Mapping the Hidden Universe: The Universe Behind the Milky Way – The Universe in HI
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Near IR Surveys and the Nearby Universe

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Abstract. Two new surveys are now underway and nearly completed whose goals are to map the sky at near-Infrared wavelengths to study subjects as varied as the structure of the Milky Way to the large scale structure of the universe. These surveys are DENIS, primarily in the southern hemisphere, and 2MASS, which is covering both hemispheres. The map of nearby large scale structure as traced by galaxies is one of the primary goals of both surveys. Combined with redshifts and, eventually, velocity independent distances from IR Tully-Fisher, from $D_n - \sigma$ studies and from SN Ia light curves, the 2-D maps produced by these surveys will be used to map the 3-D distribution of both galaxies and matter, including dark matter. This should not only precisely determine Ω_M, the mass density in both baryons and dark matter, but also provide exquisite information on the properties of galaxies and biased galaxy formation. The 2MASS redshift survey already has redshifts for 24,000 galaxies brighter than 12.2 and 40,000 galaxies brighter than 13.5 at K. With these data we can already provide estimates of the field K-band luminosity function and a wealth of information on the photometric properties of galaxies in the IR. The IR colors of galaxies have a surprisingly small range, which strengthens the justification of near-IR surveys for mapping the nearby universe.

1. Introduction

Since the discovery of galaxies and the proof in the early 20th century that the universe was much larger than the Milky Way, maps of the cosmos have been marked "here there be dragons" to mark the uncharted region of space obscured by our own galaxy, the zone of avoidance. Early attempts to probe this region at optical wavelengths generally failed (c.f. Shapley & Ames 1936). More recent attempts at optical (Santiago et al, 1995, "ORS"), radio (Henning et al 2000, "HIPASS") and far-IR — read IRAS (Schmoldt et al 1999; Rowan-Robinson et al 2000, "PSCz") — have lead to partial maps that either remain severely compromised by extinction (optical), still probe only shallowly (HI), or are low density and/or biased tracers of nearby mass (IRAS).

With two new near-Infrared (NIR) surveys, DENIS and 2MASS, we are now poised to complete the mapping of the nearby Universe. Arguably the best tracer of at least the baryonic mass in galaxies is their near-IR emission. The NIR is also an excellent wavelength range to probe through the zone of avoidance because the extinction at K-band (2.2μ) is only $\sim 1/15$th of the extinction in the B-band. In addition, since these surveys are digital and photometric, automatic extended source extraction algorithms provide much more uniform magnitudes and less biased classification.

2. The Surveys

The first of these surveys, DENIS (Deep Near Infrared Southern Sky Survey), uses a small telescope at La Silla image the sky at I, J and K_S bands. Its effective depth at K for extended sources is 12.0, and it will produce a K selected catalog of about 100,000 galaxies over the southern sky. A more complete description can be found in Mamon (2000) and references therein.

The second of these surveys, 2MASS (Two Micron All-Sky Survey), uses twin 1.3-m telescopes at Mt. Hopkins and Cerro Tololo, thus will cover the whole sky and contain galaxies fainter than K_S=14.0. This survey's primary extragalactic goal is to produce a catalog of extended sources that is essentially complete and reliable to K_S=13.5 over as much of the sky as possible. The final catalog will contain $\sim$ 1,000,000 galaxies to K_S = 13.5.

In characterizing these surveys, we have three goals: (1) photometric uniformity, (2) differential completeness, and (3) differential reliability.

Photometric uniformity is defined by the variation of the zero point of the photometry, in our case for extended sources which at high latitudes will generally be galaxies, as a function of position. For 2MASS, the stated requirement is 3% or 0.03 magnitudes over the sky, with a goal of 1%. Uniformity is essential for Large Scale Structure (LSS) studies because non-uniformities in the photometry have the same signature as density inhomogeneities. For example, if the galaxy clustering amplitude goes as $(r/r_0)^{-1.8}$ with r_0 = about 7 Mpc, then on supercluster scales of 20 Mpc or so, the amplitudes expected are about 15%. Zeropoint errors in existing catalogs, particularly those based on photographic plates and visual estimates alone such as the Zwicky catalog, have zeropoint errors estimated to be between 0.1 and 0.2 magnitude (10-20%) on the scales of interest, sufficient either to swamp or masquerade as real clustering signals.

Differential completeness and reliability refer to the completeness and reliability of the catalog at the stated limit. Differential completeness is 1.00 minus the fraction of true negatives, i.e. the fraction of galaxies that should be in the catalog at the limit (modulo photometric errors, etc.) but were missed. Differential reliability is the similar fraction of false positives at the limit. For 2MASS at K_S=13.5, the survey goal is for the extended source completeness to be better than 90% above galactic latitude 30°, and tests indicate that we will probably achieve that level of completeness even down to a latitude of 10°. Similarly, the survey goal is for the differential reliability (the probability that a source classified as extended really is extended at the stated limit) to be above 99% down to 20° and above 80% down to 10°.

The 2MASS was first proposed in 1988 by Fazio, Huchra and others as NIRAS, a Small Explorer Satellite. NASA recommended that the program be done on the ground and it was then reproposed in the early 1990's by Kleinmann et al. (c.f. Klienmann et al. 1994). Funding for the project has come primarily from NASA but also the NSF, the US Navy and Airforce, the University of Massachusetts and the Smithsonian Institution.

By definition, the primary extragalactic goals of these surveys are cosmological. With the current convergence of determinations of the Hubble Constant to a value of around 65 km/s/Mpc and an uncertainty near 10% (Mould et al 2000), and the clear possibility of determining the geometry of the Universe using supernovae (e.g. Garnavich et al. 1998; Perlmutter et al. 1999), the major remaining problem in observational cosmology is the accurate determination of Ω_M — what is the dark matter, how much is there, and how is it distributed? Related to the Ω problem are the two questions (1) what is the exact cause of our motion w.r.t. the CMB, and (2) what is the bias function of galaxies, non-linear or otherwise. To answer the second of these questions, we seek to determine how galaxies are distributed w.r.t. the dark matter distribution, as the theory of biased galaxy formation predicts that galaxies should be more clustered than the dark matter and, in detail, that the clustering of galaxies w.r.t. the dark matter will almost certainly depend on the properties of galaxies, such as luminosity or morphological type, and *vice versa*.

2MASS is now in full production, utilizing two matched telescopes with 3 channel cameras operating at the J, H and K_s bands. Over 80% of the sky has been scanned since the start of operations in 1997, and most of that data has been photometrically processed. There have been two incremental data releases, which are available from IPAC through IRSA.

http://irsa.ipac.caltech.edu/

We expect to finish scanning the sky in late 2000 or early 2001 with a final catalog release within a year of survey completion. This should be in time for the launch of SIRTF.

3. The 2MASS Redshift Survey

To measure the density field we have also begun to measure redshifts for a bright subsample of 2MASS. The first stage of the 2MASS Redshift Survey (2MRS) is measurement of redshifts for the galaxies in the extended source catalog brighter than $K_s = 12.2$. On completion of the photometric survey, this catalog should contain approximately 120,000 galaxies. This substantial increase in numbers both improves the depth of the sample, providing both reasonable sampling to z=0.07 and also increasing the "resolution" of the density field as compared to the IRAS surveys and even the ORS. Redshifts for 2MASS galaxies are being obtained at Mt. Hopkins, at Arecibo, at Nancay, soon with the Green Bank Telescope, and continually collected from the literature. 2MRS in the south will be done primarily with the 6DF survey and filled in at low galactic latitudes using the CTIO 1.5-m and other telescopes. The second stage of the 2MRS will be to measure some fraction (perhaps 1-in-10) of the remaining galaxies to our catalog limit of 13.5, a total sample of approximately 250,000 galaxies that will probe the whole-sky density field to a redshift greater than 0.1. This program will not be completed until late in the decade.

The current status of the catalog and redshift survey can be seen in the accompanying plots and also at the CfA 2MASS website

$$\mathrm{http://cfa-www.harvard.edu/\sim jmader/2MASS.}$$

Extended sources are identified in the survey using algorithms developed by T. Jarrett and T. Chester (see the 2MASS IPAC homepage:

$$\mathrm{http://www.ipac.caltech.edu/2mass}$$

The current 12.2 magnitude catalog contains some 121,000 extended sources. Figure 1 shows the sky distribution of those objects above a galactic latitude of —b— = 2°. The region below that has been excluded Approximately 24,000 of those have redshifts, and their distribution on the sky is shown in Figure 2. Not all of the extended sources w/0 redshifts will be galaxies — there is considerable confusion by multiple stars at low galactic latitude and a small fraction of the high latitude sources are artefacts, pieces of galaxies, extended sources such as planetary nebulae, or multiple stars. We are weeding these out by visual inspection, catalog matching and, when necessary, spectroscopic identifications. Approximately 40% of the sky is still either not yet photometrically scanned or not yet reduced and in the master 2MASS database.

Figures 3 and 4 show the comparison of a preliminary redshift wedge diagram for the region $1^h \leq \alpha \leq 11^h$, $12° \leq \delta \leq 30°$ and v $\leq$ 20,000 km/s from 2MASS with the CfA2 survey (m_{Zw} $\leq$15.5) which is complete, in the same volume. Even the first stage of the 2MRS, K=12.2, represents significant improvements in sampling in general and especially at low galactic latitude. The 2MASS survey, which is only about 30% complete, has ∼2750 redshifts in the plotted volume as compared to ∼1950 in CfA2. 2MRS should be a little under twice as deep as CfA and will cover the *whole sky*. These figures also easily show the great "penetrating" power of our NIR surveys compared to optically selected samples.

Figures of merit for existing and other planned surveys can be seen in Table 1. Coverage is the approximate effective fraction of the sky, depth is in effective redshift, selection is in what band.

Table 1. Properties of Wide-Angle Redshift Surveys

Survey	Coverage	Depth	Selection	Density	Total #
ORS	60%	0.02	B < 14	fair-good	5,500
CfA2+SSRS2	60%	0.04	B < 15.5	good	30,000
IRAS 1.2 Jy	85%	0.02	60 micron	poor	5,500
PSCz	90%	0.05	60 micron	poor	15,000
2dF	10%	0.25	R, I	good	250,000

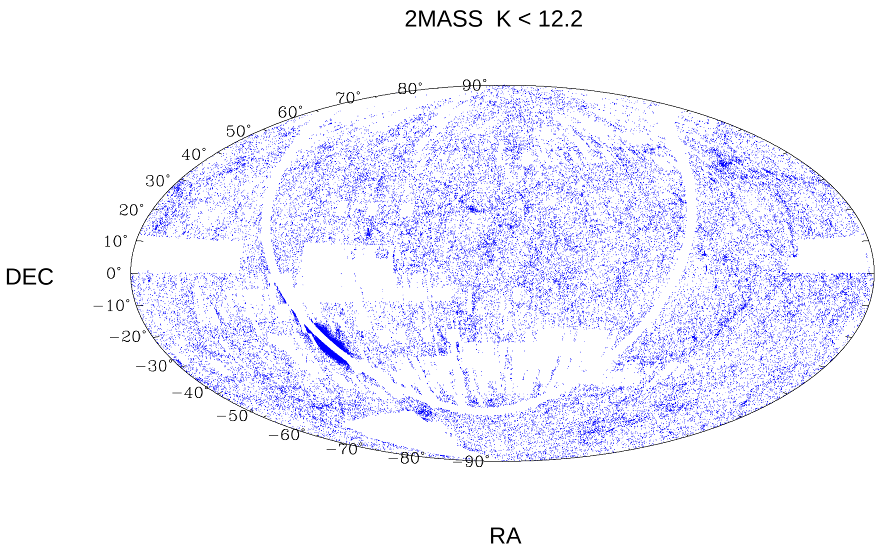

Figure 1. An all sky plot of the distribution of 2MASS extended sources brighter than $K_s = 12.2$. There are $\sim$ 89,000 objects in this plot. The immediate vicinity of the galactic plane, —b— $\leq 2°$, has been excluded.

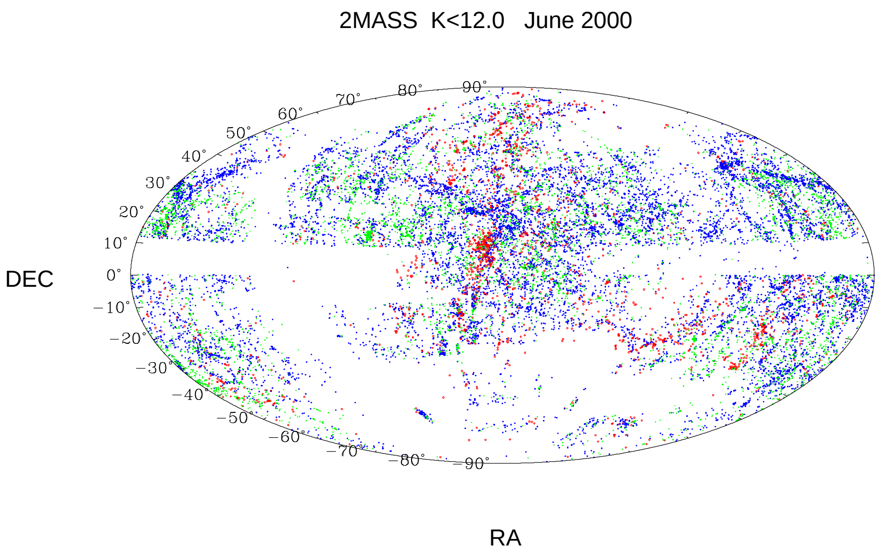

Figure 2. An all sky plot of the distribution of 2MASS galaxies brighter than $K_s = 12.0$ and with redshifts. Red points are galaxies with v $\leq$3000 km/s, blue $\leq$ 10,000 and green above 10,000. There are 21,283 galaxies brighter than 12.0 with redshifts as of June 2000.

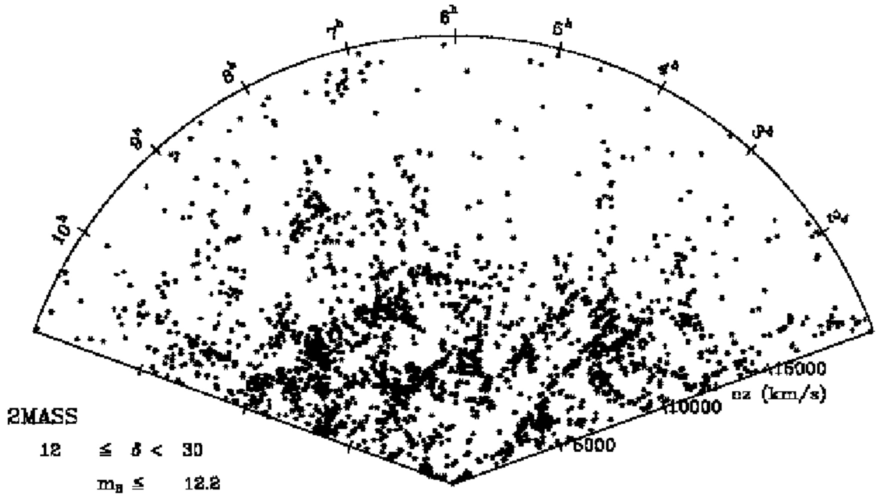

Figure 3. Wedge diagram for a sample of the 2MASS redshift survey. The sample in this volume, which is only about 30% complete, already contains ~ 2754 redshifts for 7000 galaxies, and there is still an additional 20% of the area that needs to be scanned and/or reduced.

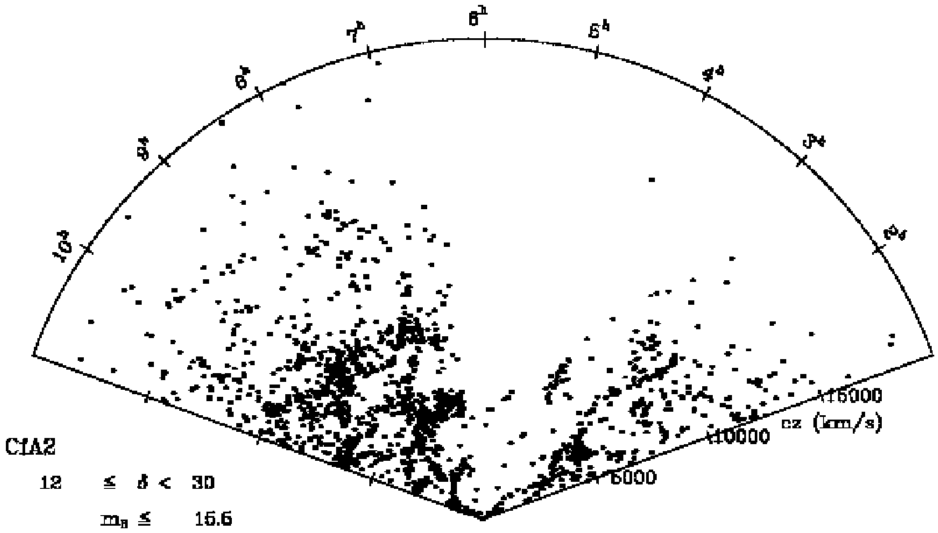

Figure 4. The wedge diagram for the CfA2 survey, complete to a blue magnitude of 15.5 for the same volume of space as shown in Figure 3 for the 2MASS redshift survey.

SDSS	20%	0.25	R, I	good	1,000,000
2MRS+6dF	>85%	0.06	K < 12.2	very good	120,000
2MRS2	>85%	0.12	K < 13.5	fair-good	250,000

4. Galaxy Properties

Even with the partial redshift data in hand, we can learn a tremendous amount about the NIR properties of galaxies that will be useful not only in cosmological studies of Ω, dark matter and cosmic flow fields, but also, for example, in the studies of stellar populations and the properties of clusters of galaxies.

One impressive result is that galaxies in the NIR have essentially the same colors independent of morphological type and that there is an extremely small scatter in the colors, even over all morphological types. Figure 5 shows the J-H, H-K color-color plot for nearby 2MASS galaxies. We restricted the redshift range to minimize the effects of K-corrections. The rms dispersion in color is incredibly small, less than 0.1 magnitude in both J-H and H-K.

Figure 6 shows the J-H, H-K and J-K colors versus morphological type. Again, the surprising result is that the colors hardly change with type, with upturns and downturns in J-H and H-K for the very late type galaxies almost exactly balancing out in J-K. In retrospect, this is almost certainly due to the fact that the NIR light of normal galaxies is dominated by red giant stars whose SED's peak at 1.6 microns almost independently of metallicity, IMF, the presence of dust, etc.

It is also worth pointing out that the extremely small scatter in NIR color combined with moderate K-corrections allow reasonably good photometric redshifts to be estimated from J-K. The preliminary regression from the 30,000 plus galaxies with redshifts in our catalog gives

$$(J - K) \ = \ 0.98 \ + \ 1.86z$$

Finally, we have tested the use of 2MASS data in the infrared Tully-Fisher relation. A more complete description can be found in the CfA 2MASS site noted above, but the 2MASS NIR photometry combined with high S/N 21-cm widths from such catalogs as that of Giovanelli and Haynes and collaborators (c.f. Dale et al 1999) yields excellent TF results when combined with accurate inclinations determined from optical imaging. Thus every HI detection or good optical rotation curve for a high inclination spiral galaxy should provide, as soon as inclinations are determined, a velocity independent distance. In our initial K $\leq$ 12.2 survey, there should be nearly 10,000 such galaxies (i $\geq 45°$), and this will provide the best map of the nearby flow field until sufficient numbers of type Ia SN are available or until surface brightness fluctuation studies with HST and NGST become cheap in terms of telescope time.

5. Summary

The new NIR surveys are transforming the way we think about local large scale structure. They are producing whole-sky catalogs that are denser and deeper

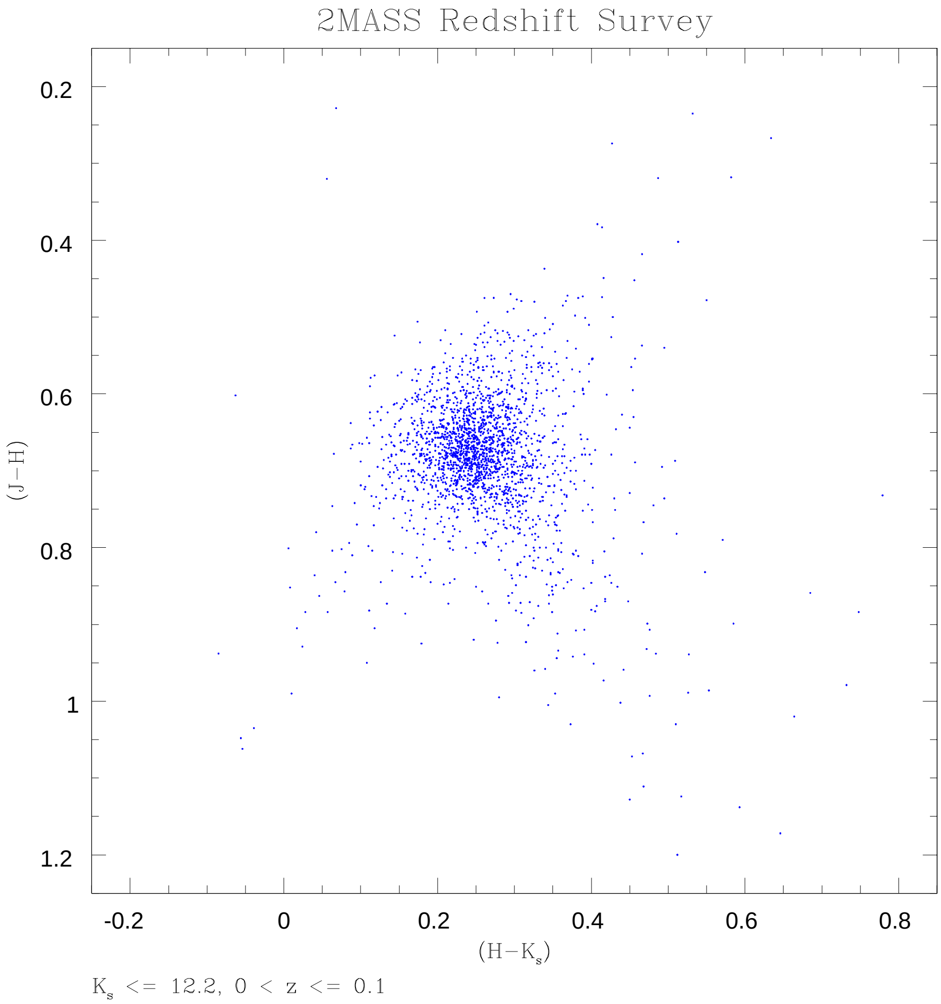

Figure 5. The J-H vs H-K color-color plot for low redshift and bright 2MASS galaxies.

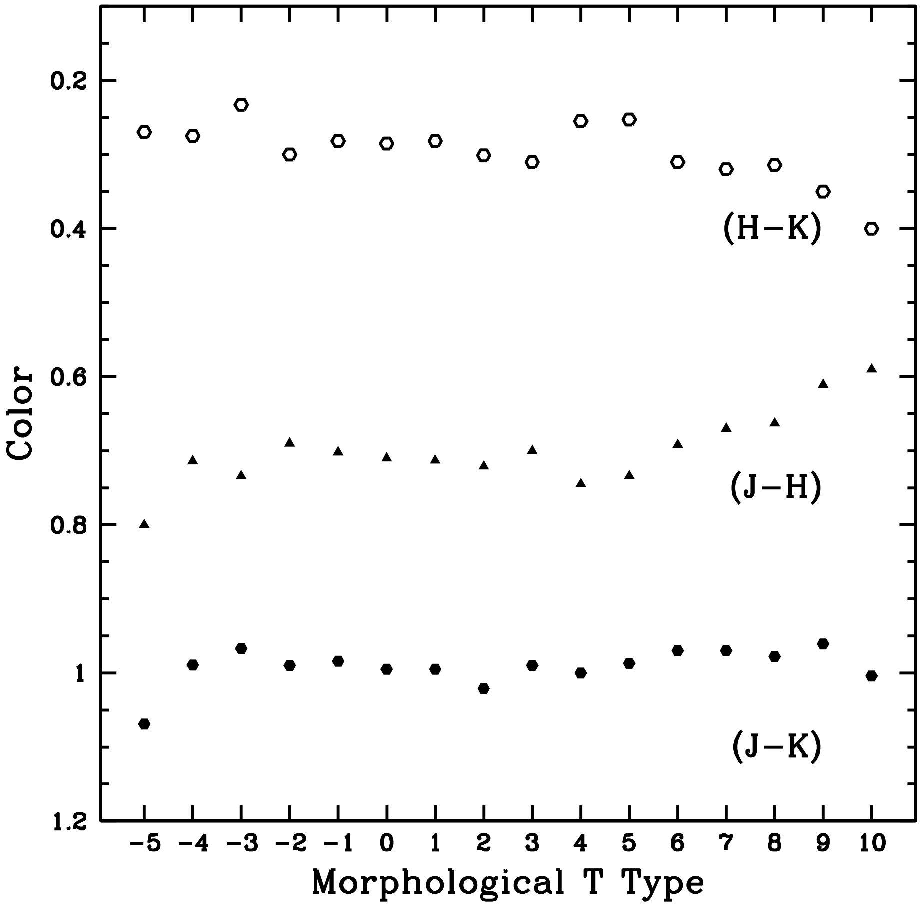

Figure 6. The NIR colors of bright galaxies versus morphological type as measured by 2mass. Shown are the mean colors for galaxies with $0.002 \leq z \leq 0.03$ with catalogued morphological types.

than anything we've had to work with ever before. Combined with HI spectroscopy, small telescope individual object work and multiobject spectroscopy with systems like the 6dF, redshift surveys of these samples can be done on reasonable timescales and will solve the Ω_M, CMB dipole and galaxy biasing problems.

2MRS is well underway. We have already found a significant number of new galaxies in obscured regions (e.g. Jarrett et al. 2000) and easily extending the existing, large area galaxy samples. And, in addition to providing the best map of the local density field ever, we are also extracting other interesting results on galaxy properties. When better optical photometry becomes available from surveys like SDSS, the 2MRS will also be a goldmine of information on stellar populations in galaxies.

Phases 2 and 3 of 2MRS will include measurement of independent distances to a large sample of edge on spirals in 2MASS, via the IR Tully-Fisher relation, to study the galaxy flow field, and hopefully, before I retire, measurement of redshifts with multifiber systems on larger telescopes, for the 1,000,000 galaxy, K=13.5 sample.

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