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2MASS and the Nearby Universe

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Abstract. The Two Micron All-Sky Survey was conceived over a decade ago for the express purpose of mapping the Milky Way and the Universe nearby. 2MASS is now complete and the final data products, including the extended source catalog (XSC), have been released. The XSC contains nearly a million galaxies to the stated completeness goal of K=13.5. While the catalog becomes incomplete at the faintest magnitudes and lowest galactic latitudes due to confusion, at the bright end the catalog is essentially complete down to very low latitudes (b less than 5 degrees), which makes it an excellent survey for the distribution of matter in the nearby Universe. Redshift information is now nearly complete for the 24,000 galaxies brighter than K=11.25 and above $|b|=5°$. We now have an amazing census of galaxy (baryonic mass) concentrations over the whole sky and inside z=0.04. Several new structures are elucidated and the characteristics of the structures are described. We also examine the match between the predicted gravitational velocity vector of the Local Group and the motions determined by other experiments including the CMB dipole.

1. Introduction

In the mid-late 1970s, several discoveries were made, based on innovations in detector technology and on the understanding of galaxies, that substantially changed our view of the Nearby Universe. The CMB Dipole was discovered by groups in Italy and Princeton (Cheng et al. 1979; Fabbri et al. 1980). The first 3-D redshift surveys were started (cf. Davis et al. 1982), and the Virgo Infall was both convincingly predicted & measured (de Vaucouleurs 1956; Silk 1974; Peebles 1976; Aaronson et al. 1982). The kinematics of the Local Universe became a cosmological test and tool and, with the realization that the Virgo supercluster was insufficient to explain the CMB dipole, the search for the source of the flow (astronomy's Nile!) became a major cosmological quest.

Together, in the 1980's these led to the discovery of even larger mass concentrations such as the Great Attractor (Lynden-Bell et al. 1988) and the Shapley Supercluster (Tully & Shaya 1984; Tammann & Sandage 1985), and the initiation of several very large scale redshift surveys based on IR and optical catalogs

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(e.g. IRAS 1.2 Jy, Strauss et al. 1992; IRAS PSC-z, Saunders et al. 2000; and the ORS, Santiago et al. 1995). Perforce then followed advanced distance surveys and catalogs (c.f. Mould et al. 1993; Willick et al. 1997). Sophisticated techniques were developed to analyse these surveys (Dekel, Bertschinger & Faber 1990; Zaroubi et al. 1995), but despite reasonable data and thorough analyses, the source of the CMB flow was not convincingly identified and there remained very significant conflicts between the results of different surveys (e.g. IRAS vs ORS, Schmoldt et al. 1999).

At the end of the 1990's, there remained a conflict between Ω_M on all measured scales and the Ω_M=1 strongly predicted from inflation and CDM. Was it real or were there problems with the data or the theory? Most of the community realized that **all** extant maps were tremendously biased, either by wavelength (read young star formation, which dominates blue and far-IR=IRAS light) or by extinction. This was the explanation pushed by the theorists — the galaxies we were measuring were not really tracing the mass.

2. 2MASS

Many of us began to think of possible solutions to this observational problem, i.e. designing surveys that would not be biased and would trace, at least, the baryonic mass in stars. The best and simplest solution was clear — go to the near IR! A survey done at 2 μm would beat extinction, the bane of optical surveys, and would select for the stars that trace the baryonic mass in normal old stellar populations. The light from old populations peaks, at z=0, at $\sim$1.6 μm. The Galactic Center is dimmed by a factor of 10^{12} at the B-band but only a factor of 10 at K. However the only all-sky survey at the time, the TMSS (Neugebauer & Leighton 1969), could barely see 8th magnitude stars, never mind distant galaxies.

The first opportunity to do such a survey came in 1988, when NASA announced an opportunity for the first Small Explorer (SMEX) missions. A group of us headed by Giovanni Fazio and driven by the desire to produce all sky maps of both galaxies and stars, proposed NIRAS, the Near IR Astronomy Satellite, to map the sky in K and L with the detectors that had been selected for SIRTF (nee Spitzer). This proposal failed, not because the scientific justification was poor but because many people on the NASA review panel for the SMEX program felt that it would be cheaper to do this survey from the ground. Based on the strongly positive response to the science, Susan Kleinmann and I started work on a ground-based version of the proposal, 2MASS, first submitted to NSF and NASA in 1991, and finally supported in 1993. Our basic idea was to use two matched small telescopes to do a simultaneous (with dichroics) JHK all-sky survey. Our goal, for the extragalactic science, was to produce an all-sky galaxy catalog complete to K$\sim$ 13.5 with extremely good photometric uniformity. Studies of clustering and flows require photometric uniformity at a level better than Δv v, so 100 km/s at 10,000 km/s demands 1% uniformity.

We succeeded. In the end, we used HgCdTe detectors instead of InSb, and surveyed the sky with matched 1.3-m telescopes at Mt. Hopkins and CTIO using a freeze-frame scanning technique suggested by Frank Low. The data taking was completed in early 2001. The final data release of 2MASS is now

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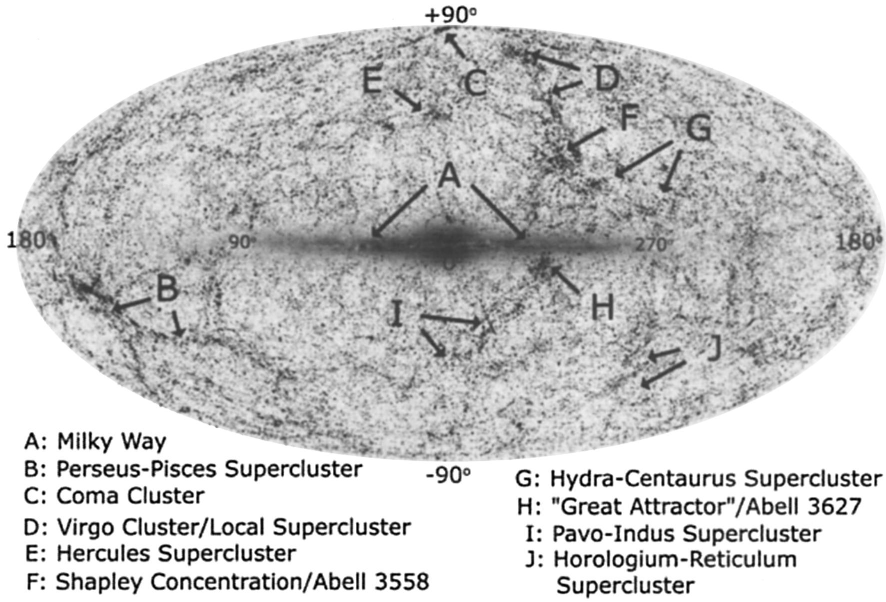

Figure 1. An all-sky Aitoff view of the 2MASS Extended Source Catslog (XSC) with major known structures labeled. The coordinate system is galactic and the 2MASS point source catalog is used to display the Milky Way itself. The plane of the Local Supercluser stands out to the right of center.

available (see Cutri et al. 2003; Jarrett et al. 2000, 2003; for descriptions of the data products and the Extended Source Catalog = XSC). Figure 1 shows our all-sky maps (e.g. Jarrett 2004) of the galaxy distribution, with well known, nearby, large-scale structures labeled.

The science team's efforts have shown the XSC to be extremely uniform, with the photometric zeropoint varying by less than 0.01 magnitude over the sky, and complete for galaxies above $|b|$=10 to $K_S \sim$13.5 (see the on-line Explanatory Supplement and related links, Cutri et al. 2003) . There are over a million galaxies in the XSC, and nearly 600,000 to the completeness limit of 13.5. The discussions below concentrate on results from the analysis of the 2MASS galaxy catalog, a subset of the XSC.

3. Galaxy Properties, Preliminary Dipole

Several results can be obtained from the XSC after a quick collation with catalogs of known galaxy redshifts and types (e.g. ZCAT, Huchra et al. 1992). There are almost 90,000 2MASS galaxies with measured redshifts.

First, in the IR, galaxies are incredibly similar. The JHK colors of galaxies have incredibly small dispersion independent of morphological type, < 0.08 mag in J-H, and 0.09 mag H-K. Second, the morphological mix of galaxies is not that dissimilar to that in optically selected samples. We have begun to systematically classify all of the galaxies in the redshift survey described below. We find that

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for the sample of 2MASS galaxies brighter than K=11.25, 40% are early types versus 30% in a B selected sample (CfA1). The major difference between 2MASS and, for example, the Updated Zwicky Catalog (Falco et al. 1999), is that there are far fewer low surface brightness, very late type galaxies in 2MASS. This is also a characteristic of most other digital catalogs (LCRS, 2dF and probably SDSS) which have not included results of specialized processors for LSB galaxies.

A very simple analysis of the 2MASS catalog also allows us to derive the 2MASS light vector, the direction of motion of the Local Group induced by the local inhomogeneities in the galaxy distribution for comparison to the CMB vector. If we add up all of the light from galaxies in the XSC, taking care to eliminate members of the local group itself, weighting each galaxy by its apparent flux remembering that both light and gravitational force go as $1/r^2$, and cutting the catalog at a magnitude limit where we believe we are moderately complete over the sky ($6 \leq K \leq 12.5$), we predict a LG motion towards l=236 b=37. This preliminary number is about 40° away from the observed CMB dipole at l=273, b=27, but we have not yet corrected for the 2MASS sky coverage mask and the GA is very near the galactic plane.

Finally, with a complete sample of redshifts for galaxies brighter than 11.25 (~20,000 galaxies above |b|=10), we can compute the K-band luminosity function for 2MASS (Figure 2). A Schechter function with $K^* = -24.2$ and $\alpha = -1.02$ is a reasonable, but not perfect, fit.

4. The 2MASS Redshift Survey

The primary extragalactic goal of 2MASS, however, was to feed the next generation of all-sky redshift survey, to fully map the nearby universe. To that end, we have been obtaining redshifts for 2MASS identified galaxies with the goal of completing a survey of all objects brighter than 13.0 over the next decade. This work is being done in phases. The first phase of the project is to complete the redshifts to all galactic latitudes for galaxies brighter than K=11.25. The second stage of the project will be to extend that to 12.25, but limiting ourselves to galactic latitudes above 5-10 degrees. The final stage is based on the 6dF survey in the southern hemisphere (Jones et al. 2004; which uses 2MASS as its parent catalog to observe to $K_{Total}=12.8 = K_{iso}=13.0$) and an as yet to be determined survey in the north.

We have nearly completed the redshifts for all ~23,000 galaxies brighter than K=11.25 and above |b|=5°, and are now pushing as deeply into the galactic plane as the coverage map and available spectrographs allow. Some initial qualitative results from this survey are shown below via two visualization techniques: Hockey Pucks and Onion Skins.

4.1. Hockey Pucks

An all-sky survey allows us to make plots of the nearby galaxy distribution that are more representative than simple strip surveys (deLapparent, Geller, & Huchra 1986). The angular nature of strips around the sky, when projected onto a plane, are somewhat deceptive of real structure. They are thin at the center and thick at the edge. While this partially makes up for the normal decrease in the selection efficiency as a function of redshift in a flux limited sample, it

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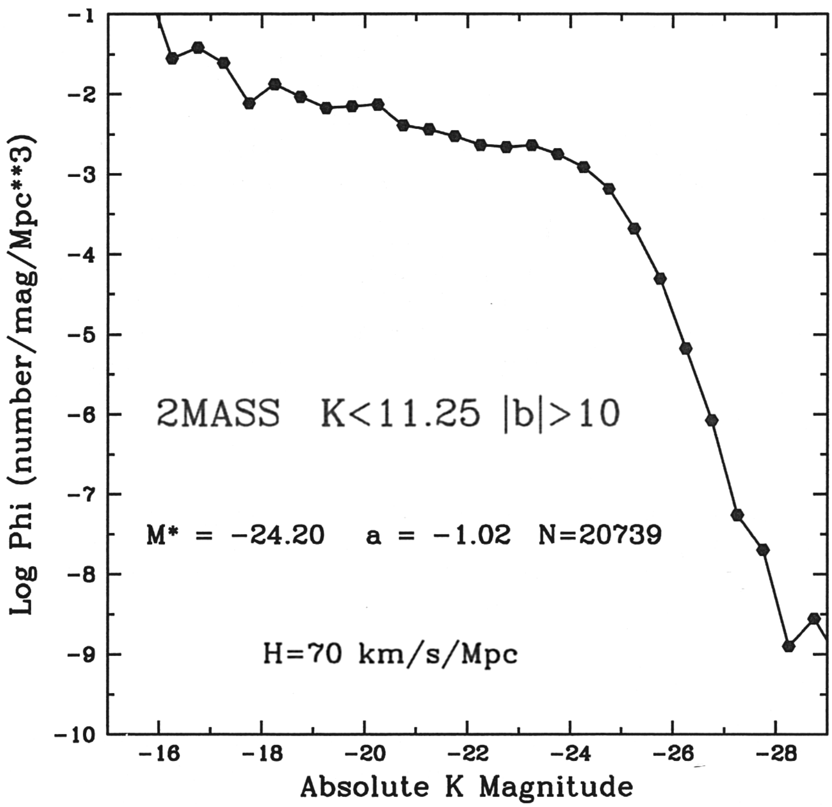

Figure 2. Space density of the ∼20,800 2MRS galaxies brighter than K=11.25 and with galactic latitude |b| ≥10 degrees.

provides a representation of structure that varies quite strongly from the center to the edge. With full sky coverage, it is possible to project actual cylinders of redshift space. Coming from Boston, I naturally call these Hockey Puck plots. Two are give in Figures 3 and 4.

Many of our favorite structures are easily seen in these plots. The northern puck has an aspect ratio of about 3.5 to 1 (30000 km/s / 8000 km/s) . It is dominated by the Local Supercluster at the center, the Great Wall at 10-14.5 hours and Pisces-Perseus at 0-5 hours. In addition, there are several new but smaller structures such as the one at 19 hours and 4000 km/s, probably best associated with the Cygnus Cluster (Huchra, Hoessel, & Elias 1977).

The southern celestial hemisphere is more amorphous. There is the well known Cetus Wall (Fairall 1998) between 0 and 4 hours, the southern part of the Local Supercluster at the center, and the Hydra-Centaurus region, but also a large and diffuse overdensity between 19 and 22 hours, a region hitherto not mapped because of its proximity to the galactic plane. This structure appears

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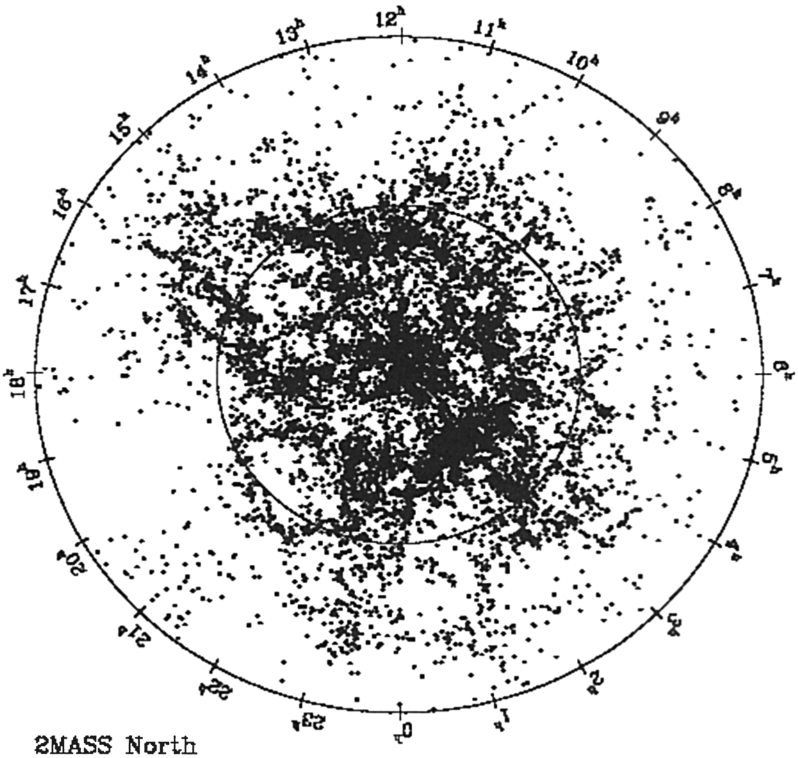

Figure 3. Hockey Puck plot — a full cylinder section — of the 2mass Redshift Survey (2MRS) in the north celestial cap. The view is looking downwards from the NCP, the thickness of the "puck" is 8000 km/s and its radius is 15,000 km/s.

to be both large and rich and should have a large effect on the local velocity field.

4.2. Onion Skins

Another projection that can highlight the properties of nearby structures are surface maps of the galaxy distribution as a function of redshift. Since these are conceptually like peeling an onion, they are best called "onion skins." Figures 5, 6 and 7 show three sets of these skins, moving progressively outward in redshift.

The first plots the distribution on the sky of all galaxies in the survey inside 3000 km/s coded by redshift in 1000 km/s skins. The plane of the Local Supercluster dominates the map, but there is also a diffuse component between 2000 and 3000 km/s and 6 to 13 hours in the south.

The next two images again show some familiar structures but with a few surprises. The Great Wall, Pisces-Perseus and Great Attractor dominate the mid ranges. The overdensity of galaxies in the direction of A3627 is high, and the comparison of the 3-6k map with the 6-9k map clearly shows why we are

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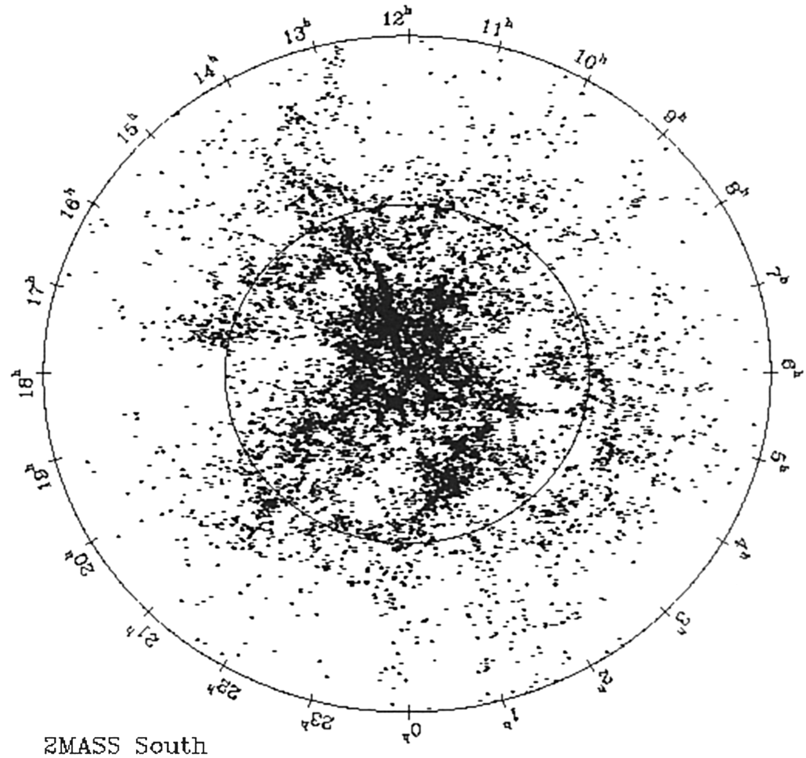

Figure 4. The same as the previous figure but for the 2MRS redshift distribution south of the celestial equator.

moving w.r.t. the CMB towards a point around 12 hours RA and in the southern hemisphere.

5. Conclusions

The first phase of the 2MASS redshift survey is nearing completion and should be released this year. It provides a spectacular 3-D view of the Local Universe unbiased by the extinction in our own galaxy. We will have a proper analysis of the CMB dipole and predictions for the local flow field very soon.

2MASS has fulfilled its goal of providing an extremely uniform, deep and unbiased survey of the nearby Universe. The characteristics of the structures are similar to what have been seen before, however we now have an essentially complete local map. Now we need to measure both redshifts and real distances to extract the full measure of cosmological information. When the full redshift survey is complete in a decade, we will have a map of the local Universe out to a tenth the speed of light.

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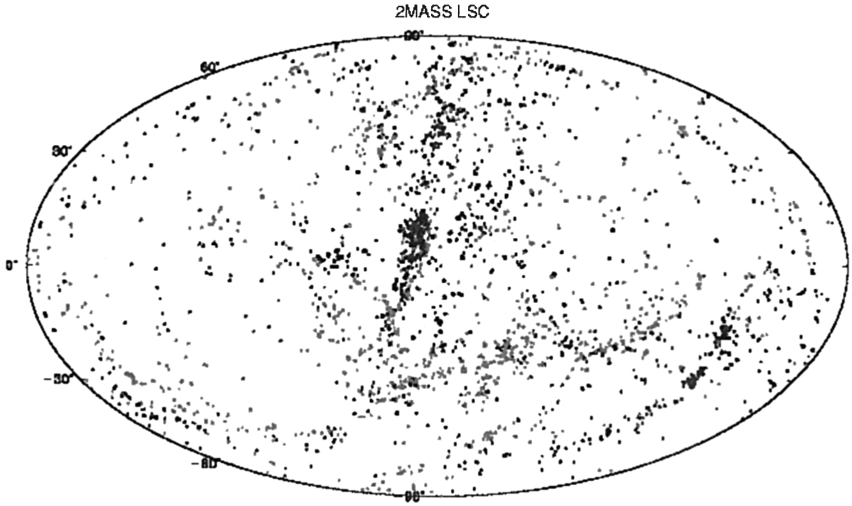

Figure 5. 2MASS galaxies inside 3000 km/s. Objects with velocities less than 1000 km/s are shown as black, mid-grey for 1000-2000 km/s, and light grey for 2000-3000 km/s. The LSC dominates.

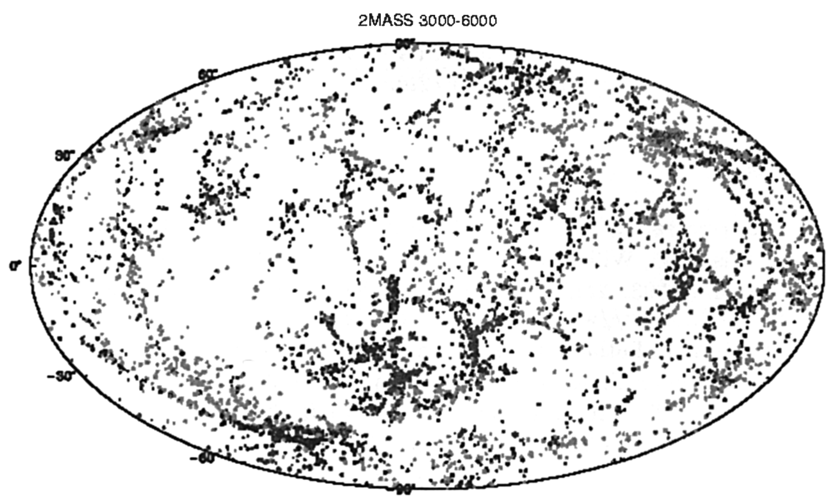

Figure 6. 2MASS galaxies between 3000 and 6000 km/s. Black shows the lowest redshift "skin," mid-grey the middle range and light grey the high 1000 km/s range.

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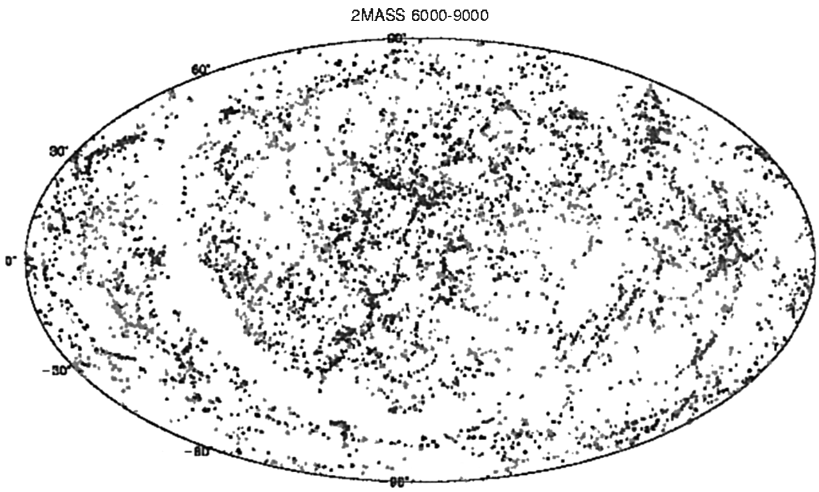

Figure 7. Ditto but now for 6000-9000 km/s.

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References

Aaronson, M., Huchra, J., Mould, J., Schechter, P., & Tully, B. 1982, ApJ, 258, 64

Cheng, E., Saulson, P., Wilkinson, D., & Corey, B. 1979, ApJL, 232, L139

Cutri, R., et al. 2003, 2MASS All-Sky Catalog of Point Sources (San Francisco: IPAC/CIT), http://www.ipac.caltech.edu/2mass/

Davis, M., Huchra, J., Latham, D., & Tonry, J. 1982, ApJ, 253, 423

Dekel, A., Bertschinger, E., & Faber, S. 1990, ApJ, 364, 349

de Lapparent, V., Geller, M., & Huchra, J. 1986, ApJL, 302, L1

de Vaucouleurs, G. 1956, Vistas in Astronomy, 2, 1584

Fabbri, R., Guidi, I., Melchiorri, F., & Natale, V. 1980, PhRvL, 45, 401

Fairall, A. 1998, Large-Scale Structures in the Universe (Chichester: Wiley/Praxis)

Falco, E., et al. 1999, PASP, 111, 438

Huchra, J., Geller, M., Clemens, C., Tokarz, S., & Michel, A. 1992, Bull. C.D.S., 41, 31

Huchra, J., Hoessel, J., & Elias, J. 1977, AJ, 82, 674

Jarrett, T. 2004, in Structure and Dynamics in the Local Universe, ed. Bland-Hawthorn (PASA), in press

Jarrett, T., Chester, T., Cutri, R., Schneider, S., & Huchra, J. 2003, AJ, 125, 525

Jarrett, T., et al. 2000, AJ, 119, 2498

https://doi.org/10.1017/S0074180900196603 Published online by Cambridge University Press

Jones, D., et al. 2004, MNRAS, submitted
Lynden-Bell, D., et al. 1988, ApJ, 326, 19
Mould, J., et al. 1993, ApJ, 409, 14
Neugebauer, G., & Leighton, R. 1969, Two-Micron Sky Survey, NASA SP 3047
Peebles, P. 1976, ApJ, 205, 318
Santiago, B., et al. 1995, ApJ, 446, 457
Saunders, W., et al. 2000, MNRAS, 317, 55
Schmoldt, I., et al. 1999, AJ, 118, 1146
Silk, J. 1974, ApJ, 193, 525
Strauss, M., et al. 1992, ApJS, 83, 29
Tammann, G., & Sandage, A. 1985, ApJ 294, 81
Tully, B., & Shaya, E. 1984, ApJ, 281, 31
Willick, J., et al. 1997, ApJS 109, 333
Zaroubi, S., Hoffman, Y., Fisher, K., & Lahav, O. 1995, ApJ, 449, 446

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