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THE DIPOLE ANISOTROPY OF THE 2MASS REDSHIFT SURVEY

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We estimate the flux weighted acceleration on the Local Group (LG) from the near-infrared Two Micron All Sky Redshift Survey (2MRS). The near-infrared flux weighted dipoles are very robust because they closely approximate a mass weighted dipole, bypassing the effects of redshift distortions and require no preferred reference frame. We use this method with the redshift information to determine the change in dipole with distance. The LG dipole seemingly converges by 60 h^{-1}Mpc. Assuming convergence, the comparison of the 2MRS flux dipole and the CMB dipole provides a value for the combination of the mass density and luminosity bias parameters $\Omega_\mathrm{m}^{0.6}/b_\mathrm{L} = 0.40 \pm 0.09$

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1 Introduction

The most popular mechanism for the formation of large-scale structure and motions in the Universe is the gravitational growth of primordial density perturbations. According to this paradigm, the peculiar acceleration vector $\mathbf{g}(\mathbf{r})$ is induced by the matter distribution around position $\mathbf{r}$ and if the density perturbations are small enough to be approximated by a linear theory, then the peculiar velocity field, $\mathbf{v}(\mathbf{r})$, is proportional to the peculiar acceleration:

$$\mathbf{v}(\mathbf{r}) = \frac{H_0 f(\Omega_\mathrm{m})}{4\pi G\bar{\rho}}\mathbf{g}(\mathbf{r}) = \frac{2f(\Omega_\mathrm{m})}{3H_0\Omega_\mathrm{m}}\mathbf{g}(\mathbf{r}), \tag{1}$$

where $H_0 = 100~h~\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$ is the Hubble constant and $f(\Omega_\mathrm{m}) \simeq \Omega_\mathrm{m}^{0.6}$ is the logarithmic derivative of the amplitude of the growing mode of the perturbations in mass with respect to the scale factor (Peebles 1980).

It is now widely accepted that the dipole anisotropy of the cosmic microwave background (CMB) is a direct and accurate measurement of the LG peculiar velocity. The LG acceleration can also be estimated using surveys of the galaxies tracing the density inhomogeneities responsible for the acceleration. If the mass can be related to light by a bias parameter, b_L, then by comparing the CMB velocity vector with the acceleration vector obtained from the galaxy surveys, it is possible to investigate the cause of the LG motion and its cosmological implications.

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Like peculiar acceleration, the flux of light received from a galaxy falls off inversely as the square of the distance. If the mass-to-light ratio is constant, we can relate the two by

$$
\begin{aligned}
\mathbf{g}(\mathbf{r}) &= \mathrm{G} \sum_i M_i \frac{\hat{\mathbf{r}}_i}{r_i^2} \simeq \mathrm{G} \left\langle \frac{M}{L} \right\rangle \sum_i L_i \frac{\hat{\mathbf{r}}_i}{r_i^2} \\
&= 4\pi \mathrm{G} \left\langle \frac{M}{L} \right\rangle \sum_i \mathrm{S}_i \hat{\mathbf{r}}_i,
\end{aligned}
\tag{2}
$$

where the sum is over all galaxies in the Universe, $\langle M/L \rangle$ is the average mass-to-light ratio and $\mathrm{S}_i = L_i/4\pi r^2$ is the flux of galaxy i. The peculiar velocity vector is derived by substituting Equation 2 into the second line of Equation 1. For a flux limited catalogue the observed LG velocity is

$$
\mathbf{v}(\mathbf{r}) = \frac{8\pi \mathrm{G} f(\Omega_\mathrm{m})}{3 H_0 \Omega_\mathrm{m} b_\mathrm{L}} \left\langle \frac{M}{L} \right\rangle \sum_i w_{L_i} \mathrm{S}_i \hat{\mathbf{r}}_i
\tag{3}
$$

where b_L is the luminosity bias factor introduced to account for the dark matter haloes not fully represented by 2MRS galaxies and $0 \leq w_{L_i} \leq 1$ is the weight assigned to galaxy i to account for the luminosity that was not observed due to the flux limit of the survey. With the inclusion of redshift information, we can calculate Equation 3 within concentric spheres with increasing radii and thus estimate the distance at which most of the LG velocity is generated generated (*the convergence depth*).

2   The Two Micron All-Sky Redshift Survey

The Two Micron All-Sky Redshift Survey (Huchra *et al.* 2005, Erdoğdu *et al.* 2006) is the densest all-sky redshift survey to date. The first phase of 2MRS is now complete. In this phase we obtained redshifts for approximately 23,150 2MASS galaxies from a total sample of 24,773 galaxies with extinction corrected magnitudes (Schlegel, Finkbeiner & Davis 1998) brighter than $K_\mathrm{s} = 11.25$. This magnitude limit corresponds to a median redshift of $z \simeq 0.02$ ($\simeq 6000 \ \mathrm{km\,s^{-1}}$). Figure 1 shows all the objects in 2MRS in Galactic Aitoff Projection. Galaxies with z ≤ 0.01 are plotted in red, 0.01 < z ≤ 0.025 are plotted in blue, 0.025 < z < 0.05 are plotted in green and z ≥ 0.05 are plotted in magenta. Galaxies without measured redshifts (around 1600) are plotted in black.

The 2MRS sample has very good photometric uniformity and an unprecedented integral sky coverage. The photometric uniformity is better than 4% over the sky including the celestial poles and the survey is essentially complete down to very low galactic latitudes (Huchra *et al.* 2005). In order to account for incompleteness at these galactic latitudes we fill the plane with galaxies sampled from adjacent longitude/distance bins.

3   Results

Figure 2 shows the three components and the magnitudes of the acceleration of the Local Group due to galaxies within a series of successively larger concentric spheres centred on the local group (top plot). The bottom plot shows convergence of the direction of the LG dipole where the misalignment angle is between the LG and the CMB dipoles ($v_{LG} = 627 \pm 22 \ \mathrm{km\,s^{-1}}$, towards $l_{LG} = 273° \pm 3°$, $b_{LG} = 29° \pm 3°$, Bennett *et al.* 2003, Courteau & Van Den Bergh, 1999).

It is evident in the top plot that the LG velocity is dominated by structures within a distance of 6000 $\mathrm{km\,s^{-1}}$. The 'tug of war' between the Great Attractor and the Perseus-Pisces is clearly evident. The dip in the velocity vector is an indication that the local flow towards the Great
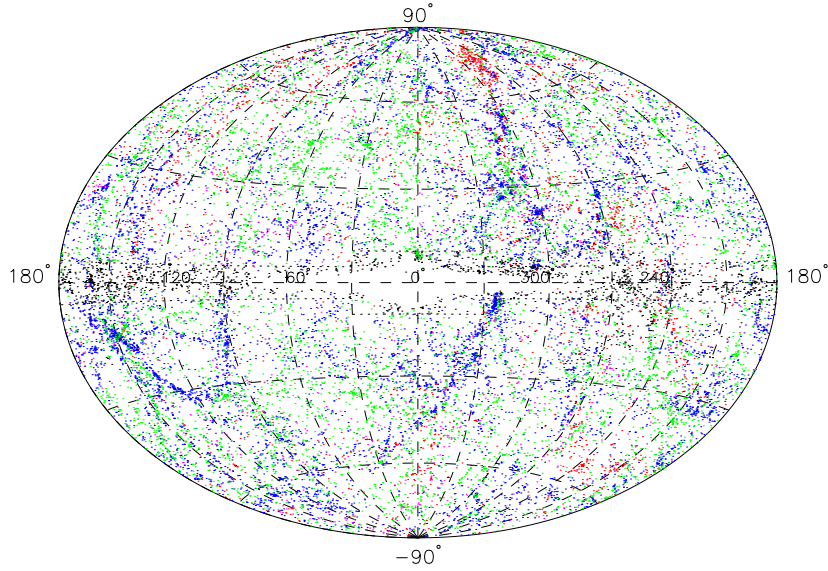
Figure 1: All Objects in the 2MASS Redshift Catalogue in Galactic Aitoff Projection. Galaxies with z ≤ 0.01 are plotted in red, 0.01 < z ≤ 0.025 are plotted in blue, 0.025 < z < 0.05 are plotted in green and z ≥ 0.05 are plotted in magenta. Galaxies without measured redshifts are plotted in black. The masked region is outlined by dashed lines.

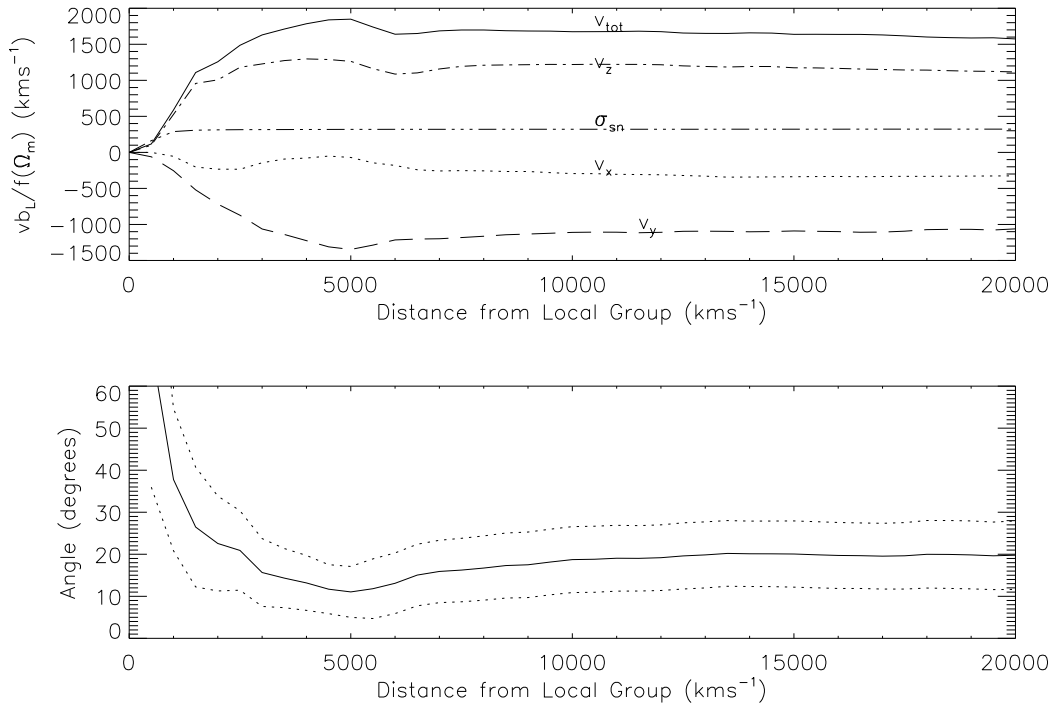Figure 2: **Top**: Three components and the magnitudes of the acceleration of the Local Group due to galaxies within a series of successively larger concentric spheres centred on the local group. **Bottom**: Convergence of the direction of the LG dipole where the misalignment angle is between the LG and the CMB dipoles. The dotted lines denote 1σ errors from shot noise.

Attractor[b] is counteracted by the Perseus-Pisces complex in the opposite direction. The dipole seems to converge by 6000 $\mathrm{km\,s^{-1}}$.

The misalignment angle between the LG and the CMB dipole is smallest at 5000 $\mathrm{km\,s^{-1}}$ where it drops to $12°\pm7°$ and increases slightly at larger distances presumably due to shot-noise. The direction of the flux dipole (l=251°±12°,b=37°± 10 °) is in good agreement with the 2MASS dipole derived by Maller *et al.* (2003). The difference in results is probably due to the fact that they use a higher latitude cutoff in the mask ($|b| < 7°$) and exclude all galaxies below this latitude. We confirm this by changing our treatment of the Zone of Avoidance to match theirs. We find that the flux dipole is very close to their dipole direction. Their limiting Kron magnitude is $K_s = 13.57$ which corresponds to an effective depth of 200 h^{-1} Mpc. As their sample is deep enough to pick out galaxies in the Shapley Supercluster, the comparison of their dipole value with our values suggests that the contribution to the LG dipole from structure further away than the maximum distance of our analysis is not significant.

Assuming convergence, we equate the velocity inferred from the CMB measurements with the value derived from a galaxy survey and obtain a value for the combination of the mass density and luminosity bias parameters: $\Omega_{\mathrm{m}}^{0.6}/b_{\mathrm{L}} = 0.40 \pm 0.09$. If we adopt $\Omega_{\mathrm{m}} = 0.23$ from the WMAP3 results (Spergel *et al.* 2006) we get $b_L \simeq 1$. This suggest that the 2MRS galaxies are unbiased.

A detailed description of the analysis and results outlined in this paper can be found in Erdoğdu *et al.* (2006).

Acknowledgments

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[b]By 'Great Attractor', it is meant the entire steradian on the sky centred at ($l \sim 310°,b \sim 20°$) covering a distance of 20 h^{-1} Mpc to 60 h^{-1} Mpc.