Dark Matter in Galaxies
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The Relationship between Stellar and Halo Masses of Disk Galaxies at $z = 0.2 - 1.2$

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Abstract. We present the results of a study to determine the co-evolution of the virial and stellar masses for a sample of 83 disk galaxies between redshifts $z = 0.2 - 1.2$. The virial masses of these disks are computed using measured maximum rotational velocities from Keck spectroscopy and scale lengths from *Hubble Space Telescope* imaging. We compute stellar masses based on stellar population synthesis model fits to spectral energy distributions including K(2.2μm) band magnitudes. We find no apparent evolution with redshift from $z = 0.2 - 1.2$ in the relationship between stellar masses and maximum rotational velocities through the stellar mass Tully-Fisher relationship. We also find no evolution when comparing disk stellar and virial masses. Massive disk galaxies therefore appear to be already in place, in terms of their virial and stellar masses, out to the highest redshifts where they can be morphologically identified.

1. Introduction

It is now widely held that most galaxies are embedded in dark matter halos. These halos form from fluctuations of largely non-baryonic mass in the early universe and initially also contain baryons in the form of a hot gaseous phase. This gas later cools, leading to star formation. The history of this star formation, and the resulting build up of stellar mass, is now being traced out (e.g., Madau et al. 1998), yet the physical details of mass assembly remain a major observational challenge. The fraction of gas mass converted into stars is regulated by poorly understood processes such as feedback, cooling, and star formation (e.g., van den Bosch 2002). Theoretical methods, such as those in semi-analytic simulations (e.g., Abadi et al. 2003), predict when galaxies form their stellar mass. It is however preferable to directly measure this evolution through observations. Perhaps the most suitable galaxy type for performing this experiment is disk galaxies where the dark halo and galaxy appear intimately tied, and virial and stellar masses are in principle directly measurable.

Early work on this problem has concentrated on the Tully-Fisher (TF) relationship, which traces the tight correlation between the luminosities and rotational velocities of disk galaxies (Verheijen 2001). Out to redshifts of $z \sim 1$ there appears to be only a slight evolution in this relationship, such that disks are at most ~ 0.5 magnitudes brighter at a given rotational velocity in comparison to those at $z \sim 1$ (Vogt et al. 1996, 1997; Ziegler et al. 2002; Böhm et al. 2003). The fact that the TF relationship does not evolve strongly with time may mask some interesting trends, as the luminosity and rotational velocities of disks can be affected by more than just stellar and dynamical masses. As such, we have begun a study to directly determine the relationship and evolution between the stellar and virial masses of a sample of disk galaxies out to $z \sim 1.2$. We use these data to address several issues including: do massive disks form their virial mass all at once, or does material accrete onto a disk over time? Is baryonic material slowly being converted into stars in disks at $z < 1$, or is most stellar mass in place by then? Our major conclusion is that we do not find significant evolution in the relationship between stellar and virial masses with redshift.

2. Data and Analysis

The sample used in this paper consists of 83 disk galaxies at redshifts from $z \sim 0.2$ to $z \sim 1.2$, with an average redshift of $z \sim 0.7$. These galaxies were taken from the Groth Strip Field Survey (Vogt et al. 1996, 1997, 2004 in prep). These galaxies were typically selected morphologically based on the appearance of a discernible disk in *Hubble Space Telescope* (HST) F814W (I_{814}) images, and in all cases with an apparent magnitude upper limit ($I_{814} = 22.5$) for which spectroscopy can be acquired (Vogt et al. 1997). We also took deep Keck or UKIRT K-band imaging for each of these systems. Our sample is therefore composed of several different data sets which as a group, or individually, are not homogeneous or complete in any sense. There are three main data products used in this analysis: HST imaging for measuring scale-lengths and optical photometry, K-band imaging, and spectroscopy for measuring V_{max} values.

The spectroscopy was acquired with Keck LRIS by observing each disk along its major axis, which was determined using HST images (see e.g., Vogt et al. 1997). The rotation curve for most systems is sampled through the [OII] line, which is visible in the observed optical for galaxies up to $z \sim 1$. Once these raw rotation curves are constructed they are fit to a model that assumes some maximum velocity at one and a half times the scale length (R_d) (Vogt et al. 1996). At radii larger than $1.5 \times R_d$, the velocity curve in this model remains at the maximum. This model rotation curve grows linearly from zero velocity at the center of the galaxy to V_{max} at $1.5 \times R_d$ (Vogt et al. 1996). The observed profile is then fit to various forms of these models, taking into account the seeing, slit width, and misalignment with the major axis, until a best fit solution is found from which the maximum velocity, V_{max}, is retrieved. We use these V_{max} values to compute our virial masses (§3).

3. Virial and Stellar Masses

Simulations have shown that neither the K-band light nor the velocity (or velocity squared), are necessarily good tracers of the total masses of disk galaxies (e.g., van den Bosch 2002). Using a series of models, van den Bosch (2002) showed through simulations that the quantity $R_d V_{max}^2/G$ gives, on average, a good representation of virial mass to within 50%. The best fitting empirical formula, found by van den Bosch (2002), is:

$$M_{\rm vir} = 2.54 \times 10^{10} M_\odot \left(\frac{\rm R_d}{\rm kpc}\right)\left(\frac{\rm V_{max}}{100\,{\rm km\,s^{-1}}}\right)^2, \tag{1}$$

where $\rm R_d$ is the scale length fit and $\rm V_{max}$ is the maximum retrieved velocity of the rotation curves. The zero point of the relationship between $\rm R_d V_{max}{}^2/G$ and virial masses is found to be independent of the amount of feedback and pre-enrichment (van den Bosch 2002). By using this formula we are making the assumption that the maximum rotation velocities derived from the LRIS spectra represent the largest observable velocity of each galaxy.

Stellar masses are based on analysis of our HST and K-band photometry. We use this photometry in typically three bands (the K-band and the two HST bands) to construct spectral energy distributions (SEDs). We then fit these SEDs to template spectra normalized by the near infrared K-band light in a procedure described in Brinchmann & Ellis (2000). The basic fitting procedure consists of comparing model SEDs through a χ^2 minimization to the best fit spectral template from Bruzual & Charlot (2003) models constructed from exponentially declining star formation rates, Salpeter IMFs, and solar metallicity stellar populations. From this, the stellar M/L ratio is determined, and using the K-band flux, a stellar mass is derived. Typical uncertainties in this method are a factor of two (Brinchmann & Ellis 2000).

4. Results

4.1. B-band and K-band Tully-Fisher Relationships

The TF relationship has been studied in disk galaxies out to redshifts $z > 0.5$ by e.g., Vogt et al. (1996, 1997), Ziegler et al. (2002) and Böhm et al. (2003). These investigations have found between 0.4 and 1 magnitude of luminosity evolution in disks at $z > 0.5$ compared to those at $z \sim 0$. This luminosity evolution is derived by assuming that the slope of the TF relationship at high redshift is the same as it is at $z \sim 0$.

After fitting the TF using using a least-squares method, we find a modest luminosity evolution for our $z < 0.7$ disks in comparison to the Verheijen (2001) nearby disk sample (Figure 1). By holding the $z \sim 0$ slope constant for the B-band TF relations, we find a brightening in the zero point of $\sim 0.7 \pm 1.0$ magnitudes in the B-band for disks at $z < 0.7$. At $z > 0.7$ we find that the zero point is fainter, by 0.1 ± 1.1. Neither of these zero point changes are statistically significant, similar to the results of Vogt et al. (1997). The B-band TF relationship is however degenerate such that we cannot separate luminosity evolution from stellar mass growth. We find the same lack of evolution in the K-band TF relationship, with a brightening of 0.5 ± 1.2 magnitudes for systems at $z < 0.7$, and a fading of 0.1 ± 1.1 magnitudes for systems at $z > 0.7$. The scatter in the TF relationship also does not appear to change significantly between the B-band or K-band.

4.2. The Stellar Mass Tully-Fisher Relationship

By comparing the mass of a dark halo with respect to the stellar mass of its disk, we can directly measure how these two components evolve with redshift. This

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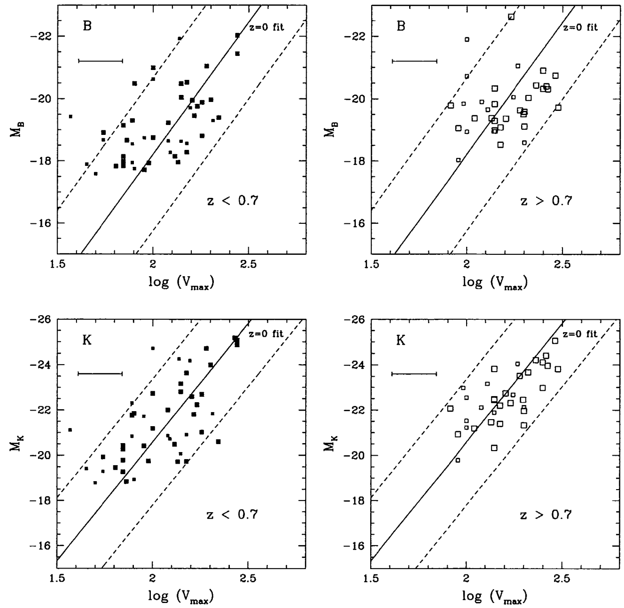

Figure 1. Rest-frame B-band and K-band TF relationships for our sample of disks. The panels are divided into two redshift bins, higher and lower than $z = 0.7$. The solid and dashed lines are $z \sim 0$ TF relations found by Verheijen (2001) and their $\pm$ 3 σ scatter. The average error is shown with large/small points having errors lower/larger than the average.

comparison is to first order independent of effects from dust, star formation histories, and galaxy sizes and thus offers more physical insight than the TF relation. The classical TF relationship between the luminosity of a disk and its maximum velocity scales such that $L \propto \mathrm{V}^{3.5}$. This coupling becomes even steeper when we consider the relationship between stellar mass and velocity in nearby disks, $M \sim \mathrm{V}^{4.5}$, in the so-called stellar mass TF relationship (Bell & de Jong 2001). Ideally we would want to measure the gas content of high redshift disks to determine their total baryonic mass content. We can however use our computed stellar masses to investigate the evolution of stellar mass with virial mass (Bell & de Jong 2001).

We investigate evolution in the stellar mass TF relation by determining the relationship between $\mathrm{V}_{\mathrm{max}}$ and M_* in the two redshift bins separated by $z = 0.7$ (Figure 2). Each panel shows a solid line which is the relationship between $\mathrm{V}_{\mathrm{max}}$ and M_* at $z \sim 0$ as measured by Bell & de Jong (2001). Just as for the B-band and K-band TF relationships there is no significant evolution in the stellar mass TF relationship zero point at either redshift range. After fitting M_* with $\mathrm{V}_{\mathrm{max}}$ we find essentially the same zero point as the relationship at $z \sim 0$. We also find that the scatter in the stellar mass TF relation appears to be nearly the same as in the K-band TF relationship.

4.3. Direct Comparison of Stellar and Dark Masses

We can go beyond the stellar mass TF relationship by directly comparing the stellar mass of a halo to its virial mass. Figure 3 shows this relationship. The

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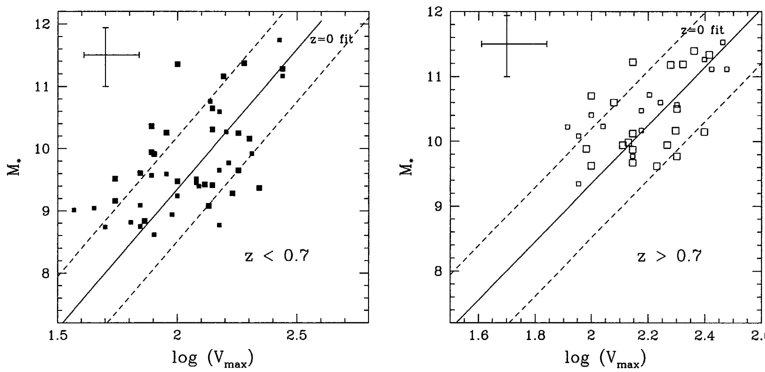

Figure 2. The stellar mass TF relationship (M_* vs. V_{max}). The solid and dashed lines are the $z = 0$ relationship found by Bell & de Jong (2001) for nearby disks and its $\pm$ 3 σ scatter. The error bar is the average error, with large points having errors lower than this average, and smaller points having errors larger than the average.

fitted relation between the virial and stellar mass does not change significantly between low and high redshifts. There is also no obvious trend in the scatter from this relationship at either high or low redshift, although the most depleted systems in stellar mass tend to have high virial masses. We cannot yet say if this is a significant effect, or just the result of small number statistics or underestimated errors. Semi-analytic model predictions for the ratio of stellar and virial masses are also shown in Figure 3.

5. Summary

We demonstrate with ground-based and HST data that it is possible to derive virial masses from long-slit spectroscopy and high resolution imaging, and stellar masses from broad-band optical and near infrared photometry. Based on an analysis of 83 disk galaxies with both stellar and viral mass estimates, we are able to trace the evolution of the stellar and dark mass components of disks from when they are morphologically identifiable at $z \sim 1$, until today. We find the following:

I. Massive disk galaxies exist out to $z \sim 1$ with virial and stellar masses as high as 10^{12} $M_\odot$, roughly as large as the most massive disks in the nearby universe. At least some disk galaxies are extremely mature even at $z \sim 1$, and appear to be forming at $z > 1.5$ (Conselice et al. 2003).

II. Similar to other studies, we find no significant evolution in the rest-frame B-band or K-band TF relation out to $z \sim 1.2$. Both relations also contain a similar amount of scatter.

III. The stellar mass TF relation out to $z \sim 1.2$ is largely consistent with that found for nearby disks. We also find no significant evolution in our sample after comparing systems at redshifts greater than and less than $z = 0.7$.

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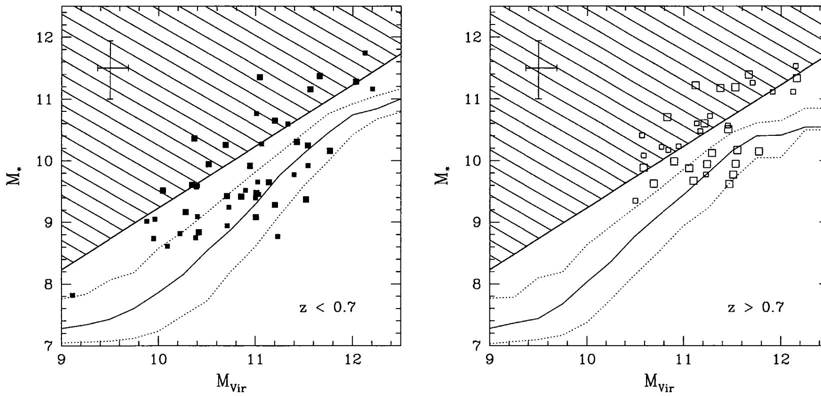

Figure 3. The relationship between stellar mass (M_*) and virial mass (M_{vir}) at redshifts less than and greater than $z = 0.7$. The thick solid line is the baryonic fraction limit and the shaded upper region is where M_*/M_{vir} is larger than the baryonic mass fraction. The thin solid line is the relationship between stellar and virial masses from the semi-analytic models of Benson et al. (2002) at $z = 0$ for the $z < 0.7$ sample and at $z = 1.0$ for the $z > 0.7$ sample. The dashed lines display the 80% range of where galaxies in these simulation are found.

IV. We find that the comparison between stellar and virial masses remains relatively similar from $z \sim 0$ to $z \sim 1.2$, with no significant change in slope or zero point.

All of these results suggest that at least the brightest disks, which are morphologically identifiable as disks, are well formed by $z \sim 1.2$. This implies that the major epoch of disk formation, and the establishment of both stellar and halo masses, occurs well before this time.

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