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On the determination of dipoles from incomplete galaxy catalogues

Manolis Plionis *Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH*

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Summary. The spherical harmonic and random filling methods, used to account for incomplete sky coverage in dipole calculations, are investigated. A study of their comparative performances is carried out and the former method is shown to be more accurate. Using both these methods, an attempt is made to find the regions responsible for the dipole in the Lahav optical catalogue. We find, in accordance with Lahav *et al.*, that the Virgo–Centaurus region provides most of the dipole power. We also find strong indications that these structures are embedded within a global underlying anisotropy which could account for the dipole even if the Virgo–Centaurus region were absent and the anisotropies in the rest of the sphere, as quantified by the expansion of the galaxy surface density to quadrupole order, were extrapolated to this region. A picture of a global anisotropy in the distribution of galaxies throughout the unit sphere on which the various 'attractors' are superimposed is favoured.

1 Introduction

One of the most favourable approaches to the study of deviations from the Hubble flow and of the fluctuations that cause the microwave background (MWB) radiation dipole are investigations of whole-sky galaxy catalogues. There have been many such studies based on the *IRAS* galaxy catalogue (Yahil, Rowan-Robinson & Walker 1986; Meiksin & Davis 1986; Harmon, Lahav & Meurs 1987), the ESO, UGC and MCG optical galaxy catalogues (Lahav 1987; Lahav, Rowan-Robinson & Lynden-Bell 1988) and on the Lick galaxy catalogue (Plionis 1987, 1988). All these studies have found that the galaxy distribution, ranging in depth from the local supercluster to a characteristic depth of 210 h^{-1} Mpc, is roughly aligned with the MWB dipole anisotropy. Such studies could be used to investigate the 'locality' of the fluctuations causing the MWB dipole, as well as the range of values of the cosmological density parameter Ω_0.

There are still a number of difficulties in addressing the above issues.

(i) Most galaxy catalogues have incomplete sky coverage.

(ii) Optical catalogues suffer from obscuration near the Galactic equator, while the *IRAS* galaxy catalogues suffer from 'cirrus' emission with a spectrum that is very similar to that of external galaxies.

(iii) There are inhomogeneities and systematics associated with plate material, and human biases.

(iv) There is not a reliable distance measure for the galaxies, which consequently makes it difficult to estimate the peculiar acceleration of the Local Group of galaxies and therefore the value of Ω_0.

Here we are mostly concerned with the first two classes of problem. Two methods have been used in the literature to overcome these problems.

(a) Expanding the observed surface-density of 'galaxies' in spherical harmonics and then correcting the coefficients of the expansion, according to a model of the data in the unobserved regions. This method was used by Yahil *et al.* (1986) to correct the *IRAS* dipole for regions contaminated by 'cirrus'. After excluding all spurious sources of infrared emission, they were left with only 47 per cent of the sky 'clear' for their dipole study. The same method was used by Lahav (1987) to model the low galactic latitude regions of his optical catalogue and by Plionis (1988) to model the unsurveyed region (Dec. $< -23°$) of the Lick galaxy catalogue.

(b) Filling the unobserved regions of the sky by randomly distributed points, each having a weight equal to the average weight in the catalogue. This method has the disadvantage of assuming no structure in the unobserved regions.⋆ This method was applied by Meiksin & Davis (1986) on a different version of the *IRAS* catalogue (using ~76 per cent of the sky) with effectively identical results to those of Yahil *et al.* (1986). It has been also used by Harmon *et al.* (1987) on a colour-selected *IRAS* catalogue and by Lahav *et al.* (1988) on a new version of the optical catalogue to account for a missing strip of 15° and for the region below $|b| = 15°$.

The aim of this paper is to study the relative merits of these two methods and to investigate the plausibility of 'great attractor' models.

2 Comparison of the spherical harmonic and random filling methods

A comparative study is presented of the two main methods used to account for galaxy catalogue incompleteness. The optical galaxy catalogue, based on the UGC, ESO and the MCG catalogues and calibrated by Lahav (1987), is used for this purpose. The UGC galaxy catalogue (Nilson 1973) covers all declinations north of $-2\overset{\circ}{.}5$, while the ESO (Lauberts 1982) covers all declinations below $-17\overset{\circ}{.}5$. Lahav (1987) filled the 'missing' strip with the MCG catalogue (Vorontsov-Veyaminov & Arkipova 1968). He homogenized the catalogues by using the Fouque & Paturel (1985) method, which converts visual magnitudes to isophotal diameters D_{25} (at surface brightness of 25 B mag arcsec^{-2}). He applied a cut-off at $D_{25} = 1.3$ arcmin and defined a sample, excluding the Local Group, of 14626 galaxies. This is the sample we use for our study.

Since the diameter of a galaxy scales with distance as $1/r$, a suitable galaxy weighting, to estimate the peculiar acceleration, is D_{25}^2. A cosec$|b|$ mask is used to account for the obscured regions, using estimates provided by Lahav (private communication). The resulting dipole direction and amplitude is

$$l = 228\overset{\circ}{.}4 \quad b = 41°, \quad A = 0.49,$$

which is 35° away from the MWB dipole. These values are used as the overall dipole in the following procedure. The errors associated with the above values are given in Lahav (1987) and are: $\delta l \sim 23°$, $\delta b \sim 8°$ and $\delta A \sim 0.38A$.

⋆Non-random filling methods could be used as well (work in progress).

The approach we use to investigate the two methods is to divide the unit sphere into equal-area bins (first dividing it into equal-area galactic latitude strips and then dividing each strip into the same number of bins). Then each bin is successively excluded from the catalogue and the whole-sky dipole is calculated by means of both the methods presented above.

The main points of the spherical harmonic method have been described in previous work (Yahil *et al.* 1986; Lahav 1987; Plionis 1988). We model the data in the excluded bin by using a sharp mask, M, with

$$M=\begin{cases}0 & \text{in excluded bin}\\ 1 & \text{in rest of catalogue.}\end{cases}$$

By using this mask, we basically extrapolate the structural pattern of the rest of the unit sphere to the excluded bin. Each whole-sky component can be represented as a linear combination of the nine 'observed' components (from the incomplete unit sphere); the monopole, the three dipole and five quadrupole components. As an illustrative example, if the masked square bin is defined by the boundaries: $l\in[\gamma,\ \delta]$ and $b\in[\alpha,\ \beta]$ (with γ, δ, α and β in rad), then the 'observed' monopole term, calculated from the unit sphere excluding that bin, would be:

$$A_0^0=\frac{1}{4\pi}\{a_0^0(K_{0,1}\Delta+2\pi P_{0,1})+a_1^0(K_{1,1}\Delta+2\pi P_{1,1})+a_1^1K_{0,2}C_1+b_1^1K_{0,2}S_1$$
$$+\frac{1}{2}a_2^0[(3K_{2,1}-K_{0,1})\Delta+\pi(3P_{2,1}-P_{0,1})]+3a_2^1K_{1,2}C_1+3b_2^1K_{1,2}S_1$$
$$+3a_2^2K_{0,3}C_2+3b_2^2K_{0,3}S_2\}, \tag{1}$$

where

$$P_{n,m}=\int_0^{\alpha}d\theta\cos^n\theta\sin^m\theta+\int_{\beta}^{\pi}d\theta\cos^n\theta\sin^m\theta\ ,$$

$$K_{n,m}=\int_{\alpha}^{\beta}d\theta\cos^n\theta\sin^m\theta\ ,$$

$$C_n=\int_0^{\gamma}d\phi\cos n\phi+\int_{\delta}^{2\pi}d\phi\cos n\phi\ ,$$

$$S_n=\int_0^{\gamma}d\phi\sin n\phi+\int_{\delta}^{2\pi}d\phi\sin n\phi\ ,$$

$\Delta=(2\pi+\gamma-\delta)$ and a_l^m are the whole-sky multipole components which we seek to find. Similar relations hold for the other eight components and therefore a 9×9 matrix, $\mathbf{T}$, can be formed, the inversion of which gives the values of the whole-sky multipole components of the galaxy distribution,

$$\mathbf{a}=\mathbf{T}^{-1}\cdot\mathbf{A}$$

where $\mathbf{A}$ is a 9×1 matrix containing the calculated monopole, dipole and quadrupole components from the incomplete data and $\mathbf{a}$ is a 9×1 matrix containing the required whole-sky components.

In the random filling method the random points are assigned a weight which is the average weight (in our case $\langle D_{25}^2 \rangle$), calculated from the catalogue excluding the bin under consideration. The number of random points is equal to the expected number of galaxies in that bin, estimated from the whole catalogue.

The dipole amplitude is defined as $|\mathbf{D}| \equiv \sqrt{(a_0^1)^2 + (a_1^1)^2 + (b_1^1)^2}$. If all the galaxies were concentrated on one point of the unit sphere then $|\mathbf{D}| = 3$.

The efficiency of the two methods may depend on the size of the unsurveyed region. To investigate this problem and to obtain statistically meaningful results, many realizations of the unit sphere are needed. One way is to generate artificial galaxy catalogues with the same characteristics as the one under study. An alternative approach is to use the same galaxy catalogue and to rotate the mask around the unit sphere (which is equivalent to rotating the unit sphere and keeping the boundaries of the mask fixed). For each rotation we model the data in the masked region by means of both methods and calculate the dipole vector of the new configuration. The advantage of this approach is that since the dipole amplitude is rotationally invariant, a direct comparison of the estimated dipoles with the overall value can be done.

The rotations are performed using the rotation matrix $R(\alpha, \beta, \gamma) = R(\gamma) R(\beta) R(\alpha)$, $R(\alpha)$ rotates the unit sphere by an angle α about the z-axis, $R(\beta)$ rotates the unit sphere by an angle β about the new y-axis and $R(\gamma)$ rotates the unit sphere by an angle γ about the new z-axis (with $0 < \alpha < 2\pi$, $0 < \beta < \pi$ and $0 < \gamma < 2\pi$). Forty-five such rotations are performed with $\delta\alpha = \delta\gamma = 120°$ and $\delta\beta = 36°$. For each rotated unit sphere, we divide the unit sphere into equal-area bins in each new coordinate system and mask them successively. The estimated dipole, using both methods, is compared with the overall dipole in the new coordinate system. The quantity we actually use is $|\mathbf{D}'|$ which is the projection of the estimated dipole vector, $\mathbf{D}_{\rm est}$, on to the overall one.

$$|\mathbf{D}'| = |\mathbf{D}_{\rm est}| \times \cos \delta\theta_{\rm over}$$

and $\delta\theta_{\rm over}$ is the angular difference between estimated and overall dipole vectors. This quantity measures how much of the overall dipole amplitude is recovered by each method.

We have investigated the efficiency of the two methods for bin sizes of $4\pi/3$, $4\pi/4$, $4\pi/6$, $4\pi/9$ and $4\pi/12$. The frequency distributions of $|\mathbf{D}'|$ are Gaussian, while the distribution of angular deviations from the overall dipole direction, $\delta\theta_{\rm over}$, resembles a half-Gaussian with approximately zero mean and with an extended tail. In Fig. 1 we present these two distributions for the $4\pi/4$ and for the $4\pi/12$ case. It must be noted that when dividing the unit sphere into smaller bins the estimated dipoles differ insignificantly from the overall dipole.

For the spherical harmonic method the distribution of $|\mathbf{D}'|$ peaks at the correct overall amplitude, while for the random filling method it peaks at smaller values. The latter method systematically underestimates the dipole amplitude. The means and 1-σ deviations are presented in Table 1.

The distributions of $\delta\theta_{\rm over}$ in the random filling case are broader (for bin size $< 4\pi/3$) than in the spherical harmonic case, with extended tails toward large $\delta\theta_{\rm over}$ and therefore the former method approximates the overall dipole direction with less accuracy than the spherical harmonic method. The medians with the interquartile range of this distribution are also presented in Table 1. Note, however, that when we divide the unit sphere in $4\pi/3$ area bins, although the distribution of $|\mathbf{D}'|$ peaks at approximately the correct overall value it has a 1-σ deviation comparable to this value and the $\delta\theta_{\rm over}$ range is larger than that of the random filling method. This indicates that we have probably reached the efficiency limit of this method.

The main conclusion of this section is that the spherical harmonic method performs better for all bin sizes ($< 4\pi/3$). The random filling method systematically underestimates the dipole amplitude for all bin sizes, while the angular deviation of the estimated from the overall dipole is larger with this method.

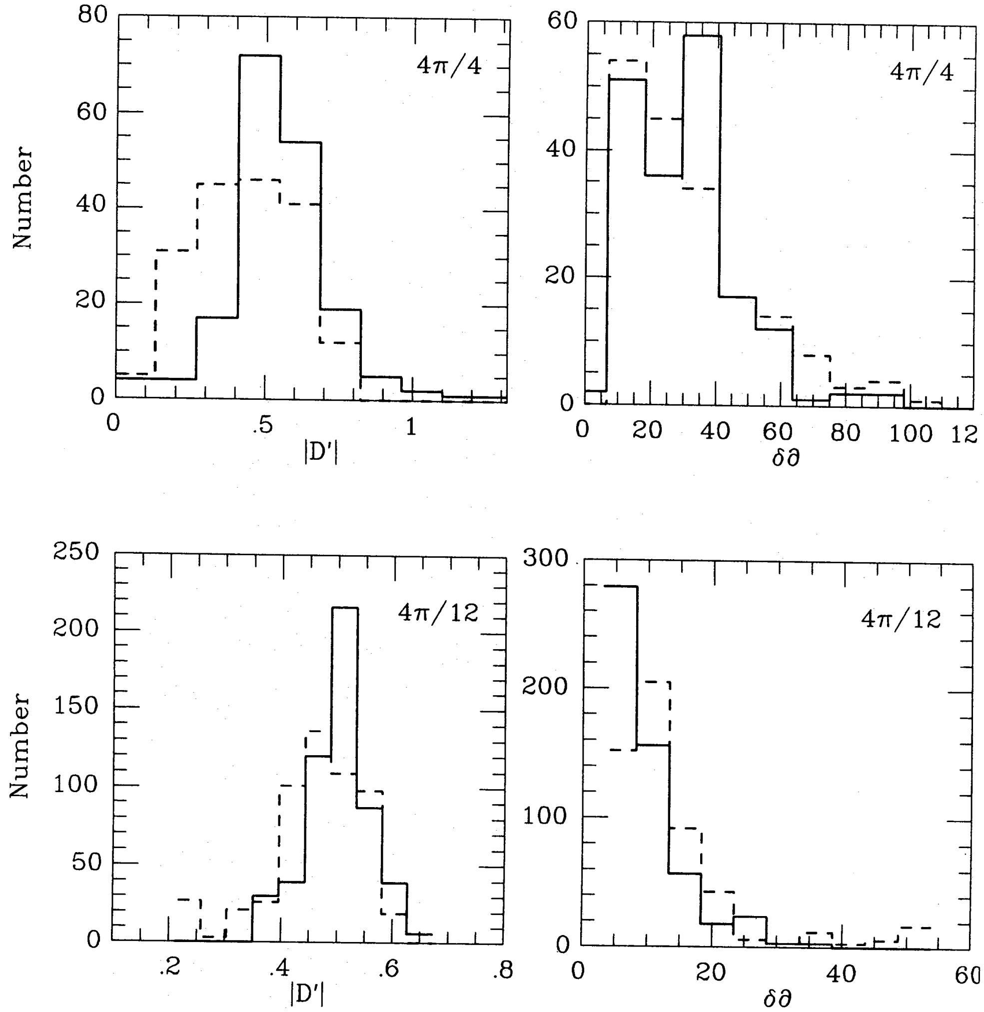

Figure 1. The distributions of the recovered amplitude, $|\mathbf{D}'|$, for the cases where the excluded cone is $4\pi/4$ and $4\pi/12$. Similarly, we present the distribution of angular deviation of the estimated dipole from the overall dipole direction for both cases. It is apparent that the spherical harmonic method more accurately approximates the overall dipole. (Solid lines represent the spherical harmonic method and broken lines the random filling one.)

Table 1. Statistics on the performance of the two methods used to account for incomplete sky coverage. The mean and standard deviation of the distribution of $|\mathbf{D}'|$ are presented in the third column, while the median with the interquartile range of the distribution of angular separations of the estimated from the overall dipole, are presented in the fourth column.

Bin size	Method	$\|\mathbf{D}'\|$	$\delta\theta_{\rm overall}$
$4\pi/3$	Sph. Harm.	0.50 ± 0.47	$24.5^{+25°}_{-10°}$
	Rand. Fill.	0.32 ± 0.19	$23^{+19°}_{-11°}$
$4\pi/4$	Sph. Harm.	0.50 ± 0.18	$24.5^{+7°}_{-14°}$
	Rand. Fill.	0.36 ± 0.17	$23.5^{+14°}_{-13°}$
$4\pi/6$	Sph. Harm.	0.49 ± 0.1	$12^{+9°}_{-5°}$
	Rand. Fill.	0.4 ± 0.13	$14.5^{+12.5°}_{-5°}$
$4\pi/9$	Sph. Harm.	0.49 ± 0.07	$7^{+6°}_{-2°}$
	Rand. Fill.	0.43 ± 0.1	$11^{+8°}_{-4°}$
$4\pi/12$	Sph. Harm.	0.49 ± 0.06	$5.5^{+4°}_{-1.5°}$
	Rand. Fill.	0.44 ± 0.08	$8^{+4.5°}_{-3°}$

3 'Great Attractor' models

An indirect way to study which regions of the sky are most responsible for shaping the overall dipole is to exclude successive regions of the catalogue and use both of the methods discussed above to account for the excluded regions. One would then expect that when masking the regions suspected of shaping the overall dipole galaxy distribution, neither the spherical harmonic nor the random filling methods would be able to restore the overall dipole.

Lahav *et al.* (1988) find that the Centaurus–Virgo region provides most of the power to the dipole (~70 per cent), while a local void provides the rest (~30 per cent). If the dipole anisotropy is caused only by these structures, then excluding them from the calculation of the dipole and applying either of the two methods to account for these regions will *not* recover the correct dipole vector.

We have calculated the dipole by excluding circular regions of angle $\alpha[\omega=4\pi(1-\cos\alpha)/2]$ centred on the two main structures, Virgo and Centaurus, which are believed to shape the overall dipole, and also excluding a 0.28π region around the position of the local void ($l=88°$, $b=-27°$). We have excluded circular regions with $\alpha=31°$ ($4\pi/14$), $53°$ ($4\pi/5$) and $60°$ ($4\pi/4$) around the Virgo ($l=284°$, $b=74°$) and Centaurus ($l=310°$, $b=29°$) clusters. Note that the

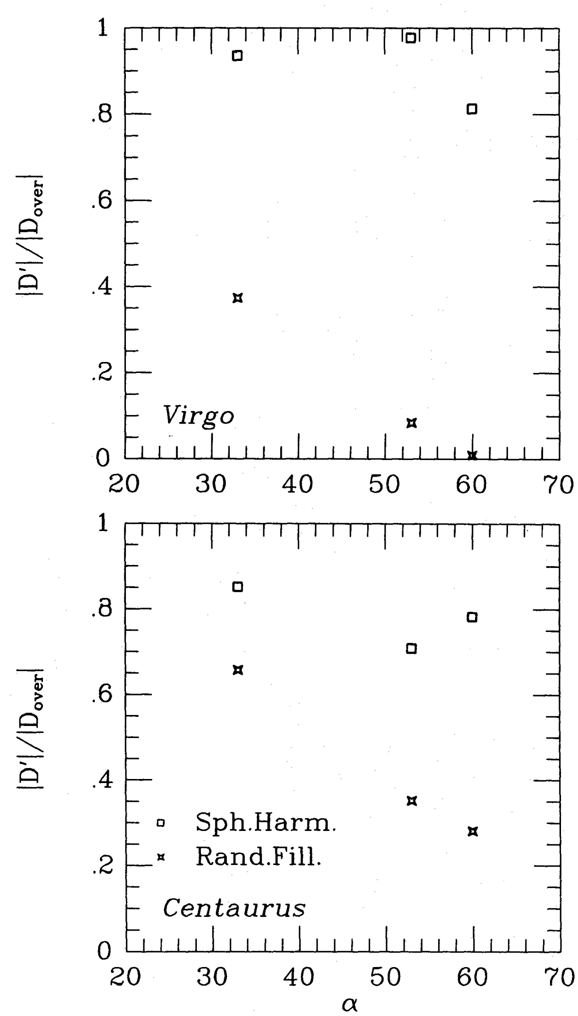

Figure 2. Here we present how much of the overall dipole vector is recovered, as a function of the radius of the excluded circular area (centred on Virgo and the Centaurus position). $|\mathbf{D}'|/|\mathbf{D}_{\rm over}|$ takes values in the range [0, 1]. A value near 1 represents a complete recovery of the overall dipole vector. In both cases the spherical harmonic method recovers the overall dipole vector with very good accuracy, even when $\alpha=60°$.

two clusters are 47° apart and therefore they are both excluded in the $\alpha = 53°$ and 60° case. The results of these estimations are presented in Fig. 2, where we plot the recovered dipole amplitude, $|\mathbf{D}'|/|\mathbf{D}_{\text{over}}|$, as a function of α around the two structures under investigation (in all cases an area of $0.28\,\pi$ around the local void is also excluded).

An estimate of the uncertainties involved in the determination of these dipoles is provided in Table 1.† For the case of an excluded circular area of $4\pi/5$ ($\alpha = 53°$) we find that the 1-σ deviation $|\mathbf{D}'|$ is ~ 0.16 for the spherical harmonic method and ~ 0.21 for the random filling one. We must be cautious, though, because the Virgo–Centaurus region contributes to the error determination in 4/5 of the trials (for $\alpha = 53°$). Therefore, the 'real' error could be larger than the one quoted above. This would be the case if the value of the restored dipole amplitude lay near the tail of the distribution, and hence by including the Virgo–Centaurus region in most of the trials the σ could shift to smaller values. However, since the value of the restored amplitude lies well within the 1-σ deviation of the distribution it is highly unlikely that the 'real' error is larger than ~ 0.16.

To investigate this point further we have excluded the galaxy distribution in this region and populated it with random points having the average weight of the catalogue. We then recalculated the errors for the spherical harmonic method in the same way as in the previous section. We still find the same broadening in the distribution of $|\mathbf{D}'|$, indicating that the value ~ 0.15–0.16 is relevant to this method for bin sizes of $4\pi/5$. Note that by excluding the void as well, the total area excluded is ~ $4\pi/4$ (for $\alpha = 53°$).

In all cases the overall dipole is *restored* with a remarkable accuracy when using the spherical harmonic method, while the random filling method fails. For example, in the $\alpha = 53°$ case around Virgo (while also excluding the void area), the dipole direction is restored within 3°.5 of the overall dipole, while 98 per cent of the overall amplitude is also restored. In this case the total number of excluded galaxies is 5712, which is ~ 35 per cent of the total number in the catalogue, while the expected number, if the galaxies where uniformly populating the unit sphere, is 4193. When using the random filling method, the values obtained are 81° and 8.5 per cent, respectively. For the same α but around the Centaurus region the dipole direction is recovered within 19° for the spherical harmonic method and 32° for the random filling method, while the amplitude is more accurately recovered by the former method (71 per cent). This behaviour indicates that extrapolating the structural pattern of the unit sphere to the excluded regions is sufficient to recover the overall dipole, and hence the structures contained in the excluded region can be accounted for by the galaxy distribution in the rest of the sphere.

The random filling method provides a different sort of information. By subtracting $|\mathbf{D}'|$, calculated with this method, from the overall dipole amplitude, we have an estimate of the contribution of the excluded area to the strength of the overall dipole. We find, in accordance with Lahav *et al.* (1988), that the circular area with $\alpha = 53°$ around Virgo, which contains most of the Centaurus region as well, provides ~ 79 per cent of the amplitude of the overall dipole. A similar circular region centred on Centaurus provides ~ 54 per cent of the overall amplitude.

The fact, though, that the spherical harmonic method recovers the overall dipole with a remarkable accuracy, provides evidence that the dipole anisotropy of the optical catalogue is not only due to one or even a few attractors, but rather a global underlying anisotropy is present on which the various nearby attractors are superimposed. As another manifestation of the above proposal we present results based on the $4\pi/3$ division of the unit sphere (Table 2).

†A similar statistical analysis to the one presented in Section 2 but using circular bins, provides similar results to those shown in Table 1.

Table 2. Dipole results dividing the unit sphere into three equal-area strips of galactic latitude and masking each one successively.

Excluded region	Method	l	b	$\|\mathbf{D}_{\rm cst}\|$	$\delta\theta_{\rm MWB}$	$\delta\theta_{\rm overall}$
$19.5° < b < 90°$	Sph. Harm.	257.7°	46°	0.4	20.7°	21.7°
	Rand. Fill.	214.8°	−28.5°	0.26	75.4°	70.6°
$-19.5° < b < 19.5°$	Sph. Harm.	220.6°	43.6°	0.53	41.5°	6.4°
	Rand. Fill.	220.3°	49.6°	0.32	42.7°	10.3°
$-90° < b < -19.5°$	Sph. Harm.	239.1°	34.5°	0.27	25.9°	10.6°
	Rand. Fill.	240.7°	56.9°	0.54	35.6°	17.7°

Using the spherical harmonic method and excluding any of the $4\pi/3$ strips, the dipole is restored with remarkable accuracy. The random filling method fails to reproduce the correct overall dipole when the north galactic cap is masked. From this we find that the region with $b > 19\overset{\circ}{.}5$ provides ~82 per cent of the overall dipole amplitude, in accordance again with the Lahav *et al.* (1988) results. Nevertheless, the remaining $8\pi/3$ of the unit sphere seem to contain the structural information of the anisotropy to restore the overall dipole to a remarkably good approximation. The statistical significance of this result is not clear, however, since the spherical harmonic method for such a binning has been shown to be not very accurate (Table 1). Note, however, that the uncertainties in the case of $4\pi/3$ are so large because the area excluded is one complete portion of the sky. If we had excluded the same total area but spread around the unit sphere, we would have had a better recovery of the dipole (smaller error). A manifestation of this is the *IRAS* dipole derived by Yahil *et al.* (1986) based only on 47 per cent of the sky.

It is clear that such behaviour of the optical dipole cannot be explained within the framework of one or even more 'attractors'. The 'Great Attractor' model of Lynden-Bell *et al.* (1988) has also been challenged by recent observational work of Lucey & Carter (1988a, b), who find that the Hydra–Centaurus supercluster has a very small peculiar velocity. Therefore, no large concentration of galaxies could lie behind this supercluster, since this would have induced a much larger peculiar velocity.

It seems plausible that the underlying distribution of galaxies has a cosmologically imprinted dipole structure and superimposed on this are the various nearby 'attractors' (like the Virgo and Hydra–Centaurus superclusters). This is also supported by the Lick dipole (Plionis 1988), which is roughly aligned with the MWB dipole, although the volume sampled is ~74 times larger than the volume of this shallower optical catalogue. The large-scale stratification of galaxies and of clusters of galaxies on the supergalactic plane, on scales of ~40 up to ~200–300 h^{-1} Mpc, further supports such a view (Tully 1986, 1987).

4 Conclusions

(i) A comparison between the spherical harmonic and random filling method used to model the incompleteness of galaxy catalogues in the determination of the dipole anisotropy in these catalogues, has shown that the former is a more reliable and accurate method.

(ii) Large regions containing the Virgo and the Centaurus superclusters can be excluded from the catalogue, and the spherical harmonic method restores the overall dipole with very good accuracy. This does not support unique 'attractor' models as the main explanation of the optical dipole anisotropy but could be evidence for a cosmological origin of the anisotropy.

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