Dynamical constraints on the Local Group from the CMB and 2MRS dipoles

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ABSTRACT

We place constraints on the dynamics of the Local Group (LG) by comparing the dipole of the cosmic microwave background (CMB) with the peculiar velocity induced by the Two Micron All-Sky Redshift Survey galaxy sample. The analysis is limited by the lack of surveyed galaxies behind the zone of avoidance (ZoA). We therefore allow for a component of the LG velocity due to unknown mass concentrations behind the ZoA, as well as for an unknown transverse velocity of the Milky Way relative to the Andromeda galaxy. We infer extra motion along the direction of the Galactic Centre (where Galactic confusion and dust obscuration peaks) at the 95 per cent significance level. With a future survey of the ZoA it might be possible to constrain the transverse velocity of the Milky Way relative to Andromeda.

Key words: large-scale structure of Universe.

1 INTRODUCTION

The amplitude of the dipole of the cosmic microwave background (CMB) is two orders of magnitude larger than the characteristic amplitude of the higher order multipoles of its anisotropies (Kogut et al. 1993). It is therefore widely believed that the CMB dipole originates from the Doppler effect of our peculiar velocity, which is induced by inhomogeneities in the local Universe (Conklin 1969; Henry 1971; Erdoğdu et al. 2006) rather than by a primordial origin (Gunn 1988; Paczynski & Piran 1990). Indeed, 21-cm surveys employing the Tully–Fisher relation for distance calibration have inferred that the peculiar velocity of the Local Group (LG) relative to distant galaxies converges within a distance of $\sim$5000 km s^{-1} or $\sim$70 Mpc (Giovanelli et al. 1998; Dale & Giovanelli 2000).[1] This important result confirms the notion that the peculiar velocity is induced within that distance, since otherwise the distant galaxies would also be moving relative to the CMB together with the LG.

Surveys of galaxies in the local universe have attempted over the past two decades to explain the amplitude and direction of the CMB dipole within a distance of $\gtrsim$100 Mpc (Lynden-Bell, Lahav & Burstein 1989; Strauss et al. 1992; Balkowski &

Kraan-Korteweg 1994; Kraan-Korteweg, Henning & Andernach 2000; Kraan-Korteweg & Lahav 2000; Kraan-Korteweg 2005). The adopted method assumes that (i) the LG peculiar motion is induced by gravity; and (ii) the amplitude of inhomogeneities in the distribution of the observed light from galaxies traces the underlying mass distribution on large spatial scales with a constant bias factor b. The latest results, based on the 2MRS (Erdoğdu et al. 2006), show convergence of the flux-weighted dipole in the galaxy survey out to $\sim$150 Mpc but still indicate a discrepancy of $24° \pm 8°$ with the direction of the CMB dipole.

The main limitation of the 2MRS sample results from the lack of sample galaxies behind the zone of avoidance (ZoA), a strip around the Milky Way disc where confusion and dust obscuration compromise the survey efficiency. For lack of better information, the 2MRS analysis is also based on the assumption that the Milky Way galaxy is moving radially towards the Andromeda galaxy (M31) with no transverse motion (Courteau & van den Bergh 1999). Our goal in this paper is to constrain the unknown peculiar velocity of the LG within the ZoA as well the unknown transverse speed of the Milky Way relative to Andromeda, by requiring a match between the 2MRS and CMB dipoles. The contribution of mass concentrations outside the survey volume of 2MRS can be ignored based on the success of Tully–Fisher surveys in converging to the CMB dipole within the same volume (Giovanelli et al. 1998; Dale & Giovanelli 2000).

The outline of this paper is as follows. We first summarize the existing data on the LG velocity from the CMB and Galactic measurements (Section 2) as well as from the 2MRS analysis (Section 3). We then compare the results from the CMB and 2MRS data sets and interpret our results in the context of transverse motion of the Milky Way relative to the LG (Section 4.1), structure beyond the extent of 2MRS (Section 4.2) and nearby structure within the ZoA

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[1] We note that the distance, at which dipole convergence is achieved, is still controversial. Surveys of galaxy clusters imply large convergence distances (Plionis et al. 2000; Ebeling, Mullis & Tully 2002; Ebeling et al. 2005; Kocevski et al. 2005; Basilakos & Plionis 2006) but are affected by the strong bias and Poisson fluctuations of clusters relative to the underlying matter distribution. In this paper, we assume that convergence is reached within the maximum Two Micron All-Sky Redshift Survey (2MRS) distance of 280 Mpc or $\sim$20 000 km s^{-1} (see in Section 4.2 for the justification of this assumption).

(Section 4.3). We conclude that the last effect is the most likely explanation for the discrepancy between the CMB and 2MRS dipoles. We also derive the likelihood function for the bias parameter b of the 2MRS galaxies. Finally, we discuss the implications of our results in Section 5. Throughout our analysis, we use Galactic Cartesian coordinates in which the x-axis is oriented towards the Galactic Centre (GC), i.e. towards longitude $l = 0$ and latitude $b = 0$, y is in the direction $l = 90°$, $b = 0$ and z is in the direction $b = 90°$.

2 CMB DIPOLE AND GALACTIC MEASUREMENTS

The velocity of the Sun with respect to the CMB is $369.5 \pm 3.0 \, \mathrm{km \, s^{-1}}$ towards $l = 264.4° \pm 0.3°$, $b = 48.4° \pm 0.5°$ (Kogut et al. 1993). In the Cartesian Galactic coordinate system,

$$v_{\odot-\mathrm{CMB}} = (-23.9 \pm 1.3, -244.1 \pm 3.1, 276.3 \pm 3.1) \, \mathrm{km \, s^{-1}}. \tag{1}$$

Here and elsewhere, we add errors in quadrature and ignore possible correlations between errors.

Courteau & van den Bergh (1999) estimate the velocity of the Sun with respect to the centre of mass of the LG to be $306 \pm 18 \, \mathrm{km \, s^{-1}}$ towards $l = 99° \pm 5°$, $b = -4° \pm 4°$:

$$v_{\odot-\mathrm{LG}} = (-47.8 \pm 26.5, 301.5 \pm 18.3, -21.3 \pm 21.3) \, \mathrm{km \, s^{-1}}. \tag{2}$$

The model used for this derivation assumed statistical isotropy of the velocity distribution of the LG galaxies, which may not be satisfied since most LG members are low-mass galaxies concentrated around the Milky Way or Andromeda. Therefore, instead of using this estimate we will sum the best estimates for the velocity of the Sun with respect to the GC, $v_{\odot-\mathrm{GC}}$, and the velocity of the GC with respect to the LG, $v_{\mathrm{GC-LG}}$.

Reid & Brunthaler (2004) have measured the proper motion of Sgr A* to be $-6.379 \pm 0.026 \, \mathrm{mas \, yr^{-1}}$ in longitude and $-0.202 \pm 0.019 \, \mathrm{mas \, yr^{-1}}$ in latitude. Since Sgr A* is almost certainly at rest with respect to the GC, its proper motion is entirely due to the component of the Sun's motion in the y and z directions. To get these velocity components it is necessary to specify the distance to the GC, for which we adopt the estimate of Eisenhauer et al. (2003): $R_0 = 7.94 \pm 0.42 \, \mathrm{kpc}$. For the x component of the Sun's velocity we take the estimate of Dehnen & Binney (1998): $10.0 \pm 0.36 \, \mathrm{km \, s^{-1}}$. Thus,

$$v_{\odot-\mathrm{GC}} = (10.0 \pm 0.36, 240.1 \pm 12.7, 7.6 \pm 0.8) \, \mathrm{km \, s^{-1}}. \tag{3}$$

The radial velocity of the Sun towards M31 is $-297 \, \mathrm{km \, s^{-1}}$ according to Mateo (1998), which is slightly different from the value ($301 \, \mathrm{km \, s^{-1}}$) given by Courteau & van den Bergh (1999). We adopt Mateo's value and include a generous error estimate: $-297 \pm 5 \, \mathrm{km \, s^{-1}}$. The direction to M31 is $l = 121.2°$, $b = -21.6°$. The unit vector in this direction is

$$\hat{n}_{\mathrm{M31}} = (-0.4816, 0.7953, -0.3681). \tag{4}$$

The component of the Sun–GC velocity parallel to this unit vector is $183.3 \pm 10.1 \, \mathrm{km \, s^{-1}}$. The remainder of the line-of-sight velocity between the Sun and M31, $297 \pm 5 \, \mathrm{km \, s^{-1}}$, must be due to the relative motion between the GC and M31. Thus, we find

$$v_{\|,\mathrm{GC-M31}} \equiv v_{\mathrm{GC-M31}} \cdot \hat{n}_{\mathrm{M31}} = 113.7 \pm 11.3 \, \mathrm{km \, s^{-1}}. \tag{5}$$

Various estimates of the total mass of M31 place it between 4/3 (Mateo 1998) and 3/2 (Courteau & van den Bergh 1999) of the mass of the Milky Way. However, we estimate the parallel component of the galaxy's velocity with respect to the centre of mass of the LG to be

$$v_{\|,\mathrm{GC-LG}} = 66.6 \pm 6.7 \, \mathrm{km \, s^{-1}}. \tag{6}$$

Combining equations (3) and (6), and assuming that the Milky Way has no transverse velocity with respect to the LG, we calculate the velocity of the Sun with respect to the LG to be

$$v_{\odot-\mathrm{LG}} = (-22.1 \pm 3.2, 293.1 \pm 13.8, -16.9 \pm 2.6) \, \mathrm{km \, s^{-1}}. \tag{7}$$

We note that this estimate agrees with that given by Courteau & van den Bergh (1999) in equation (2), to within the errors.

Combining our estimate of $v_{\odot-\mathrm{LG}}$ with the measured velocity of the Sun with respect to the CMB, $v_{\odot-\mathrm{CMB}}$ equation (1), we obtain

$$v_{\mathrm{LG-CMB}} = (-1.8 \pm 3.5, -537.2 \pm 14.1, 293.2 \pm 4.0) \, \mathrm{km \, s^{-1}}. \tag{8}$$

3 LOCAL GROUP MOTION FROM 2MRS

The 2MRS includes a sample of infrared-selected galaxies out to an expansion velocity of $\sim 20\,000 \, \mathrm{km \, s^{-1}}$. By assuming a constant mass-to-light ratio per unit volume, the light distribution of these galaxies has been used to derive the gravitational acceleration of the LG due to structure in the local universe (Erdoğdu et al. 2006). From the flux-weighted results in the CMB frame reported by Erdoğdu et al. (2006) in their table 1, the expected velocity of the LG with respect to the CMB is $(1620 \pm 327) f(\Omega_{\mathrm{m}})/b \, \mathrm{km \, s^{-1}}$ towards the direction $l = 247° \pm 11°$, $b = 37° \pm 10°$. Here, $f(\Omega_{\mathrm{m}}) \approx \Omega_{\mathrm{m}}^{0.6}$, where Ω_{m} is the matter density of the universe, and b is the mean bias factor of the galaxies contributing to the acceleration of the LG.

Tegmark et al. (2006) have combined *WMAP* (*Wilkinson Microwave Anisotropy Probe*) and Sloan Digital Sky Survey (SDSS) data to estimate $\Omega_{\mathrm{m}} = 0.24 \pm 0.02$, which gives $\Omega_{\mathrm{m}}^{0.6} = 0.425 \pm 0.021$. The 2MRS data then yield the following prediction for the velocity of the LG with respect to the CMB,

$$b v_{\mathrm{LG-CMB}} = (-214.8 \pm 110.6, -506.1 \pm 131.1, 414.4 \\ \pm 128.9) \, \mathrm{km \, s^{-1}}. \tag{9}$$

The error estimates include shot noise but not the effect of the missing information in the ZoA. The latter is discussed in Section 4.3.

A comparison of the velocity estimates given in equations (8) and (9) suggests that, regardless of the value of the bias factor b, there is a substantial discrepancy. Let us adjust b so as to minimize the magnitude of the discrepancy. The minimum occurs at $b = 1.056$. The corresponding velocity discrepancy between equations (8) and (9) is then

$$\Delta v = (201.6 \pm 104.8, -57.9 \pm 124.9, -99.2 \pm 122.1) \, \mathrm{km \, s^{-1}}. \tag{10}$$

The deviation is most significant in the x components of the two velocities. Erdoğdu et al. (2006), who noted this discrepancy, offered a number of possible explanations for the misalignment between the CMB and 2MRS dipoles. We discuss three possibilities.

4 EXPLANATIONS FOR THE DISCREPANCY BETWEEN THE CMB AND 2MRS DIPOLES

4.1 Transverse motion of the Milky Way

The velocity estimate given in equation (8) assumes that the Milky Way has no transverse motion around the LG centre of

mass. We investigate if such motion might explain the velocity discrepancy.

We begin by considering the component of $v_{\text{LG–CMB}}$ towards M31 (i.e. parallel to $\hat{n}_{\text{M31}}$) since this component is independent of the transverse velocity. Equating the components of the velocities given in equations (8) and (9) along this direction, we solve for the bias factor to obtain $b = 0.845 \pm 0.237$. The central value is not very likely since it is less than unity. Nevertheless, we substitute this estimate of the bias back into the two expressions for $v_{\text{LG–CMB}}$ to infer the transverse velocity of the galaxy around the LG centre of mass:

$$v_{\perp,\text{GC–LG}} = (252.4 \pm 130.9, 61.7 \pm 155.8, -197.2$$
$$\pm 152.6)\,\text{km s}^{-1}. \tag{11}$$

Including the reflex motion of M31, this estimate predicts the following proper motion of M31:

$$v_{\text{M31–MW}} = (-429 \pm 223, -105 \pm 265, 335 \pm 259)\,\text{km s}^{-1}. \tag{12}$$

If instead we use the estimate $b = 1.056$ which we obtained in Section 3, then

$$v_{\text{M31–MW}} = (-343 \pm 178, 98 \pm 212, 169 \pm 208)\,\text{km s}^{-1}. \tag{13}$$

In either case, we see that we require a large transverse velocity of M31 with respect to the Milky Way, whose most significant component is a large velocity towards the Galactic anticentre.

Loeb et al. (2005) constrained the proper motion of Andromeda to be $\sim 100 \pm 20\,\text{km s}^{-1}$ based on the measured proper motion of its satellite M33 and the requirement that M33 should not be tidally disrupted in the past. van der Marel & Guhathakurta (2007) assumed that M31's satellites on average follow Andromeda's motion relative to the LG; they accordingly used the line-of-sight velocities of 17 satellites of Andromeda and five galaxies at the outskirts of the LG, as well as the proper motions of M33 and IC 10, to infer $v_{\text{M31–LG}} = (97 \pm 35, -67 \pm 26, 80 \pm 32)\,\text{km s}^{-1}$. The transverse speed of Andromeda inferred by these studies is well below the central value needed to explain the discrepancy between the 2MRS and the CMB dipoles. Moreover, the x component of the velocity inferred by van der Marel & Guhathakurta (2007) is positive whereas the CMB–LG discrepancy requires a large negative value.

As a side note, we use the Courteau & van den Bergh (1999) estimate of the Sun's motion relative to the LG to obtain the velocity of the galaxy with respect to the LG:

$$v_{\text{GC–LG}} = (-57.8 \pm 26.5, 59.6 \pm 18.3, -29.0 \pm 21.3)\,\text{km s}^{-1}. \tag{14}$$

This gives a speed along the GC–LG direction of $85.9 \pm 20.9\,\text{km s}^{-1}$, which is statistically consistent with our previous more accurate estimate of $66.6 \pm 6.7\,\text{km s}^{-1}$. For the transverse speed, the estimate of Courteau & van den Bergh (1999) gives $18.6 \pm 32.4\,\text{km s}^{-1}$, which is again much smaller than the velocity discrepancy we seek to explain.

In the next two subsections, we assume that the Milky Way has negligible velocity transverse to the LG centre of mass and consider whether incompleteness in the 2MRS might explain the misalignment between the CMB and 2MRS dipoles.

4.2 Structure beyond the maximum distance of 2MRS

The 2MRS sample of Erdoğdu et al. (2006) extends out to a velocity of $20\,000\,\text{km s}^{-1}$. Fig. 6 of their paper shows that the flux-weighted dipole in the CMB frame receives most of its contribution from inside about $4000\,\text{km s}^{-1}$, which is much shorter than the limiting

distance of the survey. This suggests that any contribution from beyond the survey volume is likely to be quite small.

To verify this, we considered two logarithmically spaced velocity bins in the 2MRS sample: Bin 1, 5000–10 000 km s^{-1} and Bin 2, 10 000–20 000 km s^{-1}. From the data given in table 1 of Erdoğdu et al. (2006), we computed the mean square contribution to the quantity $(b/f(\Omega_m))\,v_{\text{LG–CMB}}$ from each of the two bins. We obtained $(162\,\text{km s}^{-1})^2$ and $(64\,\text{km s}^{-1})^2$ from Bins 1 and 2, respectively. The numerical estimates are consistent with a scale-invariant Λ Cold Dark Matter (ΛCDM) power spectrum in the linear regime, for which the mean square velocity should vary roughly as the inverse square of the distance (Peacock 1998). We then estimate the root-mean-square contribution from the rest of the universe beyond $20\,000\,\text{km s}^{-1}$ to be $(b/f(\Omega_m))\,v_{\text{LG–CMB}} \sim 80\,\text{km s}^{-1}$. For $f(\Omega_m)/b \approx 0.4$ (Erdoğdu et al. 2006), this gives $v_{\text{LG–CMB}}(> 20\,000\,\text{km s}^{-1}) \sim 30\,\text{km s}^{-1}$, which is very much smaller than the $\sim 200\,\text{km s}^{-1}$. We need to eliminate the misalignment between the CMB and 2MRS dipoles equation (10).

Peacock (1992) analysed the expected convergence of the dipole velocity with distance based on the large-scale power spectrum. He finds that the misalignment angle between the true CMB dipole and the dipole measured within a finite survey volume is expected to be negligible beyond a distance of $20\,000\,\text{km s}^{-1}$ ($\sim 280\,\text{Mpc}$). Hence, distant structure beyond the limit of 2MRS is very unlikely to be the source of the inferred discrepancy between the CMB and 2MRS dipoles.

4.3 Nearby structure in the ZoA

Finally, we consider the possibility that nearby galaxies inside the ZoA may be responsible for the discrepancy between the CMB and 2MRS dipoles. Erdoğdu et al. (2006) state that the ZoA for their survey corresponded to the area $|b| < 5°$ for $|l| > 30°$ and $|b| < 10°$ for $|l| < 30°$. Given this information plus their estimate of the contribution to $v_{\text{LG–CMB}}$ from the region of the sky covered by their survey, we estimate the root-mean-square contribution of the ZoA to each of the components of the LG velocity to be

$$\sigma_{\text{ZoA},x} = 168.7/b\,\text{km s}^{-1}, \tag{15}$$

$$\sigma_{\text{ZoA},y} = 150.2/b\,\text{km s}^{-1}, \tag{16}$$

$$\sigma_{\text{ZoA},z} = 15.5/b\,\text{km s}^{-1}. \tag{17}$$

As expected, the contribution in the z direction is small.

Multiplying equation (8) by b and subtracting from equation (9), we obtain the following estimates for the contribution of the ZoA to the velocity of the LG:

$$bv_{\text{ZoA},x} = 214.8 - 1.8b; \; \sigma = (110.6^2 + 3.5^2 b^2)^{1/2}, \tag{18}$$

$$bv_{\text{ZoA},y} = 506.1 - 537.2b; \; \sigma = (131.1^2 + 14.1^2 b^2)^{1/2}, \tag{19}$$

$$bv_{\text{ZoA},z} = -414.4 + 293.2b; \; \sigma = (128.9^2 + 4.0^2 b^2)^{1/2}, \tag{20}$$

where the root-mean-square uncertainty in each expression is given by the σ value on the right, and all quantities are in km s^{-1}. These three equations can be used to derive an expression for the likelihood of the three velocity components. Before writing this likelihood function, we note that we have calculated in equations (15)–(17) the root-mean-square expectation values of $bv_{\text{ZoA},x}$, $bv_{\text{ZoA},y}$ and $bv_{\text{ZoA},z}$, which supply us with the prior distributions of these three velocities. In addition, we have a fourth unknown quantity, namely the bias factor b, for which we adopt a flat prior.
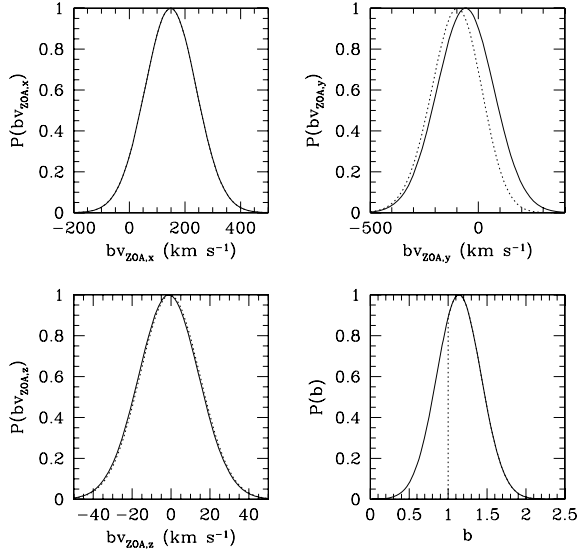
Figure 1. Marginalized probability distributions of $bv_{\mathrm{ZoA},x}, bv_{\mathrm{ZoA},y}, bv_{\mathrm{ZoA},z}$ and b. The distributions have been normalized such that their maxima are equal to unity. The solid lines correspond to a flat prior for b extending from zero to infinity, while the dotted lines correspond to a prior in which b is restricted to be $\geqslant 1$.

Figure 2. Marginalized probability distributions of $v_{\mathrm{ZoA},x}, v_{\mathrm{ZoA},y}, v_{\mathrm{ZoA},z}$ and b. The distributions have been normalized such that their maxima are equal to unity. The solid and dotted lines are as in Fig. 1. The distribution of b is identical to the one shown in Fig. 1.

We thus obtain the following likelihood function for the four unknowns:

$$P(bv_{\mathrm{ZoA},x}, bv_{\mathrm{ZoA},y}, bv_{\mathrm{ZoA},z}, b)$$

$$\propto \exp\left[-\frac{(bv_{\mathrm{ZoA},x})^2}{2(168.7)^2} - \frac{(bv_{\mathrm{ZoA},x} - 214.8 + 1.8b)^2}{2(110.6^2 + 3.5^2 b^2)}\right]$$

$$\times \exp\left[-\frac{(bv_{\mathrm{ZoA},y})^2}{2(150.2)^2} - \frac{(bv_{\mathrm{ZoA},y} - 506.1 + 537.2b)^2}{2(131.1^2 + 14.1^2 b^2)}\right]$$

$$\times \exp\left[-\frac{(bv_{\mathrm{ZoA},z})^2}{2(15.5)^2} - \frac{(bv_{\mathrm{ZoA},z} + 414.4 - 293.2b)^2}{2(128.9^2 + 4.0^2 b^2)}\right]. \quad (21)$$

By marginalizing this likelihood over any three of the four unknown quantities, we obtain the probability distribution for the fourth.

The results are shown by the solid lines in Fig. 1. We find that the bias factor has a fairly broad distribution with a 1σ range from ~ 0.85 to ~ 1.4. Since it is most unlikely that the galaxies detected by Two Micron All-Sky Survey (2MASS) would have a bias less than unity, we have repeated the calculations with a prior for b truncated below unity. The corresponding results are shown by the dotted lines.

Fig. 1 indicates that $bv_{\mathrm{ZoA},x}$ has a 95 per cent probability of being positive (a strong 2σ result), while $bv_{\mathrm{ZoA},y}$ has a 68 per cent probability of being negative (a weaker 1σ result). The most likely values of these two components are $bv_{\mathrm{ZoA},x} \sim 150\,\mathrm{km\,s^{-1}}$ and $bv_{\mathrm{ZoA},y} \sim -60\,\mathrm{km\,s^{-1}}$, though each has a broad probability distribution. When we restrict the bias factor to $b \geqslant 1$ (dotted lines in Fig. 1), the corresponding numerical results are 95 and 82 per cent, 150 and $-100\,\mathrm{km\,s^{-1}}$, respectively. The velocity component $bv_{\mathrm{ZoA},z}$ is consistent with zero, as expected.

In contrast to our analysis in Sections 4.1 and 4.2, where the particular explanations considered there were easily ruled out, now we see that acceleration from galaxies in the ZoA may well explain the misalignment between the CMB and 2MRS dipoles. The magnitude of the velocity discrepancy is consistent with the expected contribution from the ZoA (described by our estimates of $\sigma_{\mathrm{ZoA},x-z}$). Moreover, the additional acceleration from the ZoA is expected to be in the x–y plane, and most likely in the x direction, i.e. towards
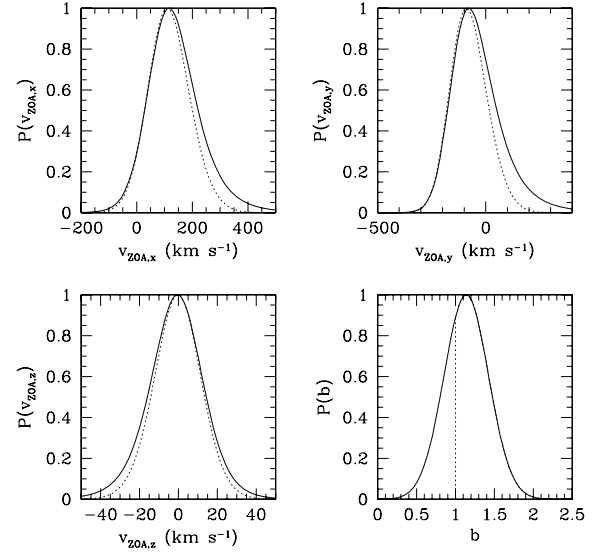
the GC where obscuration is maximum. This is exactly the sense of the velocity discrepancy. Given this encouraging agreement, we predict that a survey of the ZoA would find additional structure in the nearby universe, especially behind the GC region.

Fig. 1 corresponds to the probability distributions of the components of the bias-multiplied velocity $b\,v_{\mathrm{ZoA}}$, since these quantities are most directly related to the 2MRS survey. For completeness we show in Fig. 2 the distributions of the velocity components themselves. These were calculated in the same way, except that we considered the likelihood function $P(v_{\mathrm{ZoA},x}, v_{\mathrm{ZoA},y}, v_{\mathrm{ZoA},z}, b)$. This quantity is almost the same as the likelihood given in equation (21) except that it differs by the following Jacobian:

$$J \equiv \frac{\partial(bv_{\mathrm{ZoA},x}, bv_{\mathrm{ZoA},y}, bv_{\mathrm{ZoA},z}, b)}{\partial(v_{\mathrm{ZoA},x}, v_{\mathrm{ZoA},y}, v_{\mathrm{ZoA},z}, b)} = b^3. \quad (22)$$

Fig. 2 is generally consistent with the results in Fig. 1. For completeness we note the following numerical results: the probability of $v_{\mathrm{ZoA},x}$ being positive is 95 per cent and the most likely value of this velocity component is $120\,\mathrm{km\,s^{-1}}$ (solid line) and $110\,\mathrm{km\,s^{-1}}$ (dotted line). The probability of $v_{\mathrm{ZoA},y}$ being negative is 68/82 per cent (solid/dotted line) and the most likely value is $-80/-90\,\mathrm{km\,s^{-1}}$ (solid/dotted line).

The 2MRS results that we have used from Erdoğdu et al. (2006) correspond to their 'second method' of treating the ZoA, in which they fill the ZoA with structure consistent with that found in neighbouring latitude strips. We do not know how effective this method is at predicting the missing information. If it were perfect, there should be no discrepancy between 2MRS and the direction of the CMB dipole. In our analysis, we have assumed that 2MRS has no information at all inside the ZoA. To be consistent with this assumption, we should ideally use the results corresponding to Erdoğdu et al.'s 'first method,' in which the authors simply fill the ZoA with random galaxies. Unfortunately, their paper does not give a table of results corresponding to this method.

5 DISCUSSION

We have obtained new constraints on the dynamics of the LG by comparing the CMB and the 2MRS dipoles. The analysis is limited by the lack of surveyed galaxies behind the ZoA. In order to match the CMB and 2MRS dipoles, we have inferred excess motion (that is not accounted for by 2MRS) along the direction of the GC (in Section 4.2). This happens to be the most natural direction for hiding mass concentrations because it is associated with enhanced confusion and dust obscuration by the galaxy.

The implications of our findings have a simple interpretation. To acquire an excess peculiar velocity Δv towards the ZoA over the age of the Universe, $\Delta t = 1.4 \times 10^{10}$ yr, requires an average acceleration of order $g \sim \Delta v / \Delta t$. Assuming that this acceleration is induced gravitationally (i.e. $g \sim GM/d^2$) by a hidden object of mass M at a characteristic distance d, we get the simple scaling relation for the required mass: $M_{12} \sim 1.7 \, v_7 \, d_0^2$, where $M_{12} = (M/10^{12} \, \mathrm{M}_\odot)$, $v_7 = (\Delta v / 100 \, \mathrm{km \, s^{-1}})$ and $d_0 = (d/1 \, \mathrm{Mpc})$. According to Fig. 2, the most likely value of the excess velocity towards the GC is $\Delta v \equiv v_{\mathrm{ZoA},x} \sim 120 \, \mathrm{km \, s^{-1}}$, which requires a hidden galaxy comparable in mass to Andromeda ($M \sim 2 \times 10^{12} \, \mathrm{M}_\odot$) at a distance of ~ 1 Mpc, or a hidden galaxy cluster comparable in mass to the Coma cluster ($M \sim 10^{15} \, \mathrm{M}_\odot$) at a distance of ~ 20 Mpc. At these distances, the inner 10-kpc diameter of a hidden galaxy would occupy an angle of $\sim 0.6°$, and the inner 1-Mpc diameter of a hidden cluster would occupy $\sim 2.5°$. An extended supercluster might not be fully hidden behind the ZoA. As argued in Section 4.2, it is very unlikely that structure beyond the maximum distance of 2MRS of ~ 280 Mpc ($\sim 20\,000 \, \mathrm{km \, s^{-1}}$) accounts for the discrepancy. The ΛCDM power spectrum would typically account for a velocity offset that is an order of magnitude smaller than the central value we infer.

The above possible objects are already constrained by existing data. In particular, a new galaxy cluster must have escaped detection by dedicated ZoA searches in the X-ray band (Ebeling et al. 2002, 2005; Kocevski et al. 2005), optical galaxy searches (Roman et al. 1998; Hasegawa et al. 2000; Wakamatsu et al. 2005) and 21-cm surveys (Meyer et al. 2004; Henning, Kraan-Korteweg & Stavely-Smith 2005; Kraan-Korteweg et al. 2007). Similarly, a nearby galaxy must have escaped detection by 2MRS as well as existing 21-cm surveys. We are not in a position to evaluate how likely this is.

We note that the excess mass we predict behind the GC will have an associated infrared flux which is independent of the attractor's mass and is linearly proportional to Δv, since it scales as $\propto M/d^2$ for a fixed mass-to-light ratio. Erdoğdu et al. (2006) infer a net luminosity density of $(7.67 \pm 1.02) \times 10^8 \, h \, \mathrm{L}_\odot \, \mathrm{Mpc^{-3}}$ for the 2MRS galaxies. When compared to the average matter density of the Universe for $\Omega_{\mathrm{m}} = 0.24$ and $h = 0.7$, this results in a predicted excess radiation flux of $\sim 2.4 \times 10^9 \, v_7 \, \mathrm{L}_\odot \, \mathrm{Mpc^{-2}}$ behind the GC.

Unfortunately, the current error budget is too large to provide a useful constraint on the transverse velocity of the Milky Way relative to the Andromeda galaxy (in Section 4.1). A future survey of the ZoA might allow to determine this transverse velocity by requiring a match between the peculiar velocity inferred for the LG and the CMB dipole. The bias parameter of the surveyed galaxies, b, could be determined by requiring that the inferred radial velocity of Andromeda relative to the Milky Way will match its observed value. It would then be possible set a lower limit on the LG mass so that the two galaxies will be gravitationally bound.

Measuring the relative transverse velocity of the Milky Way and Andromeda is of great interest, since it would affect the future trajectory of the two galaxies (Cox & Loeb 2007) and will determine whether the LG is likely to be gravitationally bound (Binney & Tremaine 1986). Current methods for inferring the transverse speed (Loeb et al. 2005; van der Marel & Guhathakurta 2007) are indirect and highly uncertain. A future ZoA survey for infrared or 21-cm galaxies (Henning et al. 2005) would provide a new elegant path for constraining this unknown velocity component, which is difficult to measure otherwise.

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