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HI REDSHIFT SURVEYS AND LARGE-SCALE STRUCTURE

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Abstract. We present a review of our current state of knowledge regarding the large-scale distribution of galaxies in the local universe, highlighting the contributions that HI redshift surveys have made to this field. The instruments and methods employed in 21-cm observations are summarized, and major previous survey programs are described. The importance of HI surveys for low surface brightness galaxies, dwarfs, and galaxies at low galactic latitude is stressed. We look toward the future for redshift survey work in general, and emphasize the role that 21-cm observations will play in future studies of the spatial distributions of galaxies. The utility of the Tully-Fisher relation for providing a velocity-independent map of the universe is discussed. We describe our major survey project to obtain peculiar velocities for ~ 2000 late-type spiral galaxies, and present preliminary results regarding the large-scale velocity field in the local universe.

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1. INTRODUCTION

Over the past fifteen years our knowledge of the spatial distribution of galaxies has grown tremendously from a very sketchy outline to what is now a fairly detailed map of the local universe. The main reason for this change has been the veritable explosion in the rate at which galaxian redshifts have been measured. Whereas there were fewer than 2000 redshifts known in 1970, the total of available redshifts was more than 30,000 in 1990, and exceeded 100,000 in 1995 (although many of these are as yet unpublished).

The motivation for obtaining thousands of galaxian redshifts is simple: galaxies are the signposts of the universe, marking the locations of large concentrations of mass. The redshift of a galaxy (along with its position on the sky) represents its address - a universal zip code that allows astronomers to locate it in space. This is, of course, an outcome of Hubble's Law and the general expansion of the universe. The measurement of many redshifts allows us to create a 3D map of the universe around us. The details of the distribution of the galaxies are used by cosmologists as they attempt to understand how the universe has evolved to its current state. Since the appearance of the universe today was very likely dictated by conditions that were fixed at an early stage in its evolution, the distribution of galaxies tells us about what was going on in those very early times.

We have known about the expanding universe for decades (Hubble 1929). Why then has it taken so long for astronomers to obtain the tens of thousands of redshifts necessary for mapping the local universe? The answer is simply that the technology was not up to the task until the mid- to late-1970's. Even with the Palomar 5-m telescope, it would take hours to obtain a photographic spectrum in the 1950's for a galaxy that today would require minutes with a CCD spectrograph. The application of image tubes and 1D digital detectors such as Reticons to the measurement of galaxian spectra (e.g., Huchra et al. 1983; Kirshner et al. 1978) started the period of rapid expansion in the numbers of redshifts available. The pace has continued to grow with the subsequent introduction of CCDs, sensitive HI receivers, and multi-object spectrographs.

The aim of this paper is to review the contribution of HI 21-cm observations to the measurement of redshifts, to show how 21-cm observations complement and extend the efforts of the optical observers, and to take a look at what astronomers have learned about the universe through the efforts of those who have painstakingly obtained and analyzed all those galaxian spectra. The authors would like to stress the following caveats: (1) This paper will discuss HI *redshift surveys*, i.e., projects carried out with the primary goal of obtaining new redshifts of galaxies. All 21-cm observations yield redshift information of course, but it is beyond the scope of this paper to review all extragalactic HI observations! (2) Although optical redshift information will be used throughout, no attempt is made to give a complete review of the status of optical redshift surveys. A recent review of this field is given by Giovanelli & Haynes (1991).

2. INSTRUMENTS AND OBSERVATIONS

In many cases the main driver for carrying out a large redshift project is the equipment that is available. This is true both for optical surveys as well as those carried out at 21-cm. Therefore, it seems appropriate to begin this review of HI redshift surveys by reminding the reader about the telescopes that have been available for carrying out such programs.

2.1. Summary of Major Facilities

The table below summarizes the major radio telescopes used for 21-cm redshift work. They are listed in order of decreasing collecting area. The beam size is for 21-cm, and the velocity range given corresponds to the simultaneous bandwidth obtained under normal HI redshift observing mode (approximate numbers only). The bandwidths come from papers presenting 21-cm observations; although an attempt was made to get the most up-to-date numbers possible, recent instrumentation upgrades may result in broader ranges in some cases. The numbers in the last column come from Table 9 of Huchtmeier & Richter (1989), and reflect the total number of published HI observations of galaxies through early 1989. This is NOT the number of unique galaxies observed per site, nor is it the number of new HI redshifts produced. However, it does appear to be indicative of the relative contribution of each telescope to the 21-cm redshift industry.

Table 1. Major HI Redshift Telescopes

Observatory	Diameter [meters]	Beam Size [arcmin]	Instantaneous Bandwidth [km s^{-1}]	# Observed Galaxies
Arecibo	305	3.3	8000	8100
Nançay	300 × 30	3.6 × 22	5000	1200
Bonn	100	9	4000	1400
Green Bank	91	10	3400	6100
Jodrell Bank	76	12	4000	500
Parkes	62	15	6700	1350
Green Bank	43	21	3400	600

The two clear leaders in the 21-cm redshift survey field have been the Arecibo 305-m and NRAO Green Bank 91-m telescopes. Arecibo has the clear advantage of sheer size on its side, having more than eight times the collecting area of the next largest telescope, and 50 times more than the smallest telescope listed here. Its small beam size is a real plus when working in crowded regions or at higher redshift where the apparent diameters of galaxies approach one arcmin or less. Its obvious limitation is sky coverage. Because it has a fixed primary, it is only possible to observe sources that pass within 20 degrees of the zenith, meaning that it has a declination coverage of $-2° \leq \delta \leq 38°$. Figure 2 of Huchtmeier & Richter (1989), which plots number of galaxies observed at 21-cm vs. declination, clearly shows the dominance of Arecibo as an HI telescope: the number of galaxies observed in the Arecibo declination range dwarfs the totals from all other portions of the sky.

Before its collapse in 1988, the Green Bank 91-m dish was also extremely productive as a 21-cm redshift machine. Despite being a transit telescope, and hence having very limited integration times (4 - 8 minutes per source, depending on declination), much of the early work on HI redshifts was carried out with this instrument. It had the advantage of relatively large aperture and complete declination coverage (north of $\delta = -18°$). Its beam size was a good match for nearby spiral galaxies, and it had the advantage of being located in an area of low radio interference (the legislated radio quiet zone around Green Bank). This latter feature is a significant plus, especially in the current era where cellular phone transmissions and other types of radio noise are creating serious problems for nearly all radio observatories (see also Vanden Bout & Haynes, this volume).

The remaining telescopes in Table 1 have all played significant roles in collecting 21-cm data for galaxies. Parkes is the only radio telescope of significant size operating in the southern hemisphere, so despite the fact that it appears near the bottom of the current list it has been extremely important. The Bonn and Jodrell Bank telescopes are both fully steerable, which gives them a big advantage over those telescopes with limited sky coverage. This positive is counterbalanced by their smaller sizes and high radio interference environments, plus the fact that they are used at many other frequencies (particularly Bonn) which limits the time available for 21-cm work. Nançay, which employs the double reflector design (looking somewhat like the projection screen at a drive-in movie), has good sensitivity at southerly declinations (down to $\delta = -40°$), which, coupled with its large collecting area, makes it a particularly useful instrument for some projects. Its main drawback is the large, odd-shaped beam, which makes source overlap and beam-dilution for smaller galaxies significant problems.

The astute reader will note that no mention has been made of interferometer systems such as the VLA or Westerbork in the comments above. Despite their great importance in HI mapping and dynamical studies, synthesis radio telescopes simply haven't been used for redshift survey work. The reasons should be obvious. For one thing, these instruments are so valuable (and unique) for a large range of scientific projects that using them for redshift surveys would be a poor use of their time. From a practical standpoint, although these arrays have good sensitivity, they have been designed to operate in spectral-line mode with rather narrow total bandwidths and relatively small numbers of channels. Therefore, while they are outstanding instruments for mapping HI distributions in galaxies whose velocities are known, they are not very efficient at sampling velocity space in order to find previously unknown redshifts. The plan for hardware upgrades for the VLA under development (Bastian & Bridle 1995) includes a new correlator that would provide a significant increase in the bandwidth and number of channels offered. With such an improvement, the VLA would offer significant opportunities for searching for galaxies found within the imaged field, for example in clusters and groups of galaxies or in a blind search mode.

2.2. Observational Methods

Before going on, it seems appropriate to mention briefly the standard observational techniques used in observing galaxies at 21-cm, and to specify the type of information obtained from a successful observation.

Data acquisition and reduction procedures are fairly standardized and automated at most facilities. The observations are typically done in one of two modes: (1) **beam switching**, where the telescope observes on-source for a specified length of time, and then is moved off the source and integrates for a comparable amount of time on "blank sky". In most cases the off-source position is chosen so that the telescope tracks over precisely the same path as it followed while on the source (i.e., the same altitude and azimuth); (2) **frequency switching**, where the central frequency of the observed band is alternated between two values during the course of the observation so that the expected signal moves from one side of the observed frequency range to the other. Frequency switching has the potential to be more efficient than beam switching since, with a judicious choice of frequency settings, one can observe the source 100% of the time. However, since frequency switching only works well over rather narrow bandwidths and the proper frequency settings aren't known ahead of time (i.e., one doesn't know the redshift), beam switching is used almost universally in redshift survey work. Frequency switching *is* useful when searching for objects with velocities close to those occupied by galactic hydrogen, when even the small differences in the local HI between the ON and OFF beams prevents instrumental removal via beam switching.

Once the data have been obtained, the processing and analysis is quite straightforward. A typical procedure includes differencing the ON and OFF source scans, dividing the difference by the OFF, fitting a low-order baseline to the resulting spectrum, and then measuring any signal present. Typically, the data processing and measurement procedure takes less than half the time required to acquire the data, and the observer comes away with fully processed values for the central velocity of the HI profile, the width of the profile (characteristic of the rotational velocity of the galaxy) and integrated flux (from which one derives an estimate of the total HI mass). For redshift survey projects the recessional velocity is the main value of interest, but the other two parameters are extremely useful as well.

2.3. Future Telescope Improvements

Future 21-cm redshift work will be aided by recent improvements in the telescopes and hardware available to the radio community. Improved receivers and larger bandwidth spectrometers can make the existing telescopes more sensitive and efficient. However, the biggest gains will occur through two major telescope projects.

The Arecibo 305-m telescope is undergoing a major upgrade which is expected to be completed by late 1996 or early 1997. The upgrade includes a number of enhancements to the facility. Most notable is the replacement of the old line feeds with a Gregorian subreflector system that will correct for the aberration of the spherical primary and focus the signal to a point. At this focal point a rotating turret containing several horn feeds will be located. The final system should have substantially higher sensitivity, and also be better shielded from local radio interference. It will also allow for much broader bandwidth observations, and a new spectrometer is planned that will provide greater than 100 MHz (> 21,000 km s^{-1}) coverage in a single spectrum! Also included in the upgrade is a ground screen which rings the main reflector and greatly reduces spillover noise which was present for observations at declinations close to the telescope limit.

The radio community suffered a major setback when the NRAO 91-m collapsed in 1988. However, its replacement will soon be available and will be bigger and substantially better than its predecessor. The GBT - Green Bank Telescope - is a 100 × 110 meter off-axis paraboloid which is fully steerable and features an unblocked aperture. It will also have large bandwidth capability and be located at a low-noise site, so should prove to be a useful tool for 21-cm redshift work, particularly at declinations not covered by Arecibo. Its biggest drawback may be that it will also be in great demand for work at other frequencies as well, so HI redshift observers may have to stand in line. The GBT is slated to be in operation in late 1997.

The chapter in this volume by Vanden Bout & Haynes gives a complete description of the capabilities of these two major instruments, and hints at some of the exciting science that will be possible once they are operational.

3. HI REDSHIFT SURVEYs

Giovanelli & Haynes (1991) discuss the general techniques and limitations of the use of the HI 21-cm line as a redshift indicator, as well as reviewing HI redshift survey work through 1991. We refer the reader there for a more general review. Here we will discuss some of the major previous surveys in an attempt to illustrate the advantages of using HI observations for studying specific samples of galaxies. We divide our comments into two categories, depending on whether or not they are targeted toward galaxies identified in advance by their emission at some other wavelength.

3.1. Targeted Surveys

Nearby Galaxies and the Structure of the Local Supercluster Using the NRAO 91-m and 43-m telescopes and the Bonn 100-m antenna, Fisher & Tully (1981) measured the redshifts, HI fluxes and velocity widths for roughly 1000 nearby galaxies, supplementing their earlier survey of nearby DDO dwarf galaxies (Fisher & Tully 1975). The majority of these objects are

located in the volume of the Local Supercluster cz < 3000 km s^{-1}, and these observations served as the backbone for the development of the Nearby Galaxy Catalog (Tully 1988). These data have played an important role in determining the three dimensional structure of the Local Supercluster (Tully & Fisher 1987).

The highly flattened disk-like structure of the Local Supercluster can be seen in Figure 1, which shows the sky distribution of galaxies on at Aitoff equal area projection in celestial coordinates of ~ 5700 galaxies with known redshift cz < 3000 km s^{-1}. The figure is centered on 6^h, 0°. The large concentration of galaxies in the left side of the diagram (northern galactic cap) is the Virgo cluster. The supergalactic plane (e.g., Tully 1982) runs through Virgo, and extends northward, passing close to the north celestial pole. It can be traced around to the southern galactic cap, although the density of galaxies in the anti-Virgo region is significantly reduced compared to the north.

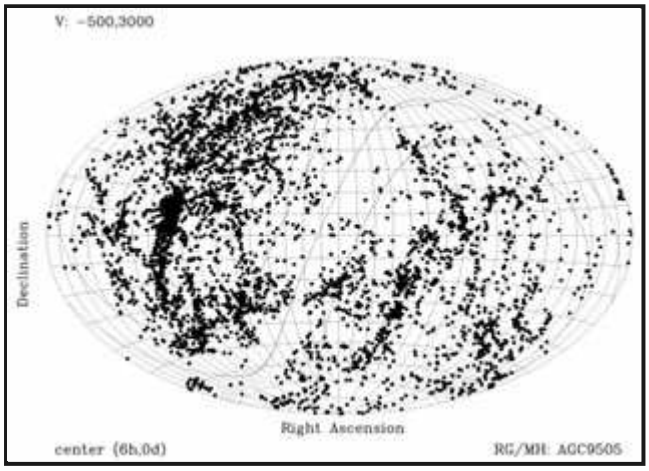

Figure 1. All-sky Aitoff projection map showing the positions of ~ 5700 galaxies with measured redshifts less than 3000 km s^{-1}. The figure is plotted in equatorial coordinates, with the center of the figure at 6^h and 0°. The dotted lines denote the location of the galactic plane and lines of b = ±20°. The Virgo cluster is the densest collection of objects on the left side of the figure. The supergalactic plane runs through Virgo, and can be traced most of the way around the sky.

HI redshifts have also contributed significantly to the understanding of the dynamical structure of the Virgo Cluster. Hoffman and collaborators (e.g., Hoffman et al. 1989a) have used the Arecibo telescope to measure the HI emission from spiral and dI galaxies included in the Virgo cluster catalog (Binggeli et al. 1985). Many of these objects are of such low optical surface brightness that optical redshift measurements are impractical. In using HI redshifts to map the distribution of blue compact dwarfs (BCDs) in Virgo, Hoffman et al. (1989b) have found that those objects are found in two main clumps, one near the cluster core but believed from its lower heliocentric velocity to be infalling from behind, and a second, more diffuse aggregate, located to the south and behind the core, coincident with the so-called W group. Most recently, Hoffman et al. (1995) have confirmed that the cluster membership assignment of Binggeli and collaborators based on the optical appearance of the galaxies works very well. "Background" galaxies as catalogued by Binggeli et al. are indeed located behind Virgo.

Dwarf and Low Surface Brightness Galaxies A number of HI redshift surveys have targeted samples of galaxies which were selected from optical catalogs as likely having significant HI content while at the same time being optically faint. Such galaxies would be difficult targets in optical redshift surveys, and in fact are often skipped over in programs that claim to represent "complete magnitude-limited" samples of galaxies. We stress that the galaxies included in the studies mentioned below represent a very heterogeneous sample, ranging from relatively nearby gas-rich dwarf irregular (dI) galaxies to more distant low surface brightness (LSB) disk galaxies with luminosities comparable to the Milky Way. As stressed by McGaugh (1996b), LSB does not necessarily imply low luminosity.

Schneider et al. (1990; 1992) used both Arecibo and the NRAO telescopes to observe a large sample of galaxies selected from the Uppsala General Catalogue (UGC, Nilson 1973) that were classified as dwarfs or had low surface brightness. The spatial distribution of this sample is discussed by Thuan et al. (1991). Bothun et al. (1986) also selected LSB galaxies from the UGC and obtained 21-cm redshifts for 375 objects using Arecibo. Specific areas of the sky were targeted in redshift surveys for dwarf galaxies by Hoffman et al. (1989a) in the Virgo cluster, and in two low density regions of space by Eder et al. (1989) and Salzer

et al. (1990). Schombert et al. (1994) have obtained HI redshifts for 134 ultra-LSB galaxies selected from searches of the POSS-II plates (e.g., Schombert et al. 1992). A few recent studies have focused on observations of dwarf and LSB galaxy samples at southern declinations using the NRAO 43-m telescope (Maia et al. 1993; Gallagher et al. 1995; Matthews et al. 1995).

The Zone of Avoidance Efforts to delineate the large-scale structure in the local universe are hampered by the obscuration at optical wavelengths close to the galactic plane. HI redshift surveys have thus contributed significantly to the mapping of the galaxy distribution at low galactic latitudes, including the region of the Great Attractor. Some surveys have targeted galaxies identified through careful examination of optical or infrared plates or images. For example, Seeberger et al. (1994) and Pantoja et al. (1994) looked at newly discovered optically selected galaxies behind the northern zone of avoidance, while Kraan-Korteweg & Huchtmeier (1992) used Bonn to observe faint galaxies in the Puppis region. A number of surveys have targeted sources discovered by the Infrared Astronomical Satellite (IRAS) using color criteria to separate stars and galaxies close to the galactic plane., e.g., Lu & Freudling (1995), Chamaraux et al. (1995), Yamada et al. (1994), Takata et al. (1994). In combination, these surveys are contributing to our understanding of the large-scale structure behind low latitude regions.

General Redshift Surveys As indicated in the preceding paragraphs, most programs for obtaining HI redshifts have focused on specific subsets of the galaxian population (e.g., LSB disk galaxies, dwarf irregulars, etc.). In contrast, a few HI survey projects were done according to the schemes of some of the well known optical surveys: obtain redshifts for all cataloged galaxies in a specific area of the sky down to a specific magnitude or diameter limit. The largest such program was carried out by Giovanelli, Haynes, and collaborators (e.g., Giovanelli et al. 1986; Bicay & Giovanelli 1987; Freudling et al. 1992; Wegner et al. 1993) using the NRAO and Arecibo telescopes. In particular, this group took advantage of the sensitivity of the Arecibo reflector, which allowed for the acquisition of redshifts in a fraction of the time required to obtain optical spectra for the same galaxies. Of course, their samples were restricted to disk galaxies (type Sa or later); the impact of this bias is discussed below. When combined with optical redshifts for the early-type galaxies, the regions of the sky surveyed by this group (most notably the southern galactic cap between 0° and 40° declination) have very complete coverage for galaxies in the UGC and CGCG (Zwicky et al. 1961-1968) down to apparent magnitudes of 15.5. Most recent surveys have focused on extending the HI database to southern declinations (e.g., Bottinelli et al. 1993) or to faint galaxies in clusters (Haynes et al. 1996).

3.2. Blind Surveys

Current catalogs of optical galaxies identify objects not only by their luminosity but also by their surface brightness. Numerous authors (e.g., Disney 1976) have pointed out that large numbers of galaxies that do not meet such selection criteria might exist. Blind HI surveys can contribute significantly to the identification of gas-rich, low luminosity and/or low surface brightness objects. To date, blind surveys have been limited to relatively small volumes (e.g., Henning 1995; Weinberg et al. 1992; Szomoru et al. 1994), and their conclusions are not definitive. Schneider (this volume) describes in detail past and current blind HI survey programs.

A new survey being conducted with the Dwingeloo 25-m telescope by Kraan-Korteweg et al. (1994) has already found a large, previously unrecognized nearby galaxy, Dwingeloo I. Note that this galaxy and another object also in Cassiopeia were detected in HI independently by Huchtmeier et al. (1995) with the Bonn telescope.

The development of multi-feed array receivers offers the opportunity to cover large volumes in much less time. The Parkes Multibeam Survey Working Group (Staveley-Smith et al. 1996) plan to use the new 13-beam multifeed receiver on the Parkes 62-m telescope to conduct two surveys. The first will be a deep HI survey for optically obscured galaxies in the zone of avoidance. The survey will target the portion of the galactic plane $|b| < 5°$ over $213° < l < 33°$, simultaneously producing not only the search for hidden galaxies, but also a survey of the Galactic HI and a 20-cm pulsar survey. 1500 hours of observing time have been requested to begin in August 1996. The second survey will cover the entire southern sky, surveying for galaxies in a six million Mpc^3 volume. A complementary survey using a four beam array receiver will be conducted at Jodrell Bank (Disney 1995). Further discussion of the potential for future redshift surveys is found in Vanden Bout & Haynes (this volume).

4. THE LOCAL UNIVERSE

The purpose of this section is to illustrate how the redshift surveys carried out over the past few decades have shaped our view of the distribution of galaxies in the local universe. A recent review presenting the current status of the field is given by Huchra & Geller (1991). Again, we make no effort to be complete here. Rather, we attempt to introduce the reader to the topography of the universe.

4.1. Pioneering Redshift Surveys

Despite the Herculean efforts of many astronomers over a fifty year period, our knowledge of the distribution of galaxies in the mid-1970's was still quite fragmentary everywhere beyond the Local Supercluster. Photographic spectroscopy was simply too

slow to allow for the rapid accumulation of the thousands of redshifts necessary to begin to map out the large-scale features in the matter distribution of the universe. Only with the advent of electronic detectors for optical spectroscopy, followed soon after by higher sensitivity receivers for 21-cm work, did a more revealing picture of the universe begin to take shape.

Building on the work of Humason et al. (1956), a group of astronomers at the Center for Astrophysics (CfA) led by M. Davis began a redshift survey for all galaxies in the CGCG with magnitudes brighter than 14.5. Known as the CfA Redshift Survey (Davis et al. 1982; Huchra et al. 1983), this effort provided the first wide-field view of the distribution of galaxies in space. Although a shallow survey by today's standards, it set the stage for current redshift surveys by showing for the first time the complexity of the spatial distribution of galaxies. The extremely clumpy, non-uniform nature of the galaxian distribution was further emphasized by small-area surveys of specific regions like Coma and Pisces-Perseus (Gregory & Thompson 1978; Gregory et al. 1981) that led to the recognition of superclusters, and pencil-beam surveys by Kirshner et al. (1978) that led to the discovery of huge underdense regions - voids (Kirshner et al. 1981).

The CfA redshift team extended their program by observing all CGCG galaxies down to magnitude 15.5 in a series of strips across the sky. The first such strip became known as the "Slice of the Universe" (de Lapparent et al. 1986), and covered a 6° × 117° area of the sky in the northern galactic cap. At the same time, the Arecibo HI redshift team was completing their work on the Pisces-Perseus supercluster, and reported their findings for over 2700 galaxies in the southern galactic cap (Haynes & Giovanelli 1986).

In Figure 2 we reproduce the galaxy distribution in the Slice. This figure includes the fainter CGCG galaxies observed by Thorstensen et al. (1989; 1995) and Wegner et al. (1990) in addition to the original sample presented by de Lapparent et al. (1986). It shows in vivid detail that galaxies are indeed not uniformly distributed, but rather are located in clusters and filaments along what the authors describe as "bubble-like" structures. Voids were seen to be a common feature - large fractions of the volume of space are completely devoid of luminous galaxies. The Coma cluster is located near the center of the volume, and lies at the point where several of the filaments converge. A single, continuous filament runs laterally across the volume at velocities between 6000 and 10,000 km s^{-1}, and has been dubbed the "Great Wall". Many additional slices have been observed by the CfA group (Huchra & Geller 1991), and show that these features extend substantial distances in the direction perpendicular to the plane of the Slice. The appearance of the large-scale structure of the local universe, when viewed in these other slices, exhibits the same general features that are present in Figure 2.

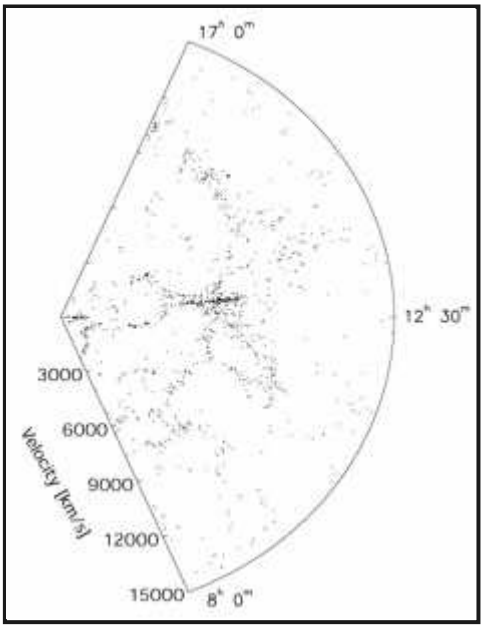

Figure 2. Cone diagram of the "Slice of the Universe." The figure plots all galaxies with known redshifts in the Slice region (RA 8^h to 17^h, Dec. 26.5° to 32.5°). The Coma cluster is located near the center of the figure, at the intersection of several filaments. The "Great Wall" runs through the Coma region and can be traced all the way across the volume surveyed. Numerous voids of various sizes and shapes occupy much of this region.

The Pisces-Perseus Supercluster: A Telling Example One of the most prominent structures seen in the UGC and CGCG catalogs is the Pisces-Perseus supercluster (PPS), a linear structure easily traceable across 5 hours of R.A. at nearly constant redshift $cz \sim 5000$ km s^{-1} (e.g., Haynes 1988). Because of the completeness of the redshift information in this region, as well as its distinctive structure, the PPS serves as a useful illustrative example of a number of issues related to large-scale structure studies.

The existence of a large-scale feature in the extragalactic sky in the PP region was noticed as early as 1932 by Bernheimer. It should thus be recognized that PP is not a random volume. Rather, as is apparent in Figure 3, which shows the sky distribution of the nearest 15,000 galaxies ($cz < 6000$ km s^{-1}), the PPS is one of the three most prominent features seen in a two dimensional examination of moderately bright galaxies, the other two being the zone of avoidance and the Virgo cluster / supergalactic plane. As discussed by Giovanelli et al. (1986), the CGCG is particularly suited to trace volume density enhacements with characteristic sizes of 5 to 20 Mpc if they are situated at a distance of 5000 km s^{-1}. Assuming the luminosity function of galaxies is universal, structures at that distance will be emphasized but not confused by background objects in a catalog containing galaxies to a limited apparent magnitude of 15.7 like the CGCG.

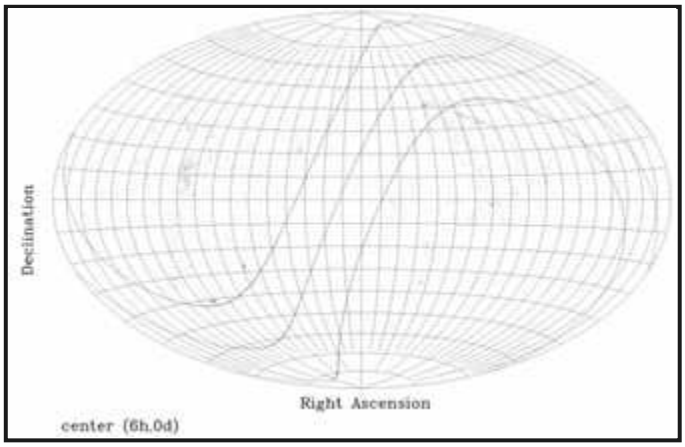

Figure 3. All-sky Aitoff projection map showing the positions of the nearest 15,000 galaxies (velocities less than 6000 km s^{-1}). The map coordinates are the same as in Figure 1. The dense concentration of points in the upper right portion of the figure is the Pisces-Perseus supercluster.

The linear structure of the main ridge of the PPS is clearly evident in Figure 4 which shows the three- -dimensional distribution of galaxies in the current redshift catalog (itself an updated version of that presented in Wegner et al. 1993). The region illustrated spans six hours of R.A. in the zone $20° < \delta < 50°$. The upper panel shows the sky distribution, while the lower panel shows the distribution of the 1589 objects with measured redshifts and magnitudes brighter than 15.7 that lie within the irregular-shaped region outlined in the upper panel. The main PPS ridge extends more than 45 h^{-1} Mpc in length before it fades into the zone of avoidance on the left side of the figure. It is best described as a linear "filament" of axial ratio 8:1, inclined by less than 12° to the plane of the sky. It represents a volume density enhancement of more than a factor of ten over its surroundings. Numerous clusters are embedded in the filament, most notably the massive Perseus cluster at RA $\sim 3^h\ 15^m$. A remarkable bifurcation of the supercluster filament occurs near RA 0^h, where the galaxies in the nearer segment are seen to be confined to an incredibly narrow range of velocities. The relative isolation of the PPS from foreground and background structures is seen in Figure 5, which shows the cone diagram for the same 1589 galaxies. Note in particular the large void between the Local Supercluter and PPS.

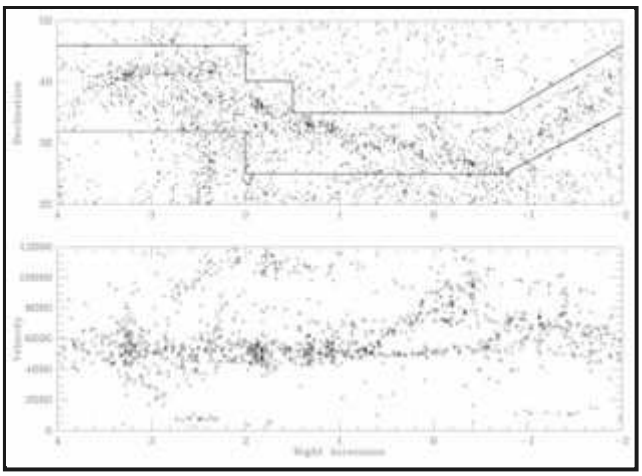

Figure 4. The PP supercluster. The upper figure plots the distribution on the sky of all galaxies with known redshift in the region RA 22^h to 4^h and Dec. 20° to 50°. The main ridge of the PP supercluster is outlined by the irregular boundary. The lower figure plots redshift vs. RA for those galaxies located within the main PP ridge. Note the strong concentration of galaxies with velocities between 4000 and 6000 km s^{-1}, and the large underdense region in the foreground of the supercluster.

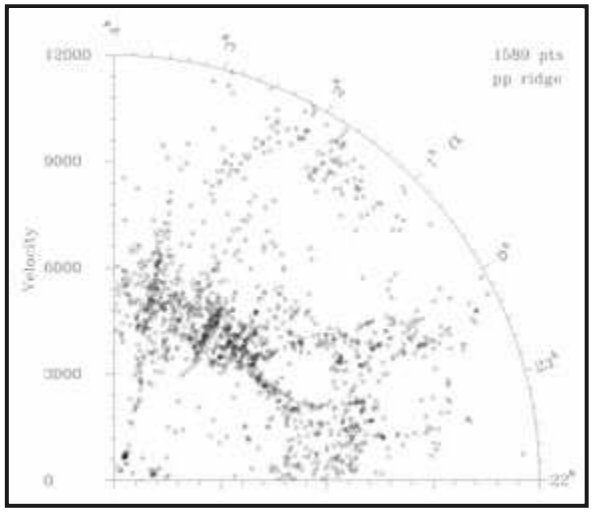

Figure 5. Cone diagram for the 1589 PP galaxies located in the main supercluster ridge outlined in Figure 4.

4.2. Current Generation of Surveys

Redshift surveys in both the optical and radio have, of course, continued. Important work has been done in the southern hemisphere (da Costa et al. 1988; Pellegrini et al. 1990) which complements the northern surveys mentioned above. By the early 1990's a large fraction of all galaxies in the UGC, CGCG, and ESO catalogs had measured redshifts. This allowed astronomers to look at large tracts of the local universe (effective depths of ~ 6000 - 10,000 km s^{-1}), mapping out details comparable to those evident in Figures 2 - 5. Once astronomers ran out of cataloged objects to observe, they simply began creating new (usually digital) galaxy catalogs in specific regions of the sky to probe even deeper.

For reasons discussed in Section 6, most of the current generation of wide-area redshift surveys are being carried out in the optical using multi-object spectrographs. Two recently completed surveys are the CfA/Dartmouth Century Survey (Kent et al. 1993; Wegner, private communication) and the Las Campanas Redshift Survey (LCRS, Shectman et al. 1996). The Century survey is an extension of the "Slice of the Universe" survey to fainter apparent magnitudes. It covers a one degree in declination

by 100 degrees in RA slice of the sky which overlays the original Slice at declination 29-30°. The magnitude limit is R = 16.5, and the effective depth is ~ 25,000 km s^{-1}. The LCRS employs a "plugboard-type" fiber positioner to observe up to 100 galaxies in hundreds of 3° × 1.5° fields. Six different declination strips have been surveyed, three each in the north and south galactic caps, producing a total of ~ 26,000 redshifts to date. Cone diagrams of the spatial distribution of the galaxies are shown in Shectman et al. (1996). Large-scale features out to z ≃ 0.15 - 0.20 are visible, including many voids on the scale of ~ 5000 km s^{-1}. One of the conclusions of these deeper surveys is that the sizes of the largest coherent structures seen are comparable to the PPS and Great Wall, and that by surveying to depths of 2- -3 times the sizes of these features one reaches the condition that the redshift samples constitute a "fair sample" of the universe. Deeper, pencil-beam surveys (e.g., Koo et al. 1993) are probing to even greater depths. In their examination of the power spectrum of the LCRS, Landy et al. (1996) have found a strong peak at ~ 100 h^{-1} Mpc. Indications of a periodicity of 128 h^{-1} Mpc have been reported in the distribution of redshifts out to and beyond z = 0.2 (Broadhurst et al. 1990).

The future of redshift surveys, at least in the northern hemisphere, will be dominated by the Sloan Digital Sky Survey (SDSS, Gunn & Knapp 1993). Using a dedicated 2.5-m telescope in New Mexico, the SDSS team will carry out a four-color imaging survey covering roughly one quarter of the entire sky to a depth of 23rd magnitude. Using the imaging data to construct catalogs of galaxies, they will then obtain redshifts for an estimated *one million* galaxies to 19th magnitude. This enormous collection of redshifts will be deep enough to map out large-scale structures at z ≃ 0.4! The survey is expected to begin in the near future, and will require 5-7 years to complete. These are exciting times!

5. Biases and Advantages of HI Redshift Surveys

Carrying out galaxy redshift surveys using HI observations introduces an obvious bias into the sample: a galaxy must have significant amounts of neutral hydrogen gas in order to be detected. Because of the roughly anti-correlated variations in HI content and optical surface brightness with Hubble type, HI redshift surveys have contributed most to studies of the distribution of spiral and irregular galaxies, and are thus complementary to optical redshift surveys. While the latter are very efficient at obtaining redshifts for higher surface brightness early-type galaxies (E and S0), they often completely miss the LSB galaxian population. Because the redshifts of late-type spirals and irregulars in particular are more easily measured in the HI line than optically, the 21-cm line surveys play a critical role in tracing the large-scale structures defined by such systems.

A particular importance of the HI line for the study of large-scale structure arises because of the segregation of galaxies in different regimes of local galaxy density according to their morphology, surface brightness and, perhaps, luminosity. Numerous observational and theoretical studies have investigated the morphology-density relation (Dressler 1980; Postman & Geller 1984) and the universality of the luminosity function (Binggeli et al. 1988). Clear evidence of morphological segregation is visible in Figure 6, which shows the sky distribution of galaxies in the PPS region with redshifts in the range 4000 km s^{-1} < cz < 7500 km s^{-1}. The upper panel shows all galaxies in the redshift window, while the middle and lower panels show, respectively, subsamples of early-type galaxies (E, S0, S0/a) and late-types (Sc, Irr). Giovanelli et al. (1986) have shown that morphological segregation can be seen even among the spiral classes, with corresponding increases in the relative proportion of Sa, Sab spirals and decreases in Sbc, Sc galaxies as the density increases. Indeed, the gradient in population fraction is evident in nearly all density regimes. Using the redshift and morphological information in the PPS database, Iovino et al. (1993) have concluded that morphology and luminosity are two independent parameters that correlate with both the clustering properties of galaxies and their distribution as a function of local density. Bright galaxies are relatively scarce in low density regions, while faint spirals and irregulars are rare in high density ones. Within each morphological class, the more luminous galaxies are preferentially found in regions of higher density than are the low luminosity ones. It is not yet known whether the process(es) responsible for such segregation reflects the local conditions at the epoch of galaxy formation or result from secular interactions with neighbors or the intergalactic environment.

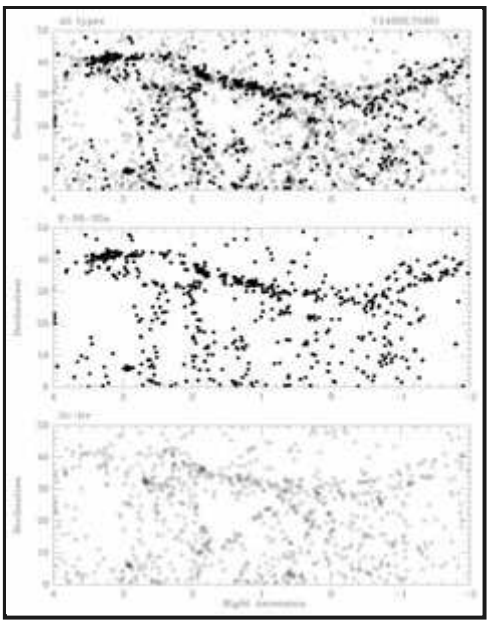

Figure 6. The same region as shown in Figure 4, but restricted to galaxies in the velocity range 4000 to 7500 km s^{-1}. The upper panel shows all galaxies, the middle plots only those with morphological types of E or S0, while the lower panel plots the late-type galaxies (Sc and Irr). Note the difference in the degree of clustering between the middle and lower panels.

Dwarf galaxies, especially those that are not actively forming stars, are notoriously difficult to observe optically and are correspondingly absent in optical redshift surveys. Due to their low surface brightnesses, these galaxies are often purposefully excluded from "magnitude-limited" redshift surveys even though their integrated magnitudes might be substantially brighter than the quoted limit. An added complication arises because the total magnitudes for LSB objects are systematically underestimated in most existing galaxy catalogs (often by 1-2 magnitudes), so they often fail to be included in survey lists in the first place. These biases apply equally to nearby LSB dwarf galaxies and more distant LSB disk galaxies. The impact of these deficiencies in the optical redshift surveys on such things as the slope of the faint end of the galaxian luminosity function is hard to assess, but could be severe (McGaugh 1994; Ferguson & McGaugh 1995).

HI observations offer at least partial rectification of this problem. As long as a galaxy has substantial amounts of HI gas, it is relatively easy to observe at 21-cm. It is therefore no accident that some of the largest HI redshift surveys have targeted dwarf and/or LSB galaxies (Fisher & Tully 1975; Thuan & Seitzer 1979; Schneider et al. 1990; 1992; Bothun et al. 1986). Studies of the spatial distributions of low luminosity galaxies have relied heavily on the use of HI redshifts (Thuan et al. 1991; Eder et al. 1989; Salzer et al. 1990; Schombert et al. 1994). Such studies are important for answering questions about the details of the formation of the large-scale structures, since the relative clustering properties of high- and low-luminosity galaxies is an important discriminant between competing theories (e.g., White et al. 1987). Of course, constructing complete samples of dwarf and LSB galaxies remains a significant challenge, but HI observations hold out the promise of obtaining fairly complete redshift information once the appropriate survey lists are available.

A final advantage of 21-cm observations is that they provide fairly complete information about the global gas content in the galaxies observed. This is due, in part, to the fact that the beam size at 21-cm is typically larger than the size of the optical disk. Therefore, HI emission profiles contribute not only accurate redshifts, but also measures of total HI content and velocity widths. This latter quantity is useful for applications of the Tully-Fisher relation (see below).

6. THE FUTURE OF HI REDSHIFT SURVEYS

HI redshift surveys have contributed substantially to our knowledge of the distribution of galaxies in the universe because of the advantages offered by 21-cm observations compared to optical surveys. Will this continue to be the case as future redshift surveys are carried out? The answer is a qualified 'no' (see also Vanden Bout & Haynes, this volume). Whereas radio telescopes, particularly Arecibo, had an advantage over optical surveys as long as (1) the latter were only observing one galaxy at a time and

(2) the typical separation between galaxies was large compared to the HI beam size, neither condition will be true for surveys that probe deeper than galaxy catalogs like the CGCG. First, modern optical redshift surveys are being carried out using multi-object spectrographs which are capable of observing several dozen to a few hundred objects simultaneously. The multiplexing advantage makes optical surveys much more efficient. Second, the density of sources on the sky increases to the point where source confusion becomes a major problem for HI surveys. In addition, beam dilution significantly lowers the HI detection rate for higher redshift galaxies as their apparent diameters get smaller.

6.1. The Niche for HI Surveys

Does this mean that HI telescopes should get out of the redshift survey business? Not at all! Observations at 21-cm will still make an important contribution to our knowledge of the spatial distribution of galaxies. There are a number of areas where HI observations will remain not only viable, but dominant. As already indicated above, many of these areas are complementary to the optical survey work.

Of particular importance will be redshift work on LSB galaxies. Multi-object surveys like the LCRS routinely miss and/or ignore LSB galaxies because it is impossible to measure an optical redshift in a reasonable amount of time. The bias this places on studies of the spatial and luminosity distributions of galaxies could be severe. HI studies of LSB galaxies - both nearby dwarfs and distant LSB disk galaxies - will remain the best (and sometimes only) hope for getting redshifts for this relatively invisible but important population of galaxies. Likewise, galaxian surveys in the zone of avoidance and blind HI surveys will remain important applications of 21-cm observations.

One other significant role that HI observations can play in helping to develop our understanding of the distribution of matter in the universe is through the application of the Tully-Fisher (TF) relation. Rather than using redshifts to map out the 3D locations of galaxies, the TF relation allows us to assign distances that are independent of the observed recessional velocity. This in turn provides a measure of each galaxy's peculiar velocity - the difference between the observed redshift and the redshift predicted for an object at the true distance of the galaxy under the assumption of a uniform cosmic expansion. The peculiar velocity of a galaxy represents its line-of-sight motion due to local gravitational influences, and can be used to estimate the underlying mass distribution in the vicinity of the galaxy. In the following section, we highlight our recent work in applying HI and optical observations to the study of peculiar velocities in the local universe.

6.2. The All-sky Tully-Fisher Survey

Tully & Fisher (1977) proposed that the width of the HI emission profile, corrected for inclination, could be used as a predictor of galaxy luminosity, and thus, in comparison with the apparent brightness, a redshift-independent distance indicator. Motivated in part by the large database of HI widths available from the Arecibo redshift surveys, and in part by the sometimes confusing results obtained by early peculiar velocity studies, we decided to carry out our own TF study. Here we present an overview of the TF method, a brief summary of previous work, and a preliminary report of the results of our work.

Basis for the TF Relation The origin of this scaling relation has been discussed in various places (e.g., Aaronson & Mould 1986; Eisenstein & Loeb 1996), but it should be noted that the relation itself is derived empirically. Freeman (1970) has presented a classic discussion of the structure of the exponential disks characteristic of most spiral galaxies. In spirals, the disk component is generally expressed in terms of surface brightness (I) as a function of radius as $I(r) = I_o\ exp(-r/r_d)$, where I_o is the central surface brightness and r_d is the disk scale length. Indeed, Freeman found that the central surface brightness is nearly constant in spirals, a characteristic commonly referred to as Freeman's Law. Its universality appears to be violated by a significant fraction of galaxies, especially ones characterized by much lower central surface brightness (e.g., Disney 1976; McGaugh 1996a). Nonetheless, the law does apply approximately to galaxies commonly found in existing catalogs, and plays an important role in a simple understanding of the origin of the TF scaling.

The total light emitted by an exponential disk is given by

$$L_d \propto r_d^2\ I_o \quad (1)$$

The mass interior to radius R is $M(R) \propto RV^2$. In the case that the rotation curve flattens beyond some radius to some V_{max}, then the total mass in the disk is

$$M_{tot} \sim r_d\ V_{max}^2 \quad (2)$$

Combining equations (1) and (2), and performing some algebraic manipulation, we can write the total disk luminosity in terms

of the mass-to-light ratio and the observables - the central surface brightness I_o and the rotation curve maximum V_{max}:

$$L_d \propto \left(\frac{M_{tot}}{L_d}\right)^{-2} \frac{V_{max}^4}{I_o} \quad (3)$$

Allowing for the possibility that a dark matter halo contributes significantly to the total mass, let us denote the fraction of the total mass contained in the disk by Γ, so that $M_d = \Gamma M_{tot}$. Then,

$$L_d \propto \left(\frac{M_d}{L_d}\right)^{-2} \Gamma^2 \frac{V_{max}^4}{I_o} \quad (4)$$

The TF scaling thus results from the simple assumptions that the dark matter fraction and disk mass-to-light ratio are roughly constant among spirals and that Freeman's law holds. In this case, $L_d \propto V_{max}^4$, similar in form both to the TF relation, and also to the analogous relation for ellipticals, $L \propto \sigma^4$, known as the Faber-Jackson relation (where σ is the stellar velocity dispersion). In practice, none of these assumptions of constancy applies. Γ, M_{tot} / L_d and I_o all exhibit some mild dependence on scale (V_{max} or L_d), so that the scaling goes more like $L_d \propto V_{max}^{\beta}$, where the value of β satisfying most empirical TF relations is in the range 3 - 3.5.

Over the 20 years since the TF relation was first proposed as a distance indicator, much discussion has focused on the precise methodology. While the details of the relation lie beyond the scope of the current review, the interested reader is referred to the following references for a more thorough discussion: Strauss & Willick (1995), Giovanelli et al. (1994; 1996b, c).

Ingredients The TF relation is commonly used in the form $M_{TF} = a + b \log V_{max}$. Most commonly, V_{max} is equated to the observed 21-cm line profile width W, suitably corrected for observing aspect $W_o = W_{obs} / \sin i$, redshift, and for the contributions of turbulence, signal-to-noise, and instrumental broadening. Imaging photometry using CCDs provides both the apparent magnitude m and the inclination, based on the observed disk ellipticity and an adopted intrinsic axial ratio. The TF relation can thus be used to derive redshift-independent distances from the combination of corrected line widths W_o and apparent magnitude m. The galaxy's peculiar velocity can then be calculated from the difference between the observed recessional velocity (corrected to some rest frame, e.g., the CMB) and the velocity expected for a galaxy at the TF-predicted distance.

Review of Peculiar Motion Results The peculiar velocity of the Local Group has several distinct components. As early as 1958, deVaucouleurs suggested that, since the Virgo cluster represents a strong local density enhancement, it should induce a measurable infall velocity on the Local Group. Models of the velocity field of the Local Supercluster have been proposed by such authors as Peebles (1976), Schechter (1980), and Tonry & Davis (1981). Input parameters generally include: (1) the infall velocity of the Local Group towards Virgo, (2) the overdensity of Virgo relative to the mean density, and (3) the exponent of the density falloff from Virgo, as $r^{-\gamma}$. Early applications of the TF relation to the Local Supercluster were presented by Aaronson et al. (1982). Sandage (1986) has pointed out that galaxies within a few Mpc of the Local Group show no bulk motion with respect to the Local Group. He concludes that, whatever peculiar velocity is associated with the Local group, it is shared by all of the galaxies within $cz \leq$ 700 - 800 km s^{-1}.

The recent COBE measurement (Kogut et al. 1993) confirms the previously recognized dipole anisotropy in the CMB of amplitude 3.3 ± 0.02 mK in the direction l, b = (265° ± 2°, +48° ± 2°). This is usually interpreted as a motion of the Local Group of amplitude 622 ± 20 km s^{-1} toward (l_{CMB}, b_{CMB}) = (277° ± 2°, +30° ±2°). It was noticed immediately that the motion of the Local Group with respect to the CMB points ~ 45° away from the direction to Virgo: a simple Virgo infall model does not agree with the magnitude or direction of the motion implied by the CMB dipole anisotropy. The discrepancy cannot be explained as being due to a rotation of the Local Supercluster.

Looking to explain the offset of the CMB apex from Virgo, Tammann & Sandage (1985) noted that the Hydra-Centaurus supercluster is located in the proper direction to contribute a component to the LG motion that, in addition to Virgo infall, might approach the CMB dipole velocity. In support of the importance of Hydra-Centaurus, Lilje et al. (1986) detected a shear in the local velocity field, with the expansion axis pointing toward the supercluster complex.

Soon thereafter, Dressler et al. (1987) and Lynden-Bell et al. (1988), analyzing the motions of 300 elliptical galaxies derived

from an application of the D_n - σ relation, proposed a best fit model that included both Virgo infall and a component of motion of 570 km s^{-1} toward a source located at a distance of cz ~ 4350 km s^{-1} hidden behind the southern galactic plane which they dubbed the "Great Attractor" (GA). Since then, much debate has focused on the validity of the GA model. Strauss et al. (1992), using the results of an IRAS-selected redshift sample, place the major perturber closer than 4500 km s^{-1}, more in line with the Hydra-Centaurus distance. Other analyses of the IRAS galaxy distribution were presented by Rowan-Robinson et al. (1990) and Scharf et al. (1992). The general conclusion which developed was that, while the local velocity field is not just due to the Local Supercluster, the magnitude of the motion and its direction toward the purported GA is very uncertain.

Results even more challenging to current theories on the large-scale structure have been proposed. Scaramella et al. (1989; 1994) noticed a concentration of rich clusters near cz ~ 14,000 km s^{-1} in the general direction of the GA and postulated that infall into that overdense region may play a role. Willick (1990) found a bulk motion of the Pisces-Perseus supercluster in the general direction of Hydra-Centaurus, while Courteau et al. (1993) found general agreement with Willick's velocity field and suggested further that the entire local universe is in bulk flow in the general direction of Hydra-Centaurus. Using a photometric technique applied to brightest cluster ellipticals for 119 clusters, Lauer & Postman (1994) found that the clusters defined a reference frame that is in motion with respect to the CMB with an amplitude of 689 ± 168 km s^{-1} toward l = 343°, b = +52° (± 23°). A complete review of peculiar-motion studies is given by Dekel (1994).

The SFI Galaxy Survey If you are confused about the state of peculiar velocity measurements at this point, so were we and our colleagues. In order to try to better understand the situation, we decided to carry out our own study. As a result, our group has undertaken a homogenous, all-sky survey of a large sample of Sc galaxies with the objective of applying the TF relation to determine peculiar motions in the local universe. The sample, which we dub SFI, covers the sky north of -42° declination to a distance of V_{LG} ~ 7500 km s^{-1}, where V_{LG} is the observed velocity measured relative to the centroid of the Local Group. In order to achieve a more even distribution in redshift and to reduce the contribution from low surface brightness and dwarf objects in the foreground, we applied a changing angular size selection criteria to our sample:

For V_{LG} < 3000 km s^{-1}, a $\geq$ 2.0 arcmin.

For 3000 < V_{LG} < 5000 km s^{-1}, a $\geq$ 1.6 arcmin.

For 5000 < V_{LG} < 7500 km s^{-1}, a $\geq$ 1.3 arcmin.

The SFI survey combines I-band CCD imaging with high sensitivity 21-cm HI line observations and emphasizes uniform data processing and analysis. Our choice of Sbc-Sc galaxies aims to minimize possible type-dependent variations in fundamental parameters such as the mass-to-light ratio. We use the survey data to examine the effects on observed properties of viewing aspect, internal extinction, and local environment. Careful sample definition, large sample size and uniform coverage both on the sky and with redshift allows analysis of Malmquist and selection bias, completeness, and statistical uncertainties for comparison with models and reconstruction of the density field.

After beginning the project, the importance of deriving an accurate TF template relation became apparent to us, and thus a second project, dubbed the Cornell-Arecibo-Palomar clusters project, was undertaken. For HI-deficient galaxies in cluster cores, for which HI velocity widths are therefore unattainable, we derived a complementary measure of rotational velocity from Hα rotation curves obtained with the Palomar 5-m telescope. Our sample consists of 798 galaxies within and near 24 distant clusters (the SCI sample). After applying strict membership criteria based on available redshift data, and following the iterative technique described in Giovanelli et al. (1996b), a template TF relation was derived using 351 galaxies. Our final cluster member TF template is shown in Figure 7.

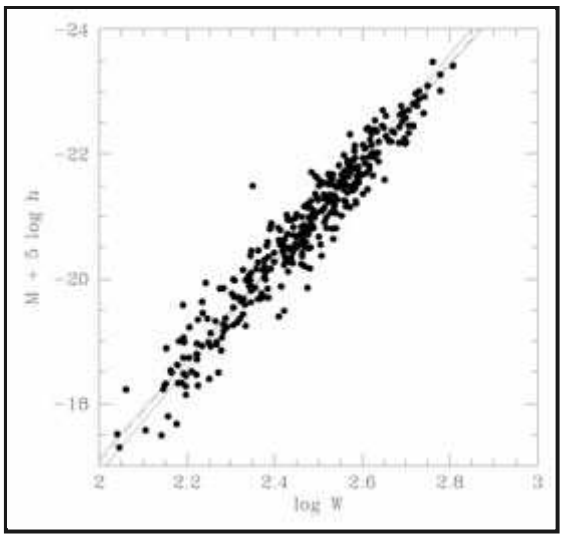

Figure 7. Template I-band Tully-Fisher relation for 351 galaxies located in 24 clusters. Lines indicate the fits to the direct, inverse, and bi-error TF relations. See Giovanelli et al. (1996b) for details.

Results from the SFI Sample The results from the SFI sample are being published in a series of papers (Giovanelli et al. 1994; 1995; 1996a, b, c; Freudling et al. 1995; da Costa et al. 1996). First of all, we emphasize that there are many subtleties in the application of the TF technique that can lead to spurious results. An inadequate TF template relation can easily simulate bulks flows or other geocentric features of the velocity field. Incorrect internal extinction laws have produced inclination-dependent peculiar velocities, increased the inferred scatter in the TF relation, and altered its slope (because of a residual dependence of extinction on galaxy luminosity [Giovanelli et al. 1995; see also Willick et al. 1996]). Because it was not realized that the main source of the observed scatter in the TF relation is the error in the velocity width and that the error depends on W, corrections for scatter in the TF relation, dubbed the "homogeneous Malmquist bias", have often been inadequate. Often, published global 21-cm line widths, including many we reported in past redshift surveys, were heavily smoothed, and thus artificially broadened. Adequate corrections for smoothing, instrumental broadening and signal-to-noise are required. It is also apparent that the TF relation becomes unreliable for small width galaxies, partly because errors dominate ($\delta W / W$ large), and partly because turbulent motions contribute a significant, but uncertain, component of the velocity. Other omissions include the failure to correct for the effect of redshift cutoff in the sample, which produces spurious peculiar velocities in the outer shells of the sample volume. For all these reasons, application of the TF method to derive peculiar velocities is a tricky business; lots of things can, and probably do, go wrong.

Our analysis of the SFI sample to derive peculiar velocities has incorporated our own data to derive the various corrections mentioned in the preceding paragraph and to estimate errors using both empirical analysis and Monte Carlo simulations.

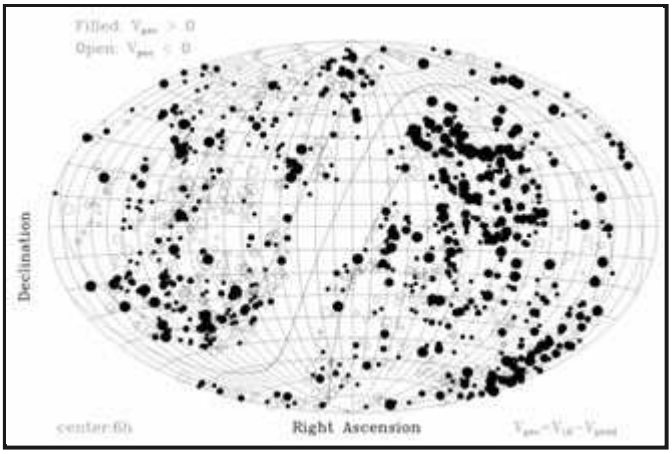

Figure 8. Map of the peculiar velocities of 1585 Sc galaxies from the SFI project. The map coordinates are the same as in Figure 1. Galaxies with positive V_{pec} (motion away) are plotted as filled symbols, while those with negative V_{pec} (motion toward us) are open symbols. The size of the symbol is proportional to the magnitude of the peculiar velocity. In this figure, V_{pec} is measured relative to the rest frame of the Local Group. Note the strong dipole signature between the north and south galactic caps: galaxies in the south are preferentially moving away, while those in the north are moving toward us.

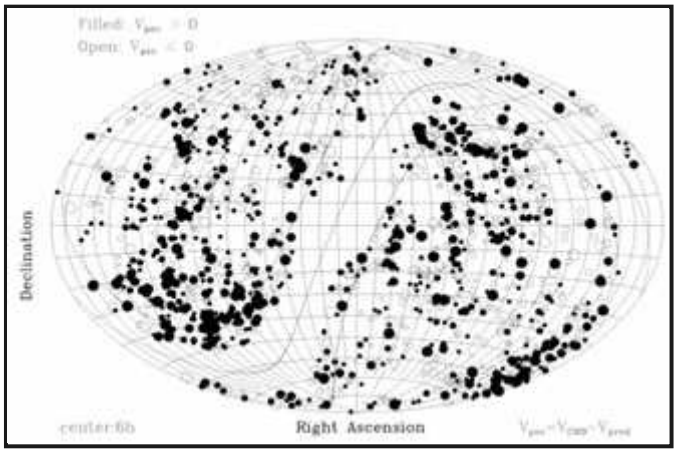

Figure 9. The same as Figure 8, except that now V_{pec} is measured relative to the rest frame defined by the cosmic microwave background. The dipole signature has disappeared. The concentration of filled symbols on either side of the zone of avoidance in the southern portion of the sky represents the infall into the Hydra-Centaurus supercluster (a.k.a. the Great Attractor).

In general, the peculiar velocities derived from the SFI and cluster samples are smaller than those found by others. Figures 8 and 9 present the visual comparison of our results for the so-called convergence depth, the volume which contains the mass responsible for our motion with respect to the CMB. Figure 8 shows the distribution on the sky of the peculiar velocities derived from the SFI sample. The symbol size reflects the amplitude of the peculiar velocity: filled circles represent positive peculiar velocities, while open ones show negative peculiar velocities. Thin lines denote the galactic plane and lines of constant latitude $b = \pm 20°$. In this figure, velocities are referenced to the rest frame of the Local Group: $V_{pec} = V_{LG} - V_{TF}$. For comparison, Figure 9 shows the corresponding diagram, but now referencing the peculiar velocities to the rest frame of the CMB: $V_{pec} = V_{CMB} - V_{TF}$. A comparison of the two figures reveals that the dipole distribution evident in Figure 8 disappears in Figure 9. Thus, we

conclude that the dipole motion inferred from the CMB observations is the dominant feature seen in maps of peculiar velocity referenced to the Local Group. The result is quantified in Table 2 which shows the dipole amplitude and direction derived from analysis of the sample in separate shells of redshift. As the sample is divided into redshift shells, both the apex and the amplitude of the motion converge toward that implied by the CMB dipole anisotropy (Kogut et al. 1993). Thus, the "convergence depth" is on the order of 6000 km s^{-1}.

Table 2. Dipoles of the Peculiar Velocity Field

V_{cmb} Window	V_{pec}(LG)	*l*	*b*	#*Gals.*
All	417±28	253±9	37±3	1585
2000-3000 km s^{-1}	333±41	268±16	41±8	235
3000-4000 km s^{-1}	437±57	242±20	24±5	303
4000-5000 km s^{-1}	551±62	236±24	37±5	372
5000-6000 km s^{-1}	566±81	281±15	24±25	270
CMB	627±22	276±3	30±3	

Examination of Table 2 shows that the region enclosed within a 6000 km s^{-1} radius of the Local Group exhibits a mild bulk flow of order 200 km s^{-1}. However, this bulk flow results from the asymmetry of the mass distribution within that volume and, in particular, the location of the Local Group in a region characterized by a large gradient in the mass density. The density field reconstructed from the observed velocity field agrees well with ones derived from redshift surveys; the known major supercluster complexes are recovered. This reconstruction, presented in da Costa et al. (1996), emphasizes the reality of voids as truly underdense regions. Using the SFI sample, Giovanelli et al. (1996a) have addressed the large-scale bulk flow model of Lauer & Postman (1994, LP) by adding in opposition the velocities of 250 galaxies in each of the cones in the apex and antapex direction of the LP bulk flow. Comparing in windows of CMB radial velocity in order to avoid complications of the Malmquist bias corrections, we find that the SFI galaxies reveal a significant component of bulk flow along the LP apex-antapex direction, but with a smaller amplitude. However, the motion appears to die down at distance shells beyond 6000 km s^{-1}. Either there is a direct conflict with the LP bulk motion, or the geometry of the mass distribution in the local universe is such that the peculiar velocity field locally (cz < 7000 km s^{-1}) is quiescent and surrounded by a concentric outer shell moving at high velocity with respect to this inner region.

7. SUMMARY

Our understanding of the distribution of matter in the local universe has changed immensely in the past two decades. The rapid increase in the number of redshift measurements available for use in analyzing the structure of the universe continues unabated. HI redshifts have contributed significantly to our current knowledge, and will continue to play an important, albeit supporting, role in the future work in this area. The Sloan Digital Sky Survey will open up the exploration of the universe to unprecedented depths, and the new generation of large ground-based telescopes will likely push pencil-beam surveys to redshifts of 1 and beyond. These are truly exciting times in observational cosmology! Stay tuned.

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