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The Tully-Fisher Relation at Intermediate Redshifts

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1 Introduction

Motivated by recent pioneering measurements of galaxy kinematics at intermediate redshifts[1,2], we have begun a pilot survey to measure rotation curves for blue, star-forming galaxies between $0.05<z<0.35$. The scientific impetus for such measurements is to construct internal velocity - luminosity relations at redshifts substantial enough to make cosmological and evolutionary tests.[3,4] Departures from a fiducial relation as a function of redshift are sensitive to both space-time curvature and the evolution of the mass-to-light ratio in galaxies. Because of this ambiguity – curvature vs. evolution – kinematics should be viewed as a new cosmological tool at intermediate redshifts to be combined with additional measurements. In particular, the apparent internal velocities, colors, surface-brightness, and image shape are all unaffected by curvature, so that this ensemble of observables can be used unambiguously to explore galaxy evolution.

Here we discuss a well-defined method of target selection which assures efficient measurement of spatially and spectrally resolved kinematics, namely rotation curves. Spatial resolution is critical since it is difficult to use integrated line-widths to distinguish between, for example, a low-mass star-forming galaxy and a high-mass galaxy with a central star-burst. For 18 of 19 appropriately selected galaxies to $B<20.5$ from [5], we have successfully measured rotation curves using the KAST spectrograph on the Lick 3m telescope with 1-2 hour integrations for each target. As a sanity check, we present preliminary results for half of our sample: We measure H_0 to be ~ 75 km s^{-1} Mpc^{-1} at a median redshift of 0.15.

2 Target Selection

There are three desiderata for selecting galaxies for rotation-curve surveys at substantial redshift: (i) A similar range of galaxies should be chosen at disparate redshifts on the basis of some objective criteria. (ii) Targets should be optimized for the available instrumental resolution. (iii) Targets should be efficient to observe. There are several well-known correlations for galaxies that when combined, point to a well-defined galaxy type. The correlations are between size

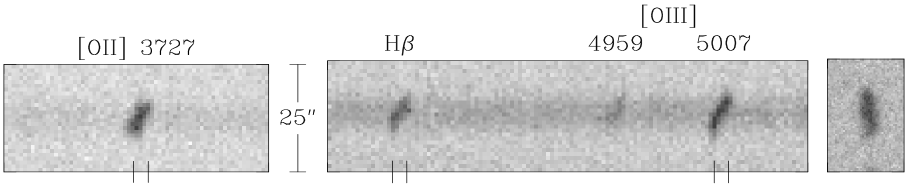

Fig. 1. An example of an observed rotation-curve spectrum for one of our higher-redshift targets at z=0.3 (sa68.5154 from [5] and [6]) using the KAST spectrograph and Lick 3m telescope. We derive a maximum rotation velocity of 405±20 km/s, peak-to-peak from [OII], Hβ, and [OIII]5007. [OIII]4959 suffers from being partly on a sky-line. [OII] appears fuzzy because we have not resolved this doublet. A gound-based B band image of the galaxy (to scale), taken in ∼ 1” FWHM seeing at the KPNO 4m, is at the far right.

and luminosity, color and emission-line strength, color and luminosity, and luminosity and internal velocity. These conspire to make the ideal rotation-curve targets blue, luminous galaxies. How luminous depends on the spatial and spectral resolution of your spectrograph and telescope, and the redshift limit of your survey. How blue depends on your desired efficiency. For our sample, we were able to measure rotation curves one at a time on a 3m telescope at a pace that outstriped the multiplexing advantage of observing red galaxies in clusters at comparable redshifts using a bigger telescope.[1] At the same time, we could spectrally and spatially resolve rotation curves to z=0.3 (see fig. 1) with 1-2” seeing and R∼1500-2500 in the red.

The ideal galaxy for intermediate and high redshift rotation curve studies has spectral type “bm” in the nomenclature of [6]. This is comparable to luminous “Sc” galaxies. However for the purposes of selecting these galaxies for surveys on 4m-class telescopes, it is much more fruitful to think in terms of spectral types. Depending on how restrictive one makes the above selection, the surface-density of luminous, blue galaxies to B=20.5 is low. Without substantially increasing telescope aperture as well as spatial and spectral resolution, fainter limits will not produce substantially greater surface-densities of viable targets: Fainter galaxies will either be at higher redshift (and apparently smaller), or lower in luminosity (and internal velocity and apparent size) at comparable redshifts. This makes selection via Hubble type rather inefficient since this requires Hubble Space Telescope (HST) images which cover little area. In contrast, ground-based, multi-band imaging can provide photometric redshifts[7] and hence spectral classification and luminosities over large areas, ideal for selecting targets for spectroscopic follow-up and pointed HST imaging (when needed). With adaptive optics and/or a 10m-class telescope, target selection strategy can be altered. Here one is optimally exploring a different redshift and/or luminosity regime than should be pursued with a conventional 4m-class telescope.

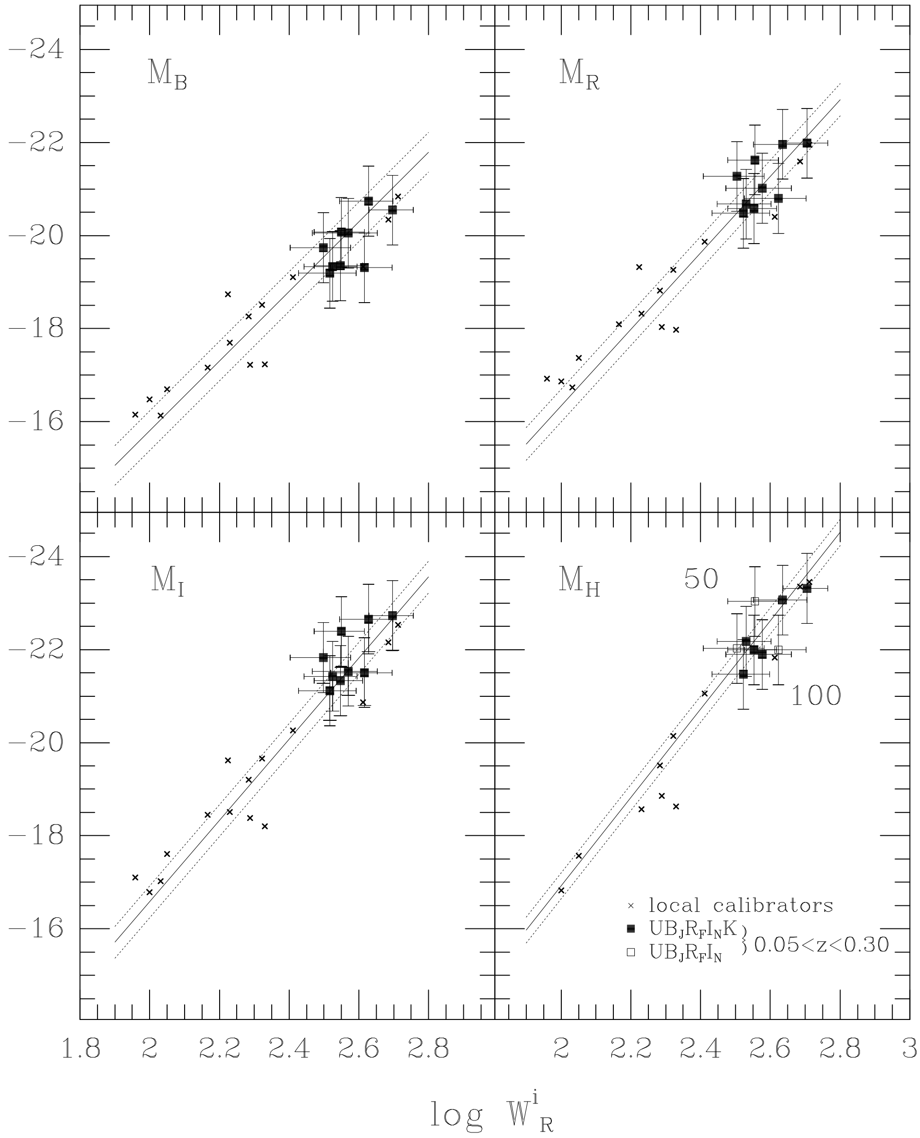

Fig. 2. The Tully-Fisher relation as derived for half our current sample (fully processed). Local calibrating galaxies from [9], with their regression slopes and dispersions are plotted for comparison. Transformation from rotation speed to 21-cm line-widths for our data use formulae in [8]. "Error-bars" in the y-dimension indicate not photometric uncertainties but different assumed values of H_0, as indicated (q_0=0.1). Galaxies in our sample represented by filled boxes have 5-band photometry including the K band; open boxes represent (two) galaxies without K band photometry. Absolute magnitudes in the B, R, I, and H bands are determined empirically by interpolating between observed bands via stellar synthesis models fit directly to the data. [6]

3 A Sanity Check

To see whether it is possible to make sensible kinematic measurements at intermediate redshifts, we have transformed emission-line maximum rotation velocities, measured now for half our sample, into 21-cm line-widths using transformations from [8]. In fig. 2 we compare our sample to the local calibrators of the Tully-Fisher relation from [9]. The errors-bars in the x-axis (velocity) are indeed estimates of measurement errors (rotation velocity, inclination, and transformation uncertainties). However, in the y-axis, the photometric uncertainties are negligible (<10%, since we have deep, multi-band photometry from which we empirically derive κ-corrections). Instead, these error bars represent a range of *assumed* values of H_0 between 50 and 100 km s^{-1} Mpc^{-1}. Relative to the local calibrators, we find average offsets indicating values between 60 and 90 km s^{-1} Mpc^{-1}, depending on band. The median redshift of this sample is 0.15. This result is preliminary since we haven't, for example, corrected for internal extinction (although the correction is negligible in the H band), or corrected for more subtle differences between our photometric system and that used in [9]. Furthermore, inclination corrections have been made on the basis of ground-based images and should be checked with higher-resolution data.

Future prospects should be even more promising. The measurement we are actually interested in making is *differential*, and not absolute. That is, we want to study the deviations from, or changes in scatter about *some* fiducial correlation of internal velocity and luminosity as a function of redshift. Instead of using integrated line-widths or transformations to another system imposed by observations of local galaxies, we can instead devise a new standard measurement of internal velocity (and luminosity) that is optimal for intermediate to high redshift studies. One possibility along these lines has already been suggested.[10]

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