To appear in: Proceedings of *Dark and Visible Matter in Galaxies and Cosmological Implications,* (Sesto Pusteria, Italy, 2-5 July 1996), eds. M. Persic, P. Salucci (ASP Conference Series)

Spatially Resolved Kinematics of Distant Galaxies

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Abstract.
A Tully-Fisher (TF) relation from Hα rotation curves of 19 luminous, star-forming galaxies reveals there is little evidence for evolution in the mass-to-light ratio (M/L) of these galaxies to $z \sim 0.3$. The near-infrared Tolman surface-brightness test for other luminous galaxies indicates their luminosity also is little changed to $z \sim 0.3$. In this redshift regime, internal velocity – luminosity relations like Tully-Fisher may provide a way to measure q_0. Discrepant results from several intermediate redshift Tully-Fisher surveys, however, must be understood first. One possibility is that different surveys sample different galaxy types and TF relations. Alternatively, M/L of some spiral galaxies may evolve rapidly with look-back time. Larger surveys are needed to resolve this issue. A different approach is to determine disk and halo M/L separately. Such measurements, even at low redshift, would be sensitive to the star formation histories of disks. We outline plans for $\lambda/\Delta\lambda \sim 10000$ integral-field spectroscopy of relatively face-on spirals using the 9m Hobby-Eberly Telescope. Rotation curves and disk stellar velocity dispersions can provide *statistical* information about the M/L of dark halos as well as luminous disks.

1. Rotation Curves of blue galaxies to $z \sim 1$

The era is now underway when faint galaxy surveys include estimates of internal kinematics. Rotation curves and line-widths are routinely measured on 3-4m class telescopes to $z \sim 0.4$ (Vogt *et al.* 1993, Franx 1993, Bershady 1995b, Bender *et al.* 1996, Rix *et al.* 1996, Simard & Pritchet 1996), and to $z \sim 1$ with 10m class telescopes (Vogt *et al.* 1996a,b). A pressing question is whether current kinematic surveys show evidence for rapid evolution in M/L, or if internal velocity – luminosity relations can be used to construct standard candles for cosmological measurements (Kron 1986, van der Kruit & Pickles 1988). How M/L changes with redshift, say as a function of total mass, will depend in part on the amount and composition of dark matter.

A number of recent pilot surveys have attempted to construct Tully-Fisher (TF) relations at intermediate redshifts with a dismaying range of results as interpreted by departures from local Tully-Fisher relations. Our survey of Hα rotation curves for blue, luminous galaxies reveals little evidence for evolution in M/L to $z \sim 0.3$ (Bershady 1995b, Bershady, Mihos, & Koo 1997). The left panel

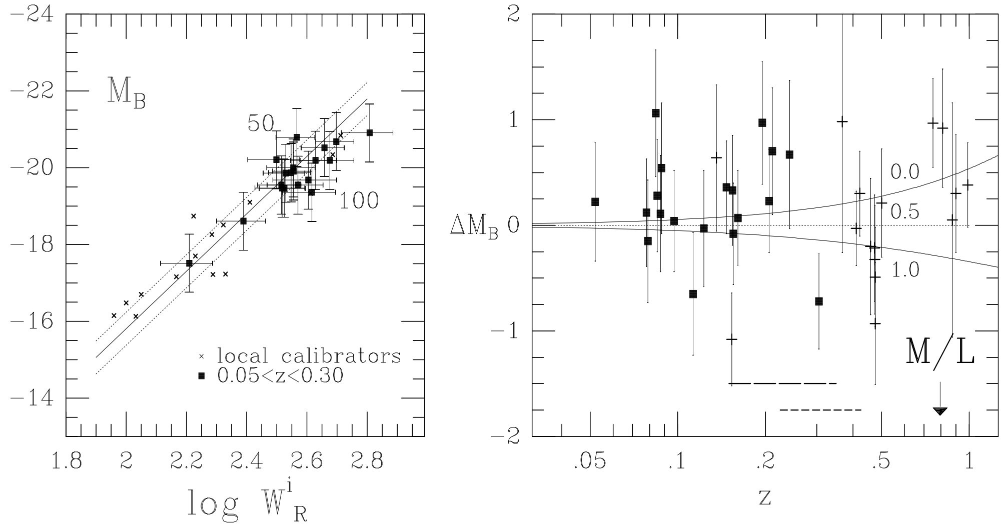

Figure 1. **Left Panel:** B band luminosity vs. line-width for 19 of 21 targets in our sample with successfully measured Hα rotation curves. These are compared to local calibrators and their regressions from Pierce & Tully (1992) assuming $H_0 = 75$ km s^{-1}Mpc^{-1}. 21-cm line-widths, corrected for inclination, are estimated from the rotation curves. Luminosities are corrected for internal reddening following Tully & Foque (1985) for consistency with Pierce & Tully (1992). "Error bars" in luminosity represent different assumptions for H_0: upper (50), lower (100). Photometric errors are <3%. **Right Panel:** Deviations in B band magnitudes for current samples at intermediate redshift from various fiducial ($z = 0$) Tully-Fisher relations assuming q_0=0.5, H_0=75 km s^{-1}Mpc^{-1}). Symbols: filled squares, our sample (Bershady, Mihos & Koo 1997); plusses, Vogt *et al.* (1996a,b); long-dashed line, average for Rix *et al.* (1996); short-dashed line, average for Simard & Pritchet (1996). Curves represent secular changes for different q_0 (labeled); arrow represents secular evolution (decrease) in M/L. Note the significant scatter within individual surveys as well as the very discrepant results between some of the surveys.

of figure 1 shows our sample closely matches the B-band TF relation of local calibrators (Pierce & Tully 1992) assuming H_0=75 km s^{-1} Mpc^{-1}. A similar agreement is found in R, I, and H-bands. A small offset is observed to increase systematically from I (negligible) to B ($\sim$+0.3 mag). The trend is consistent with underestimates of disk inclination and hence under-corrections for internal reddening in our sample. Better inclination estimates are in progress.

More relevant to the issue of evolution is an examination of differential departures from a fiducial TF relation vs. redshift (right panel of figure 1). Our sample together with those extending to $z \sim 1$ from the Keck telescope (Vogt *et al.* 1996a,b) show little evidence for dramatic changes in M/L. It is clear that with these small samples, little can be determined about q_0. However, two other samples (Rix *et al.* 1996, using [O II] λ3727 line-widths; and Simard & Pritchet 1996, using [O II] λ3727 rotation curves) find evidence for brightening of 1.5-2 mag by z=0.25-0.4. Why are there such differences between surveys spanning comparable redshifts?

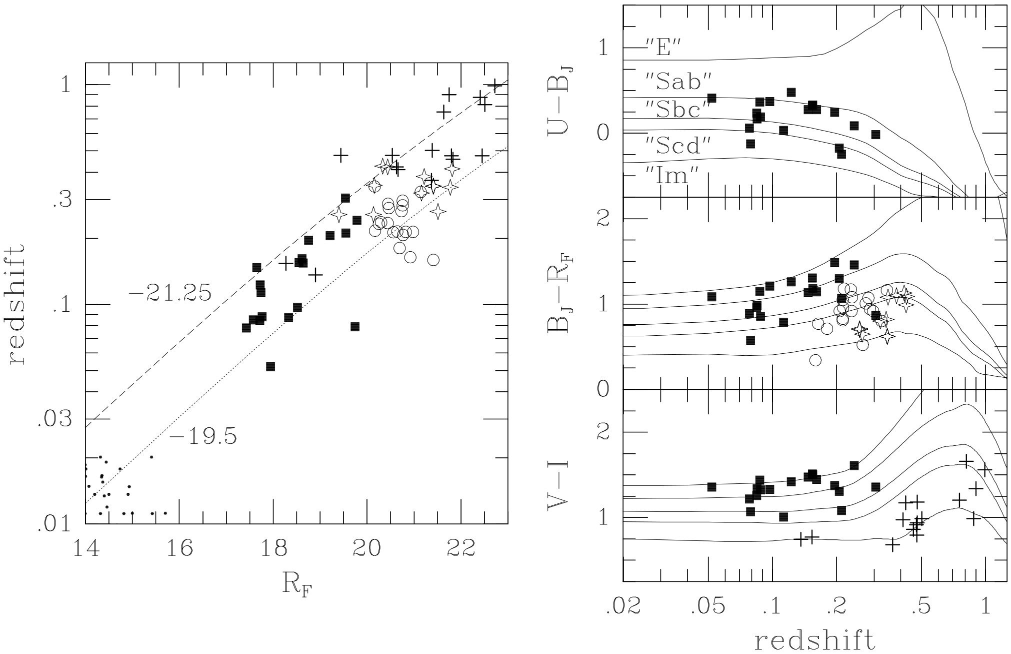

Figure 2. Scope and differences between current intermediate redshift TF surveys. **Left panel:** Hubble diagram in the R_F-band. Diagonal lines correspond to constant luminosity (q_0=0.5, H_0=75 km $s^{-1}Mpc^{-1}$, and Sbc *k*-corrections), where M_{R_F}=-21.25 is $\sim$ M*. Symbols: filled squares are 19 galaxies from Bershady, Mihos & Koo (1997); open circles are 19 of 24 galaxies with good [O II] line-widths from Rix *et al.* (1996); plusses are from Vogt *et al.* (1996a,b; R_F magnitudes are estimated from V and I); open diamonds are 12 of 24 "kinematically normal" galaxies from Simard & Pritchet (1996; R_F magnitudes are estimated from g and r). For comparison, the most distant portion of Mathewson *et al.*'s (1992) local sample is shown (dots). **Right panel:** Color vs. redshift. Colors characteristic of different Hubble types are plotted for reference. Note (1) the different range of luminosity, rest-frame color, or redshift for each survey; and (2) the small number and substantially incomplete coverage in luminosity, type, and redshift for all surveys.

The above surveys consist of samples selected to optimize telescope efficiency. Our strategy (see Bershady 1995b) was, in short, to select galaxies that were optically blue (expected to have strong line emission), but luminous in the near-infrared (expected to be large and have rapid rotation). The Rix *et al.* (1996) and Simard & Pritchet (1996) surveys relax the luminosity criteria but have (different) color or emission line-strength criteria. The samples of Vogt *et al.* (1996a,b) are selected on the basis of visual morphology from HST WFPC-2 images. For a variety of reasons, either the characteristic luminosity, rest-frame color, or redshifts of these four surveys are different (figure 2). Rix *et al.*'s (1996) sample is $\sim$1 mag lower in luminosity than the others; Simard & Pritchet's (1996) sample is intermediate in redshift between ours and Vogt *et al.*'s (1996a,b); our sample is redder (in the rest-frame) than the other three.

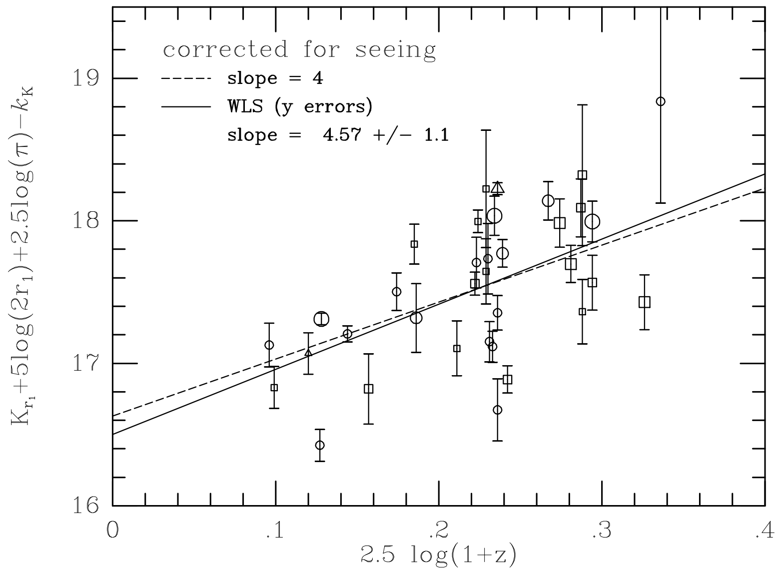

Figure 3. The Tolman surface-brightness test in the K-band for field galaxies with $M_K < -24.75$ (H_0=km s^{-1}Mpc^{-1}) from Bershady *et al.* (1994). The luminosity limit is brighter than that for our rotation curve sample in figure 1, and there is no color selection. Symbols refer to spectral types from Bershady (1995a): *bm* (triangles), *am* or *fm* (squares), *gm* (circles). Surface-brightness is measured as an average within twice the first moment of the light profile (r_1), and is k-corrected (Bershady 1995a). Size measurements have been corrected on the basis of a grid of synthetic galaxy images for a range of disk-to-bulge ratios, inclinations and sizes, which are aberrated for seeing. The aberrated model best matching an observed galaxy's size, inclination, and image concentration is used to estimate corrections. The corrections are small. The dashed line (slope of 4) indicates expectations for no luminosity evolution, assuming the expansion is real. The solid line is the best fit using a weighted linear least-squares (WLS) regression from Akritas & Bershady (1996), which accounts for the intrinsic scatter in surface-brightness as a function of galaxy type and luminosity. The observed slope is consistent with no evolution, although the uncertainty is large given the small sample size.

Selection based on luminosity, color, line-strength or morphology is not a problem for differential measurements with redshift as long as the selection is well-defined over all redshifts. What is difficult, however, is comparing samples selected with different criteria, particularly because internal velocity – luminosity relations may systematically vary with galaxy type (e.g. Rubin *et al.* 1985). Alternatively, galaxies may evolve differently depending on mass or other physical attributes. It is critical to distinguish between the above two possibilities. Most current samples, however, are either too small or probe too narrow a range of redshift to *internally* measure changes with redshift.

More troublesome are potential biases with redshift in the kinematic measurements themselves. For example, interpretation of spatially integrated line-widths suffers from the ambiguity of not knowing the spatial distribution of the line-emitting material. In the optical, a centrally concentrated star-burst compared to a blue, star-forming disk may have drastically different line-widths even though their gravitational potentials are similar. Rix *et al.* (1996) have presented the most comprehensive attempt to treat this problem to date. To complicate matters, it is likely that there are systematic differences between the spatial distribution of [O II] $\lambda 3727$ and Hα in galaxies. A comprehensive comparison of Hα and [O II] $\lambda 3727$ even within local galaxies is lacking. More subtle are the effects of spatial resolution on spatially resolved rotation curve measurements. For example, how does the apparent maximum rotation velocity change for identical galaxies observed at different distances but in the same seeing? One expects such effects are small if the galaxies remain larger than the seeing disk; still, this question must be answered in detail. Careful examination of all of the above questions is critical because of the steep slope in the relation between line-width and luminosity.

The future success of using the TF relation to study galaxy evolution and cosmology depends on two additional factors. First, samples must be assembled intelligently to make internally-consistent comparisons over substantial ranges of redshift. Surveys must be large enough to construct template relations at different redshifts and account empirically for internal absorption, as is now becoming possible locally (e.g. Giovanelli *et al.* 1995). Second, independent assessments of luminosity evolution must be available because deviations from the power-law TF relation are degenerate for changes in M and L. One possibility is the Tolman surface-brightness test, an example of which is illustrated in figure 3. While assumptions must be made about evolution in size, the beauty of this test is that surface-brightness, like line-width, is curvature independent. For the most luminous galaxies from Bershady *et al.* (1994), figure 3 indicates there is little evidence for brightening in the K-band surface-brightness to $z \sim 0.3$. One reasonable interpretation is that the luminous mass has changed little in luminous galaxies over this look-back time. Note that the sample in figure 3 is not the same as our (rotation curve) sample in figure 1, but illustrates the concept. Such studies *in the field* are easily extendible – using 10m-class telescopes or the Hubble Space Telescope – to include TF samples at $z \sim 1$ or lower luminosities. The near-infrared is advantageous because k-corrections are well-defined to high redshifts, vary little between galaxy types, and presumably trace stellar mass.

2. Disk Kinematics at low redshifts

Global kinematic measurements, such as rotation curves, are a rather blunt tool for probing dark *and* luminous matter in galaxies because they are sensitive to the total mass. For spirals, the M/L of the disk is likely to vary much more rapidly with look-back time than the halo M/L. Yet the disk constitutes only a small portion of the total mass, while providing substantially to the total light. Hence it would be desirable to independently measure the masses of the disk and halo. This is possible for spirals if rotation curve and disk scale length measurements are combined with measurements of the z-component of the disk velocity dispersion (σ_z) and scale height (Bahcall & Casertano 1984). Direct determinations of disk and total masses would alleviate the assumptions in most disk/halo decompositions, namely maximal disks and constant disk M/L (e.g. van Albada *et al.* 1985, Sackett 1995).

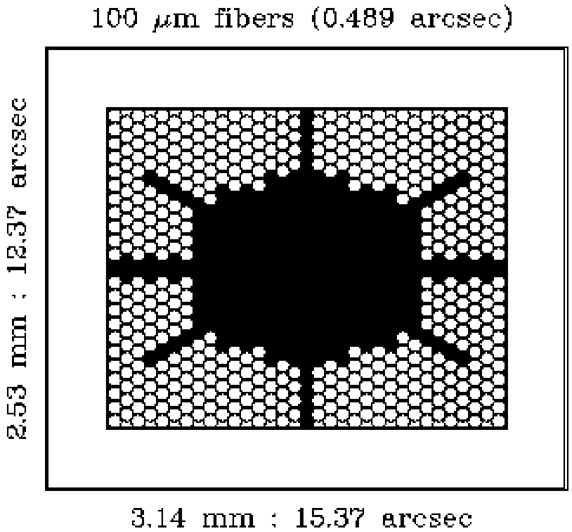

Figure 4. One of two integral field fiber array designs for galaxy kinematic studies with the HET's Medium Resolution Spectrograph (MRS). The 15 arcsec field is filled with ~0.5 arcsec diameter fibers. Dark fibers go through to the spectrograph; remaining open fibers are for packing. A second array uses 1 arcsec fibers to span a 30 arcsecs. The filling ratio is 75% in the coherent regions. Ten sky fibers are attached to the support structure (not shown). Note that diagonal axes are at $\pm 30°$ from the major axis.

How would such measurement be made? An important issue to consider is disk inclination. In order to maximize projection, face-on galaxies are preferable for measuring σ_z (which is small), while more inclined systems are preferable for rotation in order to minimize corrections. Disk scale height measurements must be made for highly inclined systems. One option is to survey similar galaxies with a range of disk inclinations. To separate σ_z from the other components of the disk velocity dispersion ellipsoid in inclined disks requires observations at multiple position angles. Such observations will also provide sensitivity to (i) non-circular motions (Franx & de Zeeuw 1992); (ii) the radial dispersion σ_R, which can be used to explore disk stability (Toomre 1964); and (iii) kinematic estimates of disk inclination (e.g. van der Kruit & Allen 1978).

Can such measurements be made? Disks generally have low surface brightness and velocity dispersions of few $\times$ 10 km/s, requiring spectral resolutions of ~8,000-10,000. There have been a number of measurements of disk velocity dispersions in nearby galaxies (e.g. recently Bottema 1993, and references therein), but they have proven difficult on 4m-class telescopes. However, integral field spectroscopy on 10m-class telescopes would make such measurements quite feasible. In addition to the increased light gathering power of a 10m telescope, multiple position angles could be observed simultaneously. We are designing integral field units for the 9m Hobby-Eberly Telescope's (HET) Medium Resolution Spectrograph specifically for observing disk kinematics. One example of an integral fields unit for the HET is illustrated in figure 4. In two hours the HET can measure a disk velocity dispersion at z=0.2 for what would take 6 hours at z=0 on a 4m telescope. A simulation of a large spiral galaxy ob-

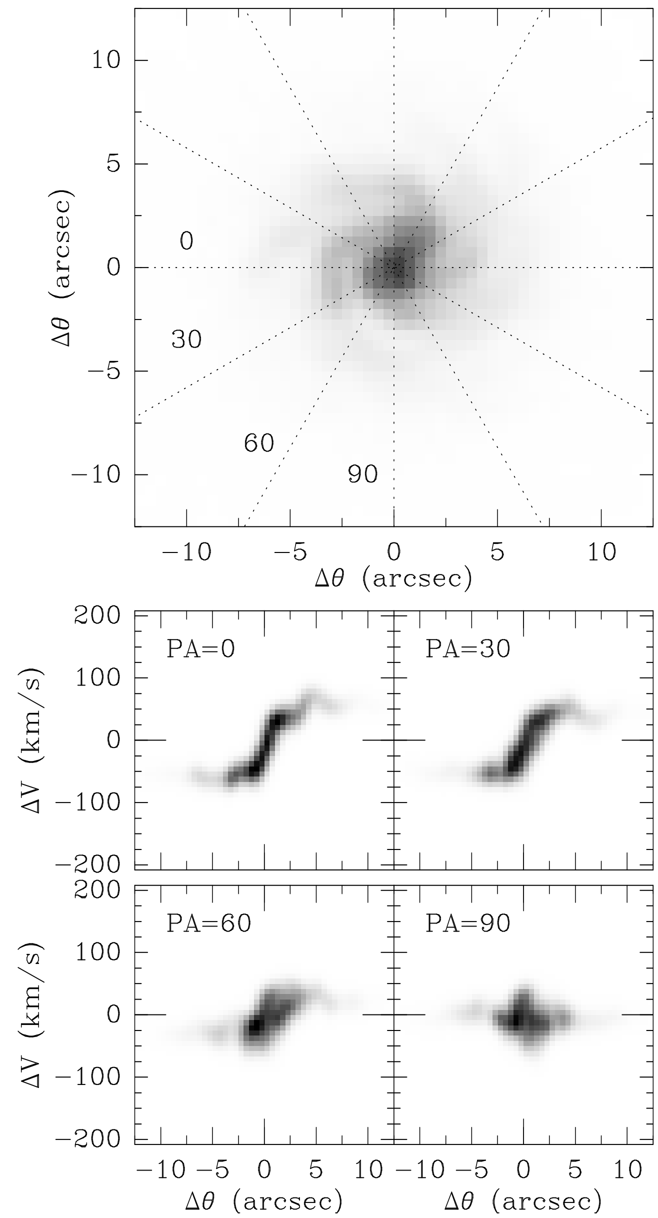

Figure 5. Simulation of a spiral galaxy observed at $z = 0.2$ in 1 arcsec seeing (FWHM) with a fiber array with 0.5 arcsec fibers and spectral resolution of 10,000 (Bershady & Mihos 1997). The galaxy has 250 km/s maximum rotation velocity, 3.75 h^{-1} kpc disk scale length, and inclination of 15°. Top panel: two-dimensional spatial image is reconstructed in Hα. Four bottom panels: spectra centered on Hα are extracted at position angles of 0, 30, 60, and 90 degrees from the galaxy major axis. Noise has not been added. Note that (1) even at 15 degrees inclination, rotation is easily detected; (2) a misalignment of the major axis would be easily detected by the presence of rotation in the minor axis; (3) while the simulation is for line-emission, schematically it shows how stellar absorption line-widths can be measured over a large number of resolution elements.

served with an integral field unit at z=0.2 is shown in figure 5. A second unit is designed for galaxies at redshifts as low as 0.05.

Even without disk scale height information for individual galaxies, integral field spectroscopy will enable us to determine the ratio of rotation speed to disk velocity dispersion in a single observation per galaxy. To first order, this ratio scales as the ratio of the total mass to the mass of the disk. Hence it should be possible to substantially improve our estimates of galaxy disk and halo masses. This in turn will allow us to better interpret observed changes in global M/L at intermediate redshifts and the nature of dark matter.

Acknowledgments. I thank C. Mihos and D. Koo for allowing me to present results of our rotation curve survey and simulations prior to publication. This research was supported in part by NASA through grant HF-1028.02-92A from STScI (operated by AURA, Inc. under contract NAS5-26555).

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