

INFRARED STUDIES OF GALAXY FORMATION AND THE HUBBLE FLOW

by

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ABSTRACT

This thesis tackles two longstanding problems in cosmology, that of galaxy formation and the extent to which the Universe is isotropic and homogeneous.

The theoretical speculation on the epoch of galaxy formation ranges from redshifts $z \sim 2 - 100$. Most models of the early phase of galaxy collapse predict high star formation rates, and hence luminosities such that they are rendered detectable with modern astronomical instrumentation. The high formation redshifts imply that these objects may be faint infrared sources with blue JHK colours. Part of this thesis is taken up with an attempt to discover such bona-fide primeval galaxies. Photometric J and K observations made at UKIRT of a blank area of sky are presented. Over several subsequent observing runs one candidate was repeatedly detected. Further interpretation on the nature of this object will depend on the outcome of planned optical and radio observations. In the context of other search attempts this is the most sensitive to date and constrains the luminosity of galaxies forming at high redshift by about an order of magnitude below the limits achieved by optical searches.

The degree of isotropy in the Hubble expansion has been the subject of conflicting experimental results in recent years. In particular, a study made in 1976, using optical magnitudes and redshifts, for an all sky sample of spiral galaxies indicates a motion of the Local Group almost orthogonal to that implied by the Cosmic Background Radiation. This thesis investigates this outstanding discrepancy using both JHK photometry and the IRAS data base. The confirmed result provides strong evidence that there may be velocity streaming ~ 1000 km/sec on scales ~ 50 Mpc. Such large streaming motions demand a high density Universe and are incompatible with a Universe dominated by "cold" dark matter.

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To My Parents

'If you postulate a Universe of objects, truth disappears'

Jean Paul Satre 1951.

CONTENTS

	Page
ABSTRACT	2
ACKNOWLEDGEMENTS	3
LIST OF TABLES	12
LIST OF FIGURES	14
CHAPTER 1 A SELECTIVE REVIEW OF COSMOLOGY	
1.1 Introduction	17
1.2 The Standard Model	19
1.2.1 Isotropy and Homogeneity	19
1.2.2 Derivation of the Friedmann Cosmologies	20
1.2.3 Nucleosynthesis	24
1.3 Formation of Galaxies and the Large-Scale Structure	25
1.3.1 Fluctuations in the Early Universe	25
1.3.2 The growth of Fluctuations prior to Decoupling	29
1.3.3 Post-Decoupling Evolution	34
1.4 Observational Probes of Primeval Inhomogeneities: Forward Into the Past	40
1.4.1 Anisotropy of the Cosmic Background Radiation	40

1.4.2 Galaxy Clustering	43
1.5 Summary	45
CHAPTER 2 AN INFRARED SEARCH FOR PRIMEVAL GALAXIES	
2.1 Introduction	47
2.2 Primordial Star Formation	47
2.3 Observational Parameters	50
2.3.1 Luminosity	50
2.3.2 Angular Diameter	52
2.3.3 Areal Density	53
2.4 Review of Previous Searches	55
2.4.1 Introduction	55
2.4.2 Searches for Single Primeval Galaxies	55
2.4.3 Background Light Measurements	56
2.5 Near-Infrared Search Programme	56
2.5.1 Introduction	56
2.5.2 Method of Detection	57
2.5.3 Method of Recognition	58
2.6 Results	60

2.7 Discussion	75
2.7.1 Upper Limits	75
2.7.2 Candidate 23b	82
2.8 Further Work	82
CHAPTER 3 BACKGROUND TO THE HUBBLE FLOW PROJECT	
3.1 Review of Anisotropic Hubble Flow Studies	84
3.1.1 Introduction	84
3.1.2 Very Distant Scales	85
3.1.3 Nearby Distance Scales	86
3.1.4 Intermediate Distance Scales	89
3.2 A Detailed Discussion of the Rubin et al. Anisotropy Study	93
3.2.1 Introduction	93
3.2.2 The Data and Corrections	94
3.2.3 Analysis and Conclusions	99
3.3 A Critique of the Rubin et al. Study	103
3.3.1 Remaining Problems and Uncertainties	103
3.3.2 Advantages of an Infrared Study	108
CHAPTER 4 NEAR INFRARED OBSERVATIONS AND DATA REDUCTION OF THE RUBIN ET AL. GALAXIES	
4.1 Introduction	110
4.2 The Observations	110

4.2.1 Telescope Parameters	110
4.2.2 Observational Parameters	111
4.2.3 Observing Procedure and Weather	112
4.3 Data Reduction	114
4.3.1 Primary Calibration	114
4.3.2 Errors and Consistency	121
4.3.3 Infrared Colours	123
CHAPTER 5 INFRARED DATA ANALYSIS	
5.1 A Preliminary Study	125
5.1.1 Sky and Redshift Distributions	125
5.1.2 Anisotropy of the Near-Infrared Data	128
5.2 Two-Variable Solutions	132
5.2.1 Introduction	132
5.2.2 Optical Two Variable Solutions	134
5.2.3 Near-Infrared Two Variable Solutions	136
5.2.4 Diameter Corrected Solutions and Absolute Magnitude Dispersion	138
5.3 Three-Variable Solutions	144
5.3.1 Background to the Tully-Fisher and Colour-Magnitude Relations	144
5.3.2 Corrections to the Infrared Tully-Fisher Relation	148

5.3.3 The Tully-Fisher slope and Associated Anisotropy Solution	151
5.3.4 The Colour-Magnitude Slope and Associated Anisotropy Solution	155
5.4 Far-Infrared Approach to Velocity Anisotropies	159
5.4.1 The IRAS Data	159
5.4.2 Anisotropy Solutions for 100 μ m Fluxes	161
5.5 Discussion of Data Analysis	166
5.6 Summary and Conclusions	168
CHAPTER 6 DISCUSSION OF ANISOTROPY SOLUTIONS	
6.1 Introduction	171
6.2 A Large-Scale Streaming Motion	171
6.2.1 Relation With the CBR Dipole Anisotropy	171
6.2.2 Distribution of the Galaxies	172
6.3 Material Content of the Universe	177
6.3.1 Introduction	177
6.3.2 Constraining the Density Parameter	177
6.3.3 Constraining Dark Matter Candidates	178

6.4 Conclusions and Further Work	185
6.4.1 Immediate Objectives	185
6.4.2 Luminosity Indicators and Other Observing Strategies	187
REFERENCES	190
APPENDIX PUBLICATIONS	201

LIST OF TABLES

Table No	Title	Page
2.1	Summary of Blank Field Observations.	67
2.2	Observations of Candidate Pixel 23b.	73
3.1	Estimates of the Local Group Motion.	91
3.2	Sources of Uncertainty in the Rubin et al. Study.	108
4.1	Comparison of JHK Extinction Estimates.	114
4.2	Near-Infrared Data of the Rubin et al. Sample of Galaxies.	115
4.3	Comparison of Repeated Observations with Calculated Uncertainties.	122
5.1	Optical Dipole Anisotropy Solutions.	135
5.2	Anisotropy Solutions Using Uncorrected IR Data.	136
5.3	Anisotropy Solutions Using IR Data with Hybrid Correction.	137
5.4	Colour Gradients for Spirals.	139
5.5	Anisotropy Solutions Using IR Data with Aperture Correction.	141

5.6	Anisotropy Solutions Using IR Data with Separate Aperture and Malmquist Corrections.	141
5.7	Point Source Catalogue 100 μ m Detections of the Rubin et al. Minimum Bias Sample.	159
5.8	Anisotropy Solutions Using Far-IR Data.	164
5.9	Summary of Solutions for the Motion of the Local Group.	168

LIST OF FIGURES

Figure No	Title	Page
1.1	Evolution of characteristic mass scales prior to decoupling.	30
1.2	Spatial density fluctuations in a Universe dominated by cold dark matter, neutrinos and baryons.	35
2.1	Putative spectrum for a primeval galaxy.	51
2.2	Angular diameter v's redshift for a 20kpc object in 4 world models.	54
2.3	JHK colour-colour diagram for a dust free primeval galaxy.	59
2.4	Search pattern for two blank fields.	61
2.5a	Signals and standard errors on each pixel at J for June 1984 observing run.	62
2.5b	Signals and standard errors on each pixel at K for June 1984 obseving run.	63
2.6a,b	Distribution of signal to noise for all pixels after June 1984 and July 1985 at J.	65
2.7a,b	Distribution of signal to noise for all pixels after June 1984 and July 1985 at k.	66

2.8	The excluded luminosities as a function of redshift.	77
2.9a,b	The excluded temperatures and luminosities for a primeval galaxy at redshifts $z = 5$ and $z = 9$.	78
2.10	Values of bright phase (Δt) implied from flux sensitivity and finite search area.	80
3.1a,b	Variation of Hubble modulus from the apex to antapex defined by Rubin et al. LGM and the CBR dipole anisotropy.	101
4.1	JHK colour-colour diagram for 40 minimum bias sample galaxies.	124
5.1	Sky coverage of galaxies with IR data.	126
5.2a,b	Redshift distributions for minimum bias sample and IR sub-samples.	127
5.3	Variation of near-IR Hubble modulus from the apex to antapex defined by the Rubin et al. LGM.	129
5.4	Variation of near-IR Hubble modulus with observed redshift.	131
5.5a,b	Variation of corrected near-IR Hubble modulus from the apex to antapex defined by the Rubin et al. LGM and the CBR dipole anisotropy.	133

5.6	Distribution of aperture corrected near-IR absolute magnitudes.	143
5.7	Near-IR Tully-Fisher relation for 40 galaxies.	152
5.8	Optical-IR colour magnitude relation for 45 galaxies.	156
5.9	Variation of optical-IR colour across the sky.	157
5.10	Correlation between 100 μ m and near-IR absolute magnitudes.	162
5.11	Distribution of 100 μ m absolute magnitudes.	163
5.12	Far-IR Hubble modulus v's observed redshift.	165
6.1	Sky distribution of all superclusters within 7000 km/sec.	174
6.2	Excluded values for the epoch of non-linear collapse for values of h in an $\Omega = 1$, neutrino dominated Universe.	180
6.3	The predicted streaming velocities as a function of scale in an $\Omega = 1$ cold dark matter dominated Universe.	182

CHAPTER 1

A SELECTIVE REVIEW OF COSMOLOGY

1.1 Introduction

The scope of this thesis is the presentation of two observational programmes which probe the Universe at high redshift and constrain the material content of the Universe. The first is a direct attempt to observe galaxies in the process of forming at high redshift. By observing in the near-infrared significant advantages are gained, compared to previous optical searches, for the formation redshifts of most interest. The second programme is the search for deviations from the Hubble flow using an all sky sample of spiral galaxies. Using linear perturbation theory, constraints on the value of Ω and the type of particle species can be made. This section gives a rapid review of recent experimental results and theoretical speculation. The rest of this chapter details the background to our present understanding of the Universe in the context of the standard model. The relationship between the galaxy formation and Hubble flow projects is emphasised by a discussion of the growth of density fluctuations in the early Universe and how they give rise to the present structure we observe today.

As yet there is no reliable theory for the formation of galaxies and the large-scale structure. Our best guess as to the relevant physics is that if gravitation has always been the dominant force on cosmic scales then it seems reasonable to construct a model based on gravitational instability. As a consequence of the possible ways matter and radiation can interact, one is confronted with two scenarios which predict a different chronology for the formation of galaxies, clusters of galaxies, and superclusters. Either one, or possibly both, of these very different possibilities may be required to account for the Universe and neither can be ruled out at present. The recent discovery of large-scale structure in the form of superclusters of galaxies, connecting filaments of galaxies between

superclusters and vast areas with apparently nothing in them at all (Gort 1983 & references therein), are all difficult to reconcile with a theory in which this structure forms from the clustering of primordial sub-galactic size units. However, theories in which this structure is formed first have difficulty in making galaxies by the time quasars are seen. There is in fact no satisfactory model of galaxy formation which can account for all these established observations. The problem is not just one for the theorists either, since most theoretical predictions require a normalisation factor. This generally involves the expansion rate or Hubble's constant H_0 and the mean mass energy density compared to that required to just close the Universe, Ω . The combined observational uncertainty in the product of these quantities amounts to a factor ~ 20 . Independent estimates of these quantities are necessary in order to allow the amount and type of matter in the Universe to be further constrained.

There is a current consensus among theorists that $\Omega = 1$, with the dominant mass being in the form of exotic particle species rather than baryons, for which the most reliable estimates give $\Omega_b < 0.19$. There is certainly strong evidence for dark material from the flat rotation curves of spiral galaxies (Rubin et al. 1985) and from the fact that the mass to light ratio increases with scale, at least to cluster sizes (Blumenthal et al. 1984 & references therein). If this hidden mass does indeed exist, then there may be a whole new outlook to cosmology, for it is possible that this mass is distributed differently from baryons and so the well-studied luminous galaxies may be irrelevant as indicators of the underlying mass distribution, making determinations of Ω from galaxy distributions misleading. Since the only direct observational evidence for this comes from the apparent enhanced clustering of rich Abell type clusters, (Bachall & Soneira 1983) the extent to which galaxies trace the mass is at the present time unclear. It may be that astronomers have not been completely misguided in thinking that by studying bright galaxies they can learn something about mass in the Universe. There is, after all, evidence of remarkable uniformity in the mass to light ratio for galaxies as indicated by mass luminosity relationships such as the Tully-Fisher relation

(Aaronson et al. 1983).

Detection of a dark matter species, either directly, or by inference from further observations, would be a landmark in physics. Indeed, until such a time it is unlikely that any theory of galaxy formation will be anything other than mere conjecture.

1.2 The Standard Model

1.2.1 Isotropy and Homogeneity

The cosmological principle is one of the cornerstones of our modern understanding of the Universe on the largest scales. The principle can be stated as; "the Universe is isotropic and homogeneous at all points in space". While the cosmic background radiation (CBR) is evidence that the Universe was hot, its isotropy also provides strong confirmation of the cosmological principle in the following way. If the dipole anisotropy in the CBR is interpreted as a locally-induced effect then there are, as yet, no residual components to the anisotropy on any scale. This is direct evidence that the Universe is isotropic about us. Unless we occupy a unique position in the Universe, we must assume that it is also exactly isotropic at every point in the Universe. It has been shown that the Universe can only be isotropic about every point if it is also spatially homogeneous (Ehlers et al. 1968), thereby vindicating the cosmological principle framework.

In order to build up a description of the Universe, the cosmological principle has to be supplemented with a description of gravitation, the most complete theory of which is supplied by the Einstein field equations. The following section outlines the derivation of the dynamical equations of the Universe on the basis of the cosmological principle.

1.2.2 Derivation Of The Friedmann Cosmologies

The general description for an isotropic and homogeneous Universe is supplied by the Robertson and Walker metric

$$d\tau^2 = dt^2 - R^2(t) [(dr^2/(1-kr^2)) + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2] \quad 1.1$$

where τ is an invariant line element, r, θ, ϕ, t are coordinates, $R(t)$ is an unknown function of time and k is a constant.

The gravitational field equations are given by

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G T_{\mu\nu} \quad 1.2$$

where $R_{\mu\nu}$ is the contracted curvature tensor formed from the metric tensor $g_{\mu\nu}$ and its first and second derivatives. R is the curvature scalar and is formed by contracting $R_{\mu\nu}$. G is Newton's gravitational constant and $T_{\mu\nu}$ is a symmetric tensor which unites the density and current of energy and momentum. The dynamical equations of the Universe are obtained by constraining the field equations with the cosmological principle, mathematically expressed as the Robertson-Walker metric. All tensors constrained by the RW metric are required to leave the four-dimensional metric form invariant. From the constraints imposed by isotropy, it can be shown that for the case of $T_{\mu\nu}$, it must be of the perfect fluid form

$$T_{\mu\nu} = (P + \rho) U_\mu U_\nu + P g_{\mu\nu} \quad 1.3$$

where U_μ is a velocity 4 vector, and both P and ρ are scalars defined as pressure and energy density respectively. The field equations then read

$$R_{\mu\nu} = -8\pi G \left[\frac{1}{2}(\rho+P)g_{\mu\nu} + (P-\rho)U_\mu U_\nu \right] \quad 1.4$$

From the relationship between $R_{\mu\nu}$ and the metric $g_{\mu\nu}$, the time-time and space-space components can be singled out to yield a first order equation for $R(t)$,

$$\dot{R}^2 + k = \frac{8\pi G \rho R^2}{3} \quad 1.5$$

The imposed constraint of isotropy represented by the Robertson-Walker metric leads to Eqn. 1.5, which is a first order differential equation for $R(t)$. In order to determine how the scale factor R varies with time we require a description for the evolution of ρ . This is supplied by the condition for energy and momentum conservation, which can be expressed as the covariant derivative of the energy momentum tensor, viz.

$$T_{\mu\nu};\nu = 0 \quad 1.6$$

This equation is satisfied if

$$R^3(t) \frac{d\rho(t)}{dt} = - \frac{d}{dt} [R^3(t)(P(t)+\rho(t))] \quad 1.7$$

A detailed discussion of the equations 1.2-1.7 can be found in Misner et al. (1980) and Weinberg (1972). To solve Eqn. 1.7 requires a relationship between ρ & P , i.e. an equation of state. Assuming that the Universe is dominated by non-relativistic matter, with an equation of state satisfying $P \ll \rho$, the solution to Eqn. 1.7 is

$$[\rho/\rho_0] = [R/R_0]^{-3} \quad 1.8$$

where the suffix 0 refers to an evaluation at the present time. On the other hand if the dominant energy density constituent is relativistic

particles, then the equation of state reads $P = \rho/3$ and

$$[\rho/\rho_0] = [R/R_0]^{-4} \quad 1.9$$

Evaluating 1.5 at the present time yields

$$k = H_0^2 R_0^2 (2q_0 - 1) \quad 1.10$$

where H_0 and q_0 are observables given by

$$H_0 = [\dot{R}_0/R_0] ; q_0 = \frac{\rho_0 4\pi G}{3H_0^2} \quad 1.11a,b$$

The standard cosmology thus reduces to the determination of the parameters q_0 and H_0 , both of which are observables. The fate of the Universe depends upon the sign of the curvature term k in Eqn. 1.10, or alternatively the ratio of ρ_0 to the critical mass density $\rho_c(\Omega)$, where ρ_c is given by

$$\rho_c = \frac{3H_0^2}{8\pi G} \sim 10^{-26} \text{ kg/m}^3 \quad 1.12$$

There are 3 general solutions to Eqn. 1.5 in a matter dominated Universe, which combine to give the Friedmann class of cosmologies (Friedmann 1922, 1924). These solutions depend on the sign of k , defined in Eqn. 1.10. It is useful to combine Eqns. 1.5, 1.10 and 1.11a,b to give

$$[\dot{R}/R_0]^2 = H_0^2 [1 - 2q_0 + 2q_0(R_0/R)] \quad 1.13$$

1) ($k = 0$, $\Omega = 1$). Substituting $q_0 = 0.5$ in Eqn. 1.13 leads to a simple equation for which the solution is given by

$$R(t)/R_0 = [(3/2)H_0 t]^2 \quad 1.14$$

and so the Universe increases without limit. This is known as the Einstein-de Sitter model.

2) ($k = -1$, $\Omega < 1$). Strictly the scale factor $R(t)$ in this case is given by hyperbolic functions. However, the general form of the evolution can be seen by taking the solutions of 1.13 at small and large values of t . At small t , hence small R , Eqn 1.13 is given by

$$[\dot{R}/R_0] = H_0^2 2q_0 (R/R_0) \quad 1.15$$

which is satisfied by $R \propto t^{2/3}$. So in this case the Universe expands like an Einstein-de Sitter model at early times. A corresponding consideration for large t gives

$$R(t) = R_0 H_0^2 (1-2q_0)^{1/2} t \quad 1.16$$

In this case the Universe is "open". The scale factor increases linearly with t and, as with case 1, without limit.

3) ($k = +1$, $\Omega > 1$). If Eqn. 1.13 is used to look for solutions to $\dot{R} = 0$, we see that they exist if $\Omega > 1$ ($q_0 > 0.5$). So the Universe reaches a maximum scale factor when $\dot{R} = 0$ and then collapses back onto itself. The exact development of the scale factor is a cycloid and the Universe is called "closed".

The age of the Universe is approximately the same in all 3 cases and is given by

$$t_0 \sim H_0^{-1} \sim 10^{10} \text{ yrs.}$$

The Friedmann cosmologies discussed above use the fact that the Universe is matter dominated today and that Eqn. 1.8 applies. However, the form of Eqns. 1.8 and 1.9 imply that the Universe must be dominated by radiation at early enough times. Near $t = 0$ the density ρ will be large and so the

curvature term in Eqn. 1.5 can be neglected and this equation then becomes

$$\dot{R}^2 = \frac{8\pi G \rho R^2}{3} \quad 1.17$$

The solution to Eqn. 1.17 is $R(t) \propto t^{1/2}$. The effect of radiation is to increase the mass energy density of the Universe and therefore slow down the expansion rate. The energy density of the present 2.7° K CBR is

$$\rho_\gamma \sim 4.4 \times 10^{-31} \text{ kg/m}^3. \quad 1.18$$

Comparing Eqn. 1.18 with 1.12 the energy densities of matter and radiation are equal when the ratio of the scale factors is $\sim 4 \times 10^{-5}$, or equivalently, at a redshift $z \sim 10^4$.

1.2.3 Nucleosynthesis

Prior to $z \sim 10^3$, when the matter and radiation decoupled, the physics of the Universe is governed by the interaction of matter and radiation. Except for the very early Universe, all fundamental particles (e, e⁺, e⁻, μ , n, p...) are in thermal equilibrium. Nucleosynthesis takes place at about $t \sim 1$ sec, when the temperature of the Universe (T) is $\sim 10^{10}$ K. The abundances of the light elements depend sensitively on the photon ratio, and the expansion timescale (Yang et al. 1984). It also depends on the neutrino half life and the number of neutrino species (Olive et al. 1981). The very detailed computation of the complete network of nuclear reactions that takes place during element production has been carried out by Wagoner et al. (1967), Schramm & Wagoner (1977), Yang et al. (1984). The predictions of abundances from these studies are : helium, $X(\text{He}) \sim 25\%$ with a tiny fraction of ^2D , ^3He , and ^7Li . Observations of these mass fractions are made in regions of low metallicity such as globular clusters, HII regions and irregular galaxies (Pagel 1982). Using the data on all these elements to derive bounds to the

density parameter Ω_b gives

$$\Omega_b < 0.035 h^2 (T_0/2.7K)^3$$

where $H_0 = 100h$ km/sec/Mpc and T_0 is the temperature of the CBR. So for values of h between 0.5-1 and $T_0 \sim 2.7-3.0$ K we have the very significant conclusion that baryons cannot close the Universe.

1.3 Formation of Galaxies and the Large-Scale Structure

1.3.1 Fluctuations in the Early Universe

In the instability scenario galaxies and the large scale structure form from smaller fluctuations in the early Universe. This section outlines current speculation regarding the origin of these fluctuations. Lifshitz (1946) showed that any fluctuation in density, spin or shear can be associated with a corresponding distortion of the metric. The general relation between a matter fluctuation density, $\delta\rho$, of length L , and a distortion in the space-time geometry Δ is given by

$$\Delta \propto \frac{\text{gravitational potential of fluctuation}}{\text{gravitational potential at horizon}} \sim \frac{G\delta\rho L^2}{G\rho(ct)^2} \sim (\delta\rho/\rho)L^2 \quad 1.19$$

where $(ct) = 1$ (Barrow 1980). It is assumed that most fluctuations generate density perturbations of the form

$$(\delta\rho/\rho) \propto M^{-\alpha}.$$

Where M is the mass scale associated with the perturbation. If a fourier initial power spectrum, $|\delta_k|^2 \sim k^n$ is assumed, where k is the comoving wavenumber, then

$$(\delta\rho/\rho)^2 \propto \int k^2 |\delta_k|^2 \exp(ik \cdot x) dk \quad 1.20$$

If the phases of k modes are random then integrating this yields

$$(\delta\rho/\rho) \propto M^{-(3+n)/6} \quad 1.21$$

and there is a corresponding distortion to the metric of

$$\Delta \propto M^{(1-n)/6} \quad 1.22$$

The preferred nature of fluctuations are those with $n=1$, $\alpha=2/3$. These fluctuations were first pointed out by Harrison (1970), Peebles & Yu (1970) and Zeldovich (1972) as being of the constant curvature form, having scale independent Δ (Eqn. 1.22). Fluctuations with $n > 1$ suffer from the requirement of a cut off at some early time to avoid diverging Δ as $M \rightarrow 0$ and a chaotic, non-Friedmannian initial state (Barrow 1980). Values of $n < 1$ are also less appealing because of divergence at large M .

Possibilities for the origin of density fluctuations are varied. One way to address the problem is to consider the starting time at which fluctuations could begin to grow from a purely statistical or "white noise" ($n = 0$) spectrum. This approach is not appealing however, since it has limited information content in that almost any subsequent fluctuation amplitude can be explained, so long as the fluctuations start at the appropriate epoch (Peebles 1968). Thus, $\delta\rho/\rho \propto \bar{M}^{1/2}$, arising at the planck time ($t_p \sim 10^{-43}$ sec), predicts a Universe of black holes today. Alternatively, the same spectrum beginning at the Compton time ($t_c \sim 10^{-23}$ sec) yields $\delta\rho/\rho \ll 1$ on galactic scales today (Barrow 1980). It thus seems worthwhile to enquire after some physical explanation for the generation of fluctuations at some particular time.

The most popular candidates are associated with the physics of the early Universe. During the thermal history of the Universe many phase transitions may have occurred (Linde 1974). These are changes of state associated with spontaneous symmetry breaking (SSB). The concept of SSB has been brought about by the recent success of the unification of

electromagnetic and weak forces and the consideration of a Grand Unified Theory (GUT) in which the electro-weak and strong forces are described by one coupling constant (Kolb & Turner 1981). The phase transition associated with GUT epoch occurs after a time $t \sim 10^{-35}$ sec, when the ambient temperature is $T \sim 10^{28}$ K. At higher temperatures all strongly and weakly interacting particles are indistinguishable, while at lower temperatures this symmetry is broken (Goldman et al. 1980). At the epoch of this phase transition it is likely that interesting phenomena occurred. One such phenomenon is inflation. This is the process by which the dynamics of the Universe are determined by a cosmological constant, viz. a constant energy density (Guth 1981). The Universe becomes trapped in a false vacuum and supercools. During this period the Universe undergoes a de Sitter phase in which the expansion is exponential (Kolb et al. 1980). This can be seen in Eqn. 1.5, since if the energy density term is made independent of R then the curvature term can be neglected, yielding an exponential solution for $R(t)$ (Sciama 1984). The de Sitter phase causes the horizon to be inflated and encompass most of the Universe today (at $t \sim 10^{-35}$ sec in the standard model, the Universe is large enough to encompass only 1 baryon). This naturally explains the large scale isotropy and homogeneity in the standard model. It is during this and subsequent similar phase transitions that seed fluctuations may have been spontaneously generated.

One popular candidate for the seeds of galaxy formation are cosmic strings (Kibble 1976, Zeldovich 1980). These are one dimensional topological knots of high energy density that arise naturally in GUTS, forming at phase transitions in the early Universe. In effect, they represent the domains of the false vacuum state mentioned above. A string has associated with it a "tension" in units of mass per unit length. This tension tends to straighten strings out as they enter the horizon. They also form closed loops through self intersection which contribute an energy density $\sim 10^{-3} \Omega$ (Albrecht & Turok 1985). It has been suggested (Vilenken 1981) that cosmic string loops can last beyond the early Universe and provide a sufficient number of perturbing potential wells of

the right size ($\delta\rho/\rho \sim 10^{-3}$ at decoupling) to be the centres of galaxy formation. Consideration of the evolution of string loops has been shown to result in a scale-free correlation function with an amplitude which is very close to that observed for Abell clusters (Kibble 1985). The relatively easy availability of strings resulting from symmetry breaking and the fact that the associated matter density fluctuations are of the constant-curvature type (Zeldovich 1980, Bardeen et al. 1983), makes them an attractive seed candidate. However, there may be problems. Strings lose energy and decay through gravitational radiation. This restricts the mass of strings to $> 10^9 M_\odot$, if they are to survive long enough to induce significant fluctuations in the matter. So if globular clusters or dwarf galaxies, with masses $\sim 10^6$ - $10^{10} M_\odot$, form before galaxies (Peebles & Dicke 1968) it is unlikely that strings play a significant role.

Carr & Silk (1983) have reviewed the possibility of formation of single bound units, or "grains" at various phase transition epochs. They define grains as non-linear, incipient single units which are bound and able to move around individually. Simple protons, can be considered as grains, however grains of this size are far too small to produce galaxies through statistical fluctuations. Interesting grains result from phase transitions, with the grain mass $\sim$ the temperature of the Universe at the phase transition. Sato et al. (1981) have suggested that black holes could form at the GUT epoch. If the Universe goes through an inflationary period then vacuum bubbles could grow to large enough sizes that black holes form from bubble-bubble collisions (Hawking et al. 1982) with mass $M \sim 1$ Kg. These black holes could then themselves act as grains. Other possibilities include X-boson grains (Zeldovich & Khlopov 1978) at the G.U.T epoch ($t \sim 10^{-35}$ sec) or W-boson grains at the phase transition associated with the Weinberg-Salam electro-weak symmetry breaking epoch ($t \sim 10^{-9}$ sec). The evolution of these units is expected to give rise to matter fluctuations which scale as $n = 0$, or $\bar{M}^{-1/2}$ (Carr & Silk 1983).

To summarise, little is certain as to the origin of matter fluctuations.

There are many potential candidates for the seeds of galaxy formation which are associated with the physics of the early Universe. At the present time strings seem the favourite option but there are other candidates which, although give $n \neq 1$, may arise naturally during phase transitions. It may be that more than one candidate is required, or that an $n = 1$ spectrum has to be abandoned. Much depends on the theories of unification and inflation, the details of which are still not fully understood (Kolb & Turner 1981).

1.3.2 The Growth of Fluctuations Prior to Decoupling

In this section the growth of fluctuations after they have entered the horizon is considered. Fluctuations during this era can be characterised by either one of two modes; isothermal or adiabatic. In the former, matter fluctuations are imbedded in a uniform thermal bath ($\delta\rho_b \neq 0$, $\delta\rho_Y = 0$). In the latter, the local entropy is held constant with matter and radiation both perturbed together ($\delta\rho_b \sim \delta\rho_Y \neq 0$). The condition for gravitational collapse dominating the pressure support of a fluctuation is that it must exceed a critical scale size known as the Jeans mass (Jeans 1902). In the radiation dominated era there are two characteristic Jeans mass scales. One is the matter Jeans mass M_{jm} , which is constant throughout the radiation era. The other is the Jeans mass for a radiation pressure supported cloud M_{jY} . The Jeans scale λ_j is given by

$$\lambda_j \sim c_s (\pi/G\rho)^{1/2} \quad 1.23$$

where c_s is the sound speed. Since $c_s \sim c$ in the radiation dominated era, and $(G\rho)^{1/2}$ is the expansion timescale, the radiation Jeans scale is $\sim$ the horizon size, during this era. The development of these two scales is shown in Fig. 1.1. The two modes are considered separately below for a Universe composed of baryons

Isothermal Fluctuations: Although the radiation field does not partake directly in the build up of inhomogeneities, it has several strong effects

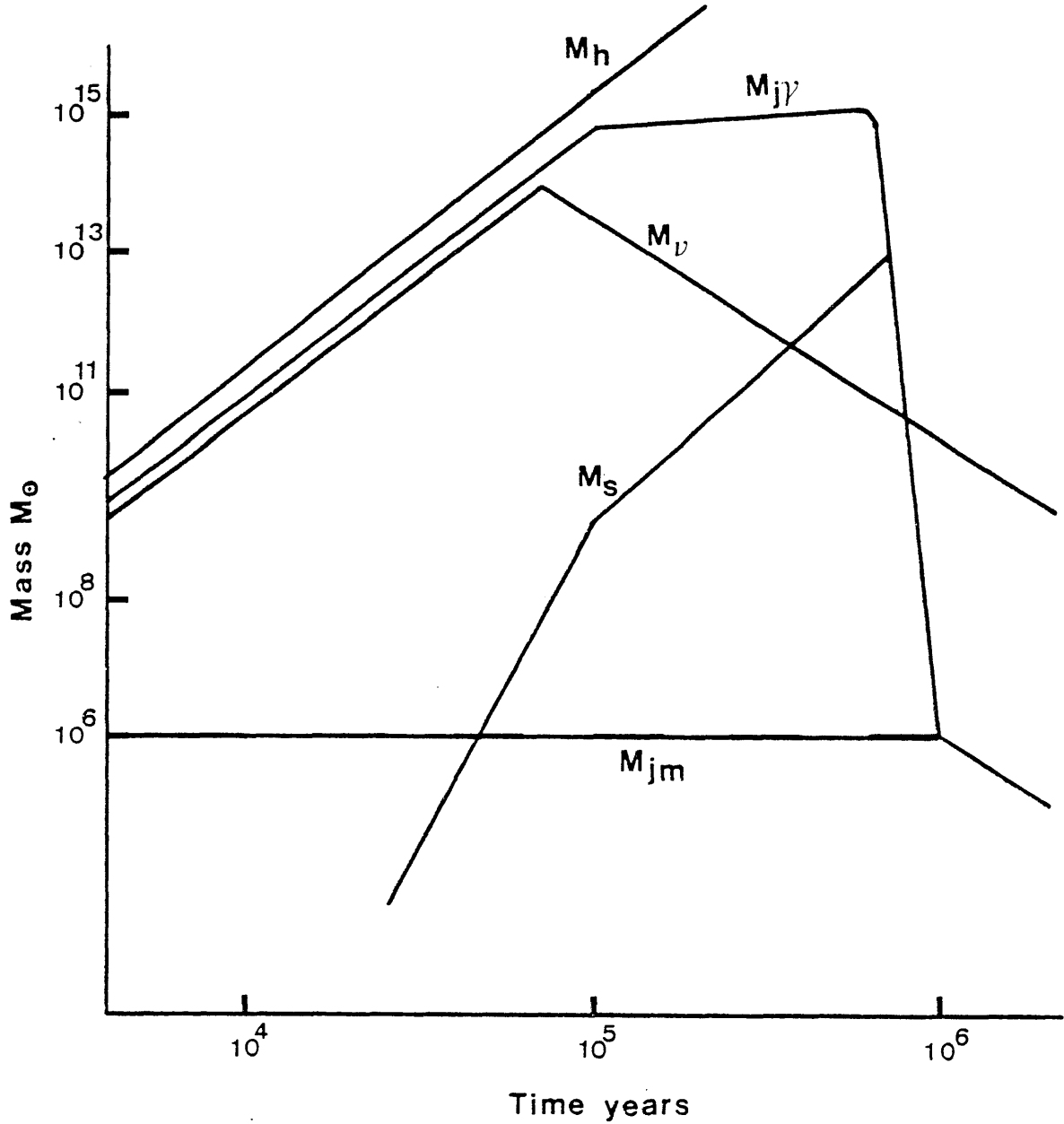


Figure 1.1 Evolution of characteristic mass scales prior to decoupling in an $\Omega = 1$ Universe (Silk 1974). M_h is the horizon mass, M_{jm} the matter Jeans mass, $M_{j\gamma}$ the radiation Jeans mass, M_s the Silk mass and M_ν the neutrino (100 eV) damping mass.

which influence these fluctuations. Firstly any isothermal fluctuation, smaller than M_{jm} , is frozen after falling inside the horizon due to photon drag. A particle in an overdensity moving with velocity V (relative to the comoving frame) feels a radiation flux $\sim T^4 V$ in its direction of motion and will eventually be stopped (Peebles 1965). An additional constraint on baryonic growth is the expansion timescale. During this era ρ_Y exceeds ρ_b and therefore the free fall time for the matter $(G\rho_b)^{-1/2}$ is larger than the expansion timescale $(G\rho_Y)^{-1/2}$ (Chernin 1973, Meszaros 1975, Guyot & Zeldovich 1970).

Matter fluctuations are frozen in by the radiation until recombination, when $\rho = \rho_b$ and $M_{jm} \sim 10^5 \Omega^{-1/2} M_\odot$. At this time only fluctuations smaller than this mass are supported by gas pressure alone and larger masses become instantly unstable. The Jeans mass will be the first scale to become gravitationally unstable if larger scale fluctuations have smaller amplitude. Peebles and Dicke (1968) first argued that this mass could explain the existence of globular star clusters which have masses of this order.

Fluctuations of huge amplitude ($> M_{jm}$) need to be hotter than the ambient radiation background in order to remain pressure supported. The tendency of a slight radiation density excess is to diffuse outward, causing the isothermal perturbation to grow (Hogan 1978). However, the diffusion timescale for this process is larger than the expansion timescale and it is only important after decoupling when the radiation drag is negligible (Peebles 1980).

Adiabatic Fluctuations: In these modes radiation and matter are closely coupled. On entering the horizon any irregularities present oscillate like pressure waves, developing a spectrum of acoustic noise (Peebles 1980). All fluctuation scales behave in this manner since the Jeans length is $\sim$ horizon size. Small amplitude adiabatic fluctuations undergo two distinct dissipative effects that erase most of the initial perturbation spectrum. Firstly at early stages, when the radiation

density dominates, the large radiative viscosity removes fluctuations on small scales. Secondly, photons tend to random walk out of high pressure regions, leaving behind residual matter perturbations below a critical mass scale M_S . The diffusion time $t_d \sim N_S t_S$, where N_S is the number of scatterings. This relation can be expressed

$$t_d \sim N_S t_S \sim (L/\lambda)^2 (\lambda/c) \sim (\lambda c)^{-1} L^2 \quad 1.24$$

where λ is the Compton scattering length, and L is the clump size. Eqn. 1.24 indicates that damping is significant for clumps smaller than $(ct\lambda)^{1/2}$, which corresponds to a mass $M_S \sim 10^{13} \Omega^{-5/4} M_\odot$, or a scale size extrapolated to the present of

$$\lambda_S \sim 2(0.036 + \Omega h^2)^{-1} \text{ Mpc} \quad 1.25$$

(Silk 1968, Peebles & Yu 1970, Chibisov 1972). M_S is called the Silk mass. This sets the scale of the first objects to form after decoupling. The evolution of M_S prior to decoupling is shown in Fig. 1.1.

The possible scenarios described so far refer to a Universe dominated by baryonic matter that may be perturbed by either isothermal or adiabatic modes. However, as previously mentioned, baryons can probably only account for $\Omega \sim 0.1$, therefore for $\Omega = 1$ non-baryonic material may well dominate the mass density. It is possible that this dark matter consists of elementary particles that decoupled from the radiation field earlier than baryons. Candidates include the fermionic components of the photon and graviton, viz. the photino ($m \sim 1 \text{ GeV}$) and gravitino ($m \sim 1 \text{ KeV}$), while other possibilities are the monopole ($m \sim 10^{15} \text{ GeV}$), neutrino ($m \sim 30 \text{ eV}$) and axion ($m \sim 10^{-5} \text{ eV}$). Associated with each candidate is a damping mass which results from the evolution in the radiation dominated era and which, as with baryons, determines the scale of the first structures to form in a Universe dominated by that candidate. It is fashionable to assume that the fundamental particles resulting from GUTS are perturbed adiabatically. This then keeps the local entropy per baryon constant and fixed by the

decay of GUT particles, such as Higgs bosons (Weinberg 1980). Both neutrinos and axions serve as illustrative examples of the range of scales on which overdensities are expected to have occurred in a non-baryonic Universe and each has been extensively explored.

The experimental reports of electron-neutrino mass detection (Lyubimov) and neutrino oscillations (Reines 1980) along with the natural appearance of a neutrino mass in GUTS (Witten 1980), suggests that implications of light massive neutrinos in the early Universe and their role in galaxy formation needs to be considered. After nucleosynthesis at $t \sim 1$ sec ($T \sim 100$ Kev) the neutrinos decouple from the thermal plasma and continue in free expansion. Neutrinos are therefore born relativistic, with a high velocity dispersion. It is this feature which characterises them as "hot" particles. As they are perturbed adiabatically, neutrino fluctuations oscillate after entering the horizon. A combination of directional dispersion, when the neutrinos are relativistic and collisionless Landau damping when they become non-relativistic erases structure on scales smaller than a comoving wavelength today corresponding to

$$\lambda_{\nu} \sim 41 m_{30}^{-1} \text{ Mpc}$$

where, m_{30} is the neutrino mass in units of 30 eV (Bond, et al. 1980, Peebles 1982a, Bond et al. 1983). The baryons remain frozen during the radiation era and fall into the potential wells created by the neutrinos after decoupling on scales above M_{ν} , given by

$$M_{\nu} \sim 10^{15} m_{30}^{-2} M_{\odot} \quad 1.26$$

The evolution of M_{ν} is shown in Fig. 1.1. The second popular non-baryonic dark matter candidate component considered is axions (Ipser & Sikivie 1983). The axion is a pseudoscalar field originally proposed to avoid large CP violation in the strong interactions (Weinberg 1978, Wilczek 1978). There is an uncertainty in the axion mass $\sim 10^4$ but for their density to be $< \Omega = 1$, they need to have mass $m > 10^{-5}$ eV (Preskill et al.

1983) and would therefore be gravitationally dominant. The longevity of helium burning stars implies that $m < 0.1$ eV (Fukugita et al. 1982). These particles are born "cold", having negligible thermal peculiar velocity with respect to the Hubble flow. This class of particles is called cold dark matter (cdm). Assuming adiabatic, constant curvature ($n=1$) perturbations the growth of cdm fluctuations can be modelled in detail and with clear predictions. Since (baryon-photon) fluctuations are damped below the Silk mass during the radiation era, axion (or any cdm) fluctuations grow only slowly until they dominate the mass density of the Universe, at which point they begin to grow as $1/(1+z)$, until $z \sim \bar{\Omega}^{-1}$ (Section 1.3.3). At decoupling it is expected that $\bar{\Omega}_{\text{cdm}} \gg \bar{\Omega}_b$ and so the baryons collapse into the potential wells created by the axions on scales larger than M_{jm} , while axion clumps survive on even smaller scales than this. Frenk et al. (1985) use high resolution simulations to show that the clustering of cdm results in flat rotation curves for galaxies, consistent with observations.

Fig. 1.2 (taken from Blumenthal et al. 1984) shows the spatial density fluctuation as a function of mass for both a neutrino and cold dark matter spectrum, assuming $n=1$, and a white noise ($n=0$) isothermal spectrum, all redshifted to the present. This figure summarises the ideas presented in this section, showing clearly the relative power of each model on different scales. It is these predictions for the density fluctuation as a function of scale which the two experiments in this thesis are designed to test.

1.3.3 Post-Decoupling Evolution

Once matter and radiation have decoupled at $z \sim 10^3$ any fluctuation larger than $M_{\text{jm}} \sim 10^5 \bar{\Omega}^{-1/2} M_{\odot}$ are free to collapse. However, density perturbations grow only linearly in an expanding medium, while non-linear effects are negligible. In particular, after decoupling the largest growing modes amplify at a rate

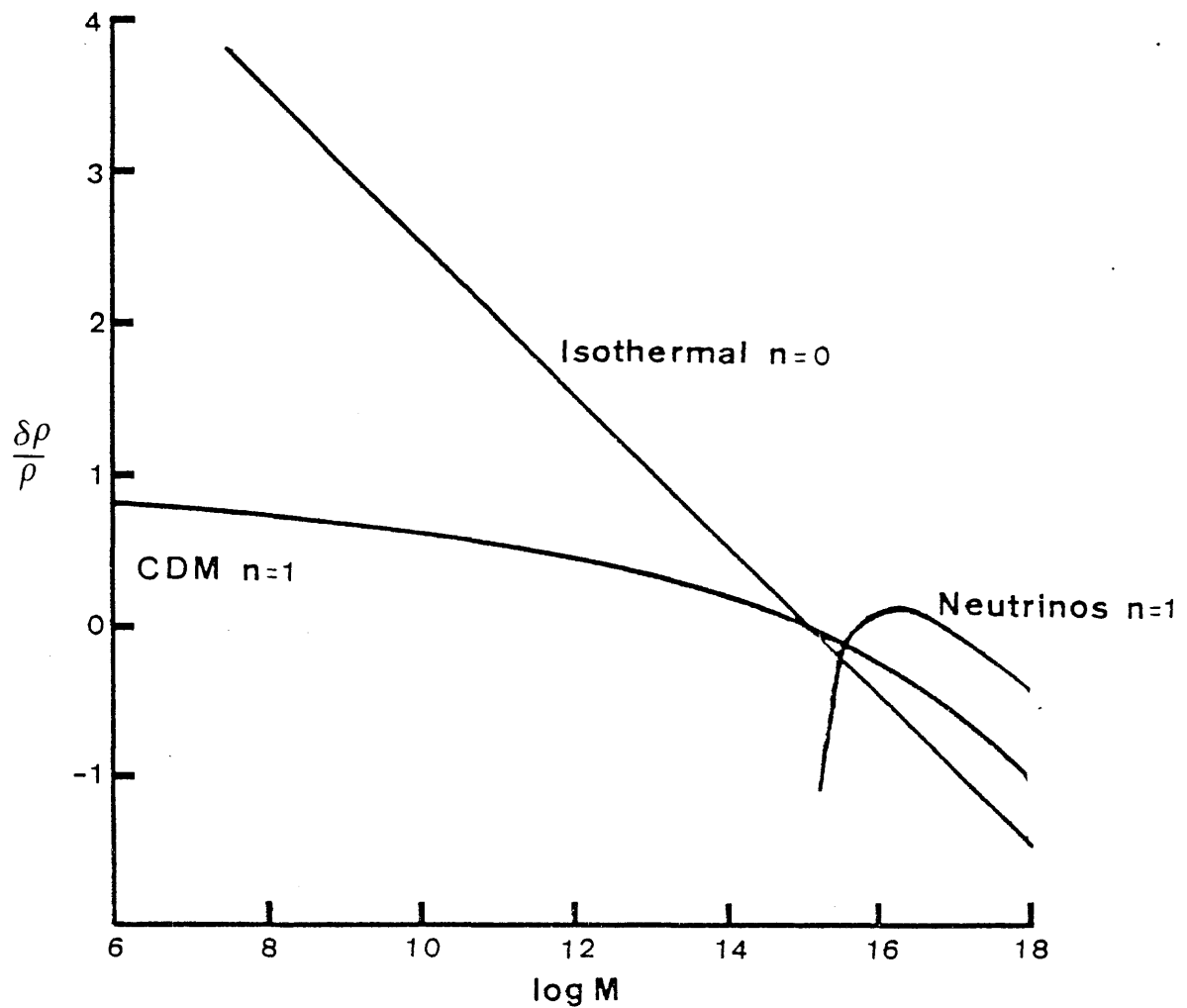


Figure 1.2 The initial spatial density fluctuations as a function of mass for the cold dark matter ($n=1$), neutrinos ($n=1$) and baryonic ($n=0$) cases, redshifted to the present, in an $\Omega = 1$ Universe (Blumenthal et al. 1984).

$$(\delta\rho/\rho) \propto t^{2/3} \propto (z+1)^{-1}$$

1.27

(Lifshitz 1946, Bonner 1957). The evolution of isothermal and adiabatic modes in this post-decoupling era is discussed below.

Bottom Up Scenario: In the case of isothermal perturbations the first objects to collapse are those of the Jeans mass $M_{jm} \sim 10^5 \Omega^{-1/2} M_\odot$, since there are no a priori reasons to expect larger fluctuation amplitudes on larger scales. Further, there is no preferred fluctuation spectrum or characteristic mass scale at decoupling in this model. Structures larger than the Jeans mass form from the hierarchical clustering of smaller masses (hence "bottom up"). Peebles & Dicke (1968) have suggested that globular star clusters are the pre-galactic progenitors of galaxies. However, recently this idea has become a less attractive possibility. Globular clusters have been shown to consist of a wide range of metal abundances which argues against a common epoch of formation. There is also little indication that, like galaxies, they are imbedded in extended dark haloes. Another candidate for the first post-decoupling condensations are population III stars of mass $\sim 10^5$ - $10^6 M_\odot$ (Carr 1975, 1979, 1981). Apart from expecting pregalactic clouds of this mass, on the basis of the Jeans mass, these super-massive objects (SMO) can provide a significant fraction of the missing mass ($\Omega \sim 0.1$) without violating limits on metal enrichment or extragalactic background light.

After decoupling there is a strong possibility of re-ionization at high redshift. The effects of such ionization could be considerable. Sources of such ionizing radiation could come from a population III of mass $\sim 10^5 M_\odot$, discussed above, however the source may also originate from star formation in a proto-cluster, in the adiabatic picture. If sufficient gas is ionized at early times then subsequent collapse is halted as the remaining gas is locked into the co-moving frame by radiation drag. This effect may also permit gas to survive long enough to become enriched before forming visible stars and galaxies. When this Compton drag becomes ineffective, clouds of gas collapse into potential wells formed by the

compact objects (Hogan 1978).

White & Rees (1978) have developed a comprehensive bottom up scenario which uses, but does not depend upon the nature of, a dark component. In this picture most of the mass in the Universe is dark and cold. It could be black holes, SMO, or axions. The dark matter over-densities form soon after decoupling, and provide the potential wells into which the remaining gas cascades, thus forming the luminous parts of galaxies. Star formation takes place with an efficiency dependent on the density. An important aspect of the theory is that it provides an upper limit to the mass of galaxies $\sim 10^{12} M_{\odot}$. This comes about because there is a critical mass above which collapse is governed by the cooling time rather than the gravitational collapse timescale. The epoch of galaxy formation in such a model can be approximated by the turn around time of a collapsing cloud in expanding co-ordinates. The relation between density and the time of maximum expansion in a spherical system is given by

$$t = (3\pi/32G\rho)^{1/2} \quad 1.28$$

(Partridge & Peebles 1967). Taking $M \sim 10^{11} M_{\odot}$ and a radius of 20kpc Eqn. 1.28 predicts a collapse time $t \sim 10^8$ yrs or at $z \sim 10-30$. If galaxies have extended haloes out to 50 kpc, as suggested by the flat rotation curves (Rubin et al. 1985), then the dynamical time is increased by a factor ~ 3 . A further constraint is imposed by Rees & Ostriker (1977). They consider the detailed dynamics and cooling of gas clouds in the early Universe. Since larger mass objects take a significantly longer time to cool, they conclude that the largest galaxies must have formed at epochs $z \sim 10$.

One problematic area for pure isothermal evolution in forming galaxies is the need for dissipation to form discs. The dynamics of spiral galaxies are dominated by rotation of the disk. Any dissipation that takes place during the collapse phase of a primeval galaxy increases the induced rotation velocity compared to the velocity required to maintain virial

equilibrium. In ellipticals the residual velocity anisotropy dominates any induced rotation and dissipationless theories have little difficulty in explaining their dynamics (Binney 1980).

Clusters of galaxies form from the hierarchical clustering of galaxies in this model (Press & Schechter 1974). Computer simulations have been useful in providing information on the formation of structure larger than clusters in this scenario. The main results from these simulations are discussed in Section 1.4.2.

The bottom up scenario can account for large voids in any one of several distinct ways. If the Universe is dominated by Λ CDM then voids could be observational evidence of biased galaxy formation, whereby galaxies form at the peaks of the matter density space distribution (Davis et. al. 1985). In this case these regions are simply too underdense to form luminous galaxies, although the void may still contain substantial mass. If mass is located in these regions then galaxies do not trace the mass distribution. Such a separation of mass and light is difficult to bring about naturally, particularly as gravity acts to cluster and therefore mix all massive material. Mechanisms by which biasing may operate during proto-galactic collapse have been proposed by Rees (1985). Alternatively, voids can be result of the systematic streaming of galaxies away from underdense regions. N-body simulations do indeed show substantial holes in redshift space, with peculiar motions high enough to have made holes in one Hubble time (Miller 1983). Also an analytical calculation of the development of holes in the space distribution of galaxies in an isothermal Universe (Peebles 1982a) concludes that peculiar velocities at the edge of the largest voids need to be as small as ~ 200 km/sec to evacuate them over the Hubble time. Another possibility to account for the large scale structure is the explosion scenario (Ostriker & Cowie 1981). If population III stars of mass $\sim 10^5 M_\odot$ are formed at early times, say $z \sim 100$, the resulting supernova explosions produce shock fronts which expand until their speeds fall below the Hubble expansion velocity. Exploding quasars, giving rise to the large-scale structure has

also been considered (Ikeuchi 1981). The attractive aspect of explosions is that collisions of shells naturally produce the observed voids and filamentary structure.

Top Down Scenario: The Silk mass $M_S \sim 10^{13} \Omega^{-5/4} M_\odot$ sets the coherence scale below which perturbations are damped. The formation of structure proceeds by the collapse and fragmentation of these proto-cluster size units. Zeldovich (1970) has developed this model in great detail. After decoupling the baryonic material is still gaseous, due to the suppression of perturbations below the Silk cut off. Planar, or pancake like configurations result from the collapse of the irregular structures (Sunyaev & Zeldovich 1972, Doroshkevich et al. 1978). Dissipation of the gas keeps the pancakes very thin and radiative cooling behind shocks allows fragmentation into subgalactic objects of mass

$$M \sim 10^8 n_0^{-1/2} M_\odot \quad 1.29$$

where n_0 is the particle number density (Jones & Wyse 1979). These objects would later merge to galaxies and further cluster to form clusters in a hierarchical fashion. Galaxy formation is triggered by pancake formation and occurs only in pancakes. Early pancakes forming would be the most massive as the gas is cooler there. They would consist of a thin layer of cold gas in the innermost part of the pancake and the best conditions for galaxy and star formation are in these pancakes. As more pancakes form, their UV and X-rays heat and ionize the environmental gas, and resulting pancakes have a thin cool layer, with a temperature $\sim 10^4$ K that fragments. Younger pancakes are less efficient at forming galaxies since quasars produce too much radiation and a late forming pancake has a temperature of about $\sim 5 \cdot 10^5$ K, so the gas cannot cool (Zeldovich 1970). A similar pancake collapse is predicted if the Universe is dominated by massive neutrinos (Zeldovich 1977).

The growth rate of the amplitude of over-densities is given by Eqn. 1.27. This growth rate implies that non-linear structure is expected to form

when $\delta\rho/\rho \sim 1$ or when $z \sim \bar{\Omega}^{-1}$ (Sunyaev 1971). If $\Omega \sim 0.1$ then structure forms at $z \sim 10$, while if $\Omega = 1$, $z \sim 1$. So pancake collapse and subsequent galaxy formation occurs only after a substantial period of time during which the largest amplitude modes ($\sim M_g$) are still linear. The detailed limits on the epoch of pancaking are imposed by the modelling of the observed galaxy two point correlation function. This is discussed in Section 1.4.2.

The attractive aspect of the adiabatic model is the close correspondence between the predicted large scale structure and that which is observed (see Section 6.3). Thus, voids superclusters and filaments are a natural consequence of the large coherence length of the theory and the subsequent pancake collapse which is expected to have taken place. These features can be seen in the numerical simulations of Dekel & Aarseth 1984, and Centrella & Melott 1983.

1.4 Observational Probes of Primeval Inhomogeneities : Forward Into the Past

1.4.1 Anisotropy of the Cosmic Background Radiation

The CBR provides the most distant reference frame with which to probe inhomogeneities in the early Universe. Fluctuations within the horizon at decoupling and which grew to form galaxies after that time are separated on the sky by an angle $\theta \sim 4^\circ \Omega^{1/2}$ (Weinberg 1972). Observations on angular scales smaller than this constrain the amplitude and type of primordial fluctuations in the gravitational instability picture of galaxy formation. Scales larger than this were not in causal contact before decoupling and fluctuations on these scales were not damped by the radiation. Thus, fluctuations on the scales of $\sim$ a few degrees would be primordial relics of the initial fluctuation spectrum (Weinberg 1972). Intrinsic dipole and quadrupole anisotropies are possible and would be expected in inhomogeneous world models. However, detection of the dipole anisotropy alone, and its coincidence in direction with galaxy studies

(Section 3.1) leads to the most plausible interpretation of the dipole component as a motion of the Local Group. The predicted anisotropies in the CBR and observational status on different scales are discussed below.

On small scales the predicted anisotropy in the CBR comes from the predicted epoch of galaxy formation and the fluctuation mode. If galaxies form when $\delta\rho/\rho \sim 1$, then perturbations must have entered the non-linear regime, by $z \sim 1/\Omega$, or $z \sim 1-10$ (Section 1.3.3). The linear growth phase in the matter-dominated era sets stringent limits on the minimum density fluctuations required at decoupling, viz. $\sim 10^{-3} - 10^{-2}$. Such large values of $\delta\rho/\rho$ are needed because not much time is available and the growth rate is slow. For adiabatic perturbations there is a simple relation between the temperature fluctuation within the perturbation and $\delta\rho/\rho$, given by

$$\frac{\Delta T}{T} \sim \frac{\Delta\rho}{3\rho} \quad 1.30$$

It is important to note, however, that the observed level of temperature fluctuation will be substantially below the value given above unless the perturbations are large enough to be optically thick (Sunyaev et al. 1970). For masses $\sim 10^{15} M_\odot$ the optical depth will be < 1 and so the radiation will penetrate several fluctuations. In this case and for isothermal perturbations the largest distortions are due to Doppler shifts caused by the motion of the material within the perturbation. Typically, the resulting anisotropies are reduced by a factor $\sim 10-100$, but this depends on the spectral index and world model (Wilson & Silk 1981). If the Universe has undergone substantial re-ionization since decoupling, as suggested in Section 1.3.3, Thomson scattering will erase any temperature fluctuations imprinted on the CBR smaller than an angular scale of $\sim 1^\circ$. However, the ionizing matter would not necessarily be uniformly distributed (i.e. it might be primeval galaxies or clusters) and might imprint its own fluctuation thumb print on the radiation (Sunyaev et. al. 1972).

The strongest observational limits on these scales are set by Uson and Wilkinson (1984a,b) and correspond to a distortion $\Delta T/T < 3 \cdot 10^{-5}$ at $\sim 4.5'$. These limits have the following implications: The adiabatic, baryon-dominated Universe, considered by Wilson and Silk (1981), can be ruled out unless $\Omega \sim 1$ and the spectral index of density fluctuations $n > 3$. Isothermal perturbations are still allowed, since there is little constraint on early reheating. In the context of non-baryonic cold dark matter, if light traces mass, small scale anisotropies exceed the current observational limits if $\Omega < 0.2 h^{-4/3}$ (Bond & Efstathiou 1984). Since the predicted small scale rms peculiar velocity field is too high in an $\Omega = 1$ cdm scenario (Davis et al. 1985), models of cdm in which light traces mass are probably incorrect. Models with a massive neutrino are not seriously constrained at present (Bond & Efstathiou 1984). Since neutrinos decouple from the radiation at an earlier epoch than the baryons, the neutrino perturbations experience an extended growth period during which the baryonic matter and radiation are unaffected (Bond et al. 1980). The predictions for the expected fluctuations depend heavily on normalising the calculations at small z . In the case of neutrinos this is done using the epoch of non-linearity (z_{NL}). The Bond & Efstathiou (1984) predictions for a neutrino, $\Omega = 1$ model lie below the observational limits unless the epoch of non-linearity occurs at $z_{NL} > 8.7$, if $h = 0.75$ and $z_{NL} > 3.5$ if $h = 0.5$.

The best current observational limits on large angular scales come from Lubin et al. (1983) and Fixen et al. (1983). These authors give limits for the quadrupole anisotropy (Q) of 0.38mK and 0.18mK respectively. Although Boughn et.al.(1981) and Fabbri et.al.(1980) reported a value for the quadrupole anisotropy, it is widely accepted that inadequate subtraction of the galactic emission component was responsible for the signal. A comparison of these results with the prediction for the Q anisotropy by Wilson (1983) tends to rule out adiabatic scenarios with spectral index $n < 0$. Therefore, these upper limits do not provide tight constraints on the initial fluctuation spectrum compared to experiments on smaller scales. However, the dependence of the Q term on n is very strong

and important conclusions could be drawn if there were a good observational number for Q. In particular, the quadrupole anisotropy also constrains the intrinsic dipole component in the CBR in anisotropic models. Typical predictions for the intrinsic dipole component are ~ 10 -100 times that above Q (Wilson & Silk 1981, Wilson 1983). Searches for a quadrupole anisotropy at the level of 0.1-0.01 mK will provide constraints on whether the well established dipole anisotropy at ~ 1 mK was at least made up in part by an intrinsic component.

1.4.2 Galaxy Clustering

The most commonly used method to describe the clustering of galaxies is the 2 point correlation function $\xi(r)$. This is defined as the probability, in excess of random, of finding two galaxies in two volume elements separated by a distance r . It can therefore be used as a measure of the density fluctuation as a function of scale. The correlation function is related to the fluctuation spectrum $|\delta_k|$ by an equation similar to Eqn. 1.20, viz.

$$\xi(r) \propto (\delta\rho(r)/\rho)^2 \propto \int k^2 |\delta_k|^2 \exp(ik \cdot x) dk \quad 1.31$$

If the initial fluctuations are assumed to have the power law form $|\delta_k|^2 \propto k^n$ and random phases, then the initial correlation function is given by

$$\xi(r) \propto r^{-(3+n)/2} \quad 1.32$$

In principle, measurement of the correlation function can provide constraints on the initial fluctuation spectrum by modelling the clustering process to the present epoch and comparing with the $\xi(r)$ observed. The early analysis of complete galaxy surveys (Kiang 1967, Neyman, Scott & Shane 1954, Totsuji & Kirihara 1969, Peebles 1974a, 1974b) indicate a scale invariant clustering hierarchy

$$\xi(r) \propto r^{-\gamma}$$

1.33

with an inferred index $\gamma \sim 1.8$ on scales $0.05 < r < 3 \ h^{-1}\text{Mpc}$. Correlations on these scales can be estimated using $\xi(r)$ or its angular equivalent $w(\theta)$, if redshifts are not available. However beyond $\sim 5 \ h^{-1}\text{Mpc}$ the clustering density contrast is small, making galaxy correlations more difficult to detect in analysis of galaxy distributions seen projected on to the sky. Recent determinations have therefore relied on redshift surveys. Davis & Peebles (1983) use the redshift (CFA) survey of Huchra et al. (1983), to determine $\xi(r)$. Their results suggest an excess on scales $2-3 \ h^{-1}\text{Mpc}$ and a steepening of the $\gamma \sim 1.8$ slope beyond $10 \ h^{-1}\text{Mpc}$. This is consistent with the break found earlier using the Lick survey (Shane & Wirtanen 1967) by Groth & Peebles (1977). Using redshifts for a complete sample of 340 galaxies, Shanks et al. (1983) also find a steepening but at $r \sim 5 \ h^{-1}\text{Mpc}$. This break may indicate that $\xi(r)$ goes negative on scales $> 10 \ h^{-1}\text{Mpc}$ and indeed both Davis & Peebles and Shanks et al. find tentative evidence for this. Such a feature may be due to the presence of voids. However, voids are typically $\sim 10-50 \text{ Mpc}$ in size so it is unlikely they have been fully sampled in existing galaxy surveys.

In principle the form of the correlation function can potentially discriminate between the different models of galaxy formation. The present clustering of galaxies can be largely understood by the modelling of the galaxy two point correlation function using N body simulations, over a wide range of scales (Fall 1979). On a detailed level the isothermal theory predicts a clustering scale that is too large on small scales and with not enough power on the scales $\sim 2-10 \ h^{-1}\text{Mpc}$. The best fit is obtained with a spectral index $n \sim 0$ (Dekel & Aarseth 1984). Recent N body simulations of the flatter ΛCDM (Fig. 1.2) spectrum, model even more closely the observed correlation function (Davis et al. 1985) when biasing is introduced. As mentioned in Section 1.3.3, biasing is a process by which it is assumed that galaxy formation takes place in regions denser than some threshold, which is specified arbitrarily in the computer simulations. In the context of ΛCDM the effect of biasing is to

cluster the light (galaxies) more than the mass.

The excess clustering seen in the CFA survey on scales $\sim 2-3 h^{-1}\text{Mpc}$ has been interpreted as pancaking. If this is so then the shape of (ξ) is reproduced in linear numerical simulations provided that the first pancaking occurred at $z < 0.5$ if $\Omega = 1$ and at $z < 2$ if $\Omega = 0.1$ (Dekel & Aarseth 1984). In the case of a neutrino dominated Universe, there is expected to be substantial clustering on scales $< 14 (\Omega h^2)^{-1}\text{Mpc}$ (Peebles 1982b). Similar conclusions have been drawn concerning the late epoch of formation in this model also (Frenk et al. 1983, White et al. 1983). The limitations of predicting the epoch of galaxy formation from numerical simulations in this way is discussed in Section 6.3.3.

1.5 Summary

Observations of the CBR and abundance of heavy elements provide strong evidence that the standard model represents a more or less correct understanding of the early Universe. In spite of this, there appears to be no one satisfactory theory which can explain the diversity of structure on all scales. Taking the information presented in this chapter together, perhaps the best theory for galaxy formation is an $\Omega = 1$, cdm model with biasing. This essentially hierarchical theory preserves the salient features of the baryon dominated isothermal model but the dark matter is not restricted to follow the light and so large voids are interpreted as regions in which galaxy formation has not "switched on", rather than being the result of excessive large scale power. The distinguishing features of models with a large coherence length is the degree of large-scale density power and the late prediction for the epoch of galaxy formation. Here, the most stringent observational constraints come from N-body simulations and clustering analysis rather than CBR anisotropy studies. The estimate of $z_{NL} \sim 1-3$ in these models is in contrast to the estimates in the isothermal scenario in which galaxies could have formed by $z \sim 10$. No reliable estimate for the epoch of galaxy formation yet exists for the cdm model. As mentioned in the introduction, the degree to which the overall

dynamics is still uncertain (Ω, H_0) is clear from the constraints. Few possibilities can be ruled out completely, given the present uncertainties in these quantities.

The rest of this thesis is concerned with two primary aspects of the questions raised here. In the next chapter a search for galaxies forming at high redshift is described. From the conclusions above it is clear that the epoch of galaxy formation is one of the prime discriminators between the different classes of theoretical speculation. The infrared waveband allows constraints to be placed on galaxies forming at redshifts as high as $z \sim 10$, for a modest investment of telescope time. The second aspect addressed is a direct investigation of putative large-scale density inhomogeneities by using an all-sky sample of spiral galaxies to measure the net deviation from the Hubble flow, averaged over a large region ($50 h^{-1}\text{Mpc}$). The advantage of this dynamical approach as a probe, is that peculiar velocities measure the gravitational mass of both light and dark matter. Fig. 1.2 indicates that neutrinos produce larger amplitude fluctuations than cdm on scales $> 10 h^{-1}\text{Mpc}$ and it may be possible to distinguish between these models by comparing the observed velocity residuals with the predictions from linear perturbation theory. Chapter 3 details the background to the Hubble flow programme and reviews the main conclusions drawn from previous experiments of a similar nature. The advantages of infrared techniques are also stressed. In Chapter 4 the observations and data reduction are described. The data analysis is presented in Chapter 5 along with a critical discussion of its limitations. The possible cosmological implications of the result from the Hubble flow project, with regard to neutrinos and cdm are clearly outlined in Chapter 6

CHAPTER 2

AN INFRARED SEARCH FOR PRIMEVAL GALAXIES

2.1 Introduction

One of the most outstanding problems facing observational cosmology is to explain the existence of galaxies and determine the epoch of galaxy formation. The gravitational instability picture (discussed in Chapter 1) gives the most complete description of galaxy formation. In this theory the size of the first objects to collapse depend on the nature of the fluctuations prior to decoupling. In this way, galaxies could have formed at any redshift between $z \sim 3-100$. In the isothermal scenario, galaxies form before clusters at $z > 10$. In the adiabatic scenario galaxy formation must have occurred at $z < 10$ and if the theory is made to fit the two point correlation function (ξ), then galaxy formation must have taken place at $z \sim 1-3$. Similar conclusions result if the Universe is dominated by neutrinos.

While there is this vast body of theoretical literature on the subject of galaxy formation, there is, as yet, little constraint from observations. The specific predictions of the isothermal and adiabatic scenarios, for the epoch of galaxy formation, make the search for young galaxies a particularly worthwhile undertaking. Moreover, in view of the expected high redshift for the epoch of galaxy formation, primeval galaxies may well be IR objects.

2.2 Primordial Star Formation

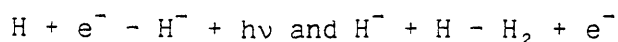
The objects we seek are the progenitors of elliptical and spiral galaxies. The details of the earliest star formation in these systems remain a matter of speculation, since little is understood about the dominant physical mechanisms which take place. In particular, estimates of the mass and temperature of the first generation of stars can only be arrived

at from very general considerations.

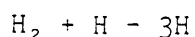
The current speculation is that after decoupling the first generation of stars forms by the collapse and fragmentation of primordial gas clouds, that were initially pressure supported. This will be the case in either the adiabatic or isothermal galaxy formation scenario, as the concept of pregalactic evolution is similar for the two models. The fate of adiabatic fluctuations of $\sim 10^{13} M_{\odot}$, is to fragment soon after forming planar "pancake" structures. Gravitational instability has the most important effect on fragmentation and this results in fragments of mass given by Eqn. 1.29, viz.

$$M \sim 10^8 n_0^{-1/2} M_{\odot}$$

where n_0 is the particle number density. In both the isothermal and adiabatic scenarios galaxies are built up by the coalescing and infall of fragments, which do not remain separate units, but reconstitute themselves into larger clouds (Larson 1974a, Gott & Thuan 1976). In the absence of any heavy metals, the most important coolant is molecular hydrogen, (Hirasawa 1969) which is produced via the reactions



These reactions can proceed due to a residual fractional ionization $\sim 10^{-4}$ $\sim 10^{-5}$ remaining after decoupling (Peebles & Dicke 1968). Density fluctuations are produced because the H_2 cooling regime is thermally unstable. A small decrease in temperature reduces the H_2 dissociation rate (which is exponentially sensitive to temperature) and therefore further enhances cooling (Sabano et al. 1977). The maximum size of resulting condensations is $< 10 M_{\odot}$. H_2 plays no further role once the temperature and density exceed 2000 K and $10^{14} m^{-3}$ respectively. At this point H_2 is destroyed by the process



Subsequent cloud collapse is adiabatic with further cooling at $T \sim 10^4$ K proceeding by Lyman alpha ($L\alpha$) radiation. Once heavy elements are produced by early generations of stars the cooling rate of a cloud is greatly increased. Molecular and grain cooling then tends to reduce the temperature to something approaching that of molecular clouds in the Milky Way, ~ 100 K. In a primeval galaxy at $z > 2.5$, star forming regions could not cool to temperatures ~ 10 K, because of the CBR at a temperature of $2.9(1+z)$ K. Since the cloud temperature determines the minimum Jeans mass (M_j), the CBR produces a low mass cut off for stars forming at high redshift. Assuming normal dust abundance, then at $z \sim 10$, $M_j > 1$ Mo. If the dust abundance is reduced, as is likely at high redshift, say by ~ 100 , a similar minimum Jeans mass occurs at $z \sim 25$ (Low & Lynden-Bell 1976). To conclude, consideration of the absence of heavy metals and heating due to the CBR, indicates that the mass function of the first generation of stars will be biased towards the high end.

In the pioneering galaxy formation scenario of Partridge & Peebles (1967a, 1967b, hereafter P & P) galaxies undergo a rapid burst of star formation lasting some 3×10^7 yrs at the onset of galaxy collapse. Similar timescales are predicted in the dissipationless collapse models of Gott (1975) and Gott & Thuan (1976), who also predict that the star formation will be completed by the time the disk forms. More recently, this picture of the bright phase has been modified. Larson's (1969, 1974b, 1975, 1976) collapse models involve both stellar and gas dynamics, with slow gas infall through a background of already-formed stars. The models incorporate a realistic star formation rate which depends on some power of the gas density. In these models the dynamical collapse timescale is $\sim 10^9$ - 10^{10} yrs. Kaufman's (1976) freefall models of the Galaxy exclude a highly luminous phase while the galaxy is still extended, since this would be inconsistent with the observed metal abundance as a function of height above the galactic plane.

Processes which may inhibit the collapse and fragmentation of clouds, such

as radiation trapping and radiation pressure, are for the most part negligible (Rees & Ostriker 1977). So star formation in young galaxies may well be a relatively efficient and spectacular affair with the likelihood that a primeval galaxy will consist of many giant HII regions with light radiated from O and B type stars. The resulting spectrum of such a young galaxy may resemble that shown in Fig. 2.1, reproduced from Sunyaev et al. (1978). This spectrum is based on the observations of MKN 33 and the infall models of Larson (1975, 1976), but its general features are common to all models which predict the formation of massive stars. The strongest features of Fig. 2.1 are the $L\alpha$ line, which could radiate as much as 15% of the bolometric luminosity, and the $L\alpha$ break at $\lambda = 912(1+z)$ Å, shortward of which the primeval galaxy will be invisible.

The spectrum in Fig. 2.1 will be observed if the primeval galaxy contains no dust. Evidence for less dust at high redshift comes from the fact that quasars are unobscured, emitting strongly in the UV and optical wavebands. In addition, the recently discovered high redshift ($z \sim 3.2$) galaxy is a strong $L\alpha$ emitter, indicating little or no dust (Djorgovski et al. 1985). Extinction caused by intervening dust is probably not important for testing models out to $z \sim 10$ (Boughn et al. 1986).

2.3 Observable Parameters

2.3.1 Luminosity

The feasibility of a primeval galaxy search depends heavily on the assumption that galaxies were ~ 100 - 1000 times brighter than they are today, and thus detectable at cosmological distances. Evidence that early galaxies were bright comes from the fact that the oldest disk stars are not particularly metal poor, with the mass fraction of heavy metals (x) ~ 1 - 2% (P&P). These metals must have been formed during the early collapse of the disk, over a period corresponding to the free-fall time (Δt), given by

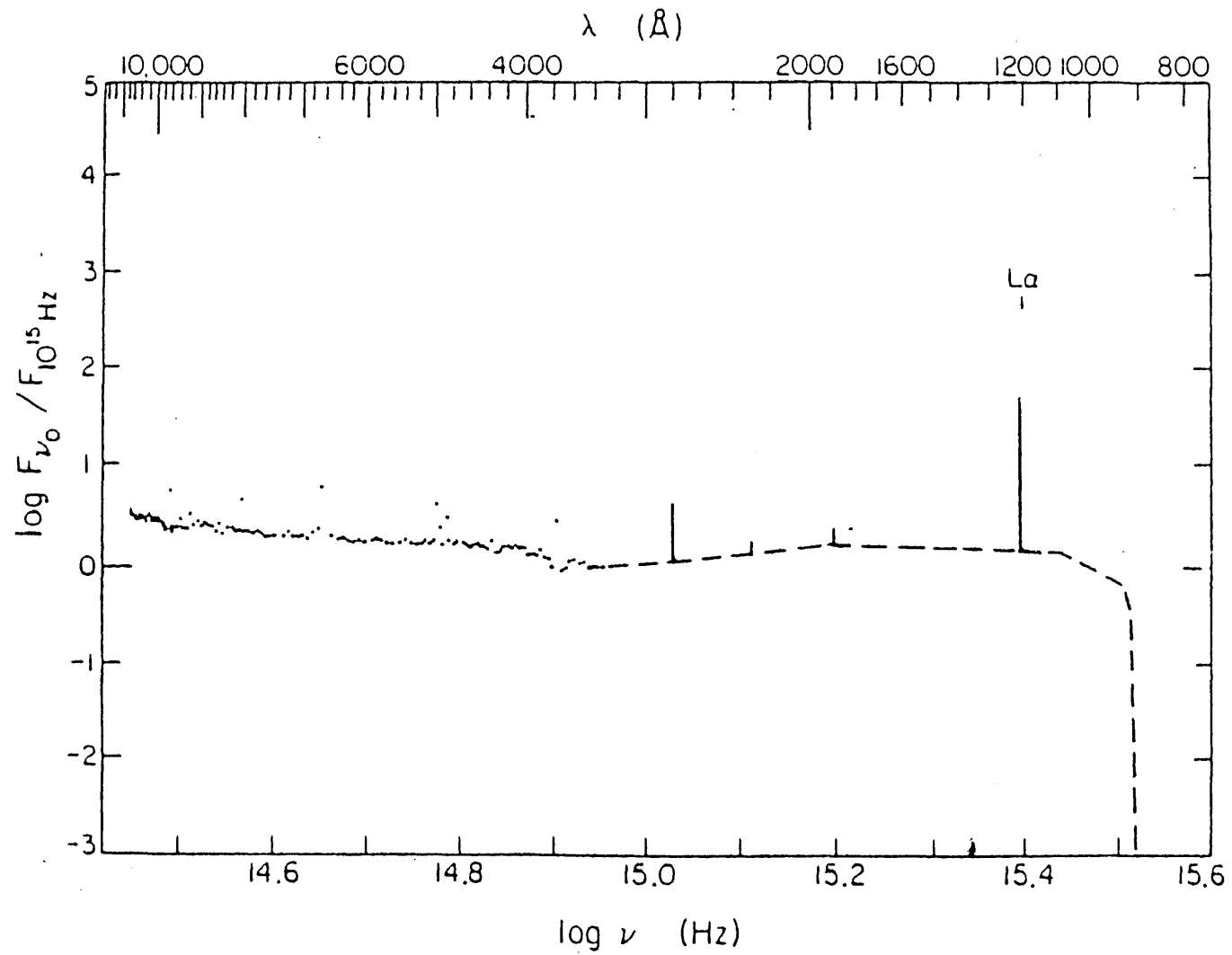


Figure 2.1 Putative spectrum for a primeval galaxy in its rest frame (Sunyaev et al. 1978). The data shortward of $\log \nu_0 \sim 15$ are from the blue galaxy MKN 33. At large wavelengths the continuum is that predicted from Larson's models.

$$\Delta t \sim (G\rho)^{-1/2} \sim 10^8 - 10^9 \text{ yrs}$$

where G is the gravitational constant and ρ the density. The luminosity is then given by

$$L^{\text{PG}} = (0.007) \frac{XMc^2}{\Delta t} \quad 2.1$$

where M is the galaxy mass $\sim 5 \cdot 10^{11} M_\odot$. Masses $M > 10^{12} M_\odot$ are prevented from collapsing due to the cooling timescale exceeding the dynamical collapse timescale, resulting in the galaxy not cooling over the Hubble time (Rees & Ostriker 1977).

Equation 2.1 predicts luminosities $\sim 10^{39} - 10^{40} \text{ W}$ for infall times $\Delta t \sim 10^8 \text{ yrs}$, consistent with the predictions of P & P, while Kaufman finds similar peak luminosities during the collapse, viz. $4 \cdot 10^{39} \text{ W}$, for a galaxy of $10^{11} M_\odot$. The longer collapse timescales predicted by Larson imply smaller luminosities $\sim 10^{38} - 10^{39} \text{ W}$. Luminosities predicted in this way are rather uncertain due to the unknown nature of the "dark matter", which constitutes the bulk of the galaxy mass (Boughn et al. 1986). For this reason the real luminosity of a typical primeval galaxy could be many times higher than any of the estimates discussed.

2.3.2 Angular Diameter

Angular diameters are given by $\theta = D/d_A$, where D is the linear diameter and d_A is the angular diameter distance given by

$$d_A = [c/H_0(1+z)^2] \frac{[q_0 z + (q_0 - 1)((1 + 2q_0 z)^{1/2} - 1)]}{q_0^2} \quad 2.2$$

The angular diameter distance is the effective distance, in a Friedmann type cosmology, for which an object of linear diameter D subtends an angular diameter θ (Weinberg 1972). Values of θ for a 20 kpc region are

shown vs, redshift in 4 world models in Fig. 2.2. The linear diameter of a primeval galaxy will depend on the star formation rate as a function of collapse. In the models of P & P, Gott (1975), and Gott & Thuan (1976) the brightest phase of the young galaxy occurs while it is extended ~ 30 kpc, hence primeval galaxies at $z \sim 10$, could very well be ~ 10 arcsec in diameter. In Larson's models the star formation rate is at its fastest stage after the galaxy has collapsed to some 10 kpc. This results in centrally condensed objects with angular diameters only a few arc secs wide (Sunyaev, Tinsley & Meier 1978).

2.3.3 Areal Density

The expected number of primeval galaxies per steradian at redshift z is given by,

(number density at z)*(volume of bright phase region subtending 1 str) or

$$N = (1+z)^3 c \Delta t d_A^2 n_0 \quad 2.3$$

where Δt is the period of the bright phase and n_0 is the local number density of galaxies. Assuming $\Delta t \sim 10^8$ yrs, $n_0 \sim 0.01 h^3 \text{Mpc}^{-3}$, a value consistent with the recent estimates of Davis & Huchra 1982, and also assuming that all galaxies went through a similar bright phase, the expected number density for $\Omega \sim 1$, can be written as

$$N = 3.4 \cdot 10^3 \frac{(n_0)}{(0.01)} \frac{(\Delta t)}{(10^8)} \frac{(z - (1+z)^{1/2} + 1)^2 h}{(1+z)} \quad 2.4$$

where n_0 is in units of Mpc^{-3} and Δt is in units of yrs. Therefore at $z = 5$, $N \sim 7 \cdot 10^3 \text{ hdeg}^{-2}$ and at $z = 10$, $N \sim 2 \cdot 10^4 \text{ hdeg}^{-2}$. If $\Omega = 0.2$ then

$$N = 8.4 \cdot 10^6 \frac{(n_0)}{(0.01)} \frac{(\Delta t)}{(10^8)} \frac{(0.1z - 0.9[(1+0.2z)^{1/2} - 1])^2 h}{(1+z)} \quad 2.5$$

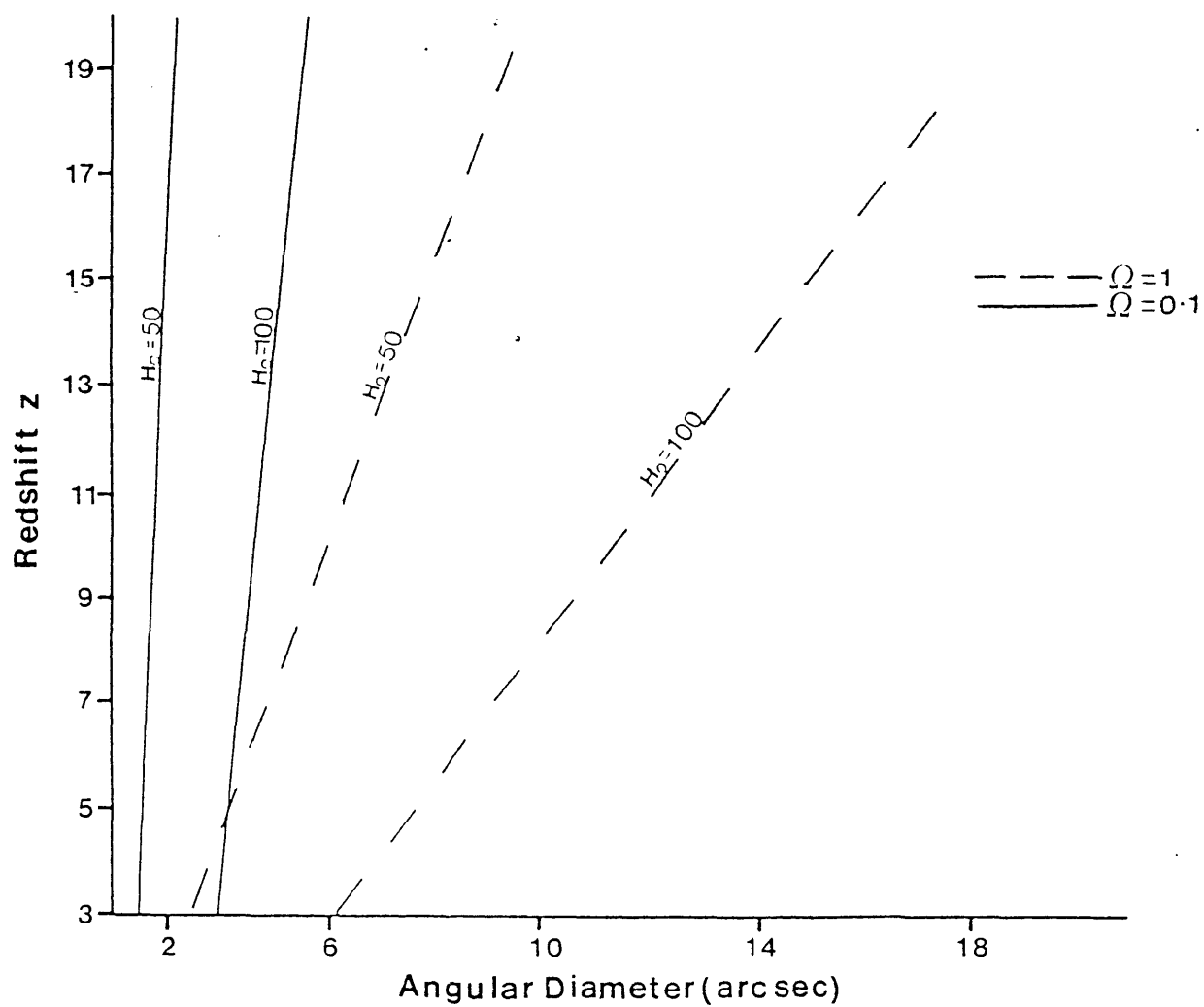


Figure 2.2 Angular diameter v's redshift for a 20 kpc region in 4 world models ($H_0 = 50$ and 100 km/sec/Mpc, $\Omega = 0.1$ and 1).

At $z = 5$, $N \sim 2.2 \cdot 10^4 \text{ hdeg}^{-2}$, while at $z = 10$, $N \sim 10^5 \text{ hdeg}^{-2}$.

Primeval galaxies are therefore not rare and these large number densities make searches for them possible without recourse to array detectors. As noted by Davis (1980), "it is much preferable to survey a small region very deep" than to scan large areas of sky.

2.4 Review of Previous Searches

2.4.1 Introduction

There have been two approaches to search for dust free primeval galaxies and determine the epoch of galaxy formation. One has been to detect a bona fide primeval galaxy directly, and the other has been to measure the integrated background light due to primeval galaxies.

2.4.2 Searches for Single Primeval Galaxies

Partridge (1974) used both photoelectric photometry and photographic plates (6200-7800 Å and 4000-6700 Å respectively) to search for primeval galaxies of angular size consistent with the P & P models, i.e. > 10 arcsec. The result of both searches was negative, with a sensitivity limit for a single object of $37 \mu\text{Jy}$. Davis and Wilkinson (1974) also looked for the P & P type objects with angular sizes 10-30 arcsec. They searched an area of $20,000 \text{ arcsec}^2$ in the red (6200-8900 Å) and they also obtained a negative result. The maximum flux density from a single object that could have escaped detection in their search is $38 \mu\text{Jy}$. While these two searches are sufficiently sensitive to test the P & P models out to $z \sim 6$, they do not constrain the models of Larson and Kaufman, which predict smaller angular sizes and luminosities. In addition, their pass bands are too blue for epochs of galaxy formation $z > 6$. Indeed P & P conclude that young galaxies in their model would have peak luminosity in the $1 \mu\text{m}$ to 3 mm wavelength region, as a result of the high formation redshift. Koo and Kron (1980) searched for the $\text{Ly}\alpha$ emission feature, which would occur if the

primeval cloud were sufficiently dense and clumpy. They used both a CCD and IV-N plates as detectors and were sensitive to objects < 5 arcsec, with a detection limit of $4 \mu\text{Jy}$. These upper limits suggest that the epoch of galaxy formation may be at $z > 5$.

2.4.3 Background Light Measurements

There have been many attempts to measure the integrated background light, (Roach & Smith 1968, Lillie 1971, Mattila 1976, Dube, Wickes & Wilkinson 1977, 1979, Spinrad & Stone 1978, Toller 1983). These experiments reached a limit of $3 \times 10^{-8} \text{ W m}^{-2} \text{ Sr}^{-1}$ at 5100 Å. This limit is below the predictions of most formation models for epochs of formation $z < 5$ (Toller 1983). However, for galaxies forming at higher redshift this limit is higher than the predicted background. For instance, P & P calculate a background, at this wavelength, which is a factor of 10 smaller, even though their formation model is one of the most luminous.

These experiments were all carried out below a wavelength of $1 \mu\text{m}$ and the results demonstrate the limitations of optical techniques. For formation redshifts of most interest, $z \sim 5-10$, primeval galaxies, and the extra-galactic background from them, will have redshifted into the near-infrared. A recent attempt has been made to detect fluctuations in the near-infrared background, at K, on scales ranging from 10-300 arcsec (Boughn et al. 1986). Monte Carlo calculations set 90% confidence level upper limits of $\sim 10 \mu\text{Jy}$ on scales ranging from 10-30 arcsec, and $200 \mu\text{Jy}$ on scales from 60-300 arcsec, if the data is interpreted as noise.

2.5 Near-Infrared Search Programme

2.5.1 Introduction

There are two aspects to any primeval galaxy search programme. Firstly, a candidate primeval galaxy has to be detected at a significant level. This involves searching enough area of sky to enough sensitivity. Secondly,

any candidate object has to be followed up by observations to discriminate between a genuine young galaxy and faint foreground objects.

2.5.2 Method of Detection

The feasibility of searching for objects at high redshift is determined partly by the expected flux density, S_ν

$$S_\nu = \frac{L^{\text{pg}} \epsilon(T'_{\text{pg}})}{4\pi d_A^2 (1+z)^4 \Delta\nu} \quad 2.6$$

(Weinberg 1972). Here L^{pg} is the bolometric luminosity, T'_{pg} is the temperature of the redshifted spectrum, ϵ is the fraction of radiation in the spectrum found in the observed frequency band $\Delta\nu$, and d_A is the angular diameter distance defined in Eqn. 2.2. Taking $T_{\text{pg}} \sim 10^4$ K, $z \sim 7$, $\Omega = 1$, $h = 1$ and using the results obtained from Eqn. 2.1, the expected flux requires integration times ~ 10 minutes per pixel, for a 5 σ detection using UKIRT at K, with an 8 arcsec aperture. This assumes a sensitivity at K for 1 σ 1 sec of 0.5 μ Jy.

The minimum area, A , needed to be searched in order that at least 1 primeval galaxy be in the beam at some time (if the distribution of primeval galaxies is represented by Poissonian statistics) is given by

$$1 - e^{-NA} > 0.9 \quad 2.7$$

A Poissonian distribution is an assumption of maximum ignorance, since there is no reliable estimates of the evolution of the clustering of galaxies with time. At the redshifts of formation tested by this experiment it is most likely that galaxies formed in independent regions of space, with clustering developing after the bright phase. This hierarchical scenario is not inconsistent with observations of the large scale structure at the present time (Chapter 1).

For areal densities $N \sim 10^4 \text{ hdeg}^{-2}$, the area required to be covered $\sim 1500 \text{ arcsec}^2$. With integration times of $\sim 10\text{-}20$ minutes per pixel, the required search area can be completed in only a few nights of telescope time.

The search strategy was a 1 dimensional deep survey, at J and K, of areas of sky that appeared blank on the Palomar Sky Survey red plates. This survey has a limiting magnitude for point sources of $m_r \sim 20.5$ (6500 A). The chosen blank fields were located near the central positions of the blank fields searched by Davis & Wilkinson (1974), at RA = 17 hrs and 22 hrs. These blank fields are well away from Zwicky clusters and known radio sources. The limit from Davis & Wilkinson (1974) of $37 \mu\text{Jy}$ or $m_r \sim 20$, provide constraints below the plate limit for extended objects. An aperture of 8 arcsec was chosen as this was the smallest with which to remain background limited and was unlikely to resolve a primeval galaxy based on the expected diameters shown in Fig. 2.2. A chop throw of 16 arcsec was adopted, which maximised the contrast of signals in the object and reference beams, based on the likely separation of primeval galaxies at $z \sim 10$ (i.e. $> 20 h^{-1/2} \text{ arcsec}$). The small chop and aperture size used made the observations less prone to sky transmission variations and other systematics.

2.5.3 Method of Recognition

Significant discrimination between extra-galactic objects and primeval galaxies can be made using an infrared JHK colour-colour diagram. The utility of colour-colour diagrams in recognising primeval galaxies has been stressed by Meier (1976). Figure 2.3 shows the colours of various possible foreground objects compared to the computed colours of dust-free primeval galaxies, assuming a Larson or P & P type spectrum, i.e an object with effective temperature $T_{\text{pg}} \sim 10^4 \text{ K}$, containing no dust. The solid line represents the observed colours of the primeval galaxy continuum only. Between $z \sim 8\text{-}11$ radiated $\text{Ly}\alpha$ will appear in the J band. If $\sim 15\%$ of the radiation shortward of the Lyman break is radiated in this

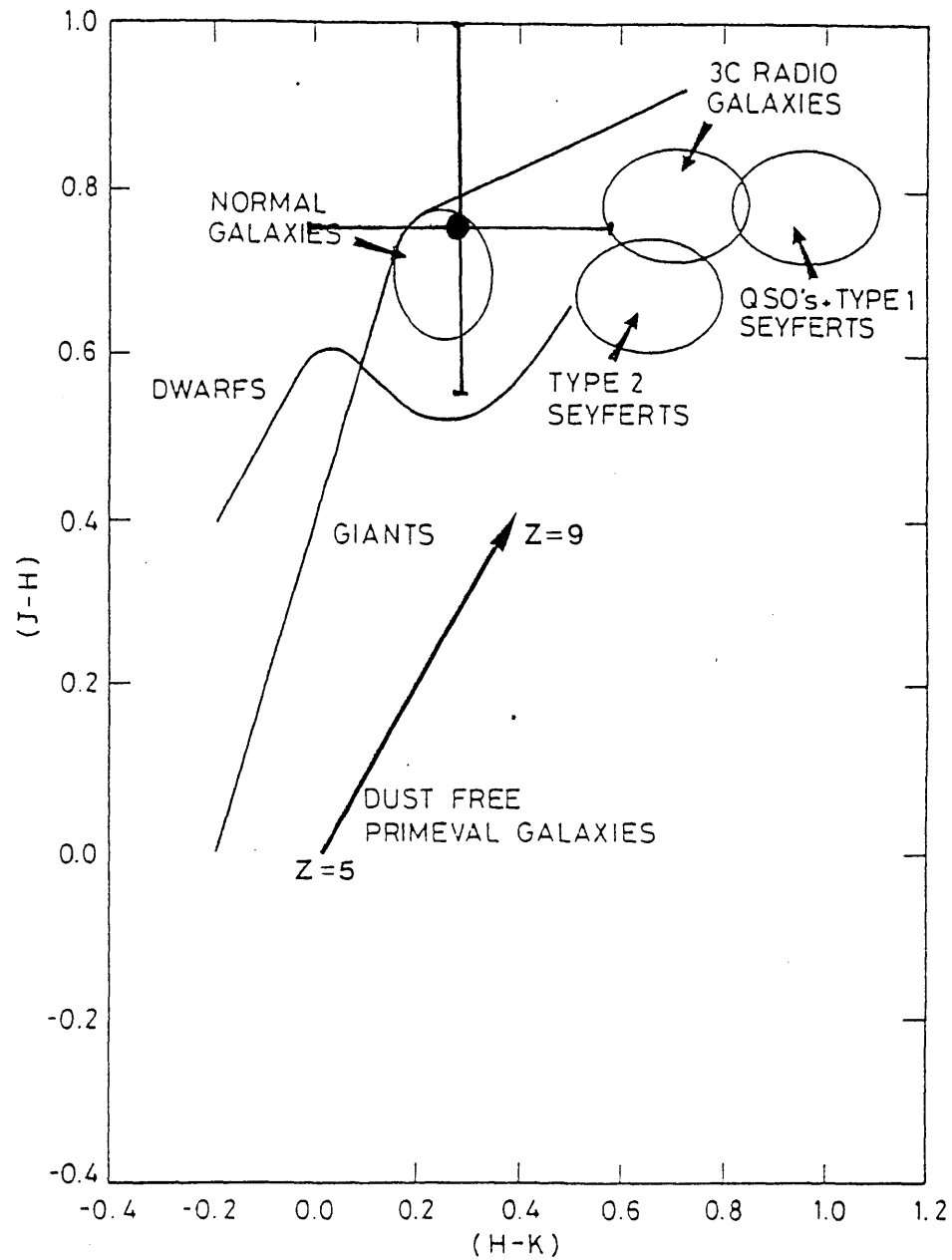


Figure 2.3 The observed J-H, H-K colour-colour diagram for a dust free primeval galaxy with blackbody temperature $T \sim 3 \times 10^4$ K, between the redshifts $z = 5-9$. The colours of some common classes of foreground objects are also shown. The colours and errors of 23b are indicated.

line, as is the case for many HII regions, then J-H may be significantly bluer, viz. $J-H \sim -0.5$ in this redshift region. In addition, some discrimination between primeval galaxies and stars can be made using multi-aperture photometry. Figure 2.2 shows that there is a reasonable chance that primeval galaxies are extended enough, so that it will be possible to resolve them even if they are centrally condensed with a size of $\sim 10\text{kpc}$. The stars likely to be confused with primeval galaxies, on the colour-colour diagram, are those of type O to K0, ie with $J-K \sim 0-0.5$ respectively. However, a star of this type, detected at $\sim 18\text{th}$ magnitude, implies an R band magnitude of 17.4-19.3 based on the R-K colours (Johnson 1966). This limit is above that of red plates, and so any detection of a faint object at K, with blue colours, in a blank field, is unlikely to be a star. A bona-fide primeval galaxy, at $z > 5$, detected at K would not be seen on optical plates due to its finite angular extent and expected reddening shortward of the Lyman break.

2.6 Results

Two observing runs, constituting a total of 7 nights, have been carried out on this project. Further observing was carried out as part of a backup programme on 2 further runs. In June 1984, in a 4 night run we searched 2 areas, totalling 1257 arcsec^2 , simultaneously at J and K with an 8 arcsec aperture using the 2-channel photometer on UKIRT. The search pattern on the sky for the two blank fields is shown in Fig. 2.4. Pixels 3 and 16 are the respective nominal blank field positions, whose co-ordinates were used for offsetting to nearby guide stars. With the exception of pixel 1, 12a and 23b, all pixels were observed on this run with a minimum integration time of 23 minutes.

The data at J and K for this run is included in Table 2.1 and plotted in Figs. 2.5a,b, where the signals and standard errors are shown for each pixel. In every case the signals represent the weighted average of two integrations of 20 and 26 blocks, or 10 and 13 minutes respectively. These observations were completed on nights 1 and 2 of this run, due to

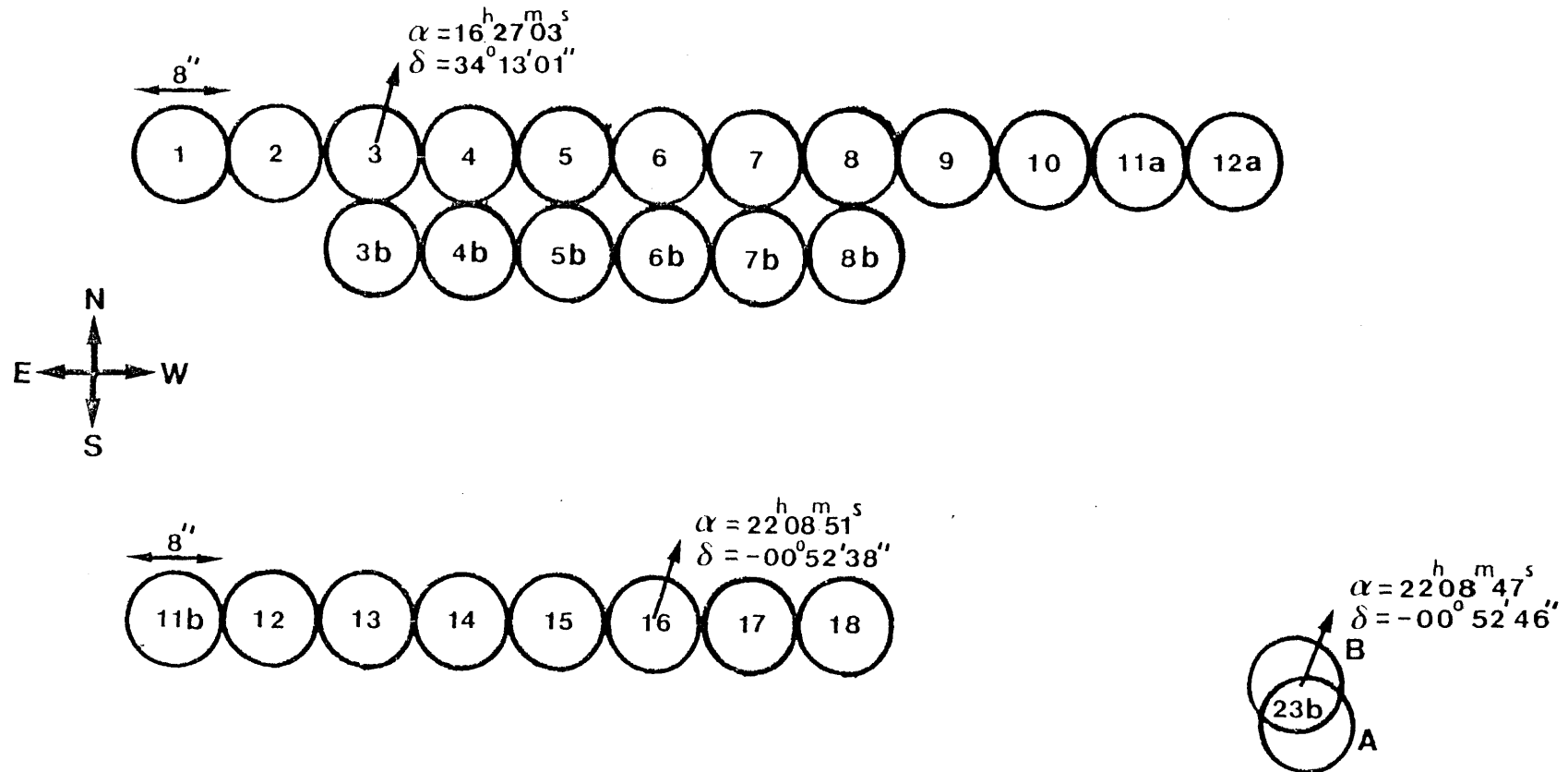


Figure 2.4 The search pattern for the two blank fields indicating the relative positions of pixels within each field. Candidate 23b was discovered serendipitously while observing the blank field at 22hr.

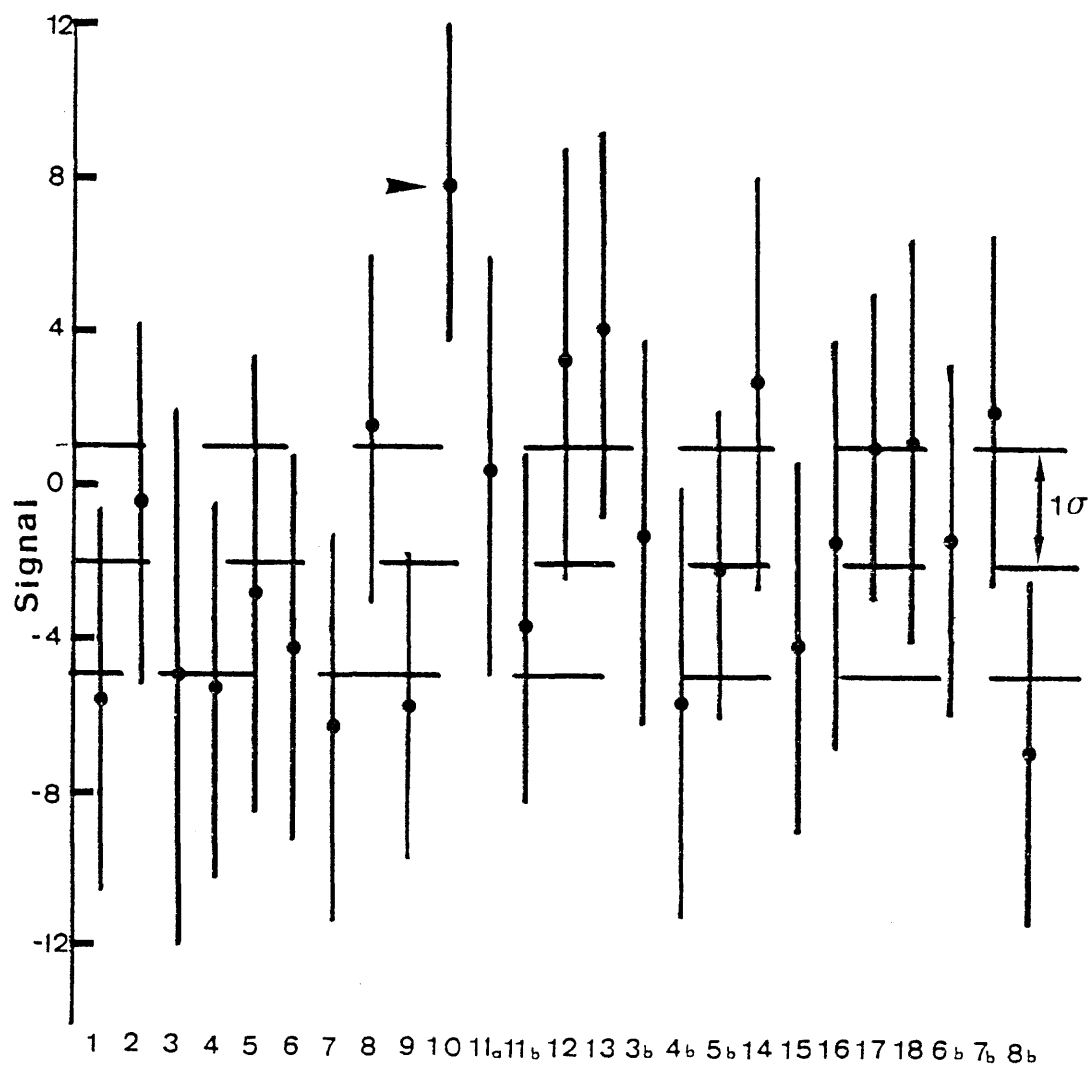


Figure 2.5a Final signals and standard errors for each 26 mins of integration time on each pixel at J during June 1984 observing run. The $\pm 1\sigma$ levels about the mean signal are indicated, along with a putative detection in pixel 10.

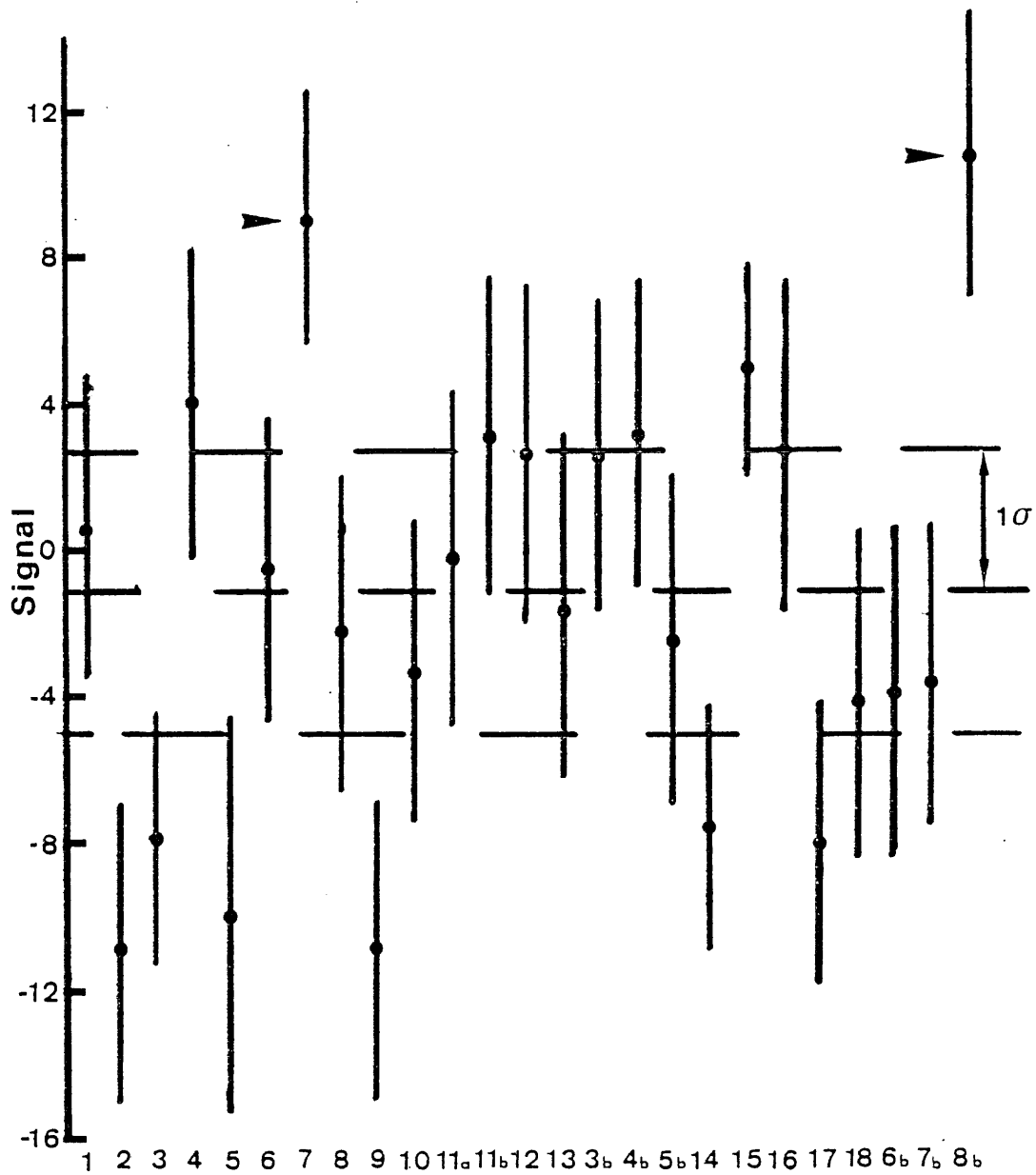


Figure 2.5b Final signals and standard errors for each 26 mins of integration time on each pixel at K during June 1984 observing run. The $\pm 1\sigma$ levels about the mean signal are indicated, along with two putative detections in pixels 7 and 8b.

non-photometric weather on nights 3 and 4. The data presented has had each integration block with signal $> \pm 2$ times the standard deviation of the blocks removed. This eliminates any signals which are the result of spikes. The number of blocks discarded in this way is small, $< 10\%$. Despite the poor weather, this run permitted us to search a useful area of sky. In addition, 1 candidate primeval galaxy was uncovered at J, and a further 2 at K, all of ~ 18 mag. These are in pixels 10, 7 and 8b, shown in Figs. 2.5a,b. In September 1984, as a back up observing programme at UKIRT, a further candidate was detected in pixel 23b at K using UKT 9 (Table 2.2). The candidate objects 10, 7, 8b, and 23b formed the basis for an observing programme which was awarded 4 nights in July 1985. During this run further integrations were carried out on these pixels, firstly to establish confirmation and secondly to obtain colours on confirmed sources. In a period of one and a half photometric nights pixels 4, 6, 6b, 7, 7b, 8, 8b, 12a, 23b were observed at K, pixels 7, 10, 12a, 23b at J and pixel 23b at H. Apart from pixel 23b, all other candidates from the June 1984 observing run were not confirmed as real sources. This is shown in Table 2.1 and Figs. 2.6a,b and 2.7a,b which display the distribution of signal to noise for all the candidates (except 23b) after June 1984 and July 1985, at both J and K. Also plotted are the theoretical curves for the distribution of signal to noise if all pixel signals are drawn from the same Gaussian noise distribution.

Our non-confirmations in July, compared to June 84, for all but one of the pixels, were made with the increased sensitivity (~ 0.15 mag at K and ~ 0.4 mag at J) of UKT 9. In other respects, both the observing procedure and observational parameters in July 1985, were identical to those of the previous year. Finally, pixel 23b was observed at JHK again in September 1985 using UKT 9. All observations of blank sky are summarised in Tables 2.1 and 2.2.

The observations of 23b have been made at two positions A and B indicated in Fig. 2.4. These two positions are the result of a small change in plate scale due to a secondary mirror replacement on UKIRT sometime after

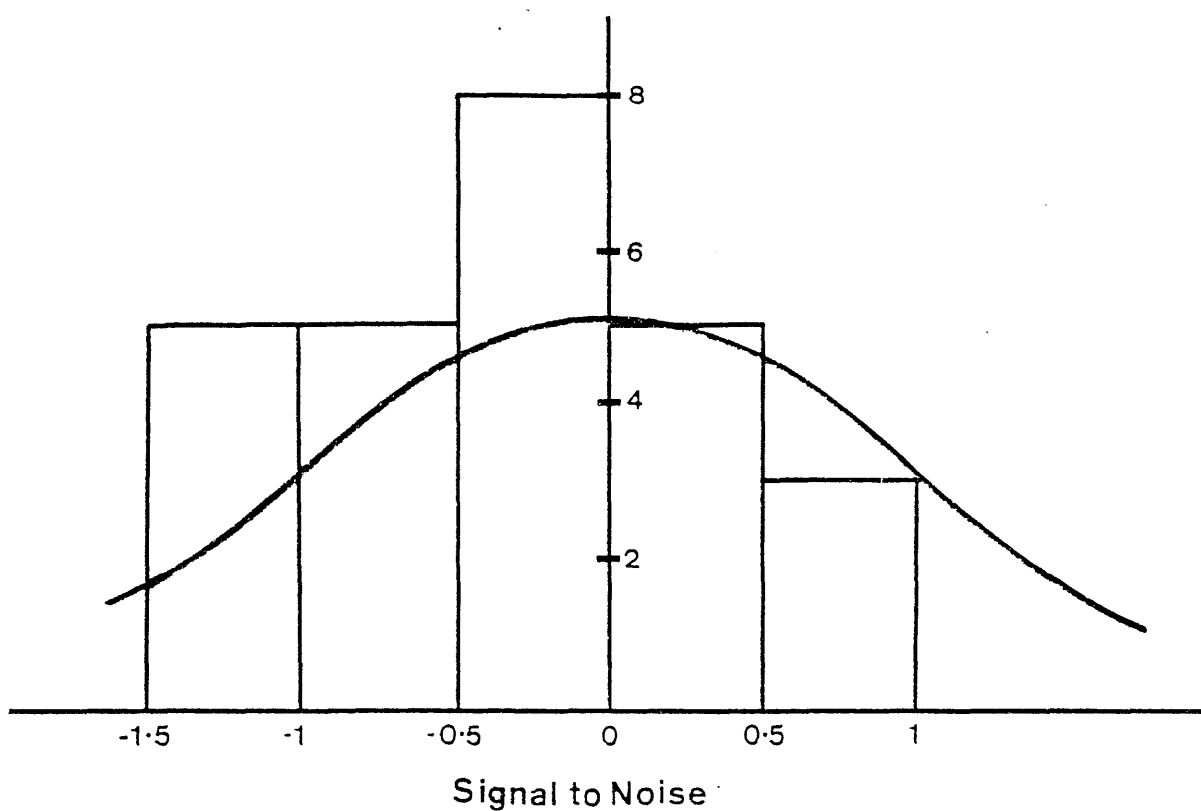
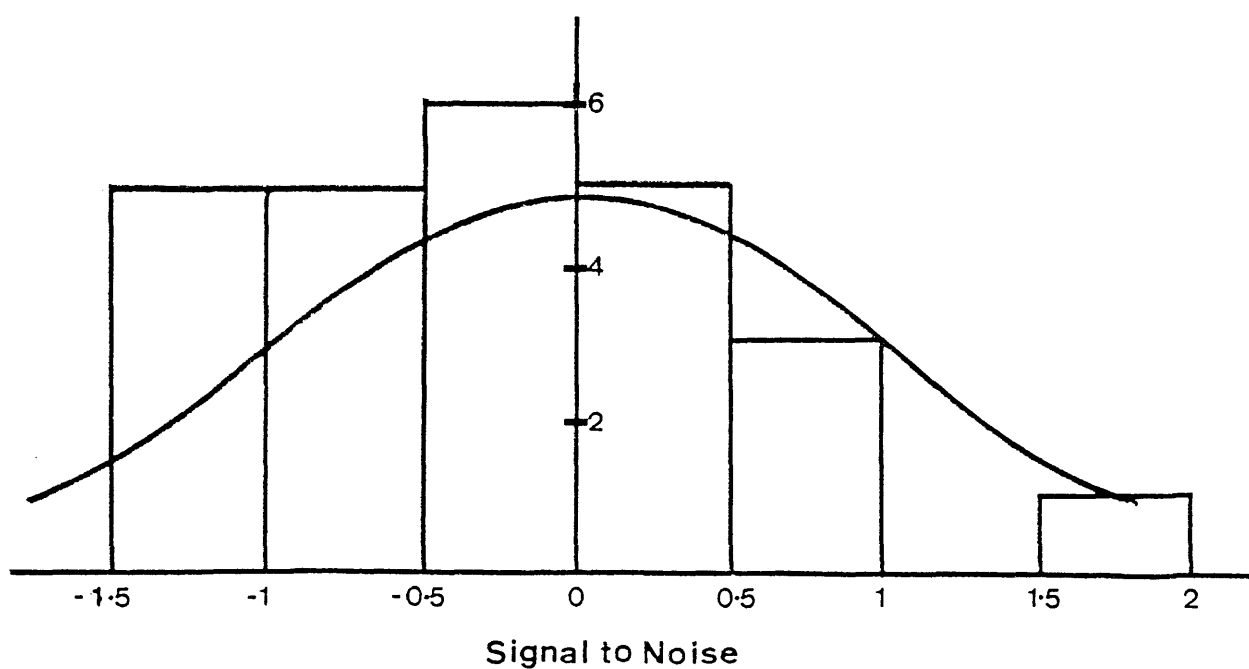
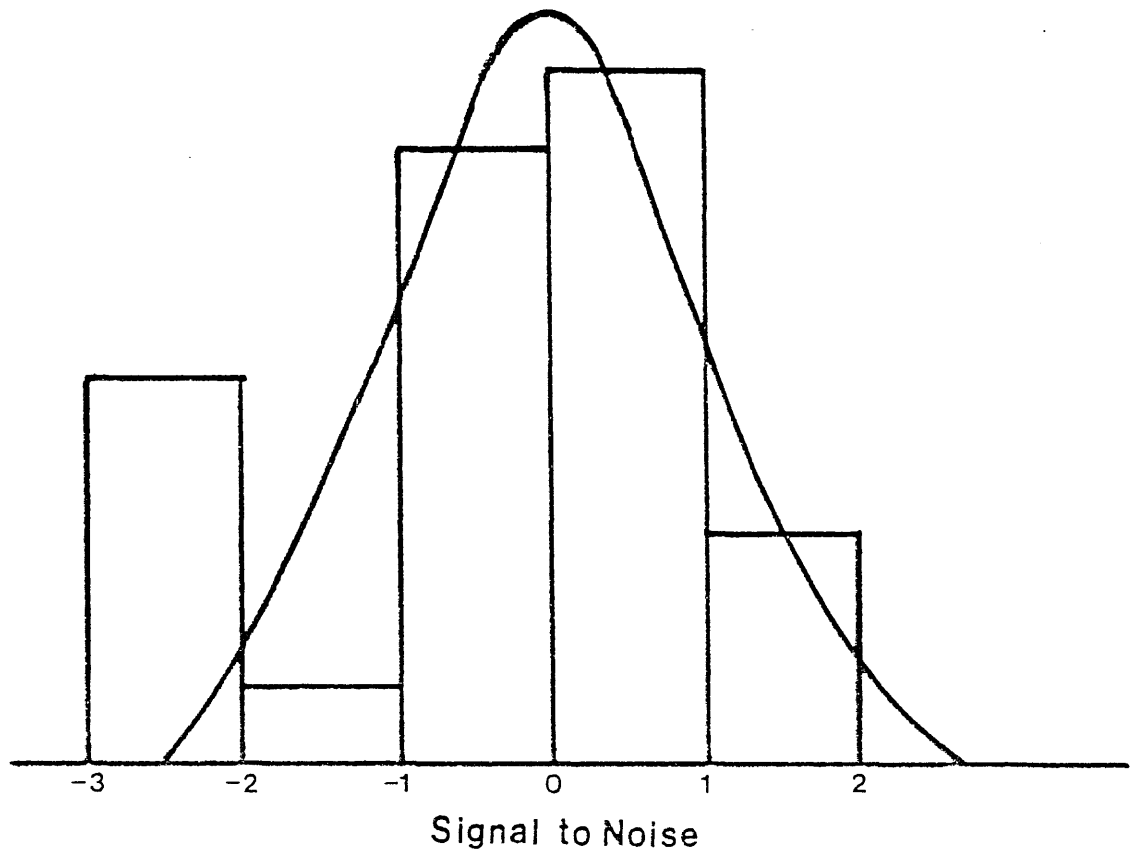
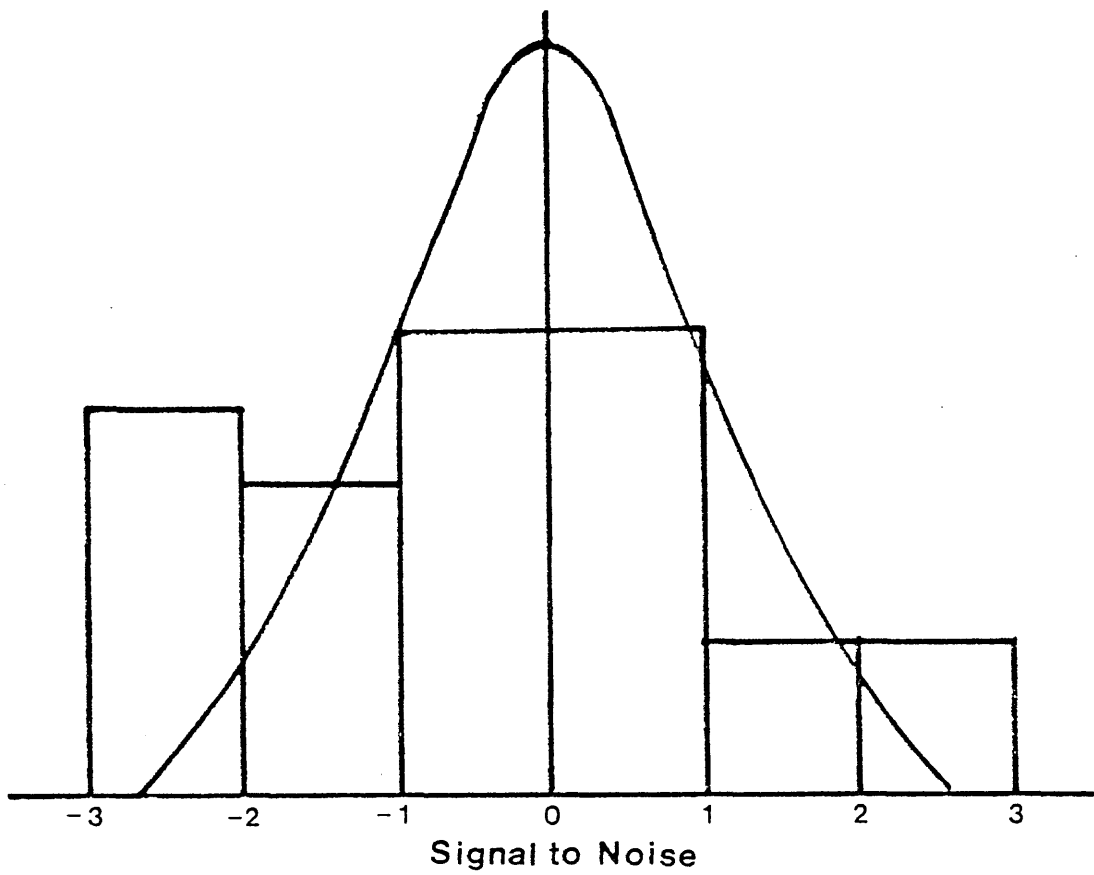


Figure 2.6a,b The distribution of signal to noise for all pixels after the June 1984 run (top) and July 1985 run (bottom) at J. The Gaussian noise distribution with zero mean is also shown.



Figures 2.7a,b The distribution of signal to noise for all pixels after the June 1984 run (top) and July 1985 run (bottom) at K. The Gaussian noise distribution with zero mean is also shown.

June 1984. Both positions A and B were observed extensively in July and September 1985, using either an 8 or 12 arcsec aperture and with chop throws of either 16 or 60 arcsec. Experiment showed no detectable difference in observed signal between these combinations. A discussion of the detections of this candidate is given in section 2.7.2.

Table 2.1

Summary of Blank Field Observations

J Intergrations

Pixel No	Date	Signal	Final Signal
1	June 1984	-4.4 ± 6.5	
	" "	-8.2 ± 9.4	-5.6 ± 5.0
2	June 1984	5.3 ± 5.6	
	" "	-12.2 ± 8.2	-0.5 ± 4.7
3	June 1984	-6.0 ± 7.0	
	" "	-4.5 ± 7.6	-5.3 ± 5.0
4	June 1984	-4.3 ± 8.0	
	" "	-13.6 ± 7.3	-5.0 ± 7.0
5	June 1984	-8.5 ± 7.3	
	" "	-8.2 ± 10.0	-2.7 ± 5.9
6	June 1984	-3.9 ± 7.9	
	" "	-4.5 ± 6.8	-4.2 ± 4.9

7	June 1984	5.0 ± 8.0	
	" "	-13.3 ± 6.3	
	July 1985	-1.5 ± 2.3	2.3 ± 1.4
8	June 1984	7.6 ± 6.0	
	" "	-6.5 ± 6.8	1.5 ± 4.5
9	June 1984	-8.0 ± 6.0	
	" "	-3.3 ± 6.2	-5.7 ± 4.0
10	June 1984	-4.3 ± 7.5	
	" "	17.8 ± 6.8	
	July 1985	-4.9 ± 2.8	
	" "	4.0 ± 2.7	
	" "	-4.2 ± 2.3	
	" "	1.4 ± 2.5	-0.5 ± 1.2
11a	June 1984	-4.0 ± 8.0	
	" "	-2.8 ± 7.6	0.4 ± 5.5
11b	June 1984	-4.0 ± 5.7	
	" "	-0.7 ± 7.2	-3.7 ± 4.5
12	June 1984	4.0 ± 7.3	
	" "	2.0 ± 8.7	3.2 ± 5.6
13	June 1984	9.2 ± 7.0	
	" "	-9.0 ± 7.0	
	" "	4.2 ± 7.0	4.2 ± 5.0
3b	June 1984	-1.7 ± 7.0	
	" "	-1.3 ± 7.0	-1.2 ± 5.0

4b	June 1984	-1.9 ± 8.2	
	" "	-0.0 ± 7.8	-5.6 ± 5.7
5b	June 1984	0.3 ± 5.4	
	" "	-5.8 ± 6.7	-2.1 ± 4.2
14	June 1984	7.3 ± 6.9	
	" "	-4.8 ± 8.7	2.8 ± 5.4
15	June 1984	-5.7 ± 5.9	
	" "	-0.7 ± 8.5	-4.1 ± 4.8
16	June 1984	-1.3 ± 6.7	
	" "	-1.9 ± 8.3	-1.5 ± 5.2
17	June 1984	4.3 ± 4.0	
	" "	-10.1 ± 7.4	1.0 ± 4.0
18	June 1984	1.3 ± 7.2	
	" "	1.2 ± 7.8	1.2 ± 5.3
6b	June 1984	3.7 ± 6.0	
	" "	-8.0 ± 7.0	-1.3 ± 4.6
7b	June 1984	0.2 ± 5.7	
	" "	4.8 ± 6.7	2.1 ± 4.3
8b	June 1984	-9.8 ± 5.6	
	" "	-1.8 ± 7.6	-6.9 ± 4.5
12a	July 1985	-2.2 ± 2.0	-2.2 ± 2.0

K Integrations

Pixel No	Date	Signal	Final Signal
1	June 84	-2.9 ± 5.2	
	" "	6.5 ± 6.8	0.57 ± 4.1
2	June 84	-13.1 ± 5.6	
	" "	-9.2 ± 5.8	-11.2 ± 4.0
3	June 84	0.3 ± 6.2	
	" "	-11.5 ± 4.1	-7.9 ± 3.4
4	June 84	-4.3 ± 5.4	
	" "	18.4 ± 7.1	
	July 85	-4.5 ± 3.6	-0.9 ± 2.7
5	June 84	-5.5 ± 7.2	
	" "	-15.1 ± 7.8	-10.0 ± 5.3
6	June 84	2.6 ± 5.8	
	" "	-3.9 ± 6.0	
	July 85	1.3 ± 6.5	0.0 ± 3.5
7	June 84	5.6 ± 4.9	
	" "	12.1 ± 4.9	
	July 85	1.3 ± 4.5	
	" "	-2.0 ± 4.2	3.8 ± 2.3

8	June 84	-5.8 ± 5.2	
		4.9 ± 7.6	
		1.0 ± 4.3	-0.6 ± 3.0
9	June 84	-13.4 ± 6.8	
		-9.5 ± 4.9	-10.8 ± 4.0
10	June 84	6.5 ± 6.5	
	" "	-7.8 ± 4.6	-3.3 ± 4.0
11a	June 84	0.6 ± 6.9	
	" "	-0.8 ± 6.0	-0.2 ± 4.5
11b	June 84	4.3 ± 4.3	
	" "	-2.9 ± 9.2	3.1 ± 4.4
12	June 84	-2.3 ± 6.3	
	" "	7.4 ± 6.3	2.6 ± 4.5
13	June 84	-2.5 ± 6.5	
		0.8 ± 7.0	
		-3.6 ± 6.3	-2.0 ± 4.0
3b	June 84	-3.3 ± 7.6	
	" "	5.2 ± 4.9	2.7 ± 4.1
4b	June 84	8.4 ± 5.8	
	" "	-2.0 ± 5.7	3.2 ± 4.1
5b	June 84	-4.2 ± 6.0	
	"	-0.2 ± 6.9	-2.5 ± 4.5
14	June 84	-14.0 ± 4.5	
	" "	0.5 ± 5.0	-7.5 ± 3.3

15	June 84	15.4 ± 4.2	
	" "	-2.3 ± 7.6	5.0 ± 2.8
16	June 84	5.7 ± 5.6	
	" "	-2.3 ± 7.6	2.9 ± 4.5
17	June 84	-16.3 ± 6.5	
	" "	-3.6 ± 4.7	-8.0 ± 3.8
18	June 84	-7.5 ± 6.3	
	" "	-0.1 ± 6.3	-3.8 ± 4.5
6b	June 84	2.0 ± 5.4	
	" "	-8.0 ± 6.1	
	July 85	3.4 ± 3.7	
	" "	-0.1 ± 5.0	0.6 ± 2.6
7b	June 84	-11.2 ± 6.9	
	" "	0.3 ± 4.9	
	July 85	-5.6 ± 4.3	
	" "	1.9 ± 5.4	-1.9 ± 2.0
8b	June 84	14.6 ± 8.9	
	" "	9.8 ± 4.7	
	July 85	-3.9 ± 4.3	4.2 ± 2.9
12a	July 85	3.3 ± 5.6	

Table 2.2

Observations of Candidate Pixel 23b

J Integrations

Date	Position A		Aperture & Chop
	Signal	Final Signal	
July 1985	6.4 ± 2.7		
" "	4.1 ± 2.5		
" "	2.2 ± 1.9	3.7 ± 1.3	
September 1985	8.0 ± 3.7		
" "	4.0 ± 3.4		
" "	1.4 ± 3.1		
	1.8 ± 2.9	3.4 ± 1.6	12"ap, 63"chop

Final magnitude = 20.2 ± 0.28

Date	Position B		Aperture & Chop
	Signal	Final Signal	
July 1985	1.8 ± 3.0		
" "	11.4 ± 3.1	6.5 ± 2.1	

Final magnitude = 19.6 ± 0.3

H Integrations

Position A			
Date	Signal	Final Signal	Aperture & Chop
July 1985	4.0 ± 3.7		
" "	6.4 ± 3.0	5.4 ± 2.3	

Final magnitude = 19.2 ± 0.4

Position B			
Date	Signal	Final Signal	Aperture & Chop
July 1985	8.7 ± 4.4		
" "	7.5 ± 4.5		
" "	5.4 ± 3.0	6.7 ± 2.2	

Final magnitude = 19.0 ± 0.3

K Integrations

Position A			
Date	Signal	Final Signal	Aperture & Chop
September 1984	16.2 ± 4.0	16.2 ± 4.0	
September 1985	11.9 ± 3.9		60" chop
" "	1.9 ± 3.7		" "
" "	5.5 ± 3.7		5"ap, 60"chop
" "	17.7 ± 4.5		
" "	2.5 ± 4.4		
" "	1.9 ± 3.7	6.2 ± 1.6	

July 1985	9.3 ± 4.9		
" "	-2.5 ± 5.0		
" "	2.8 ± 4.3		60" chop
" "	12.5 ± 5.8	4.9 ± 2.4	

Final magnitude = 18.7 ± 0.2

Position B			
Date	Signal	Final Signal	Aperture & Chop
September 1985	1.6 ± 5.5		60" chop
" "	0.3 ± 6.0		
" "	-2.4 ± 5.6		
" "	8.1 ± 4.9		
" "	-0.9 ± 8.5	2.1 ± 3.8	
July 1985	10.2 ± 5.5		
	13.3 ± 6.0		
	12.2 ± 5.2	11.9 ± 3.2	

Final magnitude = 18.9 ± 0.3

2.7 Discussion

2.7.1 Upper Limits

There are two possible conclusions which can be drawn from the results of this programme, depending upon whether candidate 23b can be recognised as a primeval galaxy. In the case that further observations show this object to be a faint foreground star or galaxy, constraints can be placed on the luminosities of galaxies forming in the early Universe. In order to place such limits it is necessary to decide on the maximum signal which could have escaped detection in this search. The pixels searched to the least

sensitivity were those with only 20 and 26 integrations in June 1984. Of these the highest signal was recorded at K in pixel 15, viz. 17 μJy . Therefore to 90% confidence pixel 15 has a smaller mean than $17 \mu\text{Jy} + 1\sigma$, where σ is the standard deviation for all the pixels observed in June 1984 and shown in Figure 2.5a, viz. $\sim 16 \mu\text{Jy}$. The limit adopted for the complete search at k is thus 33 μJy . At J the highest signal was recorded in pixel 13, as 22 μJy . In a similar manner to K, an upper limit is adopted of $22 + 1\sigma$ or 43 μJy . These two pixels thus correspond to upper limits of $\sim 2\sigma$ if they are assumed to be drawn from a parent population of Gaussian noise.

These limits are obtained from a total search area of 26 pixels or 1307 arcsec^2 . The upper limit on the luminosity (L^{pg}) of primeval galaxies v's z is shown in Fig. 2.8. The luminosity has been calculated assuming the model parameters listed and using Eqn. 2.6. For comparison the best available optical limits from the search by Davis and Wilkinson (1974) are shown. This IR search extends the upper limits on primeval galaxy detection below the D+W search for redshifts $z > 6$. The dependence of the limits on assumed intrinsic temperature is shown in Figs. 2.9a,b. Here the excluded intrinsic temperature (T_{pg}) v's L^{pg} is shown for the redshifts of $z = 5$ and $z = 9$, in the cosmology $\Omega = 1$, $h = 1$. This figure indicates that for reasonable estimates of the intrinsic primeval galaxy temperature, this experiment improves constraints on realistic luminosities of galaxies at high redshift by about an order of magnitude. These limits are below those of the Boughn et al. (1986) search. Their most sensitive search region (totalling $\sim 1728 \text{ arcsec}^2$) and carried out at CTIO with an 11 arcsec aperture, contains a pixel with a signal ~ 2.4 times the standard deviation, or $\sim 24 \mu\text{Jy}$. Therefore the maximum signal which could have escaped detection is smaller than $24 \mu\text{Jy} + 1\sigma \sim 34 \mu\text{Jy}$, at the 90% confidence level. This compares with our upper limit at k of 33 μJy . Their second search of a larger area, (88500 arcsec^2) carried out at Kitt Peak with a 70 arcsec aperture, is an order of magnitude less sensitive than this.

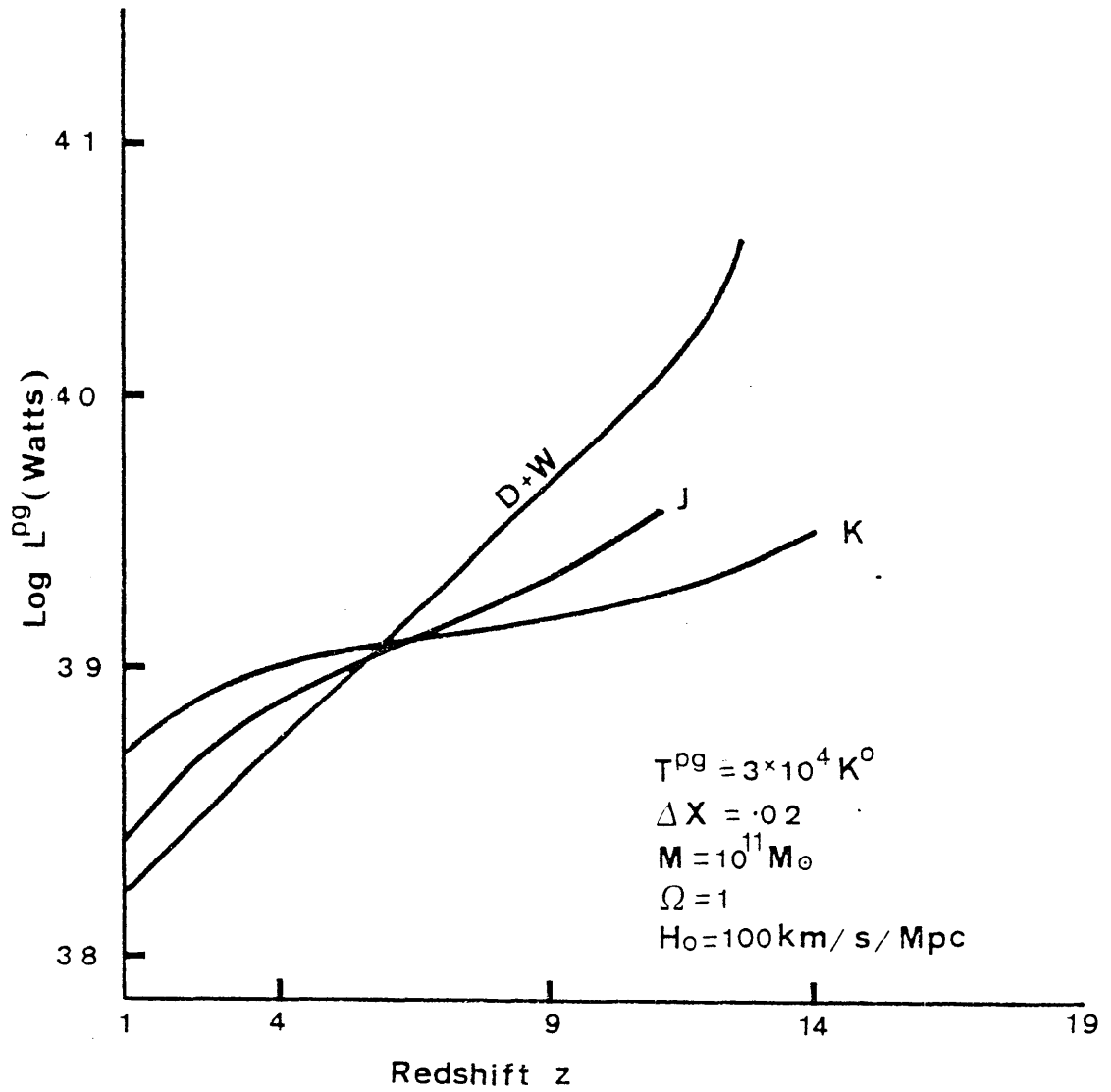
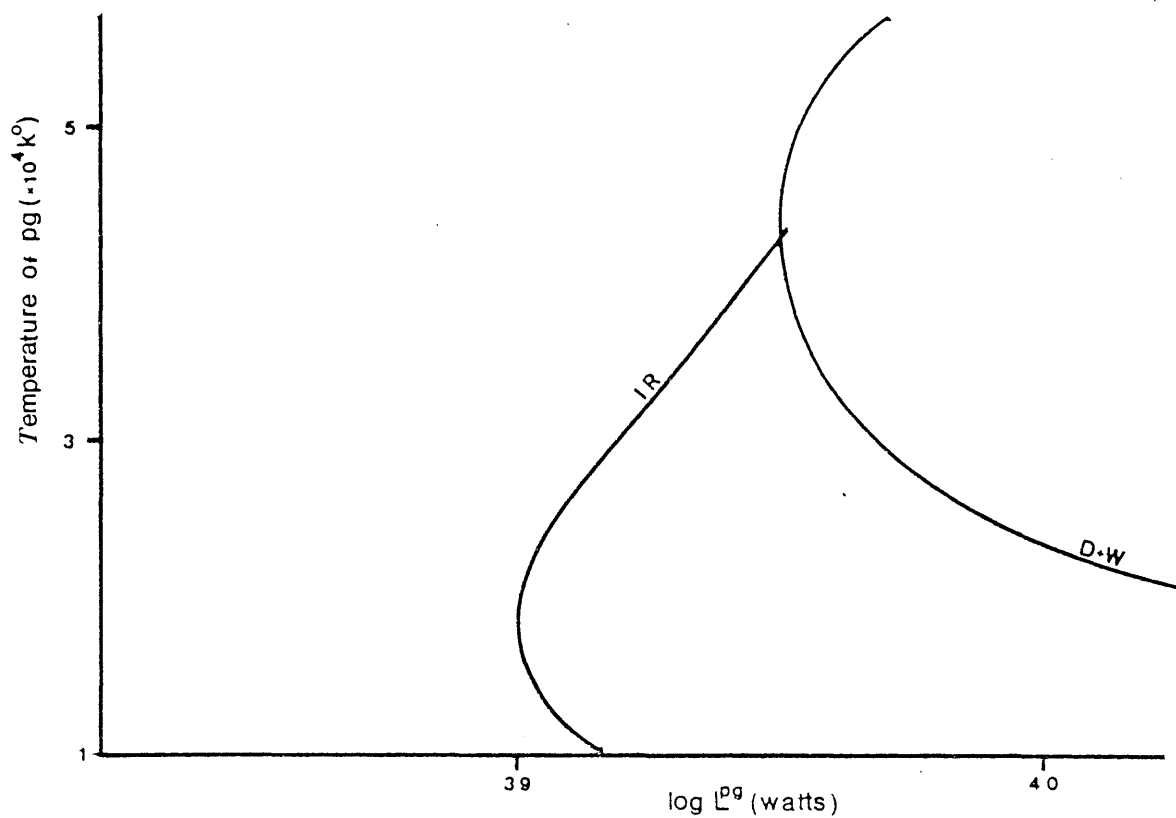
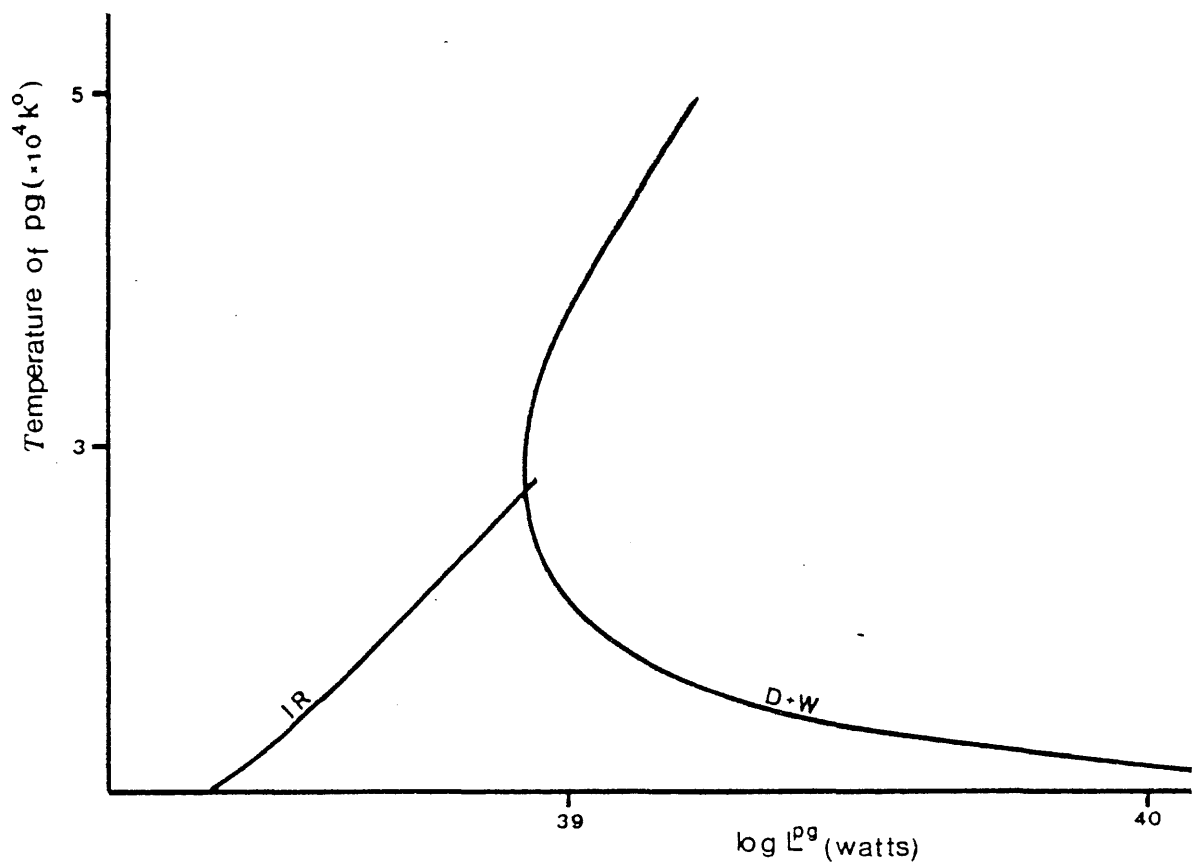


Figure 2.8 The excluded luminosities as a function of redshift for our J and K searches compared to the limits of Davis and Wilkinson 1974 (D+W). The areas above each line are excluded for the assumed parameters listed.



Figures 2.9a,b The excluded temperatures and luminosities of a primeval galaxy at redshifts $z = 5$ (top) and $z = 9$ (bottom), along with the limits from Davis & Wilkinson 1974 (D+W), assuming $\Omega = 1$, $h = 1$. Areas to the right of each curve are excluded.

A limitation on the constraints shown in Figs. 2.8 and 2.9 stems from the finite search area. If Poissonian statistics is assumed for the distribution of primeval galaxies, Eqn. 2.7 shows that the areal density of primeval galaxies (N), must be $> 2 \cdot 10^4 \text{ deg}^2$, in order to ensure with 90% confidence that at least one primeval galaxy was in the beam during the search. From Eqn. 2.3 this puts a lower limit on Δt , the period of the bright phase. However, an upper limit on Δt comes from the requirement that the maximum physically plausible luminosity (Eqn. 2.1) is larger than our luminosity limits. So for this search to be able to place limits with 90% confidence, it is essential that the luminosity limits set at UKIRT do not imply a bright phase period smaller than that necessary to ensure with 90% confidence that a primeval galaxy was in the beam. The range of possibilities is shown in Fig. 2.10. Here the maximum allowed values of Δt , based on flux sensitivity (solid lines) and the minimum values of Δt , based on the area searched (dashed lines) have been plotted against redshift for temperatures $10^4 \text{ K} - 3 \cdot 10^4 \text{ K}$, in an $\Omega = 1$, $h = 1$ cosmology. The dependence of Δt on h when estimating Δt using Eqn. 2.1 ($\Delta t \sim h^2$) and Eqn. 2.3 ($\Delta t \sim h^{-1}$) are also indicated. From this figure it can be seen that a 90% confidence level is maintained for $T_{\text{pg}} < 3 \cdot 10^4 \text{ K}$. However, if $h \sim 0.75$, the 90% limits are relevant for temperatures $T_{\text{pg}} < 2 \cdot 10^4$ and the 90% limits cannot be placed for reasonable values of T_{pg} if $h \sim 0.5$.

The photometry at J can be used to place useful limits on the possible $\text{L}\alpha$ emission from primeval galaxies in the redshift interval $8 < z < 10.5$. For the adopted 2σ flux limit of $43 \mu\text{Jy}$ at J , the limit on the possible $\text{L}\alpha$ luminosity is $\sim 4.5 \cdot 10^{38} (h^2 \Omega)^{-1} \text{ W}$. Koo and Kron (1980) derive a practical detection limit of $3.5 \cdot 10^{39} \text{ W m arcsec}^{-2}$ for the $\text{L}\alpha$ line redshifted to $z \sim 5$. The limit obtained in this IR search falls below the limit of the Koo and Kron (1980) $\text{L}\alpha$ search if the assumed diameter of a proto-galaxy is $> 5 \text{ arcsec}$. Figure 2.2 suggests that this possibility is likely for the redshift range of interest.

Due to the large number of uncertainties associated with the understanding

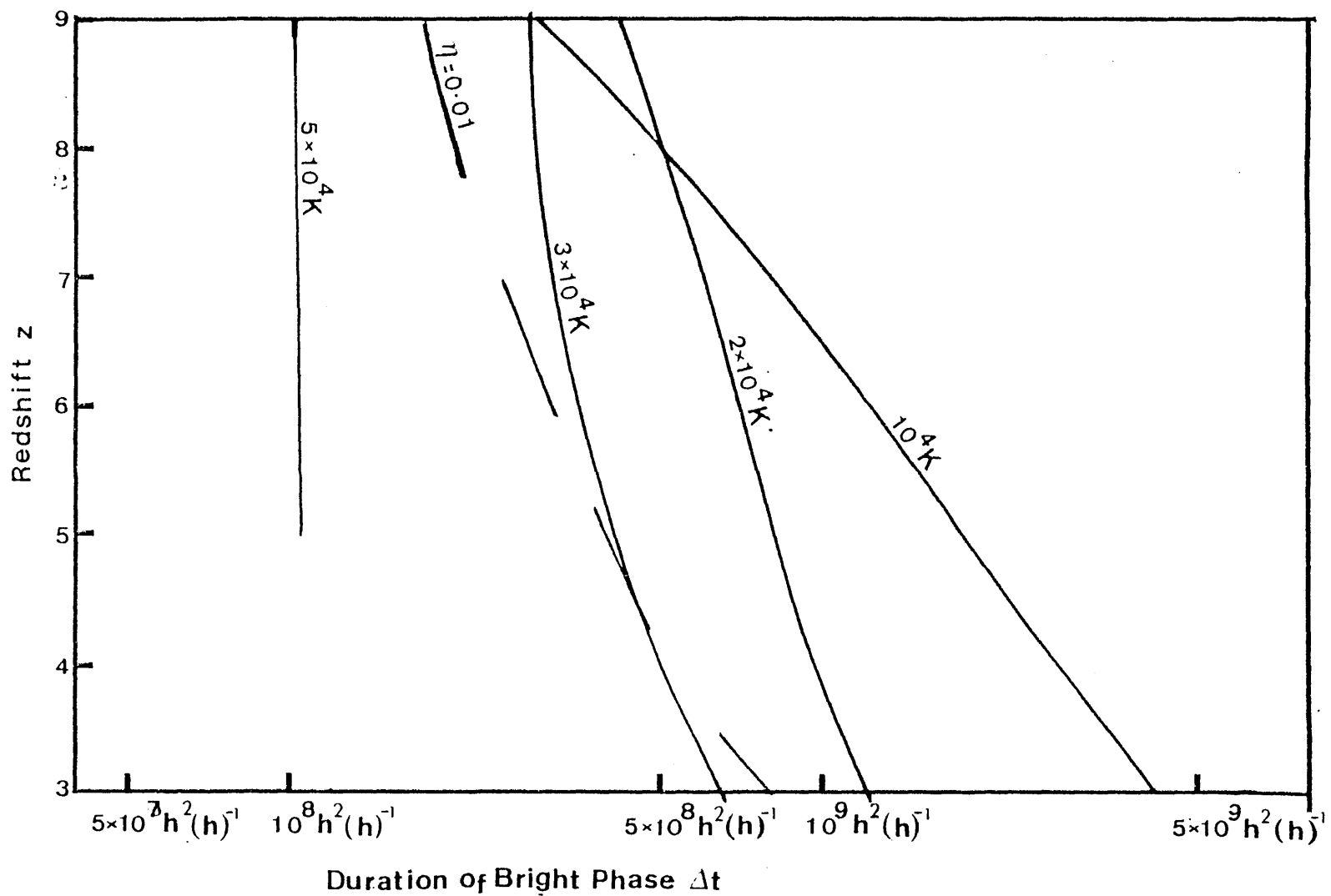


Figure 2.10 Values of the bright phase Δt implied from flux sensitivity of search (solid line) and finite search area (dashed line $(h)^{-1}$).

of galaxy formation, there are many possible reasons why the search has yielded a null result. The most probable explanations are :

- 1) The pre-dust phase of the initial burst of star formation is not long enough for primeval galaxies to be detectable in the optical or near infrared with present instrumental limitations. Dust will be particularly relevant for the slower infall models since, in that case, the bright phase occurs after many enrichment times.
- 2) Primeval galaxies are intrinsically fainter than the models tested by either the optical or IR searches, viz. $T_{\text{pg}} < 10^4$ K. Young galaxies may not resemble giant HII regions at all, but perhaps are like star forming regions suggested to occur at the centre of cooling flows in dense galaxy clusters (Fabian et al. 1984). The initial mass function is then biased towards the formation of low mass stars.
- 3) Perhaps not all morphological types go through a highly luminous phase of star formation. Tinsley (1978) suggests that only early-type galaxies were conspicuously brighter as primeval objects, since any past enhancement in the star formation rate would lead to excessively red colours. Since spirals constitute about 80% of the total number of galaxies in the Universe, the number density $n_0 \sim 0.01 \text{ Mpc}^{-3}$ may be an overestimate.
- 4) The areal density will also be reduced to a level untested at 90% confidence by this experiment if $h < 0.75$, or $\Omega > 2$. The Boughn et al. (1986) search of 88500 arcsec² is more relevant for these cosmologies.
- 5) If the universe is very open ($\Omega < 0.1$) then the upper limits on flux eliminate only those models with unrealistically large luminosities.

2.7.2 Candidate 23b

The only confirmed source in this search occurred in pixel 23b (Table 2.2). There are several pieces of information with which some discrimination between different types of objects can be made.

Firstly, this candidate was observed in September 84 and again in September 85, using UKT 9 on both occasions, and was detected each time. This rules out a solar system object, such as an asteroid, whose proper motion would easily exceed ~ 8 arcsec over a period of 1 year. The IR colours are $J-H \sim 1 \pm 0.5$, $H-K \sim 0.5 \pm 0.4$ (position A), $J-H \sim 0.6 \pm 0.4$, $H-K = 0.1 \pm 0.4$ (position B) (Table 2.2). These colours agree well within 1 σ and the weighted mean colours are

$$J-H = 0.76 \pm 0.32, H-K = 0.27 \pm 0.3$$

Such colours are of course characteristic of a normal galaxy. However, the errors are large and comparing these colours with those expected from a primeval galaxy, Fig. 2.3, the simplest dust free model for a highly redshifted primeval galaxy cannot be ruled out.

2.8 Further Work

We intend to build up a complete picture of candidate 23b with every available observational tool. The position of 23b is outside the search area covered by Davis and Wilkinson and so the only optical constraint is that from survey plates, which are not useful for constraining the nature of extended objects. An obvious possibility is to obtain a CCD picture of this candidate. Limits set by such means extend well below the expected magnitude for a galaxy in the optical, (~ 22 mag) based on an IR magnitude of 19. In addition, we intend to obtain a deep VLA map of the field in which we have found this object. Radio galaxies are a possible contaminatory class of foreground object. In addition, the magnitude of 23b is consistent with a distant radio galaxy redshifted to a level

fainter than the optical survey plate limit. No radio emission, to confusion limits, would be consistent with a primeval galaxy, while a faint radio source would have a characteristic spectral index and would demonstrate the detection of a faint radio galaxy.

Primeval galaxy searches themselves are ideally carried out by use of panoramic detectors with low noise and high quantum efficiency. The proposed UKIRT near infrared array detector will be an excellent tool for future searches at high redshift. Using the maximum pixel size of 2.3 arcsec diameter and the same integration time per pixel as used with UKT 9, it will be possible to search ~ 4 times the area to the same and thus further test scenarios in which $h \sim 0.5$.

CHAPTER 3

BACKGROUND TO THE HUBBLE FLOW PROJECT

3.1 Review of Anisotropic Hubble Flow Studies

3.1.1 Introduction

The degree of isotropy in the Hubble expansion and the extent to which the CBR is intrinsically isotropic are two of the most important problems in observational cosmology. Our understanding of the Universe at large depends on the answers to these questions, and so it is natural to ask searching questions concerning the degree and scale of putative anisotropies. Both the CBR and X-ray backgrounds appear isotropic and even radio source counts and deep galaxy counts are remarkably uniform. So, on sufficiently large scales the Universe does appear isotropic and homogeneous. However, galaxies are distributed in clusters on the scales of a few 10's of Mpc and on these scales the Universe is far from isotropic. There must be, therefore, scales on which departure from the universal expansion occurs, as a result of acceleration by density inhomogeneities, which give rise to the collapse and formation of the earliest structures (Chapter 1). Peculiar velocity studies are a powerful cosmological tool, and it is not surprising that there has been considerable investigation into systematic departures from Hubble's law on a wide range of scales.

In order to study velocity anisotropies it is necessary to have a convenient standard of rest. The "local standard of rest," (LSR) defined by the motion of nearby stars in our Galaxy, is not as fundamental as the frame defined by the centroid of the Local Group (LG) of galaxies, due to the peculiar motion of the Galactic center itself. Measurement of the Local Group motion (LGM) provides constraints on the extent to which the local Universe is isotropic and Friedmann like. In addition, a comparison between the different estimates of the LGM from galaxy surveys and the CBR provide a direct measure of the velocity field on larger scales.

Most studies conclude that our own galaxy and the LG have a component of motion towards the Virgo cluster, but among these there is significant disagreement as to the direction and amplitude of the LGM . While there appears to be no single explanation for the discrepancies, they are, in general, of two types. Firstly, estimates of the LGM deduced from the anisotropy of the CBR differ both in magnitude and direction from estimates using nearby galaxy samples. Secondly, some anisotropy estimates using the intermediate distance scales ~ 5000 km/sec show a marked discrepancy in direction when compared to nearby samples and the CBR. The Rubin et al. (1976a,b) programme is the most extensive anisotropy study outside the LSC to show this effect.

3.1.2 Very Distant Scales

A measurement of the LGM which is of particular interest is one made with respect to the cosmic background radiation. This is the most distant reference frame we can use, and has now been extensively studied with the view to detecting a dipole anisotropy in the radiation, caused by our peculiar motion with respect to this fundamental frame. The idea is simply that, given an intrinsically isotropic CBR, only a co-moving observer will observe a uniform background temperature. Otherwise, the velocity of a peculiar observer implies an increased brightness in the direction of the peculiar motion and a $\cos \theta$ dependence at angles θ away from the direction of motion. If the CBR is assumed thermal then a dipole anisotropy will result in an observed temperature given by

$$T(\theta) = T_0 \frac{(1+v/c(\cos\theta))}{(1-v^2/c^2)^{1/2}} \quad 3.1$$

where v is the peculiar velocity, c the velocity of light and T_0 the thermodynamic temperature of the CBR. The distortion of the CBR by the LGM is characterised by both its Doppler-type spectral distortion and its angular variation on the sky. Other putative large angular distortions, namely the Sunyaev-Zeldovich (1972) effect and the Sachs-Wolfe (1967) effect have different spectral and spatial dependencies. So, although it is conceivable that part of the CBR dipole anisotropy is intrinsic, the

most direct interpretation is one of entirely local dynamical effects.

Estimates of the dipole anisotropy and implied LGM are listed in Table 3.1. These studies suggest a motion for the LG of some 600 ± 50 km/sec towards $l = 264^\circ$, $b = 30^\circ$. This corresponds to a direction some 45° away from the Virgo Cluster, and implies a component of the LGM towards Virgo of some 400 km/sec.

3.1.3 Nearby Distance Scales

Galaxies at redshifts < 3000 km/sec are within, or on the edge of, the Local Supercluster (LSC). The motion of these galaxies are dominated by infall towards Virgo, which is the dominant mass component within the LSC. As a result, estimates of our own peculiar motion with respect to a background of LSC galaxies must take into account their peculiar motion using a velocity field model. Infall studies of this kind provide information on the local mass density Ω_0 , if the overdensity within the Virgo cluster is known. This is usually estimated by comparing galaxy counts in Virgo and the surrounding LSC.

It is easy to show that gravitational perturbations could cause large peculiar velocities (δV) on the scale of the LSC, (~ 20 Mpc) in accordance with the observed local density enhancement $\delta\rho/\rho$, viz.

$$\delta V \sim (\text{Hubble time}) * (\text{peculiar acceleration})$$

Using the gravitational force law and Eqn. 1.11b gives

$$\delta V \sim \frac{H_0^{-1} G \delta M}{R^2} \sim \frac{H_0^{-1} R G \rho \delta \rho}{\rho} \sim \frac{H_0 R \delta \rho \Omega_0}{\rho} \quad 3.2$$

If the galaxy distribution traces out the matter in the supercluster, then $\delta\rho/\rho \sim \delta N/N$ and the peculiar velocity δV , produced due to matter within a sphere of radius R , is

$$\delta V \sim \frac{H_0 R \delta N \Omega_0}{N} \quad 3.3$$

Work by Davis & Huchra (1982) and by Yahil et al. (1980) indicates that $\delta N/N \sim 2$ for the LSC. From Eqn 3.3 the expected peculiar velocity of a typical galaxy at the edge of the LSC is expected to be $\sim 2000 \Omega_0$ km/sec.

A more accurate estimate is obtained by using the full linear perturbation analysis. Linear considerations are an adequate approximation for the LSC since $\delta V < H_0 R$. Peebles (1980) derives the peculiar velocity due to gravitational acceleration, viz.

$$\delta V = 0.3 H_0 R \Omega_0^{0.6} (\delta N/N) \quad 3.4$$

Taking the value $\delta N/N \sim 2$, yields $\sim 670 \Omega_0^{0.6}$ km/sec.

Similar results are found from consideration of nonlinear effects, if the assumption of spherical symmetry is maintained (Davis & Huchra 1982). In reality, the behaviour of the flow is likely to be more complicated due to the pancake nature of the LSC, which can cause the velocity fields to become substantially non-radial.

The interpretations given to observations of the local velocity field are, at present, somewhat uncertain. Tonry and Davis (1981) use the central velocity dispersions of 14 ellipticals in the Virgo core and a further 53 ellipticals outside the core to estimate luminosities (Faber & Jackson 1976) and they find a Virgo infall of some 500 km/sec. This result is in agreement with the earlier determination of Aaronson et al. (1980a). They use the IR magnitude-21cm, or Tully-Fisher relation (Tully & Fisher 1977) to derive the Hubble ratio of 4 distant clusters and Virgo. These imply a LG infall towards Virgo of order 480 km/sec. However, both these determinations have been criticised. Dressler (1984) argues that Tonry and Davis ignored any aperture correction, which in turn causes an overestimate of the LG infall. In addition, Yahil (1985) reports that Aaronson suspects a bias in his early determination.

The more recent determinations give smaller infall velocities. Aaronson et al. (1982) use some 300 field galaxies with $z < 3000$ km/sec to fit a non-linear model to the Virgo-centric flow, with a resultant LG infall of 331 ± 41 km/sec and with the amplitude of the mean velocity at the position of the LG of some 250 ± 64 km/sec. Aaronson et al. (1981a) uses the infrared magnitude-21cm velocity width relation (Tully & Fisher 1977) to derive distance moduli relative to Virgo for the Fornax and Grus groups. The resultant LG infall to Virgo is 316 ± 41 km/sec. Along with other estimates, Yahil 1981; Dressler 1984; Kraan-Korteweg 1985, the most recent consensus is that the infall velocity is $\sim 250 \pm 50$ km/sec.

There have been two major studies in recent years which have examined the LGM using all sky samples of galaxies within the LSC. Hart and Davies (1982) carried out such a programme using Sbc spirals at redshifts less than 5000 km/sec and heavily biased towards ~ 2000 km/sec. Only galaxies with small line of sight infall velocities towards Virgo were considered. They used 21cm fluxes and line widths in a Tully-Fisher type relation to measure distances and obtained a motion for the LG of 436 ± 55 km/sec toward $l = 264^\circ$, $b = 45^\circ$. There is remarkable agreement in direction between this result and the CBR dipole anisotropy. The implied infall velocity into Virgo supports the higher estimates, viz. ~ 400 km/sec.

De Vaucouleurs & Peters (1984) select a sample of 600 "best observed" galaxies of all types (having distance moduli estimated by one of four independent methods) to study the LGM as a function of scale. They conclude that the LGM increases from ~ 0 to a maximum of ~ 600 km/sec, at a distance ~ 4000 km/sec and that the Solar apex moves some 160° across the sky, with 4000 km/sec defining a reference frame which is substantially at rest with respect to the CBR, in broad agreement with Hart & Davies (1982).

There are two direct consequences following from these results.

1) Using Eqn 3.4 implies that for infall velocities between 250-400 km/sec $\Omega_0 \sim 0.1-0.4$. Thus the dynamics of the LSC predict a density which although consistent with nuclear synthesis seems to rule out the

possibility that the Universe is closed by clustered matter on scales ~ 10 Mpc. In addition, Efstathiou (1985) has shown that the discrepancy between this observation and the theoretical "requirement" that $\Omega_0 = 1$ cannot be reconciled by the non-radiative decay of clustered weakly interacting material. The idea is that while such a decay must have occurred at $z > 20$, for the predicted peculiar infall towards Virgo not to exceed the upper limits, the virialisation of dense cluster cores requires that they decayed at $z < 5$.

2) A comparison of the results for the LGM from measurements of the CBR with those from the nearby galaxy studies indicate that the CBR dipole anisotropy cannot be accounted for in terms of a simple Virgo infall model. The CBR dipole anisotropy is larger by ~ 350 km/sec than the most reliable estimates of Virgo infall, viz. 250 km/s, or so, and lies some 45° on the sky from Virgo. Thus, there is a component of the CBR dipole anisotropy in the direction of Virgo of at least ~ 200 km/sec, which is not due to LG infall. There is also a component orthogonal to Virgo of ~ 400 km/sec. One possible reason for this is that the flattening of the LSC produces significant transverse velocity components making the flow exceedingly complicated. An example is a model in which the LSC has completed collapse along one axis while still expanding along the other two (Silk & Szalay 1983). In this case there is no reason to expect deviations from the Hubble flow on larger scales. However, another interpretation is that the residual velocity components in the CBR anisotropy vector are, in fact, bulk peculiar motions of the LSC, the result of acceleration due to mass concentrations that are outside of the LSC (Yahil 1985).

3.1.4. Intermediate Distance Scales

The suggestive evidence presented above makes the situation regarding intermediate distance scales, above 3000 km/sec intriguing. The method used to determine our LGM, and therefore investigate possible anisotropies on these scales, involves searching for a dipole component in the Hubble expansion using all sky samples of galaxies or clusters of galaxies and comparing these to the local and CBR estimates.

In a pioneering study, Rubin et al. (1973, 1976a 1976b) choose an all sky sample of 96 ScI-ScII spiral galaxies with redshifts between 3500-6500 km/sec to investigate the isotropy of the Hubble expansion. Using both measured redshifts and optical magnitudes they deduce an anisotropy which they infer as a LGM of 450 ± 127 km/sec towards $l = 163^\circ$, $b = -11^\circ$. A re-analysis of the Rubin et al. data was made by Schechter (1977). He showed that the formal errors Rubin et al. quoted are in fact an underestimate, since a diameter correction they make to their magnitudes, supposedly reducing the error on the LGM by a factor of 1.6, actually adds little information and results in a formalism that is less sensitive to the LGM (Section 3.2.3). The best estimate of the LGM from this data appears then to be that without the diameter correction, solution 2 of Rubin et al. (1976b), viz. 581 ± 202 km/sec toward $l = 203^\circ$, $b = -11^\circ$. This result is closer to, but still discrepant with, the microwave dipole estimate.

Visvanathan (1979) uses redshifts, isophotal V26 magnitudes and the U-V colour magnitude relation for 311 Shapley-Ames galaxies, out to 6000 km/sec, to investigate the LGM by analysing the variation of H_0 with supergalactic longitude. The variation of H_0 supports Rubin et al. in that it can be interpreted as a LGM ~ 400 km/sec in a direction nearly perpendicular to the Virgo cluster.

The Hart & Davies (1982) study is worth mentioning again here. In addition to their 21cm study, they obtained a similar result to that of Rubin et al. using optical magnitudes for their Sbc sample, viz. 397 ± 90 km/sec towards $l = 216^\circ$, $b = 27^\circ$. However, using a sub-sample of the Rubin et al. galaxies at redshifts < 5000 km/sec and supplementing this sample with southern spirals, they obtained a LGM much closer to their original 21cm result.

A summary of estimates of the LGM using nearby and intermediate distance samples of galaxies and the CBR is given in Table 3.1.

Table 3.1

Estimates of the Local Group Motion

Author	Method	V km/sec	l°	b
Very Distant Scales				
Smoot & Lubin (1979)	CBR	520 ± 75	264	33
Boughn et al. (1981)	CBR	653 ± 33	273	23
Lubin et al. (1983)	CBR	586 ± 30	267	26
Fixen et al. (1983)	CBR	614 ± 30	270	29
Intermediate Scales				
Rubin et al. (1976a,b)	96 ScI-II & Diameter Correction	454 ± 125	163	-11
Rubin et al. (1976a,b)	96 ScI-ii without Diameter Correction	586 ± 200	202	-11
Visvanathan (1979)	311 E's & So's 1000 - 6000 km/sec	397 ± 70	151	20
Nearby Scales				
Hart & Davies (1982)	84 Sbc ~ 2500 km/sec (21cm TF relation)	436 ± 55	264	45

Hart & Davies (1982)	53 Rubin et al. 1000-5000 km/sec	580 ± 130	245	35
Hart & Davies (1982)	Sbc (optical)	397 ± 90	216	27
de Vaucouleurs & Peters (1984)	100 all types ~ 1250 km/sec	280	174	68
de Vaucouleurs & Peters (1984)	100 all types ~ 2450 km/sec	462	240	54
de Vaucouleurs & Peters (1984)	100 all types ~ 3600 km/sec	788	311	35

The estimate of the LGM given by Hart & Davies (1982) using the 21cm data (Table 3.1) is in reasonable agreement with the dipole anisotropy of the CBR. Taken alone, this result suggests a simple picture in which the Universe on scales larger than ~ 3000 km/sec is relatively smooth and unperturbed. However, this idea is complicated by other results. As already mentioned, the Hart & Davies optical solution for the Sbc sample is $\sim 50^\circ$ from the 21cm solution. This may indicate possible systematics in either the optical or the 21cm data. The all 21cm Tully-Fisher type relation they used does have a large intrinsic scatter, viz. ~ 1 magnitude at constant velocity width.

De Vaucouleurs & Peters (1984) reach a similar conclusion about the isotropy of the Universe on these scales. While a glance at Table 3.1 does indeed show that the solutions for successively larger galaxy shells move toward the CBR dipole anisotropy, the solution at 3600 km/sec appears to have "overshot" by $\sim 45^\circ$ with an amplitude almost 200 km/sec larger than that of the CBR dipole anisotropy. Any interpretation of their results is made difficult due to their being no quoted uncertainties.

The conclusion reached from the studies within the LSC is that the

dominant mass overdensity, Virgo, must have only a small effect on changing solutions for the LGM on scales exceeding 4000 km/sec. From Eqn 3.2, the peculiar velocity due to a given overdensity at large R varies as $\bar{R}^2$. It is thus surprising that the Rubin et al. (1976) result shown in Table 3.1, on scales ~ 5000 km/sec, indicates a LGM almost orthogonal to the CBR dipole anisotropy and with a small component away from the Virgo cluster itself. This sample is located outside the LSC and the LGM may reflect the considerable departure from uniform Hubble flow of the galaxies due to significant fluctuations in the matter distribution on these scales. As already mentioned in section 3.1.3, the smallness of the Virgo infall estimates compared to the CBR dipole anisotropy is suggestive of bulk peculiar motion of the LSC. The results of Hart & Davies and de Vaucouleurs and Peters are challenged by the elliptical sample of Visvanathan (1979), see Table 3.1. Almost 70% of his sample is located within the LSC. Taking this result together with Rubin et al. implies that a similar velocity anisotropy must engulf the whole volume out to ~ 6000 km/sec.

The Rubin et al. study is thus interesting both because it probes regions outside the LSC and beyond any other study and also, along with Visvanathan, the result is markedly different from other studies located inside the LSC. It thus seems worthwhile to single out the Rubin et al. study in particular, for further detailed analysis and to try and reconcile the LGM estimates.

3.2 A Detailed Discussion of the Rubin et al. Anisotropy Study

3.2.1 Introduction

Rubin et al. (1973, 1976a, 1976b) analyse the isotropy of apparent magnitudes and velocities as a function of position on the sky for an all sky sample of spiral galaxies. After a comprehensive examination of their data base Rubin et al. argue exhaustively in favour of the following 3 conclusions:

- 1) For a minimum bias sample of 96 galaxies there is an anisotropy across

the sky, such that those at early right ascension and high northern declination, have velocities low for their apparent magnitudes (Rubin et al. 1973).

2) This anisotropy is unlikely to be the result of anomalous systematic biasing of the optical magnitudes or velocities across the sky (Rubin et al. 1976a).

3) The most likely interpretation of the anisotropy is that of a local group motion of 450 ± 125 km/sec toward the direction $l = 163^\circ$ and $b = -11^\circ$ (Rubin et al. 1976b).

The following sections review the procedure, data reduction scheme and analysis used by Rubin et al. to demonstrate these 3 conclusions. It also examines the critical analysis of these conclusions by other authors and highlights the remaining problems associated with this work.

3.2.2 The Data and Corrections

In order to study the anisotropy of the Hubble expansion, Rubin et al. chose an all sky sample of 200 ScI and ScII spiral galaxies with optical magnitudes between 14 and 15 and with redshifts as low as $V = 1500$ km/sec and as high as 13,000 km/sec. For these galaxies they obtained optical magnitudes for the sample from Zwicky et al. (1961-1968), and photoelectric B and V photometry from Graham (1976) for 83 programme galaxies. In addition, Rubin et al. report on angular diameters, measured directly from the Palomar Sky Survey (PSS) prints, optical velocities for 180 galaxies and 21cm velocities and fluxes for all galaxies which are north of Dec = -19° and hence are accessible to the National Radio Astronomy Observatory.

The Rubin et al. analysis of the velocities and apparent magnitudes relies entirely on the galaxies being standard candles. This assumption permits relative distances (and therefore recession velocities) to the galaxies to

be estimated, if apparent magnitudes are known. Rubin et al. adopt a strict interpretation of the van den Bergh (1960) classification system with a range of estimated luminosity classes between ScI and ScII, with over 70% of the galaxies having luminosity class (LC) < 1.5 . The ScI-ScII morphological range is thus assumed to represent a homogeneous class of galaxies, having a relatively small dispersion in absolute magnitude, and in addition being both numerous and easily distinguished on sky survey plates at a distance of over 100 Mpc. A further restriction is placed on the 200 or so in order to obtain a minimum bias sample (hereafter mbs). From an examination of a Hubble diagram ($\log V$ versus m) for all the galaxies (Rubin et al. 1976a), it is evident that over luminous galaxies are entering the sample at high redshift and underluminous galaxies are over represented at low redshift. This is the well established Malmquist effect (Malmquist 1920). Rubin et al. adopt the range $3500 < V < 6500$ km/sec, as that which shows the minimum Malmquist effect. This procedure has been outlined by Sandage and Tammann (1975a) as a successful way of minimising Malmquist biasing for a magnitude limited sample.

The study of the anisotropy of the Hubble expansion relies on the data being free of systematic errors that could give rise to an apparent velocity anisotropy. Of particular concern are the Zwicky magnitudes where there is suspicion of errors both in the zero point scale of the magnitudes and as a function of diameter. The magnitudes are estimated by the procedure of spreading the photographic image over a 1-min square and determining the magnitudes from the surface brightness of the square. For galaxies between 10th and 13th magnitude, Zwicky adjusted the magnitudes to agree with the Shapley-Ames catalogue (1932) values. Between 13 and 14.5 there is a gradual adjustment adopted. Photoelectric comparisons by Shane and Kron (1974) have shown that certain volumes of the Zwicky catalogue contain mean zero-point errors of 0.1mag or 0.2mag. The Zwicky catalogues comprise six volumes, with declination $> 3^\circ$, and are divided principally by declination zone. However, the Rubin et al. sample has a good mix of galaxies sampled on the sky and although systematic magnitude errors as a function of position on the sky are possible, they

are most unlikely. There is a possibility, however, that the Zwicky magnitudes suffer from large systematic errors as a function of diameter, such that galaxies larger than 1 arcmin are too faint. A systematic dependence of this nature was found by both Sandage and Tammann (1975b) and by Balkowski et al. (1974). In response to this problem, Graham (1976) carried out B and V multi-aperture photometry for 83 of the sample with a view to determining the zero point and scale of the magnitude system. Graham adopts an aperture system of $A/D = 1$, where A is the diaphragm size and D is the Rubin et al. measured isophotal galaxy diameter. The typical aperture correction required amounts to ~ 0.4 mag.

Further corrections are determined from the data itself, that is, from the optical magnitudes and velocities for the mbs of 96 galaxies. Rubin et al. introduce the concept of the Hubble Modulus (HM), which they ultimately use to examine the isotropy of the Hubble expansion. It is a powerful aid with which to determine corrections and examine the expansion because, while it is proportional to absolute magnitude (M), its use as a velocity anisotropy indicator demands no explicit value for either M or H_0 . The HM is defined as follows. For a galaxy of absolute magnitude M, apparent magnitude m, at a distance R, but sufficiently nearby so that there are no relativistic effects,

$$m-M = 5\log R + 25 \quad 3.5$$

where the units of R are Mpc. If all deviations from the Hubble Flow are small then

$$R = \frac{V_0}{H_0} \quad 3.6$$

where V_0 is the velocity of recession. Equation 3.5 now becomes

$$\log V_0 - 0.2m = \log H_0 - 0.2M - 5 = HM \quad 3.7$$

Thus, because HM is distance independent, for a set of standard candles, it can be used to examine systematic variations of magnitude.

Rubin et al. make 4 further corrections to the apparent magnitudes using the HM and these are discussed below, in decreasing order of importance.

1) The most significant correction applied is the unconventional one of effectively reducing each galaxy to the same linear size. The basic idea stems from the correlation Rubin et al. find between HM (i.e. absolute magnitude) and the linear dimensions of the galaxy. The relation is not unexpected and has been discussed by previous authors (Hubble 1936, van den Bergh 1961, Heidmann 1969, Freeman 1970, Heidmann et al. 1972, Sandage 1972). Rubin et al. argue that the application of the diameter relation results in a more accurate estimate of the absolute magnitudes than can be made from assigning just the mean estimate of the whole sample.

The resultant mean correction to a constant linear diameter is, $\Delta m \sim 0.4$. The application of this correction has two important consequences for the resultant local group motion. First, Rubin et al. claim an increased significance in the anisotropy, taking it from 2.8% to 3.6%. Secondly, the application of the correction displaces the direction of motion for the Local Group by some 40° in galactic longitude, away from the direction of motion implied by the dipole anisotropy of the CBR. The re-analysis of this correction by Schechter (1977) indicates that the final errors quoted by Rubin et al. are an underestimate. The key idea is the iteration Schechter performs on the diameter correction coefficient. Linear diameters are estimated from apparent diameters and velocities. But since apparent magnitudes and angular diameters are likely to be correlated and diameters are difficult to estimate from PSS anyway (Heidmann et al. 1972, Tully 1972), they add no independent information and do not reduce the scatter in the absolute magnitudes. The apparent increase in the significance of the anisotropy, on application of the diameter-luminosity relation, is a failure of Rubin et al. to iterate the solution a second time.

2) The corrections to the magnitudes for galactic extinction are on average $\Delta m \sim 0.15$ and are calculated from the variation of HM with $\csc|b|$, where b is the galactic latitude. The coefficient of galactic extinction derived in this manner corresponds to $A \sim 0.15 \pm 0.03$ and supports the extinction estimates of Peterson (1970) and Sandage (1973). Extinction corrections are potentially problematic due to their variation with position on the sky.

3) & 4) These corrections are for galaxy inclination $\Delta m(i)$ and luminosity class $\Delta m(LC)$. These are the smallest corrections, amounting to an average correction of $\Delta m(i) \sim 0.05$; $\Delta m(LC) \sim 0.08$. Rubin et al. argue that the small values of these corrections are a consequence of both careful sample selection and classification. The inclination correction is a result of the longer path length through the galaxy in viewing it at a finite inclination. The van den Bergh (1960) classification scheme adopted favours galaxies of low inclination, since these galaxies have easily identifiable spiral arm features. The distribution of inclinations for the programme galaxies is random below 60° , with a mean measured inclination for the sample of $\sim 35^\circ$. Therefore, the correction applied to the magnitudes for the effect of inclination on absorption is expected to be small. The luminosity classification results in a smaller estimated variation of absolute magnitude between classes I and II (0.2 mag) than was found for Sc's by Sandage and Tammann (1974), viz. 1 mag.

The final optical magnitudes adopted by Rubin et al. are those to which corrections 1 to 4 have been applied. The correction coefficients, which are velocity dependent, are iterated once to account for the resultant LGM. The final velocities are corrected for the Solar motion with respect to the Local Group. This is taken to be 300 km/sec towards $l = 90^\circ$, $b = 0^\circ$ (c.f., Humason & Wahlquist 1955, de Vaucouleurs & Peters 1981).

3.2.3 Analysis and Conclusions

The effect of a LGM will be to produce a systematic bias in the HM across the sky. To see this consider the components of the observed velocity V_o for a particular galaxy, viz.

$$V_o = V_H - \delta V_L + V_p \quad 3.8$$

where V_H is the Hubble recession velocity, δV_L is the component of the LGM in the direction of the Galaxy, and V_p is the peculiar velocity intrinsic to the galaxy. The HM is then given by,

$$HM = \log(V_H - \delta V_L + V_p) - 0.2m = H_0 - 0.2M - 5. \quad 3.9$$

For an all-sky distribution of galaxies, with the same absolute magnitude, and assuming H_0 is constant across the sky, an average HM can be defined thus,

$$\langle HM \rangle = \langle \log(V_H - \delta V_L + V_p) - 0.2m \rangle. \quad 3.10$$

For an all sky sample of standard candles and assuming the peculiar motions are random then

$$V_H \sim 10^{\langle HM \rangle + 0.2m} \quad 3.11$$

If there exists a LGM then galaxies in the apex direction will have smaller HM's than the mean, while galaxies in the antapex will have HM's larger than the mean. Using 3.11, then for each galaxy an estimate of the component of the LGM in that direction is

$$\delta V_L \sim 10^{\langle HM \rangle + 0.2m} - V_o \quad 3.12$$

For each galaxy δV_L can be written as a vector product between the LGM velocity vector (X, Y, Z) and a unit vector (l, m, n) in the direction of the

galaxy, viz.

$$\delta V_L = lX + mY + nZ \quad 3.13$$

Here the unit vector defines galactic coordinates. A least-squared solution of this overdetermined set of equations determines the LGM. The minimization is carried out with respect to the velocity residuals given by

$$\sum V_p^2 = \sum (V_o - V_H + lX - mY - nZ)^2 \quad 3.14$$

This method of analysis is independent of any particular value of H_o or M .

Rubin et al. use the first estimate of the LGM, found from this method, to re-determine the velocity dependent correction coefficients and thereby obtain a final, iterated solution. The anisotropy resulting from this procedure has a magnitude of 454 ± 125 km/sec and a direction towards $l = 163^\circ$, $b = -11^\circ$. It is the dipolar nature of the variation of the anisotropy across the sky which they claim is strong support for the interpretation of the anisotropy as a LGM. Figure 3.1a illustrates this idea for the Rubin et al. minimum bias sample. For each of the 96 mbs galaxies, the HM has been plotted against the cosine of the angle (θ) between the final LGM apex direction and the direction of each galaxy. The best fit regression line is shown and is given by

$$HM = (-0.042 \pm 0.011) \cos \theta + (0.954 \pm 0.006) \quad 3.15$$

The slope of HM across the sky is proportional to the magnitude of the anisotropy. The variation of HM from apex to antapex is ~ 0.084 , which combined with the definition of HM (Eqn. 3.7) and taking the value for the average redshift of the sample to be 5000 km/sec, gives an anisotropy magnitude of 500 km/sec, in agreement with the least squares solution. The gradient is smaller in every other direction of the sky. For a direct

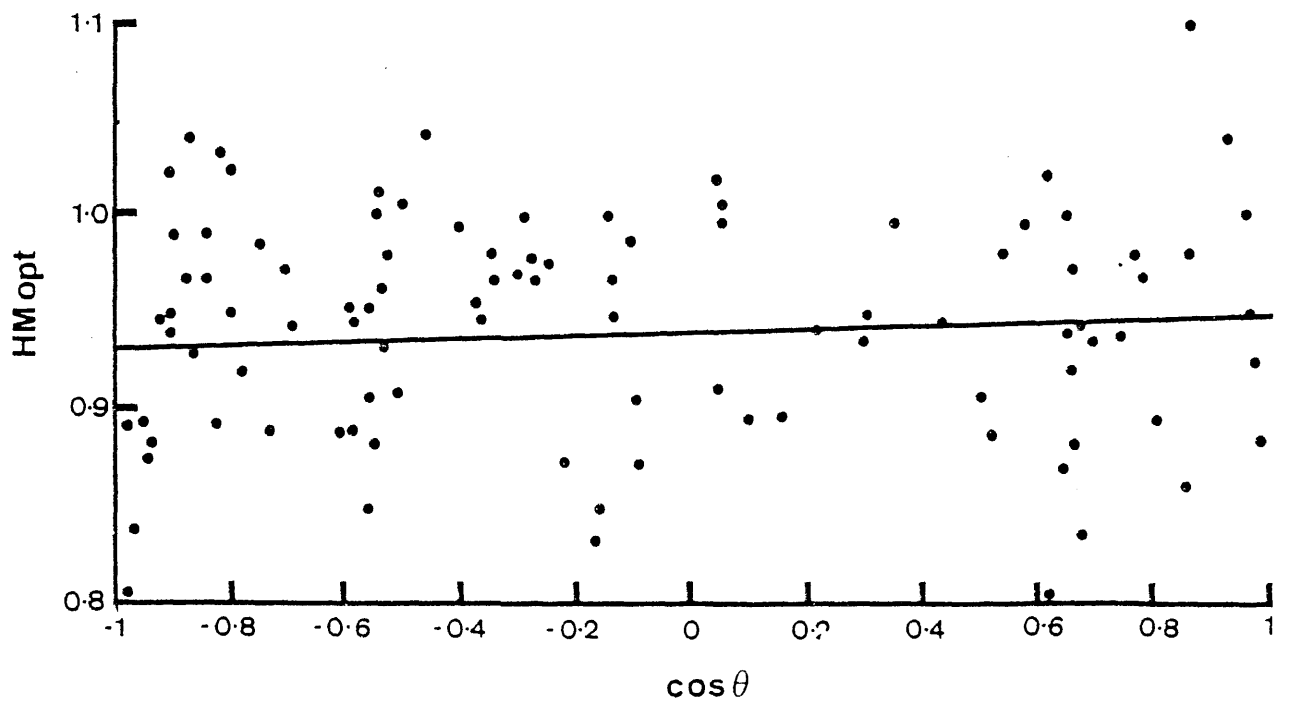
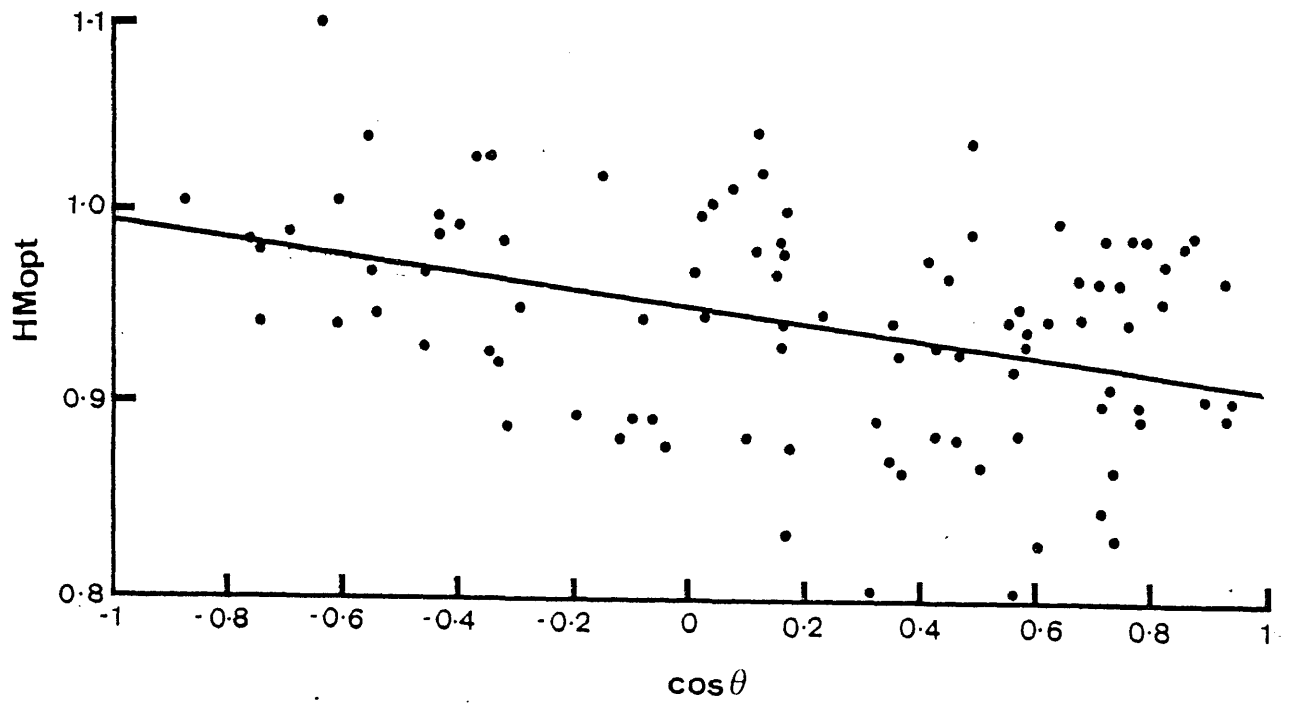


Figure 3.1a,b Variation of optical Hubble modulus from the apex to antapex defined by Rubin et al. LGM (top) and from the apex to antapex defined by the CBR dipole (bottom).

comparison, Fig. 3.1b is a similar plot except that θ here defines the angle between each galaxy and the direction of the LGM, typical of determinations from the dipole anisotropy of the CBR, viz. $l = 260^\circ$, $b = 35^\circ$. The best fit regression line is

$$HM = (+0.01 \pm 0.01) \cos \theta - (0.94 \pm 0.01) \quad 3.16$$

indicating an insignificant, if not slightly negative component of the LGM in this direction.

At the time of publication, the Rubin et al. result was in conflict with upper limits that had been set on the LGM using the CBR. The interpretation of these difficult experiments, at that time, constrained the LGM to < 300 km/sec (Partridge 1974). Therefore, the main concern of Rubin et al. was to establish that the anisotropy was indeed due to a motion of the Local Group, while concern over the direction of this anisotropy was secondary. However, with the CBR dipole anisotropy now established with $\sim 15\sigma$ confidence, it is necessary to examine the effect the correction procedure has on the direction of the anisotropy in addition to any changing amplitude.

Due to systematic effects still possibly hidden in the data, Rubin et al. consider many other solutions which incorporate modified corrections. The most important of these are: 1) Solutions, using the Zwicky magnitudes, not transformed to the Graham system but with minimum corrections applied, as appeared warranted from a comparison with the Graham (1976) mags and photoelectric observations from Shane & Kron (1974). These do not alter the LGM motion, viz. 677 ± 18 towards $l = 166^\circ$ and $b = 8^\circ$. 2) A galactic extinction law that is dependent on longitude is introduced, which is a more realistic approximation to galactic extinction and which results in a maximum correction of 2.5 times that of the conventional law. The resulting LGM increases by $\sim 1\sigma$ to ~ 600 km/sec, with an unaltered direction. 3) A variation of the absolute magnitudes across the sky could be responsible for the anisotropy. This would be the case if the

assumption of the sample being standard candles breaks down. Rubin et al. only explicitly include a correction for differences in absolute magnitudes in the form of a Malmquist bias correction. The Malmquist biasing is present at the level corresponding to an increase of 0.3 mag in M as V increases from 3500 to 6500 km/sec. The application of this further correction results in a LGM 380 ± 120 km/sec towards $l = 159^\circ$ $b = -10^\circ$. This solution is the smallest of any that Rubin et al. obtain. In addition, an examination of both the angular diameters and the 21cm line widths by Rubin et al., indicates a similarity between galaxies in the apex and the antapex hemispheres. 4) As detailed above, the application of the angular diameter-luminosity correction changes the direction of the LGM by $\sim 40^\circ$. Rubin et al. consider a solution without this correction and obtain 586 km/sec in a direction $l = 200^\circ$, $b = -10^\circ$. In view of the analysis of Schechter (1977) this is probably the best estimate of the anisotropy of all the Rubin et al. solutions. These points are taken up again in the following section which details most of what is questionable about the Rubin et al. work.

3.3 A Critique of the Rubin et al. Study

3.3.1 Remaining Problems and Uncertainties

Taken together, the comprehensive corrections applied to the data and the variety of solutions considered by Rubin et al., demonstrate the extensive analytical procedure required in order to assemble an optical data base significantly free of large systematics that it can be used to study anisotropies in the Hubble flow. There is remaining discrepancy between the direction of the LGM as inferred from this sample of galaxies and that deduced from the dipole anisotropy of the CBR and other studies, $\sim 90^\circ$ or so. This difference may be real, or it may be a consequence of the Rubin et al. optical data base and reduction procedure. If the Rubin et al. result is correct, then it implies that either the dipole anisotropy in the CBR is intrinsic or that there is considerable departure from uniform Hubble flow on scales ~ 6000 km/sec. The Rubin et al. result

may thus provide information which will substantially improve our understanding of large-scale structure. Before such an interpretation can be made it is necessary to answer some of the criticisms of this study and investigate the remaining uncertainties that may be biasing the LGM solutions. Listed below are the important aspects of this study which remain problematic and the nature of which, make an infrared study of this sample most appropriate. Some of the criticisms have been taken up by other authors.

1) There is a significant scatter in the apparent magnitudes. An estimate of the Zwicky magnitude precision can be obtained from a consideration of the scatter between the Zwicky and Graham magnitudes after application of the Zwicky/diameter correction, discussed in section 3.2.2. The intrinsic scatter in the final adopted magnitudes is $\Delta m(\text{Zw-Gr}) \sim 0.35$. Graham estimates the internal consistency of his photometry to be < 0.06 mag at B. Thus, this error is dominated by the direct estimates of the Zwicky magnitudes. This uncertainty in the apparent magnitudes suggests an explanation of the anisotropy in terms of systematic errors. The intrinsic variation of the difference between the Graham and Zwicky magnitudes ($m_{\text{GR}} - m_{\text{Zw}}$) across the sky for 25 of the programme galaxies with available data cannot be ruled out at the level of < 0.2 mag. This alone could account for 50% of the LGM or alter the apex direction by some 45° . Thus, the systematic scatter in the measurement of the apparent magnitudes alone, is large enough to account for half of the Rubin et al. effect.

2) Rubin et al. quote a dispersion in absolute magnitude (with no diameter-luminosity correction applied) of $\Delta M \sim 0.4$ mag for their sample. This is larger than earlier estimates made by van den Bergh (1960), $\Delta M \sim 0.3$. More recently Sandage and Tammann (1975b) estimate $\Delta M \sim 0.55$ mag for ScI galaxies and Tammann, Yahil, & Sandage (1979) study the luminosity functions of the spirals in the Revised Shapley-Ames catalog, concluding that there is a spread of more than 3 magnitudes difference within any given luminosity class. This compares with the decrease of only 0.2 in the absolute magnitude from ScI to ScII adopted by Rubin et al. This

illustrates again that their Sc sample has a wider range in absolute magnitude than is apparent from the Rubin et al. luminosity classification. These larger absolute magnitude dispersions are in broad agreement with our IR photometry for this sample (Section 5.2.4). Such a high dispersion in absolute magnitude can both increase the statistical error, and introduce systematic effects if there is a variation of the absolute magnitude across the sky. The high dispersion in the absolute magnitudes of Sc galaxies has been suggested as an explanation of the discrepancy between the CBR & Rubin et al. results (Tammann, Sandage, & Yahil 1980, Davis & Peebles 1983b, Hart & Davies 1982). It is worthwhile to consider the effect that a finite absolute magnitude dispersion has on the statistical uncertainty, and to quantify the extent to which sky variations in absolute magnitudes could be contributing to the anisotropy. Both of these are carried out below.

An approximate estimate of the expected uncertainty in the LGM projected on to any normal vector can be found easily by differentiating equation 3.7. This gives

$$\Delta V = (3/N)^{1/2}[(\ln 10)/5] \langle \Delta M^2 + \Delta m^2 \rangle^{1/2} V_0 \quad 3.17$$

where N is the number of galaxies at redshift V, and Δm^2 and ΔM^2 are the variances in the apparent and absolute magnitude dispersions respectively. Equation 3.17 assumes that deviations from the Hubble flow are negligible. Since ΔV is proportional to V, conclusive and unambiguous detections of velocity anisotropies are difficult on the scale of the Rubin et al. sample, since it is essential that intrinsic luminosities are accurately known. For example, to achieve a detection of 500 km/sec for a sample of 100 galaxies, located at 5000 km/sec, to a precision of 15%, which is comparable to the CBR dipole anisotropy uncertainty, requires that $\langle \Delta M^2 \rangle^{1/2} \sim 0.08$. With the dispersion for the same sample of galaxies thought to be ~ 0.5 mag an uncertainty of 200 km/sec is expected from Eqn 3.17. This indeed agrees with the precision obtained by Rubin et al. using data not corrected for apparent diameters. This uncertainty corresponds to 2.9%,

or an uncertainty in direction of $\sim 20^\circ$. The difference between the Rubin et al. and CBR apexes is significant at the 4 σ level. It is therefore unlikely that the statistical uncertainty in the mbs sample of 96 galaxies alone, can account for the 90° angular distance between these two directions.

The possible variation of intrinsic luminosities across the sky contributing to the anisotropy was not fully addressed by Rubin et al., since their analysis assumed that, to first order, the sample consisted of standard candles and any scatter in absolute magnitudes would be randomly distributed on the sky. Malmquist biasing was mentioned in Section 3.2.3, to be significant in the mbs. Fall and Jones (1976) argue that Malmquist biasing could give rise to the Rubin et al. anisotropy without recourse to any velocity anisotropy. They consider only 21 out of the 96 galaxies that lie between declinations 20° and 42° . These galaxies can be associated either with the Perseus-Pisces complex at $V \sim 4950$ km/sec (in the apex hemisphere) or Abell's supercluster no.6 at $V \sim 6400$ km/sec (in the antapex hemisphere). If apex galaxies come preferentially from the faint end of the luminosity function and antapex galaxies come preferentially from the bright end, then the Rubin et al. anisotropy could be reproduced for this subset of the Rubin et al. sample. This effect is far less pronounced when averaged over all galaxies in the two hemispheres. The velocities in these two regions for the full 96 mbs are $\langle V \text{ apex} \rangle \sim 4950$ km/sec and $\langle V \text{ antapex} \rangle \sim 5457$ km/sec. From Eqn. 3.7 the variation in M from apex to antapex coupled with the Malmquist effect amounts to 0.05 mag or 1/8th of the anisotropy. Although Fall and Jones perhaps overstated their case, Rubin et al. have not demonstrated that sky variations in intrinsic luminosities are not contributing to the anisotropy for their sample of galaxies. Schechter showed that the diameter-luminosity relation does not give rise to an improved accuracy of the LGM. So their solutions only incorporate two variables, apparent magnitudes and redshifts. The 21cm line widths listed by Rubin et al. are not used in the LGM solutions as a luminosity indicator. Such a relation exists (Tully & Fisher 1977) and is discussed in detail in Chapter 5.

Instead, Rubin et al. consider the variation of the maximum velocity width with cosine of the apex distance. The correlation has an uncertainty of 0.4 mag, for a nominal Tully-Fisher slope of 5, which transforms into an angular uncertainty of $\sim 90^\circ$. The dearth of a reliable luminosity indicator, coupled with the large magnitude dispersions, introduces the possibility of significant variation in the intrinsic luminosities of the galaxies across the sky.

3) The close proximity of the apex vector to the galactic plane may suggest an anomalous extinction correction (Tammann, Sandage, & Yahil 1980). In addition to the solutions incorporating a modified extinction law, Section 3.2.3, Rubin et al. perform an additional test, using the variation of optical-21cm colour across the sky, as a trace for extinction, since 21cm magnitudes are extinction free. While this test indicates that no grossly inaccurate correction for galactic extinction has been applied, the dispersion in the regression of optical to 21cm colour versus $\cos \theta$ is large enough that residual apex to antapex extinction cannot be ruled out at a level corresponding to $\Delta m \sim 0.2$ or $\sim 1/2$ of the observed anisotropy. Such a proportion of the anisotropy is enough to alter the apex direction by $\sim 45^\circ$.

To summarise, the Rubin et al. effect has come under much criticism with regard to the reality of the dipole anisotropy as a velocity anisotropy. These criticisms fall into two categories. Firstly, the apparent magnitudes are uncertain. This is due to difficulty in measurement and susceptibility to extinction. The second broad criticism discussed concerns the fact that no luminosity indicator has been incorporated into the solutions, which could ruin the resultant velocity dipole solutions, as these are equivalent to saying that galaxies are brighter on one side of the sky than the other. Table 3.2 shows the 1 σ rms residual on the least-squares fit, from apex to antapex, for each of the correlations across the sky studied by Rubin et al. The approximate effect on the angle of the dipole anisotropy, if the scatter is correlated on the sky, is also shown.

Table 3.2

Sources of Uncertainty in the Rubin et al. Study

Origin	RMS Mags	Max angular change to anisotropy
Apparent magnitudes		
Measurment uncertainty (mGR-mZW) v's $\cos \theta$	0.2	45°
Extinction (21cm v's opt) v's $\cos \theta$	0.2	45°
Absolute magnitudes		
Absolute mag dispersion Vmax v's $\cos \theta$	0.4	90°
Malmquist bias HM v's $\log V_0$	0.05	10°
Statistical Uncertainty		
Equation 3.17	0.15	20°

A glance at Table 3.2 reveals that any of several independent sources of uncertainty is enough to make up a significant part of the difference between the Rubin et al. and CBR dipole anisotropies.

3.3.2 Advantages of an Infrared Study

The problems listed in Table 3.2 are effectively overcome by photometry in

the IR. To begin with, any observations of the Rubin et al. mbs are useful to provide a completely independent data set with which to repeat the Rubin et al. LGM solutions, and increase the significance, or otherwise, of their result. More importantly, the IR has significant advantages over the optical for this type of study. Near IR magnitudes are less affected by extinction, compared to optical measurements, by about a factor of 10. They are also less prone to effects of variable star formation rates across the sky. This is because the peak of the galactic emission spectrum is at H, where the flux density is ~ 10 times that in the blue. This light is dominated by the old stellar population in the galaxy and dispersion in the IR absolute magnitudes should consequently be smaller than in the optical for a morphologically selected sample. The IR magnitudes should also provide a very powerful tool for determining the redshift-independent distances using two methods. Firstly, when combined with the 21cm velocity width data from Rubin et al. (i.e. by using the Tully-Fisher relation), and secondly with the OPT to IR colour magnitude relation. Aaronson et al. (1979) and Tully et al. (1982) have demonstrated the reliability of both these relations as distance indicators for spirals in determining distances to 0.45 mag. This will enable a luminosity relation to be incorporated in the analysis for the LGM and decrease the noise, while permitting the determination of the contribution to the Rubin et al. anisotropy from systematic variations in absolute magnitudes across the sky.

CHAPTER 4

NEAR INFRARED OBSERVATIONS AND DATA REDUCTION OF THE RUBIN ET AL. GALAXIES

4.1 Introduction

This chapter outlines the details of the observational procedure and data reduction scheme necessary to provide a data base sufficiently precise in order to investigate velocity anisotropies of a few hundred km/sec, for galaxies located at 5000 km/sec. Since the observation of the complete Rubin et al. mbs is the aim of this project, the primary selection criteria for the galaxies presented in this thesis was their availability during any given observing period. In order to carry out a Tully-Fisher type analysis, those galaxies were favoured for which there is 21cm data in Rubin et al. (1976a). The main emphasis in describing the observing procedure is to demonstrate the operation of the telescope on which these observations were made and to discuss the precautions which it is necessary to take when observing in the IR. While the reduction of photometric data is straightforward, it is clearly important to demonstrate that the data is internally consistent, in view of the comments in Chapter 3, before any analysis in terms of anisotropy of the Hubble flow can be made.

4.2 The Observations

4.2.1 Telescope Parameters

The IR observations of the Rubin et al. mbs presented in this thesis were made during two observing runs in December 1983 and April 1984, at the 1.5 metre Infrared Flux Collector (IRFC) on Tenerife. The telescope is ideal for this type of observing programme. It has a large enough collecting mirror that 13th magnitude galaxies can be detected at K with good signal to noise in a few minutes of integration time. In addition, the background loading on the photometer was small enough that large apertures

x

were available. For all the observations we used the ICST single channel InSb cryostat. The design of this instrument incorporates an aperture wheel, having apertures from 10-40 arcsec in diameter, and a separate filter wheel with J,H,K,L,M filters included. The telescope had a moveable TV crosshead with encoders for offsetting to guide stars located < 1.5 arcmin from a galaxy central position. The TV was sensitive enough that guide stars < 13 th mag at B could be seen in dark time. However, the TV has no baffle and in bright time the limiting B magnitude of the TV was ~ 10 . The signal from the preamp is amplified by a phase lock amplifier, which uses a reference signal directly from the tertiary mirror chopper. The chopped signal is digitised by a digital volt meter and an Aim 65 microcomputer monitors the post phase sensitive detected voltage directly from the volt meter. The voltage is sampled once every 1 sec, or so, for the duration of one half of a nod or beam switch cycle (~ 10 secs). After all the samples have been taken the telescope is noded by the Aim and a delay inacted during which time a signal averaging is performed and the data is logged on to tape and Teletype printer. The Aim acts as the reduction system by means of a 3 point algorithm which uses the data taken on successive nod cycles to remove first order linear drift and minimise non-linear effects. The details of the data logging system and data reduction algorithm are given by Morris (1984).

4.2.2 Observational Parameters

For all observations we used a 35 arcsec aperture and measured each galaxy at J ($\lambda = 1.31 \mu\text{m}$, $\Delta\lambda = 0.24 \mu\text{m}$), H ($\lambda = 1.66 \mu\text{m}$, $\Delta\lambda = 0.27 \mu\text{m}$) and K ($\lambda = 2.17 \mu\text{m}$, $\Delta\lambda = 0.375 \mu\text{m}$) (Selby 1984). Although we are more primarily interested in photometry at H, the extra integrations at J and K take relatively little time, compared to finding, and in addition, the JHK colours provide both a quality control of the data and information on internal reddening, young stars and free-free emission. The use of large apertures for this project is important for several reasons. Firstly, since this data is to be analysed for anisotropy across the sky, it must be free of systematic effects. One such bias is the oversampling of galaxies

at larger distances, compared to nearer ones when using a constant aperture. The exponential fall off of light with aperture for spiral galaxies (Fall 1980) means that smaller corrections are necessary for large apertures. Further, Aaronson et al. (1980) have demonstrated the reliability of the aperture to galaxy diameter ratio (A/D) ~ 0.3 for use in the application of the infrared Tully-Fisher relation. This is based on the dynamical argument that at larger diameters it is common for the rotation curve of spirals to turn down, indicating that the end of the halo has been reached and that material is beginning to depart from the solid body rotation apparent at smaller diameters. Therefore, observations using either larger or smaller apertures than that for which $A/D \sim 0.3$ are less desirable. Since the average isophotal diameter of the Rubin et al. sample is ~ 100 arcsec, then a 35 arcsec aperture ensures that minimal extrapolation to $A/D \sim 0.3$ is required. Finally, large apertures are less prone to pointing errors that could ruin the observations.

A chop throw of amplitude 60 arcsec was adopted. This amplitude is less than the practical limits for the chopper system on the IRFC, but is large enough that for aperture to galaxy diameter ratios $A/D \sim 0.3$, there is no significant contamination in the reference beam (Aaronson et al. 1980). A chopping frequency of ~ 10 Hz has from experience shown to optimise the filtering of $(1/f)$ electronic noise, which is the dominant noise source at low frequencies and sky photon shot noise, which dominates at frequencies > 10 Hz and which is limited by the roll off of the detector response (Morris 1984).

4.2.3 Observing Procedure and Weather

We obtained co-ordinates using the Coradograph plate measuring facility available at RGO. These positions are accurate to ~ 1 arcsec. At the telescope the galaxies were found by a multi-step procedure. First a nearby SAO star was located using the 8 inch finding telescope. After centering on the star the IRFC encoders were reset to those co-ordinates.

The telescope was then slewed to the nominal position of the galaxy and the TV was offset to the guide star position using the TV encoders. The star was then centred on the TV and the IR signal was peaked up on the strip chart. Finding in this manner usually took between 20-30 minutes. Integration times of only a few minutes were sufficient to obtain a $S/N > 10$ for most galaxies observed. With particularly faint galaxies emphasis was placed on obtaining good H band data at the expense of J and K as the H band is where a typical galaxy spectrum peaks and H is also the optimum near infrared waveband in which to minimise the effects of extinction, prevalent at J, and to minimise possible contamination from dust emission at K (Aaronson et al. 1980). Calibrations were made about twice an hour using the high quality standard stars listed by Elias et al. (1982). These stars have absolute photometric uncertainty < 0.02 mag and are typically 7-8 mag at K and so are easily detected with high precision.

There have been 3 observing runs at the IRFC to carry out this programme: June 1983 (3 weeks), December 1983 (3 weeks) and April 1984 (1 week). The June run was heavily marred by low cloud and high wind. Out of 21 nights only 4 were photometric. In the course of this run 9 galaxies were observed at J, H and K. Of these, 5 were re-observed the following April with a higher degree of reliability. The difference in the magnitudes of repeat observations in June 83 is as large as ~ 0.3 mag at H. Therefore, the data on all the galaxies observed in June were discarded. Despite the lack of useful data the June observing run did demonstrate the feasibility of the project at the IRFC. In December 1983 there was a total of 8 clear nights. During this period 33 galaxies were observed in the mbs and a further 2 not in the mbs but within the same redshift range. In the course of a week in April 1984 a further 12 galaxies were observed and several repeat observations made to check consistency.

4.3 Data Reduction

4.3.1 Primary Calibration

To calibrate the raw photometric data, the flux of each galaxy was ratioed with the flux from a standard star measured as nearly as possible in the same direction as the galaxy on the same night. The optimum standard for a given galaxy often involved the nearest calibration in airmass or sidereal time. Sometimes a combination of more than one calibration was necessary in cases where the disagreement between standards was significant. Calibrations were also used to investigate atmospheric extinction by plotting apparent magnitude against air mass. This was found to be important for the calibration stars when the air mass change between calibrations exceeded 0.1. Using calibrations separated by air mass changes > 0.1 , the average extinction estimates (Mag/Am) for our best and poorest photometric nights at the IRFC, on both runs, are shown in Table 4.1 below. For comparison, the similarly classified estimates from Johnson (1968) are also listed.

Table 4.1

Comparison of JHK Extinction Estimates

Mag/Am for 3 Excellent Photometric nights

J	H	K	
0.2	0.13	0.15	IRFC (Dec & April)
-	0.10	0.14	Johnson (1968)

Mag/Am for 4 Average Photometric Nights

J	H	K	
0.36	0.20	0.33	IRFC (Dec & April)
0.40	0.15	0.23	Johnson (1968)

The extinction estimates are derived from only 2 or 3 calibrations each night, but the consistency with the estimates of Johnson to within 10% suggests an adequate assesment of the quality of each night has been made. Air mass corrections were applied to each galaxy when the air mass difference between optimum calibration star and galaxy exceeded 0.1. If an air mass curve was not available for that particular night then an average AM curve based on other nights of similar quality weather was used. In general, the air mass corrections were ~ 5%. In one case, RF 137, they were untypically large, viz. ~ 0.45 mag at J and ~ 0.3 mag at H. The overall consistency between calibrations on each night was better than 10%. The magnitudes of all the galaxies observed in December and April are summarised in Table 4.2, along with the formal statistical errors. This data has been corrected for atmospheric extinction only.

Table 4.2

Near-Infrared Data of the Rubin et al. Sample of Galaxies

Galaxy (RF No)	Apparant Magnitude	
	December (1983)	April (1984)
1	J = 12.57 ± 0.07	
	H = 11.82 ± 0.05	
	K = 11.42 ± 0.07	

8	$J = 11.79 \pm 0.03$	
	$H = 10.99 \pm 0.06$	
	$K = 10.83 \pm 0.06$	
11	$J = 12.17 \pm 0.04$	
	$H = 11.51 \pm 0.06$	
	$K = 11.12 \pm 0.07$	
12	$J = 13.33 \pm 0.08$	
	$H = 12.53 \pm 0.09$	
	$K = 12.21 \pm 0.10$	
17	$J = 12.73 \pm 0.08$	
	$H = 11.98 \pm 0.08$	
	$K = 11.72 \pm 0.10$	
24	$J = 13.60 \pm 0.10$	
	$H = 13.04 \pm 0.16$	
	$K = -$	
30	$J = 11.91 \pm 0.07$	
	$H = 10.96 \pm 0.06$	
	$K = 10.71 \pm 0.07$	
34	$J = 13.20 \pm 0.21$	
	$H = 12.51 \pm 0.28$	
	$K = -$	
35	$J = 12.74 \pm 0.08$	
	$H = 12.04 \pm 0.06$	
	$K = 11.69 \pm 0.08$	

38	$J = 12.55 \pm 0.07$ $H = 11.90 \pm 0.07$ $K = 11.48 \pm 0.09$	
50	$J = 12.07 \pm 0.07$ $H = 11.01 \pm 0.06$ $K = 10.79 \pm 0.06$	
53	$J = 11.84 \pm 0.04$ $H = 10.95 \pm 0.03$ $K = 10.75 \pm 0.06$	
54	$J = 12.26 \pm 0.05$ $H = 11.59 \pm 0.06$ $K = 11.22 \pm 0.06$	
71	$J = 11.94 \pm 0.05$ $H = 11.14 \pm 0.05$ $K = 10.87 \pm 0.05$	
72	$J = 13.02 \pm 0.08$ $H = 12.55 \pm 0.07$ $K = 12.24 \pm 0.10$	
76	$J = 11.84 \pm 0.05$ $H = 11.03 \pm 0.05$ $K = 10.78 \pm 0.06$	
78	$J = -$ $H = 11.78 \pm 0.13$ $K = 11.79 \pm 0.28$	

77	$J = 13.04 \pm 0.18$ $H = 12.43 \pm 0.14$ $K = 11.84 \pm 0.29$	$J = 12.94 \pm 0.10$ $H = 12.43 \pm 0.19$ $K = 12.08 \pm 0.13$
79	$J = 12.94 \pm 0.10$ $H = 12.28 \pm 0.13$ $K = 12.23 \pm 0.29$	
83	$J = 12.90 \pm 0.11$ $H = 11.93 \pm 0.10$ $K = -$	$J = 12.78 \pm 0.09$ $H = 12.00 \pm 0.09$ $K = 11.71 \pm 0.09$
86	$J = 12.46 \pm 0.06$ $H = 11.81 \pm 0.07$ $K = 11.58 \pm 0.08$	
87	$J = 12.68 \pm 0.08$ $H = 11.99 \pm 0.07$ $K = 11.86 \pm 0.09$	
88	$J = 12.59 \pm 0.07$ $H = 11.85 \pm 0.07$ $K = 11.71 \pm 0.08$	
92	$J = 12.59 \pm 0.07$ $H = 12.14 \pm 0.09$ $K = 11.63 \pm 0.08$	
96	$J = 13.07 \pm 0.14$ $H = 12.37 \pm 0.20$ $K = 12.21 \pm 0.21$	$J = 13.02 \pm 0.20$ $H = 12.22 \pm 0.22$ $K = 12.25 \pm 0.36$

102	$J = 12.52 \pm 0.07$ $H = 11.79 \pm 0.08$ $K = 11.41 \pm 0.09$	
103		$J = 12.82 \pm 0.09$ $H = 12.09 \pm 0.09$ $K = 11.66 \pm 0.11$
106	$J = 12.79 \pm 0.09$ $H = 11.97 \pm 0.07$ $K = 11.91 \pm 0.13$	$J = 12.87 \pm 0.30$ $H = 12.01 \pm 0.20$ $K = -$
109	$J = 11.76 \pm 0.16$ $H = 10.88 \pm 0.10$ $K = 10.71 \pm 0.26$	
	$J = 11.90 \pm 0.07$ $H = 11.08 \pm 0.06$ $K = 10.74 \pm 0.07$	
110		$J = 11.94 \pm 0.21$ $H = 11.44 \pm 0.08$ $K = 11.00 \pm 0.12$
121	$J = 11.44 \pm 0.05$ $H = 10.62 \pm 0.05$ $K = 10.32 \pm 0.05$	
130		$J = 12.10 \pm 0.08$ $H = 11.35 \pm 0.05$ $K = 11.21 \pm 0.07$

133		$J = 13.06 \pm 0.10$
		$H = 12.23 \pm 0.10$
		$K = 11.72 \pm 0.10$
		$J = 13.06 \pm 0.16$
		$H = 12.20 \pm 0.17$
137		$J = 12.36 \pm 0.30$
		$H = 12.03 \pm 0.26$
		$K = -$
145		$J = 12.85 \pm 0.12$
		$H = 11.91 \pm 0.09$
		$K = -$
		$J = 12.87 \pm 0.13$
		$H = 11.82 \pm 0.17$
		$K = 11.74 \pm 0.20$
160		$J = 12.45 \pm 0.14$
		$H = 11.54 \pm 0.17$
		$K = 11.37 \pm 0.17$
161		$J = 12.17 \pm 0.13$
		$H = 11.26 \pm 0.11$
		$K = 10.98 \pm 0.18$
162		$J = 12.36 \pm 0.07$
		$H = 11.71 \pm 0.07$
		$K = 11.35 \pm 0.07$
164		$J = 12.31 \pm 0.06$
		$H = 11.52 \pm 0.09$
		$K = 11.21 \pm 0.12$

165		$J = 12.08 \pm 0.14$
		$H = 11.37 \pm 0.08$
		$K = 11.08 \pm 0.11$
168		$J = 11.90 \pm 0.13$
		$H = 11.25 \pm 0.08$
		$K = 10.87 \pm 0.10$
191	$J = 12.51 \pm 0.09$	
	$H = 11.47 \pm 0.07$	
	$K = 11.03 \pm 0.08$	
192	$J = 12.46 \pm 0.06$	
	$H = 11.57 \pm 0.06$	
	$K = 11.52 \pm 0.08$	
196	$J = 12.52 \pm 0.09$	
	$H = 11.71 \pm 0.09$	
	$K = 11.57 \pm 0.15$	
200	$J = 12.79 \pm 0.17$	
	$H = 11.78 \pm 0.06$	
	$K = 11.46 \pm 0.08$	

4.3.2 Errors and Consistency

The formal errors on each galaxy are calculated by assuming that the total error is a combination of 3 smaller uncertainties: 1) The S/N of the galaxy detection (s_1). 2) The S/N of calibration, which is mostly negligible (s_2). 3) The average residual between repeated calibrations that were made at similar times to the galaxy during the same night (s_3). The overall uncertainty is then given by treating each as an independent

source of statistical error,

$$S_T = (s_1^2 + s_2^2 + s_3^2)^{1/2} \quad 4.1$$

While s_1 and s_2 take care of the statistical uncertainties, s_3 represents the overall repeatability and so includes systematic effects, such as those due to weather. Although these are not well defined statistically they have been incorporated here, since they are often the dominant source of error. The photometry on repeated galaxies can be used to check the validity of S_T . A comparison between the repeat photometry and S_T is shown in Table 4.3. This table uses the data from 7 repeated galaxies.

Table 4.3

Comparison of Repeated Observations with Calculated
Uncertainties

Band	Magnitude difference between repeated observations	Estimated error for repeated galaxies (S_T)
ΔJ	0.09	0.14
ΔH	0.14	0.13
ΔK	0.22	0.20

The agreement between these two sets of figures is particularly good considering that some repeats had been done because the first observations were carried out at high air mass or under suspect photometric conditions.

A further check on the IR photometry can be made using the results of Bothun et al.(1984). They obtained multiaperture, infrared H band photometry for a sample of spirals which include some Rubin et al. galaxies. In this sample are 5 galaxies with 34.4 arcsec data and 3 galaxies with 36.2 arcsec data, for which we have 35 arcsec measurements. A direct comparison between the two data sets yields a mean difference and

standard deviation of

$$(\text{Bothun}-U_s) = -0.07 \pm 0.08$$

4.2

This has two implications. firstly, there is no significant offset in the H band magnitudes. Secondly, since the photometry of Bothun et al. has precision to 0.03 mag, then the scatter for our galaxy set is < 0.1 . This is a slightly greater precision than implied by the repeat photometry in Table 4.2, and is consistent with assumption that the Bothun comparison, here, involves galaxies which are unbiased examples of our photometry.

4.3.3 Infrared Colours

Figure 4.1 is the two colour diagram for all the galaxies with JHK photometry, with typical errors shown. Also plotted is a circle which represents the standard colours for spiral galaxies, centered at $J-H = 0.75$, and $H-K = 0.25$, and has a radius corresponding to an uncertainty in each colour of ± 0.15 mag. The mean and standard deviation of the galaxy colours are $J-H = 0.75 \pm 0.14$ and $H-K = 0.27 \pm 0.13$. Assuming that there is a similar uncertainty for all three wavebands then the standard deviation of the colours is consistent with the aforementioned estimates of the errors.

From the distribution of the galaxies about the reddening line shown in Fig. 4.1, there is little evidence, within the errors, for any internal extinction in these galaxies. The most direct interpretation of the 4 galaxies with $J-H \sim 1$ is that the photometry is systematically faint at J, since the H-K colours do not appear reddened.

The IR photometry presented in this Chapter shows internal consistency and an rms precision of < 0.1 mag. Our data is also consistent to within this uncertainty with independent observations of 8 sample galaxies by Bothun et al. (1984). Despite poor weather on both observing runs, enough data was taken in December (1983) and April (1984) to give fairly uniform sky coverage (Fig. 5.1).

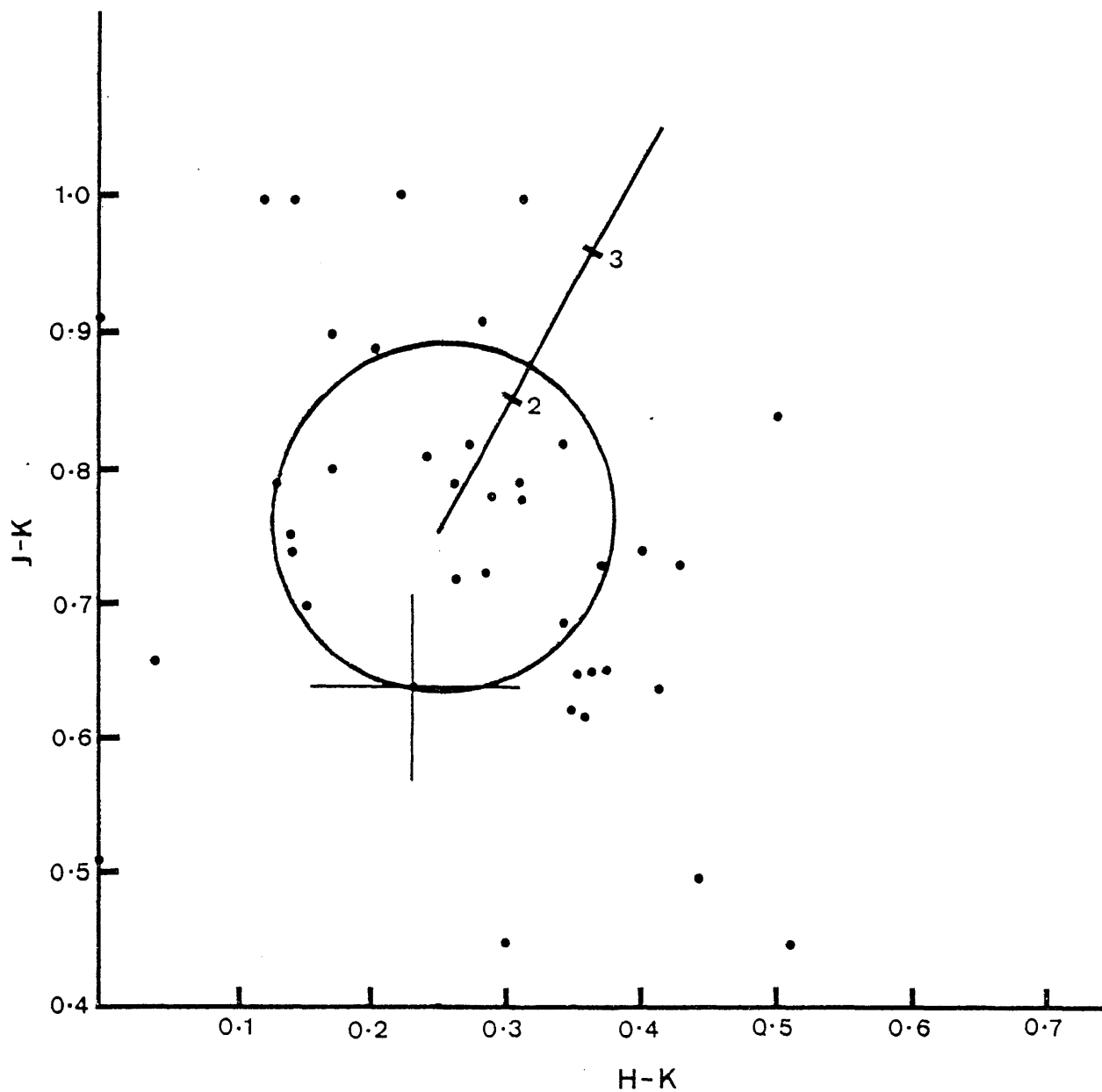


Figure 4.1 JHK colour-colour diagram for 40 mbs galaxies. Typical error bars are indicated along with the reddening line, graduated in magnitudes of optical extinction, and a circle enclosing the region within ± 0.15 of $J-H = 0.75$ & $H-K = 0.25$.

CHAPTER 5

INFRARED DATA ANALYSIS

5.1 A Preliminary Study

5.1.1 Sky and Redshift Distributions

In order to study the anisotropy of the Hubble expansion it is necessary for the galaxy sample to have as uniform a sky coverage as possible. In addition, since we wish to confront the conclusions of Rubin et al. and investigate the "Rubin-Ford effect," our sub-samples must be representative of the mbs as a whole. This is particularly important in redshift space, since putative anisotropies may be a strong function of scale. Figure 5.1 displays the sky distribution of the 45 galaxies for which we have near-IR data and the 64 detections of the mbs made by IRAS. The plot is an equal area projection of the celestial sphere with angular coordinates of galactic latitude (b) and longitude (l). Both the near-IR and far-IR (Section 5.4) samples are a good representation of the mbs coverage and both samples provide adequate coverage of the sky in most regions. The sparsely populated region, centered at $l \sim 300^\circ$, and $b \sim -30^\circ$, corresponds to a declination $< -45^\circ$. This area covers only $\sim 12\%$ of the sky and is almost orthogonal to the velocity apex vector of both the CBR and Rubin et al. dipole velocity solutions. These factors suggest that incomplete sky coverage in this region will have minimal consequence. The redshift distribution of the two IR samples, along with the full mbs are shown in Figs. 5.2a,b, where the galaxies have been placed in 500 km/sec bins. Compared to the mbs, there is little biasing of the IR samples in favour of any redshift region. In other respects also, such as inclination, velocity width, morphological classification, and diameters, the sub-sample of 45 with near-IR data and the sub-sample of 64 with far-infrared data are both representative of the mbs.

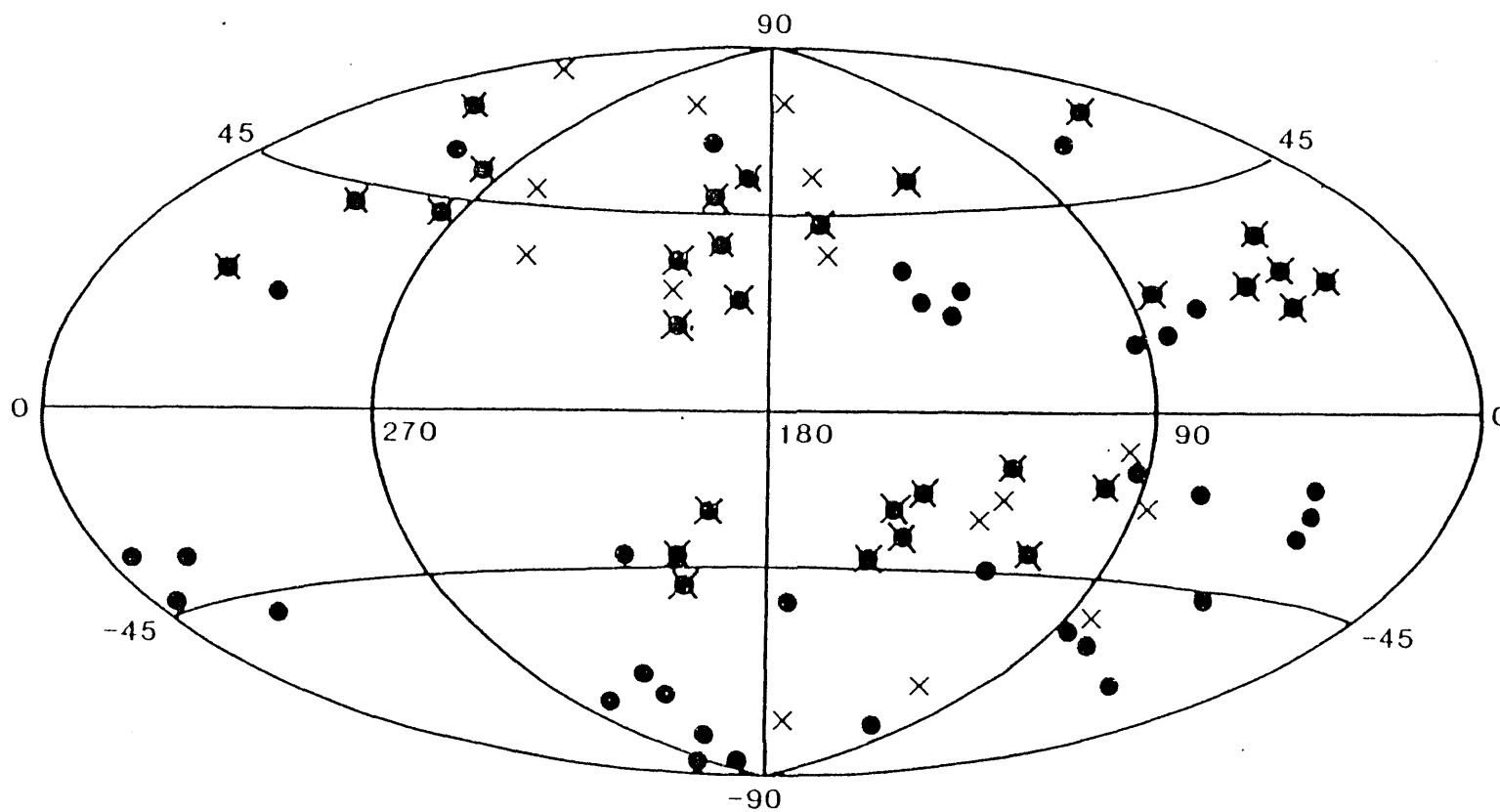


Figure 5.1 Sky distribution of mbs galaxies with near and far-IR data, in galactic coordinates. Crosses represent near-IR and spots are detections at $100\mu\text{m}$.

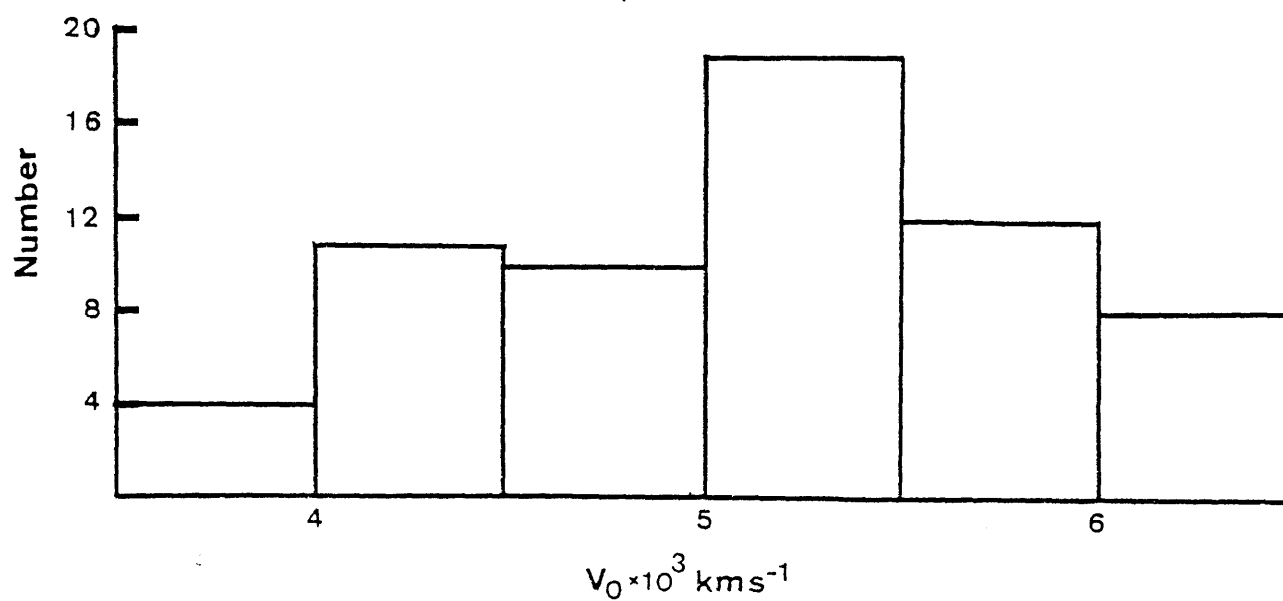
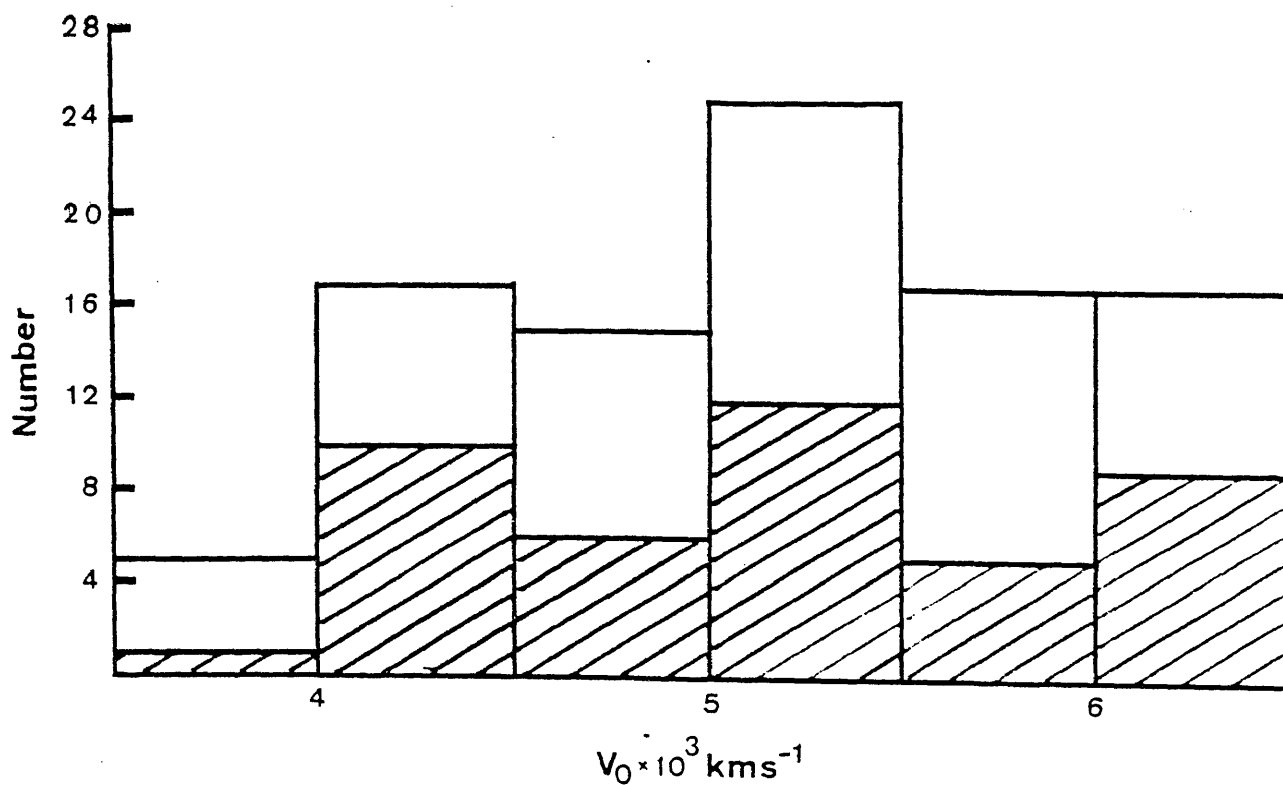


Figure 5.2a,b Redshift distributions for the full mbs, the near-IR subsample of 45 galaxies (top) and the far-IR subsample of 64 (bottom).

5.1.2 Anisotropy of the Near Infrared Data

As a first step in examining anisotropies using the IR data, the analysis carried out in this section involves the anisotropy of the H magnitudes as a function of angle from the Rubin et al. apex direction. In sections 5.2 and 5.3 the JHK data is used for a formal regression analysis. A similar analysis is carried out using the 100 μ m IRAS detections in section 5.4. The purpose here is gain immediate evidence, or otherwise, of the anisotropy as reported by Rubin et al. using the near infrared data.

The study made by Rubin et al. of the Hubble expansion employed the use of the Hubble Modulus (HM). The anisotropy of this quantity, as pointed out in Chapter 3, is independent of the average absolute magnitude for the sample and under the assumption that the galaxies are standard candles, the anisotropy of HM across the sky can be interpreted as either a motion of the Local Group or a motion of the galaxy sample with respect to the rest frame defined by the LG.

The 45 H band magnitudes listed in Table 4.2 are used in place of the optical magnitudes, to define an IR HM for each galaxy. This data has been corrected for atmospheric extinction only. Each HM is plotted against cosine of the angle between the galaxy and apex anisotropy direction $l = 200^\circ$, $b = -11^\circ$. This plot is the subject of Fig. 5.3. It is evident that there is an anisotropy in the direction defined by the Rubin et al. velocity vector. A formal least squares fit to the data gives

$$HM(H) = (-0.08 \pm 0.03) \cos \theta + 1.4 \pm 0.2. \quad 5.1$$

If this anisotropy is interpreted in terms of a dipole velocity anisotropy of the Local Group or the galaxy sample itself, then Eqn. 5.1 implies that $|VD| \sim 800$ km/sec. However, it is premature to interpret this result as a velocity anisotropy because there are two corrections which have yet to be applied in order to minimize spurious contributions to the anisotropy from

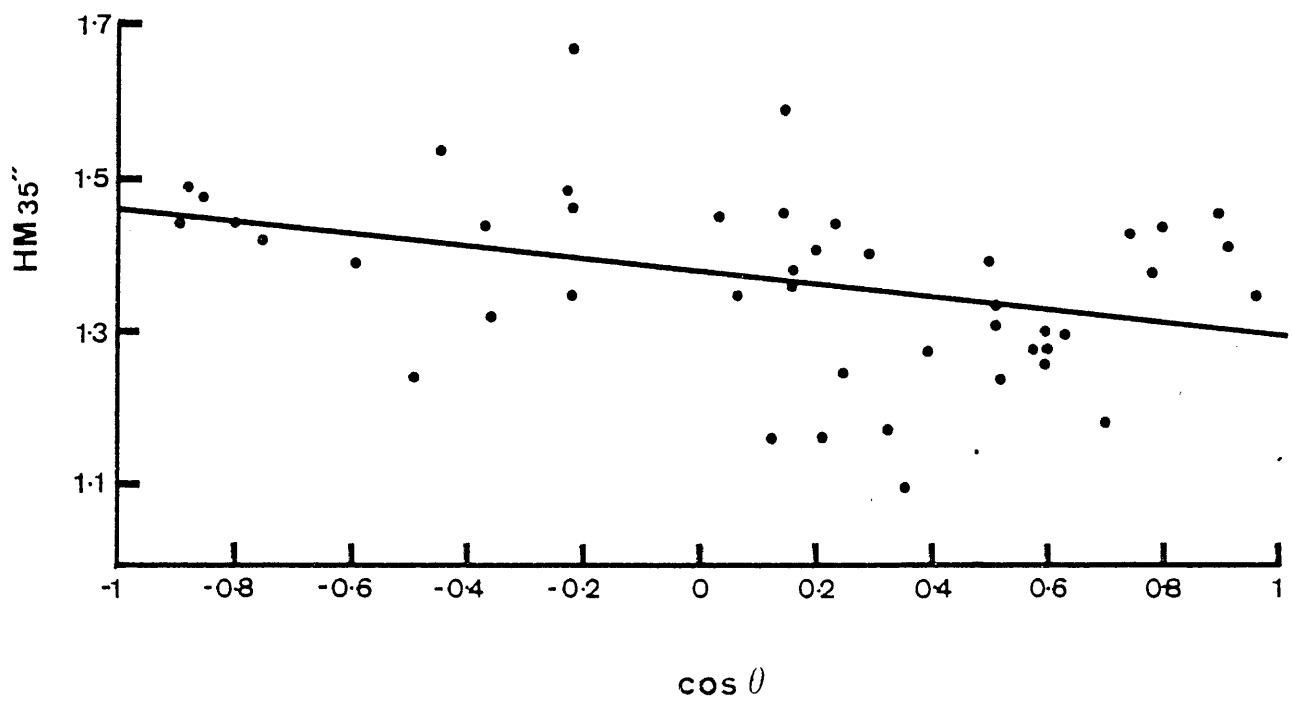


Figure 5.3 Variation of near-IR Hubble modulus from the apex to antapex defined by the Rubin et al. LGM.

biasing in the apparent magnitudes. Firstly, since a constant aperture of 35 arcsec was used, the furthest galaxies are oversampled with respect to those at the low redshift end. This problem was discussed in Section 4.2.2. Secondly, the furthest galaxies may be intrinsically brighter due to the Malmquist effect. As indicated in Chapter 3, Rubin et al. find significant residual Malmquist biasing in their sample, despite the fact that it was chosen to minimise this effect.

Ultimately, both these contributions will be corrected for individually, but for a first order approach it is possible to utilise their common dependence upon distance and make a "hybrid" correction. Both the aperture effect and Malmquist bias work in the same sense to make apparent magnitudes too bright (Eqn. 3.7) and therefore HM's too large. The coupled effect can be seen in Fig. 5.4, where HM for each galaxy, using the data of Table 4.2, is plotted against the logarithm of the redshift. The regression line is

$$HM(H) = (0.98 \pm 0.27) \log V_0 - (2.2 \pm 1). \quad 5.2$$

Galaxies at a redshift of 6450 km/sec have, on average, apparent magnitudes brighter than those at 3800 km/sec by ~ 1.1 mag at H. Identical results, within the errors, are found for both the J and K data when treated the same way. If the galaxy redshift distribution is anisotropic on the sky then the relation 5.2 will give rise to a variation of HM across the sky. As an illustration, recall that the two hemispheres defined by Fall & Jones (1976) (Section 3.3.1) have mean velocities of 5457 and 4956 km/sec respectively. The inferred difference in IR absolute magnitude between the two regions is ~ 0.2 mag and therefore not insignificant. Equation 5.2 enables an increment of HM to be identified for each galaxy which effectively reduces the absolute magnitude, and therefore the apparent magnitude, to the mean of the sample. This is done by subtracting the identified increment from the initial HM of each galaxy. The variation of the corrected HM's with the cosine of the angle from the Rubin et al. anisotropy vector ($l \sim 200^\circ$, $b \sim -11^\circ$) is shown in

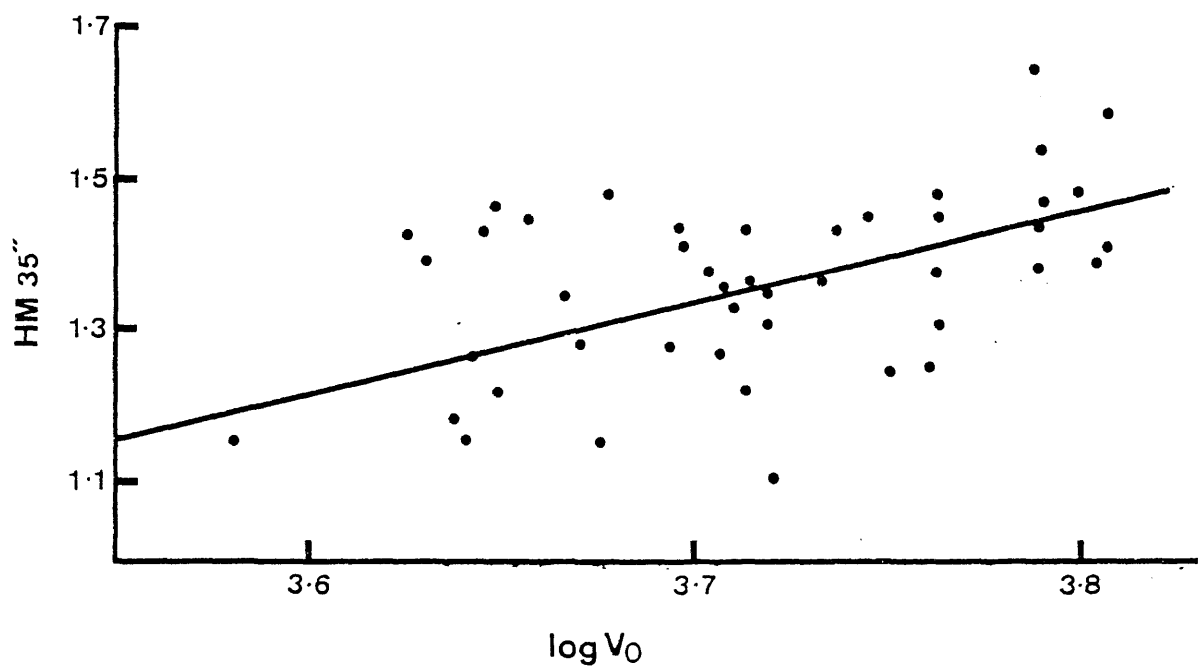


Figure 5.4 Variation of near-IR Hubble modulus with observed redshift, indicating Malmquist biasing.

Fig. 5.5a. The formal least squares regression gives

$$HM(H) = (-0.05 \pm 0.025) \cos \theta + 1.38 \pm 0.06 \quad 5.3$$

From the definition of HM this implies a residual motion of $|V_D| \sim 600 \pm 300$ km/sec.

In contrast, Fig. 5.5b shows the anisotropy implied for the H band data using an apex direction as inferred from the dipole anisotropy of the CBR, viz. $\ell = 260^\circ$, $b = 35^\circ$. The magnitudes have been corrected for the variation of HM with distance, as described above. The slope of HM in this direction is

$$HM(H) = (-0.018 \pm 0.025) \cos \theta + 1.35 \pm 0.02 \quad 5.4$$

Equations 5.3 and 5.4 are consistent with the corresponding optical regressions (Eqns. 3.15 and 3.16) discussed in Section 3.23, to within the quoted errors. This very preliminary analysis indicates that the IR data does not exhibit a significant anisotropy in the direction of the LGM, inferred from the CBR dipole. There is however, a moderately significant anisotropy of the H band data in the apex direction determined by Rubin et al.

5.2 Two-Variable Solutions

5.2.1 Introduction

The extent to which the IR data confirms the anisotropy can be formally ascertained by a linear least squares regression technique. To search for a dipole anisotropy we use Eqn. 3.14 and minimise the sum of peculiar velocities given by

$$\sum (V_p)^2 = \sum (V_o - V_H + \ell X + m Y + n Z)^2 \quad 5.5$$

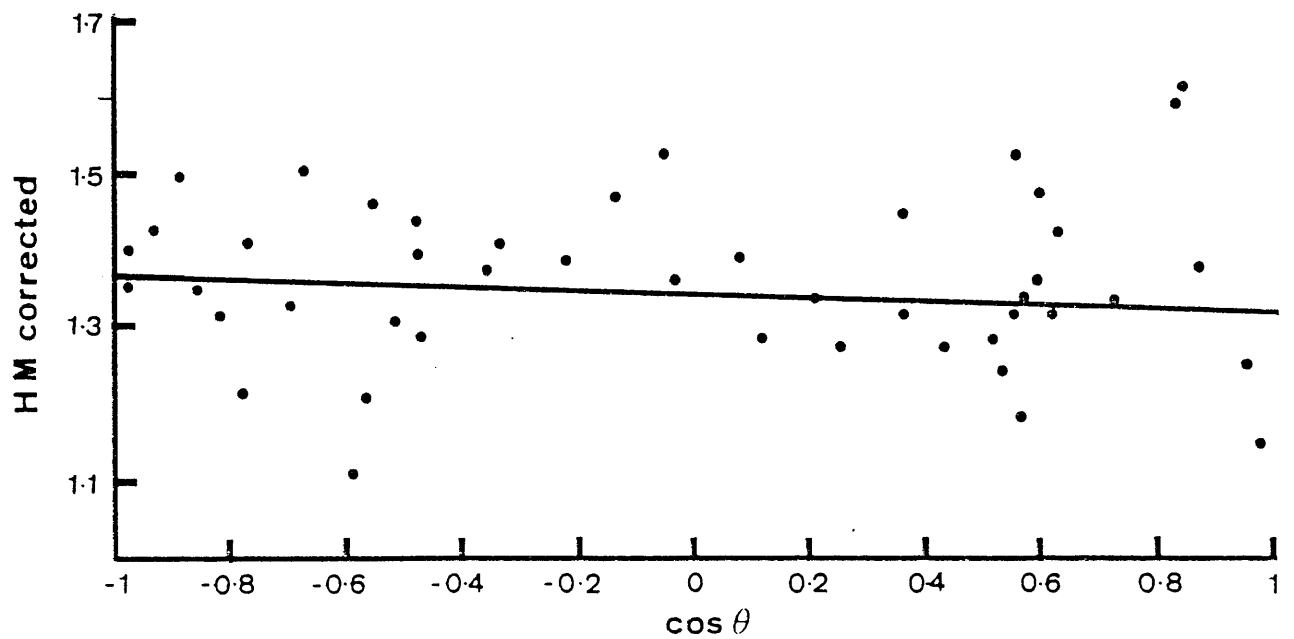
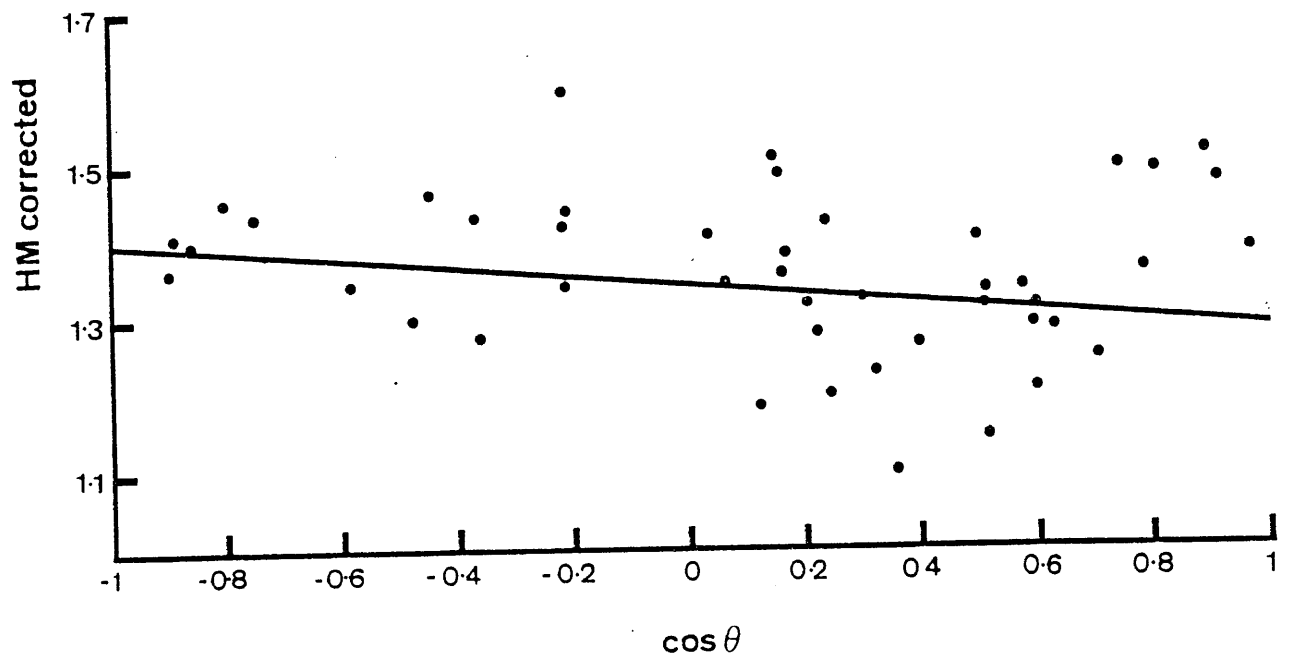


Figure 5.5a,b Variation of near-IR Hubble modulus, corrected for Malmquist biasing, from the apex to antapex defined by the Rubin et al. LGM (top) and from the apex to antapex of the CBR dipole.

in the least squares sense. Here X, Y, Z are the components of the dipole velocity anisotropy, l, m, n are the normal unit vectors in the direction of each galaxy and V_H and V_o are the Hubble and observed redshifts respectively. The purpose here is to use this formula to search for departure from the Hubble flow for the background sample. This is carried out by solving Eqn. 5.5 for the LGM and comparing the result with the local studies and the CBR to infer the Hubble flow anisotropy. Interpretation of any net velocity resulting from the minimization of 5.5 as a streaming velocity, implies that the dipole is the sum of two vectors, one the velocity of the Local Group with respect to the CBR and the other, the dipole component of the peculiar velocity of the background galaxies themselves. This restriction to a dipole solution is discussed further in Chapter 6.

All minimization solutions were carried out on the U.C.L Starlink Vax node. The analysis routine was provided by the National Algorithm Group (NAG) correlation and regression analysis programs G02BDF and G02CHF, mark 10. G02BDF calculates the cross products about zero of all the variables in the regression ($V_o - V_H, l, m, n$), the correlation-like coefficients for the dependent variables (l, m, n) in addition to all the means and standard deviations. With this as input, G02CHF performs a multiple linear regression on the set of variables. Simple Fortran IV programs were used to implement the NAG routines.

5.2.2 Optical Two Variable Solutions

To check the consistency of our regression procedure with that of Rubin et al. we first carried out solutions using the Rubin et al. optical data. In Table 5.1 are 3 such solutions using different optical data sets. All solutions use the redshifts and corrected apparent magnitudes listed by Rubin et al. (1976b). Also shown are the corresponding Rubin et al. solutions.

Table 5.1

Optical Dipole Anisotropy Solutions

This Thesis

Rubin et al.(1976b)

Optical Mags

(Corrected for Diameter), N=96

$$V_D = 439 \pm 126 \text{ km/sec}$$

$$l = 166 \pm 17^\circ$$

$$b = -11 \pm 16^\circ$$

$$V_D = 454 \pm 125 \text{ km/sec}$$

$$l = 163 \pm 17^\circ$$

$$b = -11 \pm 16^\circ$$

Optical Mags

(Not Corrected For Diameter), N=96

$$V_D = 613 \pm 200 \text{ km/sec}$$

$$l = 200 \pm 19^\circ$$

$$b = -17 \pm 17^\circ$$

$$V_D = 581 \pm 202 \text{ km/sec}$$

$$l = 203 \pm 19^\circ$$

$$b = -11 \pm 17^\circ$$

Optical Mags

(Not Corrected For Diameter), N=43

$$V_D = 850 \pm 272 \text{ km/sec}$$

$$l = 203 \pm 27^\circ$$

$$b = -30 \pm 21^\circ$$

The final solution uses the optical data for all the galaxies for which we have IR photometry at H. All these results are consistent with each other to within 1σ. The first solution provides a useful check on the Rubin et al. reduction procedure, while the close correspondence between the second and third solutions is confirmation that our galaxy sample is

representative of the full mbs of 96, in relation to the anisotropy Rubin et al. found.

5.2.3 Near-Infrared Two Variable Solutions

Several solutions with different corrections applied to the IR data are presented in this section. The magnitudes of Table 4.2 provide the first data set. These magnitudes have been corrected for atmospheric extinction only. All the galaxies for which there are J, H, or K band data are used and an identical analysis is performed at each wavelength band to that used for the optical data above. The results are listed in Table 5.2.

Table 5.2

Anisotropy Solutions Using Uncorrected IR Data

J (N=45)	H (N=45)	K (N=43)
$V_D = 871 \pm 330$ km/sec	$V_D = 992 \pm 370$ km/sec	$V_D = 1127 \pm 360$ km/sec
$l = 194 \pm 28^\circ$	$l = 201 \pm 22^\circ$	$l = 190 \pm 22^\circ$
$b = -19 \pm 22^\circ$	$b = -15 \pm 22^\circ$	$b = 8 \pm 22^\circ$

These solutions are consistent with each other and the optical solutions to within 1σ. Solutions which exclude galaxies that have photometric uncertainties > 0.2 mag, RF 96, 106, 34, and 137, are identical also. This indicates that these solutions are not influenced by a few galaxies with photometric error larger than the average for the sample. The exclusion of RF 191 and 192, galaxies which are not members of the mbs but do lie in the appropriate redshift band, does not alter the results either.

The least squares regressions obtained for J, H and K when the "hybrid" correction, discussed in section 5.1.2, is incorporated are given in Table 5.3.

Table 5.3

Anisotropy Solutions Using IR Data with Hybrid Correction

J (N=45)	H (N=45)	K (N=43)
$V_D = 479 \pm 307$ km/sec	$V_D = 621 \pm 349$ km/sec	$V_D = 727 \pm 317$ km/sec
$l = 176 \pm 40^\circ$	$l = 186 \pm 34^\circ$	$l = 179 \pm 32$
$b = -13 \pm 36^\circ$	$b = -3 \pm 31^\circ$	$b = 30 \pm 24^\circ$

The close agreement between the IR and optical data, when used in this way, demonstrates that two of the the proposed explanations for the discrepancy between the LGM, inferred from the CBR, and the Rubin et al. result, are untenable. Firstly, since the IR and optical data sets are independent, the results indicate that while errors in the optical photometry may be present, they are small compared to the anisotropy. These results confirm the recent study made by Peterson & Baumgart (1986) who examined the accuracy of the magnitudes used by Rubin et al. by carrying out multiaperture photoelectric photometry for 112 of their sample. Their results are in substantial agreement with our own and are summarised in Table 5.9. Thus, the anisotropy is real and "there on the sky". Secondly, the IR data is less susceptible to extinction by ~ 10 times and therefore an explanation of the anisotropy in terms of varying extinction on the sky is unlikely. The required extinction in the apex direction necessary to move the apex direction of our LGM from $l = 261^\circ$, $b = 35^\circ$ to $l = 200^\circ$, $b = -11^\circ$ corresponds to 0.4 mag (Chapter 3). While Rubin et al. demonstrated this to be an unlikely circumstance for the optical data, this level of extinction would affect the IR magnitudes by ~ 0.05 mag and is thus negligible. The IR colour-colour diagram (Fig. 4.1) suggests that systematic extinction is probably < 0.1 mag in the infrared, which further illustrates that extinction is not significantly contributing to the anisotropy. Finally, regressions using JHK data corrected for extinction using the extinction law of Sandage (1973) are

insignificantly different from these results.

5.2.4 Diameter Corrected Solutions and Absolute Magnitude Dispersion

Despite the important inferences that can be drawn from the agreement between the optical and near IR data sets, there are still uncertainties remaining which make an interpretation in terms of a velocity anisotropy questionable. To begin with, the hybrid correction is only a correction for absolute magnitude as a function of distance, and there is evidence that the scatter in the intrinsic luminosities is large. An uncertainty of ~ 350 km/sec implies a combined absolute and apparent magnitude dispersion of ~ 0.6 mag (Eqn. 3.17). Larger absolute magnitude dispersions within a sample make it more difficult to control systematics and in particular a variation of absolute magnitude across the sky. Such a variation cannot be accounted for by a simple velocity dependent correction.

In order to investigate Malmquist biasing and the dispersion in absolute magnitude, the data must be corrected for the aperture effect. This is conveniently carried out by converting the photometry to the standard aperture system of $\log A/D \sim -0.5$, where D is the isophotal diameter and A the aperture. This diameter system was discussed in Section 4.2.2 and is a compromise between smaller corrections at large apertures and the requirement of a system which minimises scatter in the Tully-Fisher relation. The growth curves adopted are those given by Aaronson et al. (1979). They present multi-aperture H band photometry for 11 galaxies in the Virgo cluster, 18 in Ursa Major cluster, and 3 local calibrators. Combining these with multi-aperture measurements at H of some ~ 90 spiral galaxies, they construct 3 growth curves for early (SO-Sab), intermediate (Sb-Sbc) and late (Sc-Scd) type galaxies. The Second Reference Catalogue (de Vaucouleurs et al. 1976; hereafter RC2) list 95% of the mbs and the revised morphological types (de Vaucouleurs 1959) range from $T = (3)-(5)$ or Sb-Sc and so the intermediate and late-type growth curves of Aaronson are appropriate for mbs galaxies. Since the distribution of

intensity in the disk component of most spirals can be fitted by an exponential function, with exponent proportional to radius, the change in magnitude with aperture size, or growth curve, is expected to be linear on a logarithmic scale. From Aaronson (1979) the intermediate and late type growth curves are identical over this morphological range and the formal regression for both has been computed for both types, viz.

$$\Delta H = (-2.19 \pm 0.06) \log[A/D] - (1.09 \pm 0.04) \quad 5.6$$

and is applicable for A/D between 0.1-0.5. Growth curves for the J and K wavebands can be determined from the colour gradients. Aaronson (1977) presents the colour-aperture relation for different spiral morphologies. Table 5.4 reproduces the colour changes Aaronson observed over the appropriate aperture range.

Table 5.4

Colour Gradients for Spirals

Type	$\Delta(J-H)$	$\Delta(H-K)$	No
Sb	-0.01 ± 0.01	-0.02 ± 0.02	14
Sbc	0.00 ± 0.03	-0.01 ± 0.02	14
Sc, Scd	-0.07 ± 0.04	-0.01 ± 0.04	12

Griersmith, Hyland & Jones (1982) report similar near-IR colour gradients for early type spirals. In view of the small colour changes involved, an identical correction to the J and K photometry can be made.

The diameters adopted for this correction were those listed by RC2. This diameter system is consistent with other authors and has the advantage that it is determined to the photographic isophotal level of $m \sim 25 \text{ mag/arcsec}^2$. The diameters measured by Rubin et al are taken out to the faintest features seen on the PSS plates and will be subject to larger systematic

and accidental errors since they are aggravated by the very low levels of luminosity.

The average correction to $\log A/D = -0.5$ for the IR sample, using Eqn. 5.6, is ~ 0.2 mag. The variation of the diameter-corrected HM's with redshift, immediatly gives an estimate of the individual contributions to this variation from the aperture effect and Malmquist biasing. The regression of HM with $\log V_0$, using diameter corrected H magnitudes (H_{0s}) is given by

$$HM(H_{0s}) = (0.72 \pm 0.3) \log V_0 - (1.32 \pm 1.2) \quad 5.7$$

Comparing this with the corresponding regression for the uncorrected case, Eqn 5.2, we see that the implied contribution of aperture effect to the variation of HM with $\log V_0$ is $\sim 25\%$ and therefore $\sim 75\%$ of this variation is due to Malmquist bias. As with the uncorrected case, identical results within the errors are found for both the J and K data, viz.

$$HM(J_{0s}) = (0.67 \pm 0.3) \log V_0 - (1.27 \pm 1.1) \quad 5.8$$

$$HM(K_{0s}) = (0.74 \pm 0.3) \log V_0 - (1.30 \pm 1.1) \quad 5.9$$

The solutions for the LGM using the aperture corrected data (Eqn. 5.6) are given in Table 5.5. The solutions incorporating both an aperture correction and a subsequent Malmquist correction (Eqns. 5.7-5.9) are shown in Table 5.6.

Table 5.5

Anisotropy Solutions Using IR Data with Aperture Correction

$J_{0.5}$ (N=45)	$H_{0.5}$ (N=45)	$K_{0.5}$ (N=43)
$V_D = 970 \pm 380$ km/sec	$V_D = 1108 \pm 425$ km/sec	$V_D = 1188 \pm 417$ km/sec
$\ell = 194 \pm 28^\circ$	$\ell = 202 \pm 29^\circ$	$\ell = 188 \pm 19^\circ$
$b = -26 \pm 24^\circ$	$b = -21 \pm 21^\circ$	$b = 4 \pm 21^\circ$

Table 5.6

Anisotropy Solutions Using IR Data with Separate Aperture and Malmquist Corrections

$J_{0.5}$ (N=45)	$H_{0.5}$ (N=45)	$K_{0.5}$ (N=43)
$V_D = 670 \pm 377$ km/sec	$V_D = 741 \pm 400$ km/sec	$V_D = 873 \pm 413$ km/sec
$\ell = 176 \pm 39^\circ$	$\ell = 196 \pm 41^\circ$	$\ell = 175 \pm 30^\circ$
$b = -26 \pm 34^\circ$	$b = -28 \pm 34^\circ$	$b = 18 \pm 27^\circ$

Tables 5.5 and 5.6 are analogous to Tables 5.2 and 5.3, but with aperture corrected data. The direction and anisotropy is unchanged at all 3 wavebands, within the errors. However, these solutions have more noise, and the significance of the anisotropy is now barely 2 σ . This is attributable to the aperture correction, which increases the dispersion in the absolute magnitudes and works in the opposite sense to the diameter-luminosity correction adopted by Rubin et al. They used the diameters as intrinsic luminosity indicators and thus tried to reduce the dispersion in magnitude. In effect, the IR magnitudes have been weighted by the diameters to eliminate the aperture effect. An estimate of the dispersion in absolute magnitude for the sample can now be made. The absolute magnitude is given by

$$H_{0,abs} = 5 \log H_0 + H_{0,5} - 5 \log(V_0 + \delta\Delta V) - 25$$

5.10

where $\delta\Delta V$ is the component of the velocity anisotropy in the direction of the galaxy and H_0 is Hubble's constant (100 km/sec/Mpc). Figure 5.6 shows the distribution of absolute magnitude is a good approximation to a Gaussian, with $H_{0,abs} \sim -21.7$ and $\sigma_{Habs} \sim 0.6$ mag. Since the observational uncertainties are assumed to contribute only ~ 0.1 mag, the absolute magnitude dispersion is larger than that inferred by Rubin et al. in the optical, viz. ~ 0.4 mag, but consistent with the estimated scatter between Spirals made by Sandage & Tammann (1975b) and Tammann et al. (1979), discussed in Section 3.3.1. The fact that there is no improvement in the absolute magnitude dispersion, using IR data, despite some expectation to the contrary (Section 3.3.2), implies that the sample is not a homogeneous selection of Sc spirals, but rather the dispersion reflects both a relatively broad morphological type, and range over more than one luminosity class. Application of the Colour-Magnitude relation (Section 5.3) reduces the dispersion in absolute magnitude to 0.45 mag.

To conclude, although the diameter corrected IR data is the most precise indication of the intrinsic brightness of each galaxy in the sample, the absolute magnitude dispersion of ~ 0.6 mag leads to uncertainties ~ 400 km/sec in the resulting anisotropy solutions. These do not provide a serious constraint on anisotropies ~ 500 -600 km/sec, which is the aim. These errors can be reduced either by incorporating a luminosity indicator into the analysis, or by using an infrared data base with greater coverage of the sample. Such a source of data can be found in the far-infrared sky survey carried out by the Infrared Astronomical Satellite (IRAS). Both of these approaches are the subject of discussion for the remaining sections of this chapter.

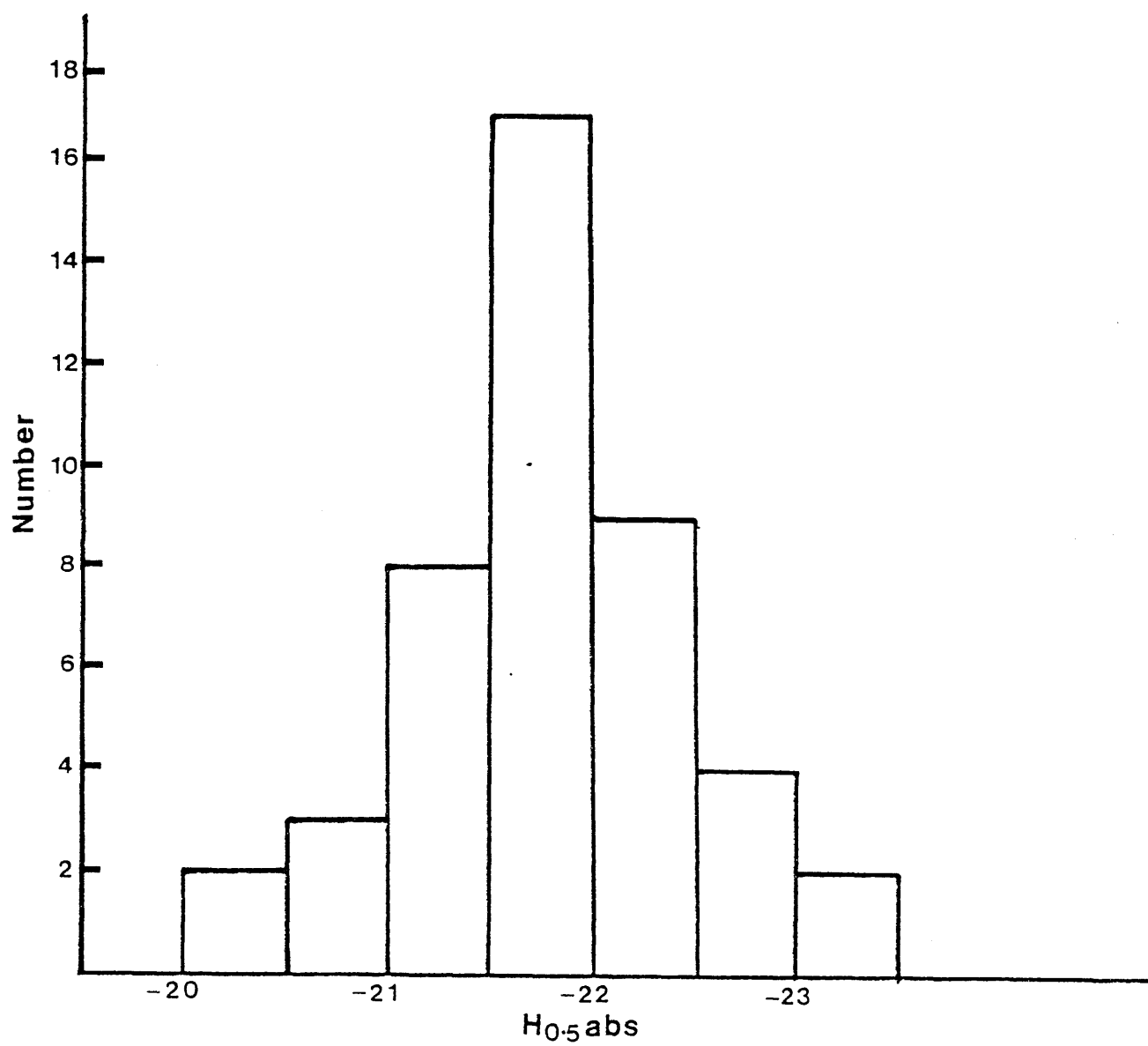


Figure 5.6 Distribution of near-IR absolute magnitudes (H_{abs}) corrected for the velocity dipole anisotropy.

5.3 Three-Variable Solutions

5.3.1 Background to the Tully-Fisher and Colour-Magnitude Relations

This section outlines the background to the third variable luminosity indicators, which will be incorporated into the solutions for the LGM. The physical interpretation of a relation between a distance independent quantity and luminosity is important for velocity anisotropy studies in order to determine how such a relation is best defined (i.e. the optimum waveband and diameter system etc.). The possible dependence of such a relation on other parameters, such as cluster environment or morphological class, is also crucial in determining how applicable a third variable is to a given sample of galaxies for which distances are required. Both these aspects of the TF and CM relations are discussed below.

The empirical correlation between HI profile widths and absolute magnitudes was first reported by Tully & Fisher (1977). They demonstrated the relation for galaxies by using three samples free of relative distance uncertainties: Virgo, Ursa Major, and the Local Group. The relation was recognised by them as being a significant extragalactic distance indicator as well as a fundamental tool for understanding galactic structure and the relation between mass and light. As mentioned above, the application to distance determination relies on the universality of the relation, accompanied with a theoretical understanding of its origin. Both these factors are, in fact, uncertain at present. In particular, the dependence of the slope on parameters such as galaxy morphology and wavelength have been the subject of much debate in the literature. Tully & Fisher (1977) found a slope using their absolute blue magnitudes and global galaxian HI profiles of -6.25 . This data contains minimal corrections but is nonetheless consistent with many subsequent estimates, using superior data. This slope implies an empirical correlation between the luminosity (L) and 21cm width (W) given by

$$L \propto W^{2.5 \pm 0.3}$$

5.11

Tully and Fisher used the empirical relation between luminosity and radius, found by Heidmann (1969) for Virgo spirals, viz.

$$L \propto R^{2.8}$$

5.12

to justify the TF relation. Thus 5.12 implies that $L \propto W^{3.1}$, if it is assumed that $M \propto W^2 R$ and $M/L = \text{const.}$, where M is the galaxy mass.

Similar slopes, with a mean of ~ -7 , have been found using B-band magnitudes by many other authors: Bottinelli et al (1980, 1983), Richter & Huchtmeier (1984), Shostak (1978) and Meisels (1983). However, a consistently higher slope is found using near-IR photometry. Using H_0 mags, Aaronson et al. (1979, 1980b) derive a slope of ~ -10 and Aaronson & Mould (1983) use a sample of 300 galaxies, finding a slope of ~ -12 . Such high slopes imply

$$L \propto W^4$$

5.13

Such a law is reminiscent of the luminosity, dispersion velocity relation found for elliptical galaxies (Faber & Jackson 1976)

$$L \propto \sigma^4$$

5.14

Aaronson et al. (1979, 1980b) give an elegant and simple interpretation to the slope of 10, which invokes 3 primary assumptions: a) All galaxies have the same mass profiles and rotation curves as a function of a dimensionless scale length (α). b) All galaxies have the same central mass surface density. c) All galaxies have the same M/L ratio. Given

$$\mu(r) = \mu_0 \exp(-\alpha r)$$

5.15

where $\mu(r)$ is the surface density distribution, the mass is given by the

normalisation of 5.15, which yields

$$M \propto 2\pi\mu_0\bar{\alpha}^2 \quad 5.16$$

and from the rotation curve

$$W^2 \propto GM\alpha \quad 5.17$$

Therefore, we have $M \propto W^4$ and if M/L is a constant, then $L \propto W^4$.

The difference in powers between the optical and near-IR is then readily explained in terms of a changing M/L , in the optical, for spiral galaxies of differing mass. More blue light per unit mass, as would result from a young population of stars, acts to make the power-law relationship considerably shallower. Such a theoretical interpretation should justify use of the TF relation as a universal distance indicator.

However, this theoretical explanation of the slope has been questioned by other authors. Bottinelli et al. (1980, 1983) note that the slope is a continuous function of the equivalent wavelength of the magnitude system used, varying from 5 in the blue to 10 in the infrared and that although it may be universal, neither slope has any particular theoretical significance. The situation is almost certainly more complicated than the Aaronson et al. prescription implies. Burstein (1982) argues that the Aaronson et al. interpretation of the physical basis for the TF relations is inconsistent with the variation of infrared surface brightness among galaxies. The argument is as follows; the mass is given by

$$M \propto W^2 R \quad 5.18$$

and surface brightness B is given by

$$B \propto L\bar{R}^2 \quad 5.19$$

Assuming $L \propto W^m$, and $B \propto W^n$ then 5.18 gives

$$M/L \propto W^{2-m} R \quad 5.20$$

while 5.18 and 5.19 give

$$M/L \propto W^{2-n} R^{-1} \quad 5.21$$

By differentiation of 5.20 and 5.21, $M/L = \text{const.}$, only if $n = 4-m$.

Burstein finds $n = 2.5 \pm 0.3$, and $m = 4 \pm 0.3$ for the Aaronson galaxy sample. Therefore he argues for an M/L relation

$$M/L \propto W^{-1.25 \pm 0.2} \quad 5.22$$

However, as Burstein remarks, any interpretation of the surface brightness variation is complicated by uncertain systematics, in particular the dependence of the TF relation on Hubble type. Aaronson et al. find little evidence for a Hubble type dependence in their IR-TF relation for spirals all the way from Sa-Sd. This agrees with the analysis by de Vaucouleurs et al. (1982), who regress the slope and zero point of the correlation independently for different Hubble types, and conclude that both are an insignificant function of Hubble type. If this is the case then the correlation between infrared surface brightness and velocity width implies a complicated interrelation between mass and luminosity.

The implication of the difference in slope between the blue and infrared TF relations is that there exists a strong correlation between B-H colour and the intrinsic mass of spiral galaxies. The relation was discovered independently by Visvanathan (1981), Tully et al. (1982) and Wyse (1982). Its physical basis lies in the connection between young stellar populations, measured in the blue, and the old giant population, which constitutes the mass. Tully et al. (1982) model the B-H colour using an exponential star forming relationship, $\text{SFR} \sim (\exp-t/\tau)$. The existence of a colour-mag relation implies that τ is inversely related to the galaxy

mass. Thus, short time constants, corresponding to more massive and earlier type galaxies had strongly-peaked starbursts in their past. Smaller mass galaxies are bluer due to continuing star formation over the life time of the galaxy itself, ~ 16 Gyr. An improved fit to the model is made with modest changes in the metallicity and IMF.

The contention that the relation will provide distance estimates good to ~ 0.4 mag is at present unverified and potentially problematic. The correlations found by Tully et al. (1982) and Wyse (1982) are interpreted as a mass dependence. However, mass is strongly correlated with Hubble type, which in turn is dependent on the environment. There is evidence that the relation may have such a dependence. Aaronson et al. (1981b) compare the colours of 22 early galaxies in Coma with 36 corresponding Virgo galaxies. They find that Virgo is redder than Coma and therefore, presumably, had lost its gas earlier. Since this implies that the colour-magnitude relation is not a constant, early type galaxies appear to be inadequate distance indicators, at least for clusters. Since the explanation for the colour-magnitude relation for ellipticals is interpreted as a metallicity-mass relation (Faber 1973), it is unclear what this implies for the B-H colour magnitude relation for spirals. In any case since our sample consists of a well defined morphological range of spirals located outside dense clusters, they should be free of strong environmental influence.

5.3.2 Corrections to the Infrared Tully-Fisher Relation

The current uncertainties regarding the underlying physical interpretation of the TF relation do not violate its use as a luminosity indicator for spiral galaxies. The correlation has been used with success in a variety of extra-galactic distance measuring programmes. Some of these were discussed in Chapter 3. Aaronson & Mould (1983) demonstrate a nominal scatter in the relation ~ 0.4 mag, using accurate IR data along with a well defined spiral sample at high inclination. Bottinelli et al. (1980) are careful to correct velocity widths for non-circular motions and derive

an optical-TF relation which they claim also has a scatter ~ 0.4 mag, as least as good as that found by Aaronson & Mould in the near-IR.

Rubin et al. (1976a) list 21cm velocity widths for a large fraction of their mbs. For our sample of 45 galaxies, 40 have 21cm data. The approach adopted in order to incorporate the TF relation into solutions for the LGM, is to derive the TF relation independently of the regression routine, using the best data set, and then to correct for absolute magnitudes in a manner similar to that carried out for the hybrid correction, discussed in section 5.2.3. The desirability of using photometry transformed to the H_0 system, as mentioned in section 4.1.2, is based on the dynamical argument that at larger diameters it is common for the rotation curves of spirals to flatten out, indicating that the material has become decoupled from the rotation. For Sc's this radius corresponds to $\sim 1/3D$. As mentioned in Section 5.2.4, the average correction amounts to ~ 0.2 mag. Due to the error in the RC2 diameters the correction to $\log A/D = -0.5$ has an uncertainty ~ 0.09 mag for each galaxy.

The velocity widths reported by Rubin et al., corrected for instrumental effects, are those measured to the point at which the flux has dropped to $\sim 20\%$ of the peak value. This definition is more indicative of the maximum rotation velocity, than one defined for a larger width, say 50%. To these widths, two corrections are applied. The first is simply to correct the widths for the line of sight inclination effect. The correction is of the form

$$W(20\%) = W(\text{obs})/\sin(i) \quad 5.23$$

where i is the angle of inclination from the plane of the sky. The maximum velocity width is given by

$$V_{\text{max}} = W(20\%)/2 \quad 5.24$$

The inclinations (i) are taken from RC2. Due to the difficulties

associated with measuring major and minor axes out to the faintest limit, this system seems better than the method used by Rubin et al. Indeed, the inclinations as listed by RC2 may be consistently smaller than the estimates of Rubin et al., $\langle \text{RC2}(i) - \text{RF}(i) \rangle \sim -10 \pm 9$. In addition, Bottinelli et al. (1983) have shown that the R25 system used by RC2 is consistent ($\sim 2\%$) with a sample of 15 inclination standards.

The second correction applied to the velocity widths is for turbulent and non-circular motions. These will produce finite velocity widths for galaxies which are almost face on. The analysis of this effect is given by Bottinelli et al. (1983). They consider a 3 component ellipsoidal velocity distribution with velocity dispersions σ_x , σ_y , σ_z , where z defines the axis orthogonal to the galactic plane. The correction to the line of sight velocity width for a Gaussian distribution is

$$W(20\%) = W(\text{obs}) - 2K(l)\sigma_i \quad 5.25$$

where $K(l) \sim 1.8$ and is calculated from the width of the error function at $W(20\%)$, while σ_i is given by

$$\sigma_i = s\sigma_z / [s^2 - \sin(i)^2(s^2 - 1)]^{1/2} \quad 5.26$$

where $s = \sigma_x/\sigma_z = \sigma_y/\sigma_z$. Taking $s = 1.5$ and $\sigma_z = 10$ km/sec, in agreement with various authors (de Vaucouleurs 1955, Feast 1964, Burke et al. 1964, Kerr et al. 1965), the corrections to the widths are ~ 45 km/sec, with a small inclination dependence. With observed velocity widths as low as 69 km/sec for our IR sample, this correction is far from negligible. The application of this correction does reduce the scatter in the TF relation by $\sim 10\%$.

5.3.3 The Tully-Fisher Slope and Associated Anisotropy Solution

The relation between $H_{0,abs}$ and V_{max} for 40 galaxies of the mbs is shown in Fig. 5.7. Here, each $H_{0,abs}$ has been defined using $H_0 = 100\text{km/sec/Mpc}$. A formal least squares analysis of this data gives

$$H_{0,abs} = (-4.0 \pm 1) \log V_{max} + 13 \pm 0.7 \quad 5.27$$

The estimates of V_{max} have errors given by

$$(\Delta V_{max}/V_{max})^2 = (\Delta W/W)^2 + (\Delta R_{25}/\tan(i))^2 \quad 5.28$$

where ΔR_{25} is the error in the measured axial ratios (~ 0.05), taken from the listings for this sample in RC2. These errors are about 3 times those of Aaronson (1982). Despite this, the case for a one sided regression, in which V_{max} is treated as the dependent variable and assumed to have all the scatter, is an oversimplification, since the magnitudes also have significant errors. The adopted slope of -4 is found using the optimum approach of a combined least squares fit, where the sum of the squares of the perpendicular distances from the lines are minimised. This procedure is a generalisation of the method employed by both Richter & Huchtmeier (1984) and Aaronson & Mould (1983), who weight the mean of the two regressions, one in which $\log V_{max}$ is treated as the dependent variable, and the other in which $\log V_{max}$ is treated as the independent variable.

The TF relation in Fig. 5.7 has a scatter that appears not to be Gaussian and a shallower slope than the estimates of authors already discussed. These difficulties are more significant than the afore mentioned problems concerning the applicability of the TF relation to galaxies of different morphological type. There are several causes for both the scatter and shallow slope. These are outlined below:

- 1) The average inclination for the sample is only 35° . Low inclinations

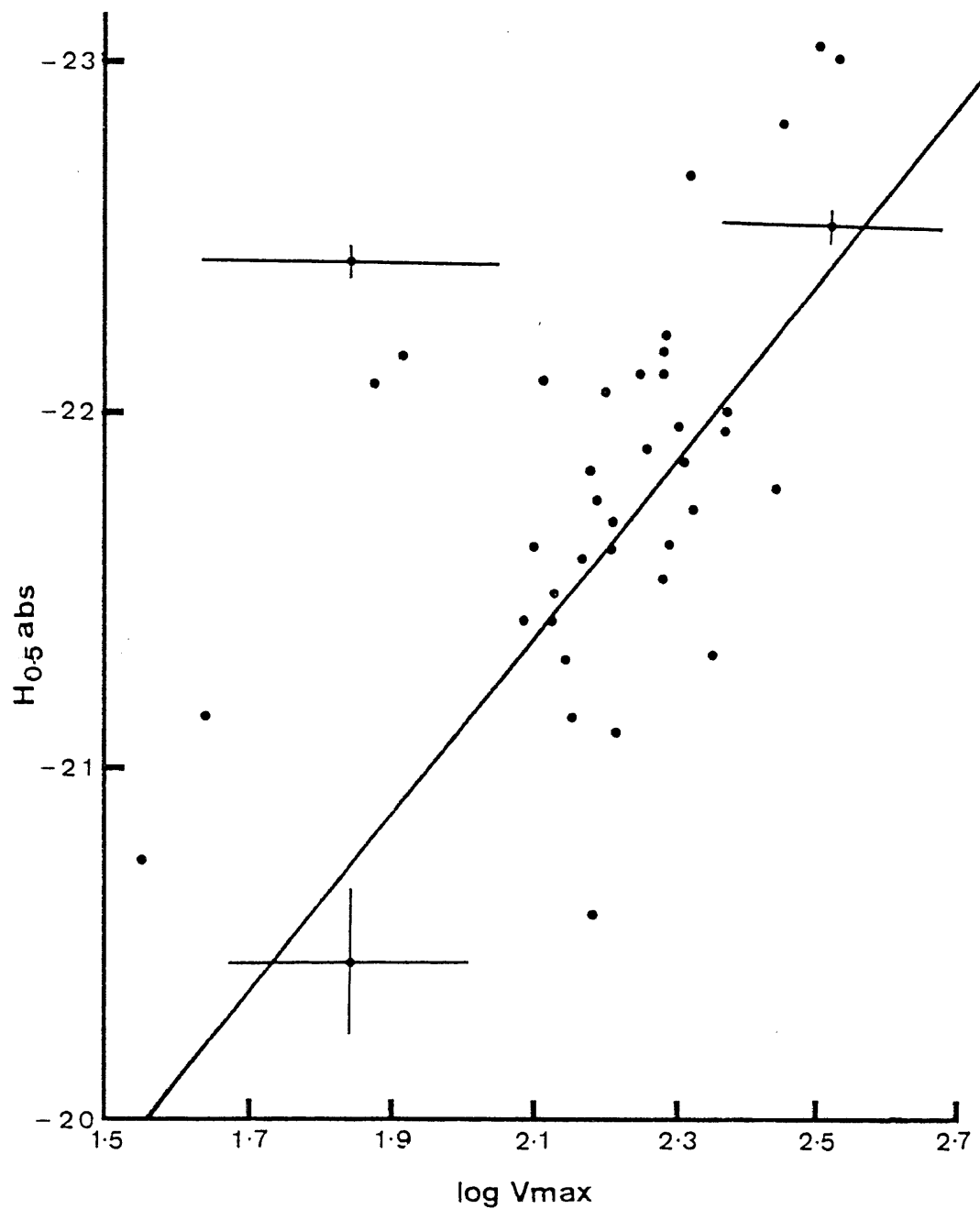


Figure 5.7 Near-IR Tully-Fisher relation for the mbs galaxies. The least squares fit has a slope ~ -4.0 . Approximate statistical error bars are shown.

result in velocity width estimates which are too large. This is the result of the tendency to measure smaller inclinations when estimating the inclinations of nearly face on galaxies. This will act to reduce the TF slope.

2) The TF slope is biased by the manner in which the galaxies were selected. Rubin et al. chose the sample to minimise the dispersion in absolute magnitude, without consideration to the velocity widths. Therefore, at the brightest end of the mbs, galaxies are included which have larger velocity widths than the average expected for their luminosity and the corresponding galaxies with smaller velocity widths than average will be excluded. By the same argument, galaxies will tend to be included at the faint end of the sample which have small velocity widths compared to the average at this luminosity and excluded if they have larger than average velocity widths. This effect is easily seen by defining a sample between two horizontal lines on a TF diagram. The latter example is almost certainly the case for the two galaxies with $\log V_{\max} \sim 1.6$ in Fig. 5.7. This biasing is compounded by having a small absolute magnitude dispersion, because as this window becomes smaller the number of such galaxies becomes a greater fraction of the total population. As an illustration, Aaronson et al. use galaxies spread over ~ 8 mags and find an intrinsic scatter of ~ 0.45 mag. Our TF relation is defined over barely 3 mags. If the number of biasing galaxies is constant then the proportion in our sample compared to Aaronson et al. is given by $8/3 \sim 3$. Our sample will contain at least 3 times the fraction of galaxies biasing the TF relation to a smaller slope.

3) The correction applied to the velocity width for turbulent and non-circular motion is almost constant and smaller velocity widths are corrected proportionately more than large widths. This in principle will reduce the slope (Bottinelli et al. 1983). Aaronson does not use this correction and this may, in part, be responsible for the different TF slopes these authors find. However, a regression using data uncorrected for turbulent motion shows this effect to be small, and therefore in this

case the other problems are probably more extreme.

Using the relation 5.27 to correct each apparent magnitude to a standard $\log V_{\max}$ the forms of HM and VH can be written

$$HM = \log V_0 - 0.2H + 0.2b \log V_{\max} \quad 5.29$$

$$V_H = 10^{\langle HM \rangle + 0.2H - 0.2b \log V_{\max}} \quad 5.30$$

where b is the TF slope. The analysis then proceeds as before by minimisation of Eqn. 5.5. This yields a dipole anisotropy for 40 galaxies with available 21cm data of

$$V_D = 846 \pm 334 \text{ km/sec}$$

$$l = 214 \pm 40^\circ$$

$$b = -33 \pm 24^\circ$$

This solution is unchanged in direction and magnitude, within the errors, from the uncorrected case. However, the previous discussion highlighted the uncertainties associated with this correction and in particular, estimating the slope. In order to investigate the stability of this result, solutions with different TF slopes were computed. The conclusion from these results is that the solutions were not significantly altered if the slope was changed by up to ± 2 , or 20%. Trial slopes outside this tolerance resulted in anisotropy solutions with smaller significance and greater noise. This experiment shows that the TF slope of ~ -4 , estimated independently of the anisotropy regression, is the appropriate slope to use since it minimises the uncertainty in the dipole regression.

To summarise, the sensitivity of the anisotropy study to variations in absolute magnitude demands that the absolute magnitudes be known to high precision. A least squares fit to the TF relation results in an optimum TF slope of -4 , which corrects absolute magnitudes by up to ~ 3 mags. A combination of the uncertain velocity widths coupled with the

narrow luminosity range make it difficult to apply this relation to the Rubin et al. sample.

5.3.4 The Colour-Magnitude Slope and Associated Anisotropy Solution

The application of this distance indicator has a significant advantage over the TF relation in that the sample consists primarily of face-on galaxies, $\langle i \rangle \sim 35^\circ$. While being the dominant source of error in the TF relation, the only inclination dependent correction applied to the C-M relation is for internal absorption in the optical, which is smaller for face on discs. These corrections amount to < 0.1 mag.

The optical data base used to construct this relation is the final one reported by Rubin et al. except that the correction to a constant linear diameter, their own luminosity indicator, has been removed. The B band magnitudes are corrected to a ratio $A/D=1$ and the IR data is reduced to the standard $H_{0.5}$ system. These standard systems are compatible with Tully et al. (1982).

The CM relation is shown in Fig. 5.8. A formal least squares regression for the CM relation gives

$$H_{0.5, \text{abs}} = (-1.85 \pm 0.25)(B-H_{0.5}) + 17.6 \pm 0.5 \quad 5.31$$

This slope is consistent with the value of -2.3 found by Tully et al. (1982) for 12 local spiral galaxies, which they argue is consistent with a TF slope of 10.

It is worthwhile at this point to consider the explicit variation of the IR-Opt colour across the sky. The variation of $B-H_{0.5}$ from the dipole apex to antapex is shown in Fig. 5.9. The formal least squares regression gives

$$B-H_{0.5} = (-0.12 \pm 0.12)\cos\theta + 2.17 \pm 0.01. \quad 5.32$$

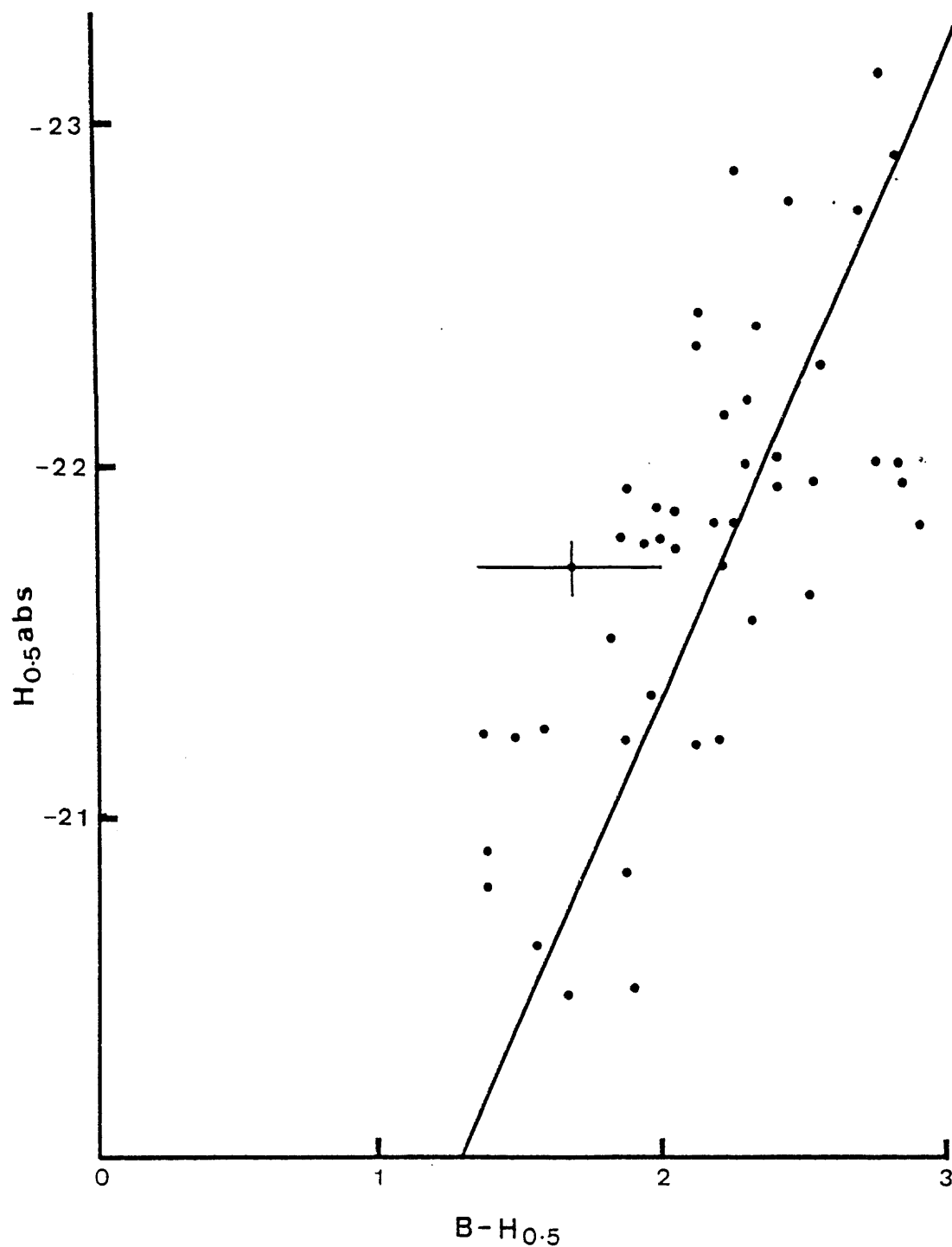


Figure 5.8 The optical-IR colour magnitude relation for 45 mbs galaxies. The optical magnitudes are from Rubin et al. 1976b, corrected to $A/D = 1$. The least squares fit has a slope ~ -1.85 . Typical errors are shown.

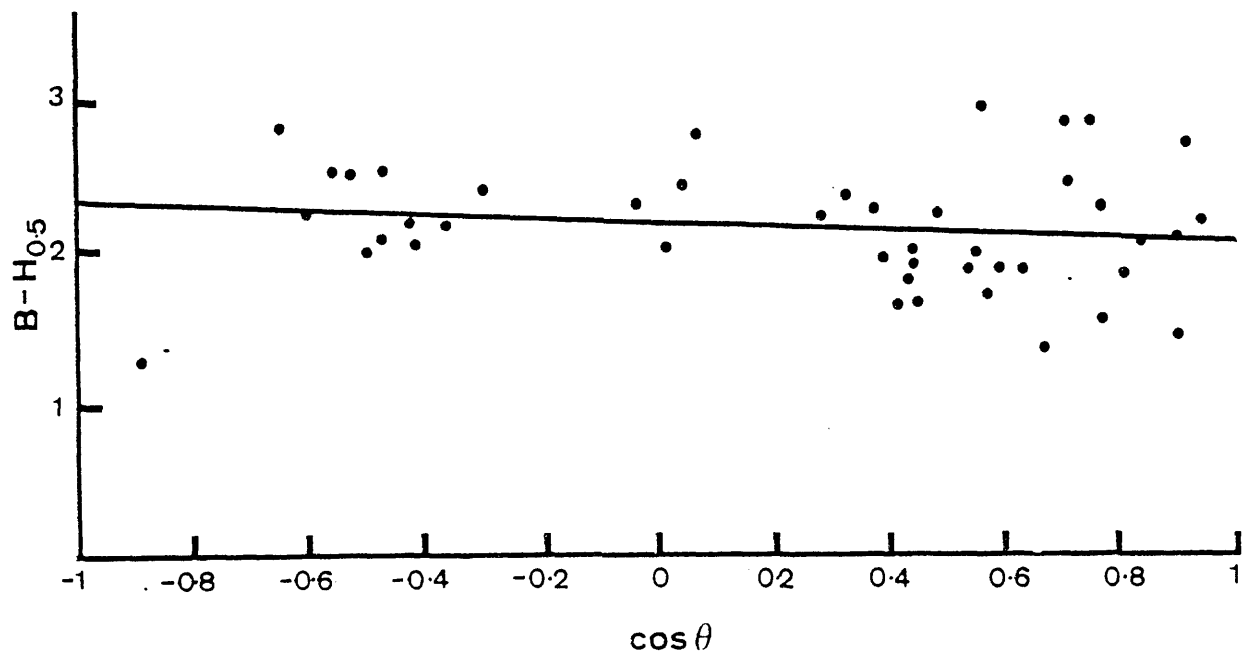


Figure 5.9 Variation of optical-IR colour from the apex to antapex direction defined by the Rubin et al. LGM.

The variation of $B-H_{0.5}$ across the sky is not significant. Adopting a nominal C-M slope of 2.0, the 1σ limit on the variation of absolute magnitude across the sky from apex to antapex is 0.48 mag. The solution for the uncorrected H band data and the uncorrected IRAS solution both imply an anisotropy ~ 1100 km/sec. If this is to be interpreted as a variation in absolute magnitude across the sky then galaxies at the apex are ~ 0.9 mag fainter than those in the antapex region. However, from the limit on the variation of $B-H_{0.5}$ across the sky we see that this possibility is ruled out at $\sim 2\sigma$.

Using Eqn. 5.31 in a similar manner to the TF relation we can write

$$HM = \log V_0 - 0.2H + 0.2b(B-H), \text{ and} \quad 5.33$$

$$V_H = 10^{<HM> + 0.2H - 0.2b(B-H_{0.5})} \quad 5.34$$

Here, b is the slope of the C-M relation. This formalism yields a dipole anisotropy for 45 galaxies of

$$V_D = 680 \pm 330 \text{ km/sec}$$

$$l = 184 \pm 35^\circ$$

$$b = -36 \pm 30^\circ$$

This result is consistent, within the errors, with the other infrared and optical solutions discussed. It should be the most reliable of all the infrared solutions so far discussed because it incorporates a third variable luminosity indicator, and the slope of the colour-luminosity relation is consistent with independent determinations. A summary of the infrared and optical dipole velocity solutions is shown in Table 5.9.

5.4 Far-Infrared Approach to Velocity Anisotropies

5.4.1 The IRAS Data

The IRAS point source catalogue (1984) contains some 250,000 well-confirmed point sources from the all sky survey. The catalogue lists the fluxes in 4 wavebands at $12\mu\text{m}$, $25\mu\text{m}$, $60\mu\text{m}$, and $100\mu\text{m}$. The measurements were made with an aperture of several arc minutes in size. This unique data base has 3 properties which make a Far-IR approach to this anisotropy study a worthwhile undertaking. 1) Since the minimum aperture size was 2 arc minutes, corrections to the data for aperture effect will be negligible. 2) The point source catalogue lists 64 of the Rubin et al. mbs at $100\mu\text{m}$ (Table 5.7). This represents a detection rate of $\sim 67\%$ for this sample. At $60\mu\text{m}$ 58% were detected, at $25\mu\text{m}$ 10%, and at $12\mu\text{m}$ only 2%. These detections are significant to at least 10 sigma, with no flag warning of either galactic cirrus or source confusion. The high detection rate at the long wavelengths is consistent with the predictions of Jura (1982). He models the Far-IR emission of a disk, using a solar neighbourhood dust abundance, and concludes that disks as far as 100 Mpc should easily be detectable with IRAS. The small percentage of detections at $25\mu\text{m}$ and $12\mu\text{m}$ is consistent with the general conclusions of Lock & Rowan-Robinson (1983) that only a fraction of galaxies at 100 Mpc will be detected.

Table 5.7

Point Source Catalogue $100\mu\text{m}$ Detections
of Rubin et al. Minimum Bias Sample

Galaxy	Flux (Janskys)	Galaxy	Flux (Janskys)
1	2.54	103	1.34
7	2.02	110	2.70

9	1.81		119	2.43
11	1.93		121	5.77
15	4.01		124	3.56
16	2.60		130	1.77
18	1.33		137	3.56
30	1.66		145	2.56
33	1.74		148	1.28
34	1.70		160	2.03
35	1.71		161	4.24
38	3.39		162	1.90
40	1.28		164	2.39
41	1.29		165	1.63
42	3.37		168	4.01
50	1.67		169	4.34
53	1.85		172	7.95
54	2.03		173	4.41
55	1.94		174	2.73
57	3.26		176	2.79
60	1.91		177	4.02
64	2.99		181	1.72
68	1.94		182	1.66
71	2.69		187	2.03
73	1.81		189	3.70
78	1.27		193	1.97
79	1.22		196	2.63
83	2.12		197	2.03
86	2.17		201	1.74
88	1.85		204	5.18
95	1.68		207	3.05
102	2.48		209	7.98

The mbs galaxies detected at 100 μm are shown in Fig. 5.1 to have a good sky coverage. In addition, the redshift distribution for this sample is similar to the mbs, as shown in Fig. 5.2.

3) There is strong evidence to suggest that this sample of galaxies will consist of "standard candles" in the far-infrared, even though they are optically selected. This requirement must be upheld, and is particularly important when there is no suitable luminosity indicator. Figure 5.10 shows the correlation between the 100 μ m luminosity and near-IR luminosity ($H_{0,abs}$). Since the near-IR is dominated by light from the old stellar population this correlation must be interpreted as the heating of interstellar dust, distributed throughout the disk, by the old stellar population (Jura 1982). This correlation suggests that standard candles in the far-IR can be selected optically or using near-IR data.

The distribution of all the 100 μ m absolute magnitudes is shown in Fig. 5.11. The magnitudes have been defined as

$$M(100) = 2.5\log f_{\nu} + 5\log V_0 \quad 5.35$$

Thus, they are a direct analogue of the near-IR absolute magnitudes. A Gaussian fit yields $\sigma_M \sim 0.43$. This compares favourably with the near infrared but there is reason to be cautious. The IRAS detection limit at 100 μ m is 1.5 Jy or $M(100) \sim 15.1$, for a galaxy at 5000 km/sec. Consequently, only the bright galaxies are detected and there is a severe depletion of galaxies < 15 mag, which results in a narrow absolute magnitude dispersion. While the IRAS sample has a well-defined absolute luminosity range, it represents a magnitude limited sub-set of the Rubin et al. mbs and is therefore susceptible to Malmquist biasing. This must be corrected, as was done for the near-infrared two variable solutions.

5.4.2 Anisotropy Solutions For 100 μ m Fluxes

The flux data is analysed in an identical manner to that previously described for other data sets. First consider the analysis without Malmquist correction. The $HM(100)$ is conveniently defined analogously to Eqn. 3.7

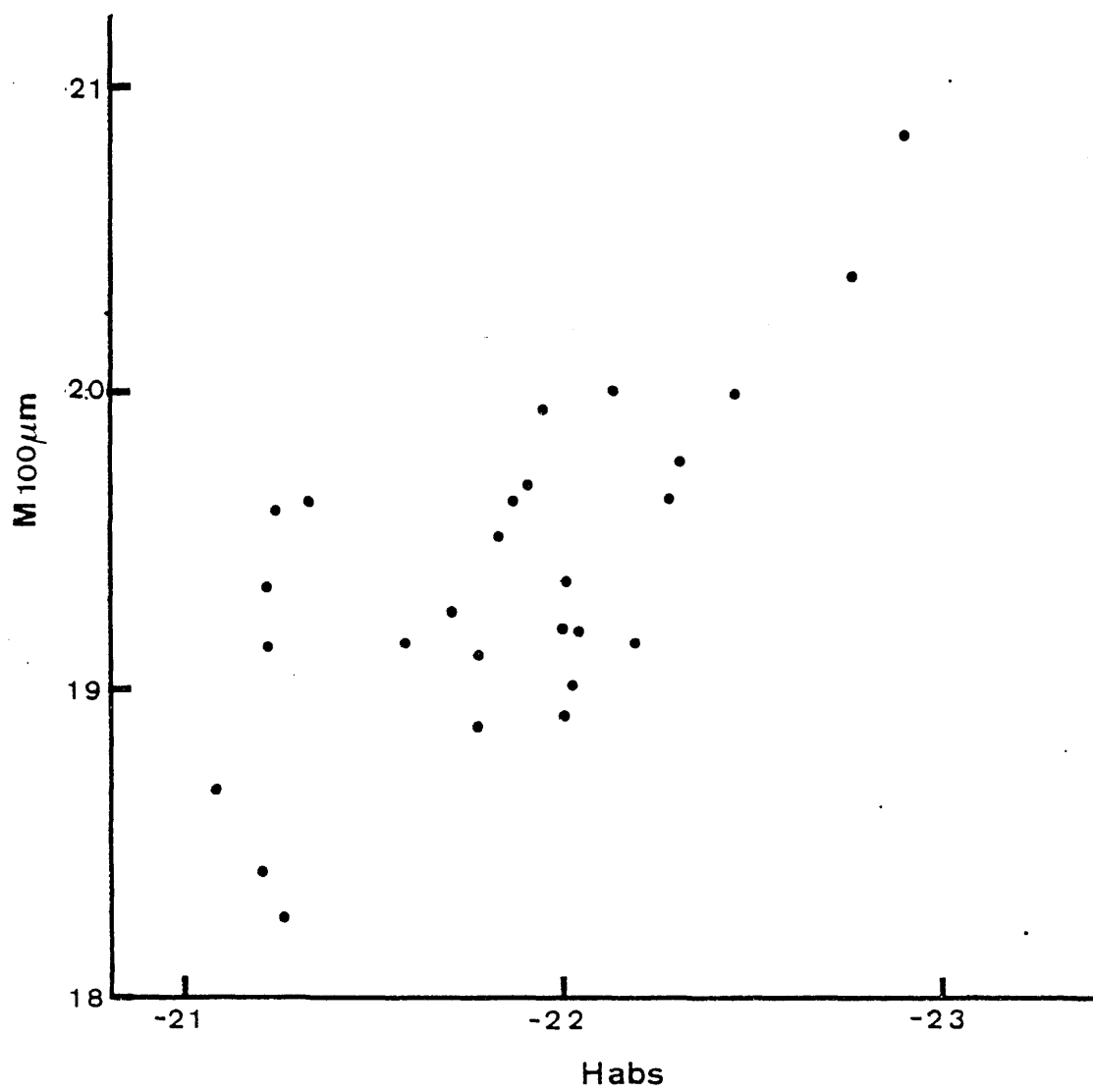


Figure 5.10 Correlation between 100μm and near-IR magnitudes.

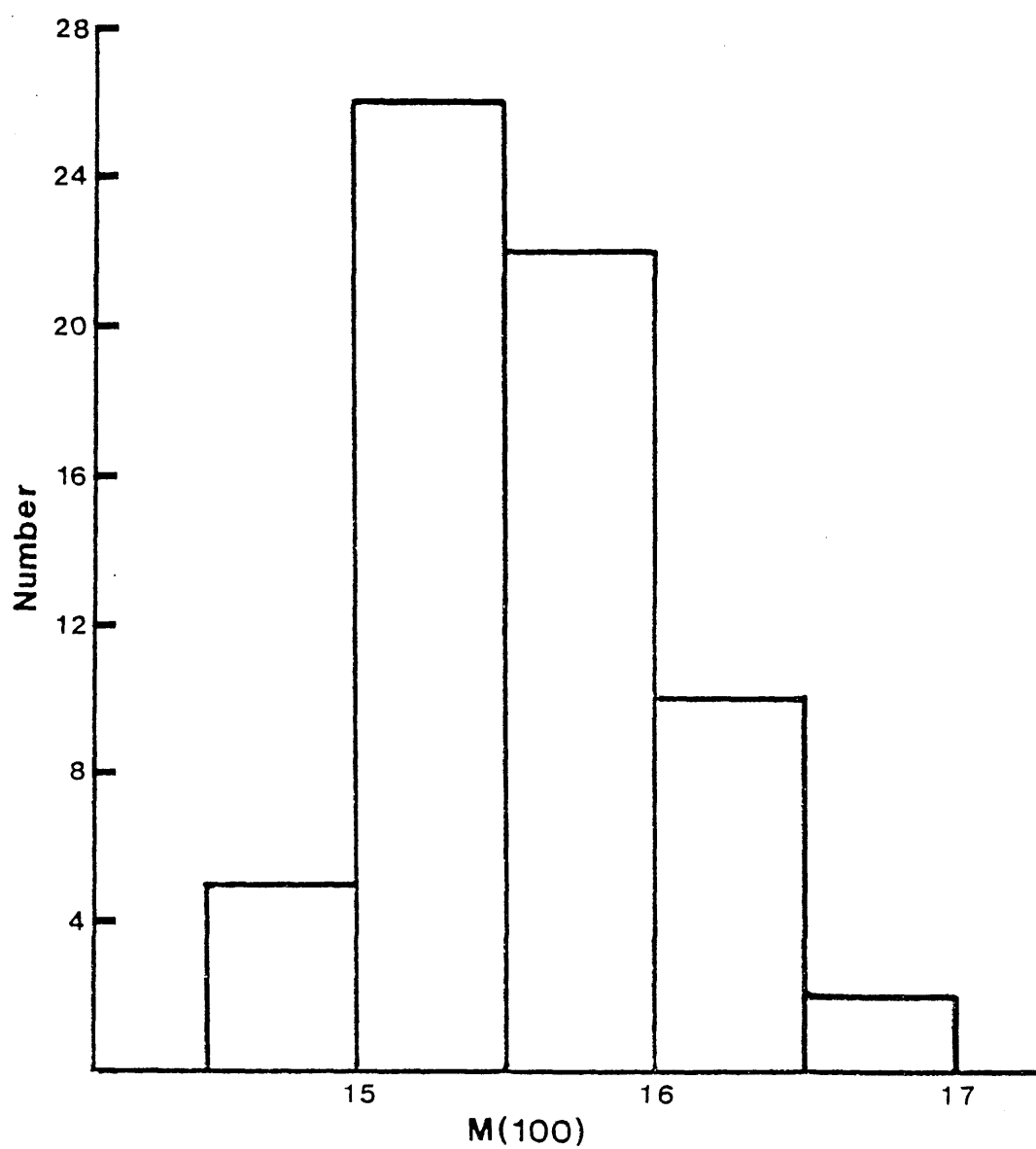


Figure 5.11 Distribution of 100mm absolute magnitudes, corrected for dipole anisotropy.

$$HM(100) = 2\log V_0 + \log f\nu \quad 5.36$$

where $f\nu$ is the 100 μ m flux. The notional Hubble velocity, V_H , is then,

$$V_H = 10^{(HM(100) - \log f\nu)/2} \quad 5.37$$

and the minimization is performed with respect to the residual $V_0 - V_H + \delta V_D$ in the usual way. The formal regression to the least squares fit is given in Table 5.8. The anisotropy is large, and with a direction almost identical to all previous IR solutions. A plot of $HM(100)$ versus redshift reveals strong Malmquist biasing, shown in Fig. 5.12. The formal regression is

$$HM(100) = (2.06 \pm 0.39) \log V_0 + 0.14 \pm 1.46 \quad 5.38$$

This degree of biasing is consistent with the variation seen in the near-IR, $\Delta M(100) \sim 1$ as V_0 goes from 3500-6500 km/sec. The correction to the magnitudes is performed in an identical manner to that for the near-IR data discussed in Section 5.1.2. The solution taking this into account is also shown in Table 5.8. The motion is unchanged in direction, and the amplitude has reduced by $\sim 2\sigma$. Further iteration does not change the solution significantly.

Table 5.8

Anisotropy Solutions Using Far-IR Data

Uncorrected, N=64

$$V_D = 1121 \pm 256 \text{ km/sec}$$

$$l = 190 \pm 14^\circ$$

$$b = -6 \pm 18^\circ$$

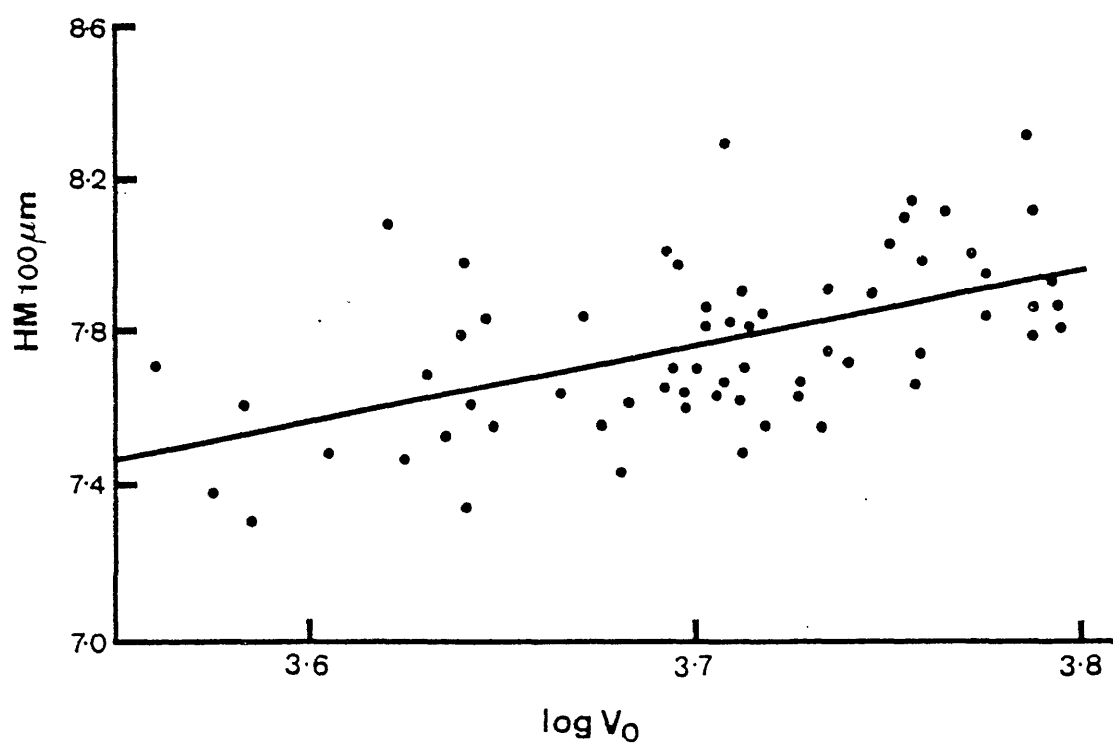


Figure 5.12 Far-IR Hubble modulus v's redshift, showing Malmquist biasing.

Malmquist Corrected, N=64

$$V_D = 662 \pm 221 \text{ km/sec}$$

$$l = 190 \pm 18^\circ$$

$$b = -6 \pm 18^\circ$$

These results are consistent with the previous corresponding solutions to within the quoted uncertainties.

5.5 Discussion of Data Analysis

An important aspect of minimization techniques is the treatment of errors and their effect on the solutions. The minimisation scheme described in this chapter (Eqn. 5.5) solves the equation $Y = mX$ in a least squares sense, where $Y = V_o - V_H$ and $mX = lx + my + nz$. In the normal way when regressing Y upon X , Y is assumed to be the variable with the dominant error, which is clearly the case here. However, the method does not explicitly use information about the errors to calculate weighted solutions. It is therefore worthwhile to discuss other possible minimisation criteria.

The range of uncertainty in Habs can be estimated from the C-M relation (Eqn. 5.31)

$$|\delta Habs|^2 = |\delta b(B-H)|^2 + |\delta(B-H)b|^2 \quad 5.39$$

From Eqn. 5.31 and Fig. 5.8, it can be seen that $\delta b \sim 0.2$, $B-H \sim 1-2.5$, and $b \sim -1.85$, and from Rubin et al. (1976a) and Table 1.2, $\delta(B-H) \sim 0.35$. Putting these figures into Eqn. 5.39 gives $\delta Habs \sim 0.6-0.8$. Since $\delta Habs \propto \delta V/V$, the uncertainty in the velocity residual ($V_o - V_H$), at constant redshift, varies by less than a factor of 2 and so, the estimated range in δV , determined by the range in $(B-H)$, is probably not significant. Accurate estimates of $\delta Habs$ demand that the errors in the B magnitudes are known. However, in view of the practical difficulty in estimating these,

due to the large systematics associated with measurements from photographic plates (Section 3.2.2), the decision not to incorporate a formal error for each Habs seems prudent.

One direct consequence of $\delta H_{\text{abs}} \propto \delta V/V$ is that if the estimates of absolute magnitude are assumed to be drawn from the same parent uncertainty distribution, for all the galaxies, then the uncertainty in the residual $(V_o - V_H)$ will be directly proportional to V_o . One way to account for this is to minimise the χ^2 given by

$$\chi^2 = \sum (V_o - V_H + lX + nY + nZ) / V_o)^2 \quad 5.40$$

The solutions presented in this Chapter are without the weighting by V_o^2 and so the solutions are probably somewhat biased by the velocity residuals of galaxies at the higher redshifts in the sample.

A further possible regression algorithm is to minimise residual quantities other than $(V_o - V_H)$. The adopted method will not necessarily give the same result as solving for the dipole anisotropy which minimises the quantity Hobs-Hpredict or minimises the scatter in the TF or C-M relations. The latter 2 solutions can be found from iteration of the corresponding solutions in Table 5.9. However, other authors have investigated minimising different residuals. Schechter (1976) tried several schemes of this kind, minimising different residuals, such as observed minus predicted magnitudes and diameters. He found that for the most part, these results were identical to the Rubin et al. (diameter uncorrected) solution. In addition, Peterson & Baumgart (1986) analyse their photoelectric data using a maximum likelihood scheme which finds the solution which maximises the probability that all the actual data (velocities and magnitudes) will be observed. Their method also incorporates the probability density function for absolute magnitudes. Their final solutions agree with the IR results (Table 5.9) and it is therefore unlikely that the solutions to the anisotropy are seriously biased by the minimization method.

No attempt has been made in this Chapter to present iterated solutions. However, both the near-IR solution with a hybrid correction and the TF solution were iterated once. This experiment showed that iteration did not change the solutions by more than 10%. The emphasis in this Chapter has been to highlight the stability of the Rubin et al. result when IR data and third variable techniques are used in the solutions. The alternative regression techniques presented in this section demonstrate some of the optimum analytical procedures for Hubble flow studies. However, at this stage, with only 45 galaxies having luminosity indicators, it does not seem particularly worthwhile to perform a more rigorous statistical analysis.

5.6 Summary and Conclusions

A summary of all the solutions discussed in this thesis for the anisotropy of the Rubin et al. galaxy sample are given in Table 5.9.

Table 5.9

Summary of Solutions for the Motion of the Local Group

Solution	No	V_D km/sec	l°	b°
Optical mags (diameter corrected)	96	454 ± 125	163 ± 17	-11 ± 16
Optical mags (not diameter corrected)	96	581 ± 202	203 ± 19	-11 ± 17
H band mags (hybrid corrected)	45	621 ± 300	186 ± 30	-03 ± 29

H _{0.5} band mags (separate aperture & Malmquist correction)	45	741 ± 400	196 ± 41	-28 ± 34
H _{0.5} band mags (with TF relation)	40	846 ± 334	214 ± 43	-33 ± 24
H _{0.5} band mags (with CM relation)	45	680 ± 330	184 ± 35	-36 ± 30
IRAS 100 μm, (Malmquist corrected)	64	662 ± 221	190 ± 18	-06 ± 18
Photoelectric Mags (Peterson & Baumgart)	112	672 ± 195	200 ± 16	-12 ± 17
Dipole anisotropy in CBR		600 ± 50	265	+35

From these results several important conclusions can be drawn about this project.

The solutions are stable over a wavelength range ~ 200. This indicates that it is extremely unlikely that extinction is biasing the solutions. By the same argument, the optical results are probably not effected by putative systematics associated with the optical data base. The result from Peterson & Baumgart (1986) using optical photoelectric photometry for 112 Rubin et al. galaxies and carrying out a rigorous maximum likelihood solution, without a luminosity indicator, yields results in substantial agreement to our own. It has also been shown that inclusion of either the TF or CM luminosity relations does not significantly alter the results. A glance at Table 5.9 shows that the infrared solutions confirm the discrepancy between the Rubin et al. anisotropy and the CBR dipole anisotropy. The smaller precision of the near-IR results is largely due to the availability of about half optical data. These important results

were not demonstrated by Rubin et al. and they answer most of the criticisms made against the Rubin et al. result by Fall & Jones (1976), Davis & Peebles (1983b), Schechter (1977), and Tammann et al. (1980). Our result does not confirm the extrapolation made by de Vaucouleurs & Peters (1984) that on scales $> 35 h^{-1}$ Mpc galaxies define a reference frame at rest with respect to the cosmic background radiation.

The cosmological implications of results presented in this Chapter are far reaching and are discussed in Chapter 6.

CHAPTER 6

DISCUSSION OF ANISOTROPY SOLUTIONS

6.1 Introduction

Analysis of the infrared data for a representative sample of the Rubin et al. galaxies quantitatively confirms the anisotropy they reported (without the diameter-luminosity correction). The results described in Chapter 5 indicate that the discordant direction for the anisotropy is probably not the result of systematics associated with the optical data base or the reduction procedure. It therefore seems necessary to interpret the "Rubin-Ford effect" as a genuine velocity anisotropy, that is, an apparent motion of the Local Group with respect to the Rubin et al. galaxy sample. This velocity anisotropy is in a direction which is significantly different from that of the dipole anisotropy in the CBR. In the following sections the physical interpretation of this effect and its astrophysical consequences are considered.

6.2 A Large-Scale Streaming Motion

6.2.1 Relation With the CBR Dipole Anisotropy

The apparent Local Group motion we have found can be interpreted either as a genuine Local Group motion, or as a systematic streaming velocity of the Rubin et al. galaxies themselves. There are, however, rather persuasive reasons why it is likely that the dipole anisotropy in the CBR provides the best current estimate of the motion of the Local Group with respect to the co-moving reference frame. Firstly, there is its almost purely dipole character, for this is the only harmonic component to the anisotropy for which there is an unambiguous detection. Limits on the isotropy of the CBR provide no evidence for any anisotropies, except the dipole, at a level greater than $\sim 10^{-4}$ (Smoot 1983). Secondly, as was discussed in Chapter 2, independent estimates of the motion of the Local Group derived

from studies of nearby galaxies lend strong support to a LG infall into the Virgo cluster of at least 250 km/sec. The close correspondence between the anisotropy vector of the CBR and the direction of Virgo is only non-coincidental if at least part of the CBR dipole anisotropy is locally induced. In addition, this provides a simple description of a very fundamental attribute of the Universe.

If the CBR dipole anisotropy gives the LGM then the velocity anisotropy we have found is due to a large-scale streaming motion of the Rubin et al. galaxies themselves. It is difficult to average these results as they are not strictly independent. However, the C-M solution provides the best 3-variable solution and therefore probably the best estimate of our motion with respect to the sample. Subtracting off our Local Group motion as inferred from the dipole anisotropy of the CBR (LGM $\sim$ 600 km/sec, toward $\ell = 265^\circ$, $b = 35^\circ$) there is a net streaming motion V_s given by

$$V_s = 970 \pm 300 \text{ km/sec, towards } \ell = 309^\circ \pm 22^\circ, b = 45^\circ \pm 28^\circ.$$

Apart from the diameter-corrected solution, all the solutions in Table 5.9 give similar streaming motions within the errors. For instance the optical, Tully-Fisher, and IRAS solutions give $V_{s(\text{opt})} = 660 \pm 200 \text{ km/sec}$, $\ell = 311^\circ$, $b = 43^\circ$, $V_{s(\text{TF})} = 980 \pm 300 \text{ km/sec}$, $\ell = 350^\circ$, $b = 55^\circ$, $V_{s(\text{IRAS})} = 823 \pm 200 \text{ km/sec}$, $\ell = 328^\circ$, $b = 30^\circ$.

6.2.2 Distribution of the Galaxies

It was outlined in Section 3.1.3 how gravitational perturbations can cause large peculiar velocities due to acceleration over the Hubble time. However, they referred to motions and density enhancements within the Local Supercluster. In this section we inquire whether such large-scale streaming is plausibly consistent with other observations bearing on the large-scale structure of the Universe and whether it is quantitatively consistent with the awareness, which has dawned only rather recently, that the Universe is rather clumpy on scales of 10 - 50 Mpc, as indicated by

the existence of superclusters (Oort 1983). While there is still active debate as to the degree of superclustering, for instance whether it is possible to define the Local Supercluster as a definitive object (Oort 1983), the Rubin et al. sample is unique in studies of this kind because it is one of the very few studies outside the Local Supercluster and as a result, the sample consists of galaxies which belong to at least 4 distinct superclusters. Chincarini & Rood (1979) examine the distribution of all 200 galaxies listed by Rubin et al. Their map reveals the existence of the Hydra-Centaurus, Hercules, Perseus, and Coma superclusters. An all sky circular diagram showing the relative positions of all superclusters within ~ 7000 km/sec is shown in Fig. 6.1. The dashed circles represent the redshift extent of the mbs. As can be seen, the mbs passes through all these superclusters. Approximately $1/3$ of the galaxies in the near-IR sample can be associated with these regions. The location of the galaxies within these superclusters may provide an explanation for the apparent streaming velocity we find. One possibility is that there is sufficient power in the density fluctuations on large scales, represented by the existence of superclusters, to induce velocities which are coherent over these scales. Marked on Fig. 6.1 are two arrows representing the direction for the streaming motion apices of the mbs shell and the CBR dipole anisotropy. It is the net streaming in the direction of the RF arrow which produces an inferred LGM that is significantly different from the CBR dipole anisotropy. It can be seen that the direction of this vector apex lies only 15° from Hydra-Centaurus, at 12hr, while the antapex points directly at the Perseus supercluster, at 2 hr. This is perhaps suggesting that the combined peculiar velocity of these superclusters is responsible for the observed streaming motion. The cause of such peculiar motions on these scales remains unclear. One possibility is that the streaming is due to a non-zero resultant gravitational attraction between the superclusters shown in Fig. 6.1, and others outside this region. Eqn. 3.2 can be used to estimate the size of this effect. Recall that

$$\delta V \propto \frac{H_0^{-1} G \delta M}{R^2} \quad 6.1$$

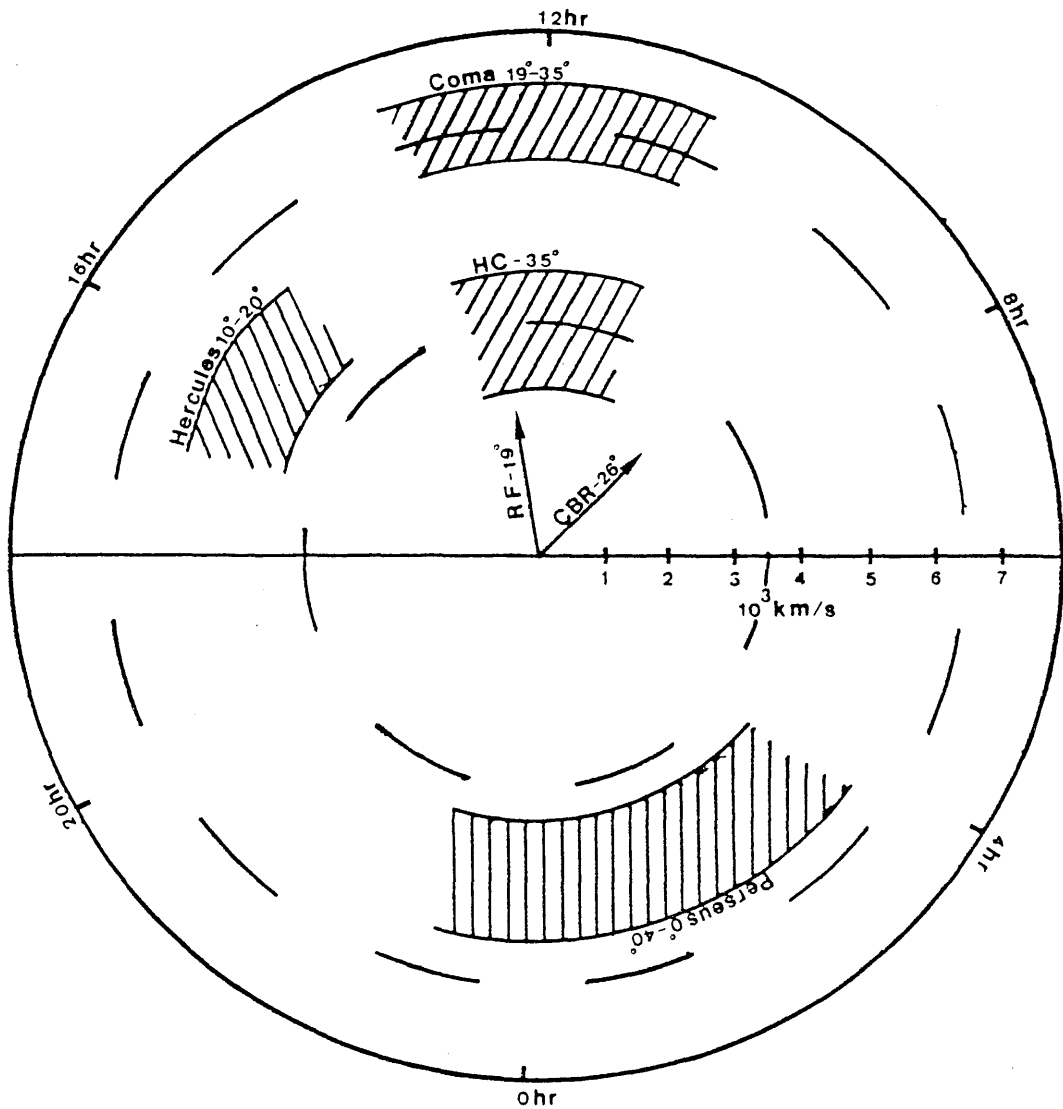


Figure 6.1 Sky distribution of all superclusters within 7000 km/sec. The angular coordinate is RA and the radial coordinate is velocity. The dashed lines show the velocity extent of the mbs. The approximate declinations are also shown along with the directions of the CBR dipole anisotropy and the Rubin et al. streaming velocity.

where $\delta M \propto \delta \rho R_0^3$. R_0 is the scale size of the supercluster and R is the typical separation. Using the relation 1.12 we have

$$\delta V \propto \frac{H_0 R_0^3 \delta \rho \Omega}{R^2 \rho} \quad 6.2$$

Consider the induced peculiar velocity of Perseus due to the combined effect of Coma and Hydra-Centaurus. From the statistics provided by Oort (1983), the distance (R) between Coma and Perseus is ~ 220 Mpc and Coma has a radius (R_0) ~ 80 Mpc. Assuming that $\delta \rho / \rho \sim 1$ for superclusters (Peebles 1980) Eqn. 6.2 gives $\delta V \sim 520 \Omega$ km/sec. A similar argument for HC, where $R \sim 160$ Mpc and $R_0 \sim 45$ Mpc, gives $\delta V \sim 200 \Omega$ km/sec. The resultant gravitational pull of Coma and HC on Perseus is $\sim 700 \Omega$ km/sec. Although this calculation is an over-simplification, it does indicate that the gravitational interaction between superclusters can give rise to large peculiar velocities of the same order as the observed streaming. More detailed calculations (Doroshkevich & Shandarin 1977) show that idealised pancakes, in the adiabatic theory for the formation of galaxies, have random velocities ~ 500 km/sec at distances ~ 100 Mpc. They note that the results of Rubin et al. can be brought into accord with their calculation if the galaxies themselves belong to other supercluster pancakes.

Since it appears that superclusters can provide the required large scale density perturbations, interpretation of the anisotropy as being due to a localised inhomogeneity ($\sim 10^{19}$) $M_\odot$ interposed on a homogeneous Universe, as suggested by Fenelly (1977), is unwarranted. Such a model also faces severe observational constraints, such as an expected CBR anisotropy of $\sim 10^{-3}$ in the direction of the inhomogeneity.

There is other evidence for large scale matter inhomogeneities which could give rise to streaming velocities. The IRAS point-source catalogue provides a unique way to generate a uniformly selected sample of galaxies over a large fraction of the sky. Recently, there has been two studies

which have analysed the isotropy of IRAS galaxies on the sky (Meiksin & Davis 1986, Yahil et al. 1986). Both of these studies find a small (10%-20%) but stable anisotropy in the galaxy distribution. The apex of the dipole points towards $l = 235^\circ$, $b = 35^\circ$. This is approximately 30° from the CBR dipole anisotropy and 40° from the streaming apex direction in Fig. 6.1. The extent to which this partial agreement is significant depends on the depth of the dipole anisotropy. Meiksin & Davis argue that it is apparent the anisotropy is dominated by clustering within $50 h^{-1} \text{ Mpc}$. However, Yahil et al. (1986) claim that the dipole extends to at least a depth of $200 h^{-1} \text{ Mpc}$. This is larger than the scale size of the local Universe shown in Fig. 6.1. Yahil et al. (1986) argue that the IRAS gravitational mass dipole gives rise to the LGM, as inferred from the CBR. Using linear perturbation theory they derive $\Omega \sim 0.85 \pm 0.15$. However, if the typical depth is as large as $200 h^{-1} \text{ Mpc}$ then the IRAS dipole moment may be measuring the gravitational field responsible for the peculiar streaming that is observed. Using the Yahil et al. argument in reverse, the expected peculiar velocity due to the IRAS dipole is $\sim 600 \text{ km/sec}$. Recent investigations (Davies & Staveley-Smith 1985, Aaronson et al. 1986) have found evidence for a motion of the Local Supercluster towards $l \sim 300^\circ$, $b \sim 30^\circ$. It is surely not a coincidence that the implied streaming direction of the Rubin et al. shell is close to the inferred direction of motion for our own Local Supercluster. The above authors interpret this result as a dynamical attraction between our LSC and the Hydra-Centaurus Supercluster, located at 3500 km/sec towards $l \sim 295^\circ$, $b \sim 35^\circ$. Our result implies that the Local Supercluster is simply partaking in the streaming which is observed for other, more distant, superclusters.

6.3 Material Content of the Universe

6.3.1 Introduction

There have been two approaches to using the peculiar velocities of galaxies to constrain the material content of the Universe. The first is to assume a dominant particle type, and under the assumption that light traces mass, use linear perturbation theory to constrain Ω . The second is to ask what particle species can give rise to the peculiar motions observed in an $\Omega = 0.2$ or $\Omega = 1$ Universe.

6.3.2 Constraining the Density Parameter

Clutton-Brock & Peebles (1981) have calculated the rms peculiar velocity of a spherical shell of galaxies in the redshift range of the Rubin et al. sample due to density fluctuations on scales significantly smaller than the shell. To estimate the size of such fluctuations they use the two point correlation function for galaxies. The assumption being tested is that the density enhancements result from the significant clustering of galaxies seen on scales < 5 Mpc, beyond which the two point correlation function falls to zero. If light traces mass then the integral of the correlation function is a measure of the mean over-density within a volume. They find

$$\langle v^2 \rangle^{1/2} = 300 \Omega^{0.6} \text{ km/sec} \quad 6.3$$

From Eqn. 6.3, the most probable streaming velocity induced by density fluctuations, consistent with the two point correlation function, is a factor 2 or 3 times smaller than the observed value. However, the distribution function for the expected rms is wide. Clutton-Brock & Peebles (1981) conclude that the probability of observing peculiar velocities as large as 800 km/sec in an $\Omega = 1$ Universe is ~ 0.1 . Values of Ω as low as 0.1-0.2 seem to be ruled out by this calculation.

One way to test whether the streaming velocity is due to the inhomogeneous distribution of galaxies is to investigate moments higher than the dipole term in the solution. These moments would be a direct consequence of the peculiar motion of individual galaxies, due to acceleration over the Hubble time, by local density fluctuations. This point has been discussed in detail by Clutton-Brock (1982), who finds that for the optical data, one quadrupole moment and two octupole moments are indeed large. These moments are 788 ± 416 km/sec, -456 ± 138 km/sec and 98 ± 39 km/sec respectively. The large quadrupole term ($3\sin^2 b - 1$) is closely coupled to the extinction correction ($\csc|b| - 1$) and so tells us more about extinction than moments of the sample. As an experiment, the IRAS $100\mu\text{m}$ data has been used to fit higher order moments in a similar manner to that of Clutton-Brock (1982). The quadrupole moment is not confirmed, consistent with the interpretation that it is caused by extinction. The two octupole components reported by Clutton-Brock (1982) are 152 ± 76 km/sec and 194 ± 53 km/sec respectively and so the IRAS data confirms these components. While the higher order moments could be the result of systematic errors, the fact that they are not all small, implies that the explanation of acceleration due to density fluctuations smaller than the sample size is tenable. The importance of higher order moments in Hubble flow studies is discussed further in Section 6.4.

6.3.3 Constraining Dark Matter Candidates

Large-scale galaxy streaming of the kind described here provides constraints on theoretical models for the formation of large-scale structure in the Universe. As discussed in Chapter 1, our best understanding of the formation of structure comes from the theory of gravitational instability, in which the size of the first bound structures to form depends on the type of particle which dominates the mass of the Universe. There are severe constraints on an $\Omega = 1$ Universe composed entirely of baryons. The fundamental difficulty is the constraint from nucleosynthesis

$$\Omega_b < 0.035h^2(T/2.7K)^3$$

6.4

where $H_0 = 100h$ km/sec/Mpc (Yang et al. 1984). The observed value of $\Omega_b \sim 0.1-0.2$ from dynamical studies (Chapter 3) is consistent with nucleosynthesis only if H_0 is near its lower observational limit (Blumenthal et al. 1984). Both the theoretical simplicity of $\Omega = 1$, in terms of the prediction from inflation (Guth 1981) and the evidence that dark matter exists in the haloes of galaxies (Rubin et al. 1985), suggests that the Universe is largely composed of non-baryonic material. This matter can be characterised as either hot or cold depending upon the dispersion velocities at a particular time. There have recently been calculations to estimate large scale streaming motions resulting from a Universe dominated by dark matter in both the hot and cold form (Vittorio and Silk 1984, Kaiser 1983).

One type of hot dark matter which has received considerable attention is neutrinos with a finite rest mass. While experimental verification of a finite rest mass has yet to be made, there are tentative experimental indications of a non-zero mass (Reines, Sobel & Pasierb 1980, Lyubimov et al. 1980). These particles are popular candidates for the missing mass since, at least in their massless form, these particles exist. Kaiser (1983) has calculated the net galaxy streaming velocity for a spatial scale of ~ 2500 km/sec in a neutrino-dominated cosmology. The calculation is performed in a similar manner to that of Clutton-Brock & Peebles (1982) except that the resultant density fluctuations are estimated by integrating over an assumed power spectrum of initial perturbations, where the index n is usually taken as $n = 1$ and $\Omega = 1$ (Chapter 1). Kaiser's result for the predicted streaming velocity on the scale of the Rubin et al. galaxies is

$$\langle V_s^2 \rangle^{1/2} = 43(1 + z_{NL})h^2 \text{ km/sec}$$

6.5

This calculation is normalised to z_{NL} , which is the redshift at which the gravitational collapse becomes non-linear. Fig. 6.2 shows the range of

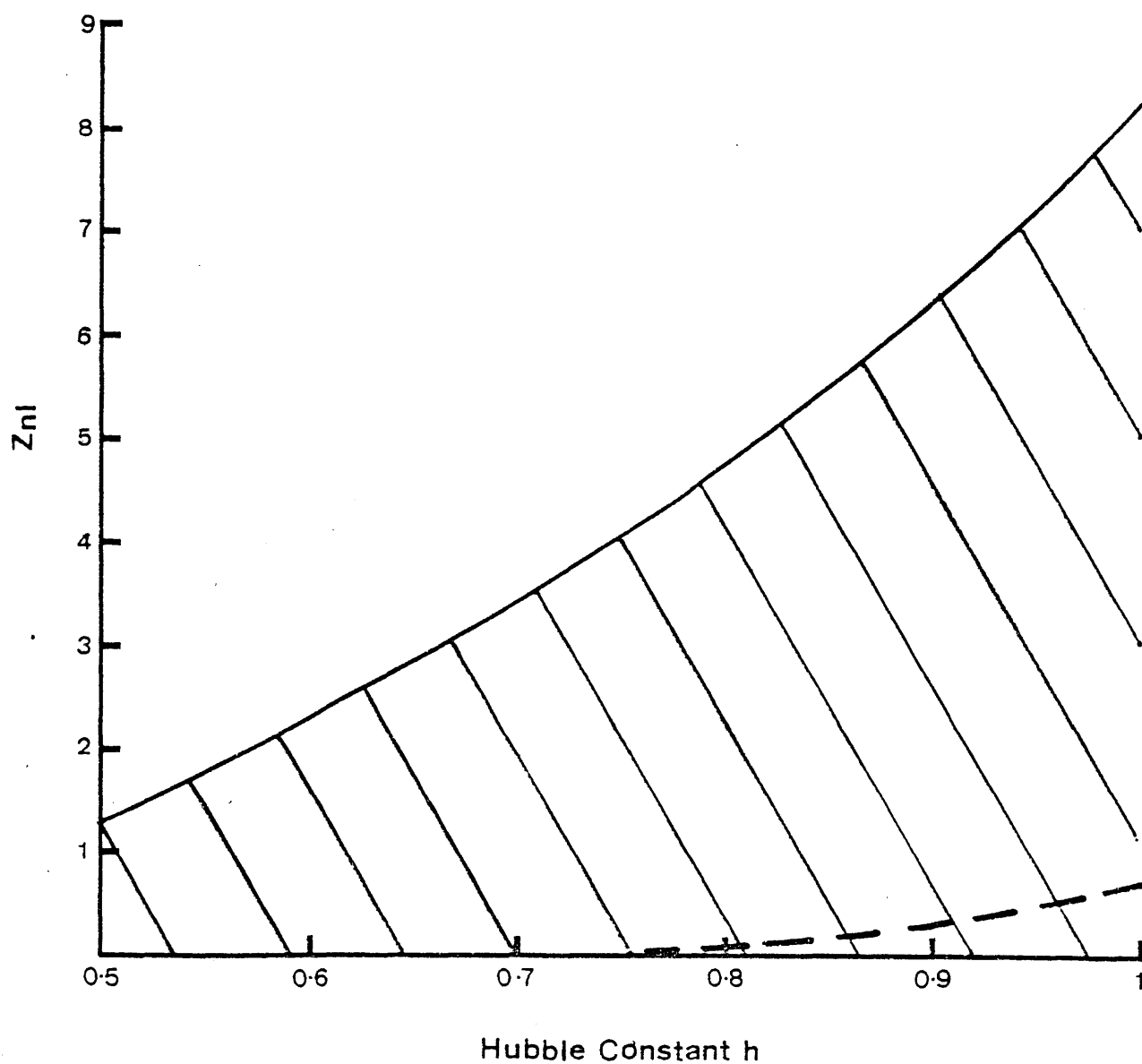


Figure 6.2 Excluded values for the epoch of non-linear collapse for different values of h if the Rubin et al. shell is streaming at ~ 400 km/sec in an $\Omega = 1$, neutrino dominated Universe (Kaiser 1983). The shaded area is excluded at 2σ if $V_s \sim 970$ km/sec. The dashed line represents the values of z_{NL} and h implied by Hart & Davies (1982).

z_{NL} and h for the 2σ lower limit on the streaming velocity of our sample (~ 400 km/sec). Since H_0 is currently thought to be within the range $0.5 < h < 1$, this gives a predicted epoch of galaxy formation in the range $1.5 < z_{NL} < 7.5$. This range is consistent with observations of quasars at a redshift of ~ 4 and is not inconsistent with upper limits on the small scale anisotropy in the CBR, in such cosmologies (Bond & Efstathiou 1984). Figure 6.2 also shows the implied streaming velocity from the observations of Hart & Davies (1982), normalised to a scale $\sim 25 h^{-1}$ Mpc (dashed line). Clearly, their result is difficult to reconcile with a neutrino-dominated Universe on the basis of this analysis, since their small streaming velocity ~ 130 km/sec implies an epoch of galaxy formation $z_{NL} < 1$, for reasonable values of H_0 .

Figure 6.3 reproduces, from Vittorio and Silk (1985), the streaming velocity predictions of different cosmological reference frames (shells of galaxies at radius r) relative to the CBR in a cold dark matter dominated Universe. The calculation has been normalised by assuming the average density fluctuation within $\sim 8 h^{-1}$ Mpc is unity. Our colour-magnitude streaming solution with 1σ error bar is shown along with the results of de Vaucouleurs & Peters (1984) and Hart & Davies (1982). Perhaps the strongest conclusion from this Hubble flow study is that for models dominated by cold dark matter it is difficult to produce streaming velocities as large as we have observed on scales of $50 h^{-1}$ Mpc (see Fig. 6.3). Large scale streaming can be reconciled with theory if the Universe is dominated by "hot" particles, of which the neutrino is a prime candidate.

Figure 6.3 highlights the discrepancy between our observed streaming and the results of other studies. Two ways these results may be reconciled in a neutrino dominated Universe are considered below. One possibility is that the predicted streaming velocity for surveys of greater depth increases. From Kaiser (1983) the predicted streaming scales as

$$V_s(r) \propto r^{-(n+1)/2}$$

6.6

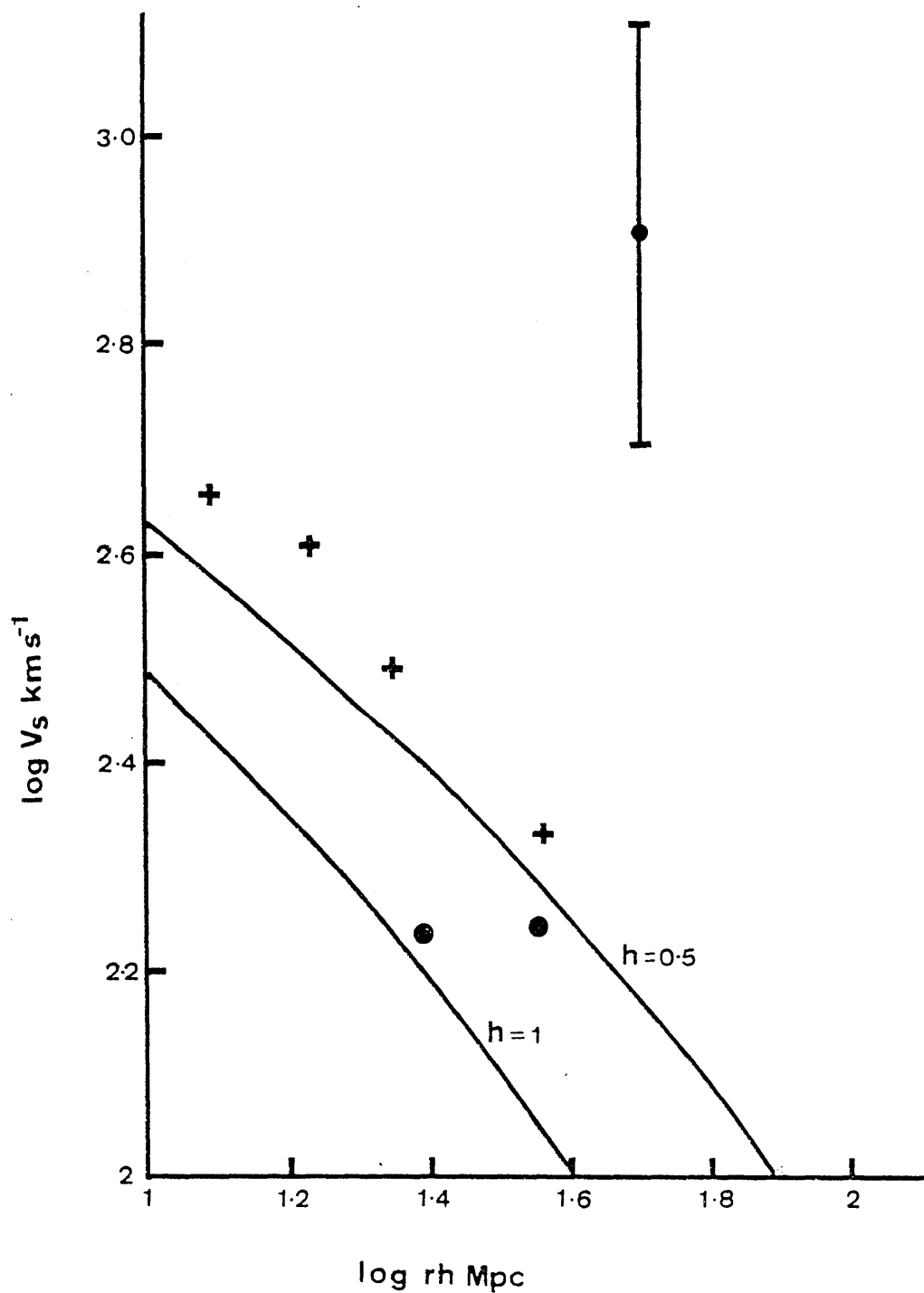


Figure 6.3 Predicted streaming velocities as a function of scale in a cdm dominated Universe, $h = 0.5-1$, (Vittorio & Silk 1985). Our V_s is shown along with the streaming inferred from the results of de Vaucouleurs & Peters (crosses) and Hart & Davies (spots).

Equation 6.6 predicts that streaming increases with depth only if $n < -1$. As discussed in Chapter 1, this is unfavourable because fluctuations diverge on large scales and negative indices strongly violate the small scale anisotropy of the CBR.

An attractive alternative is that the streaming velocity calculations, which are carried out in the linear regime, may not be valid for the Hart and Davies (1982) sample because the modes of fluctuation on this scale have undergone significant non-linear growth. In the neutrino-dominated Universe, structure is erased on scales smaller than the co-moving wavelength corresponding to

$$\lambda_v = 41 \, m_{30}^{-1} \text{Mpc} \quad 6.7$$

where m_{30} is the neutrino mass in units of 30 eV. Collapse of an initial perturbation in a neutrino dominated Universe proceeds in a similar fashion to the Zeldovich (1970) growth pattern for baryonic adiabatic fluctuations after decoupling, outlined in Chapter 1 (Bond et al. 1980). The collapse of overdense regions is essentially one-dimensional and results in planar or pancake-like configurations composed of baryonic material which has undergone significant dissipation and fallen into the potential well created by the neutrinos. If galaxies form via the fragmentation of this baryonic layer, then the collapse has entered the non-linear regime and the appropriate corrections need to be made to the linear description of the growing modes, as discussed by Szalay & Silk (1983).

The rather large velocities predicted on small scales in the adiabatic picture are in fact 1 of 3 problems associated with the linear calculations of this theory (Frenk et al. 1983). The other 2 are: 1) The coherence length λ_v is much larger than the observed scale length of the two point correlation function, which is $\sim 5 \, h^{-1} \text{Mpc}$ (Groth & Peebles 1977, Shanks et al. 1983). 2) Galaxies form from the non-linear collapse at

uncomfortably late epochs ($z \sim 1-2$), if the slope of the correlation function for galaxies, from the simulations, is constrained to match that of observation (Centrella & Melott 1983, Klypin & Shandarin 1983, Frenk et al. 1983).

Schaeffer & Silk (1984) have shown that both the streaming velocity problem and coherence length problem can be reconciled with the data if nonlinear effects are introduced. In particular, they calculate an upper limit to the net velocity dispersion on scales smaller than the coherence length, viz.

$$\langle V_s^2 \rangle^{1/2} < 550 [2/(1+z)]^{1/2} [\lambda/40h^{-1}] \Omega^{0.6} \text{ km/sec} \quad 6.8$$

With a formation redshift of $z \sim 3$ and taking a neutrino mass $m_{\nu_0} \sim 30 \text{ eV}$, Eqn. 6.8 gives

$$\langle V_s^2 \rangle^{1/2} < 180 \Omega^{0.6} \text{ km/sec} \quad 6.9$$

This is comparable with the Hart & Davis streaming measurement of $\sim 130 \text{ km/sec}$ and the prediction is substantially smaller than the linear estimate from Kaiser (1983), which is $\sim 350 \text{ km/sec}$. This illustrates the influence of non-linear gravitational effects on galaxies within superclusters.

Similar considerations can be applied to the interpretation of the scaling length of the two point correlation function. If non-linear clustering has been important in the Local Supercluster, then the predicted coherence length for the matter calculated from numerical simulations can be reconciled with the observed correlation length for galaxies (Schaeffer & Silk 1984). Finally, problem 3, the predicted epoch of galaxy formation, may not be too late if quasars and early galaxies form at the sites of maximum overdensity (Peacock & Heavens 1985). To conclude, neutrinos can produce enough power on large scales to give rise to the streaming motion we observe and are consistent with other observations

bearing on the large-scale structure.

6.4 Conclusions and Further Work

We have shown using infrared photometry that there is a residual velocity anisotropy approximately orthogonal to the dipole anisotropy in the CBR. This is most plausibly interpreted in terms of a large-scale streaming motion for this galaxy sample. The direction of the anisotropy is in suggestive agreement ($\sim 40^\circ$) with the robust IRAS dipole anisotropy, which may provide the necessary mass inhomogeneity. This indicates that the Hubble flow is not isotropic on scales as large as $50 h^{-1} \text{ Mpc}$, and if galaxies trace the mass, this tends to require a high density Universe. In the context of galaxy formation scenarios currently popular our result is inconsistent with a Universe dominated by cold dark matter, but further confirmation of large velocities on these scales would strongly suggest that the Universe is dominated by "hot" particles such as neutrinos.

6.4.1 Immediate Objectives

This thesis presents near infrared data on 45 of the 96 galaxies that constitute the mbs. We now have further observations, taken at Calar Alto, increasing the data base to 70. The completion of the mbs is the outstanding priority of this project and will provide greater confidence that the data presented here is both representative of Sb-Sc galaxies, in luminosity, and fairly samples the galaxy distribution on scales $\sim 50 h^{-1} \text{ Mpc}$. With this data the three variable solutions discussed in Chapter 5 will become significant above the 3 σ confidence level. At this stage of the research programme completion of the mbs can best be carried out by observing in the southern hemisphere. This will give greater coverage of the outstanding galaxies not yet observed and will provide an opportunity to extend the sample. The mbs coverage of sky in the south is poor, with only a few galaxies included below a declination of $\sim 40^\circ$ (see Fig. 5.1). Observations of 30, or so, spirals at low latitudes will provide equal coverage of both the northern and southern hemispheres. This avenue of

inquiry will be vigorously pursued in the near future.

Ellipticals should also be considered for anisotropy studies. These galaxies sample the peak in the galaxy luminosity function and are therefore expected to have a well defined luminosity dispersion and be less prone to Malmquist biasing. The correlation between luminosity and nuclear velocity dispersion (Faber & Jackson 1976) is pronounced with a scatter ~ 0.45 mag. First ranked cluster ellipticals sample the very peak of the luminosity distribution and have a range in absolute magnitude ~ 0.28 mag, after correction for Bautz-Morgan class and richness (Sandage & Hardy 1973). We have begun to build up a comprehensive data base of redshifts and optical magnitudes using published data. The aim is to provide a sample large enough that we can study anisotropies on the scale of the Rubin et al. and IRAS samples and in addition probe to redshifts ~ 15000 km/sec to search for putative anisotropies on the largest scales. This data will also enable us to address such questions as whether galaxies or clusters trace the mass and the related problem of biased galaxy formation. In this scheme, clusters are biased tracers of the mass, forming at the very peaks of the matter distribution (Kaiser 1984). These points can be addressed by comparing the streaming of spiral galaxies and giant ellipticals on similar spatial scales.

The solutions in this thesis have concentrated on the dipole component to the net velocity residuals. However, higher order moments may be important when comparing the results with theory. In general the calculations predicting the observed dipole assume negligible contribution from higher order moments. For instance, Kaiser's (1983) calculation for the streaming motion in a neutrino Universe assumes that the significant contributions to the gravitational perturbations come from wavelengths larger than the scale size of the shell under consideration. The shell is therefore treated as one coherent unit. If the higher order moments are large, then a solution for a net dipole term may contain little information on large-scale streaming, but simply reflect the inhomogeneous distribution of the galaxy sample and other systematics. As mentioned in

Section 6.3.2, contributions to higher order terms may come from extinction or, possibly, the large peculiar velocities of a few galaxies located near clusters. With more IR data we shall investigate the significance of the higher moments and their effect on the dipole anisotropy.

In view of the interpretation we have placed on the motion of the LSC as being due to a large-scale bulk streaming, rather than attraction towards the Hydra-Centaurus supercluster, it seems worthwhile to investigate the relative distance of HC, with a view to determining its peculiar velocity. The existence of the HC supercluster was verified in the redshift survey of Chincarini and Rood (1979). Consequently, little is known about its structure. Estimates of its redshift and size have been summarised by Oort (1983). An indication against the LSC velocity of 400 km/sec resulting from the gravitational attraction of HC alone, is the implied mass of this system. Assuming the redshift of Virgo and HC are 1000 km/sec and 3000 km/sec respectively and the infall velocities of the LG into Virgo and the LSC towards HC are 250 km/sec and 400 km/sec respectively, then $M_{HC} \sim 16 M_V$, where M_V is the mass within ~ 10 Mpc of Virgo, giving rise to the LG infall and M_{HC} is the mass of Hydra-Centaurus. This amount of mass is unlikely, at least in luminous form, since the diameter of HC is only twice as large as the LSC (Oort 1983). If the conclusions in this Chapter are correct and the LSC is partaking in a net streaming motion out to scales $\sim 50 h^{-1}$ Mpc it would be natural that the HC supercluster should partake in this motion. A comparison of the velocity residuals ($V_o - V_H$) between 40 or so spirals, ($\sigma_M \sim 0.5$) that are well identified members of the HC supercluster and nearby spirals, should be able to discriminate between these two interpretations.

6.4.2 Luminosity Indicators and Other Observing Strategies

There is little indication that in the near future distance estimates to large numbers of spirals outside the LSC, will surpass the limits attainable with the CM and TF relations. The use of spiral galaxies as

probes of the Hubble flow relies on accurate luminosity indicators. As discussed in Section 5.2.4, the Rubin et al. Sb-Sc spiral sample has an uncorrected dispersion ~ 0.6 mag, and suffers from strong Malmquist bias. Application of the colour-magnitude relation reduces this dispersion to ~ 0.45 mag. In general, it is possible to use a combination of the TF and CM relations, viz.

$$\text{Habs} = \alpha(\text{B-H}) + \gamma(\log V_{\text{max}}) \quad 6.10$$

In this way the scatter can be reduced even further, perhaps to 0.3 mag. This will provide solutions accurate to ~ 150 km/sec for 100 galaxies located at a distance of 5000 km/sec. Such precision is required to further test the Rubin et al. result on independent galaxy samples and will enable samples of galaxies to be studied in narrow angular regions on the sky. One idea is to investigate the nature of large-scale filaments and voids, mentioned in Chapter 1. Voids may form from the systematic streaming of galaxies away from these underdense regions towards the more overdense superclusters. This requires placing clear limits on streaming velocities at the level of ~ 200 km/sec (Peebles 1982a).

It has been stressed many times that the infrared has clear advantages over optical wavelengths in this type of study. Despite this, near-IR photometry has to be carried out in almost perfect conditions for high accuracy and the aperture has to be selected prior to observing since multi-aperture photometry is slow. This results in a loss of precision, due to aperture corrections. An alternative is I band CCD frames. These have all the advantages of IR photometry but with the added advantages that aperture corrections can be made directly and observing can be carried out in non-ideal conditions, by boot-strapping from nearby standards. In addition, the two dimensional data will enable the TF and CM relations to be placed on an infrared diameter system, which is perhaps more appropriate. In Section 5.3.1 the surface brightness of galaxies was shown to be an important diagnostic in the physical understanding of the TF relation. Little work has been carried out on the inclusion of surface

brightness as an additional parameter in either the TF or CM relations, or as a luminosity indicator in its own right. It seems that I band CCD frames will be a powerful tool for future studies of distance indicators. All these aspects of Hubble flow studies will be fully considered when planning future observing programmes.

Finally, the Rubin et al. study was for a long time dismissed and considered to be an anomolous result, which was probably in error. The conclusions reached in this thesis are that, on the contrary, it may have significant implications for cosmology. The time is now right for independent and extensive investigation of the Hubble flow on large scales, as such studies provide a powerful cosmological probe.

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APPENDIX

PUBLICATIONS

The research papers, to which I have contributed, are enclosed.

- 1) An Infrared Search for Primeval Galaxies
C.A. Collins, R.D. Joseph, 1985.
Proc. RAL Workshop on Extragalactic IR Astronomy, p. 148.
- 2) Evidence From IRAS Data for Large-Scale Anisotropy in the Hubble Flow.
C.A. Collins, R.D. Joseph & N.A. Robertson, 1985.
Light on Dark Matter: Proceedings of the First International IRAS Conference, Noordwijk, The Netherlands.
- 3) Large-Scale Anisotropy in the Hubble Flow.
C.A. Collins, R.D. Joseph, N.A. Robertson, 1986.
Galaxy Distances and Deviations from Universal Expansion, p. 131, eds.
B.F. Madore & R.B. Tully.
- 4) Large-Scale Anisotropy in the Hubble Flow.
C.A. Collins, R.D. Joseph, N.A. Robertson, 1986.
Nature, 320, 506.

AN INFRARED SEARCH FOR PRIMEVAL GALAXIES

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I. Introduction

One of the most outstanding problems facing observational cosmology is to explain the existence of galaxies and clusters in a Universe which was very smooth at early times. In the standard model the large scale structure forms as a result of either hierarchical clustering or fragmentation of the fluctuation scales surviving decoupling at $Z \sim 10^3$. The size of the first objects to collapse depends on the nature of the fluctuation before decoupling, in the radiation era. There are two primary types possible. Fluctuations in the matter density ($\delta\rho_b \neq 0$) within a thermal heat bath ($\delta\rho_\gamma = 0$) known as isothermal fluctuations, experience a viscous drag, due to the high temperature of the ambient medium, and are damped below scales

$$M < M_{jm}^{-1/2} 10^6 \Omega M_\odot,$$

where M_{jm} is the matter Jeans Mass at decoupling.

These early condensations could consist of baryonic particles that are perturbed isothermally and which may exist in the form of low mass stars or black holes. Similar primordial mass scales result if the universe is dominated by "cold" supersymmetric particles, such as axions or photinos (Blumenthal et al. 1984), even though the type of fluctuation associated with these particles is thought not to be isothermal. If the first masses to condense are on this characteristic scale then galaxy formation must proceed via the hierarchical clustering of these pre-galactic objects, perhaps forming a halo into which remaining gas cascades, as suggested by White and Rees (1978). Thus, galaxies form before clusters at redshifts $Z_{tf} > 10$.

Alternatively, prior to decoupling, there may be fluctuations in both the matter and radiation densities, $\delta\rho_b - \delta\rho_\gamma \neq 0$. These are termed adiabatic fluctuations. In this case photon diffusion from high density regions causes fluctuations to be damped below a characteristic mass scale. If the Universe is dominated by baryonic matter this scale corresponds to

$$M_s \sim 10^{13} \Omega^{-5/4} M_\odot,$$

termed the Silk mass (Silk 1968). Mass scales somewhat larger than this

($10^{15} M_{\odot}$) are associated with damping caused by the streaming of $10-100 \text{ eV}$ neutrinos as they become non-relativistic and are important if they dominate the mass of the Universe (Bond, Efstathiou & Silk 1980). The growth of these scales after $Z \sim 10^3$ has been studied by Zel'dovich (1970) and others. The two main conclusions are : Firstly, collapse will occur preferentially along only one axis resulting in planar or pancake structures of scales $\sim 10-100 \text{ Mpc}$. Secondly, the growth rate is linear,

$$\Delta\rho/\rho \sim (1+Z\Omega)^{-1}$$

and if non-linear fragmentation of the pancake into galaxies is associated with $\Delta\rho/\rho \sim 1$ then this must have occurred at $Z_{\text{tf}} < 10$.

Each of these scenarios is a better fit to different observational constraints. The clustering of galaxies resulting from the isothermal scenario gives a poor fit to the observed two point correlation function, $\xi(r)$, being too steep at the short range scales. However, galaxies are predicted to have formed prior to Quasar redshifts at $Z \sim 4$ and the isothermal scenario is not constrained by the low rates of galaxy evolution generally inferred from faint number counts (Ellis 1980). In addition, constraints imposed by the small scale anisotropy of the CBR are not in conflict with the isothermal scenario if re-ionisation takes place soon after decoupling. The adiabatic scenario, on the other hand, can be made to fit $\xi(r)$ but only with galaxy formation taking place at very late epochs, $Z \sim 2-3$ (Dekel & Aarseth 1984). The upper limits to the anisotropy of the CBR can only be reconciled with the adiabatic scenario if $\Omega=1$ or the Universe is dominated by massive neutrinos (Wilson & Silk 1981). Perhaps the best fit to the observed Universe, at present, is given by the cold dark matter scenario which incorporates a flatter initial fluctuation spectrum than the standard isothermal model (Blumenthal et al. 1984). Thus, this model reproduces the observed correlation function quite well and galaxy formation takes place at a comfortably high redshift.

While there is this vast body of theoretical literature on the subject of galaxy formation, previous searches have been confined to the optical wavebands. However in view of the expected redshifts for the epoch of galaxy formation, primeval galaxies may well be IR objects. The specific predictions of the two adiabatic and isothermal scenarios for the epoch of galaxy formation makes the search for young galaxies a particularly worthwhile undertaking.

II. Expected Parameters Of A Primeval Galaxy

The objects we seek are the progenitors of elliptical and spiral galaxies. The similarity between ellipticals and spiral bulges in terms of metal gradients, stellar and gas content, argues for a common epoch of formation.

1) Luminosity

Despite the wide range of published and plausible models for the formation

of galaxies, nearly all of them incorporate a highly luminous phase resulting from a very high initial rate of star formation. The luminosity is given by,

$$L_{pg} = \frac{(0.07) \Delta X M c^2}{\Delta t} \quad (1)$$

Where, M is the galaxy mass $\sim 10^{11} M_{\odot}$, ΔX is the fraction of heavy elements formed during the collapse phase $\sim 2\%$ and Δt is the duration of the bright phase.

In the scenario of Partridge & Peebles (1967a, 1967b) galaxies undergo a rapid burst of star formation lasting some 3×10^7 yrs at the onset of galaxy collapse. Using Eqn.1 this yields luminosities $< 10^{40}$ W.

More recently this picture of the bright phase has been modified. Larson's (1969, 1974, 1975, 1976) collapse models invoke slow gas infall through a background of stars already formed, and a star formation rate that depends on some power of the gas density. In these models the dynamical collapse timescale is $\sim 10^9 - 10^{10}$ yrs and the predicted luminosities are $\sim 10^{38}$ W. Kaufman's (1976) free-fall models of the Galaxy exclude a highly luminous phase while the Galaxy was still extended, since this would be inconsistent with the observed metal abundance as a function of height above the galactic plane. However, Kaufman finds peak luminosities during the collapse similar to those estimated by Partridge & Peebles (1967a), viz. 4×10^{39} W, for a galaxy of $10^{11} M_{\odot}$.

2) Spectrum

In the models of P&P and Larson the spectrum of a primeval galaxy resembles that of a giant HII region. The luminosity is assumed to be provided by O and B type stars at $\sim 10^4$ K. The significant features are the continuum break at 912 Å and the possible re-radiation of as much as 15% of the total luminosity in the L_{α} line (Meier 1976).

3) Angular Diameters

The linear diameter of a primeval galaxy depends on whether the bright phase occurred while the primeval galaxy was extended, as in the Partridge & Peebles (1967a) model, or after it had collapsed, as in Larson's models. Linear diameters thus typically range from 10-30 Kpc. Figure 1 shows the angular diameter v's redshift for the intermediate case of a 20 Kpc region for various world models.

4) Areal Density

The expected number of primeval galaxies per steradian is given by

$$N = (1+Z)^3 c \Delta t d_A^2 n_0$$

where d_A is the angular diameter distance, and n_0 is the local number density of galaxies. If all galaxies go through a highly luminous phase

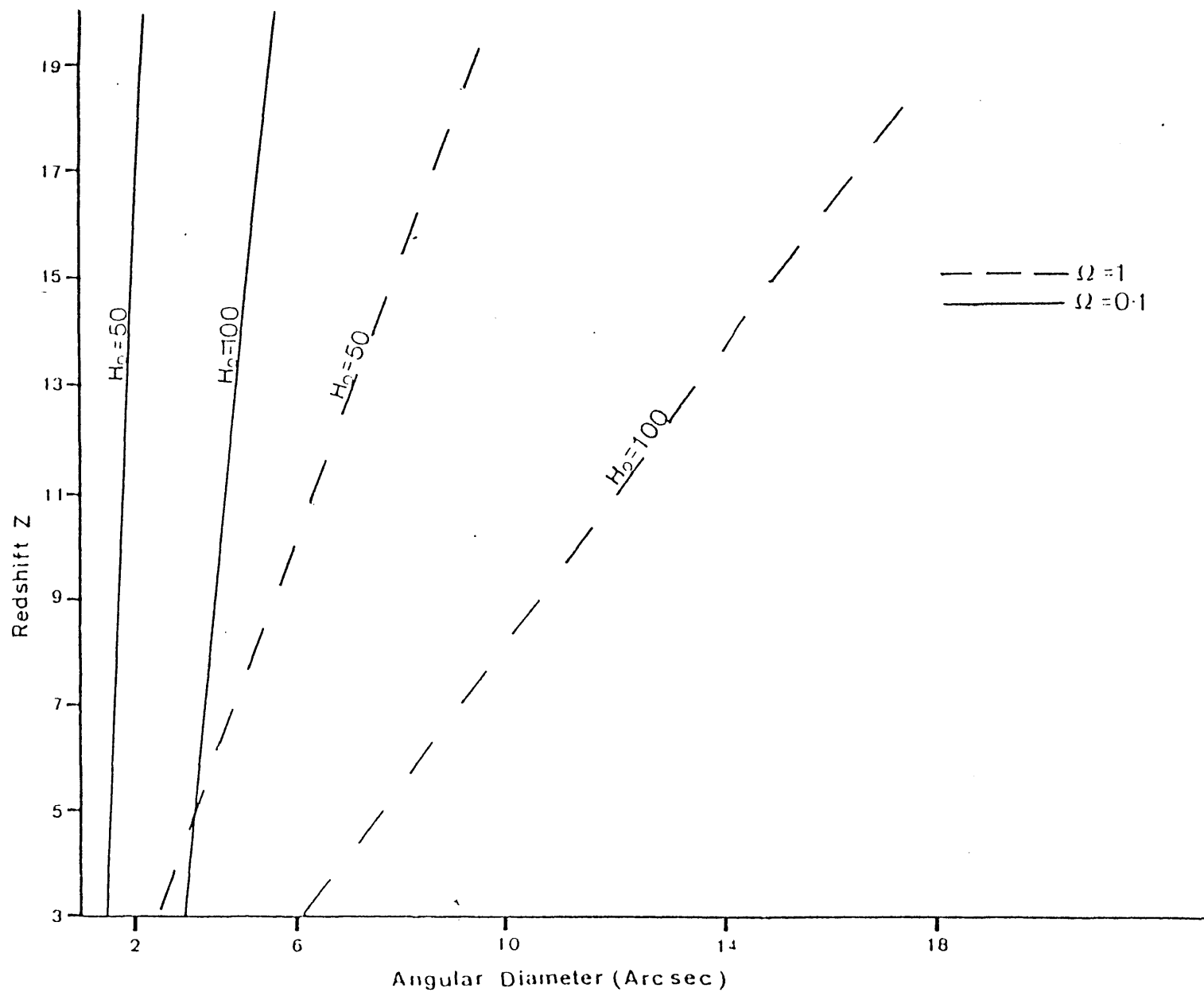


FIG.1 The expected angular diameter of a primeval galaxy with a linear size of 20 kpc in 4 world models.

then,

$$\eta_0 \sim 0.02 \text{ h}^3 \text{Mpc}^{-3}$$

and

$$N \sim 3 \times 10^4 \text{ deg}^{-2} \text{ at } Z \sim 10.$$

This is a high areal density and implies that enough area can be searched to obtain interesting limits without recourse to array detectors.

III. Limits Of Previous Searches

There have been two approaches to search for primeval galaxies and identify the epoch of galaxy formation. One has been to try and detect a bona fide primeval galaxy, and the other has been to measure the extra-galactic background light due to primeval galaxies.

Partridge (1974) used both photoelectric photometry and photographic plates (6200-7800 Å and 4000-6750 Å respectively) to search for primeval galaxies of angular size consistent with the Partridge & Peebles (1967) models, i.e. >10 arcsec. The result of both searches was negative, with a sensitivity limit for a single object of $37 \mu\text{Jy}$.

Davis and Wilkinson (1974) also looked for the P&P-type objects with angular sizes 10-30 arcsec. They searched an area of 20,000 arcsec² in the red (6200-8900 Å), and they also obtained a negative result. The maximum flux density from a single object that could have escaped detection is $38 \mu\text{Jy}$.

While these two searches are sufficiently sensitive to test the Partridge & Peebles (1967) models and to show that such models must have galaxy formation at $Z_f > 4-8$, they do not really test the more recent models of Larson and Kaufman, which predict smaller angular sizes and smaller luminosities.

Perhaps the best experiment to date is that by Koo & Kron (1980). They used both a CCD and IV-N plates as detectors. They searched for the redshifted L_α line from objects <5 arcsec, and had a detection limit of $\sim 4 \mu\text{Jy}$. These limits suggest that the epoch of galaxy formation is >5 .

There have been several attempts to measure the extra-galactic background light. The best of these are probably those of Toller (1983) and Dube, Wickes and Wilkinson (1979). These experiments reached a limit of $3 \times 10^{-8} \text{ Wm}^{-2} \text{ sr}^{-1}$ at 5100 Å. This is a factor of ten larger than the background from primeval galaxies at 5100 Å calculated by Partridge & Peebles (1967b), and smaller than that in most formation models for $Z_{\text{tf}} < 5$.

These results demonstrate the limitations of optical techniques. For formation models of most interest, $Z_{\text{tf}} = 5-10$, primeval galaxies, and the extra-galactic background light from them, will have red-shifted into the near-infrared. We have therefore embarked on a programme to search for primeval galaxies using state-of-the-art IR detection

techniques.

IV. Near IR Search Programme

There are two aspects of any primeval galaxy search programme: 1) Detection of a candidate primeval galaxy, 2) recognition, by follow up observations to discriminate between a genuine primeval galaxy and faint foreground objects.

1) Detection

The expected flux from a primeval galaxy is given by

$$F_{\nu} = \frac{L^{\text{PG}} \epsilon (T^{\text{PG}})^4}{4\pi d_A^2 (1+Z)^4 \Delta\nu}$$

where T^{PG} is the temperature of the redshifted spectrum and ϵ is the fraction of radiation found in frequency band $\Delta\nu$. Assuming $T^{\text{PG}} \sim 10^4 \text{ K}$, $Z_{\text{eff}} \sim 7$ and using the results from equation 1, the expected flux requires integration times ~ 10 - 20 minutes per pixel for a 5 sigma detection.

Our method of detection was to perform a one-dimensional deep survey on areas of sky that were blank on optical sky survey plates. Using the two channel instrument on UKIRT we searched simultaneously at J ($1.6\mu\text{m}$) and K ($2.2\mu\text{m}$). Lyman α with a redshift $8 < Z < 11$ would appear in the infrared J band. To ensure with 90% confidence that a primeval galaxy was in the beam, at some time, it was necessary to cover a minimum area of $\sim 10^3 \text{ arcsec}^2$.

We used an 8 arcsec aperture, based on the maximum likely angular size of primeval galaxies, (fig 1) and a chop amplitude of 16 arcsec, which ensured maximum contrast between the source and reference beams. Our chosen blank fields are located near the central positions of the blank fields searched by Davis and Wilkinson (1974), at RA=17hrs and 22hrs.

V. Results

We were awarded 4 nights on UKIRT in June 1984 for this programme, but only had one and a half nights of photometric weather. As a result we were only able to cover an area of 1257 arcsec^2 , about 1/2 of our planned search area.

Thus far we have uncovered 3 candidate objects.

	Waveband	Mag	Sigma
1)	<u>K</u>	17.9	5
2)	<u>K</u>	18.5	3

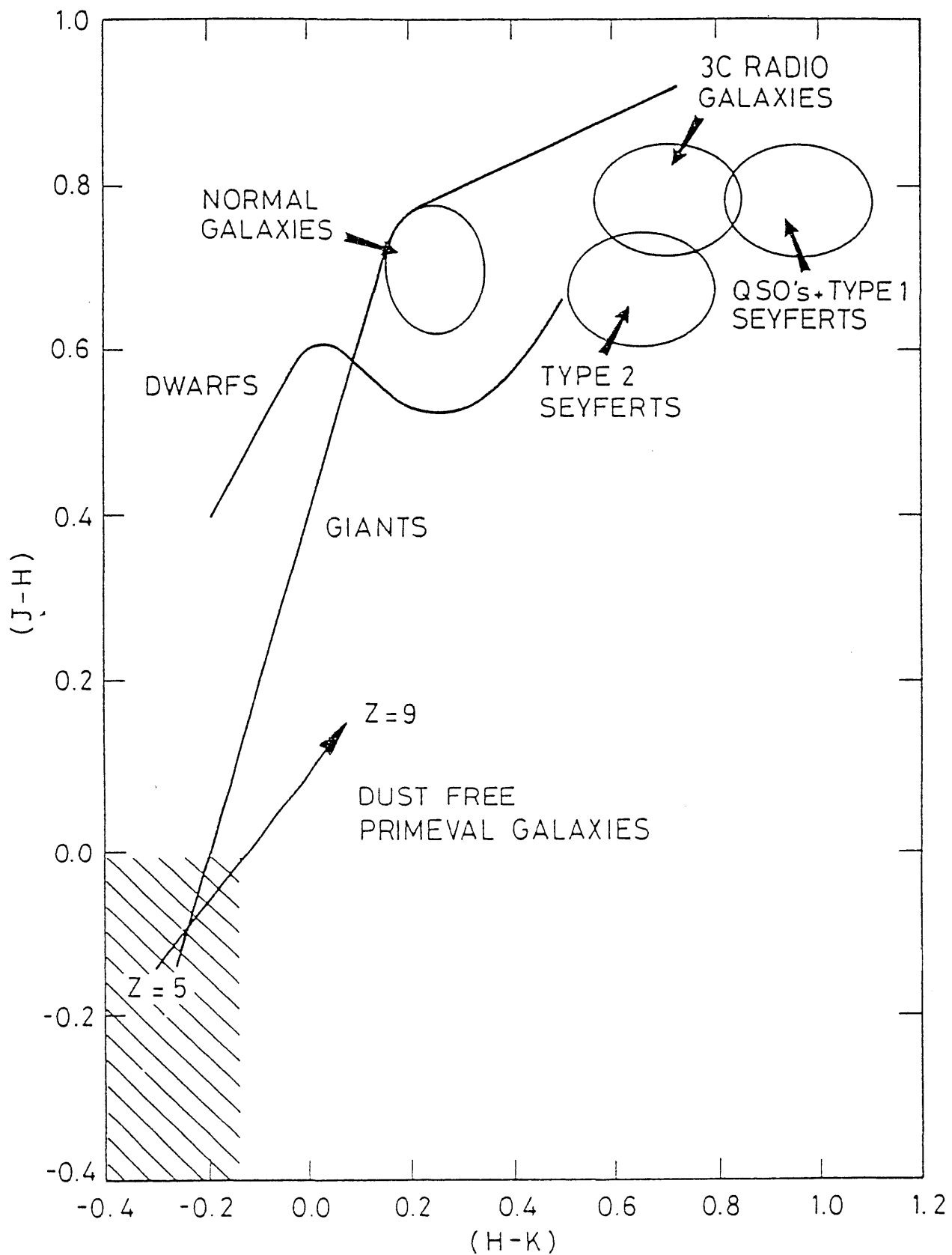


FIG.2 The $J-H$ & $H-K$ colours for common stars and extra-galactic sources together with the computed colours of a dust free primeval galaxy at high redshift. The assumed primeval galaxy spectrum is black body with a temperature 10^4 K . The shaded region indicates the colours ruled out at 3 sigma for candidate 1.

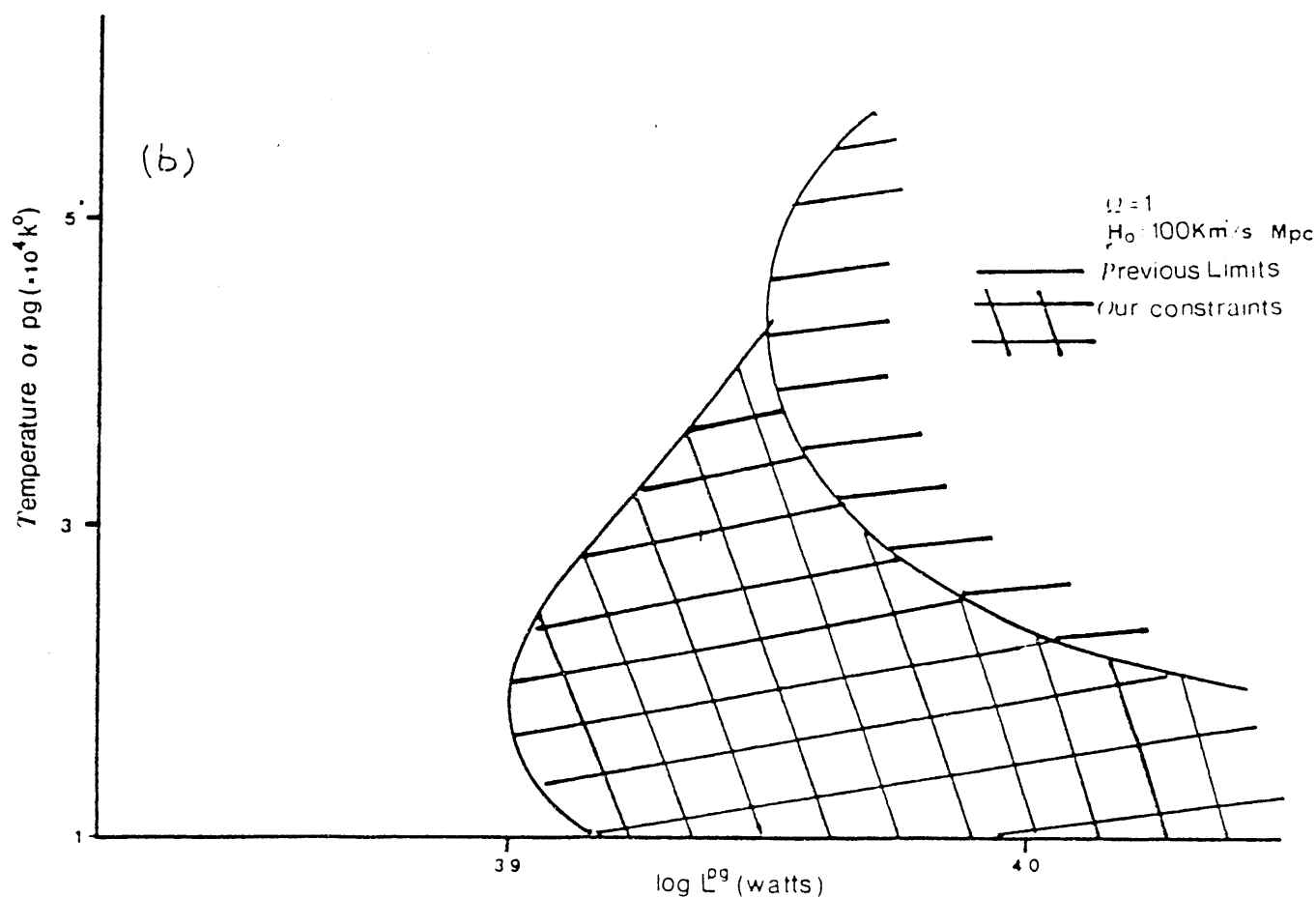
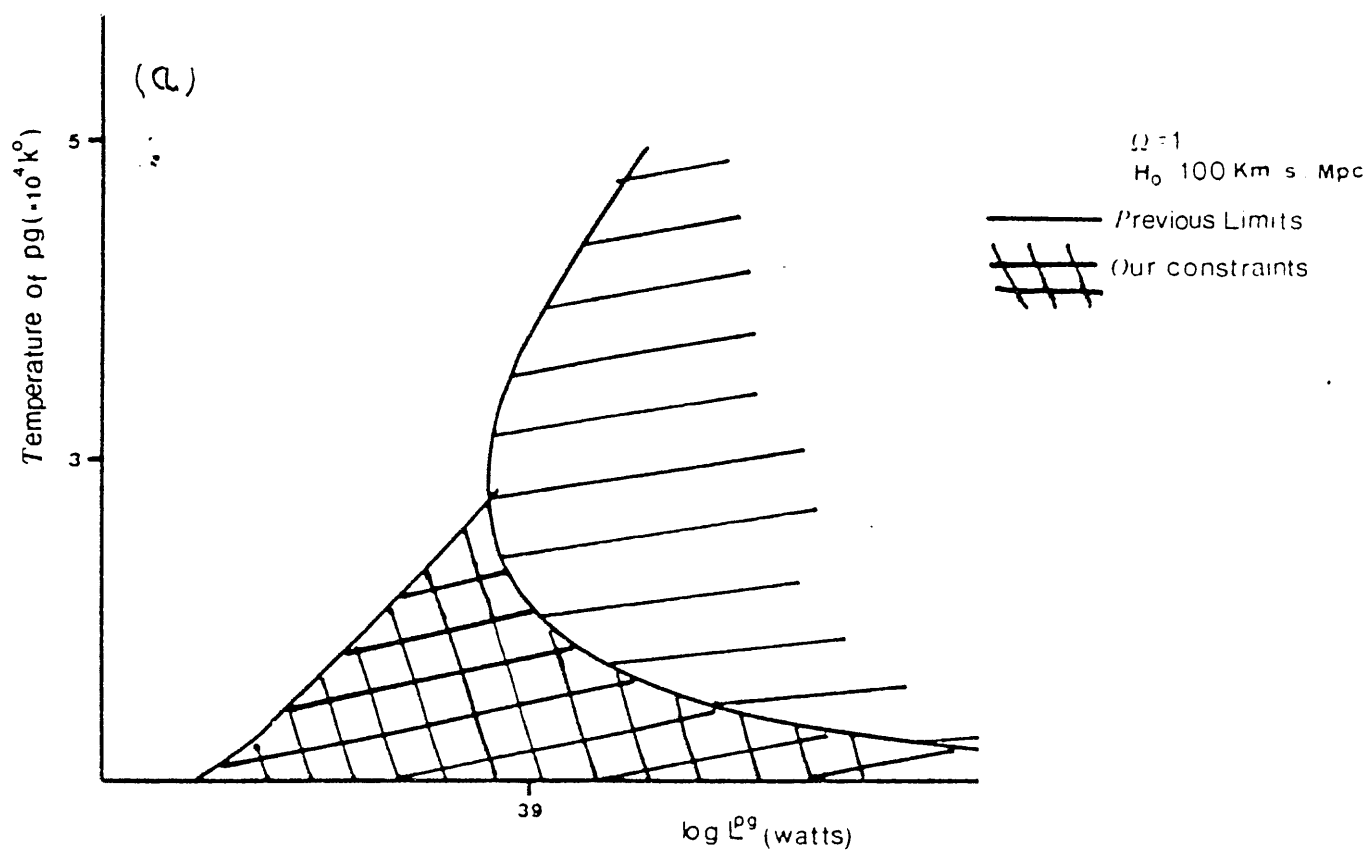


FIG.3a The excluded intrinsic temperatures and luminosities of primeval galaxies for our IR search compared to the best previous limits (Davis & Wilkinson 1974) for $Z=5$ in the listed cosmology.

FIG.3b The same as 3a except limits apply to $Z=9$.

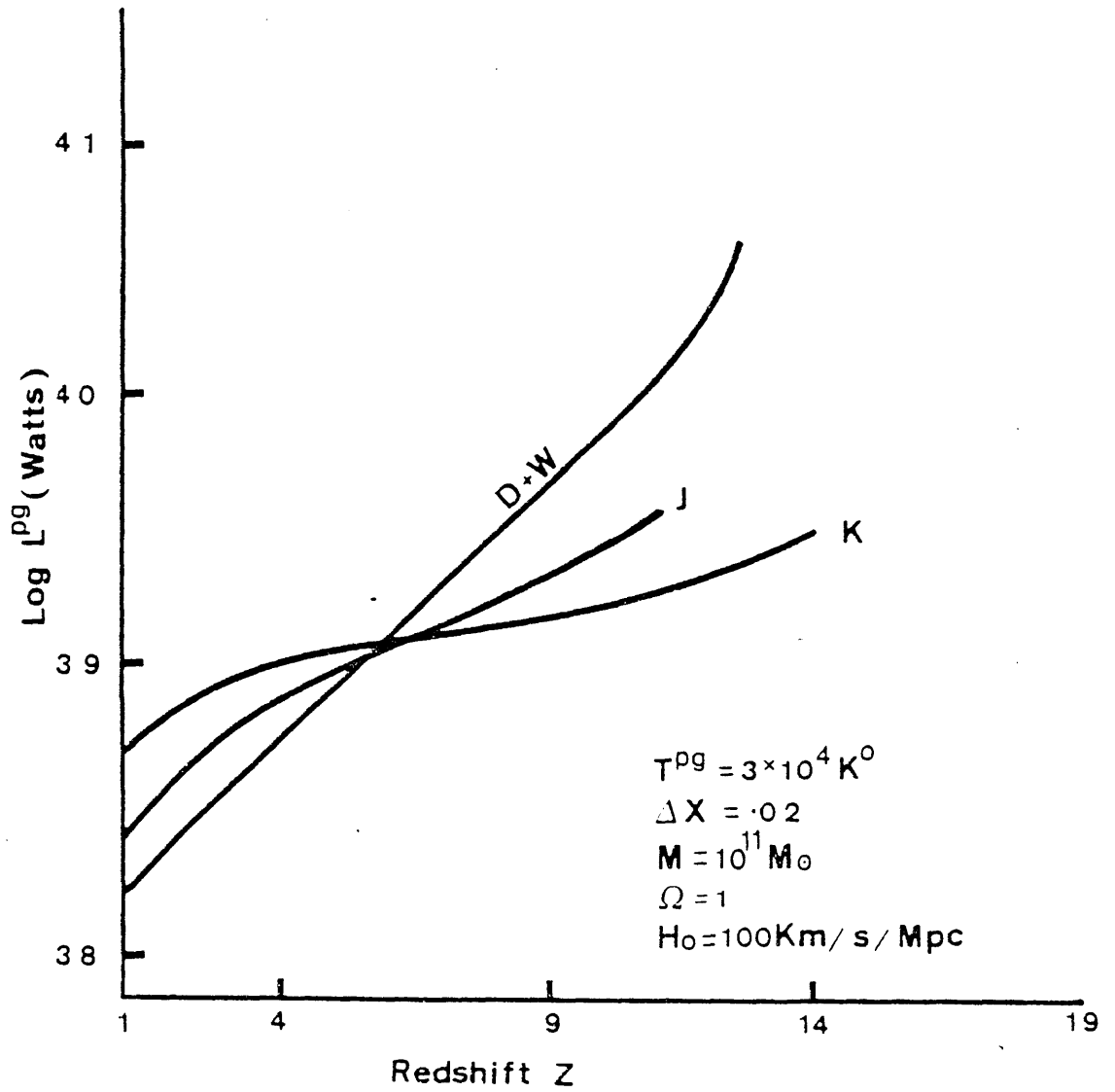


FIG.4 The excluded luminosities as a function of redshift for our J & K searches (labelled J,K respectively) compared to the limits of Davis & Wilkinson (1974). The areas above each line are excluded for the assumed parameters listed.

The magnitude and significance of each of these candidates is estimated from the statistical combination of all the separate observations (at least 2) of each pixel. Candidate 1 was observed in September and again in November 1984, using UKT9 at K on both occasions, and was detected each time. This rules out a Solar System object, such as an asteroid, whose proper motion would exceed ~ 8 arcsec over a period of 3 months.

2) Recognition

We have been awarded further observing time in July 1985 to complete the search area, confirm candidates 2) and 3) and to carry out follow-up observations of all candidates. For a first follow-up we will obtain JHK photometry. Significant discrimination between extra-galactic objects and dust-free primeval galaxies can be made using an infrared JHK colour-colour diagram. Figure 2 shows colours of various possible foreground objects compared to the computed colours of dust-free primeval galaxies, assuming a P&P or Larson-type spectrum. Also shown is the region already ruled out at the 3 sigma limit using the K detection of candidate 1 and assuming an upper limit at J. In addition multiaperture photometry will give some discrimination between genuine primeval galaxies and faint giant stars. Figure 1 shows that a 20 Kpc region is most probably extended at $Z > 5$. Clearly, tighter constraints can be placed with more accurate JHK photometry.

VI. Conclusions

If the candidate objects are not confirmed, or are faint foreground stars or galaxies, we will be able to place constraints on the luminosities of galaxies forming at early epochs about an order of magnitude smaller than those of previous searches, as shown in Figures 3a,3b & 4. Alternatively, we may have discovered a genuine example of the elusive primeval galaxies.

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EVIDENCE FROM IRAS DATA FOR LARGE-SCALE ANISOTROPY IN THE HUBBLE FLOW

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1. INTRODUCTION

Galaxies are generally assumed to have evolved from small primordial density fluctuations which have grown into the structures we presently observe. One way to confront this idea observationally is to use galaxies as test particles, to map out the large-scale gravitational potential. In this case, one can search for deviations from isotropic Hubble flow induced by fluctuations in the large-scale mass distribution (including any "dark" matter present) which have arisen from the growth of the primordial fluctuation spectrum as the Universe has evolved.

We have been engaged in an investigation of the isotropy of the Hubble flow using near-IR photometry for an all-sky sample of spiral galaxies. Herein we describe the result of using IRAS 100 μ m photometry for this same galaxy sample, and compare the solutions obtained with those using near-IR and optical photometry.

2. DATA ANALYSIS

The galaxy sample we are studying is the sample of 96 ScI-II spiral galaxies identified and classified by Rubin et al. (1976a). There are IRAS detections at 100 μ m for 64 of these galaxies in the IRAS Point Source Catalogue. Since these galaxies are in a narrowly-defined luminosity class, we can take them to be "standard candles," and use their magnitudes to infer a velocity, assuming isotropic Hubble flow. We then compare this notional Hubble velocity, v_H , with the observed recessional velocity, v_{obs} , and look for a systematic difference across the sky by solving for a dipole velocity anisotropy, v_D , which minimises, in the least squares sense, the difference between the residual $v_{obs} - v_H$, and v_D . Since we have subtracted the solar motion in the Galaxy, v_D may be interpreted either as a Local Group motion with respect to the reference frame defined by this distant galaxy sample, or as a mean deviation from uniform Hubble flow for these galaxies.

The solution for the apparent Local Group motion, v_D , obtained using the IRAS 100 μ m data, is shown in Table I. For comparison we have also included the solutions derived using near-IR photometry for the 43 galaxies in the sample we have so far observed, and the solution

reported by Rubin et al. (1976b) based on optical photometry not corrected for galaxy diameter (cf. Schechter 1977). Despite the fact that these solutions are obtained by photometry at very different wavelengths, in apertures between 35 arcsec and several arcmin, and for different subsets of galaxies in the sample, Table I shows that all the solutions are identical within the errors. There appears to be a significant dipole anisotropy in the peculiar velocities of these galaxies with respect to the Hubble flow.

TABLE I. Magnitude and direction of dipole anisotropy.

Observations	$v_D(\text{km s}^{-1})$	$l(\text{deg})$	$b(\text{deg})$
IRAS 100 μm , 64 galaxies	660 ± 220	190	-6
Near-IR, 43 galaxies	750 ± 350	180	-9
Blue, 96 galaxies	580 ± 200	203	-11
3K CBR dipole anisotropy	620 ± 40	265	35

3. DISCUSSION

This dipole anisotropy in galaxy peculiar velocities has a direction roughly orthogonal to that inferred from the dipole anisotropy in the 3K CBR, shown also in Table I (cf. Lubin et al. 1983). The latter is likely to be the best indication of Local Group motion with respect to the local co-moving frame. We therefore suggest that this velocity indicates systematic departures from isotropic Hubble flow. These galaxies have an average redshift of 5100 km s^{-1} and so this represents a deviation from isotropic Hubble flow on a scale of $\sim 100 h^{-1} \text{ Mpc}$.

This result provides strong evidence that the Universe is far from smooth on scales of $100 h^{-1} \text{ Mpc}$. It contradicts the evidence offered by de Vaucouleurs & Peters (1984) that the Hubble flow should become isotropic outside the Local Supercluster. An anisotropy of this magnitude on such a large spatial scale tends to favour a high density Universe. Comparison of this result with the predictions of various galaxy formation scenarios (cf. Schaeffer & Silk 1985), which should provide constraints on some of the ingredients of these models, is in preparation.

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LARGE-SCALE ANISOTROPY IN THE HUBBLE FLOW

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ABSTRACT. The apparent Local Group motion inferred from infrared observations of an all-sky sample of spiral galaxies is interpreted in terms of a large-scale streaming motion for these galaxies on a scale of $50 \text{ h}^{-1} \text{ Mpc}$. If this streaming is induced by large-scale density fluctuations, the fluctuations required are compatible with the observed distribution of luminous matter, but only in a closed universe. In the context of current speculation regarding non-baryonic particle species which may dominate the mass of the universe, this result seems to be inconsistent with cold dark matter models.

1. INTRODUCTION

A classic study of the Local Group motion was carried out by Rubin et al. (1976a, 1976b). They identified a sample of 96 spiral galaxies in the redshift interval $3500\text{--}6500 \text{ km s}^{-1}$ (mean redshift 5100 km s^{-1}) which were all thought to belong to a narrowly-defined luminosity class (ScI-II) and could therefore be used as standard candles. Using the measured redshifts and optical magnitudes for these galaxies Rubin et al. inferred an apparent Local Group motion of $454 \pm 127 \text{ km s}^{-1}$ toward $l = 163^\circ$, $b = -11^\circ$.

This result was criticised on a number of points, and was not confirmed by later studies using other galaxy samples (Hart & Davies 1982, de Vaucouleurs & Peters 1984). We are attempting to resolve these disagreements by re-observing the Rubin et al. sample in the near-IR. In addition to greatly reduced extinction, the IR data permits use of two powerful luminosity indicators using independent third variables, the IR Tully-Fisher relation (Aaronson et al. 1979) and the optical-IR colour-magnitude relation (Tully et al. 1982), to determine distances.

2. OBSERVATIONS AND ANALYSIS

We have so far measured 45 of the 96 ScI-II galaxies comprising the Rubin et al. "minimum bias subset" at J, H, and K in a 35 arcsec aperture using the 1.5 m Infrared Flux Collector in Tenerife. These 45 galaxies are well-distributed around the sky, as shown in Fig. 1, and have a redshift distribution representative of the entire sample.

131

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We have carried out three different solutions for the apparent Local Group motion using these H magnitudes. For the first solution the H magnitudes were corrected for effects of both Malmquist bias and use of a fixed aperture. A "composite" correction for both of these effects was obtained from the slope of a plot of absolute magnitude vs. redshift. Hubble velocities were then derived from the corrected H magnitudes, assuming all the galaxies have the same absolute magnitude. The difference between the observed redshift and the derived Hubble velocity, i.e. $v_{\text{obs}} - v_{\text{H}}$, and a putative systematic dipole velocity, v_{D} , is minimised in the least squares sense, to derive a value for v_{D} . Since the redshifts have been corrected for the solar motion with respect to the Local Group (300 km s^{-1} toward $l = 90^\circ$, $b = 0^\circ$), v_{D} is the velocity of the Local Group relative to the frame defined by these galaxies. The result is shown in the first line of Table 1.

In the second solution we have used the HI 21 cm velocity widths to construct the IR Tully-Fisher relation. Application of this relation to correct for luminosity differences among the galaxies gives the solution in line 2 of Table 1.

For a third solution, given in line 3 of Table 1, we have used the B - H vs. H_{abs} colour-magnitude relation for this sample as a luminosity indicator. We find a slope of 1.85 ± 0.3 for this relation, consistent with slopes determined for other galaxy samples (Tully et al. 1982).

We have also used 100 μm flux densities from the IRAS Point Source Catalogue, which are available for for 64 of the 96 galaxies. The distribution of these galaxies around the sky is also shown in Fig. 1. We have corrected this data for Malmquist biasing using a procedure similar to the "composite" correction for the H magnitudes described above. The resulting solution is shown in line 4 of Table 1.

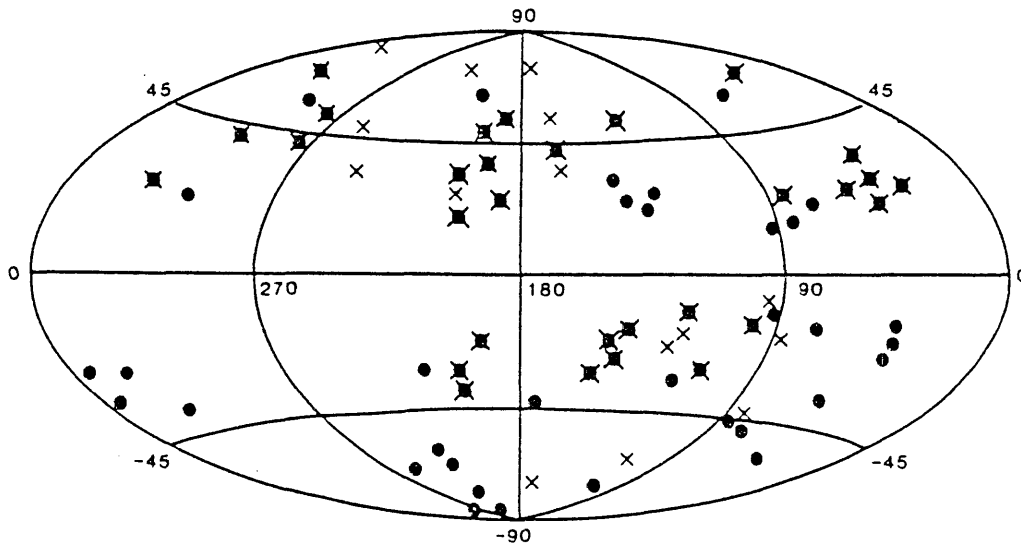


Fig. 1. Positions of galaxies observed in galactic coordinates. Galaxies observed at JHK (X), galaxies detected by IRAS (●).

In line 5 of Table 1 we have given the solution Rubin et al. obtained (1976b) for the entire sample, using the blue magnitudes without their diameter correction. To within the errors the results are independent of the photometric data used and inclusion of an independent luminosity indicator in the analysis does not change the solution. For comparison we have also listed the dipole anisotropy in the 3K cosmic background radiation (CBR) (Fixen et al. 1983, Lubin et al. 1983).

TABLE 1 Solutions for the apparent Local Group motion

Solution	v_D (km s ⁻¹)	l (deg)	b (deg)
H magnitudes, 45 galaxies	621 ± 300	186 ± 30	-03 ± 29
H mags. T-F relation, 40 galaxies	846 ± 334	214 ± 40	-33 ± 24
H mags. C-M relation, 45 galaxies	680 ± 330	184 ± 35	-36 ± 30
IRAS 100 μ m, 64 galaxies	662 ± 220	190 ± 20	-06 ± 18
B magnitudes, 96 galaxies	586 ± 200	202 ± 19	-11 ± 17
Dipole anisotropy in the CBR	600 ± 50	265	+35

3. DISCUSSION

The fact that the apparent Local Group motion we find for this sample of galaxies is so different from that inferred from the CBR, leads us to interpret our result in terms of a large-scale streaming motion induced by correspondingly large-scale density fluctuations.

Subtracting our apparent Local Group motion, v_D , from the velocity of the Local Group as inferred from the CBR dipole anisotropy gives a galaxy streaming velocity of 970 ± 300 km s⁻¹ toward $l = 305^\circ$, $b = 47^\circ$.

Recent studies by Davies & Staveley-Smith (1985) and Aaronson et al. (1986) suggest a motion of the Local Supercluster toward $l = 300^\circ$, $b = 30^\circ$. Whereas the above authors interpret this motion as dynamical attraction toward the Hydra-Centaurus Supercluster, the agreement with the direction of the streaming motion of our galaxy sample suggests instead a consistent picture in which the galaxies within a radius of $50 h^{-1}$ Mpc seem to be participating in the same overall streaming motion with respect to the fundamental cosmic reference frame.

The net streaming motion for elliptical galaxies out to redshifts of ~ 6000 km s⁻¹, discussed by Burstein et al. in this volume, seems to provide strong support for this picture.

There are two general approaches to using the peculiar velocities of galaxies to constrain models for the material content of the universe. The first is to assume that light traces mass and use linear perturbation theory to constrain the density parameter, Ω_0 . Clutton-Brock & Peebles (1981) have calculated the RMS peculiar velocity of a spherical shell of galaxies in the redshift range of this galaxy sample, due to density fluctuations consistent with the galaxy two-point correlation function. They find

$$\langle v^2 \rangle^{1/2} = 300 \Omega_0^{0.6} \text{ km s}^{-1},$$

This shows that consistency between the two-point correlation function and our large streaming velocity requires a high-density universe, and excludes cosmologies with $\Omega_0 \ll 1$.

The second approach is to ask what types of particles can produce density fluctuations of the amplitude required to induce streaming velocities on the observed spatial scales. The mass of the universe is currently thought to be dominated by "cold" or "hot" dark matter composed of some exotic particle species. One difference between these models is the resulting density fluctuation on large scales. Vittorio & Silk (1985) predict a streaming velocity on the scale of the Rubin et al. sample of $\leq 160 \text{ km s}^{-1}$ in models dominated by cold dark matter. The streaming velocity we find therefore seems to rule out cold dark matter models. If the dark matter is composed of hot particles, on the other hand, the mass fluctuation spectrum will have greater amplitude at large spatial scale, and will therefore tend to produce higher streaming velocities (cf. Kaiser 1983).

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Large-scale anisotropy in the Hubble flow

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Detection of anisotropy in the Hubble flow is one of the outstanding problems of observational cosmology. It provides information on the mass density of the Universe and the extent to which the Universe is smooth. This, in turn, permits constraints to be placed on theoretical models of galaxy formation. Our approach to this problem has been to obtain infrared photometry for an all-sky sample of Scl-II galaxies identified by Rubin *et al.*¹ at a mean redshift of $5,100 \text{ km s}^{-1}$. At this distance these galaxies provide information on the Hubble flow well outside the Local Supercluster. From observations of half the sample, well distributed across the sky, we find a systematic streaming velocity of these galaxies of $\sim 1,000 \pm 300 \text{ km s}^{-1}$. In the context of current speculation regarding non-baryonic particle species which may dominate the mass of the Universe, such large velocities on these spatial scales appear to exclude cold dark matter models.

We have used infrared photometry to measure the distances to this all-sky sample of galaxies. Infrared magnitudes have the advantage of being relatively unaffected by extinction and provide a reliable indication of distance when combined with either the optical-infrared colour-magnitude relation² or the infrared Tully-Fisher relation³. We have measured 45 of the 96 Scl-II galaxies comprising the Rubin *et al.*¹ 'minimum bias subset' in the J, H and K wavelength bands with a 35 arc s aperture using the 1.5-m Infrared Flux Collector in Tenerife. These 45 galaxies are well distributed across the sky (see Fig. 1). In particular, their redshift distribution is representative of that for the entire sample.

Our approach is to search for a systematic dipole velocity by comparing the velocities inferred from photometry with the observed recessional velocities. The analysis is carried out to find an apparent Local Group motion relative to the galaxy sample. Using the measured H magnitudes and the redshifts tabulated by Rubin *et al.*¹, we have carried out three different solutions for the apparent Local Group motion. For the first solution the H magnitudes were corrected for Malmquist bias in the sample and for the effect of using a fixed aperture. Both of these effects result in an apparent increase of galaxy luminosity with redshift. A 'composite' correction for these effects was determined from a plot of Hubble modulus (defined below) versus redshift. Hubble velocities were then derived from the corrected H magnitudes, assuming all the galaxies have the same absolute magnitude. Following the Rubin *et al.*¹ approach, one need make no assumption about the precise value of the Hubble constant, H_0 , or the absolute magnitude, M_0 , of the sample. Instead one uses the Hubble modulus, HM, defined as

$$\text{HM} = \log_{10} H_0 - 0.2 M - 5 = \log_{10} v_{\text{obs}} - 0.2 m$$

where v_{obs} and m are the redshift and apparent magnitude of a galaxy. The mean HM for the sample can then be used to find the Hubble velocity for each galaxy, assuming uniform expansion, from

$$v_H = 10^{(\text{HM} + 0.2 m)}$$

The difference between the observed redshift and the derived Hubble velocity, $v_{\text{obs}} - v_H$, and a putative systematic dipole velocity, v_D , are minimized in the least-squares sense, to derive a value for v_D . Because the redshifts have been corrected for the solar motion with respect to the Local Group (300 km s^{-1} toward galactic longitude $l = 90^\circ$, latitude $b = 0^\circ$), v_D is the

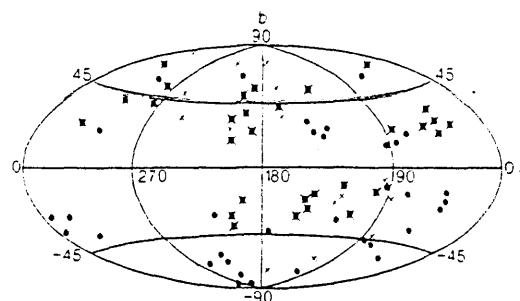


Fig. 1 Positions of galaxies observed in galactic coordinates on an equal-area projection of the celestial sphere. x, Galaxies observed in bands J, H and K; •, galaxies detected by IRAS.

velocity of the Local Group relative to the frame defined by these galaxies. The result is shown in the first line of Table 1. Identical results, within the errors, are obtained using the J and K magnitudes.

In our second solution we used the H 1.21-cm velocity widths and the infrared Tully-Fisher relation³ to find the relative luminosity of each galaxy. The solution using this relation is given in line 2 of Table 1. Evidently the resulting magnitude and direction of v_D are unchanged by using this third variable.

For a third solution we have used the $B-H$ versus H_{abs} colour-magnitude relation for this sample (Fig. 2) as a luminosity indicator. We find a slope of 1.85 ± 0.3 for this relation, consistent with slopes determined for other galaxy samples². The solution incorporating the colour-magnitude relation is given in line 3 of Table 1. Since the mean inclination of the sample is small ($\sim 35^\circ$), this solution should provide a better estimate of the Hubble velocities than the Tully-Fisher relation. The use of this third variable as an independent luminosity indicator has produced a solution essentially equivalent to the two previous ones. Thus, there is no bias in the absolute magnitudes of the galaxies in this sample sufficient to account for the velocity anisotropy observed. This is an important result which answers some of the criticisms of the original Rubin *et al.* study^{1,6}.

We have investigated the stability of this solution for a larger number of galaxies in the minimum-bias sample using 100- μm flux densities from the IRAS (Infrared Astronomy Satellite) catalogue⁷, which contains detections for 64 of the 96 galaxies comprising the sample. The distribution of these galaxies around the sky is also shown in Fig. 1. We have made corrections for Malmquist biasing similar to the 'composite' correction to the H magnitudes described above. Repeating the solution for the apparent Local Group motion using the IRAS 100- μm flux densities for these 64 galaxies gives the solution shown in line 4 of Table 1. We again find a solution which, within the errors, is identical to those found previously.

Line 5 of Table 1 contains the solution obtained by Rubin *et al.*¹, using blue magnitudes without diameter correction (the correction for galaxy diameters was shown by Schechter⁸ to give a less reliable solution). This solution is identical, within the errors, to the infrared solutions. For comparison we have also listed the velocity inferred from the dipole anisotropy in the cosmic background radiation (CBR)^{9,10}.

The results in Table 1 demonstrate that the apparent Local Group motion relative to the reference frame defined by this group of galaxies is independent of the photometric data used, over a wavelength range of a factor of 200. Use of two independent luminosity indicators in the analysis does not change the solution. We conclude therefore that there is a genuine and substantial discrepancy between the apparent Local Group motion relative to this galaxy sample and that relative to the CBR.

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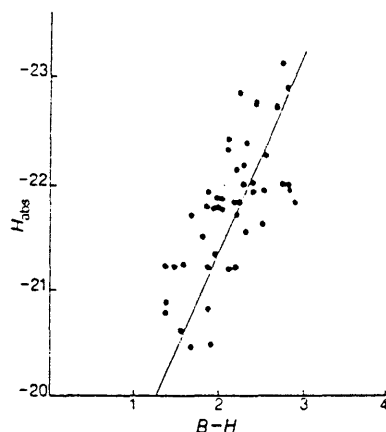


Fig. 2 Colour-magnitude relation for galaxies in the sample observed in bands J, H and K.

The fact that the apparent Local Group motion found for this sample of galaxies is so different from that inferred from the CBR leads us to interpret our results in terms of a large-scale streaming motion induced by correspondingly large-scale density fluctuations in the mass distribution of the Universe. To find the magnitude and direction of the streaming motion for these galaxies, we must subtract the apparent Local Group motion, v_D , from the velocity of the Local Group as inferred from the CBR dipole anisotropy. Using the solution in line 3 of Table 1, we find a galaxy streaming velocity of $970 \pm 300 \text{ km s}^{-1}$ toward $l = 305^\circ$, $b = 47^\circ$.

Is such a large-scale streaming consistent with other observations bearing on the large-scale structure of the Universe? Clutton-Brock and Peebles¹¹ have calculated the root-mean-square peculiar velocity of a spherical shell of galaxies in the redshift range of this galaxy sample, caused by density fluctuations consistent with the galaxy two-point correlation function. They find

$$\langle v^2 \rangle^{1/2} = 300 \Omega_0^{0.6} \text{ km s}^{-1}$$

where Ω_0 is the density parameter. This shows that, assuming that light traces mass, consistency between the two-point correlation function and our large streaming velocity requires a high-density Universe and precludes cosmologies with $\Omega_0 \ll 1$.

The streaming direction we find for this spherical shell of galaxies agrees with the streaming direction for the Local Supercluster (toward $l = 300^\circ$, $b = 25^\circ$) recently reported by Davies and Staveley-Smith¹², and is close to that found by Aaronson *et al.*¹³. This suggests a consistent picture in which the galaxies within a radius of $50 h^{-1} \text{ Mpc}$ (for $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$) seem to be participating in the same overall streaming motion with respect to the fundamental cosmic reference frame.

Our result for this galaxy sample at a redshift of $5,000 \text{ km s}^{-1}$ does not confirm the extrapolation made by de Vaucouleurs and Peters¹⁴ that galaxies at redshifts $> 3,500 \text{ km s}^{-1}$ define a reference frame at rest with respect to the CBR. The Hubble flow is apparently not isotropic on scales as large as $50 h^{-1} \text{ Mpc}$.

Yahil *et al.*¹⁵ and Meiksin and Davis¹⁶ have analysed all-sky counts of IRAS galaxies to infer a large-scale mass dipole moment. The direction of this dipole moment is $35\text{--}50^\circ$ away from the direction of the streaming velocity we find. If the effective distance of the IRAS galaxies is well outside $50 h^{-1} \text{ Mpc}$, this rough agreement may be significant.

Large-scale galaxy streaming of this kind provides constraints on theoretical models for the formation of large-scale structure in the Universe. The scale sizes of the structures which first form

Table 1 Solutions for the apparent Local Group motion

Solution	v_D (km s^{-1})	l (deg)	b (deg)
H magnitudes, 45 galaxies	621 ± 300	186 ± 30	-3 ± 29
H magnitudes with Tully-Fisher relation, 40 galaxies	846 ± 334	214 ± 40	-33 ± 34
H magnitudes with colour-magnitude relation, 45 galaxies	680 ± 330	184 ± 35	-36 ± 30
IRAS 100- μm , 64 galaxies	662 ± 220	190 ± 20	-6 ± 18
B magnitudes without diameter correction, 96 galaxies ⁴	586 ± 200	202 ± 19	-11 ± 17
Dipole anisotropy in the CBR ^{9,10}	600 ± 50	265	+35

in the gravitational instability model depend on the type of particle which dominates the mass of the Universe. This mass is currently thought to be in the form of some kind of 'hot' or 'cold' dark matter composed of exotic particle species¹⁷. The qualitative difference between these hot and cold dark matter models, for present purposes, is the resulting mass fluctuation on large scales. In models dominated by cold dark matter it is difficult to produce streaming velocities as large as we have observed on scales of $50 h^{-1} \text{ Mpc}$. For example, Vittorio and Silk¹⁸ predict streaming velocities on this scale of $\leq 160 \text{ km s}^{-1}$ in models dominated by cold dark matter. On the other hand, if the dark matter is composed of hot particles, the mass fluctuation spectrum will have greater amplitude at large spatial scale, and will therefore tend to produce higher streaming velocities. Kaiser¹⁹ has calculated the galaxy streaming velocities in cosmologies dominated by one hot dark matter candidate, massive neutrinos. Substituting 700 km s^{-1} into his result for the predicted streaming velocity on the scale of the Rubin *et al.* galaxies gives a redshift of galaxy formation of $z \approx 5$. This is consistent with other observational constraints on the epoch of galaxy formation.

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