CONTRIBUTIONS TO THE LOCAL GRAVITATIONAL FIELD FROM BEYOND THE LOCAL SUPERCLUSTER

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ABSTRACT. IRAS 60μ sources are used to map the local ($\lesssim 200h^{-1}$ Mpc, H_o=100h km s^{-1} Mpc^{-1}) gravitational field, and to determine its dipole component, on the assumption that the infrared radiation traces the matter. The dipole moment is found to point in the direction of the anisotropy of the microwave background radiation. Comparison of the two anisotropies, using linear perturbation theory, yields an estimate of the cosmological density parameter, Ω_o=0.85±0.16, with nonlinear effects increasing Ω_o by ~15%. The quadrupolar tidal field within the Local Supercluster, due presumably to the same density inhomogeneities, is detected in a kinematical study of the velocity field.

1. INTRODUCTION

The velocity field in the Local Supercluster (LSC) has been extensively studied by many authors (e.g., the review by Yahil 1985). There is general agreement that the infall velocity of the Local Group (LG) toward Virgo is 250±50 km s^{-1}. This is different from the velocity of the LG relative to the microwave background radiation (MBR): u_{MBR}= 600 km s^{-1} in a direction ~45° away from Virgo (Lubin *et al.* 1983; Fixsen *et al.* 1983). The difference between the two velocities is most easily understood as the bulk motion of the LSC, induced by density inhomogeneities on scales larger than the LSC.

The IRAS catalogue offers an opportunity for identifying a complete sample of galaxies, which are calibrated homogeneously over almost the entire sky, range in distance far beyond the limits of present redshift surveys, and are unaffected by extinction. As detailed in § 2, a dipole anisotropy is detected in the surface brightness of the IRAS 60μ sources, which is aligned with the anisotropy of the MBR (Yahil *et al.* 1985). The luminosity function of the IRAS galaxies is used to convert the angular dipole moment into the gravitational force with which these sources attract the LG. Comparison with u_{MBR} then yields an estimate of the cosmological density parameter Ω_o, on the assumption that the infrared radiation traces the total mass-energy.

The anisotropy provides only the dipole moment of the density

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distribution of the IRAS galaxies. Higher moments are unlikely to be determined for the IRAS galaxies before a complete redshift catalogue becomes available. These moments, however, result in a shear velocity field within the LSC. The measurement of the quadrupolar component of this shear field (Lilje *et al.* 1985) is reported in § 3.

2. IRAS DIPOLE ANISOTROPY

The IRAS point source catalog contains ~250,000 sources, of which only ~20,000 are galaxies. It is very easy to discriminate spectrally against the hotter stellar sources: for sources with high quality detection in the 60μ band, the condition $S_{25}<3S_{60}$ eliminates all but few of the IRAS sources identified with stars. The main problem is contamination by the infrared "cirrus" emission from interstellar dust in our own Galaxy, which is spectrally similar to the emission of external galaxies. The solution adopted involves masking the part of the sky in which cirrus is suspected. The preferred mask, so-called n=1, covers about half the sky (for details see Yahil *et al.* 1985).

It is assumed that there exists a universal luminosity function $\Phi(L)$ for the IRAS galaxies (Yahil *et al.* 1980), so the number of galaxies observed in a luminosity range dL, and in a volume element d^3r, can be written as

$$dN = D(\vec{r})d^3r\ \Phi(L)dL \quad , \tag{1}$$

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

The luminosity function of the IRAS galaxies is well represented by a two-power function

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

(the limit $\beta\to\infty$ is a Schechter function). Lawrence *et al.* (1985) give $C=(11.5\pm0.4)\times10^6 h\ L_\odot\ Mpc^{-3}$, for a fit of $\Phi(L)$ of the form of equation (2), where $L=\nu L_\nu(60\mu)/L_\odot$. As the area which they study has a source density which is 18% higher than that for the whole sky (outside the mask), their value should be corrected to $C=(9.7\pm0.3)\times10^6 h\ L_\odot\ Mpc^{-3}$.

For this particular luminosity function, the product of the flux and the dipole moment of the surface brightness, hereafter loosely referred to simply as the dipole moment, is given by

$$4\pi S\vec{\sigma}(S) = 12\pi S^2\Delta S^{-1}\ \Sigma\ \hat{r}_i = \frac{3C}{4\pi}\int D(\vec{r})(\vec{r}/r^3)(1+r^2/\beta r_*^2)^{-\beta}d^3r \tag{3}$$

Here the surface brightness is *differential* in flux, the sum over the unit vectors in eq. (3) being only over the sources in a flux bin ΔS. The distance $r_*=\sqrt{(L_*/4\pi S)}$ is that at which a source with luminosity L_* is seen with flux S. Except for the cutoff factor, $(1+r^2/\beta r_*^2)^{-\beta}$, to be discussed below, and the parameter C, which characterizes the luminosity function at the faint end, this dipole moment is seen to be identical to the density moment

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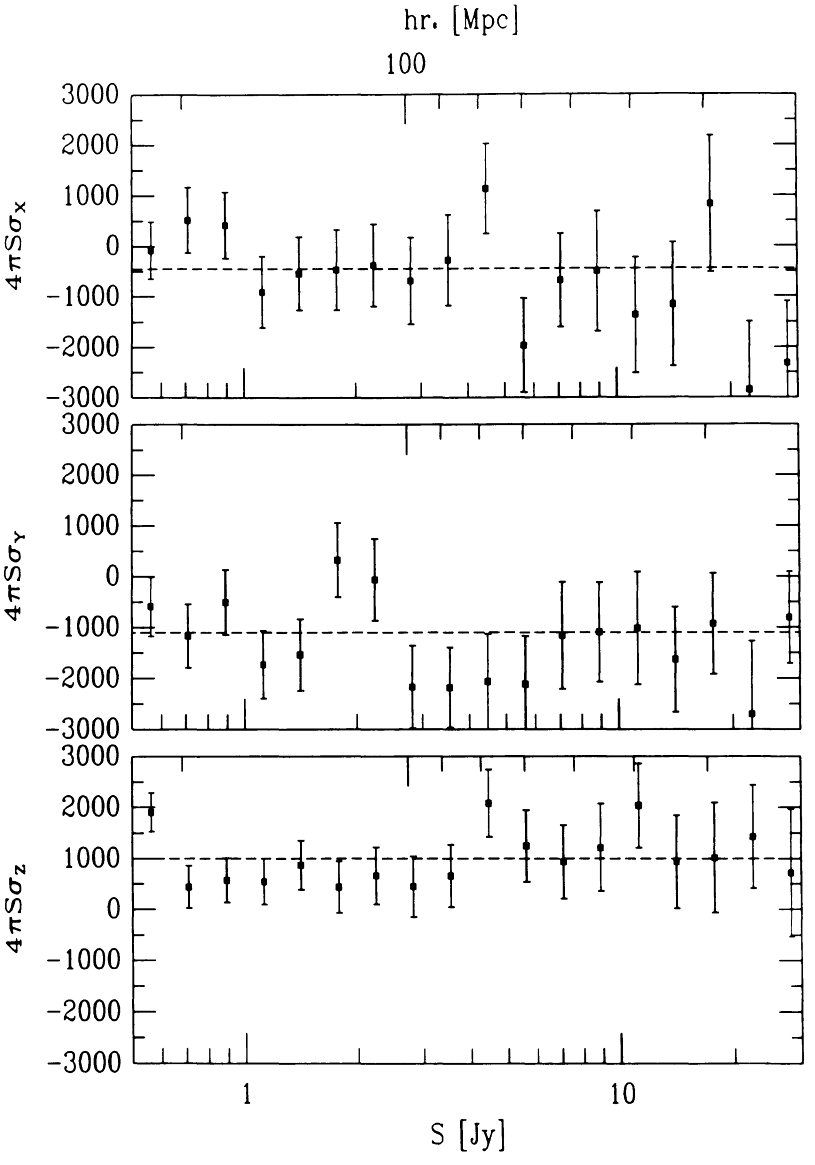

Fig. 1: Components of the dipole moment $4\pi S\vec{\sigma}(S)$. Data points at different flux bins are statistically independent; errors are *statistical* sampling ones. The dashed lines are the means of the data points, weighted by the inverse of the sum of the variances of the three components for each flux bin. The upper axis shows r_*, the distance at which a source with luminosity L_* is seen with flux S.

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$$\vec{G} = (3/4\pi) \int D(\vec{r})(\vec{r}/r^3)d^3r \quad , \qquad (4)$$

which is proportional to the peculiar acceleration.

Fig. 1 shows the three components of the dipole moment $4\pi S\vec{\sigma}(S)$, derived in a harmonic analysis including terms through quadrupole, using the mask n=1. It is assumed in the analysis that the spherical harmonic expansion derived in the unmasked part of the sky can be extrapolated without modification to the entire sky. (This is different from assuming that the masked area is isotropic, and does not contribute to the dipole and higher moments.) Points in different flux bins in Fig. 1 are statistically independent, and each one measures the dipole moment in its flux bin. Each point is therefore an independent estimate of the density moment in equation (4), with a cutoff at distance $r_*(S)$; the r_* scale (corresponding to $L_*=(5.0\pm0.9)\times10^{10}h^{-2}\ L_\odot$, Lawrence *et al.* 1985) is marked on the top axis.

While there is scatter in the data, it can be seen in Fig. 1 that the dipole moments are consistent with being independent of S, presumably because the density inhomogeneities giving rise to the dipole terms occur over distances that are smaller than the appropriate r_*, and the cutoff term has little effect. If this interpretation is correct, then the dipole moments measure $\vec{G}$ itself, without the cutoff factor. The average over flux, $\langle 4\pi S\vec{\sigma}(S)\rangle$, can therefore be taken, yielding a better estimate of $\vec{G}$. This average is shown as dashed lines in Fig. 1, and is given in Table 1, together with those of the masks n=0 and n=2. Only *statistical* sampling errors are quoted. To these must be added probably comparable errors due to residual cirrus contamination, and extrapolation into the masked area of the sky, as well as systematic observational errors.

TABLE 1

Average Dipole Moment[a]

Mask	X-comp.	Y-comp.	Z-comp.	Mag.	l	b	θ_{MBR}	Ω_o[b]
n=0	-580±210	-910±200	700±150	1290±190	237±11	33±10	34±12	1.15±0.29
n=1	-450±190	-1100±180	990±140	1550±170	248±9	40±8	26±10	0.85±0.16
n=2	-300±180	-1240±170	960±140	1590±160	256±8	37±8	19±9	0.81±0.14

[a]Flux averaged dipole moment, $\langle 4\pi S\vec{\sigma}(S)\rangle$, in units of Jy str^{-1}. Each flux bin is weighted by the inverse of the sum of the variances of its three components. All errors are *statistical* IRAS errors only.

[b]Determined from linear perturbation theory. Nonlinear effects increase these values by ~15%.

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The direction of the velocity of the LG relative to the MBR (l=277, b=29) is close to the one determined for the IRAS dipole moment, as shown in Table 1. Given the statistical and systematic errors in the IRAS dipole moment, the difference in direction is quite acceptable. The direction of the velocity of the LG relative to the MBR is also uncertain by a few degrees, due to measurement errors, uncertainties in the solar velocity relative to the LG, and the neglect of the random ("thermal") peculiar velocity of the LG relative to nearby galaxies.

If the IRAS dipole moment is measuring the gravitational field responsible for the MBR anisotropy, then its magnitude can be used to determine Ω_o. In linear perturbation theory (Peebles 1980), the peculiar velocity is parallel with, and proportional to the peculiar acceleration, and hence to $\vec{G}$:

$$\vec{u} = \frac{2}{3}\Omega_o^{-0.4}H_o^{-1}\vec{g} = \frac{1}{3}\Omega_o^{0.6}H_o\vec{G} \qquad (5)$$

Substituting u_{MBR}=600 km s^{-1}, and using $C=(9.7\pm0.3)\times10^6 h\ L_\odot\ Mpc^{-3}$ to convert $\langle 4\pi S\sigma(\vec{S})\rangle$ to $\vec{G}$, yields $\Omega_o=0.85\pm0.16$ (statistical IRAS error only). This is inconsistent with the dynamical estimates obtained from the Virgocentric flow model and the cosmic virial theorem, Ω_o=0.1-0.2 (e.g., the review by Yahil 1985).

The difference between the determinations of Ω_o from the Virgocentric infall and the cosmic virial theorem on the one hand, and the dipole anisotropy of the IRAS galaxies on the other hand, may be due to a number of causes. The *statistical* IRAS errors quoted for Ω_o may seriously underestimate the total error. The extensive mask used in this investigation may hide considerable structure, whose contribution to the gravitational field is not given by a simple extrapolation.

The IRAS galaxies seem to extend far enough to cover all the superclusters giving rise to the local gravitational field, as witnessed by the insensitivity of the dipole moment to the cutoff r_* ($200h^{-1}$ Mpc for S=0.5 Jy). The distances of these local superclusters are more likely to be of the same order as deduced from the kinematical study of the shear velocity field in the Virgo supercluster (§ 3), i.e., R~$50h^{-1}$ Mpc. It is therefore unlikely that the inclusion of more distant galaxies by deeper surveys will change the IR dipole moment.

In fact, the above guess of the distance of the perturbations giving rise to the dipole moment can be used to estimate the size of the nonlinear corrections. Yahil (1985) shows that, for a spherically symmetric perturbation, $\vec{u}$ is smaller than the linear estimate, eq. (5), by a factor $(1+\langle D\rangle)^{-0.25}$, where $\langle D\rangle=|\vec{G}|/R$ is the mean density in a sphere centered on the perturbation, with us at the periphery. For the mask n=1, $\langle D\rangle$~0.40, so the nonlinear effects increase Ω_o by ~15%. The actual perturbations giving rise to the dipole moment undoubtedly deviate significantly from this simple spherically symmetric model, but the estimate of both the sign and the size of the nonlinear correction are probably reasonable.

The IRAS galaxies are different from optically selected galaxies in the absence of elliptical galaxies, and in the predominance of emission line galaxies. A preliminary study of the two-point correlation function of the IRAS galaxies (Rowan-Robinson and Needham 1985) indicates that it is similar to that deduced from optically selected surveys, i.e., $\xi(r) \propto r^{-1.8}$, but the normalization constant is lower by a factor ~2. This is not too different from the diminution by a factor ~1.5 found by Davis and Geller (1976) for spiral galaxies in general. It is not clear, however, how this translates into density estimates of specific structures. In fact, Yahil *et al.* (1980) find the same Virgocentric density profile for early and late type galaxies.

There remains the possibility that the difference between the Virgocentric and IRAS results is real, showing that either the optically selected galaxies, or the IRAS galaxies, or both, do not trace the total mass-energy, and the determinations of Ω_o are therefore biased.

3. TIDAL VELOCITY FIELD IN THE LOCAL SUPERCLUSTER

By the equivalence principle, the mean gravitational field in the LSC can not be determined by measurements within it. An external reference frame, such as the MBR, is required in order to measure the bulk free-fall velocity which this mean field imparts to the LSC. Thus, the dipole moment of the density structure outside the LSC, which has presumably been measured from the distribution of the IRAS galaxies, leads to no observable consequences within the LSC.

The higher moments of these same density inhomogeneities, however, also result in a tidal field within the LSC (Binney and Silk 1979; Palmer 1983). The leading quadrupolar tidal acceleration is given by

$$\vec{g}_t = \Sigma_t \cdot \vec{r} \tag{6}$$

where Σ_t is a symmetric traceless shear matrix.

Except near the central Virgo cluster, the growth of density perturbations in the LSC can be approximated by the linear theory. The systematic peculiar velocity field should therefore be parallel with, and proportional to, the local gravitational acceleration, eq. (5). Since the gravitational acceleration is the sum of the ones due to the LSC and the external tidal field, it follows that the total peculiar velocity can be well approximated as a sum of the two peculiar velocities due to each field separately.

Lilje *et al.* (1985) have performed a Tully-Fisher fit to the velocity field in the LSC, along the lines of Aaronson *et al.* (1982), but adding the shear velocity field which follows from eq. (6). They find that at the distance of the Virgo Cluster the eigenvalues of the tidal field are ~200 km s^{-1}, but the component in the direction of Virgo is only 46±70 km s^{-1}. The determination of Ω_o from the Virgocentric infall is therefore little affected by the addition of the tidal field. The residual random ("thermal") velocity of the LG relative to its nearest neighbors is 72±37 km s^{-1}, which is not statistically significant.

The validity of the tidal field fit has been checked in a variety of ways, including separate fits to subsets of the data in the distance ranges 300 km s^{-1}<v<1000 km s^{-1}, 1000 km s^{-1}<v<2000 km s^{-1}, and 2000 km s^{-1}<v<3000 km s^{-1}. They yielded identical results within the errors. This is a sensitive test of the form of the tidal velocity field, which is expected to grow linearly with distance.

It is interesting to note that the eigenvector corresponding to the largest positive eigenvalue of Σ_t points toward the Hydra-Centaurus supercluster (Chincarini and Rood 1979; Hopp and Materne 1985), the nearest supercluster to the LSC. Although the tidal field is not due to a single nearby supercluster (the eigenvalues are not properly related), a rough estimate of the distance of the perturbers can be made by comparing the r.m.s. of the eigenvalues of the tidal velocity field with the bulk velocity of the LSC. This gives

$$R \sim (500/165) R_V \sim 50h^{-1} \text{ Mpc} \tag{7}$$

For details see Lilje *et al.* (1985).

4. ACKNOWLEDGMENTS

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DISCUSSION

N. BAHCALL: Aren't you seeing mostly late-type galaxies in your sample? What is the effect of omitting essentially all the early-type galaxies?

YAHIL: The problem is somewhat worse than that. We don't use regions with large cirrus indicators, i.e., regions with a large density of 100 μ sources. The result is that the centers of rich clusters look like cirrus. For example, look at the region of the Virgo Cluster in the northern-hemisphere map I showed. You notice one or two "cirrus" bins, but they are not cirrus, they are the Virgo Cluster. So there is a bias both against early-type galaxies and against the cores of rich clusters. All I can say is that, since most of the mass in superclusters is not in the central clusters, I hope we won't be too badly affected by these biases when we use large areas of the sky to measure the dipole moment.

E. TURNER: Given the differences between the IRAS "colors" of stars and galaxies, and given the huge range of L_{IR}/L_B quoted earlier by Frank Low, it would appear that the IRAS fluxes are determined by a galaxy's dust content and/or current star formation rate (and distance, of course). It seems unlikely that either is particularly well correlated with the total mass distribution or even the total baryonic mass. Is this a fundamental limitation on the use of the otherwise excellent IRAS data set for this method of determining Ω_o?

YAHIL: The only question is whether the IRAS galaxies are good tracers of the total mass-energy on a very large scale. Nobody knows the answer. A redshift survey of IRAS galaxies might be helpful.

DAVIS: A correlation analysis has been made of the IRAS galaxy list. We found the angular correlation to be consistent with that of nearby spiral galaxies, but scaled to a distance of approximately 100 $(h_{100})^{-1}$ Mpc. This is also consistent with the observed surface density of the IRAS galaxies and their overlap with the CfA catalog.

FABER. Did you discover any new nearby clusters near the galactic plane?

YAHIL: Not yet. We look so deep that a nearby cluster is only a small perturbation. It's like looking at the poster by Peebles and Groth and trying to find the Virgo Cluster. It isn't easy. We are now searching the sky for regions of high surface brightness to try to find objects and to measure their redshifts. (I suspect that people will only be satisfied with our results when we have measured redshifts for at least a fair sub-sample of the objects.)

SCHECHTER: I don't think that it is enough to look at the shape of the spatial correlation function. You also want to know the amplitude. And isn't that your entire paradox: you have measured it and it is different for galaxies and for the 60 μ sources?

YAHIL: Yes, you're absolutely right. All I can say at the moment is that Mike Rowan-Robinson tells me that the angular correlation function is intermediate between those found for the Zwicky and Shane-Wirtanen catalogues. The characteristic L_* is also intermediate. So it's in the right ball park. But whether the normalization comes out exactly right or whether we're missing a factor of two is going to be critical.

FELTEN: What is the sign of the probable effect on your results of masking a large region of the sky?

YAHIL: The effect could go either way. A larger IRAS anisotropy for the same MBR anisotropy implies a smaller Ω_0 (see equation 5).

GUNN: You have quoted us statistical errors, but could you comment on the possibility of systematic errors introduced by the width of the luminosity function of IRAS galaxies? The observed optical luminosity function always looks rather like a Gaussian around L_*, but the infrared luminosity function must be much broader than that. Since the correlation function takes a rather different moment of the luminosity function than the counts do, I would suspect the possibility of large systematic errors.

YAHIL: I don't know how big the effect would be.

LOW: Much as I hate to pour cold water on such an exciting IRAS result, I have to ask what you have done in your analysis about three major causes of systematic error in the production of the catalog. The first is the South Atlantic anomaly, which is unfortunately in the South Atlantic (laughter). The second is that the satellite scanned in one direction across the sky. As a result, it always went through the galactic plane in the same direction. We applied a significant hysteresis correction after the threshold detection, because this effect was not discovered until late in the analysis. The third effect is just the effect of radiation. The polar horns, as they're called, are brighter in one hemisphere than the other at a given time of year. IRAS detected sources which were bright above the local noise, and that noise was often produced by activity in the van Allen belts. These effects will certainly affect the accuracy and precision of your result, and may change it altogether.

YAHIL: Let me deal with your points one by one. We did nothing about the South Atlantic anomaly and just took the IRAS fluxes as they are given in the catalogue. We are aware of the errors introduced by crossing the plane, and threw out all the data within 5° of the plane. The masks actually throw out much more than that, sometimes up to b = 30°. But we were also careful to throw out the areas with hysteresis problems. Perhaps you think the effect is larger than we took into account - that should be checked. As for problems caused by the van Allen belts, we didn't do anything about those either. But I want to point out that our result is independent of the flux limit that we used; we get the same answer for the dipole moment even if we use a fairly high flux limit. I would expect effects of the type you mentioned to be very sensitive to the flux level. But that's my only defense.