THE DISTRIBUTION OF INFRARED GALAXIES IN SPACE AND THEIR SIGNIFICANCE FOR COSMOLOGY

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ABSTRACT

Infrared wavelengths are free of several of the problems that plague optical galaxy surveys. At high galactic latitude >99% of 60μ sources in the IRAS Point Source Catalog, after deletion of obvious stars, are galaxies. At lower latitudes care has to be taken to avoid confusion with emission from interstellar dust (the 'cirrus'). IRAS galaxies have been used to determine the direction of the gravitational acceleration acting on the Local Group due to galaxies and clusters within about 200 Mpc. This agrees well with the direction of the microwave background dipole. The density of matter in the universe, distributed like IRAS galaxies, needed to account for the observed velocity of the Local Group, corresponds to $\Omega_0 = 1.0 \pm 0.2$. In the standard hot Big Bang model, 90-95% of this matter would have to be non-baryonic.

1. Introduction. Galaxy surveys at optical wavelengths have so far failed to derive a convincing value for the velocity of the Local Group of galaxies with respect to the cosmological reference frame. While some determinations are in reasonable agreement with the value derived from the dipole component of the microwave background anisotropy (Hart and Davis 1982, Aaronson et al 1986), which we take here to be

$$v = 600 \text{ km sec}^{-1} \text{ towards } (l,b) = (277, 29) \quad (1)$$

(Lubin et al 1983, Fixsen et al 1983, Yahil et al 1986),

others are wildly discrepant from this value (Rubin et al 1976, de Vaucouleurs 1978, Sandage et al 1979, de Vaucouleurs and Peters 1981, de Vaucouleurs et al 1981, Aaronson et al 1982). Attempts to explain these discrepancies in terms of large-scale streaming motions seem premature. A more likely explanation of the discordant optical results is a combination of the known problems of current galaxy surveys:

(i) there is no all-sky galaxy survey with a well-calibrated homogeneous magnitude scale deeper than the Revised Shapley Ames Catalogue (Sandage & Tammann 1981), which has a completeness limit of about $m_B = 12$ mag. For a typical galaxy with absolute magnitude $M_B = -21$, this corresponds to a survey depth of only 40 Mpc, a volume clearly dominated by the Virgo Supercluster.

(ii) the strength of extinction by interstellar dust is a matter of lively controversy. Estimates of polar extinction range from 0 to 0.3 magnitudes of visual extinction (Sandage 1973, de Vaucouleurs et al 1976, Burstein & Heiles

1978) and at lower galactic latitudes the uncertainty can be 1 magnitude or more. The neutral hydrogen column-density (Burstein & Heiles 1978, 1982) and the IRAS 100μ background intensity (Rowan-Robinson 1986a) offer useful indicators of the column-density of interstellar dust associated with diffuse neutral gas, but there is little prospect of an effective indicator of the column-density of dust in lines of sight with significant concentrations of molecular gas.

(iii) for studies of late-type galaxies, the strength of extinction by internal dust and its dependence on the orientation of the galaxy is even less well known than that by interstellar dust in our Galaxy.

The IRAS Point Source Catalog provides us with a database for cosmological studies free of the above problems. Interstellar and internal extinction are neglible at far infrared wavelengths, the calibration is carried out in a homogeneous way over the whole sky (Neugebauer et al 1984) and outside the Galactic plane, regions of strong 'cirrus' emission and the 4% of the sky which lies in coverage gaps, the survey is 98% complete and 99.9% reliable (Rowan-Robinson et al 1984). Lawrence et al (1986) have shown that at high galactic latitudes, >99% of 60μ sources (after exclusion of sources which are obviously stellar) can be identified with galaxies and that the median depth of the IRAS 60μ survey is 200 (50/H_0) Mpc, where H_0 is the Hubble constant in km s^{-1} Mpc^{-1}. Known systematic errors can be shown to be small (see section 4 below). There remains the problem of emission from interstellar dust (the infrared 'cirrus'), which has to be carefully controlled to achieve reliable results (see section 3 below).

In this paper I review the work carried out by my group at Queen Mary College, London, in collaboration with Amos Yahil of Stony Brook University, N.Y., and colleagues at the Royal Greenwich Observatory. We have used the unique qualities of the IRAS 60μ survey to derive the direction of the gravitational acceleration acting on the Local Group due to galaxies and clusters within about 200 Mpc. This direction agrees well with that of the microwave background dipole. From the 60μ luminosity function for galaxies derived from a redshift survey of IRAS sources we estimate the density of matter in the universe, distributed like the IRAS galaxies, required to accelerate our Galaxy to its observed velocity today (eqn (1)). I shall also comment on the parallel work of Meiksin and Davis (1986).

2. USING IRAS GALAXIES TO MAP THE LOCAL GRAVITATIONAL FIELD

We assume that IRAS 60μ galaxies trace the matter in the universe and that there exists a universal luminosity function $\Phi(L)$, so the number of galaxies in luminosity range dL, volume element d^3r, can be written

$$dN = D(\underline{r})\ d^3r\ \Phi(L)\ dL \tag{2}$$

where $D(\underline{r})$ is the local relative density function (D=1 corresponds to the mean density of the universe).

Then the smoothed surface brightness due to sources is (Yahil et al 1986)

$$4\pi\sigma(S,\omega) = 4\pi S \frac{dN}{dSd\omega} = \int D(\underline{r})dr \int L\Phi(L)\ \delta\left[S - \frac{L}{4\pi r^2}\right] dL. \tag{3}$$

The peculiar gravitational acceleration $\underline{g}$ acting on the Local Group is proportional to the density moment

$$\underline{G} = \frac{3}{4\pi} \int D(\underline{r}) \left[\frac{\underline{r}}{r^3}\right] d^3r = 3\underline{g}/4\pi G\rho_o \quad . \tag{4}$$

Now the QMC-RGO redshift survey (Lawrence et al 1986) yields a 60μ luminosity function which can be well represented by (Fig 1)

$$\Phi(L) = CL^{-2}\ (1 + L/\beta L_*)^{-\beta} \tag{5}$$

with $C = (5.75 \pm 0.2) \times 10^6\ (H_o/50)\ L_\odot\ Mpc^{-3}$

$$\beta = 2.4^{+1.5}_{-0.8}.$$

Substitution into eqn (3) gives

$$4\pi S\sigma(S,\omega) = C \int D(\underline{r})(1 + r^2/\beta r_*^2)dr \tag{6}$$

where $r_* = (L_*/4\pi S)^{1/2}$.

The dipole moment of this

$$4\pi S\underline{\sigma}(S) = \int 3\ S\ \sigma(S,\omega)\ \hat{\underline{r}}\ dw$$

$$= \frac{3C}{4\pi} \int D(\underline{r}) \left[\frac{\underline{r}}{r^3}\right] (1 + r^2/\beta r_*^2)^{-\beta}\ d^3r \tag{7}$$

is now of the same form as $\underline{G}$ except for the cutoff factor $(1+r^2/\beta r_*^2)^{-\beta}$, which has only a small effect.

3. THE SAMPLE USED

To evaluate eqn (7) we have used IRAS 60μ sources brighter than the completeness limit of 0.6 Jy (Rowan-Robinson et al 1986a). Stars have been excluded by omitting sources with $S(25\mu)>3S(60\mu)$: virtually all such sources are identified with catalogued stars. Lawrence et al (1986) have shown that $\gg$99% of the remaining sources at $b>60^o$ are galaxies.

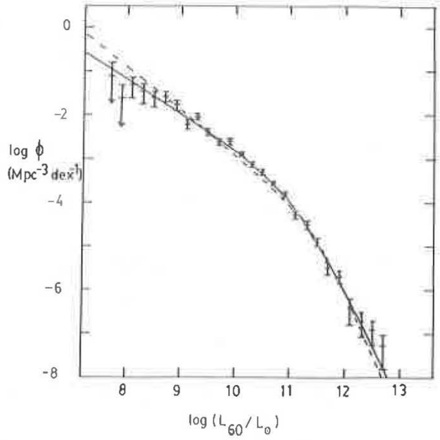

Fig 1: 60μ luminosity funciton derived by Lawrence et al (1986), compared with 2 simple analytical models. The dashed curve is eqn (5).

To avoid contamination by 'cirrus' and regions of very high source-density like the Milky Way and the Magellanic Clouds, we exclude $|b|<5^o$ and any one degree square bin which has been flagged in the IRAS Point Source Catalog as a region of exceptionally high source-density. We also exclude any one square degree bin in which the cirrus flag CIRR1 (the number of 100μ only sources in a 1 sq deg area centred on a source) has been set > n. After investigating the sensitivity of our results to the value of n, and the values of n found in known clouds of 'cirrus' (eg Rowan-Robinson et al 1986a), we adopt the conservative value n = 1.

The excluded areas, including the 4% of the sky in coverage gaps, define a mask, which is illustrated in Fig 2 a and b. Little of the sky remains unmasked below $|b|=30^o$. The spherical harmonic components have been calculated over the un-masked area only (this modifies the orthogonality matrix for the harmonics). We are essentially assuming that the un-masked area is representative of the whole sky. Fig 3a,b show the distributions of IRAS 60μ sources in the unmasked area.

Fig 5 of Yahil et al (1986) shows the 3 components of $4\pi S\underline{\sigma}(S)$, eqn (7), as a function of S, together with the average over all S. The amplitude of the dipole component is 20% of the mean surface brightness at 2 Jy and 10% at 0.6 Jy. Table 1 gives the direction of the average dipole and the angular displacement from the microwave background dipole, θ_{CBR}, for 3 values of the cirrus mask parameter n = 0, 1, 2. The direction of the IRAS dipole agrees well with that of the microwave background dipole. This suggests that we have now identified the cause of our motion with respect to the microwave background,

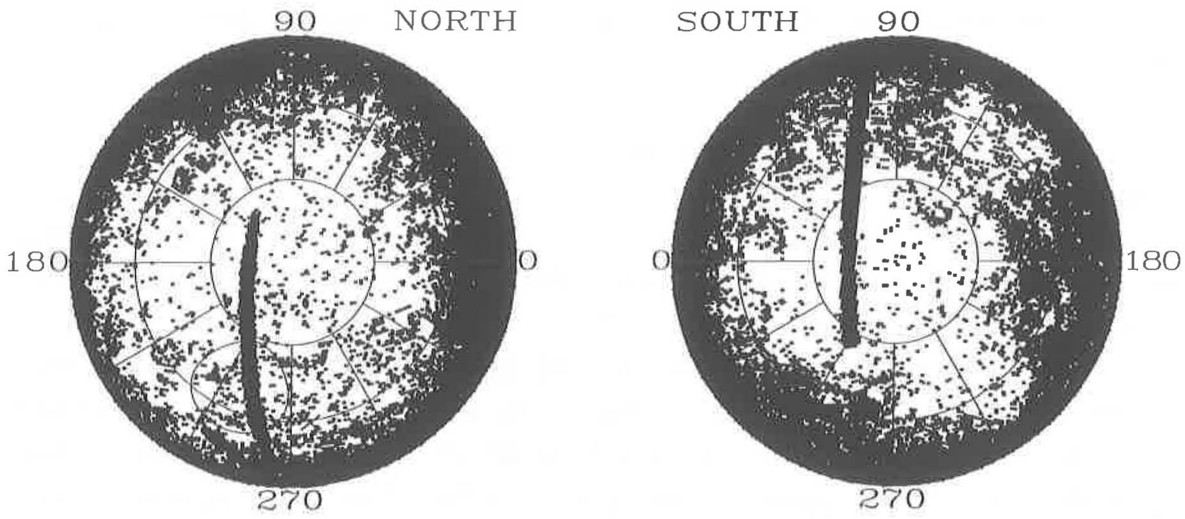

Fig 2: Equal area projections of the north and south Galactic hemispheres showing the mask n=1.

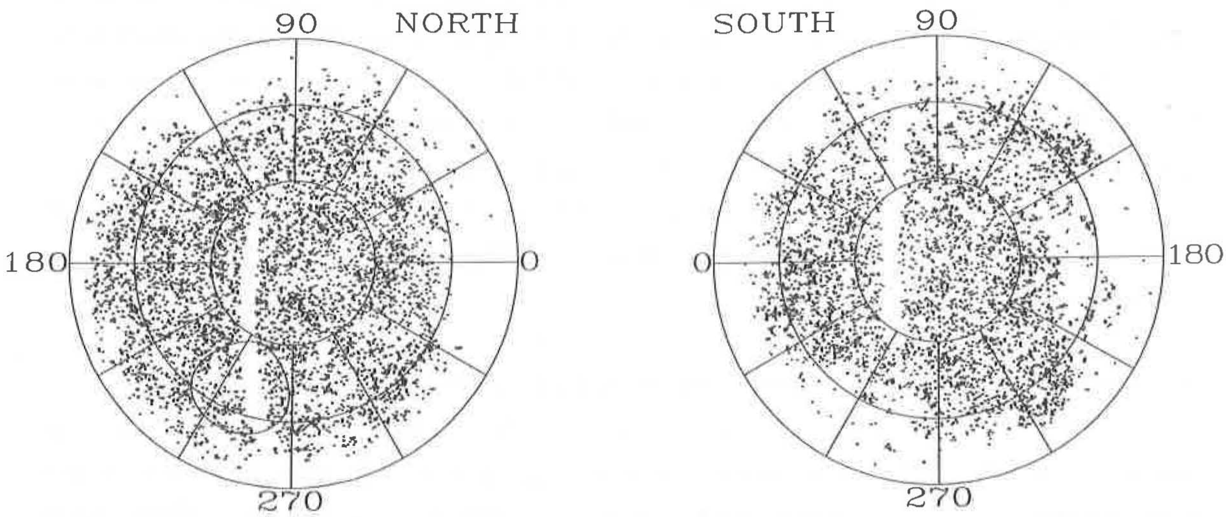

Fig 3: Equal area projections of the north and south Galactic hemispheres showing the IRAS 60μ sources in the unmasked region. Also shown are the 90% confidence limit of the IRAS dipole moment, and the direction of the microwave background dipole moment (large cross).

namely the net gravitational attraction of galaxies and clusters within about 200 Mpc.

Meiksin and Davis (1986) have also studied the IRAS dipole and the direction they derive, (l,b) = (235, 43.5), is similar to ours. However there are some key differences of approach and also some puzzling discrepancies between their work and ours (Rowan-Robinson 1986b). They have been much less severe than us in excluding regions affected by cirrus and in fact exclude only 24% of the sky, compared with 53% excluded by the n=1 mask. They have used a different colour condition to exclude stars, $S(60\mu)>3S(12\mu)$, but this should have led to the exclusion of only a further 6% of the sample. However I find (i) Meiksin and Davis appear to have used less than half of the sources in the IRAS catalog satisfying their constraints, (ii) their quoted dipole amplitude is less than half of that found by Yahil et al (1986), (iii) the amplitude of their 2-dimensional covariance function for IRAS galaxies is more than twice that found by Rowan-Robinson and Needham (1986). (i) may be caused by using upper limits to the 12μ flux in place of the actual 12μ flux, $S(12\mu)$, in their colour condition. (iii) is almost certainly due to a substantial contamination of their sample by cirrus (Rowan-Robinson 1986b). (ii) may be a combination of the severe incompleteness of their sample, its contamination by spurious cirrus sources and their treatment of excluded areas by populating them uniformly with artificial sources. The agreement of the IRAS dipole direction with that of Yahil et al (1986) can perhaps be taken as evidence of the robustness of the IRAS dipole.

4. POSSIBLE SOURCES OF SYSTEMATIC ERROR IN THE IRAS SURVEY

The known systematic errors in the IRAS data have been extensively discussed in the IRAS Explanatory Supplement (1984) and their implications for cosmological studies have been discussed by Rowan-Robinson et al (1986a), Yahil et al (1986) and Rowan-Robinson and Needham (1986). The major effects which could contribute to the IRAS dipole are:

(A) photon-induced responsivity enhancement ('hysteresis') as the detector field of view crosses the Galactic plane and other bright sources. The magnitude of this effect is <1% at 60μ at high Galactic latitudes, but great care would have to be taken when working within 20^o of the Galactic plane.

(B) responsivity changes due to particle hits on orbits passing near the edge of the South Atlantic Anomoly, but where bias boost was not applied to the detectors. This affects about 15% of orbits and the magnitude of the effect is $\leqslant 7\%$ at 60μ, so the net effect on the 60μ fluxes is $\leqslant 1\%$. Moreover the effect would have opposite signs at 60 and 100μ and the 60 and 100μ source-counts at $|b|>60^{\circ}$ are well correlated with each other. The effects of the Polar Horns of the radiation belts on fluxes in the IRAS Point Source Catalog are likely to be even smaller than that of the SAA.

To explain the observed dipole, a dipole calibration error at 60μ would have to have a 7% amplitude at 0.6 Jy and 13% amplitude at 2 Jy.

5. CALCULATION OF Ω_o

We can now calculate how much matter there needs to be in the universe, distributed like the IRAS galaxies, to accelerate the Local Group to its observed velocity with respect to the microwave background (eqn (1)). In linear perturbation theory, our peculiar velocity would be (Peebles 1980):

$$\underline{u} = \frac{1}{3}\,\Omega_o^{0.6}\,H_o\,\underline{G} \qquad (8)$$

$$= \frac{1}{3}\,\Omega_o^{0.6}\,H_o\langle 4\pi S\underline{\sigma}\rangle/C, \text{ using eqns (4) and (7).}$$

Using the value for C of Lawrence et al (1986), eqn (5) above, and correcting for the fact that the area they surveyed has a source-density 18% above the average for the unmasked sky, we find

$$\Omega_o = 0.85 \pm 0.16 \quad . \qquad (9)$$

Applying a small correction for the effects of non-linearity (see Yahil et al (1986) our final result is

$$\Omega_o = 1.0 \pm 0.2 \quad . \qquad (10)$$

In the standard hot Big Bang picture, this would imply that 90-95% of the matter in the universe would be non-baryonic, since consistency with the observed primordial helium and deuterium abundances requires $\Omega_{b,o} \simeq 0.05-0.1$.

6. DISCUSSION

The calculations of this paper are based on a number of assumptions, which I now discuss in turn.

(i) The 60μ luminosity has to be a measure of the mass of a galaxy. In support of this is the good correlation of 60μ luminosity with optical luminosity (Rowan-Robinson et al (1986b), which in turn is well correlated with galaxy mass. The minority of IRAS galaxies with exceptionally high infrared-to-optical ratios do not invalidate this assumption.

(ii) IRAS galaxies have to be a good tracer for the overall matter distribution, most of which has to be dark and non-baryonic. It is known that ellipticals and lenticulars are biassed towards rich clusters of galaxies, but

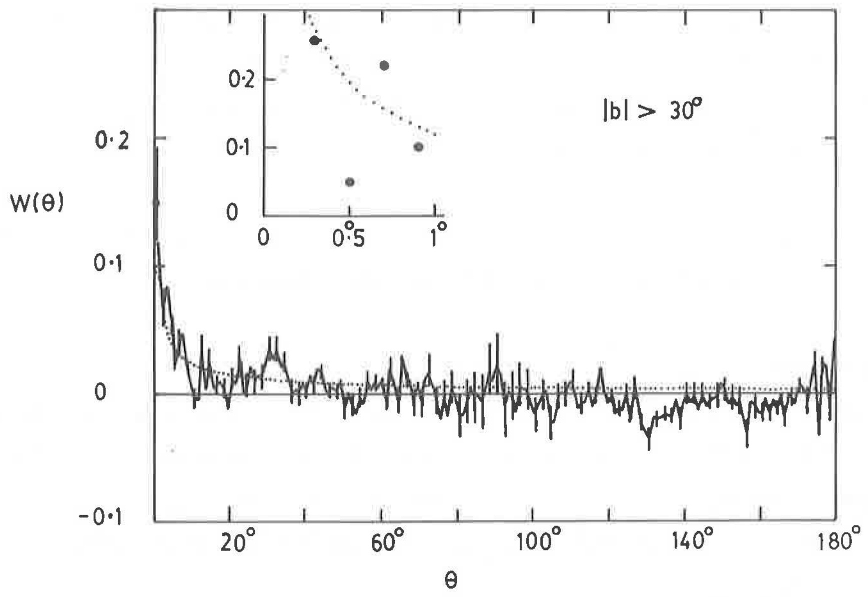

Fig 4: **Angular correlation function for IRAS sources at $|b|>30^o$, with 1^o bins. Inset is shown data for $12^1<\theta<1^o$. The dotted curve is $\omega(\theta)=0.12\ \theta^{-0.7}$. (from Rowan-Robinson & Needham 1986)**

IRAS galaxies are predominantly spirals and are the best available candidate for an unbiassed tracer of matter. The distribution of IRAS galaxies (Fig 3) shows clear evidence for clustering and many of these concentrations of IRAS sources correspond to known clusters of galaxies at distances ranging from 20-160 $(50/H_0)$ Mpc. However the distribution is markedly less clustered than the corresponding distribution of optically selected galaxies (eg Fig V.4 of Lonsdale et al 1985). Rowan-Robinson and Needham (1986) have calculated the 2-dimensional covariance function for IRAS 60μ sources outside the n=1 mask (Fig 4). While the power-law form is similar to that found in optical studies, the amplitude is considerably lower. Using the redshift survey of Lawrence et al (1986), Rowan-Robinson and Needham (1986) have calculated the 3-D covariance function corresponding to the model fit in Fig 4 and find

$$\xi(r) = (r/r_0)^{-1.7} \qquad (11)$$

where $r_0 = 4.1 \pm 0.7\ (50/H_0)$ Mpc.

which can be compared with a typical value of $10(50/H_0)$ Mpc found in optical studies.

If IRAS galaxies too are biassed tracers of matter then the density estimate (10) would be a lower limit.

(iii) we have to assume that there are no clusters (or voids) behind the mask which are so pronounced as to invalidate the assumption that the unmasked sky is representative of the whole sky. We plan to carry out a careful search for IRAS galaxies at low galactic latitudes to try to check this.

I conclude that the IRAS survey has provided us with an exceptionally rich database for cosmological studies. We have determined the direction of the gravitational acceleration due to galaxies and clusters within about 200 Mpc and find it to agree well with the direction of the microwave background dipole. We have therefore, I believe, found the cause of our motion with respect to the cosmological frame. The density of matter in the universe, distributed like the IRAS galaxies, required to explain our observed velocity with respect to the microwave background corresponds to $\Omega_0 = 1.0 \pm 0.2$. Most of this matter would in the standard model, have to be non-baryonic.

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