ABSTRACT

The unprecedented sky coverage and photometric uniformity of the Two Micron All Sky Survey (2MASS) provides a rich resource for investigating the galaxies populating the local universe. A full characterization of the large-scale clustering distribution is important for theoretical studies of structure formation. 2MASS offers an all-sky view of the local galaxy population at 2.15 μm, unbiased by young stellar light and minimally affected by dust. We use 2MASS to map the local distribution of galaxies, identifying the largest structures in the nearby universe. The inhomogeneity of these structures causes an acceleration on the Local Group of galaxies, which can be seen in the dipole of the cosmic microwave background (CMB). We find that the direction of the 2MASS clustering dipole is 16° from the CMB dipole, confirming that the local galaxy distribution accelerates the Local Group. From the magnitude of the dipole, we find a value of the linear bias parameter $b = 1.06 \pm 0.17$ in the $K_s$ band. Thus, the linear bias parameter of $K_s$-selected galaxies is similar to the bias parameter found in other wave bands.

Subject headings: cosmic microwave background — galaxies: clusters: general — infrared: galaxies — large-scale structure of universe

1. INTRODUCTION

Since the discovery of a dipole in the cosmic microwave background (CMB; Corey & Wilkinson 1976; Smoot, Gorsten, & Muller 1977; Lubin, Epstein, & Smoot 1983; Fixsen, Cheng, & Wilkinson 1983), it has been identified as the Doppler signature of our motion relative to the CMB rest frame. Strong evidence in favor of this interpretation has been provided by the observation of a similar dipole in the surface brightness of radio galaxies in the same direction (Blake & Wall 2002). Blake & Wall make the distinction between velocity dipoles caused by our motion and clustering dipoles that measure the distribution of galaxies. Attempts to measure the clustering dipole of local galaxies in the 1980s (Meiksin & Davis 1986; Yahil, Walker, & Rowan-Robinson 1986; Lahav 1987; Villumsen & Strauss 1987) from only the fluxes and positions of galaxies led to results that were within 30° from the CMB velocity dipole. The inclusion of redshift information led to a controversy over at which distance the clustering dipole converged (Strauss & Davis 1988; Lynden-Bell, Lahav, & Burstein 1989; Rowan-Robinson et al. 1990; Plionis & Valdarnini 1991; Scaramella, Vettolani, & Zamorani 1991). Through the 1990s, progressively larger redshift surveys were used in an effort to determine where the clustering dipole converged and to improve the calculation of cosmological parameters (Strauss et al. 1992; Hudson 1993; Smolctld et al. 1999; Rowan-Robinson et al. 2000). These improvements included determining the shot noise in the sample, optimizing the window function for smoothing, and estimating the contribution of nonlinear effects to the velocity dipole (Strauss et al. 1992). With these efforts, Schmoldt et al. (1999) and Rowan-Robinson et al. (2000) have recently determined that the clustering dipole converges at 150–200 $h^{-1}$ Mpc.

The Two Mass All Sky Survey (2MASS; Skrutskie et al. 1997) is the first near-infrared $(JHK_s$ passbands) all-sky survey. 2MASS has an effective image resolution of 1" and 100 times greater sensitivity than the far-infrared all-sky survey, $IRAS$. Most passbands tend to be sensitive to the star formation rate, while the $K_s$ passband is most sensitive to stellar mass (Bell & de Jong 2001), which probably makes the $K_s$ band a better tracer of total mass. Therefore, 2MASS offers us a unique opportunity for calculating a flux-weighted clustering dipole.

The median depth of the survey is $z = 0.073$, or 220 $h^{-1}$ Mpc (Bell et al. 2003), a distance past where the dipole has been shown to converge. At a limiting magnitude of $K_s = 13.57$ mag, 2MASS includes all $L_s$ and brighter galaxies out to 200 $h^{-1}$ Mpc. We can use the 2MASS luminosity function (Bell et al. 2003) measured using redshifts from the Sloan Digital Sky Survey (SDSS) early data release (Stoughton et al. 2002) to determine the completeness of the survey as a function of distance. The result is that the survey contains 60% of the total luminosity and 76% of the total flux inside 200 $h^{-1}$ Mpc. Thus, 2MASS is a fairly complete survey of the total flux in the local universe. Since we expect the clustering dipole to be dominated by bright objects, any missing flux is unlikely to contribute significantly to the dipole. Later we show that this is true by demonstrating the convergence of the clustering dipole as a function of apparent magnitude.

2. THE 2MASS CATALOG

The 2MASS final release extended source catalog is the most complete resource of local galaxy observations at near-infrared wavelengths. The catalog contains over 1.6 million sources, and for most Galactic latitudes ($|b| > 20°$), it has a greater than 90% completeness and a greater than 98% reliability down to $K_s \leq 13.5$ mag (Jarrett et al. 2000b). For $5 < |b| < 20°$, in regions where the stellar density is less than $10^4$ deg$^{-2}$ with $K_i < 14$ mag stars, the catalog maintains its high completeness and is still greater than 80% reliable (Jarrett et al. 2000a). Hereafter, we adopt the Kron (1980) magnitudes, which attempt to recover the “total” galaxy flux using apertures related to the galaxy radius (limited in 2MASS to a 5° minimum). 2MASS Kron magnitudes underestimate the true total flux systematically by 0.1 mag for $K_s > 11$ (Bell et al. 2003), which we correct for when converting magnitudes to flux. The extended source catalog is 97.5% complete within the SDSS early data release.
Fig. 1.—Growth of the clustering dipole shown as a function of the number of galaxies used to compute it ordered by their flux. The corresponding limiting $K_s$ magnitude is shown on the top axis. The dipole quickly rises to 80% of its final value. The faintest 300,000 galaxies only change the dipole value by less than 5%. Also shown is the growth of each component of the clustering dipole, which likewise quickly converge to their final value.

for extinction-corrected Kron magnitudes of $K_s \leq 13.57$ mag (Bell et al. 2003). While the reliability decreases at lower Galactic latitudes, we will adopt this limiting flux and explore the effect of a brighter cutoff later on. The photometry of the catalog is very uniform with errors of less than 0.1 mag (Nikolaev et al. 2000). We have performed an analysis of the galaxy density with a number of possible contaminants and find that the cross-correlation is always less than 5% (Maller et al. 2003).

In the region $l > 230^\circ$ and $l < 130^\circ$, we mask out the plane ($|b| < 7^\circ$) and extend this to $|b| < 12^\circ$ in the region $l > 330^\circ$ and $l < 30^\circ$, where stellar densities exceed 10$^4$ stars deg$^{-2}$. This region also contains most of the Milky Way extended sources: globular and open clusters, planetary nebulae, H ii regions, young stellar objects, nebulae, and giant molecular clouds (Jarrett et al. 2000a). We remove Milky Way extended sources outside of the mask using a color criteria. First we apply an extinction correction based on Galactic dust maps (Schlegel, Finkbeiner, & Davis 1998) to create a foreground-corrected catalog of galaxies with $K_s < 13.57$ mag. From the overlap with the 6104 SDSS spectroscopically confirmed galaxies, we find that bright ($K_s < 12$ mag) galaxies have dust-corrected colors narrowly clustered around $0.8 < J-K < 1.2$. We exclude extended sources brighter than $K_s = 12$ mag with $J-K < 0.75$ or $J-K > 1.4$, which are rare at Galactic latitudes $|b| > 10^\circ$ but are many times more common at $|b| < 10^\circ$. At fainter magnitudes, the spread in $J-K$ colors increases, so we only remove objects with $J-K < 0.5$, which again clearly show a strong Galactic latitude dependence. This cut removes 20,181 objects from the catalog of which 85% have $|b| < 20^\circ$. We also remove 17 galaxies that are members of the Local Group. This leaves us with 743,979 galaxies covering 90% of the sky (see Fig. 3). Note that applying no dust correction reduces the number of galaxies to 699,507.

3. MEASURING THE CLUSTERING DIPOLE

The inhomogeneity of these structures causes a gravitational acceleration on the Local Group of galaxies. The CMB velocity dipole (Lineweaver et al. 1996) results from the motion of the Sun relative to the CMB standard of rest. This motion can be broken down into two parts: the motion of the Sun relative to the Local Group and the motion of the Local Group with respect to the CMB. Using the most recent values (Courteau & van den Bergh 1999), we find that the Local Group velocity relative to the CMB is 622 km s$^{-1}$ in the direction $l_{\text{cmb}} = 272^\circ$, $b_{\text{cmb}} = 28^\circ$.

Since both the gravitational force and the flux fall off as distance squared, the net acceleration of the Local Group is proportional to the dipole of the light distribution for a constant mass-to-light ratio $T$. Thus,

$$\mathbf{g} = G \sum_i \frac{m_i}{r_i^2} = GT \sum_i S_i \hat{r}_i,$$  \hspace{1cm} (1)

where $S_i$ is the flux received from each galaxy and $\hat{r}_i$ is a directional unit vector. Stellar mass-to-light ratios vary by only a factor of 2 in the $K_s$ band (Bell & de Jong 2001), so the assumption of a constant mass-to-light ratio is good for the stellar population. However, the light may be a biased tracer of the total mass (Kaiser 1984); if there is linear biasing, then the true acceleration would be a factor 1/b times the measured value. If the biasing is more complicated than linear, then the gravitational acceleration need not point in the same direction as the flux dipole. Thus, testing that the two are aligned can verify if linear biasing is a valid assumption.

Linear theory can be used to estimate the resultant velocity (Peebles 1980, p. 435), which depends on the matter density of the universe $\Omega_m$. The expected velocity of the Local Group is therefore

$$v = \frac{2}{3} \frac{f(\Omega_m)}{bH_i} \Omega_m g,$$  \hspace{1cm} (2)

where $f(\Omega_m) = \Omega_m^{5/6}$ (Peebles 1980) and $H_i$ is the Hubble constant. Of course, this is only true in linear theory. Nonlinear N-body simulations show that the velocity of a region like the Local Group is typically within 8$^\circ$ of the computed linear acceleration and within 12$^\circ$ at the 90% confidence level (Ciecielag, Chodorowski, & Kudlicki 2001; Davis, Strauss, & Yahil 1991). Ciecielag et al. (2001) found that in a cold dark matter model, the velocity inferred from the acceleration overestimated the true velocity by 6.5% and had an rms uncertainty of 11%. Measuring the light dipole therefore achieves two aims: (1) It verifies that the CMB dipole is truly caused by the Sun’s motion, and (2) it can determine a combination of $T_k$, $\Omega_m$, and $b$. Since $\Omega_m$ and $T_k$ can be measured by other means, we can therefore determine the value of $b$.

To accurately calculate a clustering dipole, we need to consider the effect of the masked region. We address this in two ways: by cloning the sky above and below the masked regions (Lynden-Bell et al. 1989) and by filling the masked region with randomly chosen galaxies such that it has the same surface density as the unmasked area. We apply both methods to estimate the uncertainty contributed by the masked region. Filling the mask using a spherical harmonic analysis (Rowan-Robinson et al. 2000) is a more accurate method than those we have employed; however, the uncertainty associated with how the masked region is filled is fairly small in any case.

Figure 1 shows the convergence of the magnitude of the clustering dipole as a function of the flux limit of the survey. The dipole mostly arises from galaxies with $K_s < 12$ mag, the
brightest 50,000 galaxies. The dipole converges at fainter magnitudes, and the addition of 300,000 galaxies with $K_s > 13.2$ changes the dipole by less than 5%. We also show the convergence for each component of the clustering dipole. This is compelling evidence that the dipole has converged in the 2MASS sample and that any flux we are missing in low-luminosity galaxies is a minor contribution.

To estimate the effect of shot noise on our calculation, we perform bootstrap resampling on the galaxy catalog. We first bin the galaxies by their fluxes and then resample each flux bin to ensure that the resampled catalog has the correct flux distribution. Performing the resampling 100 times, the standard deviation of the clustering dipole direction is $\Delta l = 0.76$, $\Delta b = 0.73$, and in magnitude it is 0.5%. We find that the systematic uncertainties are much larger than the shot noise.

The most important source of systematic error in our calculation is our treatment of the mask. Cloning the sky above and below the mask gives a dipole pointing toward $l = 265^\circ$, $b = 40^\circ$. If instead of cloning the adjacent sky we fill the mask with randomly selected galaxies, the direction of the dipole changes to $l = 266^\circ$, $b = 47^\circ$. We adopt the mean of these two measurements ($l_{\text{dipole}} = 264^\circ 5 \pm 2^\circ$, $b_{\text{dipole}} = 43^\circ 5 \pm 4^\circ$) as the best-fit dipole, with the error bars reflecting the mask-filling uncertainties. The dipole calculated by using only galaxies brighter than $K_s = 13$ and by filling the mask with cloning points to $l = 258^\circ$, $b = 42^\circ$, which verifies that missing fainter galaxies are not introducing any significant error.

The 2MASS clustering dipole is $16^\circ$ from the CMB velocity dipole. This is larger than the average separation of $8^\circ$ found in the $N$-body simulations and is outside the 90% confidence limit of $12^\circ$. Therefore, we conclude that the 2MASS-determined clustering dipole is only marginally consistent with the direction of the Local Group motion given the uncertainties caused by nonlinear effects and systematic errors.

Interestingly, our clustering dipole is $15^\circ$ from the dipole measured most recently using the IRAS Point Source Catalog Redshift (PSCz) survey (Rowan-Robinson et al. 2000). This is larger than the systematic errors in either calculation and therefore suggests differences caused by the passband of the survey or differences in the methods used to calculate the clustering dipole. The clustering dipole measured by Rowan-Robinson et al. (2000) is not a flux dipole, but instead it is measured by the overdensity of galaxies smoothed over a given scale.

As a first step in understanding this discrepancy, we identify 12,831 2MASS counterparts to PSCz galaxies out of 14,592 galaxies in the PSCz survey. We expect that most of the unmatched galaxies are fainter than 13.57 in the $K_s$ band. We find that the 2 $\mu$m flux dipole of the PSCz galaxies points toward $l = 267^\circ$, $b = 50^\circ$, only a few degrees from the flux dipole of the entire 2MASS catalog. Thus, we conclude that the difference between our result and that of Rowan-Robinson et al. (2000) is due to the type of dipole calculated and not to the type of galaxies used.

The discrepancy of the two dipoles calculated from the same galaxies but with different methods may be due to a small number of bright galaxies that unduly influence the flux dipole. If we consider the flux dipole for the entire 2MASS sample from galaxies fainter than $K_s = 8$ mag (removing 375 galaxies), we find that the resulting dipole is within a few degrees of the CMB velocity dipole (see Fig. 2). Likewise, removing galaxies brighter than $K_s = 8$ from the PSCz sample (210 galaxies) yields a flux dipole within a few degrees of the CMB velocity dipole. So the discrepancies both between the two surveys and between both surveys and the CMB are due to the brightest galaxies.

The magnitude of the 2MASS clustering dipole is $10.3 \pm 0.7$ times the solar flux in the $K_s$ band, which is equivalent to an apparent $K_s$ magnitude of 0.80 or $(1.03 \pm 0.07) \times 10^{-3}$ $L_\odot$ kpc$^{-2}$. Again, the errors are dominated by the systematic uncertainties in the treatment of the masked area.

4. ESTIMATING THE LINEAR BIAS

Using the Wilkinson Microwave Anisotropy Probe, Bennett et al. (2003) recently determined the matter density of the uni-

![Location of the 2MASS clustering dipole shown relative to the CMB velocity dipole. Also shown is the location of the clustering dipole calculated from the IRAS PSCz survey (Rowan-Robinson et al. 2000). The squares are used to show the clustering dipole when using the cloning method, while the diamonds indicate that the mask was filled with random galaxies. The 2MASS dipole is $16^\circ$ from the CMB velocity dipole and $15^\circ$ from the PSCz clustering dipole. If we consider only 2MASS galaxies fainter than $K_s = 8$ mag (this removes 375 galaxies), then the clustering dipole moves to the crosses, in excellent agreement with the CMB velocity dipole. Thus, we conclude that the $16^\circ$ difference between 2MASS and the CMB is caused by the bright galaxies, where the assumption of a constant mass-to-light ratio is probably not valid. Also shown is the 2 $\mu$m flux dipole for the galaxies in the PSCz survey (square with a multi cross) and removing the brightest ones (square with a cross and a multi cross).]
verse to be $\Omega_m = 0.27 \pm 0.04$, and $H_0 = 71 \pm 4 \text{ km s}^{-1} \text{Mpc}^{-1}$ (Spergel et al. 2003). From the 2MASS luminosity function, we can determine the $K'$ luminosity density of the universe to be $J_K = (5.27 \pm 0.11) \times 10^{-5} h L_\odot \text{Mpc}^{-3}$ (Bell et al. 2003), and therefore the average mass-to-light ratio is $\mu_r = 71 h^{-1} \pm 5 M_\odot/L_\odot$. Using these values in equation (2), we find that the expected velocity in linear theory is $705b^{-1} \pm 80 \text{ km s}^{-1}$ compared with the value measured from the CMB of $622 \text{ km s}^{-1}$. Including the 6.5% overestimate and the 11% uncertainty between the linear prediction and the measured velocity in non-linear $N$-body simulations (Ciecielag et al. 2001), we find that $b = 1.06 \pm 0.17$.

There are many methods for measuring the biasing parameter that yield differing results. Using the bispectrum, a value of $b = 1.04 \pm 0.11$ is found in the $b_1$-band–selected Two-Degree Field Galaxy Redshift Survey (2dFGRS: Verde et al. 2002), and $b = 0.83 \pm 0.13$ is found for the IRAS-selected galaxies in the PSCz survey (Feldman et al. 2001). Most measurements determine a combination of $\Omega_m$ and $b$ for which we will take $\Omega_m = 0.27$. Then Peacock et al. (2001) find $b = 1.06 \pm 0.17$ using redshift space distortions, and Hawkins et al. (2002) find $b = 0.93 \pm 0.17$ from two-point correlation functions, both for the 2dFGRS. Comparing peculiar velocities with the density fields measured in galaxy surveys, Blakeslee et al. (1999) find $b = 1.09 \pm 0.21$ for IRAS and $b = 1.75 \pm 0.54$ for the $b_1$-band–selected Optical Redshift Survey (Santiago et al. 1995). The biasing parameter that we estimate from the clustering dipole is in good agreement with all of these results, which are consistent with $b = 1$.

Therefore, it does not appear that $K'$-band–selected galaxies are clustered differently than galaxies selected in optical wave bands. The measurement of the 2MASS clustering dipole would be greatly improved by a more detailed study of the brightest galaxies; however, we do not expect this to significantly change the value of the $K'$-band biasing parameter. Thus, we conclude that the biasing parameter is not a strong function of wave band, which can be used to help constrain theories of the formation and evolution of galaxies.

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Fig. 3.—Upper two images: Southern and northern Galactic hemispheres in Lambert’s projection. Lower image: Whole sky in an Aitoff projection. The color denotes the smoothed flux density measured in units of the solar K-band flux deg$^{-2}$. In the lower image, the Galactic center has been masked out (dashed line), and adjacent regions have been cloned to fill the masked region. We have labeled the most prominent structures: (S) “Shapley” complex, which includes Hydra-Centaurus in the foreground; (P-I) Pavo-Indus wall; (P-P) Perseus-Pisces chain; (H-R) Horologium-Reticulum supercluster; (V) Virgo supercluster; (UM) Ursa Major cloud; (N) NGC 1600 group; and (GW) the “Great Wall.” The green line delineates the super–galactic plane along which many of these structures lie. Also, the CMB (white cross) and 2MASS (green cross) dipoles are shown.