THE 2MASS REDSZHIFT SURVEY—DESCRIPTION AND DATA RELEASE

JOHN P. HUCHRA1,15, LUCAS M. MACRÉ2, KAREN L. MASTERS3,4, THOMAS H. JARRETT5, PERRY BERLING1, MICHAEL CALKINS1, AIDAN C. CROOK6, ROC CUTRI7, PIRIN ERDOĞDU7, EMILIO FALCO8, TEDDY GEORGE9, CONRAD M. HUTCHESON9, OFER LAHAV7, JEFF MADER10, JESSICA D. MINK1, NATHALIE MARTIMEAU11, STEPHEN SCHNEIDER12, MICHAEL SKRUTSKIE13, SUSAN TOKARZ1, AND MICHAEL WESTOVER14

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
2 George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA; lmacri@tamu.edu
3 Institute for Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth, PO1 3FX, UK; karen.masters@port.ac.uk
4 SEPNet (South East Physics Network), UK
5 Infrared Processing and Analysis Center, California Institute of Technology, 770 S Wilson Ave., Pasadena, CA 91125, USA
6 Microsoft Corp., 1 Microsoft Way, Redmond, WA 98052, USA
7 Department of Physics and Astronomy, University College London, London WC1E 6BT, UK
8 Canada–France–Hawaii Telescope, 65-1238 Mamalahoa Hwy, Kamuela, HI 96743, USA
9 Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94309, USA
10 Keck Observatory, 65-1120 Mamalahoa Hwy, Kamuela, HI 96743, USA
11 Planétarium de Montréal, 1000 rue Saint-Jacques, Montréal, Québec H3C 1G7, Canada
12 Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA
13 Department of Astronomy, University of Virginia, Charlottesville, VA 22904, USA
14 McKinsey & Co., 1420 Fifth Ave., Ste 3100, Seattle, WA 98101, USA

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ABSTRACT

We present the results of the 2MASS Redshift Survey (2MRS), a ten-year project to map the full three-dimensional distribution of galaxies in the nearby universe. The Two Micron All Sky Survey (2MASS) was completed in 2003 and its final data products, including an extended source catalog (XSC), are available online. The 2MASS XSC contains nearly a million galaxies with $K_s \leq 13.5$ mag and is essentially complete and mostly unaffected by interstellar extinction and stellar confusion down to a galactic latitude of $|b| = 5^\circ$ for bright galaxies. Near-infrared wavelengths are sensitive to the old stellar populations that dominate galaxy masses, making 2MASS an excellent starting point to study the distribution of matter in the nearby universe. We selected a sample of 44,599 2MASS galaxies with $K_s \leq 11.75$ mag and $|b| \geq 5^\circ$ ($\geq 8^\circ$ toward the Galactic bulge) as the input catalog for our survey. We obtained spectroscopic observations for 11,000 galaxies and used previously obtained velocities for the remainder of the sample to generate a redshift catalog that is $97.6\%$ complete to well-defined limits and covers $91\%$ of the sky. This provides an unprecedented census of galaxy (baryonic mass) concentrations within $300$ Mpc. Earlier versions of our survey have been used in a number of publications that have studied the bulk motion of the Local Group, mapped the density and peculiar velocity fields out to $50\ h^{-1}$ Mpc, detected galaxy groups, and estimated the values of several cosmological parameters. Additionally, we present morphological types for a nearly complete sub-sample of 20,860 galaxies with $K_s \leq 11.25$ mag and $|b| \geq 10^\circ$.

Key words: catalogs – galaxies: distances and redshifts – surveys

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

Between the mid-1970s and the early 1980s, several discoveries were made based on innovations in detector technology and better understanding of galaxies that substantially changed our view of the nearby universe. The cosmic microwave background (CMB) dipole was convincingly measured (Corey & Wilkinson 1976; Smoot et al. 1977; Cheng et al. 1979), the first ground (CMB) dipole was convincingly measured (Corey & Wilkinson 1976; Smoot et al. 1977; Cheng et al. 1979), the first

In the 1980s, this quest led to the discovery of even larger mass concentrations such as the Great Attractor (Burstein et al. 1986; 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 (e.g., Strauss et al. 1992; Santiago et al. 1995; Saunders et al. 2000). Perforere then followed advanced distance surveys and catalogs (Mould et al. 1993; Willick et al. 1997). Sophisticated techniques were developed to analyze these surveys (Dekel et al. 1990; Zaroubi et al. 1995), but despite reasonable data and thorough analyses, the source of the CMB dipole was not convincingly identified and there remained very significant conflicts between the results of different surveys (e.g., Schmoldt et al. 1999).

Near the end of the 1990s, a conflict remained between $\Omega_M$ on all measured scales and the $\Omega_M = 1$ strongly predicted from inflation and cold dark matter models. Was the discrepancy real or were there problems with the data and/or the theory? Most of the community realized that all extant maps were tremendously

15 This paper is mostly based on the text written by John Huchra before his death in 2010 October.
biased, either by extinction or by wavelength (read “young star formation,” which dominates both blue and far-infrared light). This was the explanation advocated by the theorists—the galaxies being measured were not really tracing the mass.

Fortunately, the overall Ω problem was solved soon thereafter with the discovery of dark energy (Riess et al. 1998; Perlmutter et al. 1999) coupled with the accurate determination of the Hubble constant (Freedman et al. 2001) and the measurement of the large-scale geometry of the universe through observations of fluctuations in the CMB (Spergel et al. 2003). Still, several very significant questions remain. Can we accurately (to a few percent) observationally account for the matter density in the nearby universe? How is matter distributed? In particular, can we explain gravitationally the motion of the Milky Way with respect to the CMB? Do we understand the differences, if any, in the distribution of ordinary baryonic matter and dark matter (i.e., the bias function)? These questions are yet unanswered and clearly drive the detailed understanding of galaxy and large-scale structure formation and evolution.

Despite all of the aforementioned work, even the galaxy density field of the Local Supercluster (LSC) is not in good shape. Despite high-quality data on the flow field, Tonry et al. (2000) found there are many missing elements to the model of the LSC, including possible local sources of the observed quadrupole field and the “Local Anomaly.”

2. THE TWO MICRON ALL SKY SURVEY

The Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) had its origins in a proposal to NASA for a “Near InfraRed Astronomical Satellite” by G. Fazio, J. Huchra, J. Mould, and collaborators in 1988. The survey was eventually carried out by a team led by astronomers at the University of Massachusetts (UMass) using twin 1.3 m telescopes located at Mount Hopkins, AZ (starting in 1997) and Cerro Tololo, Chile (starting in 1998). Scans were completed by 2001 and the final data release was made available in 2003 through IPAC.16

2MASS mapped the entire sky in the J, H, and K bands, avoiding many of the observational biases that affected previous optical and far-infrared all-sky surveys. The effects of interstellar extinction are reduced by 10× relative to the B band and the spectral energy distributions of most galaxies peak at near-infrared wavelengths. Moreover, K-band luminosities are a useful proxy for baryonic mass as the stellar mass-to-light ratio is fairly constant across galaxy types at this wavelength (e.g., within a factor of two; Bell & de Jong 2001). This makes the near-infrared the spectral region of choice to map the distribution of matter in the nearby universe.

The 2MASS photometric pipeline produced a complete and reliable extended source catalog (XSC; Jarrett et al. 2000; Jarrett 2004) of \(\sim 10^{6}\) objects with \(K_s \leq 13.5\) mag and a mean photometric accuracy better than 0.1 mag. Moreover, the database included information on the photometric structure of the galaxies (photometric profiles, axis ratios, etc.). 2MASS provided the first modern, all-sky, highly accurate catalog of galaxies. A few years later, the Sloan Digital Sky Survey (SDSS; York et al. 2000) started to provide overlapping deeper optical data which eventually covered \(\sim 35\%\) of the sky (Aihara et al. 2011), but 2MASS remains the only modern survey which can be used to construct a uniform, all-sky, three-dimensional map of the Local Universe.

16 http://www.ipac.caltech.edu/2mass/

Figure 1. Distribution of 2MASS galaxies with \(K_s \leq 11.75\) mag in Galactic coordinates (Aitoff projection). Blue dots represent galaxies outside our survey area. Note that due to stellar confusion we cannot cover, even to this bright magnitude limit, the very central region of the galaxy, but we do cover \(\sim 91\%\) of the sky.

(A color version of this figure is available in the online journal.)

Two decades before 2MASS, the first flux-limited all-sky galaxy catalog was created from observations by the IRAS satellite at 60 \(\mu\)m (Strauss et al. 1990). Since galaxies were unresolved by IRAS, the point source catalog formed the basis of a redshift survey (PSCz; Fisher et al. 1995; Saunders et al. 2000). Among other problems, the PSCz catalog gave little weight to ellipticals (which are dim at 60 \(\mu\)m because this wavelength is dominated by dusty star formation) and suffered from severe confusion in regions of high density. However, the uniform full-sky coverage was unique at the time.

2.1. The Zone of Avoidance

2MASS is an excellent probe of the zone of avoidance for bright galaxies, as was discussed in depth by Huchra et al. (2005). Figure 1 is an updated version of Figure 8 from Huchra et al. (2005) showing the 2MASS XSC coverage at \(K_s \leq 11.75\) mag, limited only by confusion near the galactic center. Figure 2 is an updated version of Figure 7 from Huchra et al. (2005) and shows the galaxy surface density versus galactic latitude for several magnitude limits. At the bright magnitudes surveyed by 2MRS, the catalog is essentially complete to very low latitudes.

3. THE 2MASS REDSHIFT SURVEY

The primary extragalactic goal of 2MASS was to feed the next generation of all-sky redshift surveys to fully map the nearby universe. To this end, we started a program in 1997 September to obtain the required spectroscopic data for a magnitude-limited sample of galaxies: the 2MASS Redshift Survey (2MRS). Our initial survey limits of \(K_s = 11.25\) mag and \(|b| = 10^\circ\) (20,860 galaxies; hereafter 2MRS11.25) were progressively increased to final values of \(K_s = 11.75\) mag and \(|b| = 5^\circ-8^\circ\) (44,599 galaxies; the full 2MRS), allowing us to steadily complete our view of the Local Universe.

2MRS builds and improves on the previous generation of local surveys (see Table 1) and is complementary to contemporaneous larger, deeper surveys, notably 2dF (Colless et al. 2001), SDSS (Aihara et al. 2011), and specially 6dFGS (Jones et al. 2004, 2005, 2009) which also used the 2MASS XSC as its input catalog and provided a large number of redshifts for our survey.
magnitudes measured in an elliptical aperture defined at the band. We selected as our primary set of magnitudes the isophotal magnitude measurements for each extended source in each XSC. The 2MASS photometric pipeline performed a variety between depth and sky coverage given available telescope time require this level of completeness and tradeoffs must be made the whole sky, since many cosmological measurements do not These larger surveys have not attempted to be complete over

We obtained spectra for 11,000 galaxies that met the selection criteria listed above, plus an additional 2,898 galaxies beyond the catalog limits. Observations were carried out between 1997 September and 2011 January using a variety of facilities which are listed in Table 2. The majority of the spectra obtained for this survey were acquired at the Fred L. Whipple Observatory (FLWO) 1.5 m telescope, which mostly targeted galaxies in the northern hemisphere. In the southern hemisphere, we relied heavily on observations by the 6dFGS project (Jones et al. 2004, 2005, 2009) but also carried out our own observations using the Cerro Tololo Interamerican Observatory (CTIO) 1.5 m telescope. We initially targeted $K_s < 11.25$ mag galaxies to obtain a complete all-sky sample (Huchra et al. 2005) while 6dFGS observations were still ongoing. Later, we targeted galaxies below the Galactic latitude limit of 6dFGS and filled gaps in their coverage.

3.2. Observations, Data Reduction, and Analysis

The initial selection of sources was based on the 2MASS XSC. The 2MASS photometric pipeline performed a variety of magnitude measurements for each extended source in each band. We selected as our primary set of magnitudes the isophotal magnitudes measured in an elliptical aperture defined at the $K_s = 20$ mag/arcsec$^2$ isophote. We also include in our data tables the “total extrapolated magnitudes” derived by the pipeline, but do not use them for our sample selection. In the case of galaxies with angular sizes much greater than the width of a single 2MASS scan, we used the photometry presented in the 2MASS Large Galaxy Atlas (LGA) by Jarrett et al. (2003). We applied a modest extinction correction to the 2MASS XSC or LGA magnitudes using the maps of Schlegel et al. (1998).

We selected 45,086 sources which met the following criteria.

1. $K_s \leq 11.75$ mag and detected at $H$.
2. $E(B-V) \leq 1$ mag.
3. $|b| \geq 5^\circ$ for $30^\circ \leq l \leq 330^\circ$; $|b| \geq 8^\circ$ otherwise.

We rejected 324 sources of galactic origin (multiple stars, planetary nebulae, and HII regions) or pieces of galaxies detected as separate sources by the 2MASS pipeline. Additionally, we flagged 314 bona fide galaxies with compromised photometry for reproprocessing at a future date. Some of these galaxies have bright stars very close to their nuclei which were not detected by the pipeline. Others are in regions of high stellar density and their center positions and/or isophotal radii have been incorrectly measured by the pipeline. Lastly, some are close pairs or multiples but the pipeline only identified a single object. A detailed explanation of the steps taken to reject and reprocess the flagged galaxies is given in the Appendix.

In summary, the final input catalog contains 44,599 entries which are plotted using black symbols in Figure 1. Galaxies outside the survey area are plotted in blue and outline the “zone of avoidance” described previously. In this work, we present redshifts for 43,533 of the selected galaxies, or 97.6% of the sample.

3.1. Sample Selection

The initial selection of sources was based on the 2MASS XSC. The 2MASS photometric pipeline performed a variety of magnitude measurements for each extended source in each band. We selected as our primary set of magnitudes the isophotal magnitudes measured in an elliptical aperture defined at the $K_s = 20$ mag/arcsec$^2$ isophote. We also include in our data tables the “total extrapolated magnitudes” derived by the pipeline, but do not use them for our sample selection. In the case of galaxies with angular sizes much greater than the width of a single 2MASS scan, we used the photometry presented in the 2MASS Large Galaxy Atlas (LGA) by Jarrett et al. (2003). We

![Figure 2. Surface number density vs. galactic latitude for three cuts in the 2MASS XSC at $K_s = 11.75$, 12.5, and 13.25 mag. While the number counts drop sharply in the $5^\circ \leq |b| \leq 10^\circ$ bin for the 13.25 mag sample, the incompleteness is reduced for the 12.5 mag sample and it is essentially zero for the 11.75 mag sample. The upturn in all samples at $90^\circ$ is due to the Coma supercluster.](image)
Figure 3. Top panels: typical spectra obtained in this project. Left: absorption-line spectrum obtained at the FLWO 1.5 m telescope. Right: emission-line spectrum obtained at the CTIO 1.5 m telescope. Bottom panels: results of the cross-correlation technique used to measure the redshifts.

Table 2

| Observatory/Telescope | Camera | Grating (l mm\(^{-1}\)) | Coverage (Å) | Res. (Å) | No. of Gals. with \( K_s \leq 11.75 \) | No. of Gals. with \( K_s > 11.75 \) |
|-----------------------|--------|------------------------|--------------|---------|-------------------------------|-------------------------------|
| Fred L. Whipple       | 1.5 m  | FAST                   | 300          | 3500–7400 | 5                             | 7590                         | 2596                         |
| Cerro Tololo          | 1.5 m  | RCSpec                 | 300          | 3700–7200 | 7                             | 3245                         | 238                          |
| McDonald              | 2.1 m  | es2                    | 600          | 3700–6400 | 4                             | 114                          | 50                           |
| Cerro Tololo          | 4 m    | RCSpec                 | 527          | 3700–7400 | 3                             | 48                           |                              |
| Hobby–Eberly          | 9.2 m  | LRS                    | 300          | 4300–10800| 9                             | 3                            |                              |

At FLWO, most observations were carried out by P. Berlind and M. Calkins, with additional observations by J. Huchra, L. Macri, A. Crook, and E. Falco. Additional spectra were obtained in queue mode by other CfA-affiliated observers. At CTIO, observations were carried out by J. Huchra, L. Macri, and the SMARTS consortium queue operators. At McDonald, observations were carried out by J. Mader, T. George, and resident astronomers. Exposure times ranged from 120 s to 2400 s with an average value of 550 s. Some galaxies were observed on multiple nights (sometimes with increased exposure times relative to the first exposure) to improve the quality of the redshift measurement. The total “open shutter” time for the observations was approximately 2100 hr. Bias and flat frames (dome or internal quartz lamp) were obtained daily. Comparison spectra were obtained before or after each science exposure using a variety of He, Ne, and Ar lamps. Stellar and galaxy radial velocity standards were observed nightly.

The spectra were reduced and analyzed in a uniform manner using IRAF. Images were debiased and flat-fielded using routines in the CCDRED package and one-dimensional spectra were extracted using routines in the APEXTRACT package. Dispersion functions were derived from the comparison lamp spectra and applied to the observations using routines in the ONEWAVE package. The spectra obtained at FLWO were processed by S. Tokarz and N. Martimbeau using the automated pipeline described in Tokarz & Roll (1997). Two typical spectra are shown in the top panels of Figure 3.

Radial velocities were measured by the usual technique of cross-correlating spectra against templates (Tonry & Davis 1979) using the XCSAO task in the RVSO package (Kurtz & Mink 1998). We used a variety of templates developed at the Harvard-Smithsonian Center for Astrophysics. The bottom panels of Figure 3 show the results of the cross-correlation technique for the two representative spectra. Figure 4 shows histograms of internal velocity uncertainties for the galaxies observed at FLWO and CTIO. The median uncertainty values for spectra that only contain absorption lines are 29 and 41 km s\(^{-1}\) for FLWO and CTIO, respectively, while the corresponding values for emission-line spectra are 12 and 24 km s\(^{-1}\).

The reduced spectra are available for further analysis at the Smithsonian Astrophysical Observatory Telescope Data
3.3. Matching with Previous Redshift Catalogs

We retrieved the SDSS-DR8 spectroscopic catalog\footnote{http://data.sdss3.org/sas/dr8/common/sdss-spectro/redux/galSpecInfo-dr8.fits} and searched for counterparts to 2MASS sources using a tolerance radius of 2\arcsec. We found 7069 matches to galaxies without 2MRS redshifts (including 390 galaxies with multiple SDSS observations for which we calculated a weighted mean redshift). These are identified with the catalog code “S.”

We retrieved the 6dFGS-DR3 spectroscopic catalog\footnote{http://www-wfau.roe.ac.uk/6dFGS/6dFGSzDR3.txt.gz} and searched for counterparts to 2MASS sources using a tolerance radius of 10\arcsec. We only selected redshifts measured with the 6dF instrument (code = 126 in column 17 of their catalog), with velocity quality 3 or 4 (equivalent to velocity uncertainties of 55 and 45 km s$^{-1}$, respectively). We obtained 11,763 matches to galaxies without 2MRS redshifts. These are identified with the code “6.”

We performed a literature search for galaxies without 2MRS, 6dF, or SDSS redshifts using the NASA Extragalactic Database (NED). First, we carried out a “Search by Name” query using the 2MASS IDs of the galaxies as input. This returned 12,694 redshifts that were incorporated into our catalog. We refer to these redshifts as the “NED default” set, and they are identified with the catalog code “N.” Next, we performed a “Search near Position” query using the 2MASS coordinates of the galaxies for which no redshift information had been returned by the previous query. We used a tolerance radius of 1\arcmin 3 for the search, which resulted in an additional 11,763 redshifts. These are identified with the code “O.”

Lastly, we matched the 2MASS XSC against J. Huchra’s personal compilation of redshifts (ZCAT) and found velocities for an additional 749 galaxies which had no corresponding information in NED, including 455 galaxies observed by J. Huchra or collaborators prior to the start of 2MRS but were never published. We also identified 77 galaxies for which the ZCAT and NED redshifts were in disagreement and we gave preference to the ZCAT values. Detailed information on these galaxies and those for which we assigned alternative NED redshifts (see preceding paragraph) is provided in the Appendix. Galaxies with ZCAT redshifts are identified with catalog code “O.”

Our catalog gives preference to 2MRS redshifts over any previously published SDSS or 6dF value, to SDSS over 6dF, to 6dF over NED, and to NED over ZCAT, except for the cases described above. We list the additional redshifts for galaxies with multiple measurements in the Appendix, to allow interested readers to assign a different set of precedences or to compute weighted mean redshifts.

Figure 5 shows a comparison of redshifts for all 2MASS galaxies observed by us and by 6dFGS or SDSS. The average redshift difference for galaxies in common between each pair of catalogs is the following: $2 \pm 61$ km s$^{-1}$ for $N = 2511$ galaxies in 2MRS and 6dFGS; $14 \pm 35$ km s$^{-1}$ for $N = 1940$ galaxies in 2MRS and SDSS; $11 \pm 55$ km s$^{-1}$ for $N = 3187$ galaxies in 6dFGS and SDSS. The dispersions are consistent with the typical velocity uncertainties of each survey (30–40 km s$^{-1}$ for 2MRS, 45–55 km s$^{-1}$ for 6dFGS, and 5 km s$^{-1}$ for SDSS).

3.4. The 2MRS Catalog

The 2MRS catalog is presented in Table 3 and is also available at the 2MRS Web site. It contains 29 columns that are described below, including the original 2MASS XSC column names in square brackets when applicable.

\begin{itemize}
  \item 1. ID: 2MASS ID [designation]
  \item 2. R.A.: right ascension (deg, J2000.0) [sup_ra]
  \item 3. Decl.: declination (deg, J2000.0) [sup_dec]
  \item 4. $l$: Galactic longitude
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Distribution of velocity uncertainties for the galaxies observed at FLWO (left) and CTIO (right). The samples are further divided according to the absence or presence of emission lines.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Histogram of velocity differences for galaxies observed by any two of 2MRS, 6dFGS, or SDSS.}
\end{figure}
### Table 3
2MRS Catalog

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) | (21) | (22) | (23) | (24) | (25) | (26) | (27) | (28) | (29) |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. | 2MASS ID | R.A. | Dec. |
| (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

**Notes.** Codes for Column 27: [C]TTO, [M]cDondall, [F]LWO, [N]ED 2MASS ID match, NED position [M]atch, [O]ther sources in ZCAT, [J]DSS-DR8, and [D]FGS.

This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.
Table 4

ADS Bibcode—Bibliographic References

| ADS Bibcode | Reference |
|-------------|-----------|
| 1969MSAIt..40.559B | Barbon (1969) |
| 1970ApJ...160...33B | Burbidge (1970) |
| 1970ApJ...160L...33B | Burbidge (1970) |
| 1971ApJ...168...321C | Chincarini & Rood (1971) |
| 1971CGPG.C...0000Z | Zwicky & Zwicky (1971) |
| 1972ApJ...172L...37B | Burbidge & Strittmatter (1972) |
| 1972ApJ...173...247S | Stockton (1972) |
| 1972AuJPh..25...233W | Whiteoak (1972) |
| 1972MNRAS.158...277T | Tritton (1972) |
| 1971JHuchra (1971) | ZC, NN (22pp), 2012 April |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

1. \( \sigma \) as Galactic latitude
2. \( K_{s0} \) as extinction-corrected \( K_s \) isophotal magnitude [k_m_k20fe]
3. \( H_{k0} \) as for \( h_m_k20fe \)
4. \( J_{k0} \) as for \( j_m_k20fe \)
5. \( K_{s1} \) as extinction-corrected “total” extrapolated \( K_s \) magnitude [k_m_ext]
6. \( H_{k1} \) as for \( h_m_k20fe \)
7. \( J_{k1} \) as for \( j_m_k20fe \)
8. \( \sigma(K_{s0}) \) uncertainty in \( K_{s0} \) [k_msig_k20fe]
9. \( \sigma(H_{k0}) \) uncertainty in \( H_{k0} \) [h_msig_k20fe]
10. \( \sigma(J_{k0}) \) uncertainty in \( J_{k0} \) [j_msig_k20fe]
11. \( H_{k20} \) as for \( h_m_k20fe \)
12. \( J_{k20} \) as for \( j_m_k20fe \)
13. \( E(B-V) \) from Schlegel et al. (1998)
14. \( r_{iso} \) as \( r_{iso} \) but for “total magnitude” extrapolation radius [r_k20fe]
15. \( r_{ext} \) as \( r_{iso} \) but for “total magnitude” extrapolation radius [r_ext]
16. \( b/a \) as axial ratio from co-added \( JHK \) images [sup_ba]
17. flags: photometry confusion flags from 2MASS XSC database. “Z” in the first column indicates magnitudes from the 2MASS LGA. [cc_flg, k_flg_k20fe, h_flg_k20fe, j_flg_k20fe].
18. Morphological Type Codes used in 2MRS

Table 5

Morphological Type Codes used in 2MRS

| Code | Comment |
|------|---------|
| A    | unbarred (A) |
| X    | mixed type (AB) |
| B    | barred (B) |
|      | Peculiar |
|      | Double or Multiple |
|      | Unclassifiable |
|      | Region |
|      | Irr II |
|      | S..., Sc-Irr, Unclassified Spiral |
|      | Galaxy that has never been visually examined. |

Notes. The morphological information is encoded in Table 3 following the ZCAT convention. It is a five digit code (I2, A1, I1, and A1). The first two digits are the numerically coded type, the next letter (if present) is the Bar type, the next digit (if present) is the numerically coded luminosity class, and the final letter (if present) denotes morphological peculiarities.

Figure 6 shows the distribution of galaxies as a function of redshift for the 2MRS main sample and selected surveys from Table 1.
Table 6
Redshifts for Galaxies in the 2MASS XSC Beyond the Main 2MRS Catalog Limits

| 2MASS ID         | R.A.    | Decl.    | \(v\) (km s\(^{-1}\)) | \(\sigma(v)\) (km s\(^{-1}\)) | Vel | Bibliographic Code |
|------------------|---------|----------|-------------------------|-------------------------------|-----|--------------------|
| 00000256+0817537 | 0.01063 | 8.29817  | 11721                   | 37                            | O   | 20112MRS.MMT..0000H |
| 00000896+0817338 | 0.03729 | 8.29272  | 12280                   | 36                            | O   | 20112MRS.MMT..0000H |
| 00001215+0205503 | 0.05069 | 2.09740  | 6506                    | 35                            | O   | 20112MRS.JPH..0000H |
| 00005299+0803392 | 0.22079 | 8.06090  | 11917                   | 35                            | O   | 20112MRS.JPH..0000H |
| 00005467+0803442 | 0.22779 | 8.06231  | 11952                   | 10                            | O   | 20112MRS.JPH..0000H |
| 00015848+1203580 | 0.49370 | 12.06618 | 60938                   | 55                            | O   | 20112MRS.JPH..0000H |
| 00021610−2926230 | 0.56700 | −29.43970| 18213                   | 40                            | C   | 20112MRS.CTIO..0000H |
| 00023474−2948240 | 0.64483 | −29.80667| 17766                   | 31                            | C   | 20112MRS.CTIO..0000H |
| 00032067−3008493 | 0.83607 | −30.14699| 20407                   | 38                            | C   | 20112MRS.CTIO..0000H |
| 00033524+1700158 | 0.89692 | 17.00435 | 16512                   | 42                            | O   | 20112MRS.JPH..0000H |
| 00042025+3120313 | 1.08443 | 31.34198 | 5073                    | 31                            | O   | 20112MRS.JPH..0000H |
| 00052335−0810122 | 1.34734 | −8.17015 | 9099                    | 46                            | O   | 20112MRS.MMT..0000H |

Note. Codes for Column 6: [C]TIO, [M]cDonald, and [F]LWO.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 7
Redshifts for Galaxies not in the 2MASS XSC which were Observed Serendipitously

| 2MASS IDa | R.A.    | Decl.    | \(v\) (km s\(^{-1}\)) | \(\sigma(v)\) (km s\(^{-1}\)) | Vel | Bibliographic Code |
|-----------|---------|----------|-------------------------|-------------------------------|-----|--------------------|
| 13294821−2340551 | 202.45088 | −23.68197 | 5029                   | 52                            | C   | 20112MRS.CTIO..0000H |
| 10245589−1726331 | 156.23289 | −17.44251 | 7811                   | 43                            | C   | 20112MRS.CTIO..0000H |
| 10104329−1530289 | 152.68038 | −15.50803 | 8388                   | 29                            | C   | 20112MRS.CTIO..0000H |
| 01574403−0649389 | 29.43346  | −6.82746  | 8434                   | 21                            | C   | 20112MRS.CTIO..0000H |
| 10324638−1238045 | 158.19324 | −12.63549 | 8491                   | 45                            | C   | 20112MRS.CTIO..0000H |
| 10324555−1238140 | 158.18977 | −12.63721 | 8579                   | 43                            | C   | 20112MRS.CTIO..0000H |
| 11111075−0628055 | 167.79479 | −6.46819  | 8676                   | 14                            | C   | 20112MRS.CTIO..0000H |
| 03452702−0728392 | 56.36260  | −7.47756  | 10504                  | 31                            | C   | 20112MRS.CTIO..0000H |
| 16265144−7709323 | 246.71447 | −77.15896 | 13333                  | 41                            | C   | 20112MRS.CTIO..0000H |
| 16311208−2615525 | 247.80033 | −26.26458 | 13380                  | 55                            | C   | 20112MRS.CTIO..0000H |
| 03190550−2140362 | 49.77291  | −21.67673 | 15624                  | 32                            | C   | 20112MRS.CTIO..0000H |
| 01135502−3659473 | 18.47924  | −36.99647 | 15814                  | 56                            | C   | 20112MRS.CTIO..0000H |
| 16385916−6421059 | 249.74644 | −64.35169 | 16320                  | 46                            | C   | 20112MRS.CTIO..0000H |
| 23342933−6921154 | 353.62221 | −69.35433 | 25413                  | 49                            | C   | 20112MRS.CTIO..0000H |

Note. a Pseudo-2MASS ID generated from the celestial coordinates of the object.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

4. COSMIC CARTOGRAPHY

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 (de Lapparent et al. 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 provides a representation of structure that varies quite strongly from the center to edge. With full-sky coverage, it is possible to project actual cylinders of redshift space. Given the long-term association of redshift surveys with the Harvard-Smithsonian CfA, we naturally call these “Hockey Puck” plots. Code to generate these plots is available as part of the 2MRS data release.
Figure 7. Hockey Puck plot—a full cylinder section—of 2MRS in the north celestial cap. The view is looking downward from the NCP, the thickness of the “puck” is 8000 km s$^{-1}$, and its radius is 15,000 km s$^{-1}$.

Two “Hockey Puck” diagrams shown in Figures 7 and 8 highlight the vast improvement in coverage through the galactic plane afforded by 2MRS as compared to even CfA2, the densest survey of the nearby universe (Huchra et al. 1995, 1999). Plotted are top-down views of cylindrical volumes with a radius of 15,000 km s$^{-1}$ and thickness of 8000 km s$^{-1}$, yielding an aspect ratio of about 3.5–1. The pucks show the galaxies in the northern and southern celestial hemispheres, respectively—i.e., all galaxies above and below the celestial equator with redshifts placing them in the cylinder and with $K_s \leq 11.75$ mag. Many of our favorite structures and several prominent voids are easily seen in these plots.

The northern puck is dominated by the LSC at the center, the Great Wall (now straight in this cylindrical projection) at 10–14.5 hr, and Pisces-Perseus at 0–5 hr. In addition, there are several new but smaller structures such as the one at 19 hr and 4000 km s$^{-1}$, probably best associated with the Cygnus Cluster (Huchra et al. 1977).

The southern celestial hemisphere is more amorphous. There is the well-known Cetus Wall (Fairall et al. 1998) between 0 and 4 hr, the southern part of the LSC at the center, and the Hydra-Centaurus region, but also a large and diffuse overdensity between 19 and 22 hr, a region hitherto not mapped because of its proximity to the galactic plane. This structure appears 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 9–11 show three sets of these skins, moving progressively outward in redshift, while Figure 12 shows the entire 2MRS catalog with the major structures of the Local Universe labeled. These figures use Galactic coordinate projections; the corresponding equatorial coordinate projections are shown in Figures 15–18.

Figure 9 shows the distribution on the sky of all galaxies in the survey inside 3000 km s$^{-1}$ color coded by redshift in 1000 km s$^{-1}$ skins. The plane of the LSC dominates the map, but there is also a diffuse component between 2000 and 3000 km s$^{-1}$ and 6–13 hr in the south. The next two figures again show some familiar structures but with a few surprises. The Great Wall, Pisces-Perseus, and the Great Attractor dominate the mid ranges. The overdensity of galaxies in the direction of A3627 is high, and the comparison of Figure 10 with 11 clearly shows why we are moving with respect to the CMB toward a point around $l = 270^\circ$ and $b = 30^\circ$.

5. GALAXY MORPHOLOGIES

Morphological types are listed in Table 3 for all of the 20,860 galaxies in 2MRS11.25. We used the classifications listed in
ZCAT (based on RC3, NED, and other catalogs) when available, but 5682 of these galaxies had no type information. They were visually examined and classified by J. Huchra using blue plates from the Digitized Sky Surveys. These new morphological types are identified by code “JH” in column 24 of the catalog. We also list morphological types from the literature for fainter galaxies in the catalog, when available.

Morphological typing in 2MRS uses the modified Hubble sequence (de Vaucouleurs 1963; de Vaucouleurs et al. 1976). Elliptical galaxies have integer types $-7$ through $-5$. S0 galaxies range from integer type $-4$ (E/S0) through 0 (S0/a), in a sequence from least to most pronounced disks. Spirals are assigned integer types 1 (Sa) through 9 (Sm), without distinction between barred, unbarred or mixed-type. Irregular and peculiar galaxies are assigned integer types 10 and above. The format for the morphological type designations is described in detail in Table 5.

The distribution of the galaxies in 2MRS11.25 by morphological type is shown in Figure 13, while Figure 14 shows histograms by redshift for the three broad morphological classes described above. While the histograms show the same pattern as Figure 6, spirals dominate the data set at lower redshifts, while ellipticals flatten near $z \approx 0.03$ and extend to higher redshifts, as expected given their higher luminosity.

6. PREVIOUS RESULTS FROM 2MRS

The 2MRS11.25 sample has been used in several publications.

1. Erdoğan et al. (2006a) calculated the acceleration on the Local Group (LG). Their estimate of the dipole seems to converge to the CMB result within 60 $h^{-1}$ Mpc, suggesting that the bulk of the motion of the LG comes from structures within that distance. They also carried out an analysis of the dipole weighting the sample by its luminosity (rather than the counts) and found relatively minor changes.

2. Erdoğan et al. (2006b) calculated density and velocity fields. All major LSCs and voids were successfully identified, and backside infall on to the “Great Attractor” region (at 50 $h^{-1}$ Mpc) was detected.

3. Westover (2007) measured the correlation function and found a steeper relationship between galaxy bias and luminosity than previously determined for optical samples, implying that near-infrared luminosities may be better mass tracers than optical ones. The relative biasing between early- and late-type galaxies was best fit by a power law with no improvement when stochasticity was added, leaving open the possibility that populations of galaxies may evolve between one another.

4. Crook et al. (2007) produced a catalog of galaxy groups, which was later used to model the local velocity field in Crook et al. (2010).

5. Erdoğan & Lahav (2009) predicted the acceleration of the LG generated by 2MRS in the framework of $\Lambda$CDM and the halo model of galaxies. Their analysis suggested that it is not necessary to invoke additional unknown mass.
Figure 9. 2MASS galaxies inside the 3000 km s$^{-1}$ sphere in Galactic coordinates (centered at $l = 0^\circ$ and following the convention of $l$ increasing to the left). Heliocentric velocities are color coded with red, blue, and green representing bins of increasing redshift/distance. Red for $V_h < 1000$ km s$^{-1}$, blue for $1000 < V_h < 2000$ km s$^{-1}$, and green for $2000 < V_h < 3000$ km s$^{-1}$.

Figure 10. Same as Figure 9, but for velocities between 3000 and 6000 km s$^{-1}$.

Figure 11. Same as Figure 9, but for velocities between 6000 and 9000 km s$^{-1}$. 
Figure 12. Same as Figure 9 but for all 2MRS galaxies, spanning the entire redshift range covered by the survey (from $z = 0$ in purple to $z = 0.08$ in red).
2MRS has produced an essentially complete map of the Local Universe out to $z \sim 0.08$. While the characteristics of the structures are similar to what has been seen before, we now have a nearly full view of the nearby universe. Now we need to measure not only the redshifts, but also real distances (e.g., Masters et al. 2008) to extract the full measure of cosmological information.

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APPENDIX

In this appendix, we present all-sky plots of the 2MRS data set in the equatorial coordinates in Figures 15 through 18 as well as supplementary tables 8 through 13. Table 8 lists 324 sources of galactic origin which were removed from the catalog.

Figure 15. 2MASS galaxies inside the 3000 km s$^{-1}$ sphere in equatorial coordinates (centered at R.A. = 0° and following the convention of R.A. increasing to the left). Heliocentric velocities are color coded with red, blue, and green representing bins of increasing redshift/distance. Red for $V_h < 1000$ km s$^{-1}$, blue for $1000 < V_h < 2000$ km s$^{-1}$, and green for $2000 < V_h < 3000$ km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 16. Same as Figure 15, but for velocities between 3000 and 6000 km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 17. Same as Figure 16, but for velocities between 6000 and 9000 km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 18. Same as Figure 12, but in equatorial coordinates (centered at R.A. = 0° and following the convention of R.A. increasing to the left).

(A color version of this figure is available in the online journal.)

Table 8

| 2MASS ID | Reason for Rejection                        |
|----------|---------------------------------------------|
| 00031127−5444588 | Piece of galaxy 00031064−5444562 |
| 00240535−7204531 | Globular cluster in SMC                   |
| 00255209−0939420 | Piece of galaxy 00255246−0939427          |
| 00265282−7132113 | Globular cluster in SMC                   |
| 0036578+2134078 | Piece of galaxy 00364500+2133594          |
| 00460635−0134343 | Piece of galaxy 00460539−0134232          |
| 00520075+6821243 | Image flaw                                 |
| 00523957−2637338 | Star cluster (NGC 288)                    |
| 00524844−2637078 | Star cluster (NGC 288)                    |
| 00525061−2635148 | Star cluster (NGC 288)                    |
| 00525389−2635418 | Star cluster (NGC 288)                    |
| 00584299+5628334 | Image flaw                                 |
| 01024864−0624482 | Piece of galaxy 01024825−0624419          |
| 01081982−7252599 | Star cluster in SMC (NGC 419)             |
| 01240782−7309037 | H$\alpha$ region in SMC                   |

Jarrett used the original 2MASS LGA pipeline to reprocess 72 of the flagged galaxies by the date this paper was submitted for publication. These galaxies are listed in Table 9. The remaining 242 flagged galaxies are separated in two categories. Table 10 lists 87 objects for which the photometric parameters are expected to exhibit little change after reprocessing, but would still benefit from such a procedure. These galaxies have...
Table 9

2MASS XSC Objects with Reprocessed Photometry

| 2MASS ID          | Original         | Reprocessed       |
|-------------------|------------------|-------------------|
|                   | $K_0$ (mag)      | $r_{iso}$ (log₁₀′′) | $b/a$ |
| 00143065−0710028  | 10.150           | 1.524             | 0.880 |
| 00144455−0720423  | 8.771            | 1.721             | 0.700 |
| 00424581−2333406  | 9.956            | 1.394             | 0.740 |
| 00510187−0703247  | 9.317            | 1.531             | 0.400 |
| 00545028+2914482  | 8.758            | 1.721             | 0.680 |
| 00564266−0954500  | 9.588            | 1.695             | 0.860 |
| 01025152−6536359  | 9.107            | 2.040             | 0.140 |
| 01243377+0145335  | 8.801            | 1.818             | 0.980 |
| 01253143+0145335  | 8.598            | 1.793             | 0.760 |
| 02251418−4025268  | 10.955           | 1.243             | 0.320 |
| 02383270−0640386  | 8.630            | 1.751             | 0.700 |
| 03011224−4454285  | 7.721            | 1.748             | 1.000 |
| 03053084+4250076  | 8.548            | 1.859             | 0.360 |
| 03422928−1329168  | 8.577            | 1.989             | 0.240 |

Notes. All properties of the reprocessed galaxies are listed in Table 3 under their respective 2MASS IDs. The contents of this table are intended to provide an overview of the changes due to the reprocessed photometry.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 10

2MASS XSC Galaxies with Suspect Photometry Flagged for Reprocessing at a Later Date

| 2MASS ID          |
|-------------------|
| 00364500+2133594  |
| 01310193+4903364  |
| 00152527−0705233  |
| 00253199−0709366  |
| 00352772−0921216  |
| 00527394+4144467  |
| 00594211+3602171  |
| 00505558+4031671  |
| 00325400−3703449  |
| 00322491−1613594  |
| 00321474+3803504  |
| 00328466+3633226  |
| 00392830+1323417  |

Notes. All properties of the flagged galaxies are listed in Table 3 under their respective 2MASS IDs. This table is only intended to provide an index of the galaxies with suspect photometry.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 11

2MASS XSC Galaxies with Compromised Photometry Flagged for Reprocessing and Removed from Catalog

| 2MASS ID          |
|-------------------|
| 00093966+5301008  |
| 00112204+0623372  |
| 00151096−2352551  |
| 00203715+2339334  |
| 00244982−4021070  |
| 00271148+5103476  |
| 00293249+5105057  |
| 00350737+4929082  |
| 00385467+0703458  |
| 00452278+5353203  |
| 00580474−8140329  |
| 01074777+7312247  |

Notes. These galaxies are not part of our catalog and therefore we do not list their photometric properties. This table is only intended to provide other users of the 2MASS XSC an index of galaxies that we consider to have compromised photometry.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

not been removed from the catalog. Table 11 contains 165 galaxies with seriously compromised photometry, which have been removed from the catalog. Table 12 lists 77 galaxies for which the ZCAT and NED redshifts were in disagreement and preference was given to the former, as well as 258 galaxies for which we assigned alternative NED redshifts. Table 13 lists additional redshifts for galaxies with multiple measurements from our survey, 6dF and/or SDSS.
Table 12
Alternative Redshifts Chosen over Default NED Redshifts

| 2MASS ID     | NED Alternative | \(v\) (km s\(^{-1}\)) | \(\sigma_v\) (km s\(^{-1}\)) | Qual | Bibcode | cat | sep | Alternative \(v\) (\(\sigma_v\)) (km s\(^{-1}\)) | Bibcode | Comments |
|--------------|-----------------|--------------------------|-------------------------------|------|---------|----|----|--------------------------|---------|----------|
| 00014401−3025082 | ... ... ... ... | 8604 | 64 | M | 0.0 | 20032dF...C...0000C | & | | |
| 00062997−3218179 | ... ... ... ... | 13531 | 150 | M | 0.0 | 1998MNRAS.300..417R | | | |
| 00072080−2807072 | ... ... ... ... | 18048 | 54 | M | 0.2 | 1998AJ....116....1D | | | |
| 00084652−3100399 | ... ... ... ... | 16609 | 89 | M | 0.0 | 20032dF...C...0000C | | | |
| 00105717−3512292 | ... ... ... ... | 14910 | 30 | M | 0.0 | 1986MNRAS.220...901P | | | |

Several discrepant redshifts in NED; alternative value given preference over default one

| 00570857−2155112 | ... ... ... | 19307 | ... | ... | | | | | | Only z in NED with known provenance |
| 01155764+0510435 | 5827 | 8 | 2006AJ....131..185R | 5294 | 17 | M | 0.0 | 2003AJ....126.2268W | | | |
| 01194146−3306209 | 9286 | 8 | 2003A&AS....412...57P | 5813 | 35 | M | 0.0 | 1998AJ....116....1D | | | |
| 02471331+1631590 | 8517 | 20 | 1995ApJ...449..527L | 11794 | 36 | M | 0.0 | 1995A&AS...109...383L | | | |
| 03153355−1552455 | 34674 | 39 | 1993AJ....105.1637H | 24977 | 51 | M | 0.0 | 1993AJ....105.1637H | | | |

Disagreement between NED and ZCAT redshifts; latter value given preference

| 00344891+0723713 | 555 | 10 | 1993ApJ...88..383L | 5205 | 28 | O | 0.0 | 20112MRS.ZMA...0000H | SAO/TDC spectral archive #T26890 |
| 00544855+1100260 | 11425 | 408 | 1995A&AS...109...383L | 11852 | 51 | O | 0.0 | 20112MRS.MMT...0000H | SAO/TDC spectral archive #M03249 |
| 01193495+3210495 | 17568 | 210 | 1970PASP...82.1374v | 17902 | 40 | O | 0.0 | 20112MRS.JPH...0000H | |
| 01465644+3206354 | 10505 | 10 | 1991RC3.9.C...0000d | 14700 | 43 | O | 0.0 | 20112MRS.ZMA...0000H | SAO/TDC spectral archive #T26803 |
| 01532586+7115067 | 6595 | 300 | 1996MNRAS.281...425M | 6838 | 38 | O | 0.0 | 20112MRS.JPH...0000H | | |

Notes. A few representative lines are provided here for guidance on its format and contents. Code for Column 8: NED position [M]atch and [O]ther sources in ZCAT. (This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
### Table 13

| 2MASS ID | $\nu$ (km s$^{-1}$) | $\sigma(\nu)$ (km s$^{-1}$) | Vel src | Bibcode |
|----------|---------------------|----------------------------|---------|----------|
| 00010597−5359303 | 9415 | 45 | 6 | 20096dF...C...0000J |
| 00021610−2926230 | 18334 | 45 | 6 | 20096dF...C...0000J |
| 00023474−2948240 | 17753 | 19 | N | 1999PASP...111..438F |
| 00023794+1638377 | 6530 | ... | N | 2000ApJS...129...547B |
| 00031064−3008493 | 20304 | 45 | 6 | 20096dF...C...0000J |
| 00034964+0203594 | 29320 | ... | N | 2000ApJS...129...547B |
| 00042463−5257316 | 9851 | 45 | 6 | 20096dF...C...0000J |
| 00043594−4528463 | 11794 | 45 | 6 | 20096dF...C...0000J |
| 00054167−5429144 | 10879 | 45 | 6 | 20096dF...C...0000J |
| 00055960−1359448 | 5730 | 45 | 6 | 20096dF...C...0000J |
| 00062990−3530042 | 10768 | 45 | 6 | 20096dF...C...0000J |
| 00065396+0821027 | 11596 | 52 | N | 1999PASP...111..438F |
| 00070925−2505122 | 19118 | 45 | 6 | 20096dF...C...0000J |

**Notes.** Code for Column 4: [N]ED 2MASS ID match, [S]DSS-DR8, and [6]dFGS.

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