Astro2020 Science White Paper

The Evolution of the Tully-Fisher Relation: Characterizing the Assembly of Rotation-Dominated Disk Galaxies over cosmic time

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: We describe how to examine the properties of rotation-dominated (RD) disk galaxies over cosmic time by probing a large range in mass and luminosity, down to the sub-L* population. The science goal is to characterize the evolution of RD disk galaxies through: 1) the regularity of disk galaxies and their stability vs. their stellar and halo mass, 2) the evolution of the Tully-Fisher (TF), 3) their star formation rates and chemical enrichment vs radius, and 3) the development of stellar bulges and bars. Accomplishing these goals will require an extensive, targeted survey of disks galaxy populations using a “layer-cake” approach that makes use of a broad range of telescope apertures. Small, 3-4-meter class telescopes are currently used to characterize the local galaxy populations down to luminosities well below L*, mid-sized 8-meter class telescopes should continue to be used to characterize the more luminous $0.5 < z < 1.5$ populations and JWST and the ELTs will eventually be used to explore the $z < 1.5$ populations as they come on line. The results of this effort will form the foundation for understanding galaxy evolution and assembly that pertains to the “Galaxy evolution” panel of the Astro2020 Decadal Survey.

The research to date on the evolution of galaxies has revealed that the star formation rate of disk galaxies has dropped by approximately 10x since z $\sim$1 (Madau et al. 1998). Similarly, the familiar morphological forms of galaxies are present to z $\sim$ 1 but become rare at higher redshifts. Thus the epoch of peak assembly also appears to coincide with the epoch of peak star formation. The role of dark matter halos in these processes is unclear and is only addressable through galaxy kinematics. However, the correlation between a disk galaxy's luminosity and/or stellar mass and its rotational velocity, known as the Tully-Fisher relation (TFR; Tully & Fisher 1977), demonstrates that the dark matter halo plays a critical role in the star formation history of disk galaxies. To date, kinematic surveys of disk galaxies with 8-10 meter class telescopes have produced mixed conclusions. Early surveys appeared to suggest rapid evolution in the TFR (e.g., Vogt et al. 1997) but it appears that these surveys were not sufficiently deep to reach the maximum in disk rotation curves and much deeper surveys reveal a well-defined TFR at z $\sim$ 1 with more modest evolution (e.g., Miller et al. 2011). Nevertheless, there is evidence that disordered disks become more common with increasing redshift, e.g., Kassin et al. 2007; Foster-Schreiber et al. 2009. At low redshift the TFR is well defined with low scatter over factors of 100x in galaxy luminosity (e.g., Pierce & Tully 1992; Tully & Pierce 2000). The available data at high redshifts suggests that the scatter increases rapidly for z $>$ 1.5. IFU spectroscopy of the z $\sim$ 1 disks, e.g., Wright et al. 2007, 2009; Lemoine-Busserolle & Lamareille 2010; Vergani et al. 2012, reveal that the disks are only marginally stable with V/σ $\sim$ 2-4, compared with $\sim$ 10 for the cold disks of today. At higher redshifts (z $>$ 2) there is evidence of hotter, morphologically irregular disks, e.g., Genzel et al. 2006; Genzel et al. 2008; Cresci et al. 2009; Lemoine-Busserolle et al. 2010 ; Gnerucci et al. 2011; Genzel et al. 2014) along with much greater scatter in the TFR, although the available samples are too small for definitive conclusions. In fact, at the present time the main reason for which all attempts at unravelling the evolution of disc galaxies at high redshift have proven inconclusive is that these studies have probed only the bright inner regions ($< 1-2$ arcsec scale-lengths) of very bright and massive galaxies.

It is possible to address this question, through a large kinematic survey focused on the evolution of the TFR, the stability of rotation-dominated (RD) disk galaxies, and their star formation history over cosmic time. The primary goal should be to construct an unbiased Tully-Fisher relation using rest frame bandpasses and stellar mass in order to characterize its evolution and the various sources of scatter.

The detailed science goals that this type of surveys will enable are:

(1) Characterizing Ordered Rotation of the Gas: Signatures will include: the largest velocity gradient along the morphological major axis, velocity gradient that flattens at larger radii, line-width FWHMs that are coincident with geometric and kinematic centers, and in best cases a spider diagram in the velocity field. And quantify the stability and degree of disorder of the disks (V/σ) over a broad range of halo masses (V_{max}) over cosmic time.

(2) Sample the turnover of disk rotation curves and measure V_{max}: This can be done only if accurate rotation curves up to 3-4 disk scale lengths are obtained via Hα.

(3) Characterize violent Star-Formation Processes by determining if the gas in the observations and the best-fit models is stable to global SF using the Toomre Q parameter, measuring star-formation rates through line strengths (e.g., Weiner et al. 2007), and looking for evidence of outflows in the emission lines. Compare the star formation rate vs. stellar mass (e.g., Bundy et al. 2009; Pacifici et al. 2015) vs. V_{max} thanks to the Hα equivalent width and mid-IR photometry from JWST

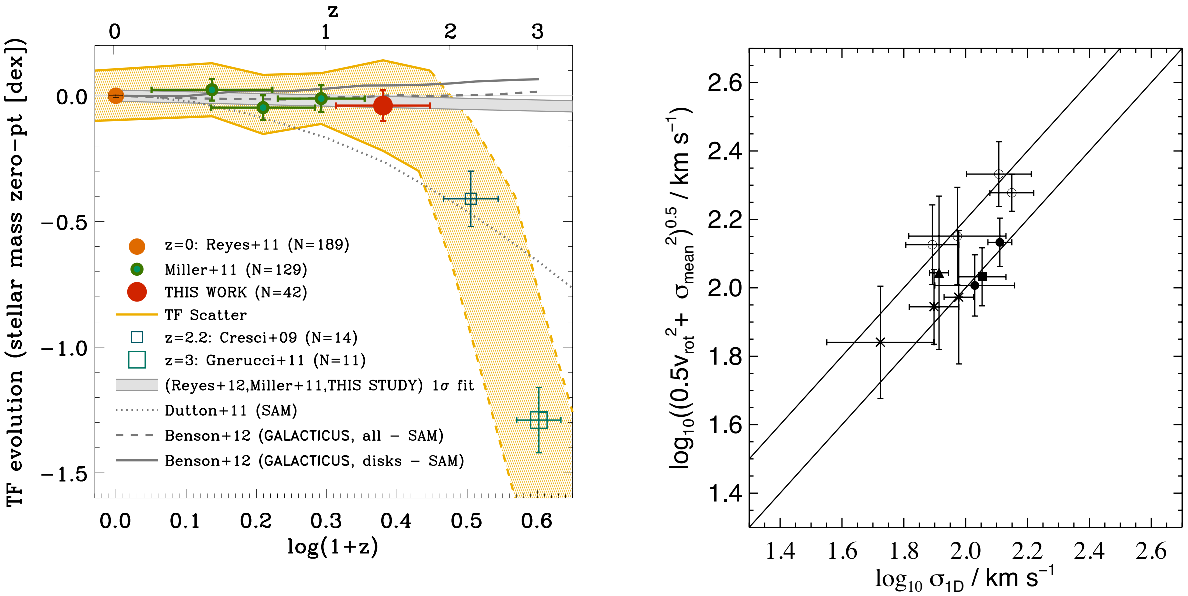

Figure 1: *Left*: The evolution in the stellar mass TFR from a variety of studies (Miller et al. 2012). Note that the evolution for z $<$ 1.5 is modest but increases rapidly at higher z. The increased scatter is attributed to hotter, less regular disks. *Right*: The combined $(0.5V_{rot}^2 + \sigma_0^2)^{0.5}$ velocity for several disks measured via IFU spectroscopy of disks vs. their integrated line-width velocity dispersion (Lemoine-Busserolle & Lamareille 2010). The symbols are *open cirle*: RD disks and *filled symbols*: Dispersion Dominated (DD) rotating disks, with in particular *asterisk*: $z \sim 3$ galaxies from Lemoine-Busserolle et al. 2010). The diagonal lines are the same as in Wright et al. 2007, i.e. a $1:1$ line and Rix et al. 1997 $\sigma = 0.6V_c$ line (V_c is the circular velocity). This plot illustrates the evolution of the dynamical mass which takes also into account the contribution from the random motions in the gas. And It shows an increase of the dynamical mass for z $\sim$ 3 to $\sim$ 1.4 for the DD rotating discs. Note the high disk velocity dispersion for the z $>$ 1 systems.

(4) Confirm the presence of Bulges, Bars & Tidal Features: The high quality JWST imaging will allow the identification of systems with bulges and bars and will help construct separate TFRs and identify and quantify tidally disturbed systems using the CAS & Gini parameters (Conselice 2003; Lotz et al. 2003). IFU spectroscopy is necessary to measure Lick indices of bulges to constrain their age and metallicity compared with the disks (e.g., Thomas, Maraston & Bender 2003).

(5) Radial metallicity gradients, and their evolution, are fundamental constraints of the chemical evolution of galaxies. The emission-line metallicity gradients, determined through oxygen abundances of HII regions across the galaxy disk of redshifted galaxies, can be compared to those of nearby spiral galaxies to determine how much the gradient has evolved, looking back in time. Chemical evolutionary models in a cosmological context diverge greatly at high redshift depending on whether enhanced feedback is included in the computation (e.g., Gibson et al. 2013), and metallicity gradients of redshifted galaxies are the sole constraints on these scenarios. It has been recently shown (Stanghellini et al. 2015) that strong-line abundances based on O3S2N2 index (Marino et al. 2013) are more accurate than those from the O3N2 or N2 indexes. The O3S2N2 index is based on the Hα, Hβ, [OIII], [NII], and [SII] emission line detection, and it is better constrained than the other indices. Multi-NIR band spectra of galaxies with 2 $<$ z$<$ 2.5 will yield a legacy of

spectra where O3S2N2 oxygen abundances can be derived for accurate gradient determination at high redshift, for a large and homogeneously-selected sample of disk galaxies, measured with high angular resolution, and out to large galacto-centric radii, providing strong constraints on chemical evolution models. Measurements of Hβ, [OIII] and MgII + Fe should allow the characterizationof the abundance gradients of disks, and enable the metallicity of the ionized gas and the stellar bulges to be measured. And detailed mapping of dust reddening over these disks from the Balmer decrement (for the subset of sample with Hβ measurements), when combined with the kinematic data will help to characterize the enrichment histories as a function of stellar and halo mass over cosmic time. And when compared with those of local galaxies, allow the star formation rates and histories of disk galaxies to be characterized vs. radius as well (e.g., Thomas, Maraston & Bender 2003).

(6) Measure the stellar kinematics (e.g., Newman et al. 2015). A comparison of the stellar and gas kinematics will provide a measurement and/or a constraint on the outflow of ionized gas and any dependence on the star formation surface density. These measures need to be compared with the latest models of disk formation and evolution that include feedback from supernovae and AGN winds.

(7) Identifying and studying low-luminosity AGN through excitation diagnostics, using high angular resolution to isolate the nucleus from the rest of the disk. The high angular resolution and the kinematics of the Hβ + [OIII] region for the subsample, will also allow the identification of low luminosity AGN and thus provide a measurement of their volume density over a broad range of redshifts. Surveys to date of the local volume have revealed the luminosity function of AGN over a broad range in luminosity but our knowledge at high redshifts is limited to only the most luminous AGN.

(8) Test and compare with the predictions of disk galaxies formation models, specifically the prediction of a log-normal distribution of sizes and specific angular momentum (e.g., Barnes & Efstathiou 1987). Indeed, the Tidal Torque Theory predicts that disks form when baryons settle at the bottom of dark matter potential wells and acquire their angular momentum via tidal interaction with the halo (e.g., Fall & Efstathiou 1980; Mo et al. 1998). The disks are predicted to be both thicker and be more gas rich than the thin disks present at low redshift. The dark matter content of disk galaxies could be assessed in the context of galaxy formation.

Recommendations:

Adaptive Optics assisted Integral Field Spectroscopy (AO-IFS) is essential to provide the spatial resolution and sensitivity necessary to acquire high-quality, 2d kinematics for hundreds of RD-disk galaxies, down to sub-L* population and up to z $\sim$ 2.5. HST and JWST multi-band photometry within selected imaging surveys such as CANDELS, COSMOS and GOODS, will enable the stellar masses and star formation histories to be derived from SED fitting (e.g., Bundy et al. 2009; Pacifici et al. 2015). This will be vital for ensuring the selection of an unbiased sample. In addition, to obtaining the rotation speed of a galaxy, the velocity obtained from the rotation curve has to be corrected for inclination effects. JWST imaging data we will be able to obtain precise estimates for the inclinations. Together these data will allow the selection of rotation-dominated disk galaxies with emission lines, known stellar mass and favorable, accurate orientations. In addition, to build unbiased samples, which span stellar and halo mass, stellar mass density, and metallicity, hundred of galaxies at each redshift should be targeted making the use of multiplexed AO-IFS capabilities essential. In order to study the evolution of the Tully-Fisher relation, fairly matched samples at low and high redshift to compare with each other are needed. The ability to interpret the results obtained from the high redshift galaxies depends heavily on the proper construction of a local comparison sample.

AO-IFS with instruments on 8-10 class telescopes has begun and should continue to help build samples of local galaxies (z <1.5) to span the expected ranges in SFR, stellar mass and V_{max}. The large aperture of ELTs and AO-IFS will make it possible for the first time (higher diffraction-limited angular resolution combined with high S/N allowing the kinematics' measurements out to larger scale radii) to target higher redshifts RD disks galaxies, as well as allowing independent measurements of the disk kinematics via stellar absorption lines. The result of such unbiased carefully selected AO-IFS data will prove to be an unrivaled set of observational kinematic data for disk galaxies and characterize their evolution over cosmic time.

References

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