroscopy accuracy in identifying composite objects and narrow-line AGN. Finally we report here the identification of a different parameter space occupied by narrow line AGN than that proposed by Lacy. SED fitting suggests that these are all AGN outshined by their host galaxy. Deeper X-ray data are required in order to be able to fully constrain the properties of these sources.

Most of the results presented in this chapter are published in [283] and will also appear in [342].

4.8 Continuation

In the next Chapter I will describe the largest X-ray survey performed in ELAIS-N1. X-ray and spectroscopic data from GMOS/WIYN are combined in an effort to fully understand the properties of luminous X-ray AGN and especially those with $70\mu\text{m}$ counterparts.

Chapter 5

The ELAIS-N1 Chandra Shallow Survey

I propose to survey the sky for you: it will have to be marked out in acres

Aristophanes (456-386 BC)

5.1 Overview

In this Chapter I present the X-ray catalogue and first results from our 5ks Chandra survey of SWIRE ELAIS-N1. We have used ACIS-I to survey a contiguous area of $> 1 \text{ deg}^2$ down to $1.04 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $9.41 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ for the 0.5-2.0 and 2-8 keV bands respectively. This represents the largest X-ray survey performed in ELAIS-N1 with almost 90% overlap with IRAC sources detected by SWIRE. Compared with the ROSAT ultradeep survey, it reaches the same depth in soft x-ray but over an area ~ 3 times larger while at the same time is by a factor of ~ 10 deeper than the ASCA LSS survey. As a result, we are detecting relatively bright objects, feasible to detect in other wavebands but still faint enough to be representative of the AGN population which makes up the X-ray background. A total of 658 unique X-ray sources have been detected, 564 with an IRAC counterpart, 439 among them with both an IRAC and an optical counterpart. Most of the discussion in this Chapter is focused in the population with detections in optical, infrared and X-ray wavelengths.

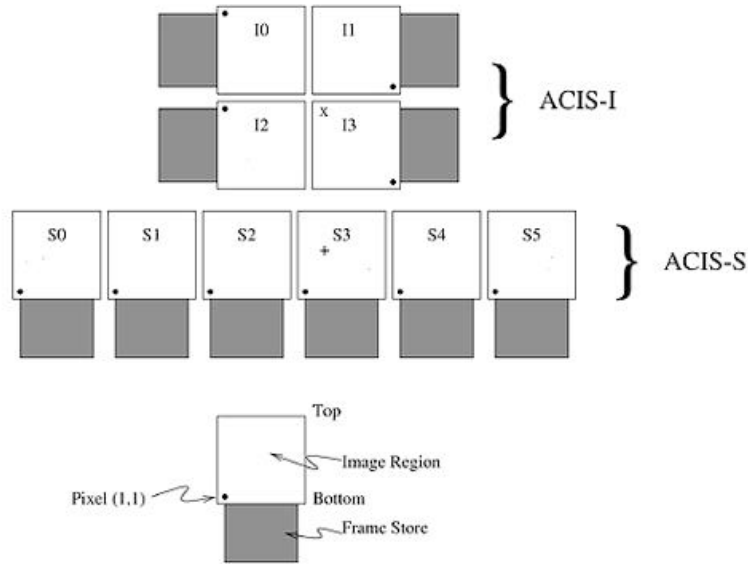


Figure 5.1: The ACIS focal plane [1].

5.2 Introduction

X-ray surveys have proved to be by far the most efficient way of finding AGN, and in a relatively shallow survey such as this, AGN completely dominate the source population. When a hard band pass is available, as with Chandra $> 2\text{keV}$, one can detect AGN that might otherwise be completely missed in other surveys due to obscuration. X-ray observations therefore bring us a step closer to the true AGN population. In order to study in detail this population, the multiwavelength properties of AGN need to be examined. This is only really possible in a shallow, bright survey, as the deepest X-ray surveys reveal objects too faint for effective follow-up. Our main goal is to exploit the full power of SWIRE's multi-wavelength observations and determine the broad band, optical to far-infrared SEDs of a large sample of X-ray selected AGN.

The benchmark work on unobscured AGN SEDs has been the atlas of Elvis [91]. AGN SEDs can be decomposed into four components: the UV blue bump which dominates optically selected QSOs, the X-ray power law, the far infrared dust emission and the radio emission, probably from synchrotron emission. These are thought to reflect, respectively the contributions of the thermal emission of the accretion disk, high energy processes close to the black hole, re-radiation of AGN light by the dust torus in AGN unification models and in some cases emission from a relativistic jet.

Focal plane arrays:	
I-array	4 CCDs placed to lie tangent to the focal surface
S-array	6 CCDs in a linear array tangent to the grating Rowland circle
CCD format	1024 by 1024 pixels
Pixel size	24.0 microns (0.4920 ± 0.0001 arcsec)
Array size	16.9 by 16.9 arcmin ACIS-I 8.3 by 50.6 arcmin ACIS-S
On-axis effective Area	110 cm^2 @ 0.5 keV (FI)
(integrated over the <i>PSF</i>	600 cm^2 @ 1.5 keV (FI)
to >99% encircled energy)	40 cm^2 @ 8.0 keV (FI)
Quantum efficiency	> 80% between 3.0 and 5.0 keV
(frontside illumination)	> 30% between 0.8 and 8.0 keV
Quantum efficiency	> 80% between 0.8 and 6.5 keV
(backside illumination)	> 30% between 0.3 and 8.0 keV
Charge transfer inefficiency(parallel)	FI: $\sim 2 \times 10^{-4}$; BI: $\sim 2 \times 10^{-5}$
Charge transfer inefficiency(serial)	S3(BI): $\sim 7 \times 10^{-5}$; S1(BI): $\sim 1.5 \times 10^{-4}$; FI: ($< 2 \times 10^{-5}$)
System noise	$< \sim 2$ electrons (rms) per pixel
Max readout-rate per channel	~ 100 kpix/sec
Number of parallel signal channels	4 nodes per CCD
Pulse-height encoding	12 bits/pixel
Event threshold	FI: 38 ADU (~ 140 eV) BI: 20 ADU (~ 70 eV)
Split threshold	13 ADU
Max internal data-rate	6.4 Mbs ($100 \text{ kbs} \times 4 \times 16$)
Output data-rate	24 kb per sec
Minimum row readout time	2.8 ms
Nominal frame time	3.2 sec (full frame)
Allowable frame times	0.2 to 10.0 s
Frame transfer time	40 μsec (per row)
Point-source sensitivity	$4 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}$ in 10^4 s (0.4-6.0 keV)
Detector operating temperature	-90 to -120°C

Figure 5.2: ACIS characteristics [1].

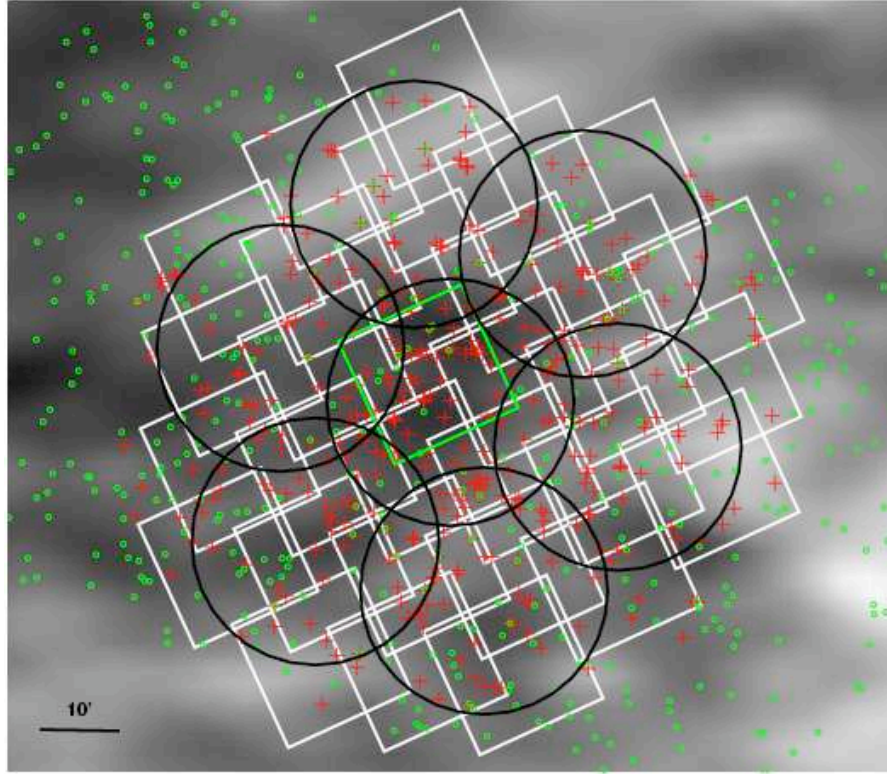


Figure 5.3: The ELAIS-N1 central region. Previous Chandra data consisted of only a single, moderate depth (75ks) ACIS-I pointing (green square) as part of the ELAIS Deep X-ray Survey [222]. We have extended this coverage by a factor of 12 (white squares), by overlapping 30×5 ks ACIS-I exposures giving even coverage over 1 deg^2 . Small green circles show the ISO $15 \mu\text{m}$ sources, only four of which overlap with X-ray sources. Red crosses show the ISO radio detections from the VLA survey [55] (black circles) that cover the X-ray area. The background gray scale images show the Galactic extinction at $100 \mu\text{m}$ from Schlegel [310] from 0.16 (dark regions) to 0.8 MJy/sr. Figure and caption from Nandra et al [237].

The broad-band SEDs will tell us therefore about the balance of power between the thermal disk, hot corona and jet and crucially the geometry, covering fraction and nature of obscuring material.

As described in Chapter 2, ELAIS-N1 has been surveyed in several different wavebands. Optical data, which include ugrIZ optical imaging and SWIRE IRAC data from $3.6\text{--}8 \mu\text{m}$ provide superb photometric redshifts and also allow us to estimate the galaxy contribution to the SED and optical extinction. Most critically, SWIRE MIPS data enable us to measure the far-infrared energy distribution where the bulk of the bolometric luminosity of obscured AGN is emitted, and where most of the energy from star formation emerges after absorption by dust. The key-point, how-

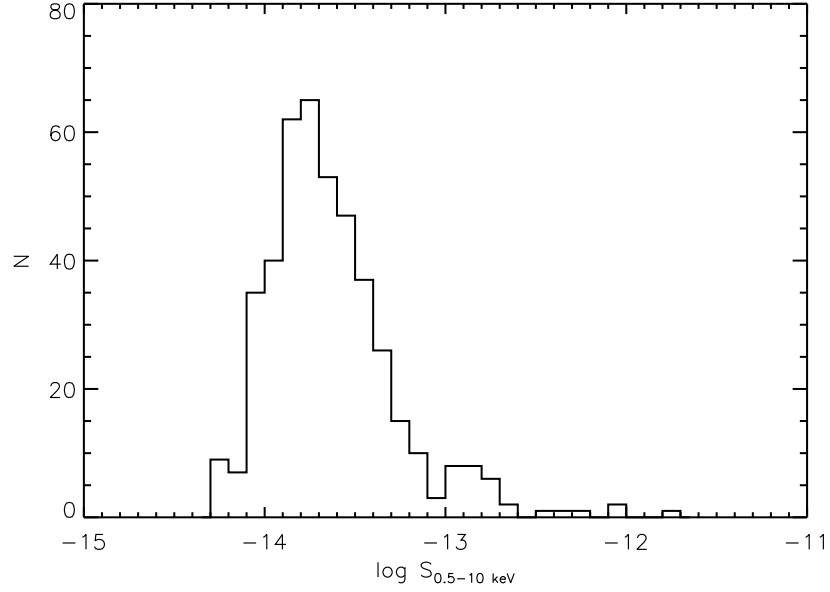


Figure 5.4: 0.5-10 keV flux distribution of all X-ray sources with SWIRE counterparts.

ever, is that AGN heated dust emission is warm and exhibits a broad peak at 2-20 μm whereas cooler starburst emission peaks at 100-200 μm . Only with multi-band infrared data can they therefore be decomposed.

The key science goals of this survey are mainly to study the obscuration, unification and the nature of the X-ray populations and the starburst-AGN connection. The latter is described in great detail in Chapter 6. Regarding the first, according to the unification model [189][276] described in Chapter 1, AGNs are surrounded by an optically thick dust torus and the absence or presence of optical broad lines is accounted for by orientation. Although this model has been extremely successful for local Seyfert galaxies, deep and wide X-ray surveys have, however, shown that the AGN which make up the X-ray background do not fit in this picture. Unification models predict that at high redshifts, there should be a large number of Type II QSOs, the counterparts of the high redshift broad line AGN seen in optical and soft X-ray surveys. These have not been found in large numbers [134]. Many objects show no clear evidence for AGN activity in their optical spectra and show simply absorption lines or emission lines indicative of low ionization [26]. In deep surveys, however, these investigations are hampered by the fact that a large fraction of the X-ray sources are too faint for effective follow-up in other wavebands. The solution to that problem are wide shallow surveys with Spitzer and optical coverage.

Table 5.1: Observations Summary

Sequence	Observation ID	Exposure	α_{2000}	δ_{2000}	Data mode
		(ks)			
900355	5855	4.75	16 06 15.40	+54 21 22.30	Very Faint
900356	5856	4.55	16 06 15.40	+54 33 22.30	Very Faint
900357	5857	4.56	16 06 15.40	+54 45 22.30	Very Faint
900358	5858	4.56	16 07 37.40	+54 09 22.30	Very Faint
900359	5859	4.76	16 07 37.70	+54 21 22.30	Very Faint
900360	5860	4.55	16 07 38.10	+54 33 22.30	Very Faint
900361	5861	4.46	16 07 38.50	+54 45 22.30	Very Faint
900362	5862	4.43	16 07 39.00	+54 57 22.30	Very Faint
900363	5863	4.95	16 08 58.50	+53 57 22.30	Very Faint
900364	5864	4.75	16 08 59.30	+54 09 22.30	Very Faint
900365	5865	4.67	16 09 00.10	+54 21 22.30	Very Faint
900366	5866	4.96	16 09 00.90	+54 33 22.30	Very Faint
900367	5867	4.75	16 09 01.70	+54 45 22.30	Very Faint
900368	5868	4.76	16 09 02.60	+54 57 22.30	Very Faint
900369	5869	4.76	16 10 20.10	+53 57 22.30	Very Faint
900370	5870	4.76	16 10 21.30	+54 09 22.30	Very Faint
900371	5871	4.76	16 10 22.50	+54 21 22.30	Very Faint
900372	5872	4.96	16 10 24.90	+54 45 22.30	Very Faint
900373	5873	4.75	16 10 26.20	+54 57 22.30	Very Faint
900374	5874	4.76	16 10 29.90	+55 07 49.20	Very Faint
900375	5875	5.13	16 11 41.70	+53 57 22.30	Very Faint
900376	5876	4.75	16 11 43.30	+54 09 22.30	Very Faint
900377	5877	5.13	16 11 44.90	+54 21 22.30	Very Faint
900378	5878	4.76	16 11 46.50	+54 33 22.30	Very Faint
900379	5879	4.85	16 11 48.10	+54 45 22.30	Very Faint
900380	5880	4.65	16 11 49.80	+54 57 22.30	Very Faint
900381	5881	4.66	16 13 05.20	+54 09 22.30	Very Faint
900382	5882	4.66	16 13 07.20	+54 21 22.30	Very Faint
900383	5883	4.66	16 13 09.20	+54 33 22.30	Very Faint
900384	5884	4.66	16 13 11.30	+54 45 22.30	Very Faint

5.3 Chandra X-Ray Observatory and ACIS-I

The Chandra X-ray Observatory [351], formerly known as the Advanced X-ray Astrophysics Facility (AXAF) was launched on 23rd July 1999 as part of NASA's Great Observatories Program in a highly elliptical, high-earth orbit in order to ensure a high observing efficiency as the satellite spends 75% of its time above the Earth's radiation belts and the fraction of the sky occulted by the Earth is small. Chandra's orbital period is 63.5 hours allowing long continuous observations of more than 160ks. Chandra has a $0.5''$ full-width-half-maximum (FWHM) point spread function (PSF) which is not a strong function of energy. It also provides an order of magnitude better resolution than any other X-ray mission. The Chandra mirror has an effective area of approximately $0.8m^2$ below 2 keV and $0.4m^2$ between 2 and 5 keV [311] which in conjunction with the two gratings onboard, the Low Energy Transmission Grating [44] and the High Energy Transmission Grating [224] provides resolving powers in excess of 500 over the energy range 0.3-7 keV. The combination of high resolution imaging, large collecting area and sensitivity to high energies is unique to Chandra and allows the study of faint absorbed sources in crowded fields.

The instrument used for this work was the Advanced CCD Imaging Spectrometer [116] which offers the capability to simultaneously acquire high-resolution images and moderate resolution spectra. ACIS contains 10 planar, 1024×1024 pixel CCDs (Figure 5.1); four arranged in a 2×2 array for ACIS-I used for imaging and six in a 1×6 array for ACIS-S used either for imaging or as a grating readout. When ACIS-I is selected in imaging, 6 chips are used which enhances the chance of serendipitous science but at the price of increased total background counting rate and therefore an enhanced probability of saturating telemetry. ACIS characteristics are summarized in Figure 5.2. ACIS CCDs are primarily made of silicon with a gate structure on one surface defining the pixel boundaries. The reason ACIS-I was chosen over ACIS-S is its superior PSF over the whole fields and lower background. The ACIS-I full field of view is $16.9' \times 16.9'$ (285 arcmin^2), and the sky-projected ACIS pixel size is $\sim 0.492''$. The PSF is smallest at the lowest photon energies and for sources at small off-axis angles. The 95% encircled-energy radius at 1.5keV for off-axis angles of $0'-8'$ is $\sim 1.8''-7.5''$ [162][103]. The PSF is approximately circular at small off-axis angles, broadens and elongates at intermediate off-axis angles, and becomes complex at large off-axis angles.

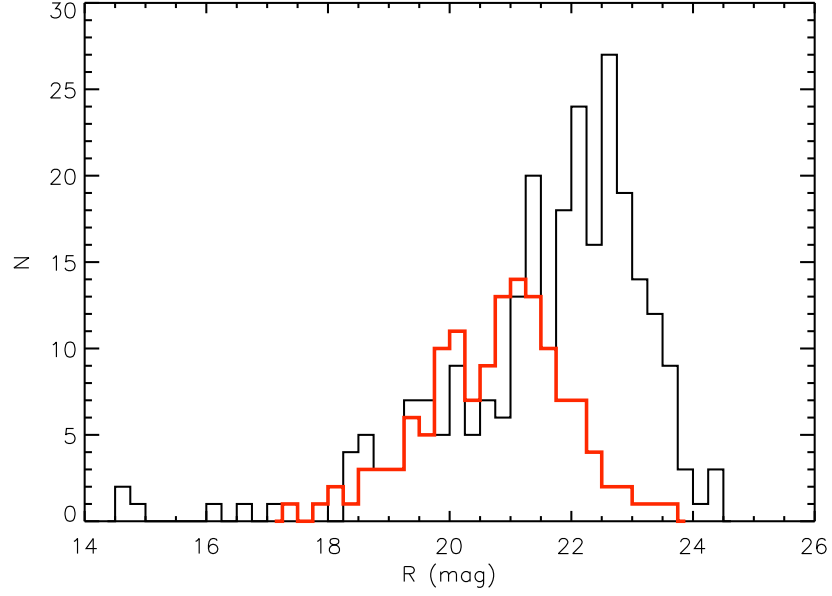


Figure 5.5: Observed R-magnitude distribution of the 439 X-ray sources with both a SWIRE and an optical counterpart. The red line represents the distribution of objects fitted with a QSO optical template and the black line those fitted with a galaxy optical template.

5.4 Observations and Data Reduction

Our ELAIS-N1 observation program consisted of 30 Chandra observations taken between 31st January 2006 and 8th March 2006. The observations are summarised in Table 5.1 and a layout of the survey is given in Figure 5.3. The four ACIS-I CCDs were operated in all of the observations which were taken in Very Faint Mode to improve the screening of background events and thus increase the sensitivity of ACIS in detecting faint X-ray sources. The observations were made by overlapping the 30 ACIS-I exposures giving even coverage over 1 deg^2 . We have chosen to overlap the $\sim 16.9' \times 16.9'$ ACIS-I fields by $12'$, for two reasons. First this guarantees contiguous coverage even with random roll angles, eliminating the need for a large number of constrained observations. Second it results in the edges of the fields typically receiving double the exposure of the aim points.

The exposure time for each observation was $\sim 5 \text{ ks}$, reaching broadband (0.5-10 keV), soft-band (0.5-2 keV) and hard-band (2-10 keV) fluxes of $5.64 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$, $1.04 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $9.41 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ respectively which represents a similar depth in the soft X-ray band as the ROSAT ultradeep survey [197], but over an area ~ 3 times larger and a factor of ~ 10 deeper

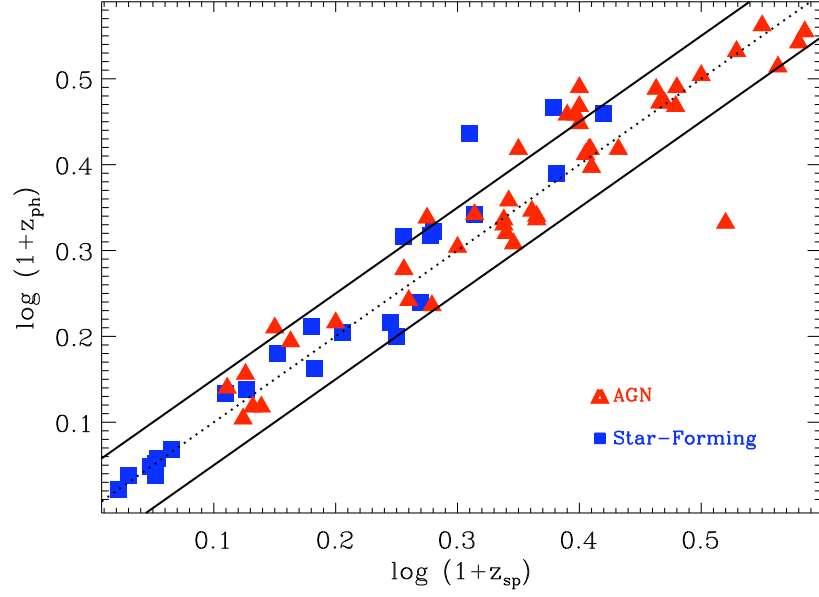


Figure 5.6: Comparison between photometric and spectroscopic redshifts in $\log(1+z)$ of the 73 sources with available spectroscopic redshifts. Solid lines represent 20% agreement in $1+z$. Red filled triangles represent either the spectroscopically identified AGN from our sample [342] or AGN best fit from the SED template fitting for the rest of the sources. Blue filled squares represent the star-forming sources identified either from spectroscopy [342] or SED fitting.

in the hard band than the ASCA LSS survey [343]. As a result, by performing the survey to this depth we are detecting relatively bright objects, feasible to detect in other wavebands but still faint enough to be representative of the AGN population which make up the X-ray background. Figure 5.4 shows the 0.5-10 keV flux distribution of all X-ray sources with IRAC counterparts.

Data reduction was performed using the Chandra X-ray Center Chandra Interactive Analysis of Observations (CIAO) data analysis software, version 3.4 and the Chandra Calibration database (CALDB), version 3.4.0. Data reduction pipeline was developed by Nandra et al [239][341]. The basic steps are summarized below.

- We first used the ACIS-PROCESS-EVENTS tool in order to apply correct gain maps and geometry solutions to all raw data and to clean all observations by identifying likely background events.
- Data are cleaned by filtering the event files using standard screening criteria from ASCA in order to remove bad and flaring pixels, bad columns and cosmic

ray afterglows. Each observation was checked with CIAO ASPECT calculator to check for known aspect errors.

- The filtered event files were then further filtered to include only events within 0.5-8 keV energy range. Periods of flaring background, where the background count rate is significantly higher than is typical, were removed.
- A new file with accurate RA, Dec is created using CELLDETETC and background lightcurves were created excluding the counts from these sources.
- Event files and images are constructed in the soft, full, hard and ultra-hard band. Effective exposure maps of individual observations are created with MERGE-ALL for each of the four bands taking into account the effects of vignetting, gaps between chips, bad column and bad pixel filtering and are required for converting observed counts to flux. The maps were created at a single energy representative of the photons in each band which represent the mean photon energies of detected sources in each band, determined post hoc.
- These maps were then combined using DMREGRID to produce effective exposure maps. Before merging, the individual event files are aligned using the ALIGN-EVT task.
- An initial source list is produced at a Poisson probability 10^{-4} at different energy bands which is then used in order to extract PSFs and calculate PSF radii at the representative energy of each of the four bands at the position of each candidate source.
- We then extract a radial profile of the PSF image by extracting counts from concentric circles centred on the source position out to a radius of 30 arcsec. The last step is to use WAVDETECT to extract counts to get the poisson probabilities of sources and centroid positions. These probabilities are then subjected to a threshold and in case where centroid and WAVDETECT probabilities give different results the sources are flagged. Position of sources in different bands are matched in order to create an all band list, region files and to do the count extraction. The final output is a table of sources, positions, net counts, errors, background counts, count rate, count rate errors and detection probability in each band. The Off Axis Angle (OAA) for each source is also output as well as a flag about whether the WAVDETECT or centroid position was used. In addition the hardness ratio (HR) for each is also given, defined

as

$$HR = \frac{H - S}{H + S} \quad (5.1)$$

where H and S are the net hard and soft band counts, corrected to on-axis values.

5.5 Cross Correlation with SWIRE

A total of 698 X-ray sources were detected. Due to the large overlap between different obsids a large number of duplicate sources was detected. Duplicates were removed by selecting the source with the smallest off-axis-angle. The X-ray source list was cross-correlated with the final version of the SWIRE ELAIS-N1 source list using a search radius of 3 arcsec corresponding to the value of the quadratic sum of the Chandra positional uncertainty which is roughly 2 arcsec and of the infrared positional uncertainty fixed to 2 arcsec:

$$\sigma_{total} = \sqrt{\sigma_X^2 + \sigma_{IR}^2} \quad (5.2)$$

For the cross correlation we have used the same method presented in §3.6. The majority of X-ray sources has a unique optical and infrared counterpart within the positional uncertainty. In the case of multiple matches the closest sources was chosen as the counterpart. A SWIRE infrared counterpart is matched to 605 sources (Figure 5.7). The remaining 93 X-ray sources do not have either an infrared or optical counterpart. The number of random associations has been calculated using the same method used in §3.6. The average number of random associations (Figure 5.8) was 41 ($< 8\%$). All of these sources were removed from the catalogue version used for the remaining part of this thesis. The final catalogue contains 439 X-ray sources with both an IRAC and an optical counterpart. The catalogue is presented in Appendix B and contains information about the infrared, optical and X-ray properties of the sources found. There is an additional population of 125 X-ray sources with IRAC counterparts but no optical associations presented in Appendix C. This can be due to the relatively shallow optical coverage of ELAIS-N1 or it might imply that all these sources are high-redshift heavily reddened QSO. At the time of writing the effort of determining reliable photometric redshifts was under way, so no secure conclusions can be derived until this is finalised. For the remaining of this work we have used only the X-ray catalogue associated with the SWIRE catalogue with optical associations which ensures accurate photometric redshifts and precise SED

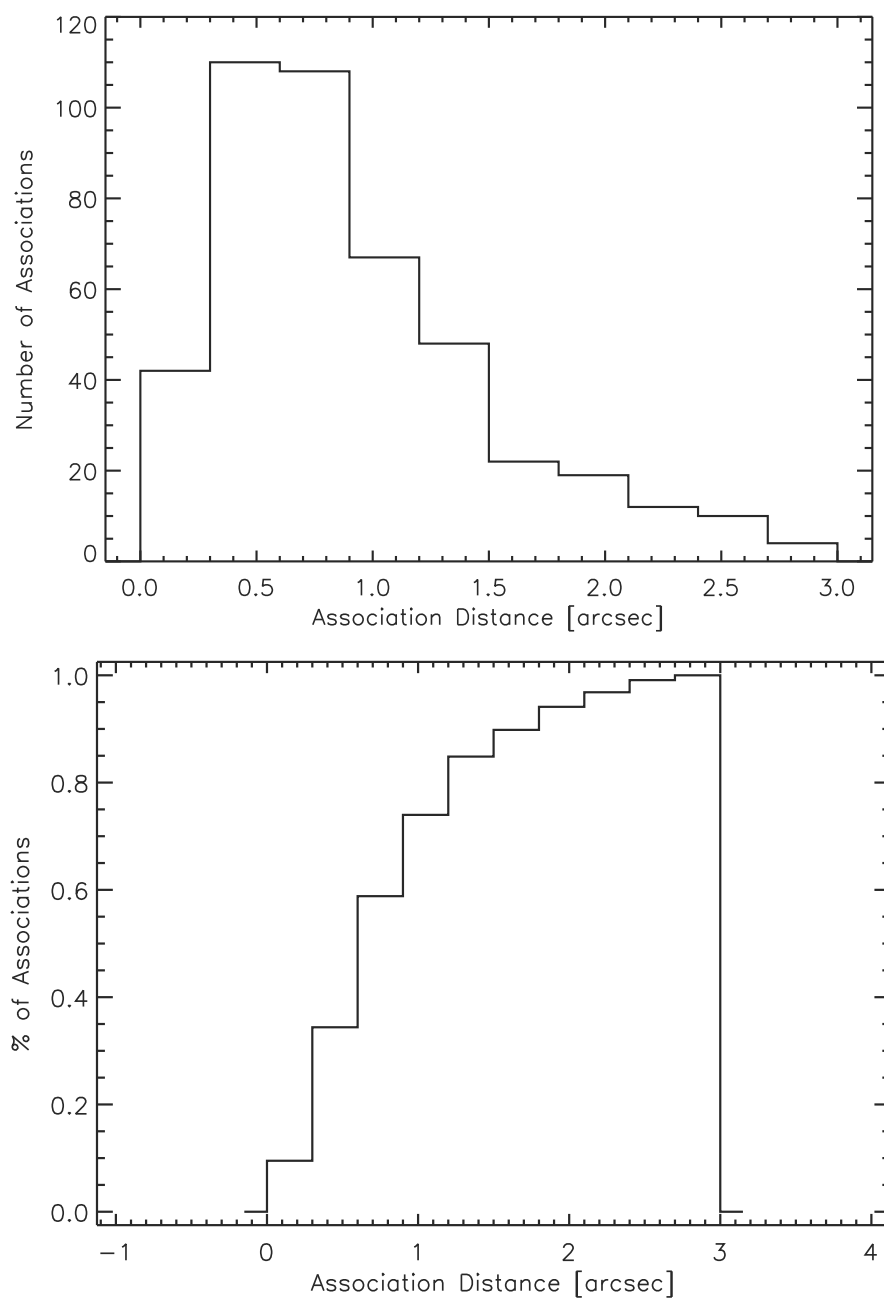


Figure 5.7: Astrometric accuracy. Positional difference between X-ray sources and SWIRE.

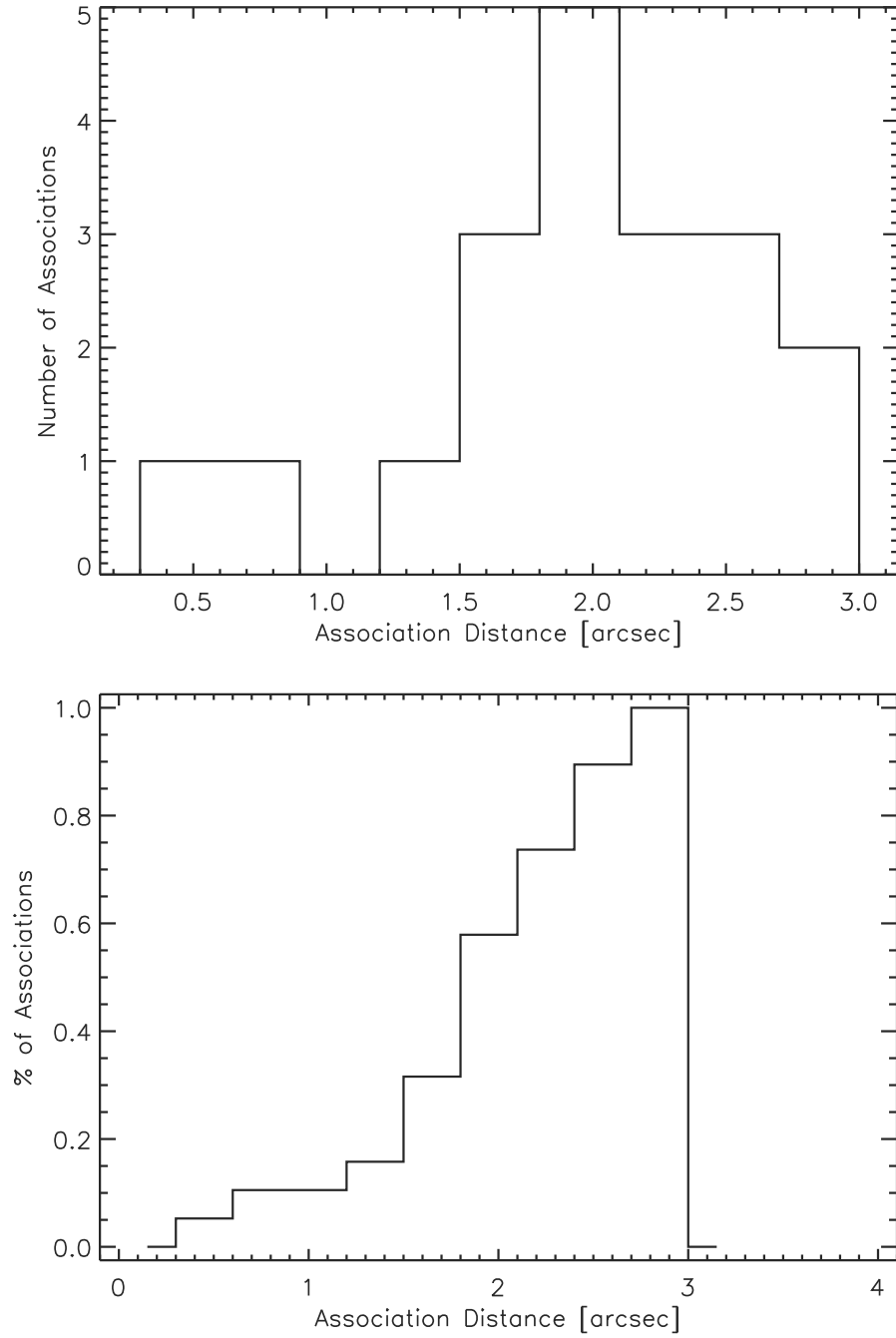


Figure 5.8: Number of the average expected random associations between SWIRE and the X-ray catalogue.

template fitting. Figure 5.5 shows the distribution of R magnitudes of all X-ray sources with optical associations.

5.6 Optical Spectroscopy

Spectroscopic observations were carried using various facilities with WIYN, Gemini and Keck. For 73 of our sources we have reliable spectroscopic redshifts, 8 from GMOS [342], 49 from WIYN [342] and 6 from Keck [36]. In addition 10 spectroscopic redshifts were retrieved from NED. For the rest of the sources we have applied the latest version of the ImpZ code [283] to get accurate photometric redshifts. In Figure 5.6 the comparison between photometric and spectroscopic redshifts is plotted with an excellent agreement between the two. Reliability and accuracy of the photometric redshifts are measured via the fractional error Δz , the systematic mean error $\overline{\Delta z}$, the 1σ dispersion σ_z and the rate of catastrophic outliers, defined as the fraction of sources with $|\Delta z/(1+z)| > 0.15$. $\Delta z/(1+z)$, $\overline{\Delta z}/(1+z)$ and σ_z are calculated as follows:

$$\Delta z/(1+z) = \left(\frac{z_{phot} - z_{spec}}{1 + z_{spec}} \right) \quad (5.3)$$

and

$$\overline{\Delta z}/(1+z) = \sum \left(\frac{z_{phot} - z_{spec}}{1 + z_{spec}} \right) / N, \quad (5.4)$$

and

$$\sigma_z^2 = \sum \left(\frac{z_{phot} - z_{spec}}{1 + z_{spec}} \right)^2 / N, \quad (5.5)$$

where N is the number of sources with spectroscopic redshifts. The systematic mean error is -0.001, the rms is 0.12 and the catastrophic outlier fraction is 13.7%, 10 sources out of 73. Even though these values are not as satisfactory as those achieved for galaxy populations it has to be reminded that most of the sources are AGN or AGN dominated and this result is better than what has been previously obtained for AGN samples where the fraction of outliers is usually higher than 25% [180].

5.7 Redshift Distributions

The redshift distribution of the whole sample of 439 sources based on photometric redshifts and spectroscopic redshifts, where available, is given in Figure 5.9. The distribution peaks at $z \sim 1$, consistent with the redshift distribution of other X-ray selected samples [26][80]. About 43% of the sources are at redshift below 1 and 17%

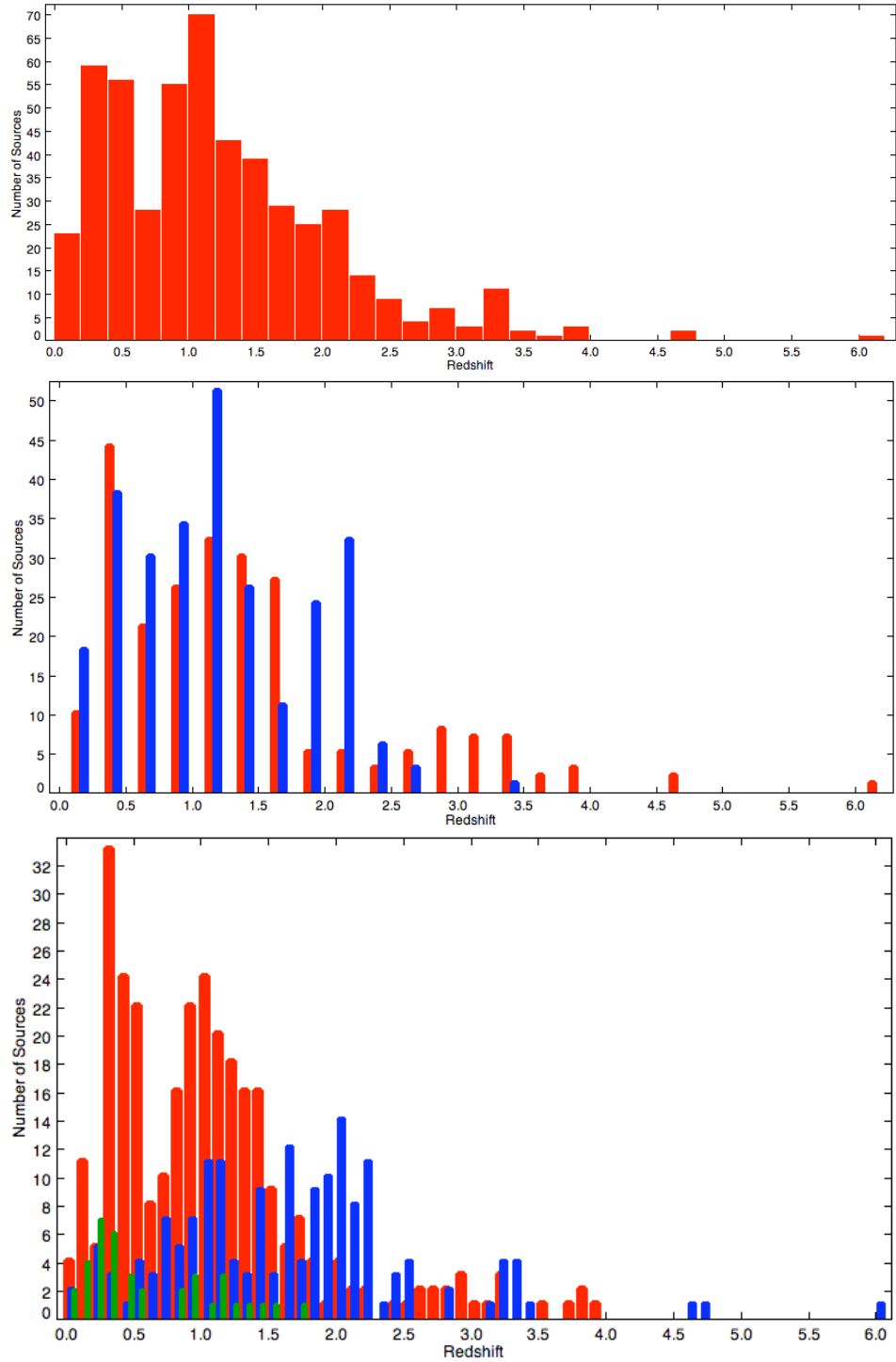


Figure 5.9: **Top:** Redshift distribution of all 439 X-ray sources with a SWIRE counterpart. **Middle:** Redshift distribution of the entire sample (except the 15 Cirrus fitted sources) color-coded according to the infrared SED template best fit. Blue spikes are sources fitted with a dust torus and red spikes are sources fitted with a starburst template (M82 or Arp220). Except one all high redshift ($z > 3$) sources have a starburst dominating their infrared emission **Bottom:** Redshift distribution of all sources (except Cirrus best fit sources) color labeled according to the best fit from optical SED fitting. Population is dominated by galaxies (red spikes). High redshift sources are both fitted with QSO (blue spikes) and galaxy templates. The three sources at $z > 4$ are all fitted with a QSO template. Green spikes are ellipticals.

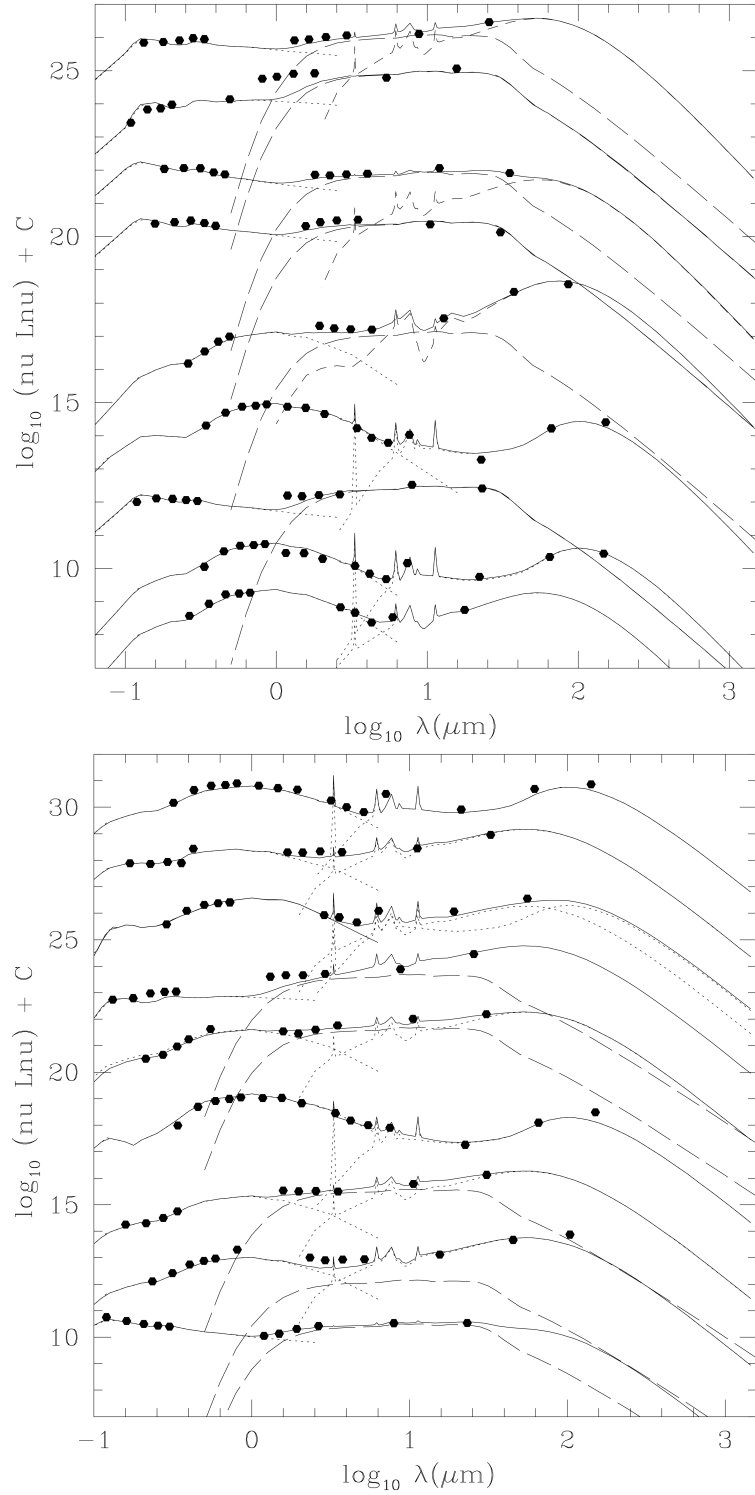


Figure 5.10: Optical to far-infrared SEDs in $\nu f\nu$ of all 18 X-ray sources with $70\mu\text{m}$. 11 of these sources are composites with both an AGN and a starburst component contributing to the total infrared emission, 3 are AGN dominated, 3 are pure starbursts and 1 is fitted with a cirrus template. Solid curves show the total predicted SED. Dotted curves show the optical-NIR and starburst templates, AGN dust torus are shown as a long dashed curve and cirrus templates are shown as a short dashed template. The three sources dominated by AGN dust torus and a QSO optical template all have available spectra (Figure 5.11).

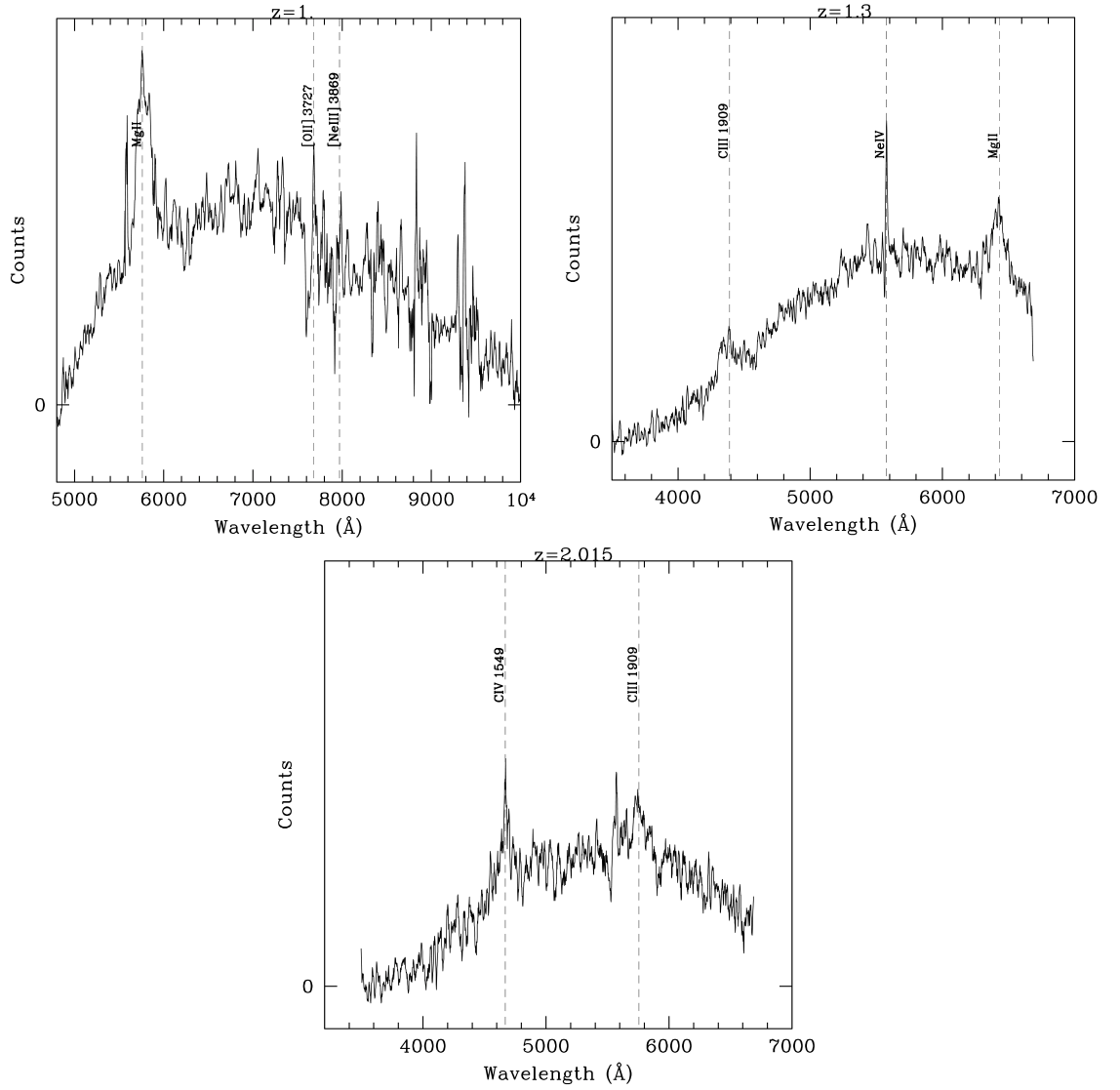


Figure 5.11: Optical spectra of all three AGN dominated X-ray sources with $70\mu\text{m}$ detections [342]. All identified emission features are labeled.

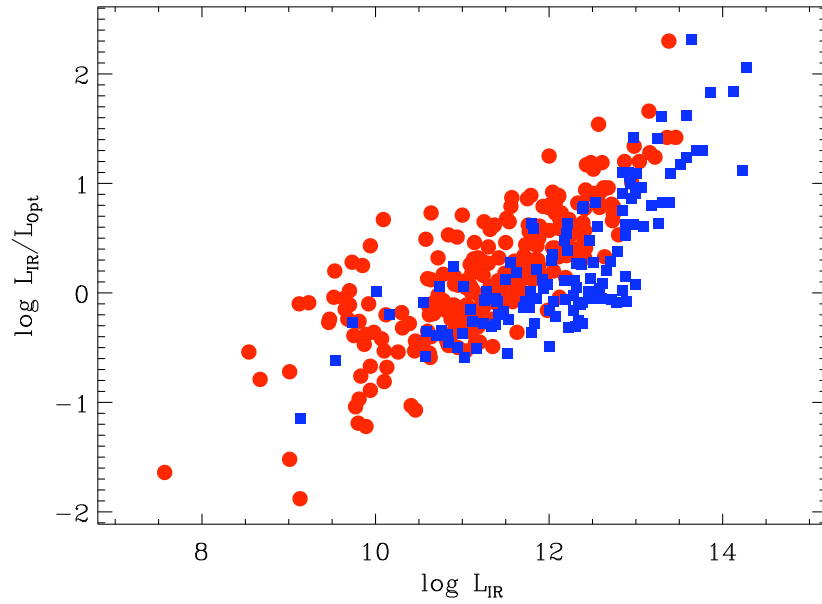


Figure 5.12: Ratio of infrared to optical bolometric luminosity versus 1-1000 μm infrared luminosity, for all X-ray sources with 24 μm detections. Red circles are sources fitted with a galaxy optical template and blue squares are QSO fitted sources. X-axis is in solar luminosities.

are at redshift above 2. There are 23 sources at redshift greater than 3 of which 2 sources at redshift greater than 4 and 1 source at redshift of 6.02 which if real would be the second highest redshift X-ray selected source ever found. The objects at redshift 6.02 and 4.62 have only a single optical band. The redshift is determined from a fit to this plus 3.6 and 4.5 μm . The object at redshift 4.71 has 3 optical bands, r, i, Z, plus 3.6, 4.5, so the redshift is determined with a fit using 5 photometric bands and it is highly believable. Non-detection at U, g, could be due to Lyman drop-out.

In Figure 5.9, the redshift distribution of the different classes of sources according to their best optical and infrared SED template fit is also plotted. The distribution starts to cut off sharply at redshift of ~ 1.5 , because the depth of the optical data is $R \sim 24.5$ (Figure 5.5). Normal galaxies dominate the distribution up to redshift of 1.5 with QSOs dominating in numbers at higher redshifts while ellipticals cut-off sharply at $z \sim 1$ (bottom Figure 5.9). Strong starbursts seem to dominate the infrared emission of high redshift X-ray sources (middle Figure 5.9). This may be due to observational limitations. Lack of far-infrared data means that for the SED fittings we used data up to 24 μm . 24 μm corresponds to rest frame 3 μm at these z so any conclusions, on the mid-IR SED, are an extrapolation. In all three distributions

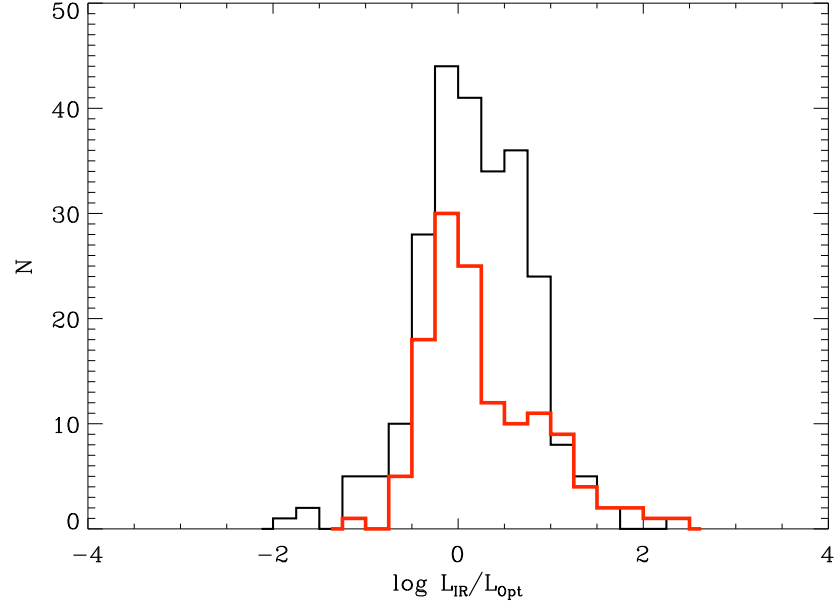


Figure 5.13: Histogram of $\log L_{IR} / L_{Op}$ for QSOs (red solid line) and galaxies (black solid line).

peaks arise at $z \sim 0.3$ and $z \sim 1.1$ which may indicate large scale structure effects.

5.8 Results

All of our sources have $3.6 \mu\text{m}$ and $4.5 \mu\text{m}$ detections, 80% have $5.8 \mu\text{m}$, 79% have $8 \mu\text{m}$ and 83% have $24 \mu\text{m}$. There are 18 sources with $70 \mu\text{m}$ detections. In Figure 5.10 we show the SEDs of all X-ray sources with $70 \mu\text{m}$. All three sources fitted with an AGN template have broad line spectra [342] in agreement with SEDs. Spectra of these objects are shown in Figure 5.11. The nature and the properties of these sources are discussed in Chapter 6 where a $70 \mu\text{m}$ /X-ray sample is compiled from 3 available SWIRE fields.

SED template fitting method indicates that 55% of the sources are dominated by a dust torus, 42% by a starburst and the remaining 3% (15) appear to be cirrus dominated. According to the optical template SED fitting 33% are QSOs, 60% are spirals and the remaining 7% are ellipticals. We find that 42% of the sources are composite with a strong contribution from both a starburst and an AGN contribution. All composites have $24 \mu\text{m}$ detections and 11 have also $70 \mu\text{m}$. In comparison, in the entire ELAIS-N1 only 9% of the sources are composite. Overestimation of

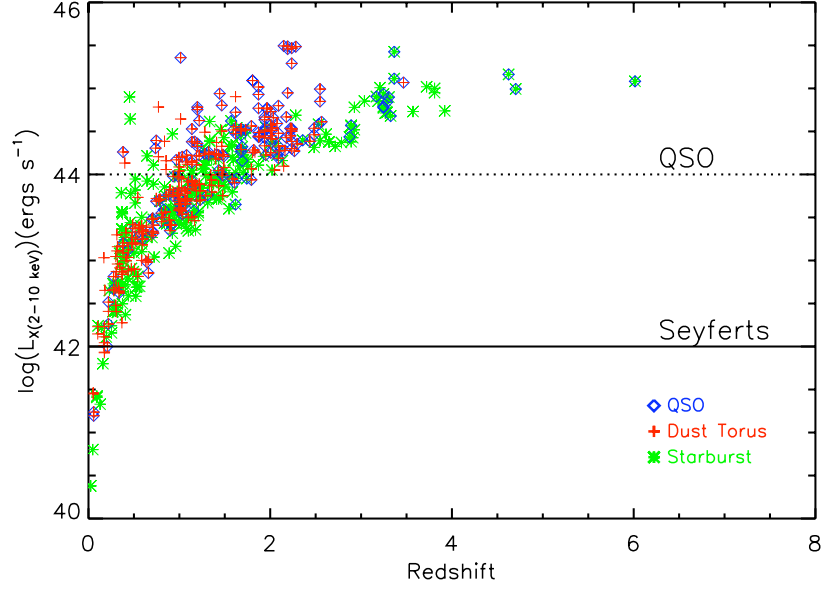


Figure 5.14: Distribution of rest-frame 2-10 keV X-ray luminosity and redshift for 290 sources within our sample with hard X-ray detections. Solid line marks the upper boundary of the X-ray luminosity produced by an ultraluminous starburst and the dotted line represents the boundary region between QSOs and Seyfert-like galaxies. Sources are color-coded according to their SED template fit. Red crosses are sources dominated by a dust torus, green stars are sources dominated by a starburst and blue diamonds are sources fitted with a QSO optical template.

composites is more pronounced when far-infrared data become available. From the 18 70μ /X-ray sources, 11 are composites (61%).

Infrared SED template fitting for sources with infrared excess at $\lambda \geq 8\mu m$ allow us to estimate the bolometric infrared luminosity, which is also a measure of the total star formation rate in a galaxy, when there is no contribution from a torus. This estimate is highly uncertain if only data up to $24\mu m$ are available [283]. However, this sample represents the brightest examples of AGN lying at high and intermediate redshifts while far-infrared samples are usually biased towards low redshifts. As a result, for a sample like this, we have to rely to $24\mu m$ detections in order to measure L_{IR} .

Figure 5.12 shows the ratio L_{IR}/L_{OP} versus L_{IR} with different colours coding sources fitted with a QSO or a galaxy optical template. All of the sources in this plot have $S_{24} > 200\mu Jy$ and 24 have also $70\mu m$ or/and $160\mu m$ detections. Since the optical bolometric luminosity of a galaxy corrected for extinction, is a measure of the stellar mass, the ratio L_{IR}/L_{OP} is a measure of the specific star formation rate in

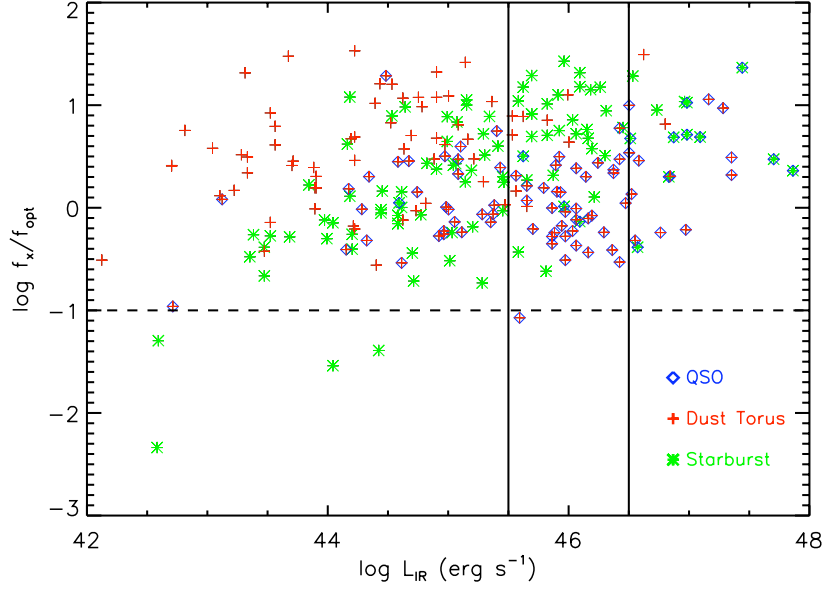


Figure 5.15: X-ray-to-optical flux ratio versus bolometric Infrared Luminosity (1-1000 μm). Colour coding is the same as Figure 5.14. Dashed line represents the boundary between AGN and galaxies. Solid lines indicate the ULIRG and HLIRG limits.

the galaxy which is the rate of star-formation per unit mass in stars. In the case of AGN this ratio represents the torus covering factor. Around 8% of the X-ray sources are HLIRG compared to only 3% of HLIRGs found among the general SWIRE population in ELAIS-N1. An additional 32% of the X-ray sources are ULIRG again significantly higher than the parent population with $\sim 9\%$. Almost 60% of the X-ray sources have $L_{\text{IR}}/L_{\text{OP}} > 0$ consistent with the presence of very dusty systems. There are 154 LIRG sources with $S_{24} > 200 \mu\text{Jy}$ that their SED is torus dominated. 95 of these sources are fitted with a QSO template and the rest with a galaxy template implying that for this sample the ratio between Type-1/Type-2 is $\sim 2/1$. Figure 5.13 shows the distribution of $\log(L_{\text{IR}}/L_{\text{Opt}})$ for galaxies and quasars.

Figure 5.14 shows the hard X-ray luminosity versus redshift. Here L_X is the rest-frame X-ray luminosity given by:

$$L_X = \frac{4\pi d_L^2 S_X}{(1+z)^{1-\alpha_x}} \quad (5.6)$$

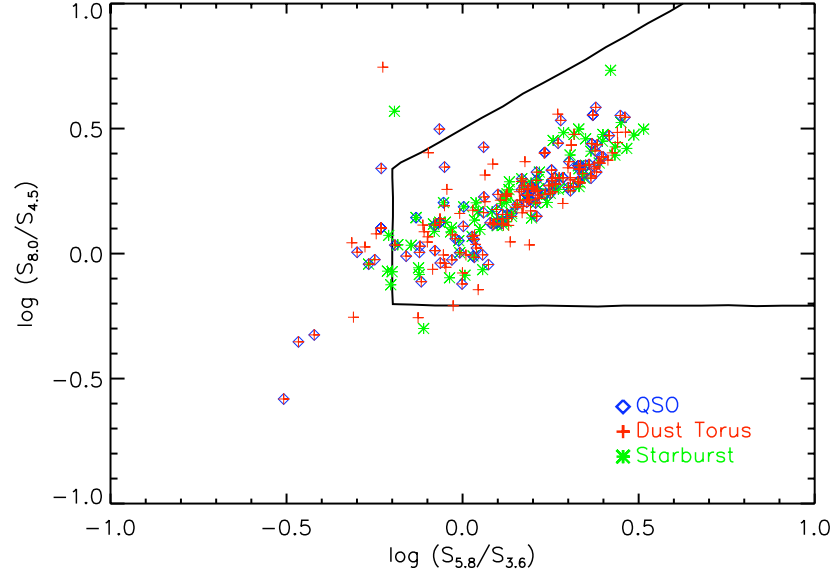


Figure 5.16: IRAC color-color plot for all X-ray sources with detections in all IRAC bands. Colour coding as Figure 5.14. Solid line marks the region expected for AGN.

where d_L is the luminosity distance and α_x is the spectral slope which is calculated on the basis of the X-ray hardness ratio for each source

$$\alpha_x = \frac{\log[(1 - HR)/(1 + HR)]}{2\log 2} \quad (5.7)$$

and flux S_X is calculated from the observed X-ray count rate adopting the α_x in a consistent way. X-ray luminosity is by itself an important discriminator of the primary power source. The maximum achievable X-ray emission by young stellar populations by an ultraluminous starburst is $L_{2-10 \text{ keV}} \sim 1.5 \times 10^{42} \text{ ergs s}^{-1}$ [254]. This limit is shown in Figure 5.14 as a solid line separating AGN from star-forming sources. Almost all of our sources (98%) with hard x-ray detections lie above this limit. 58% of these sources are Seyfert like galaxies and the remaining are QSO [50].

In Figure 5.15 the X-ray-to-optical flux ratio for all sources with R-band detections versus bolometric infrared luminosity is plotted. X/O is defined as the ratio of the 2-10 keV flux to optical (R band) flux given by the equation [152]:

$$X/O = \log(f_X/f_R) = 5.50 + \log f_x + R/2.5 \quad (5.8)$$

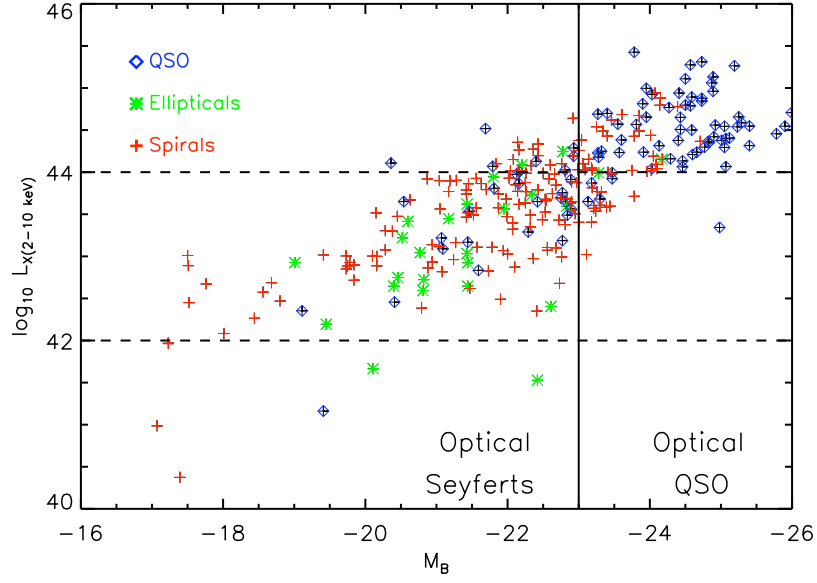


Figure 5.17: Absolute rest frame B-band magnitude versus hard X-ray luminosity. Red crosses are sources fitted with a galaxy template, green stars are elliptical-like galaxies and blue diamonds are sources fitted with a QSO template. Dashed lines are from Figure 5.14. Solid vertical line marks the optical transition between Seyfert and QSOs.

As expected given the X-ray survey depth, most of the sources have $\log(f_X/f_R) > -1$, plotted as a dashed line, indicating that they are likely to be AGNs and not normal galaxies [8]. There are four sources below this limit, all starburst dominated. None of them is fitted with a QSO optical template. One of the sources has $\log(f_X/f_R) < -2$ which implies a quiescent system with very low-level SFR.

In mid-infrared, AGNs are characterised by red and almost featureless spectra [349][135]. These properties make their IRAC colors unique among other infrared sources, such as galaxies and stars which both appear blue in IRAC colors, providing a powerful tool to identify them [139][185]. In Figure 5.16 we plot the IRAC colors of X-ray sources with detections in all four IRAC channels, with the red region empirically defined to contain luminous AGN [185]. The majority of our X-ray sources in this shallow survey have red colors, indicative of the presence of AGN, as expected. The majority of the sources that lie outside the AGN region are fitted with a QSO template. These sources are probably narrow line AGN that Lacy’s diagnostic fail to constrain (see Chapter 4).

Figure 5.17 shows the absolute B magnitude as a function of the hard X-ray lu-

minosity. The lower number of sources at $M_B > -20$ can be due to the X-ray flux limit. At the brightest luminosities ($M_B < -23$) X-ray sources are predominantly QSOs and there seems to be a correlation between optical and X-ray luminosity, consistent with the light of the two bands coming from the AGN. The scatter is higher at lower optical luminosities which can point to the fact that the AGN do not contaminate the host galaxy light significantly. The 6 sources with $L_X < 10^{42} \text{ erg s}^{-1}$ are mostly associated with bright $R < 19$, extended objects at low redshift ($z < 0.3$). Parameter space at luminosities higher than $10^{44} \text{ erg s}^{-1}$ is mainly populated by high redshift sources fitted with a QSO optical template. However there is a number of sources that are fitted with galaxy templates which can be Type-2 QSO candidates [221]. The majority of the sources in the middle part of the X-ray luminosity region are associated with extended Seyfert-like sources.

Figure 5.18 shows the star formation rate versus redshift for all X-ray sources that are fitted with a galaxy template. Star formation rates have been estimated using the conversion from 60 μm luminosity [293][281] given by:

$$\phi_* = 2.2 \times \varepsilon^{-1} \times 10^{-10} \times (L_{60}/L_\odot) \quad (5.9)$$

where ε is the fraction of UV light absorbed by dust, taken as 2/3. The bolometric corrections at 60 μm needed to convert L_{IR} to L_{60} are 3.48, 1.67 and 1.43 for cirrus, M82 and Arp220 templates respectively. As it can be seen from Figure 5.18 the plot is consistent with a star-formation history where the star-formation rate increases from $z = 0$ to $z \sim 2$ and then remains steady. There is no clear connection between hardness ratio and star formation rates.

Figure 5.19 shows dust mass versus stellar mass for all X-ray sources fitted a galaxy template [283]. Dust masses have been estimated using radiative transfer models for cirrus [85] and starburst components [283]

$$M_{Dust}/M_\odot = \kappa \times L_{IR}/L_\odot \quad (5.10)$$

where $k = 1.3 \times 10^{-3}$, 2.7×10^{-4} and 1.1×10^{-4} for cirrus, M82 and Arp220 respectively. Stellar masses have been estimated using a set of empirical templates [18]. For most galaxies M_{Dust}/M_* ranges between 10^{-4} and 10^{-2} . There is a significant number of sources with exceptionally high values of this ratio which presumably have gas masses relative to the stellar mass, assuming the usual gas to dust ratio [283]. Sources with very low values of this ratio, ranging between 10^{-12} and 10^{-9} ,

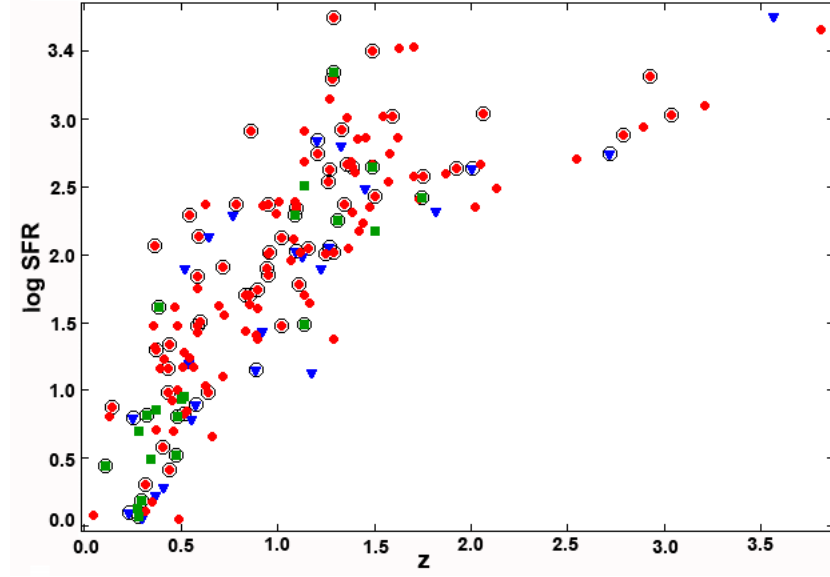


Figure 5.18: Star formation rate in $M_{\odot} \text{ yr}^{-1}$ versus redshift color coded for all X-ray sources fitted with an optical template. Blue triangles are starbursts, red circles are spirals, green boxes are ellipticals and black circles are sources with $HR > -0.25$.

not plotted on this diagram, are mostly fitted with a QSO template [283] This diagram does not show any evidence for any kind of connection between hardness ratios and dust mass.

5.9 Summary

In this chapter we have presented the sample of X-ray sources detected in the 1 deg^2 shallow (5ks) survey of ELAIS-N1 with ACIS-I on Chandra. Of the 698 X-ray sources detected, 86% have an IRAC counterpart and 67% have also an optical counterpart. We have also cross-correlated the X-ray/IRAC/Optical catalogue with our spectroscopic catalogue of our observation campaigns with GMOS and WIYN resulting in 54 common sources. Nineteen additional spectroscopic redshifts were retrieved from NED. Comparison between spectroscopic and photometric redshifts shows that in $>85\%$ of cases there is an agreement between photometric and spectroscopic estimates.

At the flux limits of this X-ray survey, the vast majority of the sources is expected to be AGN dominated. X-ray luminosities in the hard band and ratio of X-ray-to-optical and infrared luminosities are consistent with this expectation. All sources

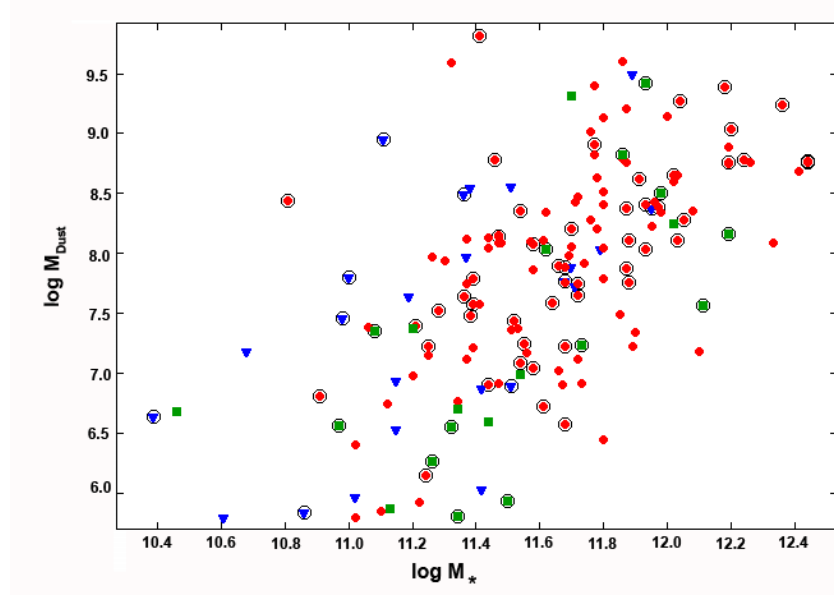


Figure 5.19: Dust mass versus stellar mass in $M_{\odot} \text{ yr}^{-1}$ color coded by optical SED type. Colours and symbols from Figure 5.18. Both axis in logarithmic scale.

that are fitted with a starburst template which have X/O typical of AGN have high hard X-ray luminosities suggesting that all are indeed AGN with the host galaxy emission dominating in the optical and infrared bands.

Broad-band optical to far-infrared SEDs of the X-ray sources show a broad range of properties. 55% of the sources are dominated by a dust torus template, 42% by a starburst and the remaining 3% (15) are dominated by cirrus emission. According to the optical template SED fitting 33% are QSOs, 60% are spirals and the remaining 7% are ellipticals. Almost half of the X-ray sources have composite SEDs with both a starburst and an AGN contribution. In comparison, less than 10% of the entire SWIRE ELAIS-N1 population appear to be composites. Percentage of U/HLIRG within the X-ray catalogue is by a factor of > 3 than the U/HLIRG population within the entire SWIRE-EN1 similar to the $24\mu\text{m}$ excess we see in the X-ray sources. This emission which is due to emission by dust torus, as revealed by both the IRAC color-color plots and SED fitting, is present regardless of the optical spectrum, SED fit or X-ray hardness. We have estimated that the ratio between Type-1 and Type-2 QSOs is $\sim 2/1$.

Bright X-ray selected AGN seem to be associated with luminous $M_B < -20$ hosts with the most extreme hard X-ray emitters associated with ultra-luminous point-

like sources at $M_B < -23.5$.

Star formation rate estimations revealed a large population of star-forming X-ray sources fitted with a galaxy template. Most of these sources exhibit very high values dust mass comparable to the stellar mass present in the host galaxy. Nonetheless, no clear connection between dust mass and hardness ratio could be established.

5.10 Continuation

Template fitting of all luminous X-ray sources with $70\mu\text{m}$ detections revealed not only that most of them are composite objects with contributions from both an AGN and a starburst component but also that only 3 out of 18 appear to be AGN dominated with 14 out of 18 been starburst dominated. For a sample of luminous X-ray AGN, such as this, an overestimation in composite objects might imply an underlying relation between star-formation and AGN activity. In the next Chapter I am investigating this hypotheses for the entire sample of $70\mu\text{m}/$ X-ray sources from three SWIRE fields close to the peak of AGN activity.

Chapter 6

X-ray/ $70\mu\text{m}$ SWIRE Sources Unveil Evidence for AGN Star-Formation Connection

A hidden connection is stronger than an obvious one

Heraclitus (535-475 BC)

6.1 Overview

In this chapter I present an analysis of the multiwavelength properties of a sample of twenty-eight X-ray sources with $70\mu\text{m}$ detections in the redshift range between $0.5 < z < 1.3$. We have derived their broad-band optical to far-IR SEDs using the wealth of SWIRE optical and infrared data from CDFS, ELAIS-N1 and Lockman Hole. Previous studies [112][28][261][333][260][106] have focused on X-ray selected samples of $24\mu\text{m}$ sources. This is the first study utilizing the MIPS $70\mu\text{m}$ identifications of X-ray selected sources, optimized to explore the relation between AGN and star formation close to the peak of the accretion history of the Universe. The number of associations between the two wavebands far exceeds the expected number of random associations, assuming that there is no causal link between the two wavebands. For the SED fitting we have used at least 8 photometric bands for each object. Availability of far-IR detections increases significantly the accuracy and reliability of the extracted SEDs. X-ray luminosities indicate that the vast majority of our sources (26/28) are AGN dominated. 27 out of 28 sources in our sample show evidence for the presence of starburst activity. Of these sources, 19 have composite SEDs. High values of intrinsic column densities suggest that 19 sources are obscured

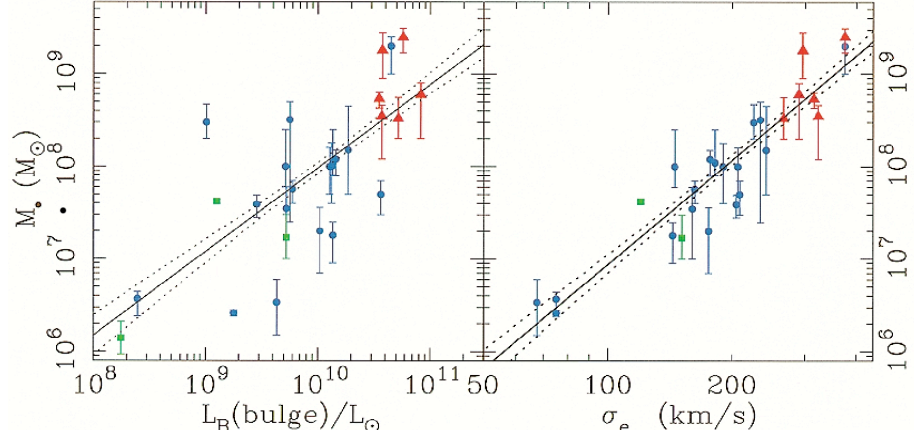


Figure 6.1: Black hole mass versus (a) bulge luminosity and (b) velocity dispersion. Solid and dotted lines are the best-fit correlation and their 68% confidence bands fitted only to the galaxies with spatially resolved kinematics. Error bars are representative of the reverberation mapping uncertainties. Figure and caption from [118].

AGN at X-rays but composites at infrared, suggesting that star-formation is taking place in these systems. All these findings suggest that there is a strong relationship between AGN and star-formation in agreement with Hopkins' QSO mode merger models [151] where there is a stage of AGN evolution where obscuration and star-formation co-exist. The sample studied here consists of the brightest examples of an underlying population that future infrared and X-ray missions will reveal.

6.2 Introduction

In the last few years there has been increasing observational evidence that the formation and evolution of galaxies and the build-up of supermassive black holes at their centers are strongly interconnected, embodied in the $M_{BH} - \sigma$ relation [118] seen in Figure 6.1. This has prompted attempts to model the interplay between black hole growth and star formation and to explore implications on the evolution of AGN [94]. Processes like galaxy suffocation, harassment and ram-pressure stripping have also been proposed to explain the star-formation density relation [133]. Their main handicap is that they operate in the densest environments such as massive clusters while the vast majority of galaxies are in less dense regions where alternative mechanisms dominate.

Recent attention has focused on models where AGN feedback regulates the star-

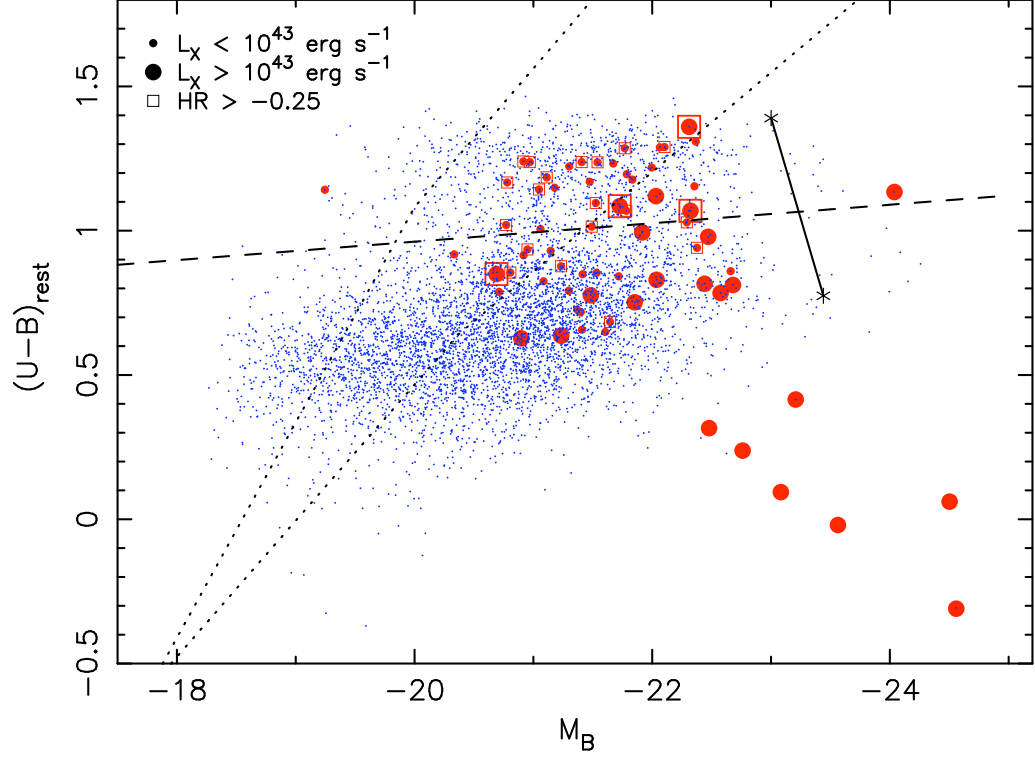


Figure 6.2: Colour Magnitude Diagram from EGS X-ray sources. Rest frame U-B color is shown against B-band absolute magnitude for DEEP2 comparison galaxies (small dots) and X-ray sources (circles) in the range $0.6 < z < 1.4$. Squares indicate hard X-ray sources and larger symbols indicate more luminous objects. Dashed line separates red and blue galaxies and dotted lines show the DEEP2 completeness limits at $z = 1 - 1.4$ [122]. Solid line shows the effect of AGN contamination on the color: upper star represents a pure elliptical template, the lower one is contaminated by a QSO contribution. The majority of X-ray sources lie in luminous red galaxies in and around the transition region between the blue cloud of star-forming galaxies and the red sequence of passively evolving bulges. This is consistent with AGN activity being associated with the process that quenches star formation in massive galaxies, causing the migration of blue galaxies to the red sequence. Figure and caption from [238].

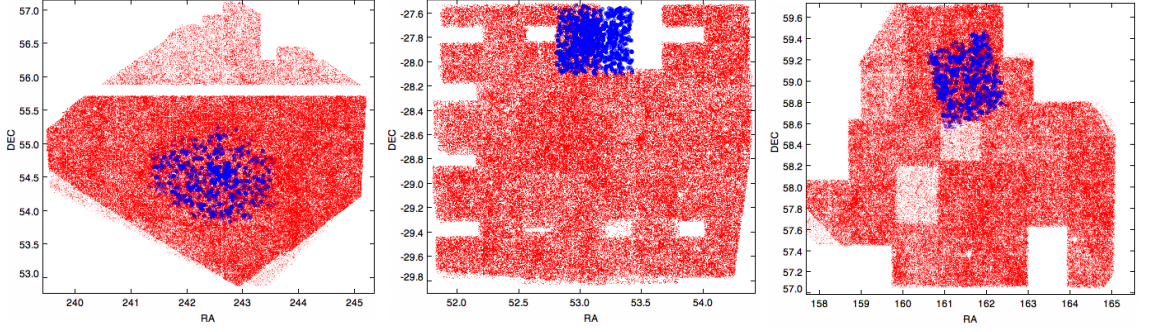


Figure 6.3: SWIRE optical coverage of ELAIS-N1 (left), CDFS (middle) and Lockman (right). CDFS optical coverage is smaller by a factor of 2 and 2.4 compared to ELAIS-N1 and Lockman respectively. X-ray coverage is denoted by the blue regions.

formation in the host galaxy. Key feature of these models is that they can potentially link the apparently independent observations between star-formation, AGN activity and large scale structure consistent with the $M_{BH} - \sigma$ relation. In the radio-mode model [65], accretion of gas from cooling flows in dense environments may produce low luminosity AGN which in turn heat the bulk of the cooling gas and prevent it from falling in the galaxy centre to produce stars. On the other hand, in the QSO-mode model [151], gas-rich galaxy mergers funnel gas to the central galaxy regions triggering both powerful starbursts and AGN activity. The inflowing gas and dust clouds not only produce stars and feed the AGN, but also obscure the central engine for most of its active lifetime. It is only at later stages that AGN outflows kick in, heating and blowing away the gas and dust clouds. This allows the AGN to shine unobscured for a short period ($\sim 10^8 \text{ yr}$), before it runs out of fuel and being extinguished. This feedback process also very rapidly quenches any ongoing star formation leaving behind a red passively evolving remnant. The QSO-mode likely dominates in poor environments, as the high velocity encounters, common in dense regions, do not favour mergers.

The attractiveness of the merger/AGN feedback model is that it is consistent with a number of properties of both AGN (duty-cycle, N_H distribution) and galaxies (bimodality of colour-magnitude relation [32][38]). A clean observational test however, that will confirm or refute this model remains to be established. A clean prediction of the simulations, that can be tested observationally, is that there should be an association between obscured X-ray sources and AGN activity. Sub-mm observations of high redshift ($1 < z < 3$) luminous ($L_X \sim 10^{45} \text{ erg s}^{-1}$) QSOs tentatively suggest

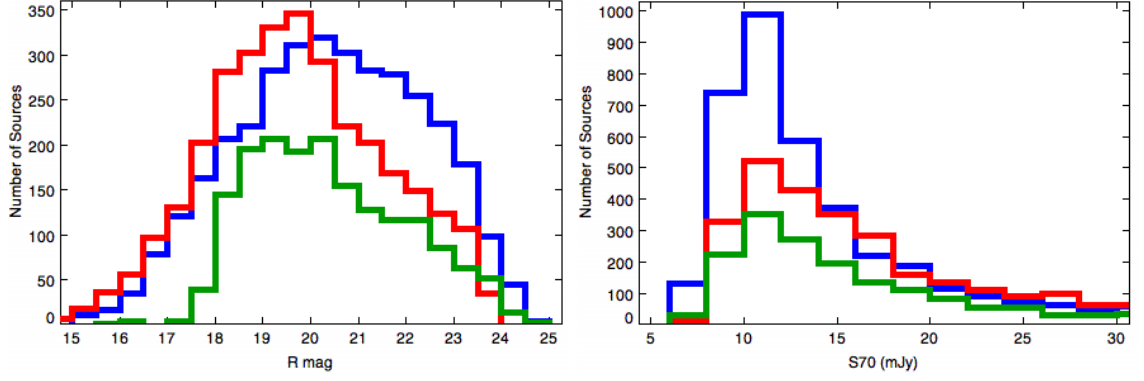


Figure 6.4: **Left:** Distribution of R magnitudes of all 70 μm sources in SWIRE ELAIS-N1 (red solid line), SWIRE Lockman Hole (Blue Solid Line) and SWIRE CDF-S (green solid line). CDF-S optical photometry is 2 magnitudes deeper than optical photometry in ELAIS-N1. Numbers in y-axis are in 10^4 . **Right:** Distribution of 70 μm fluxes up to 30 mJy where the bulk of 70 μm sources lie. Colours are the same as left. It is evident that the number of 70 μm sources are proportional to optical coverage.

such an association [249] while X-ray surveys of ULIRG shown that 70% of ULIRGs contain a buried AGN [111]. In the case of moderate redshift ($z \sim 1$) and luminosity ($L_X \sim 10^{43} \text{ erg s}^{-1}$) systems however, which represent the dominant AGN component in the universe [25], the link between obscuration and star-formation activity is still an open issue with observational facts pointing to a more complex AGN/starburst connection than that adopted in current models. Observation show that X-ray and/or optically-selected AGN are often found in early-type bulge-dominated galaxies [238] with evidence of star-formation events that have terminated in the recent past [166]. These observations are consistent with a time lag between the peak of the star-formation and the black hole accretion in these systems.

6.2.1 The Need for Multi-Wavelength Data

As mentioned above, the interplay between AGN, star-formation and environment, particularly at intermediate redshifts ($0.5 < z < 1.3$), where AGN and star-formation peaks, is not well constrained. At lower redshifts ($z < 0.1$), availability of large spectroscopic surveys such as 2dFGRS, SDSS, DEEP2 have made feasible to quantify this link, favouring QSO-mode scenarios [166] based on optical emission line selection methods. However, these methods are known to be missing a substantial fraction of AGN especially those who are low luminosity AGN and obscured [236]. On the other hand, while X-ray surveys are proved to be by far the most efficient way of finding AGN, selection methods based on mid-IR [28] or radio [225]

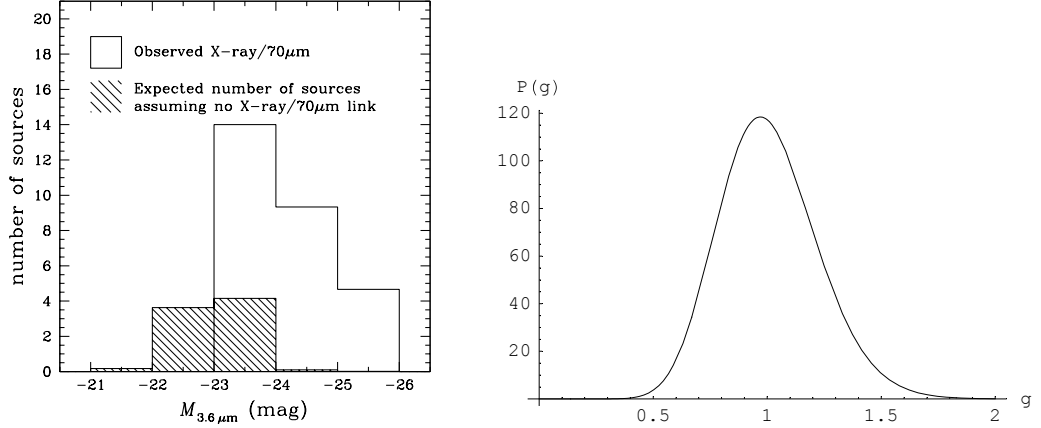


Figure 6.5: Left : Open histogram : The 3.6 μm absolute magnitude ($M_{3.6}$) distribution of the X-ray/70 μm sources identified in SWIRE fields with available Chandra observations. **Shaded histogram :** $M_{3.6}$ distribution of the expected number of X-ray/70 μm associations in the surveyed area based on the observed fraction of X-ray sources identified with 3.6 μm SWIRE counterparts and the fraction of 70 μm sources with 3.6 μm identifications. The shaded histogram assumes that the X-ray and 70 μm are unrelated. We find 28 X-ray/70 μm associations with only 8 expected. This excess suggests that the mechanisms responsible for the X-ray and 70 μm emission are linked. **Right :** Distribution of the correlation function $P(g)$.

have shown the existence of a large population of obscured AGN missed by the X-rays [76]. In addition, hard X-ray selection fails to detect the luminous narrow-line AGN in the numbers predicted by cosmic X-ray background models. On the other hand, infrared selection methods cannot isolate the entire X-ray population of AGN while radio surveys detect only the radio-loud population of obscured AGN which represents only the 10% of the total AGN population [28]. In order to obtain a complete picture of the AGN population multi-band SEDs are needed to evaluate whether black hole accretion is associated with concurrent star-formation. As a result a sample of multi-wavelength data over a large area is needed in order to fully understand and model the AGN population.

Spitzer Space Telescope presents the opportunity to revolutionize our understanding of AGN populations over $0.5 < z < 1.3$. The extreme sensitivity and multiple widely spaced observing bands of IRAC and MIPS, coupled with their ability to rapidly map large areas of sky, makes finding large samples of galaxies out to high redshifts orders of magnitude easier than with previous observatories. The MIPS 70 μm channel in particular is a powerful new tool for studying infrared populations

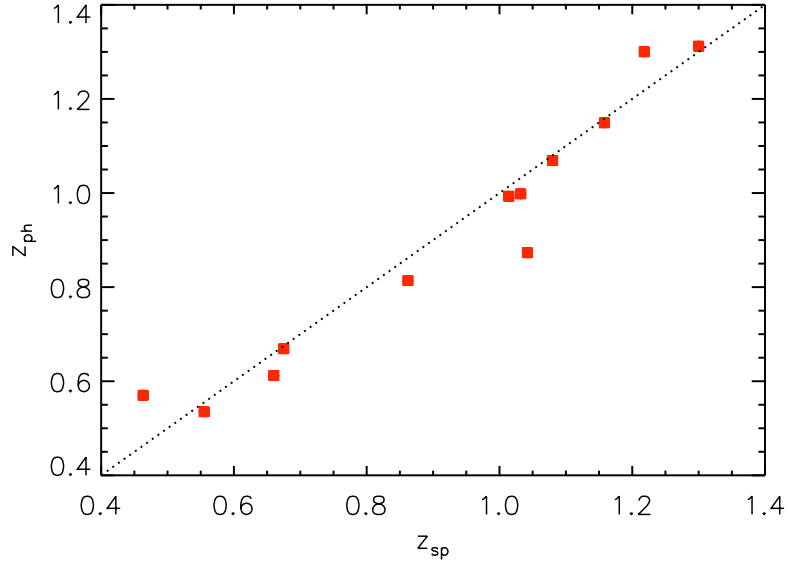


Figure 6.6: Comparison between available spectroscopic redshifts and derived photometric redshift values with excellent agreement between the two.

over $0 < z < 1$; at these redshifts the rest-frame emission is always longward of $35\mu\text{m}$, meaning we are sampling thermal continuum emission from moderately hot dust, giving good sensitivity to both starbursts and AGN. Initial results [113] suggest that the $70\mu\text{m}$ counts at $\geq 15\text{mJy}$, are mostly moderately obscured starbursts, with a small number of reddened AGN at $0.5 \leq z \leq 1$. The $70\mu\text{m}$ Spitzer sources may thus be a prime example of the kind of source that ISO and SCUBA surveys may miss – ISO because it lacked sensitivity at longer wavelengths and SCUBA because the sources are likely too faint, and may harbour dust that is too hot for SCUBA to see.

Existence of multi-wavelength data, spanning from optical to X-ray in a large area in order to avoid selection biases is essential. SWIRE survey currently provides the deepest $70\mu\text{m}$ catalogue over a large area of the sky, a total of 49 deg^2 to a limiting flux of 2.75mJy . Such a unique combination of area and sensitivity is essential to identify a sufficiently large sample of X-ray/ $70\mu\text{m}$ sources. Because of instrumental limitations (e.g. sensitivity, confusion), any sample selected at far-IR wavelengths $> 24\mu\text{m}$, represents the brightest and rarest examples of the underlying population. Deeper pencil-beam surveys are therefore not well suited for the proposed study. The SWIRE also benefits from a homogeneous set of multi-waveband optical photometry (*ugriz*). When combined with the IRAC and MIPS data these provide accurate photometric redshifts (see Chapters 4 and 5). Additionally, the

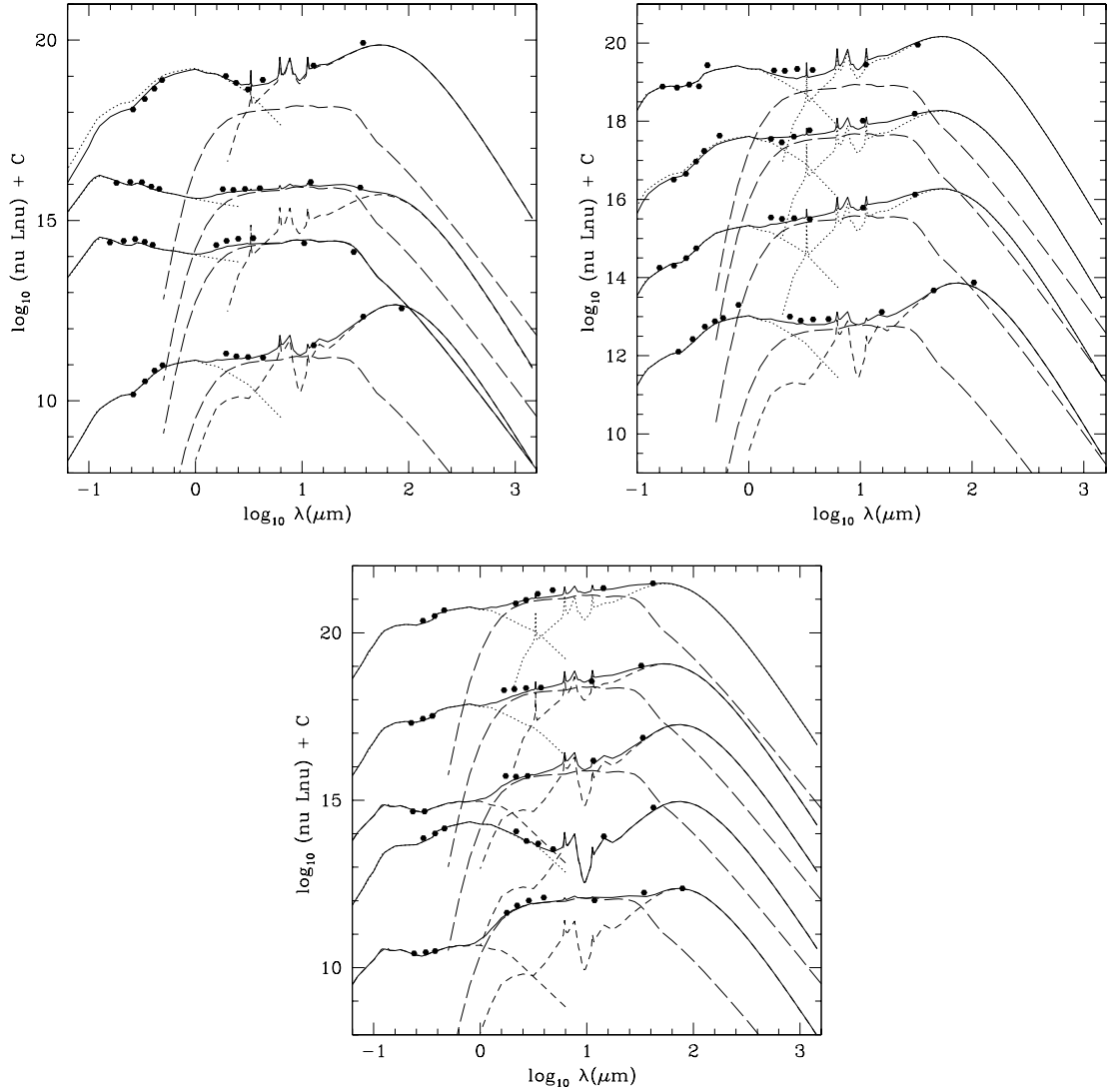


Figure 6.7: Optical to far-infrared SEDs in νf_{ν} of 13 X-ray sources with $70\mu\text{m}$ from ELAIS-N1 and CDFS. Solid curves show the total predicted SED. Dotted curves show the optical-NIR and starburst templates, AGN dust torus as a long dashed curve and cirrus template as a short dashed template.

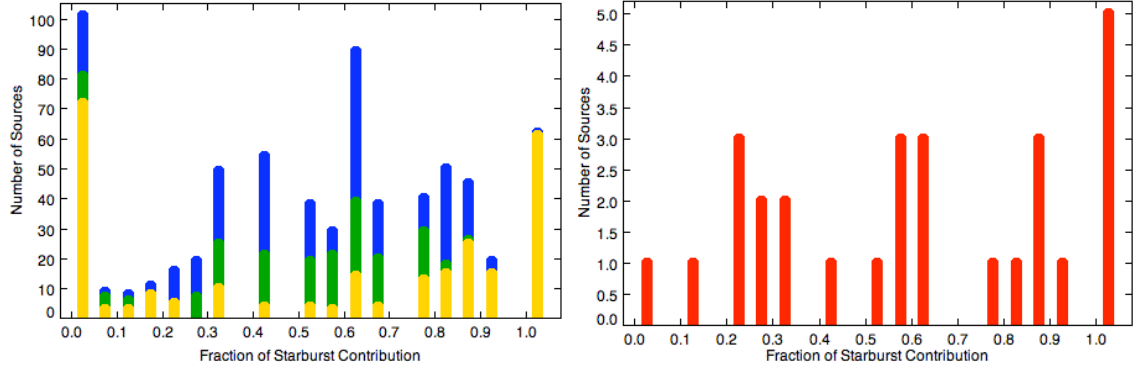


Figure 6.8: **Left:** Distribution of the fraction of starburst contribution of all $70\mu\text{m}$ sources in Lockman (blue spikes), ELAIS-N1 (green spikes) and CDFS (yellow spikes) that lie between $0.5 < z < 1.3$. **Right:** Distribution of the fraction of starburst contribution of the sample of 28 X-ray/ $70\mu\text{m}$ sources. Multiple colors are to be interpreted as side-by-side.

multi-wavelength observations can be used to explore the relative importance of star-formation and AGN activity at the mid- and far-IR using template fittings. Most critically, SWIRE $70\mu\text{m}$ MIPS data, measure the far-IR energy distribution, where the bulk of the bolometric luminosity of obscured, and perhaps unobscured, AGN is emitted, and where most of the energy from star-formation emerges after absorption by dust. Another key feature of using MIPS data is that it directly probes the warm AGN dust-heated emission from the torus and in addition the cooler starburst emission.

In this study we combine X-ray, optical and infrared data from three SWIRE fields in order to construct the Spectral Energy distributions of X-ray selected luminous $70\mu\text{m}$ sources and constrain their dominant energizing source, star-formation or AGN activity.

6.3 Data

The selection of the SWIRE fields used for this study was driven by the existence of overlapping large area X-ray surveys. At the time of writing, SWIRE fields that satisfied this criterion were ELAIS-N1, Lockman Hole and CDF-S.

6.3.1 ELAIS-N1

SWIRE ELAIS-N1 was imaged by IRAC and MIPS with the observations centered at the position $16^h00^m, +59^d01^m$ covering a total of 9.18 deg^2 . Optical imaging has been taken in U, g, r, i, Z bands for $\sim 9 \text{ deg}^2$ in SWIRE ELAIS-N1 area allowing to find optical associations and derive accurate photometric redshifts for 218117 sources (for more details see Chapter 2). Optical coverage of ELAIS-N1 is given in Figure 6.3. The sheer number of $70 \mu\text{m}$ sources with optical associations over the whole area at a limiting flux of 7.14 mJy is 3223. X-ray coverage in ELAIS-N1 consists of two ACIS-I surveys. The shallower consists of 30×5 ks ACIS-I exposures giving even coverage over an area $> 1 \text{ deg}^2$. This survey has detected 658 X-ray sources. The sample was cross correlated with the SWIRE ELAIS-N1 with a maximum separation of matched points around a great circle of 3 arcsec (see §5.5). The cross-correlation resulted in 439 common sources between the SWIRE ELAIS-N1 band merged catalogue with optical associations and the X-ray catalogue. 18 of these sources have also $70 \mu\text{m}$ detections. For more details about this survey, findings, flux limits, data reduction refer to Chapter 5. There is an additional deeper X-ray survey in the center of the 5ks one taken as part of the ELAIS-N1 Deep X-ray Survey [222]. This is a single, 75ks ACIS-I pointing centered on $16^h10^m20.11^s, +54^d33^m22.3^s$. Sources were detected to flux levels of $2.3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 0.5 - 8 keV band, $9.4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 0.5 - 2 keV band and $5.2 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 2 - 8 keV band. Using the same cross-correlation method as before, we found 43 common sources with SWIRE, one with $70 \mu\text{m}$ detection.

6.3.2 Lockman Hole

Optical data taken in Lockman Hole consists of 25 pointings covering a total of $\sim 11 \text{ deg}^2$. All pointings have r and i observations, 22 have g and 4 have U. Additionally one pointing goes deeper, covering the Spitzer SWIRE Validation Field. Optical completeness limits are (Vega): U $\sim$ 25, g $\sim$ 25, r $\sim$ 24, i $\sim$ 23.3 across the field with the deepest pointing reaching limiting magnitudes of U $\sim$ 25, g $\sim$ 25.7, r $\sim$ 25, i $\sim$ 24. Spitzer IRAC and MIPS observations follow the observing plan described in Chapter 2 which covers a total area of 11 deg^2 . The latest band merged catalogues with optical associations contain a total of 229239 sources, 4046 of which are $70 \mu\text{m}$ sources at a limiting flux of 6.73 mJy. Available X-ray data were obtained with ACIS-I in a 3×3 raster for a total area of 0.6 deg^2 centered at $10^h46^m, +59^d01^m$ [261]. Exposure time for each pointing was 70ks, reaching a broad band, 0.3 - 8 keV, flux limit of $\sim 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}$ detecting a total of 827 unique sources. An infrared/optical

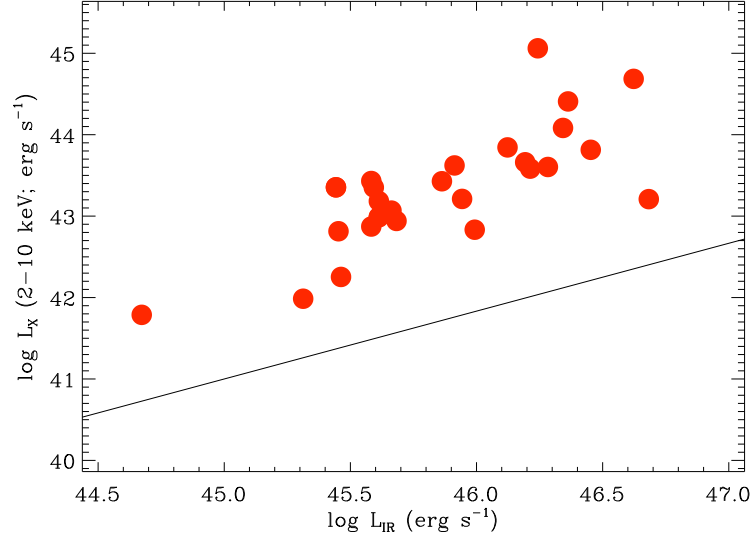


Figure 6.9: 2-10 keV luminosity as a function of the infrared bolometric luminosity. Red circles represent the X-ray/70 μ m sources within $0.5 < z < 1.3$. The continuous line is the X-ray/IR luminosity relation for star forming galaxies [266].

counterpart is matched to 667 sources, 35 with 70 μ m detections.

6.3.3 CDF-S

In support of SWIRE, the CDFS field was observed for 18 night with the MOSAIC II camera on the 4m telescope at Cerro Tololo. 15 pointings covered a total of $\sim 4.5 \text{ deg}^2$ in four filters, U, g, r, i to 5σ depths of 24.5, 25.4, 25, 24 Vega magnitudes respectively with an additional 1.5 deg^2 Z pointing to 23.3 and a deep 0.33 deg^2 pointing centered at $03^h31^m14^s - 28^d36^m$ at $U \sim 25.2$, $g \sim 25.7$, $r \sim 25.5$, $i \sim 24.5$. Spitzer observations with IRAC and MIPS covered a total of 7.83 deg^2 in seven bands. Band merged catalogues with optical associations contain 149767 sources with 1766 70 μ m sources at a limiting flux of 6.98 mJy. The Extended Chandra Deep Field South [198] is 0.3 deg^2 , 250 ks/pointing contiguous ACIS-I pointing which reaches sensitivity limits of $1.1 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 0.5 - 2 keV band and $6.7 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 2 - 8 keV band. There are 5 common sources with SWIRE MIPS 70 μ m catalogue with optical counterparts. ECDFS is flanking the 1Ms CDF-S survey [123] reaching flux limits of $5.5 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 0.5 - 2 keV band and $4.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the hard 2 - 10 keV band. It has detected 316 unique sources which when cross-correlated with SWIRE using a 3 arcsec search radius (see §3.6 and 5.5) It finds a match to 117 sources with IR/optical counterpart. Four of these sources have 70 μ m detections.

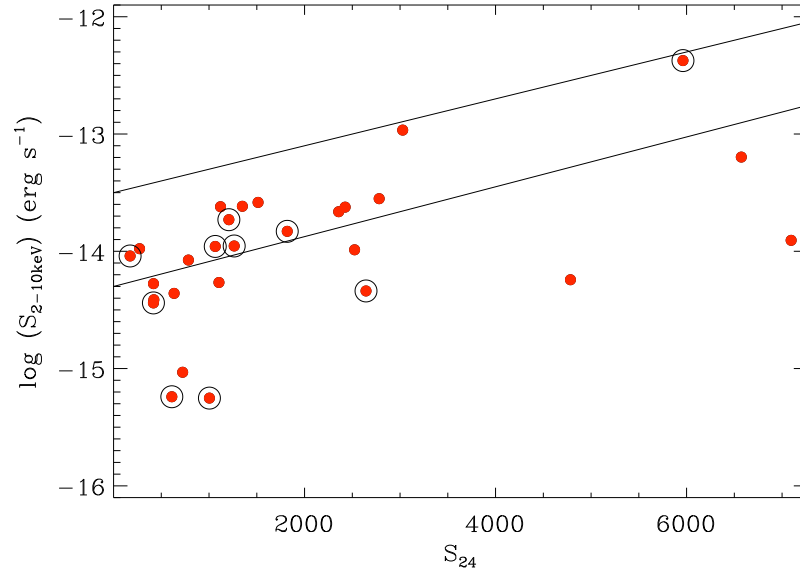


Figure 6.10: 2-10 keV flux versus the Spitzer MIPS $24\mu\text{m}$ observed monochromatic flux for our sample. The solid lines denote the region occupied by hard X-ray selected AGN [256]. Open circles are sources with $\log N_H < 22$.

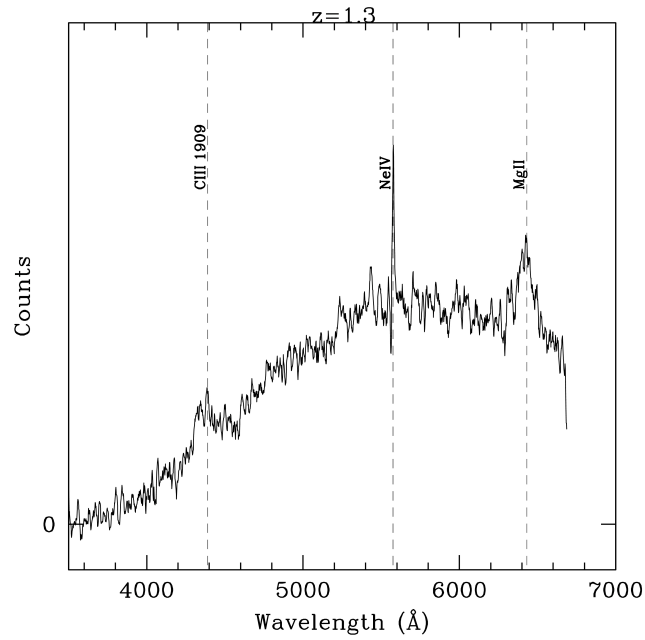


Figure 6.11: Optical spectrum of SWIRE 187890+515803 obtained with WIYN. Detected emission features labelled. Broad lines are indicative of QSO presence in agreement with SED fitting methods.

6.4 Selection of the Sample

The sample of the X-ray/ 70 μm sources studied in this work has been compiled from the complete sample of 71 SWIRE 70 μm sources with X-ray counterparts from ELAIS-N1, Lockman and CDF-S. We limit the redshift range of our sample to $0.5 < z < 1.3$, in order to explore the possible AGN/star-formation connection at an epoch close to the peak of AGN luminosity density, resulting in a total of 28 sources. The X-ray, optical, infrared properties and SED model predictions for these sources are given in Table 6.1. The sample consists of 5 CDFS sources, 1 from the 1 Ms survey and 4 from the ECDFS, 8 are ELAIS-N1 sources, 7 from the 5ks survey and one from the EDXS and 15 sources are from Lockman.

We have tried to estimate the expected number of X-ray/70 μm associations, assuming that there is no causal link between the two wavebands, in order to perform a statistical comparison with the observed number of associations (28). We define as N the number of SWIRE sources with redshifts between $0.5 < z < 1.3$ that lie within the X-ray coverage (A_1, A_2, A_3 are the numbers of ELAIS-N1, Lockman, CDFS sources respectively) and as B the number of X-ray sources within the same redshift interval (B_1, B_2, B_3 are the numbers of ELAIS-N1, Lockman, CDFS sources respectively). From A we select C which is the number of N sources with 70 μm detections. The actual number of sources for each field is:

$$A_1=20937, B_1=216, C_1=162$$

$$A_2=14369, B_2=272, C_2=185$$

$$A_3=3734, B_3=177, C_3=36$$

.

Based on the two-point galaxy correlation function, the probability of a galaxy to be detected in both X-ray and 70 μm is given by:

$$P_{X,70} \times dV_X \times dV_{70} = (P_X \times dV_X) \times (P_{70} \times dV_{70}) \times (1 + g) \quad (6.1)$$

where $P_i \times dV_i$ are probabilities following poisson statistics, approximated by delta functions due to the large numbers of the samples used here:

$$P(B_i|\nu_{Bi}A_i) = \frac{e^{-A_i\nu_{Bi}} \times (A_i\nu_{Bi})^{B_i}}{B_i!} = \delta(\nu_{Bi} - B_i/A_i) \quad (6.2)$$

$$P(C_i|\nu_{Ci}A_i) = \frac{e^{-A_i\nu_{Ci}} \times (A_i\nu_{Ci})^{C_i}}{C_i!} = \delta(\nu_{Ci} - C_i/A_i) \quad (6.3)$$

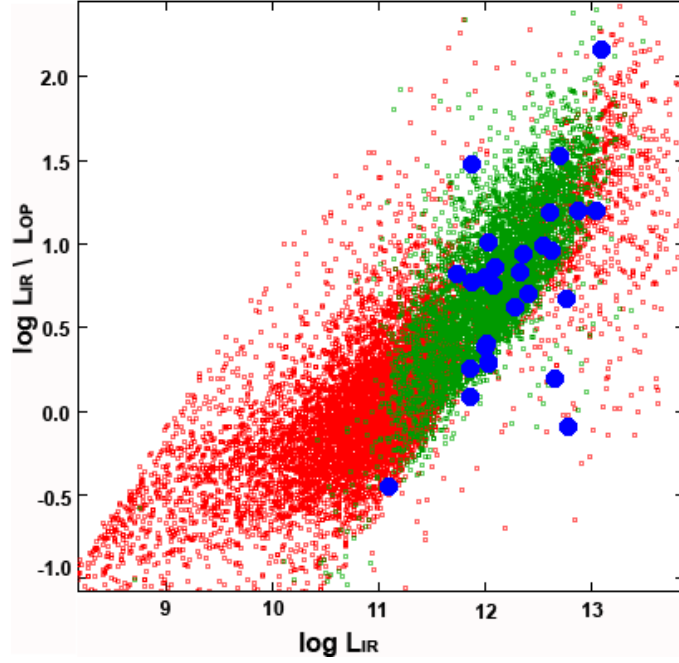


Figure 6.12: Ratio L_{ir}/L_{opt} versus L_{ir} for the entire sample of $70\ \mu\text{m}$ sources (red filled circles). Green filled circles are the $70\ \mu\text{m}$ sources within the $0.5 < z < 1.3$ interval from all three available fields. Large blue filled circles represent the 28 sources of our $70\ \mu\text{m}$ sources with X-ray detections in the same redshift interval.

$$P(BC_i|\nu_{BCi}A_i) = \frac{e^{-A_i\nu_{BCi}} \times (A_i\nu_{BCi})^{C_i}}{C_i!} = \delta(\nu_{BCi} - C_i/A_i) \quad (6.4)$$

and $(1+g)$ is a number associated with ν_{Ii} (Jaffe, priv. comm):

$$\nu_{BC} = \nu_B\nu_C(1+g) \quad (6.5)$$

From equation 6.5 and equations 6.1-6.4 we can produce the distribution of $P(g)$ solving arithmetically the $P(\nu_{Bi}\nu_{Ci}g)$ (Jaffe, priv. comm.) (Figure 6.5). The ratio $P(max)/P(0) > 10^3$ can be interpreted as the likelihood ratio which is indicative of an underlying relation between the two wavebands (Jaffe, priv. comm.). A gaussian fit to $P(g)$ suggests that the difference in σ between $P(max)$ and $P(0)$ is 6σ . It has to be mentioned here that the latter is only a rough estimate, since a source of uncertainty was not taken into account by making the δ function approximation, and as a result is only indicative of the underlying relation between the two wavebands (Jaffe, priv. comm.). Further work is needed in order to determine the actual amount of extra-correlation between X-ray and $70\mu\text{m}$. sample comprises the 7.5% of the total $70\mu\text{m}$ population in the same redshift interval and within the X-ray coverage. It also comprises the 45% of the entire $70\mu\text{m}/\text{X-ray}$ population found in

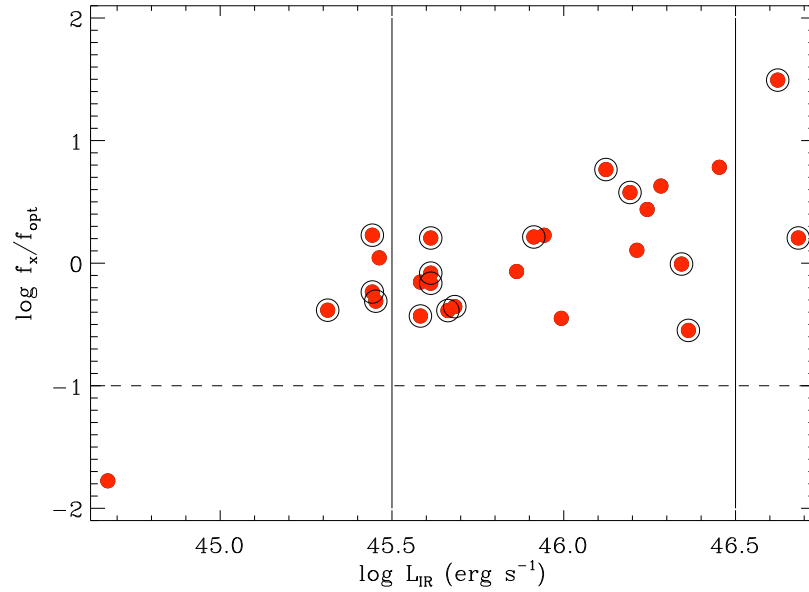


Figure 6.13: The logarithm of the X-ray to optical ratio as a function of the bolometric infrared luminosity. Dashed line marks the the AGN domination limit while vertical solid lines indicate limits for ULIRGs and HLIRGs. Open black circles indicate sources with high column densities $\log N_H > 22$.

a total of $> 2 \text{ deg}^2$ SWIRE area. This sample is the largest $70\mu\text{m}/\text{X-ray}$ sample compiled so far with the additional advantage of complete coverage in infrared, optical and X-ray, used here, plus a wealth of radio, UV, sub-mm which can be utilised in the future for further investigations.

6.5 Spectral Energy Distributions

In order to classify the SEDs and estimate photometric redshifts of the sources in our sample, optical to far-IR data are combined and fitted with a library of galaxies and AGN templates [283]. U band to $4.5 \mu\text{m}$ photometric data are fit using a library of 14 templates, 3 QSO, 1 Starburst and 10 galaxy templates [283]. At longer wavelengths, stellar contribution is subtracted from the photometric data by extrapolating the best fitting galaxy template from previous steps. The residuals are then fitted with a mixture of four templates, cirrus, M82, Arp220 and dust torus. The above modelling not only provides an estimate of the total infrared luminosity ($3\text{-}1000\mu\text{m}$) but also provide an estimate of the luminosities of the four components, solar masses (M_*), dust mass and star formation rates. 12 out of 28 sources in our sample have available spectroscopic redshifts either by our own projects or from

publicly available data from NED with excellent agreement between spectroscopic and photometric values (Figure 6.6). For sources without spectroscopic redshifts we use the photometric redshifts estimated from the latest version of the ImpZ code [283]. The minimum number of photometric bands available for all sources without available spectra is at least 5 providing accuracy in the redshift estimation of at least $\delta z / (1 + z_{\text{spec}}) \sim 0.02$. Availability of reliable $70 \mu\text{m}$ detections for all of our sources and $160 \mu\text{m}$ detections for 7 of our sources secures the accuracy of the derived SEDs with at least 8 photometric bands from optical to far-infrared used for fitting. Starburst dominated and quasar dominated sources can be discriminated on the basis of the presence or absence of the classical UV excess and flat optical SED in QSOs or from the mid-IR excess characterizing the spectra of AGN. The latter is due to emission of very hot dust not present in starburst regions. The diagnostic power offered by broad band optical/infrared SEDs for disentangling AGN and starburst activity is based on the fact that the typical peak around $1 \mu\text{m}$ of the stellar emission in normal galaxies corresponds to a minimum of the spectrum of quasar nuclei between the UV bump and the near-IR hot dust component.

6.6 Results

Figure 6.7 shows the spectral energy distributions of all ELAIS-N1 and CDFS sources in our sample. 18 out of 28 sources are starburst dominated, 9 out of 28 are torus dominated and one source is cirrus dominated. Of the 18 starbursts, 12 have a significant torus contribution ranging from 5 to 50% to the $8 \mu\text{m}$ emission. The remaining 6 starburst dominated sources show no evidence of torus contribution. Among the 9 torus dominated sources there are 7 sources with composite SEDs with significant starburst contribution which ranges between 10 and 40% of the total $8 \mu\text{m}$ emission. Finally the cirrus dominated source also shows evidence of ongoing star-formation.

In Figure 6.8 we show the distributions of the fraction of the starburst contribution for the entire $70 \mu\text{m}$ population within the redshift range of interest in all three fields. From a total 1329 sources, 20% (274) show no starburst activity and an additional 15% (200) appear to be pure starbursts. The remaining 65% of the $70 \mu\text{m}$ population has composite SEDs with both an AGN and a starburst contribution. The percentage of composites in the X-ray/ $70 \mu\text{m}$ sample is higher (78%) but not significantly different.

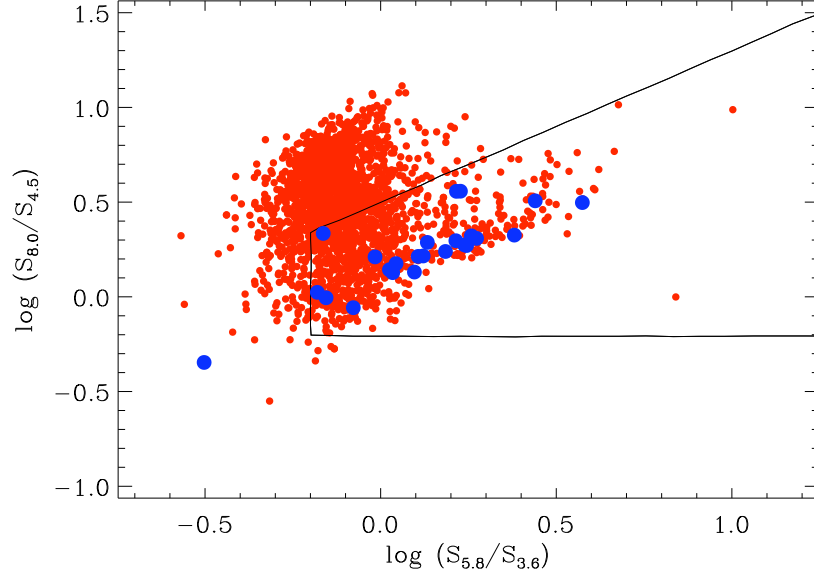


Figure 6.14: Spitzer IRAC colors. Solid lines denote the region which is used as an AGN diagnostic tool. Red dots are the general $70\ \mu\text{m}$ population. Blue large circles are the $70\mu\text{m}/\text{X-ray}$ sources with detections in all IRAC bands.

26 out of 28 sources in our sample have $L_{X2-10\text{keV}} > 10^{42}\ \text{erg s}^{-1}$ (Table 6.1) and are therefore AGN dominated in the X-ray. Nineteen sources present high absorbing column densities ($N_H > 10^{22}\ \text{cm}^{-2}$) and are thus classified as X-ray obscured AGN. Column densities have been calculated assuming a value of $\Gamma = 1.9$. The remaining nine sources have $N_H < 10^{22}\ \text{cm}^{-2}$ and are classified as unobscured. Figure 6.9 shows the X-ray luminosity in the 2-10 keV spectral band after correcting for obscuration, against L_{IR} for the entire sample of X-ray/ $70\mu\text{m}$ sources. We use Ranalli's relation (solid line) to discriminate between AGN and systems dominated by star-formation [266]. All of our sources lie above Ranalli's relation suggesting that their X-ray emission is dominated by AGN activity. In Figure 6.10 we also plot the observed mid-IR flux at $24\mu\text{m}$ versus the hard X-ray flux for our sample and we adopt Piccinotti's diagnostic (the area between the two solid lines) for hard X-ray selected AGN [256]. Almost half of our sources (13/28) lie below the AGN area. These have less X-ray emission for their mid-ir flux density and thus they should be associated with the most heavily absorbed sources. Only 4 of these sources are classified as unobscured from their N_H values tentatively suggesting that star-formation is taking place in these objects.

Far-infrared detections are indicative of the presence of cool dust heated by young

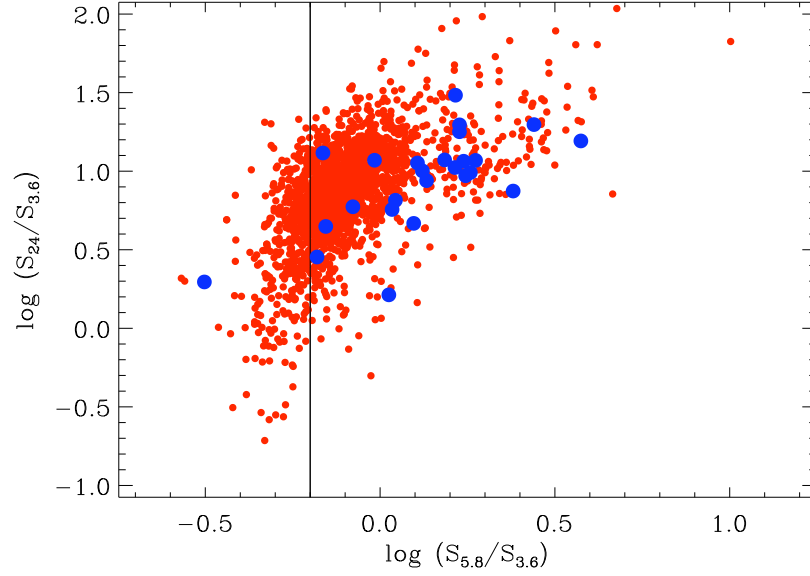


Figure 6.15: IRAC/MIPS colour-colour plots. Solid line represents the predicted obscured AGN parameter space. Colours from Figure 6.14.

stars which is also supported by optical SED fitting with only 3 sources fitted with a QSO template and the remaining fitted with spirals, starbursts or young ellipticals. Although most of our sources are AGN dominated in X-ray, 27 show the presence of a strong on-going star-formation event which dominates in the case of 16 sources and contributes of up to 10% of the infrared emission even in the case to most luminous hard X-ray QSO in our sample with $L_{X2-10keV} > 10^{45} \text{ erg s}^{-1}$. Template fitting suggests that 19 sources are composites with contributions from both a torus and a star-forming component. This has strong implications as these sources are the brightest examples of a population that future more sensitive far-infrared mission (Herschel, SPICA) will unveil. As this sample includes the best candidates for accreting black holes with ongoing star formation, this result is strong evidence for models that assume the simultaneous build-up of supermassive black holes and the host-galaxy stellar population [151]. The absence of star-formation signature in one of our sources implies that the $70 \mu\text{m}$ emission is most likely from dust heated by the AGN. This is in complete agreement with optical spectroscopy for this object, where the presence of broad MgII and CIII lines are conclusive of QSO presence (Figure 6.11).

Figure 6.12 shows the ratio L_{ir}/L_{opt} versus L_{ir} for entire sample of $70 \mu\text{m}$ sources within the $0.5 < z < 1.3$ interval from all three available fields. Sources with X-ray

detections, denoted with the large blue filled circles, occupy the upper right parameter space which can be translated as a high torus covering factor, in the case of the 9 AGN dominated sources or very high specific star formation rates for the starburst dominated sources. All of the sources in the X-ray/ $70\mu\text{m}$ sample are U/HLIRG. This implies that we are detecting the most distant counterparts of IRAS ULIRGs which represent a small fraction of the galaxy/AGN population both in local and in higher redshifts.

In Figure 6.13 we plot the X-ray to optical flux ratio defined as the ratio of the 2-10 keV flux to optical flux. Here we use the R band magnitudes given by equation [152]:

$$X/O = \log(f_x/f_o) = 5.5 + \log f_x + 0.4 \times R \quad (6.6)$$

Quiescent systems with low level star formation have $\log f_x/f_{opt} < -2$ while more active galaxies have $-2 < \log f_x/f_{opt} < -1$ with AGN dominated systems typically having $\log f_x/f_{opt} > -1$. All of our sources except one pure starburst appear to be AGN dominated in X-rays. Vertical lines indicate the ULIRG and HLIRG classes. Although there is no tight relation, increase of X/O results in higher infrared luminosities. Both HLIRGs in our sample are obscured in X-rays indicative of high amounts of dust present in these objects. More than half of the ULIRGs in the sample are obscured in X-ray.

Figure 6.14 shows the IRAC colors of the general $70\mu\text{m}$ sample overplotted by our sample. Sources with X-ray detections follow the trend of the general population and lie within the AGN area except one source, which is a source fitted with a pure starburst template. The fact that most of our sources are within the AGN region can be attributed to the fact that all 20 sources plotted here, although they are fitted with a starburst template, show evidence for an AGN contribution. In the case of the IRAC/MIPS diagnostic (Figure 6.15), which utilizes $24\mu\text{m}$ fluxes again only one source lies outside the AGN wedge. As discussed in Chapter 4, IRAC/MIPS color-color plots are less sensitive in isolating AGN from star-forming galaxies than the SED fitting method. What these plots tell us is that most of our objects have red colours which suggest the presence of AGN that are probably obscured.

In Figure 6.16 we have plotted the 2-10 keV X-ray luminosity versus the ratio of the torus luminosity/optical luminosity (top) and versus the torus luminosity/X-ray luminosity (bottom). In the case of Type-1 QSOs, optical luminosity is the black hole luminosity and for non Type-1 QSOs, black hole luminosity is associated with the

X-ray luminosity. Objects with very high fractions of L_{tor}/L_X suggest that either a significant absorption correction does need to be applied, or more interestingly there may be some Compton thick objects in the sample [283]. Objects that have L_{tor}/L_X or $L_{\text{tor}}/L_{\text{opt}} < 0$ seem to be very weak or absent torii. For these objects far-infrared emission might originate from star-formation. Figure 6.17 shows the redshift versus SFR for the entire SWIRE population overplotted by our sample. This plot shows that $70\mu\text{m}$ and $70\mu\text{m}/\text{X-ray}$ population are not different in their star-formation properties but it seems that the latter population has a higher stellar mass content than the general population but similar or even less dust mass (Figure 6.18). This implies that we are detecting the most luminous and/or less obscured sources of the $70\mu\text{m}$ population.

6.7 Discussion

We have derived broad band optical/infrared SEDs for a sample of 28 SWIRE X-ray sources with detections in $70\mu\text{m}$ (and $160\mu\text{m}$ for 25% of them) using Rowan-Robinson's SED fitting method [282]. Our sample was selected to lie within $0.5 < z < 1.3$ close to the peak of the AGN luminosity density. 26 out of 28 of our sources have X-ray luminosities indicative of AGN domination in the X-ray, 19 of which exhibit high obscuration column densities $N_H > 10^{22} \text{ cm}^{-2}$ with a mixture of hardness ratios. This is further supported by Figure 6.9 which shows that all of our sources are AGN dominated in X-ray. The number of sources in this redshift interval with X-ray/ $70\mu\text{m}$ detections far exceeds the expected number of sources and it is representative of the $70\mu\text{m}$ population since it consists of $\sim 50\%$ of all $70\mu\text{m}$ SWIRE sources with X-ray counterparts found within $\sim 2 \text{ deg}^2$. Broad band SEDs show that 19/28 sources are composite, with strong contributions both from a starburst and AGN activity, while in total 27/28 show the presence of a very strong star-formation component which dominates in 19 sources. 12 of these starburst dominated sources have hard X-ray luminosities $L_X > 10^{43}$. Only 9 sources are fitted with a torus template and the rest are fitted with a starburst template except one source that is fitted with a cirrus template which nonetheless show evidence of starburst activity contributing up to 20% in infrared emission. An intriguing finding is that most of our sources (25/28) are fitted with a galaxy template rather than with a QSO template. This is in agreement with the transition phase from the blue to red cloud agreeing with the fact that triggered AGN activity in 0.5-1 Gyr quenches star formation causing galaxies to transit from the blue to the red cloud passing from the green cloud where most of the X-ray sources lie (Figure 6.2). The fact that

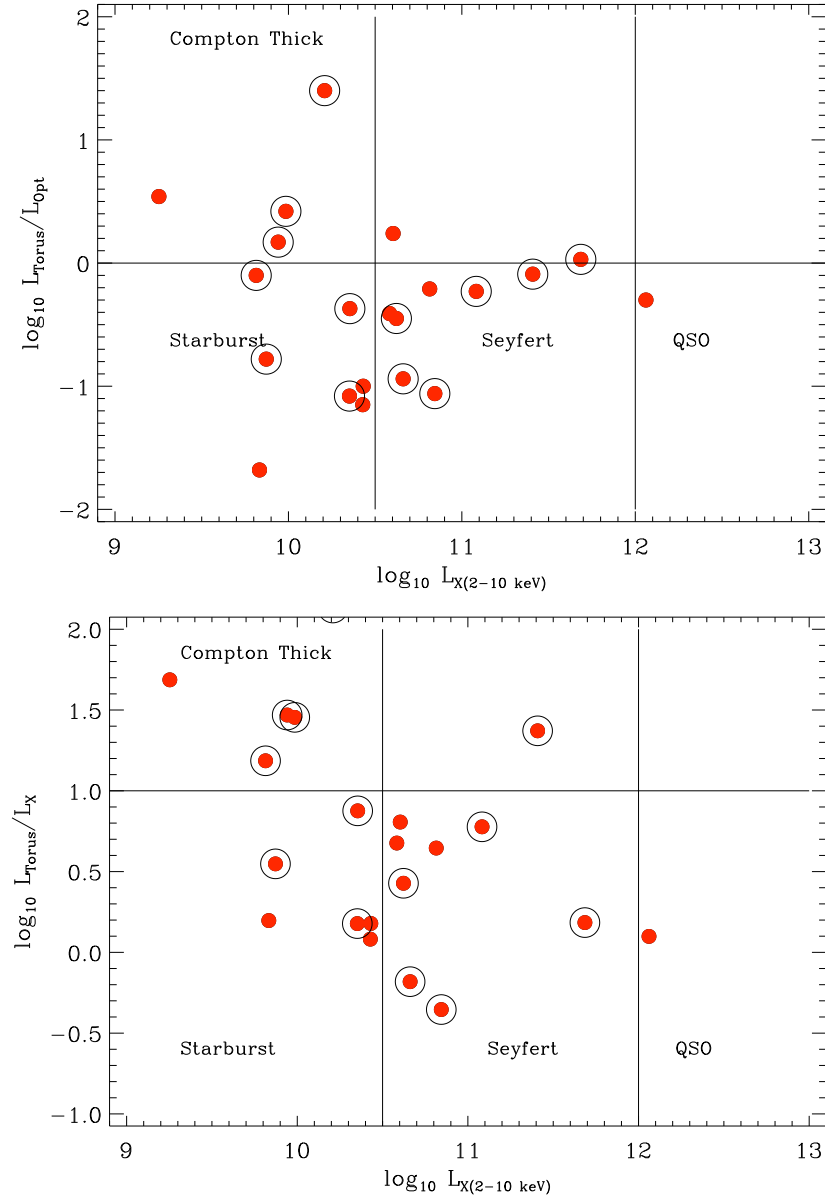


Figure 6.16: 2-10 keV X-ray luminosity versus the ratio of the torus luminosity/optical luminosity (top) and versus the torus luminosity/X-ray luminosity (bottom). Open black circles are sources with $\log N_H > 22$. Solid lines are from [283].

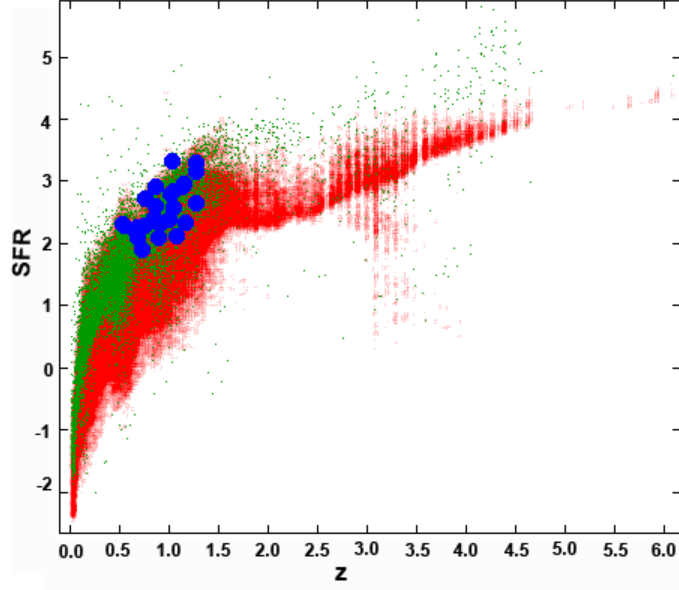


Figure 6.17: Star formation rate in $M_{\odot} \text{ yr}^{-1}$ versus redshift. Red dots is the entire SWIRE population of galaxies. Green dots are galaxies with $70\mu\text{m}$ detections. Blue large circles are galaxies within the sample of $70\mu\text{m}$ /X-ray sources.

9 of our sources are fitted with an early type galaxy with evidence of ongoing star formation is also in agreement with results from local samples that conclude that the prerequisites for an AGN is a central massive black hole and a gas supply that fuels both star formation and accretion. This is further supported by the fact that most of the sources in this sample have composite SEDs.

All of our sources have high X/O ratios. Fiore postulates that this is because the nuclear emission is obliterated by dust [105]. This is in agreement with IRAC/MIPS color-color plots which are indicative of the presence of high masses of dust that obscure the central engine. The X-ray to mid-IR diagram in Figure 6.10 can provide additional information on which sources have large intrinsic columns with the highly absorbed sources showing a low ratio of absorbed X-ray to mid-IR flux. According to Piccinotti's diagnostic half of our sources appear to be unobscured although they have large column densities. This scattering can be due to the fact that infrared and X-ray emission originate from a single dominant physical process which can be the large contribution of star-formation [215]. This is evidence that gas is needed to feed the black hole and this is possibly the same gas that is used to form stars. It is also possible that the same mechanism that is responsible for the formation of the stars is also responsible for triggering accretion.

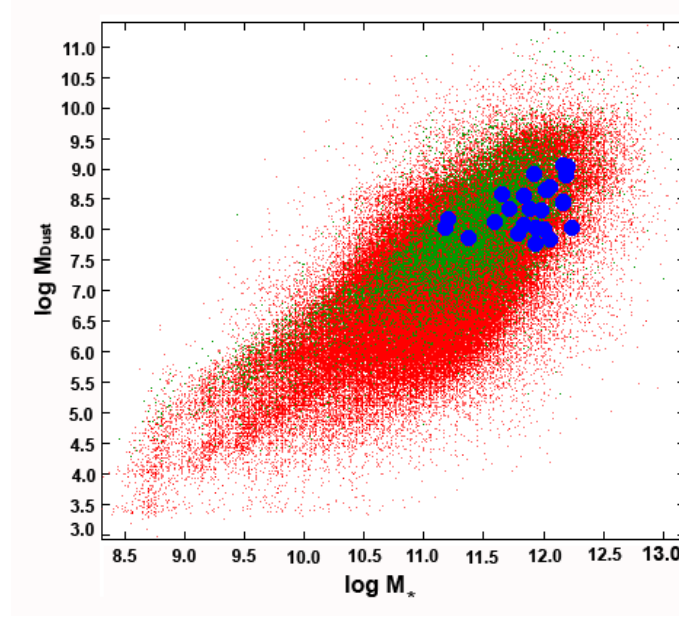


Figure 6.18: Dust mass versus stellar mass in $M_{\odot} \text{ yr}^{-1}$. Colours and symbols from Figure 6.17. Both axis in logarithmic scale.

In the mid-IR, AGN are characterised by red and almost featureless spectra. These properties make their IRAC colors unique among other IR sources providing a powerful tool to identify them. However, this diagnostic is effective only when the AGN is the dominant energy source. In cases where thermal radiation produced by dust in star forming regions is more luminous than that produced by the AGN then the infrared emission of the AGN cannot be distinguishable. In these sources the AGN can either manifest itself in longer infrared wavelengths or in X-rays. Lacy's diagnostics in Figure 6.14 and 6.15 suggest that all of our sources, except one which is a pure starburst have relatively red colours compared with normal galaxies possibly as a result of high obscuring columns of dust.

An interpretation for the above findings is to suggest that star formation is interconnected with AGN activity with the starburst activity feeding the central black hole. The fact that most of our sources are obscured and half of the sources have a hard spectrum ($HR > -0.2$) is further supporting Hopkins models which predict that there is a stage of AGN evolution where obscuration and star-formation coexist. The existence of soft spectra within our sample implies that the same gas that is used for star-formation is also used for the AGN activity. On the other hand, the existence of large number of QSOs with no starburst activity suggests that star-formation is not a requirement for AGN activity. An alternative explanation is that AGN activity

suppress star formation in galaxies leaving behind a red remnant and an unobscured AGN. This is supported by the fact that all of our X-ray/ $70\mu\text{m}$ sources show evidence of an ongoing co-evolution of the two components. The higher fraction (20%) of the composite objects compared to the general population of $70\mu\text{m}$ sources might suggest that these sources are in the epoch of transition between the red and the blue region (Figure 6.2) in agreement with the QSO mode merger models where an initial merger provides gas to feed both the black hole and star-formation but with time QSO expells all the gas via strong relativistic winds.

6.8 Conclusion

We have used a combination of SWIRE infrared and optical data to construct broad band SEDs of all $70\mu\text{m}$ sources with X-ray detections that lie in the redshift range $0.5 < z < 1.3$ from all available X-ray surveys in ELAIS-N1, Lockman Hole and CDF-S. Our sample consists of 28 sources that exceed the expected number of random associations between X-ray and $70\mu\text{m}$ at a significance level of 6σ . This implies a strong underlying relation between the two wavebands. High X-ray luminosities and intrinsic column densities suggest that most of the sources in the sample consists of obscure AGN with 4 candidates for Compton Thick AGN. Broad band SEDs revealed a bright X-ray population consisting mostly of composite objects with both a starburst and an AGN contribution with strong presence of a star-formation component in 27/28 sources and with high star formation rates. These findings suggest the existence of a strong connection between AGN and star-formation. The fact that all of the sources in the sample are U/HLIRG with no significant differences in star-formation when compared with the general population implies that we are detecting the brightest examples of a large underlying population that future, more sensitive infrared and X-ray missions will unveil. On the other hand the higher fraction of composites in this sample might imply that we are detecting objects at the phase of transition during which AGN activity quenches star-formation. Herschel will provide us with higher sensitivity and longer far-infrared wavelengths which will enable us not only to go deeper and detect more X-ray sources but also constrain the SEDs of these intriguing population with much higher accuracy.

Table 6.1: The Sample

SWIRE ID	RA	DEC	R ^a	z ^b	S ₂₄ ^c (mJy)	S ₇₀ ^d (mJy)	log L _{OP} ^e (L _⊙)	log L _{IR} ^f (L _⊙)	J ^g	NIRTEM ^h	SB ⁱ	AGN ^j	L _X ^k (ergs s ⁻¹)	HR ^l	log nH ^m (cm ⁻²)
321633+92325	53.01070	-28.0559	22.71	1.158(N)	1.296	11.05	11.17	12.70	Scd	SB	0.5	0.5	4.02 × 10 ⁴³	-0.65	19.89
333660+104500	52.95020	-27.8006	24.46	1.080(N)	0.649	9.10	10.4	11.88	SB	SB	0.65	0.35	1.80 × 10 ⁴²	-1	19.84
330988+96541	52.84090	-27.8564	22.37	1.032(N)	4.835	23.88	10.94	13.10	Sdm	AGN	0.2	0.8	1.62 × 10 ⁴³	0.67	23.30
320960+91942	53.02180	-28.0710	21.26	0.675(N)	2.573	10.36	11.02	12.03	Scd	AGN	0.2	0.8	9.62 × 10 ⁴²	0.03	22.48
32324+96250	52.87520	-27.9341	19.94	0.660(N)	1.042	22.08	11.54	11.09	Scd	SB	1.	0	6.14 × 10 ⁴¹	-1	19.85
420588+668581	242.8029	55.1398	22.40	1.281(p)	3.028	13.32	11.84	13.04	Sbc	AGN	0.4	0.6	4.85 × 10 ⁴⁴	0.83	23.60
214385+656474	242.7405	54.6853	22.78	1.270(p)	1.819	11.57	11.67	12.87	Sbc	SB	0.55	0.45	6.53 × 10 ⁴³	-0.42	21.71
187890+515803	242.1485	54.3915	17.87	1.218(T)	6.573	11.02	12.87	12.78	QSO	AGN	0	1	2.57 × 10 ⁴⁴	-0.23	22.46
229099+776704	243.2645	54.7213	21.41	1.138(p)	1.065	10.03	11.67	12.63	Scd	SB	0.55	0.45	3.84 × 10 ⁴³	-0.59	20.11
170014+551158	242.3050	53.9083	18.28	1.014(N)	5.962	12.24	12.46	12.66	QSO	AGN	0.1	0.9	1.16 × 10 ⁴⁵	-0.41	21.61
394229+493844	242.0366	54.9437	21.75	0.862(p)	2.425	43.92	11.42	12.61	Sbc	SB	0.9	0.1	4.59 × 10 ⁴³	1	23.56
413830+620799	242.5559	55.1139	20.14	0.542(p)	2.524	26.28	11.2	12.00	Sbc	SB	0.8	0.2	7.46 × 10 ⁴²	1	22.89
204010+598815	242.4509	54.6031	22.20	1.042(N)	1.349	16.68	11.55	12.54	Sbc	SB	0.85	0.15	6.99 × 10 ⁴³	1	23.67
565328+350856	161.1307	59.0938	20.19	1.300(S)	1.540	7.060	12.09	12.76	QSO	AGN	0.25	0.75	1.22 × 10 ⁴⁴	-0.02	22.79
556904+186869	161.1924	58.8248	22.92	1.280(p)	0.401	9.460	11.42	12.36	Sbc	SB	0.85	0	1.63 × 10 ⁴³	-1	19.83
559289+357549	161.0156	58.9841	22.08	1.208(p)	0.414	8.000	11.74	12.03	SB	SB	1	0	1.53 × 10 ⁴³	-0.24	22.38
550620+186176	160.8418	58.8223	21.18	1.051(p)	0.634	8.28	11.66	12.28	Scd	SB	0.75	0.25	2.68 × 10 ⁴³	-0.49	19.83
558670+357570	160.9785	58.9840	21.84	1.005(p)	1.014	8.42	11.33	12.08	Scd	SB	1	0	1.17 × 10 ⁴³	1	23.65
548614+315733	161.2412	58.5606	0.00	0.905(p)	0.246	9.52	11.61	12.01	Sdm	SB	0.65	0.35	9.80 × 10 ⁴²	-0.03	22.56
564383+357288	161.2706	58.9965	20.94	0.862(S)	2.431	10.61	11.50	12.33	Scd	SB	0.55	0.45	6.81 × 10 ⁴²	1	23.74
557564+186250	161.0506	58.9162	21.53	0.845(p)	0.400	7.96	11.73	12.03	Ell	SB	1	0	2.70 × 10 ⁴³	0.23	22.79
572831+372860	161.9630	58.8611	20.97	0.762(p)	2.729	35.28	11.71	12.41	Ell	SB	0.95	0.05	6.52 × 10 ⁴²	-0.34	21.87
564428+230933	160.8412	59.2151	20.19	0.754(p)	1.227	11.5	11.61	12.00	Scd	SB	0.35	0.65	9.68 × 10 ⁴¹	-0.42	21.42
567225+227588	160.8542	59.2861	21.14	0.690(p)	1.124	10.18	11.10	11.87	Scd	AGN	1	0	2.26 × 10 ⁴³	1	23.43
564840+337822	161.7609	58.7560	22.87	0.644(p)	0.728	11.14	10.91	11.73	Scd	SB	1	0	2.26 × 10 ⁴³	-0.05	22.38
560804+179386	160.7222	59.1727	20.87	0.614(p)	1.141	14.04	11.77	11.86	Scd	Cirrus	0.2	0	8.73 × 10 ⁴²	-0.03	22.37
576100+227425	161.2141	59.3296	19.54	0.570(S)	2.872	13.44	11.60	11.86	SB	AGN	0.25	0.75	4.02 × 10 ⁴³	0.07	22.45
551246+363869	161.0331	58.7437	20.13	0.535(S)	7.358	28.2	11.24	12.10	Sbc	AGN	0.3	0.7	1.80 × 10 ⁴²	0.19	22.54

^aVega R magnitudes^bSpectroscopic z are denoted with N (retrieved from NED), T (from Trichas et al

2007), S (from Smith et al 2007) and photometric redshifts with p.

^cObserved 24 μ m fluxes in mJy^dObserved 70 μ m fluxes in mJy^eBolometric Optical Luminosity (H₀ = 72 km s⁻¹ Mpc⁻¹, λ = 0.7)^fBolometric Infrared Luminosity (1 – 1000 μ m) (H₀ = 0.72 km s⁻¹ Mpc⁻¹, λ = 0.7)^gOptical SED best fit^hInfrared SED best fitⁱFraction of Starburst contribution at 8 μ m^jFraction of AGN contribution at 8 μ m^kHard band (2 – 10 keV) X-ray Luminosity (H₀ = 0.72 km s⁻¹ Mpc⁻¹, λ = 0.7)^lHardness Ratios^mIntrinsic Column Density

Chapter 7

Conclusions

The roots of education are bitter, but the fruit is sweet.

Aristotle (384-322 BC)

In this Thesis a study of SWIRE populations from the viewpoint of their infrared, X-ray and optical properties has been presented. GMOS and WIYN spectroscopic observations and shallow Chandra observations of SWIRE ELAIS-N1 field, formed the basis of the work. SWIRE multi-wavelength data provided reliable photometric redshifts of large samples of galaxies and detailed spectral energy distributions of extreme infrared populations. The optical spectroscopic data used, directly estimate redshifts and identify different populations. As a result, spectroscopy provided a highly efficient way in calibrating photometric redshift techniques and testing template fitting results. The X-ray data used, directly probe high energy processes within galaxies and offered a view that is largely unaffected by dust and gas. All this information was combined in an effort to understand the main phenomenological properties of galaxies and quasars over a large wavelength range, providing a large set of natural targets for future surveys.

The main results and findings of this thesis are:

- We have carried out the largest optical spectroscopic follow-up of ELAIS-N1 and the largest X-ray survey in the same field. We have extended ELAIS-N1 X-ray coverage by a factor of 12. Compared with the ROSAT ultradeep survey, it reaches the same depth in soft X-ray but over an area ~ 3 times larger while at the same time is by a factor of ~ 10 deeper than the ASCA LSS survey.
- GMOS/WIYN data reduction pipeline achieved a success rate of 88% in successfully extracting spectra and identifying prominent lines.

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- All HLIRGs at $z > 0.7$ are broad line QSO. Their broad band spectral energy distributions show that they are all AGN dominated. Half of them have a starburst contributing 10 to 40 % to the $8\mu\text{m}$ emission.
 - All ULIRGs at $z > 1.5$ are broad line QSO. ULIRGs at $z < 1.5$ show evidence of both broad and narrow line regions. Their SEDs are a mixture of pure AGN or starburst dominated sources and composites.
 - We have identified two very interesting populations: elliptical galaxies with very strong ongoing starbursts and cirrus LIRGs.
 - The only cirrus ULIRG found in the sample shows evidence of both a broad and a narrow line region.
 - The overall accuracy of the ImpZ code is found to be very good with $\sigma_{tot}=0.09$, $\overline{\Delta z}/(1+z) = -0.008$ and 4.4% catastrophic outliers when compared with sources with good quality spectra available.
 - For luminous X-ray AGN, ImpZ is more accurate than any other available code. The systematic mean error is -0.001, the rms is 0.12 and the catastrophic outlier fraction is 13.7%.
 - We have identified a new parameter space in the IRAC colour-colour plots where searches for Type-2 AGN should concentrate. This parameter space is occupied predominantly by narrow line AGN from the GMOS/WIYN sample. The fact that these sources are missed by X-ray surveys suggest that their central engine is obscured by the host galaxy.
 - Rowan-Robinson's template fitting method achieves the same accuracy as optical spectroscopy in isolating AGN from star-forming galaxies and identifying composite objects and is far superior to IRAC/MIPS colour-colour plots.
 - The Type-1 to Type-2 ratio is found to be 1:2 for luminous X-ray AGN from the Chandra shallow survey.
 - Bright X-ray selected AGN are associated with luminous $M_B < -20$ hosts with the most extreme hard X-ray emitters associated with ultra-luminous point-like sources at $M_B < -23.5$.
 - We find more X-ray/ $70\mu\text{m}$ associations in our fields compared to the expectation assuming no causal link between the two wavebands. This difference is significant at the $> 99.99\%$ level. This implies that there is an underlying link

between the two wavelength regimes, suggesting that the emission mechanisms at these different wavebands are associated.

- All X-ray/ $70\mu\text{m}$ sources are U/HLIRG with the same level of star formation rates as the general $70\mu\text{m}$ population but higher stellar masses. This implies that we detect the most luminous and/or less obscured AGN.
- Most of the X-ray/ $70\mu\text{m}$ sources are obscured AGN at X-rays but composites at infrared, suggesting that star-formation is taking place in these systems. This is evidence in favor of QSO mode merger models where there is a stage of AGN evolution where obscuration and star-formation co-exist. Also this is evidence that the same gas supply that is used for star-formation is also used for AGN activity. In this case, the mechanism that drives the gas to the nuclear black hole is also causing star-formation.

The work in this thesis is suitable for many future developments. With regards to X-ray data analysis techniques, several advances can be made. Source extraction from the mosaiced images will increase the sensitivity, flux determination and number of sources and possibly will enable us to extract X-ray spectra of selected sources. In addition, inclusion of a cross-correlation method that utilizes likelihoods will possibly result in a lower fraction of random associations between the X-ray and the SWIRE catalogue.

Analysis of larger samples of narrow-line AGN both from publicly available or awarded data (e.g. We have already been awarded time and observed 60 of these objects with ESO's 3.6m and additional 25 with Aristarchos 2.3m telescopes) especially from regions with X-ray coverage will enable us to further constrain the nature of these objects that cannot be isolated from available infrared diagnostics.

The X-ray/ $70\mu\text{m}$ analysis can be extended to additional fields with overlapping multi-wavelength data (e.g. EGS). Adaptation of a physical model for estimating random associations between the two wavebands will provide us with a more robust figure of the expected overestimation. These sources will constitute the natural targets of future surveys with higher sensitivities (e.g. Herschel) and availability of far-infrared spectroscopy which is detrimental in isolating the dominant mechanism producing the far-infrared emission.

Another interesting finding of this Thesis is the large number of X-ray sources with

infrared counterparts that lack optical associations. The first step is to try to measure photometric redshifts to establish whether these are the expected high- z Type-2 QSOs or very faint local sources. The next step is to perform different diagnostics and try to combine this sample with similar samples from fields with deeper X-ray surveys (e.g. CDF-N/S).

A P P E N D I X A

Catalogue of Properties of SWIRE Sources Observed with GMOS and WIYN

The catalogue listing the astrometric coordinates, photometric properties, spectroscopic redshifts and quality flags.

Column 1: Right ascension of the source (J2000)

Column 2: Declination of the source (J2000)

Column 3: IRAC $3.6\mu\text{m}$ flux (μJy)

Column 4: MIPS $24\mu\text{m}$ flux (μJy)

Column 5: R -band magnitude (Vega)

Column 6: Optical template type (1-2 elliptical galaxies, 3-11 galaxies, 13-15 QSOs)

Column 7: M_B corrected for extinction

Column 8: $\log_{10}$ of bolometric optical luminosity, in solar units

Column 9: Spectroscopic redshift from our GMOS/WIYN runs

Column 10: Quality flag of spectroscopic redshift

Column 11: $\log_{10}$ of bolometric infrared luminosity, in solar units

Column 12: Infrared template type (dominated by 1=cirrus, 2= M82 starburst, 3=A220 starburst, 4=AGN sust torus, 5=single band excess, 6=no excess)

RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
244.086	55.1308	81.47	531.59	22.17	5	-22.7	11.48	0.941	2	12.88	3
242.696	53.3702	103.67	0.	21.72	1	-22.02	11.34	0.7	2	0.	6
242.742	53.3823	45.7	270.51	22.65	10	-20.21	10.41	1.118	1	10.58	4
242.787	53.3794	15.15	0.	22.83	11	-21.25	10.91	0.838	3	0.	6
242.698	53.3865	32.5	222.56	22.	8	-21.74	10.98	0.661	2	11.18	5
242.694	53.3951	14.86	0.	22.72	9	-21.8	10.97	0.681	2	0.	6
242.798	53.3922	19.45	0.	22.39	9	-22.08	11.09	0.736	3	0.	6
242.782	53.3981	61.78	0.	21.94	7	-21.58	10.95	0.646	3	0.	6
242.691	53.4032	13.82	155.78	23.48	7	-21.	10.72	1.07	2	11.32	5
242.723	53.4104	11.93	0.	22.2	11	-20.32	10.53	0.514	3	0.	6
242.739	53.4144	16.	0.	22.84	3	-19.6	10.28	0.599	1	0.	6
242.71	53.4268	9.06	0.	22.47	3	-18.8	9.96	0.375	1	0.	6
242.745	53.4429	17.43	140.81	23.14	1	-19.58	10.36	0.585	1	10.55	5
242.817	53.447	59.07	0.	23.15	2	-21.35	11.03	0.885	2	0.	6
243.648	53.6343	6.05	0.	22.58	5	-17.27	9.31	0.176	1	0.	6
243.576	53.64	50.57	295.5	22.3	8	-22.56	11.31	1.041	2	11.6	2
243.556	53.6434	22.8	0.	22.07	11	-21.56	11.03	0.691	9	0.	6
243.591	53.6703	60.5	462.16	21.76	7	-22.32	11.24	0.839	1	11.61	2
243.665	53.6755	73.17	0.	22.35	5	-22.14	11.25	0.836	1	0.	6
243.653	53.682	78.64	178.49	22.18	8	-22.84	11.42	0.56	1	11.23	5
243.543	53.6953	7.63	0.	22.54	1	-18.44	9.91	0.442	1	0.	6
243.648	53.699	11.49	0.	22.89	9	-21.8	10.98	0.984	2	0.	6
243.574	53.7069	6.64	0.	22.5	9	-21.91	11.02	1.19	1	0.	6
243.632	53.71	18.36	175.83	23.08	11	-22.13	11.26	1.01	1	11.76	5
242.787	54.2228	46.6	0.	22.31	11	-22.48	11.4	0.815	1	0.	6
242.791	54.2258	14.19	0.	22.9	7	-20.33	10.45	0.644	9	0.	6
242.734	54.2346	54.86	201.31	22.7	9	-20.21	10.34	0.631	1	10.33	4
242.859	54.2378	5.4	0.	22.7	6	-17.64	9.41	0.192	2	0.	6
242.857	54.246	30.42	0.	22.7	7	-21.75	11.02	0.988	9	0.	6
242.797	54.2508	21.96	174.98	22.56	8	-21.77	10.99	0.802	3	11.41	5
242.813	54.2536	9.	147.93	22.88	10	-21.54	10.95	0.792	9	11.43	5
242.76	54.2626	140.58	0.	21.65	5	-22.84	11.53	0.798	2	0.	6
242.745	54.2659	34.67	0.	23.15	3	-21.25	10.94	0.794	9	0.	6
242.758	54.2708	100.5	0.	23.15	2	-21.88	11.24	0.958	1	0.	6
242.8	54.2897	13.33	0.	22.05	11	-20.51	10.61	0.782	2	0.	6
242.622	54.3953	98.1	0.	22.46	2	-21.78	11.2	0.787	3	0.	6
242.682	54.3993	15.42	0.	22.16	9	-22.67	11.32	1.02	1	0.	6
243.337	54.4063	30.54	165.93	22.49	7	-21.63	10.97	0.84	2	11.19	5
243.271	54.4094	43.9	0.	22.05	7	-21.11	10.76	0.61	1	0.	6
242.694	54.4104	36.8	190.8	22.65	7	-21.37	10.86	0.432	1	11.18	4

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RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
243.247	54.4126	38.72	358.06	22.42	7	-18.99	9.91	0.781	2	10.41	4
242.702	54.4159	34.53	271.11	22.01	9	-21.99	11.05	1.15	1	11.15	4
242.589	54.4203	31.52	604.29	21.55	8	-21.04	10.7	0.19	9	10.64	2
243.287	54.4276	124.5	0.	21.57	2	-21.75	11.19	0.623	2	10.73	5
243.301	54.4312	122.13	295.75	22.5	7	-21.23	10.81	0.67	2	10.69	4
242.429	54.4348	79.6	0.	22.64	2	-21.46	11.07	0.748	2	0.	6
243.318	54.4359	59.69	157.84	22.02	5	-21.57	11.03	0.755	9	10.89	5
242.577	54.4356	85.84	0.	22.23	4	-22.16	11.28	0.8	3	0.	6
242.679	54.4386	41.94	140.45	23.06	6	-22.1	11.2	0.948	1	11.47	5
243.372	54.4406	51.36	224.13	22.85	1	-20.78	10.84	0.805	2	10.81	4
242.615	54.4436	17.44	283.43	22.94	11	-22.13	11.26	1.2	1	11.92	5
242.675	54.4486	9.62	0.	22.51	7	-19.64	10.17	0.327	2	0.	6
242.542	54.4527	34.24	157.96	22.33	7	-21.53	10.93	0.794	2	11.06	5
242.678	54.453	102.51	465.29	21.61	11	-23.51	11.81	1.32	1	12.04	2
243.257	54.4519	39.29	0.	22.32	6	-20.62	10.61	0.633	2	10.12	4
242.614	54.4576	18.31	0.	22.97	11	-22.29	11.32	1.395	2	0.	6
242.498	54.4559	8.07	0.	22.94	10	-20.42	10.5	0.745	3	0.	6
243.349	54.4625	41.49	156.99	21.55	6	-21.05	10.78	0.515	2	10.71	2
242.443	54.4614	10.03	0.	22.72	9	-23.01	11.46	0.75	1	0.	6
242.636	54.4651	20.94	0.	22.56	1	-19.86	10.47	0.495	9	0.	6
242.553	54.4656	45.17	615.28	23.43	5	-23.18	11.67	1.4	1	12.6	2
242.71	54.4683	60.36	0.	22.11	2	-20.65	10.75	0.6	1	0.	6
242.518	54.4712	14.57	0.	22.89	11	-23.48	11.8	2.045	2	0.	6
242.694	54.4765	32.09	273.4	22.27	8	-20.35	10.42	0.576	1	10.76	4
242.752	54.4804	34.74	253.84	22.71	7	-21.86	11.06	0.79	2	11.58	5
243.265	54.4783	7.43	0.	22.01	9	-20.78	10.57	0.203	2	0.	6
242.507	54.4825	55.6	0.	22.88	1	-21.54	11.15	0.847	2	0.	6
242.747	54.4856	32.9	330.28	22.7	8	-22.32	11.21	0.96	1	11.97	5
242.461	54.4908	15.19	0.	21.88	8	-20.44	10.46	0.563	3	0.	6
242.534	54.4958	55.18	230.78	22.33	8	-21.05	10.7	0.668	2	10.59	4
242.687	54.5015	58.2	224.74	22.57	7	-22.49	11.31	1.08	3	11.77	5
242.498	54.5043	63.04	474.23	22.31	11	-22.92	11.58	0.892	2	11.88	5
242.709	54.5066	45.06	0.	22.51	7	-22.91	11.48	0.654	9	12.46	2
242.495	54.5095	9.92	0.	23.32	8	-20.36	10.43	0.494	2	0.	6
242.736	54.5099	14.01	0.	22.74	8	-21.	10.68	0.867	1	0.	6
242.508	54.514	11.59	0.	22.72	6	-19.47	10.15	0.477	2	0.	6
242.737	54.5132	16.4	159.28	23.35	7	-21.1	10.75	1.03	2	11.32	5
242.744	54.518	12.92	0.	23.42	11	-21.11	10.85	0.967	2	0.	6
242.571	54.518	11.6	0.	22.64	10	-21.43	10.9	1.117	2	0.	6
242.639	54.5215	11.26	0.	21.91	11	-20.38	10.56	0.556	2	0.	6
242.555	54.5288	19.01	161.1	22.84	11	-21.74	11.1	1.115	2	11.41	5

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RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
242.543	54.5327	14.09	179.09	23.07	8	-21.2	10.76	0.929	3	11.31	5
242.734	54.535	18.62	0.	22.58	11	-21.56	11.03	0.878	3	0.	6
242.669	54.5374	56.63	441.26	22.89	5	-22.49	11.4	0.799	4	11.9	5
242.663	54.5406	5.83	0.	23.15	9	-20.82	10.58	0.937	2	0.	6
242.774	54.5411	7.66	0.	22.97	9	-22.06	11.08	1.044	2	0.	6
242.54	54.5457	48.72	0.	23.46	2	-21.17	10.96	0.87	2	0.	6
242.536	54.549	106.43	0.	22.61	1	-22.46	11.52	0.879	2	0.	6
242.752	54.5485	44.19	139.84	22.2	7	-21.79	11.03	0.735	3	11.	5
242.534	54.5519	29.57	420.37	22.32	8	-22.15	11.14	1.1	3	12.03	2
242.639	54.5598	9.84	0.	21.82	10	-20.22	10.42	0.633	2	0.	6
242.763	54.5621	12.53	0.	22.05	8	-20.65	10.55	0.585	2	0.	6
242.538	54.5641	71.34	340.79	22.19	10	-18.51	9.73	0.613	3	9.77	4
242.669	54.5687	25.9	180.18	22.57	9	-22.62	11.3	0.627	1	11.6	5
242.665	54.5724	39.84	0.	21.6	7	-21.21	10.8	0.984	2	0.	6
242.784	54.5723	14.85	0.	22.82	11	-21.78	11.12	0.501	2	0.	6
242.572	54.5753	16.29	0.	23.04	9	-23.06	11.48	2.197	2	0.	6
242.65	54.5787	82.35	428.7	22.4	7	-23.05	11.54	1.322	2	11.68	2
242.873	54.58	8.03	0.	22.46	7	-19.2	9.99	0.523	9	0.	6
242.778	54.5827	26.37	213.51	22.7	11	-22.22	11.3	1.154	2	11.64	5
242.646	54.584	24.02	0.	21.72	9	-24.41	12.02	0.803	2	0.	6
242.754	54.5881	20.9	0.	22.84	2	-19.39	10.24	0.527	2	0.	6
242.634	54.5878	56.86	0.	22.11	2	-20.71	10.77	0.623	1	0.	6
242.665	54.5956	50.38	0.	23.26	4	-21.87	11.17	0.821	4	0.	6
242.762	54.5961	18.04	195.15	22.4	10	-21.93	11.1	0.917	1	11.49	5
242.819	54.6001	4.24	0.	23.08	3	-23.02	11.65	1.571	1	0.	6
242.808	54.603	34.56	134.41	22.26	10	-22.43	11.3	1.226	1	10.86	4
242.751	54.6059	14.94	196.84	21.75	11	-20.46	10.59	0.644	1	10.53	5
242.731	54.6099	42.34	0.	22.24	1	-20.82	10.86	0.444	1	0.	6
242.729	54.6291	7.98	0.	23.47	8	-20.39	10.44	0.742	2	0.	6
242.529	54.6425	29.27	0.	22.67	11	-22.1	11.25	1.22	1	0.	6
242.477	54.6464	37.11	254.69	22.3	4	-20.95	10.8	0.641	1	11.01	5
242.504	54.6553	46.54	522.66	23.42	2	-22.23	11.38	1.088	2	12.14	2
242.412	54.6644	9.22	146.	22.52	9	-20.97	10.64	0.943	1	11.01	5
242.482	54.6798	22.75	152.28	22.42	3	-20.02	10.45	0.599	1	10.62	2
242.433	54.6862	80.73	0.	23.3	2	-21.78	11.2	0.904	1	0.	6
242.527	54.6896	36.92	304.08	22.6	7	-22.14	11.17	1.074	2	11.74	5
242.431	54.6934	48.09	197.45	22.31	7	-22.21	11.2	0.791	1	11.42	5
242.43	54.6976	36.15	466.02	23.4	5	-24.23	12.09	0.872	9	12.73	2
242.511	54.7048	33.69	180.3	22.63	11	-20.74	10.7	0.754	1	10.69	4
242.503	54.7098	46.88	0.	22.89	5	-21.87	11.14	0.82	3	0.	6
242.431	54.7135	14.84	177.28	22.82	8	-21.24	10.78	0.674	3	11.28	5

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RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
241.289	54.7945	33.3	377.98	22.37	8	-22.02	11.09	0.923	3	11.68	5
241.347	54.7984	42.	207.71	22.46	6	-21.49	10.95	0.774	3	11.17	5
241.359	54.802	42.22	672.88	23.23	6	-20.76	10.66	0.818	3	11.83	4
241.371	54.806	73.88	0.	22.15	7	-21.84	11.05	0.808	2	0.	6
241.259	54.81	5.1	0.	22.74	11	-19.37	10.15	0.549	1	0.	6
241.277	54.8136	18.74	0.	22.65	11	-21.97	11.2	1.16	1	0.	6
241.297	54.8218	11.27	0.	22.06	11	-20.2	10.49	0.468	2	0.	6
241.37	54.8255	107.92	715.27	22.87	5	-22.91	11.56	1.214	1	12.1	4
241.319	54.8291	5.02	0.	22.44	10	-19.65	10.19	0.299	1	0.	6
241.239	54.8435	11.73	149.5	23.17	11	-21.62	11.05	1.486	2	11.58	5
241.351	54.8546	10.33	0.	21.74	11	-20.19	10.48	0.406	3	0.	6
244.18	55.093	15.23	0.	23.35	1	-19.66	10.39	0.602	2	0.	6
244.156	55.0969	8.74	187.42	21.81	8	-18.39	9.64	0.214	2	9.82	5
244.191	55.0998	42.3	308.43	22.7	6	-21.78	11.07	0.839	3	11.52	5
244.103	55.1119	50.69	188.51	21.56	2	-18.11	9.73	0.281	1	9.35	4
244.208	55.1179	60.2	0.	21.87	6	-22.04	11.17	0.694	9	0.	6
244.154	55.1209	55.44	200.22	23.49	3	-21.79	11.16	1.129	1	11.46	2
244.195	55.1338	38.23	246.84	22.21	7	-21.78	11.03	0.82	2	11.3	5
244.118	55.1369	72.51	445.61	22.53	5	-22.42	11.37	1.06	3	12.25	1
244.168	55.1398	48.59	452.86	22.17	9	-21.87	11.	0.62	3	11.35	4
244.091	55.1439	34.14	258.07	21.88	10	-22.81	11.45	1.101	2	11.73	5
244.166	55.1471	8.1	0.	21.54	9	-18.98	9.85	1.066	3	0.	6
244.114	55.1524	27.08	0.	22.68	2	-19.67	10.36	0.542	2	0.	6
244.18	55.1601	18.98	303.23	22.92	11	-21.7	11.09	0.908	2	11.6	5
244.15	55.1629	15.43	147.69	21.83	7	-19.93	10.29	0.26	3	10.39	5
244.079	55.1657	4.33	0.	22.33	9	-19.36	10.	0.312	9	0.	6
244.172	55.1695	60.3	249.49	22.74	6	-22.52	11.36	1.072	2	11.75	5
243.206	55.3242	56.19	493.79	22.5	7	-22.38	11.27	0.963	3	11.89	2
243.217	55.331	46.72	0.	21.71	2	-20.15	10.55	0.462	1	0.	6
243.232	55.3572	7.44	0.	22.23	10	-19.99	10.33	0.241	2	0.	6
243.18	55.3616	30.5	0.	23.11	5	-20.93	10.77	0.268	1	0.	6
243.085	55.368	6.27	0.	22.33	9	-19.27	9.96	0.471	1	0.	6
243.107	55.3759	16.79	201.43	22.19	9	-22.45	11.23	0.927	1	11.78	5
243.212	55.3803	6.74	0.	22.12	8	-17.25	9.18	0.157	1	0.	6
243.233	55.3842	56.92	0.	22.87	3	-21.67	11.11	0.251	2	0.	6
243.232	55.3955	6.57	0.	23.28	11	-20.13	10.46	0.642	2	0.	6
243.229	55.4059	30.81	0.	22.51	2	-19.84	10.42	0.613	1	0.	6
241.611	55.4093	52.3	0.	22.68	5	-21.77	11.11	0.951	2	0.	6
241.612	55.4197	5.99	0.	22.76	9	-20.98	10.65	0.694	1	0.	6
241.624	55.4244	26.66	0.	22.89	6	-21.14	10.81	0.262	2	0.	6
241.549	55.4298	16.	0.	22.52	8	-20.99	10.68	0.651	1	0.	6

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RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
241.501	55.4355	56.71	696.07	21.92	1	-21.09	10.97	0.707	2	11.41	2
241.522	55.4404	36.6	173.9	22.22	3	-20.69	10.72	0.664	9	10.76	5
241.519	55.4455	9.12	211.21	21.61	10	-18.33	9.66	0.272	9	9.74	5
241.623	55.4541	7.33	0.	21.99	11	-18.82	9.94	0.313	1	0.	6
241.579	55.4642	114.75	537.03	22.97	1	-22.6	11.57	0.97	1	12.09	2
241.605	55.4684	8.34	0.	22.64	5	-18.42	9.76	0.267	1	0.	6
241.495	55.477	5.6	0.	22.18	8	-17.26	9.19	0.176	2	0.	6
241.559	55.4822	23.14	0.	22.05	8	-21.33	10.81	0.731	1	0.	6
241.589	55.4851	38.79	231.5	22.16	11	-22.76	11.51	1.35	1	11.22	4
242.695	54.4104	0.	0.	22.65	7	-21.95	11.09	0.432	2	0.	6
242.683	54.4763	11.26	0.	22.45	13	-22.6	11.55	1.34	2	0.	6
242.718	54.4985	29.7	218.94	22.42	14	-19.64	10.37	0.538	1	10.42	4
242.731	54.5932	48.	605.02	22.04	15	-23.27	11.82	0.883	1	12.92	4
242.746	54.6362	9.86	0.	22.39	13	-22.14	11.37	1.57	3	0.	6
241.373	54.8511	14.27	249.01	21.61	13	-21.8	11.23	1.079	2	11.83	4
244.212	55.1726	9.6	0.	23.14	15	-21.13	10.96	0.36	1	0.	6
242.823	54.2747	1225.53	4877.57	16.96	2	-21.53	11.1	0.144	3	11.04	1
242.766	54.7228	1232.13	6426.94	16.4	7	-20.27	10.42	0.063	3	9.91	1
242.672	54.1756	293.18	5136.	18.23	11	-22.46	11.39	0.227	3	11.42	1
242.831	54.2158	970.93	2802.88	16.69	7	-20.59	10.55	0.069	3	10.28	1
242.442	54.3573	936.67	2917.6	16.3	10	-22.6	11.37	0.066	3	10.91	1
242.716	54.2311	1243.69	2345.19	16.5	3	-20.75	10.74	0.063	3	10.17	1
243.259	54.4795	767.	2189.41	17.29	6	-22.53	11.37	0.126	3	11.33	1
242.766	54.4015	121.74	972.49	18.29	10	-20.28	10.44	0.13	3	9.95	2
242.91	54.3228	189.77	1695.49	18.99	8	-22.69	11.36	0.339	3	11.28	2
242.396	54.5177	110.86	2261.87	19.28	15	-24.7	12.39	0.572	3	12.67	2
242.517	54.2274	183.5	1905.62	19.99	13	-24.92	12.48	1.	3	13.31	4
242.612	54.1772	105.91	1177.43	19.26	7	-21.37	10.86	0.3	3	11.01	1
242.149	54.3915	879.25	6573.06	17.87	13	-25.9	12.87	1.3	3	12.78	4
242.53	53.9706	180.42	3586.62	18.89	15	-25.78	12.82	2.015	3	12.84	4
242.196	53.9749	159.26	0.	19.33	1	-21.26	11.04	0.329	3	0.	6
242.658	54.0919	510.86	0.	18.48	2	-22.17	11.36	0.339	3	0.	6
242.593	54.0962	143.28	498.26	19.32	1	-20.86	10.88	0.334	3	10.36	5
242.688	54.0963	129.69	166.65	19.7	1	-20.54	10.75	0.343	3	9.58	4
242.668	54.1066	609.2	0.	18.23	2	-22.47	11.48	0.337	3	0.	6
242.669	54.1086	416.98	0.	18.41	1	-22.52	11.54	0.338	3	0.	6
242.15	54.1256	110.	131.39	19.75	1	-20.67	10.8	0.337	3	9.88	5
242.048	54.132	116.42	0.	19.41	1	-20.14	10.59	0.333	3	0.	6
242.39	54.1409	1987.5	310.6	15.93	1	-20.8	10.85	0.047	3	8.71	5
242.865	54.1529	68.37	320.86	19.66	3	-19.69	10.32	0.337	3	9.37	2
243.018	54.1604	729.57	168.7	17.35	1	-21.57	11.16	0.135	3	8.99	4

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RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
242.87	54.1656	160.44	0.	19.24	1	-21.	10.93	0.355	3	0.	6
242.871	54.1664	176.81	0.	19.19	1	-21.35	11.07	0.335	3	0.	6
242.866	54.1711	196.79	532.8	17.85	11	-17.97	9.6	0.092	3	8.35	1
242.934	54.1695	61.11	389.46	18.62	9	-17.12	9.1	0.065	3	7.89	2
242.61	54.1741	106.78	0.	19.45	5	-20.76	10.7	0.271	3	0.	6
242.915	54.1801	138.16	218.58	19.39	5	-21.26	10.9	0.271	3	10.07	2
242.949	54.1924	168.36	667.33	19.05	7	-22.36	11.26	0.334	3	10.82	4
242.784	54.1936	145.98	536.18	19.32	4	-21.26	10.93	0.339	3	10.67	1
242.648	54.2016	19.91	234.16	19.35	9	-17.13	9.1	0.048	3	8.19	5
243.06	54.2124	213.01	0.	18.99	2	-20.81	10.81	0.329	3	0.	6
242.614	54.2129	802.94	174.5	17.5	1	-22.74	11.63	0.268	3	9.9	5
242.839	54.2129	117.84	1380.31	18.37	10	-19.82	10.26	0.049	3	10.15	3
242.881	54.2259	118.56	310.72	19.67	2	-20.26	10.59	0.333	3	9.83	2
242.895	54.2347	168.21	1090.96	19.28	8	-22.58	11.32	0.336	3	11.22	1
242.747	54.2356	14.44	0.	19.97	9	-17.09	9.09	0.041	3	0.	6
242.865	54.2396	224.44	0.	19.15	2	-21.33	11.02	0.335	3	0.	6
242.896	54.2572	57.7	479.18	18.71	8	-17.1	9.13	0.218	3	8.62	3
242.75	54.2599	379.15	139.72	18.66	1	-21.02	10.94	0.267	3	9.18	4
243.051	54.2598	158.66	1987.74	19.84	11	-22.9	11.57	0.394	3	11.87	2
242.844	54.2661	163.44	0.	20.	5	-21.85	11.14	0.461	3	9.5	4
243.237	54.2686	60.03	0.	20.41	2	-19.64	10.35	0.341	3	0.	6
242.86	54.272	134.68	0.	19.42	1	-21.06	10.95	0.331	3	0.	6
242.931	54.2746	223.52	996.65	19.36	7	-22.61	11.36	0.341	3	11.1	1
242.814	54.2743	154.27	0.	19.17	1	-20.95	10.91	0.342	3	0.	6
242.9	54.2763	1110.1	0.	17.5	2	-22.8	11.61	0.338	3	0.	6
242.902	54.2782	361.72	1153.27	20.41	9	-20.16	10.32	1.06	3	10.32	4
242.823	54.2793	193.75	621.68	19.02	11	-22.66	11.47	0.143	3	10.72	1
242.844	54.2853	169.96	0.	19.42	2	-21.	10.89	0.336	3	0.	6
242.868	54.2891	576.12	0.	18.29	2	-22.41	11.45	0.34	3	0.	6
242.82	54.2955	150.3	789.66	20.4	6	-20.87	10.7	0.5	3	10.61	4
242.918	54.2948	100.22	249.13	19.67	4	-20.86	10.76	0.341	3	10.74	3
242.779	54.3112	48.02	446.34	20.5	7	-21.11	10.76	0.315	3	11.02	1
242.499	54.3174	90.63	0.	20.05	2	-20.07	10.51	0.329	3	9.62	5
242.445	54.3183	262.15	1452.76	19.64	7	-23.11	11.56	0.5	3	12.23	2
242.333	54.3207	160.99	0.	19.67	1	-21.6	11.17	0.469	3	0.	6
242.762	54.3556	84.43	139.6	20.13	2	-19.86	10.43	0.27	3	9.69	5
242.665	54.3781	76.33	0.	19.86	5	-20.68	10.67	0.336	3	9.71	5
243.322	54.3791	228.86	1053.28	19.47	1	-20.02	10.54	0.266	3	10.13	4
242.606	54.3897	6084.26	575.91	14.74	1	-22.42	11.5	0.065	3	9.	5
243.001	54.3922	2238.44	285.96	15.85	1	-21.31	11.05	0.063	3	8.7	5
243.332	54.4101	199.04	783.38	20.12	10	-23.21	11.61	1.532	3	11.15	4

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RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
242.169	54.4133	65.55	505.51	20.16	7	-21.5	10.91	0.263	3	11.28	1
243.343	54.4326	179.17	2328.29	20.09	8	-22.49	11.28	0.453	3	11.89	4
243.09	54.4359	78.85	425.08	20.64	7	-21.57	10.94	0.338	3	10.75	1
243.095	54.532	150.13	525.43	19.47	7	-22.53	11.33	0.274	3	11.03	2
242.425	54.5501	54.47	325.69	20.32	8	-20.74	10.58	0.212	3	10.34	1
242.717	54.5559	113.72	0.	20.92	2	-21.12	10.94	0.473	3	0.	6
242.658	54.56	488.56	140.81	17.71	1	-21.29	11.05	0.152	3	9.28	2
242.773	54.5646	105.89	722.4	20.09	8	-22.42	11.25	0.389	3	11.56	3
242.835	54.5854	898.61	594.87	17.	2	-20.11	10.53	0.127	3	9.01	5
242.74	54.5953	131.5	168.46	20.88	1	-19.94	10.51	0.508	3	9.69	4
242.513	54.6078	212.74	1311.47	18.58	8	-22.32	11.21	0.268	3	11.19	1
242.696	54.6165	27.55	0.	21.37	9	-24.65	12.11	2.7	3	13.09	5
243.134	54.7014	129.92	0.	19.34	1	-20.41	10.69	0.27	3	0.	6
242.452	54.7184	72.91	588.71	21.48	9	-23.85	11.8	1.555	3	11.95	4
242.866	54.1715	0.	0.	17.85	11	-18.39	9.76	0.092	3	0.	6
242.94	53.9788	238.35	2897.07	18.56	13	-24.98	12.5	2.5	3	12.01	4
242.694	54.0014	154.38	469.4	19.78	15	-25.19	12.59	0.752	3	12.34	4
242.237	54.0539	152.93	1444.31	19.15	15	-25.67	12.78	1.9	3	12.72	4
242.804	54.0586	148.14	1608.55	20.	15	-24.59	12.35	0.97	3	12.48	4
242.945	54.0687	174.94	1561.45	20.75	13	-24.91	12.48	0.69	3	13.09	4
242.258	54.0933	250.65	1213.66	19.38	13	-23.13	11.77	0.904	3	11.53	4
242.644	54.1318	142.28	1025.15	20.08	15	-23.66	11.98	1.235	3	11.96	4
242.816	54.1575	121.04	1824.71	20.13	13	-25.07	12.54	1.924	3	12.58	4
243.052	54.1602	645.7	3304.04	18.57	15	-25.05	12.53	1.06	3	12.48	4
242.539	54.1796	83.92	1276.45	20.66	13	-24.27	12.22	0.336	3	12.6	5
243.247	54.251	407.18	2363.31	19.07	13	-24.46	12.3	1.18	3	12.28	4
242.07	54.268	52.3	517.58	19.94	15	-25.06	12.54	1.31	3	12.22	4
242.296	54.2671	184.65	2258.24	19.45	15	-24.82	12.44	0.01	3	12.45	4
242.433	54.2823	55.9	1013.43	19.92	14	-25.35	12.65	2.847	3	12.6	4
242.945	54.2943	148.2	1152.91	19.86	14	-24.9	12.47	1.07	3	12.36	4
243.046	54.3197	111.92	1542.13	19.9	13	-24.6	12.35	1.53	3	12.37	4
242.047	54.3475	199.79	3196.56	19.41	13	-24.37	12.26	1.32	3	12.88	4
242.131	54.3524	89.32	788.82	19.78	15	-23.98	12.11	1.2	3	11.83	4
242.02	54.3565	127.46	929.87	19.32	13	-22.77	11.62	2.21	3	11.03	4
242.749	54.3648	77.67	1122.36	20.44	13	-23.95	12.09	1.1	3	13.	4
242.884	54.3867	47.07	302.63	20.58	13	-25.14	12.57	3.17	3	12.59	4
242.428	54.4153	78.47	934.21	19.59	13	-22.84	11.65	2.383	3	11.34	4
242.906	54.4291	467.48	5003.16	20.83	14	-25.29	12.63	1.392	3	13.26	4
242.892	54.4592	119.85	1105.69	18.99	13	-26.41	13.08	2.86	3	13.15	4
242.585	54.5054	103.39	903.06	20.	13	-22.49	11.51	0.81	3	11.16	4
242.591	54.5177	81.67	623.01	19.78	15	-24.89	12.47	1.01	3	12.25	4

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RA	DEC	S _{3.6}	S ₂₄	R	J1	M _B	$\log L_{OP}$	Z	Flag	$\log L_{IR}$	J2
242.871	54.5266	81.59	708.63	20.77	13	-22.42	11.48	1.217	3	11.4	4
242.498	54.5541	64.87	738.94	20.55	15	-22.94	11.69	1.571	3	11.58	4
242.688	54.6034	440.87	1495.03	18.87	15	-26.15	12.97	0.563	3	12.89	4

A P P E N D I X B

Catalogue of Properties of SWIRE Sources Observed with Chandra ACIS-I

The catalogue listing the astrometric coordinates, photometric properties, hard-band X-ray fluxes and hardness ratios.

Column 1: Right ascension of the source (J2000)

Column 2: Declination of the source (J2000)

Column 3: MIPS $24\mu\text{m}$ flux (μJy)

Column 4: R -band magnitude (Vega)

Column 5: Optical template type (1-2 elliptical galaxies, 3-11 galaxies, 13-15 QSOs)

Column 6: $\log_{10}$ of $(1+z)$ where z is the estimated photometric redshift
Column 7: M_B corrected for extinction

Column 8: $\log_{10}$ of bolometric optical luminosity, in solar units

Column 9: $\log_{10}$ of bolometric infrared luminosity, in solar units

Column 10: Infrared template type (dominated by 1=cirrus, 2= M82 starburst, 3=A220 starburst, 4=AGN sust torus, 5=single band excess, 6=no excess)

Column 11: Full band (0.5-10 keV) X-ray fluxes in $\text{ergs}/\text{cm}^2/\text{s}$

Column 12: Hardness Ratios

RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
242.264	54.9561	281.01	22.04	11	0.136	-20.22	10.49	10.07	4	5.88E-15	-1.0
242.216	54.9333	327.38	23.11	4	0.466	-24.1	12.06	12.34	5	1.5E-14	-0.19
242.268	54.9591	0.0	22.82	6	0.318	-22.11	11.2	0.0	6	9.52E-15	-1.0
242.731	54.5932	605.02	22.04	15	0.458	-23.27	11.82	12.92	4	2.74E-14	-0.33
242.694	54.4104	190.8	22.65	7	0.278	-21.37	10.86	11.18	4	1.23E-14	-1.0
242.553	54.4656	615.28	23.43	5	0.39	-23.18	11.67	12.6	2	5.63E-14	-0.64
243.095	54.532	525.43	19.47	7	0.18	-22.53	11.33	11.03	2	1.02E-13	-0.47
243.343	54.4326	2328.29	20.09	8	0.202	-22.49	11.28	11.89	4	1.74E-14	1.0
243.247	54.251	2363.31	19.07	13	0.33	-24.46	12.3	12.28	4	6.88E-14	-0.39
243.332	54.4101	783.38	20.12	10	0.248	-23.21	11.61	11.15	4	1.06E-13	-0.71
243.052	54.1602	3304.04	18.57	15	0.342	-25.05	12.53	12.48	4	1.46E-13	-0.63
242.871	54.5266	708.63	20.77	13	0.308	-22.42	11.48	11.4	4	1.22E-14	1.0
242.835	54.5854	594.87	17.	2	0.038	-20.11	10.53	9.01	5	1.46E-14	1.0
243.051	54.2598	1987.74	19.84	11	0.216	-22.9	11.57	11.87	2	1.58E-13	-0.49
242.945	54.2943	1152.91	19.86	14	0.468	-24.9	12.47	12.36	4	4.23E-14	-0.37
242.906	54.4291	5003.16	20.83	14	0.49	-25.29	12.63	13.26	4	4.86E-14	-0.28
242.902	54.2782	1153.27	20.41	9	0.118	-20.16	10.32	10.32	4	5.66E-14	-0.1
242.881	54.2259	310.72	19.67	2	0.104	-20.26	10.59	9.83	2	3.16E-14	-1.0
242.816	54.1575	1824.71	20.13	13	0.472	-25.07	12.54	12.58	4	5.22E-14	-0.77
242.949	54.1924	667.33	19.05	7	0.156	-22.36	11.26	10.82	4	2.41E-14	0.02
242.945	54.0687	1561.45	20.75	13	0.504	-24.91	12.48	13.09	4	6.17E-14	-1.0
242.94	53.9788	2897.07	18.56	13	0.282	-24.98	12.5	12.01	4	1.18E-14	0.02
242.804	54.0586	1608.55	20.	15	0.458	-24.59	12.35	12.48	4	8.36E-14	-0.61
242.452	54.7184	588.71	21.48	9	0.418	-23.85	11.8	11.95	4	1.08E-13	-0.33
242.688	54.6034	1495.03	18.87	15	0.516	-26.15	12.97	12.89	4	1.95E-13	-0.48
242.445	54.3183	1452.76	19.64	7	0.212	-23.11	11.56	12.23	2	1.91E-14	-0.45
242.433	54.2823	1013.43	19.92	14	0.542	-25.35	12.65	12.6	4	1.82E-14	-1.0
242.428	54.4153	934.21	19.59	13	0.232	-22.84	11.65	11.34	4	2.45E-14	0.14
242.749	54.3648	1122.36	20.44	13	0.418	-23.95	12.09	13.	4	7.11E-14	0.0
242.606	54.3897	575.91	14.74	1	0.038	-22.42	11.5	9.	5	1.41E-14	1.0
242.517	54.2274	1905.62	19.99	13	0.436	-24.92	12.48	13.31	4	3.85E-14	-1.0
242.669	54.1086	0.0	18.41	1	0.138	-22.52	11.54	0.0	6	9.44E-15	-1.0
242.694	54.0014	469.4	19.78	15	0.51	-25.19	12.59	12.34	4	1.96E-13	-0.27
242.53	53.9706	3586.62	18.89	15	0.468	-25.78	12.82	12.84	4	3.94E-14	-0.27
242.513	54.6078	1311.47	18.58	8	0.134	-22.32	11.21	11.19	1	1.98E-13	-0.47
242.047	54.3475	3196.56	19.41	13	0.336	-24.37	12.26	12.88	4	6.55E-14	-1.0
242.02	54.3565	929.87	19.32	13	0.204	-22.77	11.62	11.03	4	1.99E-14	-0.3
242.296	54.2671	2258.24	19.45	15	0.418	-24.82	12.44	12.45	4	4.03E-14	-0.11
242.237	54.0539	1444.31	19.15	15	0.488	-25.67	12.78	12.72	4	3.06E-14	-1.0
242.258	54.0933	1213.66	19.38	13	0.24	-23.13	11.77	11.53	4	1.46E-13	-0.76

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
242.149	54.3915	6573.06	17.87	13	0.346	-25.9	12.87	12.78	4	1.05E-13	-0.13
242.131	54.3524	788.82	19.78	15	0.358	-23.98	12.11	11.83	4	3.88E-14	-1.0
242.07	54.268	517.58	19.94	15	0.514	-25.06	12.54	12.22	4	1.21E-14	-1.0
242.421	54.6702	288.26	22.	15	0.468	-22.67	11.58	12.21	4	2.43E-14	-1.0
242.405	54.6756	280.53	22.6	11	0.322	-22.81	11.53	11.78	4	2.53E-14	0.43
242.401	54.6365	376.54	22.52	8	0.412	-23.27	11.59	12.5	2	2.24E-14	-1.0
243.275	54.5831	3256.94	16.66	5	0.052	-21.46	10.98	10.83	1	5.98E-15	-1.0
242.748	54.5589	795.22	21.5	14	0.64	-24.41	12.28	14.12	2	3.52E-14	-0.23
242.79	53.9688	3013.	14.88	2	0.044	-22.61	11.53	10.46	1	7.E-14	0.61
242.305	53.9083	5962.01	18.28	13	0.304	-24.87	12.46	12.66	4	8.37E-13	-0.41
242.015	54.8839	4637.25	14.54	3	0.02	-21.15	10.91	10.1	1	1.34E-14	-1.0
241.442	54.6527	1307.85	18.26	9	0.068	-20.88	10.61	9.94	4	1.67E-13	-0.27
241.417	54.527	5408.92	16.04	6	0.058	-22.41	11.32	10.84	1	3.6E-14	0.59
241.628	54.3354	5643.19	18.51	13	0.242	-24.03	12.12	12.12	4	1.75E-13	-0.48
241.329	54.35	280.41	18.62	8	0.162	-22.92	11.45	10.95	1	1.61E-12	-0.43
242.446	55.0926	1860.94	18.19	13	0.14	-22.89	11.67	11.16	4	5.29E-13	-0.52
243.264	54.7213	1065.	21.41	7	0.33	-23.39	11.67	12.63	2	3.21E-14	-0.59
243.254	54.7749	197.45	21.74	15	0.588	-23.62	11.96	13.58	2	1.05E-14	-1.0
243.249	54.7428	414.7	24.33	1	0.396	-23.28	11.84	12.38	2	1.22E-14	1.0
243.213	54.8037	252.75	21.41	8	0.268	-22.82	11.41	11.33	2	1.89E-14	-1.0
243.197	54.7795	287.41	22.36	9	0.22	-20.36	10.4	10.72	4	9.42E-15	-1.0
243.164	54.7575	194.18	21.22	13	0.256	-21.46	11.1	10.76	4	1.71E-14	-1.0
243.559	54.7143	0.0	19.48	6	0.164	-22.14	11.21	0.0	6	8.66E-13	-0.45
243.506	54.7623	1036.01	20.44	3	0.178	-21.61	11.09	11.1	4	1.26E-14	-1.0
243.504	54.7926	2399.54	19.65	13	0.366	-24.17	12.18	12.29	4	3.78E-14	-1.0
243.415	54.7604	0.0	22.87	9	0.3	-21.1	10.69	0.0	6	1.06E-14	-1.0
243.111	54.7256	417.47	21.6	15	0.468	-23.07	11.74	12.84	4	1.96E-14	-1.0
243.362	54.8814	0.0	99.	11	0.66	-24.07	12.04	13.46	5	1.28E-14	-1.0
243.364	54.9039	481.11	24.33	1	0.398	-23.31	11.86	12.2	1	1.77E-14	-1.0
243.352	54.721	0.0	23.14	10	0.632	-23.77	11.84	0.0	6	1.5E-14	-1.0
243.34	54.7027	402.38	21.07	13	0.086	-18.71	10.	9.73	4	1.67E-14	-1.0
243.307	54.7315	0.0	23.24	2	0.264	-21.17	10.96	0.0	6	1.51E-14	0.22
243.276	54.8156	820.09	19.88	13	0.382	-24.13	12.16	11.8	4	3.1E-14	0.42
243.266	54.4754	0.0	99.	2	0.32	-21.8	11.21	11.99	5	1.6E-14	1.0
243.238	54.5329	155.18	23.34	10	0.57	-23.04	11.55	12.45	5	9.22E-15	1.0
243.232	54.6396	208.92	24.25	4	0.168	-17.5	9.42	10.09	4	1.47E-14	1.0
243.202	54.5013	196.48	23.61	5	0.496	-24.12	12.05	12.19	5	1.07E-14	-1.0
243.128	54.5807	1043.26	22.87	6	0.33	-22.26	11.26	12.43	4	2.45E-14	-1.0
243.481	54.4571	1380.31	18.83	5	0.136	-22.07	11.23	11.	2	1.14E-13	-0.24
243.467	54.5997	307.1	20.74	13	0.314	-22.51	11.52	11.24	4	2.11E-14	-1.0
243.447	54.4752	1064.27	20.09	13	0.46	-24.66	12.38	13.18	4	2.67E-14	-0.29

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
243.417	54.6413	1274.04	18.68	8	0.166	-22.95	11.47	11.45	1	1.14E-13	-0.4
243.382	54.5162	0.0	19.63	2	0.098	-20.11	10.53	0.0	6	9.75E-15	-1.0
243.272	54.463	1409.29	21.43	6	0.284	-22.92	11.52	12.11	2	1.33E-13	-0.41
243.217	54.4672	243.33	20.16	3	0.18	-21.94	11.22	10.63	4	2.46E-14	-0.16
243.164	54.2717	345.98	21.8	13	0.33	-21.79	11.23	11.82	4	3.95E-14	-0.17
243.444	54.3625	1118.62	20.74	10	0.042	-17.23	9.22	9.12	4	7.55E-14	-0.36
243.377	54.3192	343.45	21.21	8	0.068	-17.94	9.46	8.67	4	1.59E-14	-1.0
243.372	54.4346	1353.74	19.48	13	0.346	-24.11	12.16	12.	4	4.14E-14	-1.0
243.342	54.4208	266.64	99.	2	0.364	-22.34	11.43	12.	2	9.91E-15	1.0
243.119	54.3278	531.59	21.48	13	0.302	-21.65	11.17	11.8	4	1.94E-14	-1.0
243.338	54.4402	4109.52	19.92	13	0.448	-24.73	12.41	12.79	4	1.31E-13	-0.35
243.315	54.2399	0.0	23.47	8	0.622	-23.55	11.71	0.0	6	2.18E-14	-1.0
243.302	54.3013	0.0	99.	5	0.328	-22.05	11.22	0.0	6	9.13E-15	-1.0
243.3	54.3203	246.84	21.26	15	0.478	-23.48	11.91	11.91	4	1.51E-14	-1.0
243.272	54.3732	368.44	20.67	13	0.086	-19.11	10.16	9.54	4	3.E-14	-0.25
243.272	54.4636	0.0	21.02	6	0.188	-21.22	10.85	10.78	4	7.49E-14	-1.0
243.267	54.4603	158.2	22.45	11	0.198	-20.15	10.47	10.6	5	3.05E-14	1.0
243.258	54.3163	171.	99.	3	0.624	-24.56	12.27	12.8	5	3.07E-14	-1.0
243.073	54.3382	798.48	22.61	9	0.36	-22.08	11.08	13.38	3	2.1E-14	1.0
243.208	54.0871	185.25	23.62	8	0.436	-22.36	11.23	12.11	5	3.54E-14	-0.34
243.177	54.1261	826.61	20.8	13	0.48	-24.33	12.25	12.19	4	2.15E-14	-1.0
243.164	54.1475	573.74	21.18	13	0.386	-23.23	11.81	11.73	4	1.95E-14	-1.0
243.129	54.131	176.31	22.95	6	0.352	-22.54	11.37	11.71	5	1.62E-14	-0.21
243.541	54.077	345.86	21.19	9	0.382	-23.75	11.75	11.71	4	4.26E-14	-0.53
243.466	54.0775	1461.22	18.95	8	0.134	-22.73	11.38	11.7	3	1.84E-14	-0.06
243.452	54.0949	652.84	21.48	8	0.376	-23.68	11.75	12.39	2	1.65E-14	-1.0
243.432	54.2056	2343.98	19.2	13	0.392	-24.92	12.48	12.39	4	1.06E-13	-0.36
243.387	54.2235	118.26	21.8	13	0.366	-22.02	11.32	11.25	4	3.54E-14	-1.0
243.364	54.2157	676.51	20.94	13	0.082	-18.72	10.	10.01	4	1.02E-14	-1.0
243.35	54.1474	224.13	99.	14	0.846	-26.5	13.11	14.23	5	9.02E-15	-1.0
243.325	54.1299	371.34	22.15	5	0.306	-22.84	11.53	11.83	2	1.36E-14	1.0
243.307	54.0857	224.62	99.	4	0.37	-23.19	11.7	12.09	2	1.86E-14	0.33
243.218	54.0669	318.81	20.12	15	0.388	-23.9	12.07	11.52	4	1.5E-13	-0.2
243.211	54.2069	632.07	23.25	1	0.33	-22.83	11.66	12.24	4	2.32E-14	-0.42
242.964	54.932	550.43	22.4	11	0.188	-19.71	10.29	11.	4	9.03E-15	-1.0
242.954	54.8925	0.0	99.	11	0.344	-21.1	10.85	0.0	6	9.25E-15	-1.0
242.887	54.9247	184.77	22.44	9	0.446	-23.14	11.51	11.41	4	1.25E-14	-1.0
242.871	54.9087	0.0	99.	7	0.542	-22.6	11.35	0.0	6	1.09E-14	-1.0
242.871	54.8488	1064.51	20.28	13	0.156	-21.09	10.95	11.01	2	2.92E-14	0.06
243.143	55.0698	965.13	21.47	3	0.264	-22.66	11.51	11.5	4	1.34E-13	-0.61
243.112	55.0064	882.65	22.08	14	0.502	-24.	12.11	12.37	4	1.89E-14	-1.0

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
243.093	54.8728	2450.26	18.04	13	0.024	-19.41	10.28	9.13	4	2.27E-14	-1.0
243.032	55.0485	846.3	20.37	15	0.51	-24.6	12.35	12.97	4	1.61E-14	-0.21
243.01	54.9605	935.18	22.5	5	0.372	-23.78	11.91	12.72	2	3.E-14	-0.59
242.919	54.6807	266.16	21.92	5	0.264	-22.25	11.3	11.41	2	3.96E-14	0.23
242.914	54.6942	270.87	21.26	2	0.17	-20.6	10.73	10.61	4	3.32E-14	0.64
242.909	54.8825	0.0	21.31	6	0.142	-19.75	10.26	0.0	6	1.21E-14	1.0
242.851	54.7627	0.0	22.33	9	0.332	-23.21	11.54	0.0	6	1.82E-14	-0.32
243.216	54.6962	0.0	22.71	11	0.516	-23.46	11.79	0.0	6	3.11E-14	-0.08
243.1	54.839	1123.81	19.44	11	0.098	-21.9	11.17	10.62	1	1.18E-14	1.0
242.984	54.8205	351.78	21.88	9	0.248	-21.35	10.79	10.73	4	3.3E-14	-1.0
242.97	54.6951	656.1	20.91	7	0.2	-21.57	10.94	11.23	4	1.18E-14	1.0
242.932	54.6698	0.0	22.3	5	0.228	-21.04	10.81	10.13	4	1.61E-14	-0.22
242.748	54.7193	242.73	21.09	9	0.392	-23.96	11.84	11.35	4	3.54E-14	-1.0
242.881	54.6181	201.31	21.83	11	0.126	-19.16	10.07	9.81	4	1.65E-14	-1.0
242.87	54.5529	0.0	22.56	8	0.59	-24.14	11.94	0.0	6	1.38E-14	1.0
243.137	54.5995	0.0	23.98	3	0.158	-17.51	9.45	9.73	4	1.64E-14	0.17
243.058	54.6372	541.74	21.14	13	0.51	-23.95	12.09	12.84	4	1.3E-13	-0.41
243.043	54.5655	291.4	21.01	3	0.194	-21.48	11.04	10.92	2	6.37E-15	-1.0
243.019	54.6323	727.71	20.8	15	0.348	-22.87	11.66	12.2	4	1.23E-14	-1.0
242.853	54.2298	481.72	20.72	13	0.182	-21.07	10.94	10.59	4	2.64E-14	0.05
242.851	54.3296	0.0	99.	4	0.418	-23.26	11.73	12.56	5	1.42E-14	-1.0
242.849	54.4427	255.53	99.	7	0.334	-21.45	10.9	11.79	4	2.05E-14	0.14
243.077	54.4483	584.12	21.49	15	0.508	-23.95	12.09	12.95	4	2.32E-14	-1.0
243.075	54.3841	199.74	22.04	9	0.36	-22.65	11.31	11.36	4	1.24E-14	-1.0
242.766	54.4379	211.21	22.81	4	0.33	-22.58	11.45	11.57	1	2.96E-14	-1.0
243.045	54.438	1782.44	20.28	13	0.286	-23.3	11.83	11.7	4	2.47E-14	-0.12
243.042	54.2697	177.16	22.84	7	0.606	-24.39	12.07	12.73	5	2.42E-14	-0.02
243.012	54.4192	1431.03	19.75	5	0.158	-21.73	11.09	11.12	2	8.4E-15	1.0
242.973	54.4095	0.0	23.27	10	0.412	-22.11	11.17	0.0	6	8.86E-15	1.0
242.97	54.4468	0.0	23.53	4	0.306	-21.42	10.99	10.85	4	3.21E-14	-0.34
242.917	54.3116	517.1	20.9	4	0.236	-22.65	11.48	11.39	2	8.3E-15	-1.0
242.896	54.4659	0.0	22.2	13	0.262	-20.54	10.73	0.0	6	2.21E-14	0.34
242.892	54.4052	1129.61	22.34	15	0.438	-22.93	11.68	13.29	2	1.03E-14	1.0
242.891	54.4586	0.0	20.02	1	0.078	-19.05	10.15	0.0	6	1.47E-14	-1.0
242.886	54.2874	238.14	99.	9	0.34	-21.44	10.83	11.09	4	1.29E-14	-1.0
242.857	54.4553	208.8	22.93	13	0.318	-20.36	10.66	10.9	4	5.39E-14	-0.12
242.868	54.0909	733.63	21.15	13	0.49	-23.81	12.04	12.31	4	2.32E-14	0.43
242.824	54.1168	271.96	21.93	9	0.386	-23.06	11.48	11.39	4	1.29E-14	1.0
242.809	54.2038	0.0	22.02	7	0.182	-21.33	10.85	0.0	6	1.04E-14	-1.0
243.012	54.1786	660.57	19.66	8	0.2	-22.74	11.38	11.24	4	2.4E-14	-1.0
242.975	54.2474	282.22	21.56	9	0.288	-23.3	11.57	11.61	2	1.68E-14	-0.01

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
242.949	54.2612	290.31	20.75	13	0.296	-22.32	11.44	10.94	4	2.37E-14	-1.0
242.905	54.1762	257.83	21.68	13	0.49	-23.46	11.9	11.85	4	1.65E-14	-1.0
242.773	54.0362	159.41	99.	3	0.36	-22.6	11.48	11.72	5	2.8E-14	0.08
242.77	53.9967	300.58	99.	6	0.458	-23.45	11.74	12.3	5	1.26E-14	-1.0
243.134	53.9021	210.97	21.94	8	0.55	-24.5	12.09	12.41	5	1.23E-14	-1.0
243.132	53.8893	208.19	23.26	5	0.124	-17.33	9.33	9.53	4	1.88E-14	-1.0
243.124	53.935	851.73	20.21	13	0.286	-22.77	11.62	11.42	4	4.18E-14	-0.36
242.706	54.0051	503.46	20.63	9	0.234	-22.55	11.27	10.86	4	1.99E-14	-1.0
243.047	53.8508	0.0	99.	9	0.63	-23.39	11.61	0.0	6	1.5E-14	-1.0
243.024	53.9478	152.28	17.32	1	0.064	-21.2	11.01	9.13	5	1.12E-14	-1.0
243.007	53.9085	1136.85	23.21	11	0.344	-21.56	11.03	12.57	2	8.39E-15	0.34
242.96	54.0853	0.0	23.24	7	0.384	-22.33	11.25	0.0	6	1.56E-14	1.0
242.909	53.9917	0.0	22.72	7	0.296	-22.75	11.41	0.0	6	2.53E-14	-0.1
242.87	53.8624	0.0	21.5	13	0.47	-23.32	11.84	13.25	2	3.16E-14	-0.42
242.808	54.0298	1325.96	20.62	15	0.518	-25.01	12.52	12.61	4	1.42E-14	1.0
242.794	54.033	0.0	22.53	11	0.128	-18.25	9.71	9.71	4	2.96E-14	-1.0
242.547	55.2195	0.0	22.69	9	0.14	-18.36	9.6	9.85	4	3.56E-14	-1.0
242.542	55.2837	1041.21	22.34	6	0.368	-23.4	11.72	12.68	1	4.93E-14	0.23
242.501	55.1601	265.92	21.35	9	0.116	-19.17	9.92	9.68	4	1.16E-14	-1.0
242.884	55.2029	2308.96	18.28	11	0.146	-22.9	11.57	11.04	4	3.55E-13	-0.66
242.87	55.2115	971.17	22.02	3	0.2	-20.63	10.7	11.57	2	3.74E-14	1.0
242.803	55.1398	3027.5	22.4	5	0.358	-23.61	11.84	13.04	4	6.9E-14	0.83
242.721	55.0945	1174.65	20.19	13	0.49	-24.77	12.42	12.71	4	1.19E-14	1.0
242.646	55.1175	1127.79	19.49	10	0.15	-21.78	11.04	10.64	4	5.15E-14	-0.27
242.404	55.0451	917.67	19.08	7	0.17	-22.68	11.39	11.43	1	2.96E-14	-1.0
242.601	55.0671	246.23	21.75	9	0.278	-23.24	11.55	11.46	2	1.61E-14	0.2
242.591	55.0613	179.09	20.52	7	0.12	-20.79	10.63	10.1	2	1.2E-14	-0.01
242.587	55.2403	291.28	21.51	11	0.136	-19.84	10.34	9.87	4	2.14E-14	-1.0
242.56	55.1403	864.41	22.57	7	0.344	-22.43	11.29	12.48	2	9.07E-15	1.0
242.556	55.1139	2523.92	20.14	6	0.188	-22.1	11.2	12.	2	9.03E-15	1.0
242.403	55.1119	884.34	20.23	13	0.508	-24.85	12.45	12.34	4	1.9E-14	-1.0
242.56	54.9836	532.68	21.19	15	0.478	-23.55	11.93	12.84	4	4.54E-14	-0.18
242.526	54.9148	0.0	23.63	11	0.292	-20.48	10.6	0.0	6	6.04E-15	-1.0
242.513	54.8943	1000.87	19.86	7	0.144	-22.56	11.34	10.86	2	5.01E-14	-0.34
242.659	54.8643	1325.96	21.59	14	0.632	-24.27	12.22	14.28	2	1.98E-14	-0.02
242.639	54.8503	187.3	20.91	13	0.55	-24.43	12.29	12.07	4	3.53E-14	-0.48
242.62	54.9185	0.0	99.	11	0.692	-24.2	12.09	0.0	6	1.06E-14	-1.0
242.603	54.9528	384.51	20.57	13	0.526	-24.63	12.36	12.88	2	1.48E-14	-1.0
242.478	54.9673	147.21	23.64	11	0.284	-20.69	10.68	11.14	5	9.3E-15	-1.0
242.531	54.8979	922.86	20.84	15	0.252	-21.88	11.27	11.28	4	3.24E-14	-1.0
242.525	54.8473	261.81	21.81	8	0.29	-23.	11.48	11.56	2	1.27E-14	1.0

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
242.798	54.84	574.95	21.36	13	0.478	-23.52	11.92	13.01	2	1.96E-14	-1.0
242.751	54.7014	305.77	21.08	7	0.304	-23.34	11.65	11.2	4	1.62E-13	-0.19
242.743	54.6475	252.75	23.49	2	0.176	-18.55	9.91	10.64	5	2.E-14	-1.0
242.741	54.6853	1818.67	22.78	5	0.356	-23.19	11.67	12.87	2	2.96E-14	-0.42
242.732	54.65	430.27	22.17	4	0.298	-22.63	11.47	11.11	4	2.23E-14	0.11
242.711	54.6657	295.87	22.12	9	0.394	-22.96	11.44	12.12	4	9.29E-15	-1.0
242.685	54.6967	952.57	23.61	6	0.302	-21.04	10.77	11.56	4	1.73E-14	1.0
242.613	54.8357	0.0	23.54	15	0.548	-21.69	11.19	0.0	6	1.94E-14	0.01
242.61	54.7314	276.06	21.76	10	0.114	-18.7	9.81	9.7	4	1.43E-14	-1.0
242.573	54.8733	486.31	99.	9	0.3	-20.85	10.6	11.25	4	3.57E-14	-1.0
242.502	54.3745	175.23	21.98	13	0.22	-20.31	10.64	10.55	4	6.54E-15	-1.0
242.463	54.4672	126.68	22.86	15	0.536	-22.29	11.43	11.62	4	1.34E-14	-1.0
242.461	54.2993	0.0	22.09	7	0.174	-21.07	10.74	0.0	6	1.25E-14	-1.0
242.789	54.3436	402.5	21.56	9	0.29	-23.32	11.58	11.72	2	3.96E-14	-0.29
242.72	54.3732	0.0	23.75	5	0.348	-22.07	11.23	0.0	6	1.24E-14	-1.0
242.712	54.3249	286.69	99.	8	0.106	-18.8	9.8	9.65	4	2.6E-14	-0.4
242.701	54.31	814.05	22.39	14	0.636	-24.57	12.34	13.51	2	1.33E-14	1.0
242.692	54.3913	236.33	23.46	5	0.368	-22.74	11.5	11.23	4	1.53E-14	-1.0
242.398	54.2658	549.59	22.09	5	0.268	-22.16	11.26	11.32	4	7.65E-14	0.44
242.625	54.4006	252.15	99.	9	0.01	-17.39	9.21	7.57	5	2.1E-14	0.17
242.557	54.2676	501.89	21.67	14	0.552	-23.67	11.98	12.46	4	2.02E-14	-1.0
242.545	54.2824	229.69	23.15	8	0.484	-23.	11.48	12.42	4	9.07E-15	-1.0
242.519	54.2386	304.68	20.51	13	0.234	-21.94	11.29	10.84	4	1.61E-14	-1.0
242.509	54.1555	259.76	21.86	8	0.44	-24.02	11.89	12.29	2	1.39E-14	0.01
242.461	54.2213	370.38	21.96	9	0.116	-18.56	9.68	9.7	4	3.4E-14	-0.42
242.867	54.1906	224.5	22.56	7	0.326	-22.44	11.29	11.73	2	2.48E-14	-1.0
242.793	54.2419	0.0	22.42	9	0.274	-21.22	10.74	0.0	6	1.87E-14	-1.0
242.788	54.2045	601.03	22.2	7	0.278	-21.82	11.04	11.5	4	3.17E-14	-1.0
242.772	54.2175	0.0	99.	8	0.592	-23.72	11.77	0.0	6	9.99E-15	-1.0
242.729	54.1668	0.0	99.	5	0.486	-24.05	12.02	12.74	5	1.82E-14	1.0
242.715	54.127	365.3	22.89	8	0.304	-21.33	10.82	11.13	4	1.5E-14	-1.0
242.392	54.2034	0.0	22.23	9	0.386	-22.76	11.36	0.0	6	2.62E-14	-0.04
242.648	54.1945	200.22	22.41	7	0.498	-24.18	11.99	11.63	4	9.06E-15	1.0
242.635	54.2772	309.63	22.7	9	0.3	-21.92	11.02	11.09	4	1.45E-14	-1.0
242.6	54.1015	405.88	21.39	15	0.298	-21.81	11.24	11.09	4	3.69E-14	-0.19
242.576	54.2437	762.61	21.15	7	0.204	-21.42	10.88	11.3	4	2.53E-14	1.0
242.563	54.0966	924.43	21.15	13	0.47	-23.91	12.08	12.35	4	1.51E-14	0.21
242.562	54.0601	308.3	22.59	8	0.212	-20.07	10.31	10.84	4	9.94E-15	-1.0
242.321	54.0795	212.06	22.62	9	0.34	-21.84	10.99	11.04	4	4.3E-14	-0.19
242.472	53.9441	0.0	22.65	8	0.3	-21.52	10.89	0.0	6	1.04E-14	1.0
242.447	53.9795	255.17	22.26	11	0.39	-23.01	11.61	12.21	2	1.57E-14	-1.0

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
242.778	53.9643	480.99	21.52	8	0.38	-23.69	11.76	12.35	4	2.79E-14	-1.0
242.77	53.8323	1749.84	20.08	10	0.248	-23.25	11.63	12.04	4	4.E-13	-0.39
242.431	53.9612	0.0	21.9	13	0.43	-22.6	11.55	12.97	2	2.57E-14	-1.0
242.747	54.0186	0.0	22.18	14	0.59	-23.41	11.88	0.0	6	1.41E-14	-1.0
242.712	53.9448	829.15	21.08	14	0.502	-24.4	12.27	12.32	4	3.29E-14	-0.4
242.669	53.799	549.47	22.1	13	0.414	-22.73	11.61	12.4	4	4.58E-14	-1.0
242.632	53.9343	446.58	99.	9	0.3	-21.24	10.75	11.37	4	1.47E-14	-1.0
242.605	53.9372	156.51	99.	8	0.388	-22.14	11.14	11.93	5	1.49E-14	-0.32
242.423	53.8745	391.75	21.29	13	0.492	-24.05	12.13	12.05	4	1.43E-14	-1.0
242.602	53.8978	0.0	20.42	8	0.148	-21.	10.68	0.0	6	5.93E-15	-1.0
242.527	53.953	518.43	22.21	6	0.316	-22.68	11.43	11.86	1	9.01E-15	-1.0
242.506	54.0167	174.74	21.95	15	0.428	-22.4	11.47	11.39	4	2.42E-14	-0.19
242.497	54.0773	1900.79	21.89	15	0.65	-24.73	12.4	13.7	4	2.97E-14	1.0
242.235	54.9873	290.07	22.17	11	0.328	-23.18	11.68	11.69	2	9.37E-15	-1.0
242.162	55.0549	0.0	21.61	7	0.14	-19.41	10.08	0.0	6	3.14E-14	0.1
242.158	55.0461	152.4	22.55	11	0.348	-22.26	11.31	11.6	5	1.37E-14	-1.0
242.152	54.8561	252.88	19.26	11	0.09	-21.47	10.99	9.8	2	3.69E-14	0.05
242.137	54.9732	776.01	21.08	11	0.3	-23.14	11.66	11.58	4	6.02E-14	0.05
242.392	55.0042	205.9	19.79	14	0.62	-25.99	12.91	12.99	2	2.49E-14	-0.34
242.385	54.7958	859.22	99.	1	0.3	-21.71	11.21	11.77	4	4.19E-14	-1.0
242.329	54.9485	258.07	21.24	2	0.18	-20.93	10.86	10.67	2	7.22E-14	-1.0
242.325	54.9402	0.0	23.72	7	0.328	-21.05	10.74	0.0	6	9.38E-15	1.0
242.311	54.9009	178.12	22.26	8	0.306	-21.99	11.08	11.24	2	9.48E-15	1.0
242.303	54.8907	434.14	21.49	11	0.15	-19.78	10.32	10.12	4	2.43E-14	1.0
242.285	55.0188	149.74	22.71	7	0.348	-22.35	11.25	10.9	4	1.57E-14	-1.0
242.226	54.785	203.12	23.44	7	0.452	-22.95	11.49	11.48	4	1.87E-14	-1.0
242.152	54.7834	621.92	20.93	6	0.07	-18.01	9.56	9.52	4	1.23E-14	-1.0
242.129	54.7608	507.44	21.49	13	0.51	-23.6	11.95	12.56	4	2.2E-14	-0.15
242.104	54.6544	264.47	21.92	11	0.192	-20.28	10.52	10.64	4	3.2E-14	-0.47
242.359	54.8345	0.0	22.25	9	0.448	-23.34	11.59	11.35	4	1.9E-14	-1.0
242.272	54.7739	341.88	21.21	13	0.302	-22.16	11.38	11.12	4	1.47E-14	-1.0
242.257	54.866	152.4	22.65	9	0.346	-21.88	11.01	10.9	4	1.92E-14	-1.0
242.183	54.5218	0.0	99.	7	0.39	-22.19	11.19	0.0	6	9.35E-15	-1.0
242.141	54.5814	306.98	22.52	13	0.42	-22.97	11.7	12.53	2	1.19E-14	-1.0
242.1	54.5372	0.0	23.23	11	0.316	-21.19	10.88	10.95	4	4.58E-14	-0.4
242.093	54.601	683.87	99.	5	0.406	0.0	2.4	12.72	2	3.14E-14	-0.36
242.084	54.4929	1626.66	20.89	13	0.316	-23.22	11.8	11.92	4	1.49E-14	-1.0
242.311	54.4188	206.26	22.93	11	0.338	-22.28	11.32	11.18	4	2.03E-14	-1.0
242.266	54.6438	332.46	20.92	13	0.294	-22.13	11.37	11.	4	6.E-14	-0.26
242.214	54.5673	158.2	22.78	6	0.276	-21.43	10.93	11.11	5	5.94E-15	-1.0
242.12	54.3229	323.76	21.01	13	0.278	-21.89	11.27	11.55	4	1.06E-14	-1.0

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
242.103	54.3419	1411.7	20.29	13	0.446	-24.83	12.44	12.28	4	9.34E-15	-1.0
242.089	54.4385	0.0	23.48	3	0.322	-21.7	11.12	12.04	5	2.59E-14	-0.17
242.509	54.424	335.72	21.52	8	0.396	-23.88	11.84	12.41	2	4.31E-14	-1.0
242.487	54.3873	473.63	21.11	7	0.086	-18.44	9.69	9.64	4	2.34E-14	-0.2
242.389	54.2952	860.06	21.25	9	0.3	-22.72	11.34	12.07	4	1.86E-14	-0.36
242.069	54.3051	0.0	22.13	7	0.302	-22.26	11.22	12.11	2	3.61E-14	-0.38
242.36	54.3476	198.65	99.	1	0.33	-21.95	11.31	11.36	4	9.23E-15	1.0
242.24	54.3561	341.15	21.18	9	0.51	-24.71	12.14	11.98	4	2.11E-14	-0.12
242.21	54.3318	174.74	22.83	6	0.59	-24.89	12.31	12.64	5	9.08E-15	-1.0
242.19	54.3736	194.43	20.39	3	0.164	-21.27	10.95	10.6	1	5.41E-14	-0.37
242.184	54.4544	0.0	23.49	15	0.756	-24.03	12.12	0.0	6	1.27E-14	-0.02
242.196	54.0722	526.76	21.35	9	0.32	-22.87	11.4	12.12	4	2.14E-14	-1.0
242.071	54.203	299.73	22.46	11	0.242	-20.84	10.74	10.72	4	3.71E-14	-1.0
242.368	54.2639	191.17	22.76	10	0.356	-22.02	11.14	11.76	5	2.68E-14	-0.18
242.29	54.0068	582.31	21.81	13	0.394	-23.29	11.83	11.79	4	1.59E-14	-1.0
242.261	54.0308	2741.29	20.04	15	0.504	-24.89	12.47	13.77	4	2.14E-13	-0.51
242.232	54.2376	678.32	21.81	8	0.382	-23.55	11.71	12.56	2	9.32E-15	-1.0
242.226	54.2113	472.54	21.23	13	0.364	-22.75	11.61	12.38	2	1.22E-14	0.01
242.205	54.1831	161.58	23.67	3	0.286	-20.87	10.79	10.64	4	2.72E-14	1.0
242.197	54.0984	0.0	22.6	10	0.344	-22.04	11.15	0.0	6	1.52E-14	1.0
242.211	53.992	424.48	20.45	11	0.182	-22.56	11.43	11.53	3	5.77E-15	-1.0
242.135	53.9107	452.98	99.	6	0.378	-23.46	11.74	12.35	2	1.04E-14	1.0
242.129	53.9255	1860.94	19.78	8	0.2	-22.95	11.46	11.6	4	3.E-14	-1.0
242.104	53.9566	0.0	22.5	9	0.376	-22.57	11.28	0.0	6	1.51E-14	-1.0
242.462	53.9768	1699.12	99.	1	0.33	-22.2	11.41	12.14	4	4.12E-14	-0.04
242.438	54.0552	512.75	21.02	15	0.458	-23.57	11.94	12.94	4	2.68E-14	-0.31
242.094	54.0804	146.36	23.17	7	0.384	-22.66	11.38	11.88	5	1.88E-14	-1.0
242.405	54.0223	570.12	20.32	13	0.18	-21.44	11.09	10.7	4	3.68E-14	-0.29
242.319	53.9203	213.14	22.62	7	0.26	-21.1	10.76	10.67	4	1.82E-14	-1.0
242.31	53.824	213.27	22.68	8	0.42	-23.01	11.49	13.15	3	4.6E-14	-0.47
242.287	54.0786	620.35	23.09	1	0.266	-21.43	11.1	11.42	4	1.98E-14	0.3
242.059	53.9673	146.85	19.67	5	0.13	-21.08	10.83	9.94	2	4.44E-14	-0.42
241.914	54.889	474.84	23.17	4	0.322	-22.07	11.25	12.07	2	6.85E-15	-1.0
241.914	54.8915	520.	22.43	8	0.318	-22.64	11.34	11.85	2	7.58E-15	-1.0
242.125	54.992	146.48	99.	7	0.306	-21.28	10.83	10.91	4	2.37E-14	1.0
241.747	54.9727	214.59	19.52	5	0.12	-20.97	10.78	9.81	2	1.05E-14	-1.0
242.068	55.0597	507.8	19.72	13	0.308	-23.47	11.9	11.77	4	5.69E-14	-0.45
242.037	54.9437	2424.9	21.75	5	0.27	-22.54	11.42	12.61	2	1.39E-14	1.0
241.993	54.8872	188.39	21.28	9	0.138	-19.73	10.14	9.75	4	4.46E-14	-0.2
241.992	54.8462	1994.98	18.95	15	0.428	-25.4	12.67	12.39	4	4.22E-14	-0.36
241.969	54.8603	165.08	22.04	9	0.324	-22.88	11.41	11.48	5	1.54E-14	-0.02

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
241.939	54.9146	229.21	23.7	4	0.41	-22.97	11.61	12.24	5	3.19E-14	-0.59
241.935	54.8562	556.47	99.	7	0.414	-24.09	11.95	12.74	2	2.04E-14	-0.02
241.932	55.0812	423.51	21.75	9	0.372	-23.08	11.48	11.57	4	1.7E-14	-1.0
241.919	54.9821	504.78	22.52	15	0.64	-23.78	12.03	13.86	2	7.22E-14	0.18
241.729	54.8786	135.25	23.19	7	0.594	-24.07	11.94	12.95	3	2.22E-14	1.0
241.799	54.708	332.34	22.15	9	0.37	-22.65	11.32	11.36	4	1.99E-14	-1.0
241.792	54.7658	204.45	99.	9	0.682	-24.22	11.94	13.36	5	1.84E-14	-1.0
241.769	54.8806	995.32	19.65	13	0.242	-22.89	11.67	11.38	4	3.44E-14	1.0
241.72	54.7625	0.0	19.54	1	0.104	-20.4	10.69	0.0	6	1.5E-14	1.0
242.194	54.7779	444.28	21.07	9	0.378	-23.83	11.78	12.11	4	3.28E-14	-1.0
241.715	54.6734	0.0	24.05	8	0.438	-22.01	11.09	0.0	6	1.72E-14	-1.0
242.031	54.685	367.84	21.29	15	0.416	-22.96	11.7	12.18	4	1.1E-14	-1.0
242.029	54.7285	816.47	19.49	13	0.14	-21.59	11.15	10.57	4	4.65E-14	-0.49
242.013	54.8225	0.0	23.88	11	0.334	-20.77	10.71	0.0	6	2.02E-14	-1.0
241.957	54.6823	717.81	18.51	8	0.15	-22.76	11.39	11.13	1	2.77E-14	-1.0
241.929	54.7258	334.75	22.96	9	0.336	-21.45	10.83	11.51	4	7.89E-15	-1.0
241.929	54.659	0.0	23.03	7	0.32	-21.63	10.97	11.17	4	4.14E-14	-0.35
241.898	54.6707	639.43	22.37	13	0.628	-24.5	12.31	13.4	5	1.75E-14	-1.0
241.871	54.7469	0.0	23.43	8	0.372	-21.87	11.03	0.0	6	1.59E-14	-0.19
241.852	54.6759	1068.38	19.41	9	0.022	-17.07	9.08	8.54	4	5.E-14	-0.61
241.662	54.7016	340.19	22.18	9	0.432	-24.07	11.88	13.16	3	2.03E-14	-1.0
241.833	54.5093	184.64	22.84	8	0.578	-23.78	11.8	12.58	5	9.67E-15	1.0
241.81	54.5859	401.41	21.42	13	0.48	-23.47	11.9	11.94	4	2.71E-14	-1.0
241.78	54.5893	437.28	21.56	7	0.268	-22.5	11.31	11.49	2	2.98E-14	1.0
241.766	54.5132	0.0	21.67	7	0.234	-21.56	10.94	11.06	1	9.94E-14	-0.32
242.04	54.5701	439.21	22.15	9	0.214	-20.45	10.43	10.94	4	2.4E-14	0.44
241.999	54.5519	0.0	22.78	6	0.308	-21.98	11.15	0.0	6	1.31E-14	1.0
241.741	54.5179	797.99	99.	7	0.314	-21.44	10.89	11.75	4	1.64E-14	-0.24
241.991	54.5642	262.29	21.61	8	0.374	-23.52	11.69	11.81	2	1.56E-14	-1.0
241.979	54.6304	666.73	20.72	7	0.156	-22.	11.11	10.87	2	1.36E-14	1.0
241.97	54.4889	0.0	99.	11	0.34	-21.55	11.03	11.3	4	1.7E-14	-1.0
241.909	54.6247	221.24	20.78	13	0.488	-24.29	12.23	12.51	2	1.32E-14	0.01
241.902	54.6205	538.48	20.04	13	0.274	-22.82	11.64	11.47	4	2.9E-14	-0.1
241.853	54.475	196.96	99.	2	0.438	-24.17	12.16	12.12	5	1.59E-14	0.2
241.817	54.3493	528.33	22.35	13	0.418	-22.04	11.33	13.64	3	6.02E-15	-1.0
241.817	54.2406	231.74	21.39	13	0.342	-22.16	11.38	11.5	4	5.44E-14	-0.5
241.797	54.3223	0.0	99.	11	0.594	-22.83	11.54	0.0	6	1.22E-14	-1.0
241.788	54.4421	0.0	99.	11	0.674	-24.15	12.07	0.0	6	2.27E-14	-0.18
241.783	54.2762	204.69	22.63	7	0.106	-17.52	9.32	9.23	4	2.51E-14	-0.28
241.758	54.2838	0.0	22.93	11	0.368	-22.43	11.38	12.51	5	8.42E-14	-0.41
242.076	54.3031	0.0	99.	10	0.558	-24.22	12.02	0.0	6	1.39E-14	-1.0

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
242.04	54.4234	421.34	21.04	15	0.412	-23.18	11.78	11.79	4	1.25E-14	-0.02
242.004	54.3329	143.71	21.03	2	0.168	-20.77	10.8	10.26	2	1.49E-14	1.0
241.723	54.2794	604.77	20.7	15	0.106	-19.63	10.36	10.16	4	3.67E-14	-1.0
241.968	54.233	197.57	19.97	5	0.148	-21.24	10.9	10.46	1	1.32E-14	1.0
241.956	54.2174	523.86	21.93	11	0.12	-19.84	10.34	9.98	4	6.09E-14	-0.4
241.876	54.4067	509.37	20.11	13	0.23	-22.29	11.43	11.38	4	2.44E-14	-0.23
241.873	54.3191	0.0	22.42	10	0.406	-22.9	11.49	0.0	6	5.92E-15	-1.0
241.846	54.2518	766.72	99.	1	0.3	-20.91	10.89	11.54	4	1.56E-14	-1.0
241.719	54.4105	796.54	20.1	2	0.138	-20.82	10.82	10.62	2	2.36E-14	-1.0
241.788	54.1385	400.57	21.44	8	0.188	-22.	11.08	10.94	2	6.93E-15	-1.0
241.782	54.1213	0.0	99.	14	0.75	-25.96	12.9	0.0	6	1.95E-14	-1.0
242.145	54.2379	157.47	21.79	9	0.114	-18.68	9.73	9.46	4	3.08E-14	-0.18
241.773	54.1153	149.14	21.55	13	0.428	-22.93	11.69	12.04	5	3.54E-14	-0.21
242.036	54.1596	217.73	22.02	11	0.276	-21.87	11.16	11.05	4	1.43E-14	1.0
242.006	54.1575	151.8	22.84	7	0.48	-23.83	11.85	12.05	5	9.35E-15	-1.0
241.988	54.1343	345.38	21.94	11	0.478	-24.01	12.01	12.42	4	2.38E-14	0.16
241.971	54.1504	0.0	22.17	6	0.2	-20.38	10.51	0.0	6	1.83E-14	0.51
241.96	54.17	754.76	20.8	15	0.41	-23.4	11.87	12.93	2	6.E-14	0.31
241.731	54.2146	717.08	20.05	7	0.234	-23.18	11.59	11.62	2	2.32E-14	-0.05
241.947	54.1363	0.0	99.	6	0.338	-21.78	11.07	0.0	6	6.07E-15	-1.0
241.916	54.1783	1460.01	20.5	6	0.252	-23.26	11.66	12.07	2	3.08E-14	0.42
241.908	54.2245	673.49	22.11	6	0.354	-23.41	11.72	12.24	2	2.67E-14	0.01
241.902	54.1877	141.77	23.18	11	0.33	-21.42	10.97	10.81	4	2.38E-14	-0.12
241.88	54.0656	500.07	21.32	8	0.068	-18.61	9.73	9.01	4	2.01E-14	-1.0
241.869	54.1314	0.0	22.06	7	0.28	-22.32	11.24	0.0	6	1.86E-14	-0.32
241.854	54.2102	575.55	20.13	13	0.306	-23.04	11.73	12.03	4	1.36E-14	-1.0
241.84	54.1095	267.61	21.39	3	0.158	-20.1	10.48	10.3	4	2.86E-14	-0.11
241.839	54.1874	628.69	21.61	13	0.392	-22.81	11.64	11.85	4	1.7E-14	0.22
241.691	54.0739	798.36	21.53	13	0.396	-23.47	11.9	11.98	4	2.62E-14	-0.34
241.476	54.6433	727.35	18.82	2	0.108	-21.23	10.98	10.45	2	2.79E-14	-1.0
241.461	54.6854	162.3	19.24	2	0.108	-20.81	10.81	9.77	2	1.64E-14	1.0
241.444	54.778	751.86	21.47	2	0.122	-19.01	10.09	10.58	2	1.97E-14	1.0
241.409	54.8561	2677.29	17.97	6	0.132	-22.84	11.49	11.18	2	3.08E-14	-1.0
241.743	54.85	3432.05	19.92	14	0.482	-25.12	12.56	13.39	4	3.74E-14	-0.44
241.709	54.8235	0.0	17.48	13	0.292	-25.55	12.73	12.88	1	2.49E-14	-1.0
241.705	54.8072	258.91	20.19	2	0.128	-20.46	10.67	10.39	1	4.36E-14	-0.46
241.656	54.763	423.75	22.59	4	0.23	-20.81	10.74	11.35	2	1.5E-14	-1.0
241.64	54.8701	2407.99	22.75	5	0.396	-23.96	11.98	13.22	4	1.94E-14	-0.02
241.639	54.7235	0.0	22.17	7	0.356	-23.	11.51	12.33	5	4.31E-14	0.47
241.61	54.8046	0.0	22.11	13	0.428	-22.37	11.46	0.0	6	2.28E-14	-1.0
241.6	54.8035	229.21	99.	3	0.398	0.0	2.44	12.19	1	1.13E-14	1.0

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RA	DEC	S ₂₄	R	J1	Z	M _B	log L _{OP}	log L _{IR}	J2	S _{0.5–10}	HR
241.596	54.6568	340.67	20.79	9	0.172	-20.94	10.63	10.31	4	4.08E-14	-0.58
241.408	54.7691	0.0	22.51	10	0.426	-22.99	11.53	0.0	6	1.58E-14	-0.01
241.592	54.7837	0.0	21.34	14	0.634	-25.25	12.61	0.0	6	2.23E-14	-0.31
241.556	54.693	358.9	21.95	6	0.29	-22.5	11.36	11.59	2	1.64E-14	-1.0
241.55	54.7161	570.12	23.19	5	0.372	-23.09	11.64	12.41	4	1.23E-14	1.0
241.541	54.7465	0.0	21.33	2	0.2	-21.43	11.06	0.0	6	1.49E-14	0.02
241.538	54.6751	170.03	18.74	1	0.112	-21.44	11.11	9.89	5	1.28E-14	1.0
241.519	54.8237	600.67	19.74	15	0.51	-25.23	12.61	12.3	4	1.33E-14	1.0
241.478	54.8165	457.2	21.31	15	0.458	-23.28	11.82	12.21	4	3.02E-14	-0.43
241.484	54.623	445.73	22.13	7	0.432	-24.07	11.94	12.4	1	3.99E-14	-1.0
241.47	54.5036	525.43	20.9	8	0.17	-20.82	10.61	10.78	4	2.9E-14	-1.0
241.455	54.6587	387.89	18.36	7	0.138	-22.81	11.44	10.41	2	1.05E-13	-0.26
241.746	54.6243	198.77	22.86	8	0.29	-21.17	10.75	12.	3	1.81E-14	1.0
241.741	54.4844	294.9	22.69	11	0.114	-17.76	9.51	9.94	4	5.28E-14	-0.55
241.707	54.5695	3305.25	20.52	1	0.142	-20.52	10.74	11.32	2	2.72E-14	1.0
241.41	54.6564	2478.03	21.05	13	0.498	-24.57	12.34	13.58	4	2.27E-13	-0.35
241.688	54.4197	438.49	20.52	7	0.07	-18.48	9.71	9.47	4	1.61E-14	-1.0
241.683	54.5213	1545.75	20.38	14	0.126	-20.41	10.68	10.74	4	1.57E-14	-0.2
241.557	54.6444	308.91	21.54	9	0.136	-19.42	10.02	9.92	4	2.29E-14	-1.0
241.544	54.6075	391.63	99.	1	0.36	-22.78	11.64	12.98	3	3.18E-14	1.0
241.511	54.4853	494.04	21.34	9	0.292	-23.44	11.63	11.88	2	1.59E-14	1.0
241.503	54.3726	201.91	23.27	8	0.322	-21.2	10.76	10.91	4	9.74E-15	-1.0
241.487	54.3957	0.0	21.41	9	0.562	-24.77	12.16	0.0	6	1.1E-14	-1.0
241.452	54.4941	0.0	99.	7	0.35	-22.68	11.39	0.0	6	1.69E-14	0.12
241.444	54.3418	264.35	20.83	3	0.184	-21.39	11.	10.55	2	7.15E-15	-1.0
241.618	54.261	0.0	23.14	13	0.334	-20.32	10.64	0.0	6	1.05E-14	-1.0
241.593	54.3705	1188.05	19.37	2	0.072	-19.45	10.27	9.89	4	6.14E-14	-0.58
241.581	54.2862	543.79	21.26	15	0.5	-23.88	12.07	12.18	4	1.36E-14	-1.0
241.552	54.3173	877.33	20.68	13	0.45	-23.99	12.11	13.07	4	2.01E-14	-1.0
241.548	54.4132	364.82	20.54	15	0.216	-21.75	11.21	10.83	4	9.17E-15	-1.0

A P P E N D I X C

Catalogue of Properties of SWIRE Sources Observed with Chandra ACIS-I without Optical Associations

The catalogue listing the astrometric coordinates, photometric properties, hard-band X-ray fluxes and hardness ratios.

Column 1: Right ascension of the source (J2000)

Column 2: Declination of the source (J2000)

Column 3: IRAC $3.6\mu\text{m}$ flux (μJy)

Column 4: IRAC $4.5\mu\text{m}$ flux (μJy)

Column 5: IRAC $5.8\mu\text{m}$ flux (μJy)

Column 6: IRAC $8\mu\text{m}$ flux (μJy)

Column 7: MIPS $24\mu\text{m}$ flux (μJy)

Column 8: Error in MIPS $24\mu\text{m}$ flux (μJy)

Column 9: Full band (0.5-10 keV) X-ray fluxes in $\text{ergs}/\text{cm}^2/\text{s}$

Column10: Hardness Ratios

RA	DEC	$S_{3.6}$	$S_{4.5}$	$S_{5.8}$	S_8	S_{24}	ES_{24}	$S_{0.5-10}$	HR
242.19	54.3109	12.33	13.92	0.0	0.0	0.0	0.0	9.88E-15	-1.0
242.193	54.3107	30.45	34.18	0.0	0.0	0.0	0.0	9.87E-15	-1.0
241.825	54.751	15.95	21.55	0.0	0.0	0.0	0.0	2.16E-14	-0.1
242.082	54.1358	29.72	30.94	0.0	0.0	0.0	0.0	1.56E-14	-1.0
242.08	54.136	30.58	45.12	62.21	78.48	258.53	10.98	1.56E-14	-1.0
242.099	54.1057	65.69	86.1	153.23	241.5	658.23	13.28	2.04E-14	1.0
242.033	54.4237	4.63	6.44	0.0	0.0	139.68	10.44	1.39E-14	-0.57
242.05	54.5166	82.05	96.45	151.37	183.69	565.69	12.24	1.24E-14	-1.0
242.381	53.9964	13.55	23.48	49.09	54.23	207.14	11.43	1.49E-14	0.2
242.351	54.2183	49.32	81.34	106.06	197.93	518.43	12.93	1.4E-14	1.0
242.407	54.1697	6.31	10.45	0.0	0.0	206.94	12.12	1.76E-14	-1.0
242.487	54.2136	10.18	16.74	0.0	0.0	0.0	0.0	1.71E-14	0.0
242.231	54.4278	49.85	52.95	66.07	86.39	223.87	12.12	1.85E-14	-0.16
242.377	54.6978	47.58	59.25	61.26	0.0	197.1	10.16	1.55E-14	-0.44
242.755	53.9139	13.26	12.55	0.0	0.0	0.0	0.0	1.82E-14	-1.0
242.842	54.3703	22.05	34.61	42.91	67.51	336.7	12.24	1.78E-14	-0.32
242.85	54.8082	16.47	21.58	36.35	46.57	0.0	0.0	2.12E-14	1.0
242.586	55.0885	85.03	113.	107.36	175.35	552.89	12.59	1.51E-14	-0.66
242.986	54.8469	9.39	11.83	0.0	0.0	0.0	0.0	1.51E-14	-0.01
242.985	54.8478	41.18	45.97	43.56	40.05	0.0	0.0	1.51E-14	-0.01
241.513	54.42	19.56	21.52	0.0	0.0	0.0	0.0	1.58E-14	0.22
241.594	54.3939	35.42	39.53	0.0	43.79	0.0	0.0	1.36E-14	0.02
241.714	54.3704	23.11	28.04	0.0	0.0	0.0	0.0	1.58E-14	-1.0
241.508	54.5782	27.13	38.87	67.24	96.47	271.52	11.05	2.72E-14	-1.0
241.602	54.5606	17.87	29.47	49.07	79.12	326.85	12.24	1.44E-14	0.02
241.611	54.4852	17.16	23.88	0.0	37.47	268.96	11.25	1.71E-14	1.0
241.587	54.8319	6.2	5.65	0.0	0.0	0.0	0.0	1.48E-14	-1.0
241.64	54.7236	62.02	58.52	82.8	66.63	614.72	13.16	2.67E-14	0.47
241.822	54.2233	41.93	60.18	75.68	112.54	236.08	12.82	1.6E-14	-1.0
242.006	54.1452	11.69	13.63	0.0	0.0	0.0	0.0	1.01E-14	-1.0
241.776	54.3555	31.4	37.05	43.24	45.18	311.49	12.7	1.01E-14	-1.0
241.84	54.3389	9.36	14.24	0.0	36.47	0.0	0.0	9.75E-15	-1.0
241.866	54.245	39.66	38.62	35.87	0.0	0.0	0.0	1.85E-14	-0.04
241.923	54.35	49.71	46.94	62.98	61.1	0.0	0.0	3.21E-14	0.02
241.991	54.3679	15.64	21.43	0.0	54.2	207.73	12.12	1.5E-14	0.22
242.091	54.354	31.23	41.71	50.25	120.69	366.62	12.24	1.49E-14	-1.0
241.848	54.5526	0.0	11.93	0.0	0.0	0.0	0.0	1.01E-14	-1.0
241.956	54.6342	32.21	50.38	76.62	133.46	358.95	11.05	1.3E-14	-1.0
241.992	54.7148	30.72	41.59	66.89	96.06	251.44	10.51	1.8E-14	1.0
241.804	54.9781	11.88	17.57	0.0	0.0	0.0	0.0	1.85E-14	1.0

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RA	DEC	$S_{3.6}$	$S_{4.5}$	$S_{5.8}$	S_8	S_{24}	ES_{24}	$S_{0.5-10}$	HR
241.881	55.0488	0.0	28.84	0.0	0.0	0.0	0.0	1.65E-14	-1.0
242.215	53.953	27.42	21.39	0.0	0.0	0.0	0.0	9.25E-15	-1.0
242.311	53.8243	3.83	0.0	0.0	0.0	0.0	0.0	1.91E-14	-0.47
242.26	54.0484	22.78	22.99	0.0	31.13	0.0	0.0	1.51E-14	-1.0
242.1	54.3675	13.6	14.23	0.0	0.0	0.0	0.0	1.62E-14	1.0
242.193	54.4705	31.82	54.88	102.67	193.86	571.6	12.24	1.66E-14	-1.0
242.302	54.4653	9.	12.04	0.0	36.08	0.0	0.0	1.67E-14	-1.0
242.305	54.3895	252.06	476.5	987.6	1932.85	4888.99	16.05	1.86E-14	1.0
242.36	54.3467	0.0	0.0	0.0	0.0	241.79	10.8	1.4E-14	1.0
242.081	54.624	17.74	19.06	0.0	0.0	0.0	0.0	1.67E-14	0.17
242.222	54.5508	41.51	44.51	67.8	65.82	477.87	12.7	9.19E-15	-1.0
242.324	54.591	15.74	21.15	34.32	64.92	344.18	12.01	1.06E-14	-1.0
242.106	54.844	6.16	0.0	0.0	0.0	0.0	0.0	1.91E-14	-0.03
242.37	54.8091	12.24	20.82	46.67	66.56	399.31	12.82	1.38E-14	-0.01
242.449	54.7674	6.58	7.86	0.0	0.0	0.0	0.0	1.55E-14	1.0
242.061	54.8794	39.	39.07	43.73	78.45	398.33	12.47	1.66E-14	-0.2
242.311	54.9105	13.76	11.31	0.0	0.0	0.0	0.0	9.55E-15	-1.0
242.45	53.8984	35.47	36.88	0.0	47.35	0.0	0.0	1.63E-14	1.0
242.466	53.93	10.03	11.5	0.0	0.0	0.0	0.0	1.07E-14	-1.0
242.492	53.9195	8.2	7.67	0.0	0.0	0.0	0.0	1.37E-14	1.0
242.521	53.9065	25.6	32.53	54.51	0.0	0.0	0.0	1.37E-14	-0.43
242.601	53.991	24.05	38.08	53.22	70.38	357.17	13.05	9.66E-15	-1.0
242.601	53.8984	23.27	34.84	51.93	79.16	484.57	12.93	9.65E-15	-1.0
242.603	53.9665	30.62	44.47	56.75	156.78	749.59	13.51	1.02E-14	-1.0
242.623	53.8648	0.0	23.	0.0	0.0	0.0	0.0	1.66E-14	1.0
242.626	53.9869	21.94	18.97	0.0	0.0	0.0	0.0	3.74E-14	0.35
242.626	53.9877	16.17	18.72	0.0	0.0	0.0	0.0	3.74E-14	0.35
242.638	53.9083	31.24	32.35	0.0	50.32	0.0	0.0	1.89E-14	0.67
242.746	54.0177	11.27	11.73	0.0	0.0	0.0	0.0	1.71E-14	-1.0
242.541	54.1368	11.42	8.79	0.0	0.0	0.0	0.0	1.5E-14	1.0
242.561	54.06	0.0	0.0	30.28	0.0	0.0	0.0	1.62E-14	-1.0
242.616	54.1096	20.94	28.05	0.0	0.0	0.0	0.0	9.54E-15	-1.0
242.624	54.0851	112.64	100.	71.96	172.63	409.15	13.05	1.45E-14	-1.0
242.517	54.2559	39.26	46.65	0.0	55.38	0.0	0.0	1.55E-14	1.0
242.518	54.2562	0.0	36.24	52.99	0.0	902.58	13.05	1.55E-14	1.0
242.546	54.2828	11.06	13.41	0.0	0.0	0.0	0.0	1.48E-14	-1.0
242.567	54.3475	8.31	10.39	0.0	0.0	0.0	0.0	9.6E-15	-1.0
242.687	54.3187	22.47	22.16	0.0	47.26	0.0	0.0	1.63E-14	1.0
242.694	54.4099	0.0	15.67	0.0	0.0	0.0	0.0	9.88E-15	-1.0
242.423	54.7972	10.76	0.0	0.0	0.0	0.0	0.0	1.65E-14	-1.0
242.663	54.7219	16.44	19.61	0.0	0.0	176.2	13.05	1.28E-14	1.0

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RA	DEC	$S_{3.6}$	$S_{4.5}$	$S_{5.8}$	S_8	S_{24}	ES_{24}	$S_{0.5-10}$	HR
242.733	54.7007	8.91	9.67	0.0	0.0	0.0	0.0	1.6E-14	0.2
242.572	54.9171	30.19	34.08	49.52	65.58	0.0	0.0	1.75E-14	1.0
242.767	54.898	31.11	36.59	40.12	0.0	0.0	0.0	1.58E-14	-1.0
242.472	55.2037	23.88	35.68	64.17	88.6	280.78	12.35	1.55E-14	-1.0
242.56	55.1248	39.87	49.94	57.56	71.8	275.07	12.35	9.75E-15	-1.0
242.61	55.0971	13.76	16.07	0.0	0.0	0.0	0.0	1.35E-14	0.01
242.662	55.1376	27.55	35.52	30.37	58.35	200.44	12.24	1.96E-14	0.35
242.745	55.2024	26.67	38.85	65.59	79.24	339.26	13.28	1.58E-14	0.2
242.758	53.9683	25.21	29.89	0.0	0.0	268.77	12.24	1.36E-14	-1.0
242.829	53.857	26.77	31.17	0.0	0.0	0.0	0.0	1.52E-14	-1.0
242.985	53.9201	26.09	32.86	65.28	91.34	374.3	10.78	1.25E-14	-0.55
243.017	53.9137	13.93	19.9	0.0	0.0	0.0	0.0	1.53E-14	-0.1
242.992	54.1247	30.69	32.73	0.0	117.95	451.29	11.66	1.62E-14	1.0
243.022	54.1067	18.87	19.18	0.0	0.0	0.0	0.0	9.85E-15	-1.0
242.931	54.2543	28.86	24.75	0.0	0.0	0.0	0.0	1.55E-14	1.0
242.974	54.4095	0.0	9.59	0.0	0.0	0.0	0.0	1.33E-14	1.0
242.976	54.343	24.37	31.35	0.0	52.97	176.5	11.49	9.56E-15	-1.0
243.044	54.3726	8.34	11.51	0.0	0.0	0.0	0.0	1.92E-14	-1.0
242.841	54.5676	6.83	14.21	0.0	0.0	0.0	0.0	1.2E-14	-1.0
242.863	54.472	11.73	17.73	0.0	0.0	378.24	12.47	1.61E-14	-0.03
242.912	54.6623	19.82	23.54	0.0	0.0	0.0	0.0	1.52E-14	-1.0
242.85	54.7581	9.31	13.34	0.0	58.29	425.89	10.69	1.83E-14	-0.23
242.931	54.6696	0.0	14.62	0.0	0.0	0.0	0.0	1.44E-14	-0.22
242.939	54.9169	26.46	36.3	38.18	78.35	380.41	11.37	9.84E-15	-1.0
243.008	54.9143	19.91	20.19	0.0	0.0	0.0	0.0	1.06E-14	-1.0
243.084	54.9865	37.39	42.78	28.98	0.0	0.0	0.0	2.05E-14	-0.14
243.122	54.0955	7.67	0.0	0.0	0.0	0.0	0.0	1.47E-14	-0.03
243.24	54.1754	68.66	89.89	124.71	165.25	309.33	11.78	1.66E-14	0.22
243.331	54.2986	14.19	16.15	0.0	0.0	0.0	0.0	1.63E-14	-0.3
243.452	54.0944	0.0	56.21	0.0	0.0	0.0	0.0	1.6E-14	-1.0
243.38	54.4549	36.47	43.23	0.0	0.0	0.0	0.0	1.75E-14	0.19
243.407	54.3957	0.0	20.49	51.05	0.0	0.0	0.0	1.07E-14	-1.0
243.508	54.3454	57.22	63.41	59.45	35.39	0.0	0.0	1.51E-14	-0.67
243.204	54.4949	13.57	15.12	0.0	0.0	0.0	0.0	1.62E-14	0.32
243.337	54.5204	4.97	0.0	0.0	0.0	368.2	10.78	1.53E-14	1.0
243.37	54.5279	8.71	12.69	0.0	0.0	0.0	0.0	1.09E-14	-1.0
243.382	54.5168	0.0	0.0	45.32	53.73	308.54	12.93	1.05E-14	-1.0
243.46	54.606	27.42	31.69	0.0	0.0	0.0	0.0	1.57E-14	1.0
243.46	54.5613	54.32	57.91	53.6	0.0	0.0	0.0	1.41E-14	-0.21
243.48	54.5745	10.53	13.67	0.0	0.0	0.0	0.0	1.68E-14	-1.0
243.343	54.8455	35.71	44.13	28.9	0.0	169.23	10.43	1.53E-14	-1.0

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RA	DEC	$S_{3.6}$	$S_{4.5}$	$S_{5.8}$	S_8	S_{24}	ES_{24}	$S_{0.5-10}$	HR
243.344	54.7002	12.17	11.47	0.0	0.0	240.41	12.59	1.11E-14	-1.0
243.36	54.7361	12.66	16.8	0.0	0.0	0.0	0.0	9.69E-15	-1.0
243.416	54.7597	0.0	0.0	43.39	0.0	224.46	12.24	1.15E-14	-1.0

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