Rotation Curves and M/L Evolution for Galaxies to $z = 0.4$

M. A. Bershady[1], M. P. Haynes[2], R. Giovanelli[2], D. R. Andersen[3]

[1] *Department of Astronomy, University of Wisconsin, 475 N Charter Street, Madison, WI 53706,*
[2] *Center for Radiophysics & Space Research and National Astronomy & Ionosphere Center, Cornell University, Ithaca, NY 14853*
[3] *Dept. of Astron. & Astrophys., Penn State, University Park, PA 16802*

Abstract.
We present results from an on-going [O II] λ3727 and Hα rotation-curve survey to study the evolution of the mass-to-light ratio (M/L) of spiral galaxies selected over a wide, well-defined range in rest-frame color to $z = 0.4$. Optical–near-infrared photometry and long-slit spectra are combined to measure residuals from a fiducial Tully-Fisher (TF) relation as a function of redshift and galaxy spectral type. While we do find a type-dependence in the B-band TF relation, there is little evidence the dependence has changed with look-back time. Larger or more detailed kinematic studies will yield further insights. We demonstrate, for example, how integral field spectroscopy will provide fundamentally new and more precise information about the evolution of star-forming disks.

1. Evolution of star-forming galaxies

The study of galaxy evolution has focused largely on the relative frequency (counts) of photometric properties as a function of redshift and magnitude, such as luminosity, color, and image structure. To this it is now possible to add kinematic estimates of mass. Measurements of global changes in mass and light, M/L, are sensitive to both the star-formation and mass assembly histories of galaxies. For some galaxies, such as starbursts (see Jangren *et al.*, these proceedings, for an extreme example), mass may change abruptly via merging events. The disks of large galaxies seen today, however, are presumably long-lived; these dynamically cold disks, if they have accreted matter in recent times, have done so slowly. On the other hand, galaxy formation models require today's disks to form late, at $z \leq 1$ (Mo *et al.* 1998; Weil *et al.* 1998). Optical rotation curve measurements can probe this intermediate redshift regime directly.

Over the past year we have begun a rotation-curve survey at Palomar Observatory of galaxies selected between $0.2 < z < 0.4$. This survey extends the rotation-curve sample of Bershady, Mihos & Koo obtained at Lick Observatory (Bershady 1997) both in redshift, luminosity, and galaxy type. While the Lick sample was purposefully limited to the brightest, late-type galaxies with the reddest optical-infrared colors, the Palomar sample is representative of the observed distribution for colors bluer than an un-evolving Sa galaxy and L>0.1L*. The hall-mark of the combined data set is (a) simultaneous, spatially resolved kinematic measurements made in [O II] and Hα at all redshifts; (b) pre-existing multi-band images, and (c) a well defined parent sample (Munn *et al.* 1997)

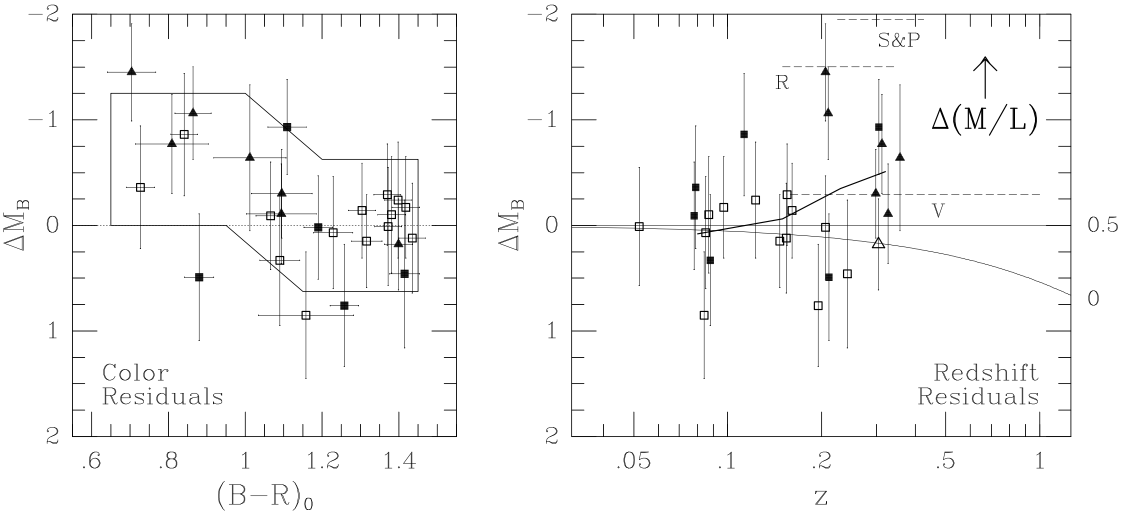

Figure 1. B-magnitude residuals of the TF relation for our surveys plotted vs rest-frame $B-R$ color (left panel), and redshift (right panel). Pierce & Tully's (1992) TF calibration, inclination and extinction corrections are adopted; however, H_0=69 km s^{-1}Mpc^{-1} (Giovanelli *et al.* 1997b), and q_0=0.5 are assumed. In both panels our Lick and Palomar samples are shown as squares and diamonds, respectively. In the color-residuals diagram: open symbols $z < 0.175$; filled symbols $z > 0.175$. The enclosed area demarks the region occupied by Pierce & Tully's (1988) local cluster sample. In the redshift-residuals diagram: Open symbols $B-R > 1.15$; filled symbols $B-R < 1.15$. Average offsets from other surveys are labeled, dashed lines (V, Vogt *et al.* 1996, 1997; R, Rix *et al.* 1997; and S&P, Simard & Pritchet 1998). Light, solid curves represent secular changes for different labeled q_0. The heavy, solid curve is the average offset in our combined samples as a function of redshift, ignoring any color-dependence in the B-band TF relation. However, the observed trend of more negative offsets with bluer color accounts for the trend in redshift. We find little evidence that this color trend evolves with redshift for our sample.

with spectroscopic redshifts. The combined samples now number 40 galaxies with high-quality rotation curves. We find [O II] rotation curves are generally of lower quality than Hα both in spatial extent, S/N, and spectral resolution. The results presented here use Hα rotation curves only.

Figure 1 shows the residuals from a fiducial B-band Tully-Fisher relation as a function of rest-frame B-R color and redshift for 26 galaxies currently analyzed from our sample. Since the cosmological dependence on magnitude is weak for $z \leq 0.5$, the redshift-residuals diagram can be used to measure evolution: the arrow represents the effect of decreasing M/L. As reported previously (Bershady 1997), there is significant difference between the residuals we find, and those found in the surveys of Rix *et al.* (1997) and Simard & Pritchet (1998). Now that our sample contains a wider range of types and redshifts, we are in a better position to address these discrepancies. Indeed, we find an offset between blue and red galaxies within our own sample. Local B-band type-dependencies in the TF-relation are well known (Roberts 1978, Burstein 1982, de Vaucouleurs *et al.* 1982, Rubin *et al.* 1985), and have been measured at intermediate redshift by Rix *et al.* (1997). Based on our sample alone, the type-dependence (as parameterized by color) has not evolved. Hence, *we still find no evidence for evolution of the TF-relation* to $z = 0.4$.

Assuming this particular class of relatively massive disk galaxies has evolved at these look-back times, evolution has been both in color, luminosity, and mass such that galaxy M/L remains within the range observed locally. Since the range of observed rotation speeds at a given luminosity and color does not change with redshift in our sample, we have no compelling evidence that mass has changed substantially. A likely possibility is that the relative fraction of galaxies (red to blue) changes, but at a fixed rotation speed and size (or mass). To confirm this, larger intermediate-z samples are needed for detailed comparison to local templates (e.g. Giovanelli *et al.* 1997a). To refine inferences of mass evolution, independent measures of luminosity evolution are also needed. Promising diagnostics include surface-brightness, rotational asymmetry (e.g. Conselice 1997), and emission line-strength compared, for example, at fixed color and line-width.

2. Disk Kinematics and Integral Field Spectroscopy

In addition to gathering larger kinematic samples with more sophisticated photometric diagnostics, there is yet another direction for intermediate redshift kinematic surveys: spatial maps of disk velocity and velocity-dispersion. These can be readily obtained from Fabry-Perot images or integral-field spectra of optical and near-infrared emission lines. Detailed kinematic studies are invaluable for several reasons. For example, modeling suggests that when distant galaxies are observed with a single slit, slit mis-alignment and spatial resolution significantly affect the inferred rotation velocities. While some of these systematics can be corrected reliably with spatially-resolved spectra (Vogt *et al.* 1996, Bershady & Mihos 1999), the corrections assume axisymmetric velocity fields. Velocity maps remove many of these problems, most notably kinematic vs photometric position-angle mis-alignments, and inclination errors due to disk asymmetries. Figure 2 illustrates the potential power of integral-field spectroscopy for mapping velocity fields in galaxies; with 10m-class telescopes, these measurements can be made easily at intermediate redshift (e.g see Andersen & Bershady, these proceedings). Detailed kinematic studies will be necessary to calibrate larger, statistical surveys using only a single fiber or slit per target.

Non-axisymmetric components of disk velocity fields are interesting in their own right, particularly if the incidence (or amplitude) of the asymmetries change with look-back time. Such an increase might be expected if the 'harassment' or mass-accretion rate were higher or more irregular in the past. Ideally, comparisons would be made between kinematic and photometric asymmetry (e.g. Kornreich *et al.* 1998), using optical or near-infrared light for both measures.

Most challenging will to measure stellar velocity dispersions in galaxy disks, near and far. Such measurements are of critical importance for estimates of disk mass and M/L (see Bosma, Fuchs, and Quillen, these proceedings). While Fabry-Perot's are powerful for single emission-line measurements over a large dynamic range in angle, for absorption line measurements of single targets, integral-field spectrographs with large étendue will be the instruments of choice.

Acknowledgments. We thank C. Mihos & D. C. Koo for allowing us to present data in advance of publication.

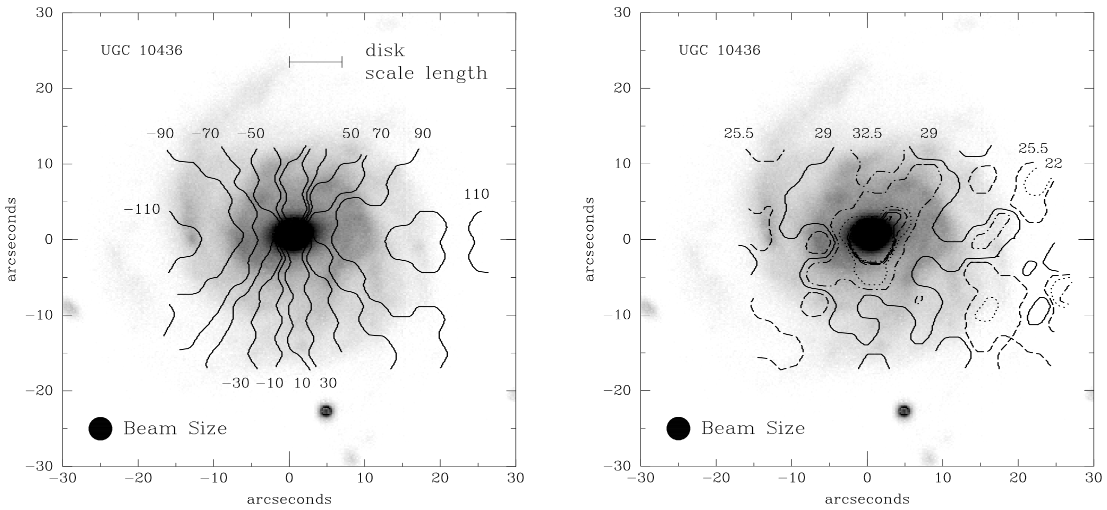

Figure 2. R-band image of UGC 10436 at $z \sim 0.03$ superimposed with contours of velocity (**left panel**) and velocity dispersion (**right panel**), as measured in Hα (km s^{-1}) with WIYN's Densepak (Andersen & Bershady 1999). The photometric axis ratio implies an inclination of $< 10°$), while modeling of the kinematic map yields an inclination of $\sim 35°$, indicating a photometric asymmetry in the disk. Velocity dispersions (σ) have been corrected for beam-smearing; the effect is small outside of the central beam. These high signal-to-noise Hα measurements can be obtained with integral field spectroscopy in 0.5 hours on a 3.5m telescope. With a few times higher étendue, comparable measurements could be made in stellar absorption in reasonable exposure times.

References

Andersen, D. R. & Bershady, M. A. 1999, in preparation
Bershady, M. A. 1997, A.S.P. Conf. Ser. vol 117, 537
Bershady, M. A. & Mihos, C. 1999, in preparation
Burstein, D. 1982, ApJ, 253, 539
Conselice, C. J. 1997, PASP, 109, 1251
Giovanelli, R. *et al.* 1997a, ApJ, 477, L1
Giovanelli, R. *et al.* 1997b, AJ, 113, 53
Kornreich, D., Haynes, M. P., & Lovelace, R. V. E. 1998, AJ, 116, 2154
Mo, H. J., Mao, S., White, S. D. M. 1998, MNRAS, 295, 319
Munn, J. A. *et al.* 1997, ApJS, 109, 45
Pierce, M. J. & Tully, R. B. 1988, ApJ, 330, 579
Pierce, M. J. & Tully, R. B. 1992, ApJ, 387, 47
Rix, H.-W. *et al.* 1997, MNRAS, 285, 779
Roberts, M. S. 1978, AJ, 83, 1026
Rubin, V. C. *et al.* 1985, ApJ, 333, 522
Simard, L. & Pritchet, C. J. 1998, ApJ, 505, 96
de Vaucouleurs, G. *et al.* 1982, ApJ, 254, 8
Vogt, N. P. *et al.* 1996, ApJ, 465, L15
Vogt, N. P. *et al.* 1997, ApJ, 479, L121
Weil, M.L., Eke, V.R., Efstathiou, G. 1998, MNRAS, 300, 773