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The Tully-Fisher Relation in Cluster S0 Galaxies

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Abstract

We present a dynamical study of 10 Coma and 8 Virgo Cluster S0 galaxies in order to better understand their evolutionary history using the Tully-Fisher relation (TFR). If S0s were spirals in the past, later modified by outside mechanisms, then they may adhere to the TFR defined by late-types with a magnitude shift due to the subsequent heating of the stellar disk. If, however, S0 luminosities bear little resemblance to those of spiral disks with similar rotation speeds, this may indicate that their evolution has been regulated by processes more characteristic of elliptical formation, such as mergers. Our current results, using stellar absorption rotation curves and I- and H-band luminosities for the S0s, indicate a small offset in zero-point luminosities compared to the late-type TFR, along with a much larger scatter than is observed or predicted for late-types.

1.1 Introduction

S0s show diverse structural, kinematic, photometric, and spectroscopic properties. Analytic arguments and numerical simulations from Bekki, Shioya, & Couch (2002) suggest two formation scenarios to explain this. The first, in which spirals maintain their thin-disk component, is a gradual transformation with efficient stripping of halo gas and suppressed star formation. The second is a rapid transformation of a spiral through a merger with another, less massive disk galaxy. The latter would produce a red S0 with a thicker disk and a bigger bulge because of triggered central starbursts and dynamical heating of both disks. We attempt to test these scenarios by exploring the Tully-Fisher relation (TFR) for S0s.

There have been 4 studies of the S0 TFR. Dressler & Sandage (1983) observed 27 field S0s and found considerable scatter in their TFR. Neistein et al. (1999) observed 18 field S0s with a scatter in the TFR of ~ 0.7 mag, and concluded that S0s are a morphological mixed bag, produced by different formation and evolutionary scenarios. Hinz, Rix, & Bernstein (2001) observed 13 Coma S0s and found ~ 0.5 mag. They found a small offset in the I-band luminosity between late-types and S0s, implying a larger fraction of stellar mass in S0s than in late-types, and again suggested that formation histories lead to S0s with diverse properties. Mathieu, Merrifield, & Kuijken (2002) investigated the detailed dynamics of 6 S0s and found a scatter in the TFR equivalent to that known for late-types. Their S0s were systematically offset from the late-type I-band TFR by ~ 2 magnitudes, which is what would be expected if star formation in these galaxies had been truncated in the last few Gyrs. The contradiction among studies on the dynamics of S0s may be due to small sample sizes and poor rotation curve data. Therefore, we present results on a new, larger sample of S0s from the Coma and Virgo clusters.

1.2 Observations and Data Reduction

1.2.1 Sample Selection

Our goals in this work are to increase the sample size of S0s in the Coma cluster from the Hinz, Rix & Bernstein (2001) sample, to extend the magnitude range of the sample on the faint end, and to improve the signal-to-noise on S0 rotation curves. We chose S0s in the Virgo and Coma clusters using the following criteria: inclination angle $> 50°$, lack of interaction with other galaxies in the cluster, and bright enough to be sure of obtaining a rotation curve in a reasonable exposure time. In addition, we excluded large Virgo S0s whose major axes exceeded the spectrograph slit length.

1.2.2 Imaging and Spectroscopy

I-band images of the Coma S0s were obtained at the 1.55 m Kuiper telescope. Typical integrations were 6×300 s per S0 at airmasses of 1.1-1.8. Landolt (1992) photometric standard stars were observed in V- and I-bands at airmasses of 1.1-1.5. For the Virgo sample, we obtained H-band magnitudes and images from the Galaxy On Line Database Milano Network (GOLD Mine; Gavazzi et al. 2002).

Elliptical isophotes were fitted to each S0 using a task that calculates the mean intensity, ellipticity and position angle for each isophote. The sum of counts in each isophote minus the sky background level was converted to an I magnitude for each S0. Two-dimensional models of the S0s were created using an $R^{1/4}$ bulge and exponential disk fitting routine (Rix & Zaritsky 1995) to obtain scale radii of the disks and effective radii of the bulges.

Long-slit spectra of 14 Coma S0s were obtained at the 6.5 m MMT with the Blue Channel Spectrograph (Schmidt, Weymann & Foltz 1989). We used a 1200 lines mm^{-1} grating with a 1.5" $\times$ 180" slit for a wavelength coverage of 4530-6020 Å. Spectra of 10 Virgo S0s were taken at the SAO Tillinghast 1.5 m telescope with FAST (Fabricant et al. 1998). We used a 600 lines mm^{-1} grating and a 1.52" $\times$ 70" slit for a coverage of 3600-5600 Å. G- and K-giants were observed as kinematic templates for modeling the S0 spectra. He-Ne-Ar-Fe and quartz lamp exposures were taken for wavelength calibration purposes and flat-fielding uses, respectively. Reduction techniques are further described in Hinz, Rix, & Bernstein (2001).

Kinematics for the S0s are derived from the stellar absorption lines using the technique of Rix & White (1992), where 2-D galaxy spectra are binned into a series of 1-D spectra and are fit by χ^2 minimization with a combination of shifted and broadened stellar templates. Kinematic data for the S0s typically extend out to ~ 2.5-3 kpc. For six of them, we could not extract rotation curves out to the regime where the rotational velocity is dominant, and we removed them from the sample, leaving 10 remaining Coma S0s and 8 Virgo S0s.

1.3 Results

1.3.1 Determination of Rotation Curves

Each observed velocity along the major-axis of the galaxy, $v_{obs}(R)$, is corrected for inclination angle, i, using the output of the elliptical isophote fitting program and assuming a disk axis ratio of 0.22 (Neistein et al. 1999). An asymmetric drift correction must be performed where there is significant velocity dispersion to obtain the circular velocity, $v_c(R)$, at each point. This correction is carried out as described in Hinz, Rix & Bernstein (2001). The final form of the circular velocity is

$$v_c^2 = v_\phi^2 + \sigma_\phi^2 (2\frac{R}{R_{exp}} - 1)$$

where v_ϕ is the azimuthal velocity and σ_ϕ is the azimuthal velocity dispersion. Error bars on $v_c(R)$ include propagation of uncertainties in v_{obs}, σ_{obs}, and i.

To obtain a maximum circular velocity value for each S0, we calculate a series of model curves based on the bulge-disk decompositions. This maximal disk fitting (Courteau & Rix 1999) has been shown to trace the total mass of the inner parts of spirals successfully, even though it is a fit to the stellar light only. We add an infinitely thin exponential disk model and a bulge model from Hernquist (1990) in quadrature to produce a model rotation curve for each S0. The effective M/L is adjusted, and the best-fitting model curve is extracted through χ^2 minimization. Only rotation-dominated data are included in the fit, as approximations and systematics in the drift correction lead to large errors in the calculated v_c if σ_ϕ is large.

1.3.2 Rotation-Luminosity Relations

Figure 1.1a shows absolute I-band magnitude versus maximum predicted circular velocity for the Coma S0 sample, assuming v_z = 6942 km s^{-1} for Coma (Zabludoff et al. 1993) and H_0 = 80 km s^{-1} Mpc^{-1}. Velocity error bars are calculated from a likelihood ratio test, i.e. $\delta v_{max} = |v_{max}(\chi^2_{min}) - v_{max}(\chi^2_{min} + 1)|$.

The linear best fit (Rix et al. 1997) of the form $M_I(\log v_c) = M_I(2.3) - \alpha(\log v_c - 2.3)$ produces a relation where the slope is obviously not well constrained by the data. To make a direct comparison with the late-type TFR, we re-fit the data by holding the slope at the late-type spiral value, α = 7.46 (Mathewson et al. 1992). For this value the best fit is $M_I(2.3) = -21.27 \pm 0.40$ and $\sigma = 0.82^{+0.39}_{-0.25}$. Figure 1.1a includes the late-type I-band TFR (Mathewson et al. 1992) and the best fit line to the Neistein et al. (1999) field S0s. Also shown are the best-fit lines to the Hinz, Rix, & Bernstein (2001) Coma sample and to our combined Coma S0 sample with α = 7.46.

The value of the scatter for the Coma S0s, $\sigma = 0.82^{+0.39}_{-0.25}$, is larger than that found in the I-band for late-types, where σ ranges up to 0.35 mag (Giovanelli et al. 1997), and also larger than that predicted by numerical simulations (Steinmetz & Navarro 1999). The S0 scatter is consistent, however, with the Neistein et al. (1999) study of field S0s (σ = 0.7 mag) and Hinz, Rix & Bernstein (2001) (σ = 0.53 mag). It is not consistent with a study using different techniques to recover the kinematics (Mathieu, Merrifield, & Kuijken 2002), who find ~ 0.3 mag for a sample of 6 S0s. Explanations for their lower scatter include the low statistical significance that can be achieved with only 6 cases and the fact that their S0s are not representative because they were chosen to contain small bulges. Such S0s are the prime candidates to have formed from gas-stripped spirals.

Furthermore, Mathieu et al. (2002) find an I-band offset from the late-type TFR of ~ 1.8 mag, whereas Neistein et al. (1999) find an offset of ~ 0.5. The offset for our combined Coma S0 sample, ~ 0.6 mag, is nearly identical to that found by Neistein et al. (1999). Stellar population models (Worthey 1994) predict that an S0 comprised of a 5 Gyr old single burst population is ~ 0.53 mag fainter in the I-band than a late-type with the same age population with star formation bursts every 1 Gyr. Our Coma results would agree with differences in star-forming history of this general type, although the scatter in our data and the simplicity of the modeling would allow substantial variation.

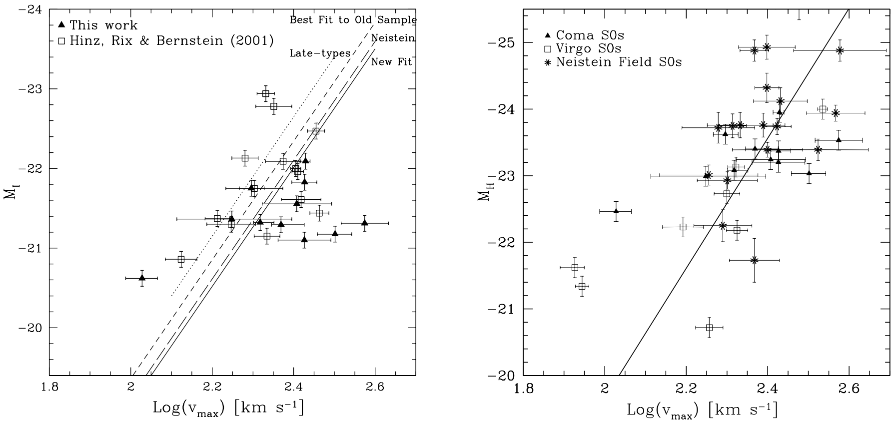

Fig. 1.1. The I-band S0 TFR on the left, and the H-band S0 TFR on the right.

We also construct an H-band TFR, adding in the Virgo S0 sample. Studies of the H-band TFR for late-types in a variety of environments indicate scatter values consistent with ≤ 0.5 mag. Coma S0 H-band photometry is provided by Gavazzi et al. (2000). There is little scatter in an H versus I-band comparison, with no outliers that would signal spurious errors in our Coma photometry. The data are consistent with an $I-H$ color of 1.8 for almost all S0s in the sample.

Figure 1.1b shows absolute H-band magnitude versus maximum predicted circular velocity for the Virgo S0s (open squares), the H-band Coma S0s (solid triangles), the Neistein et al. (1999) field S0s (asterisks), and an H-band fit from Pierce & Tully (1992) (solid line). Mathieu et al. (2002) use the Pierce & Tully (1992) fit for comparison to their data. Fixing the slope at the Pierce & Tully (1992) value for late-types, we find that the Virgo S0 sample alone yields $M_H(2.3) = -22.97 \pm 1.06$ and $\sigma = 1.33^{+1.28}_{-0.52}$. The scatter here is much greater than the observed scatter of the late-type H-band TFR. There is no significant change in either the values for the zero-point or the scatter found for Virgo S0s as compared to Coma S0s, despite their differences in population and richness. A fit to both the new Coma and Virgo cluster H-band S0 data with the Pierce & Tully (1992) slope gives $\sigma = 1.27^{+0.67}_{-0.39}$ and $M_H(2.3) = -22.76^{+0.68}_{-0.66}$. Echoing the findings of Hinz, Rix, & Bernstein (2001), the relation between H-band luminosity and v_c for cluster S0s is poorly defined, and there is a small offset in the H-band luminosity at a given circular velocity between late-types and S0s.

We convert the Neistein et al. (1999) I magnitudes to H, for the purposes of comparison to the field S0s, assuming an $I-H$ value of 1.8. The cluster S0s occupy the same parameter space as these field S0s, with a large scatter and poorly determined slope. We interpret this to mean that cluster S0s are not solely produced by an evolutionary scenario in which spirals are stripped of gas upon entering the cluster potential but are instead the outcome of minor mergers or of multiple possible formation histories, just as we might expect of field S0s. Simulations by Kodama & Smail (2001) show that the bulges of late-type spirals (Scdm) are not luminous enough to evolve into the bright bulges of S0s simply as a result of stopping the star formation in the disk or by harassment in the cluster environment. They suggest that one way to form cluster S0s might be to accrete field populations that are not the same as a 'pure' field population, that S0s could be formed if galaxies accreted into clusters are pre-processed in subcluster units or groups, or if accreted members are somehow intrinsically biased toward earlier types. They comment that most of the small-bulge Scdm galaxies may have already been transformed to bulge-strong galaxies by minor mergers or through bar-formation due to strong galaxy-cluster interactions. In this case, we would not expect a purely late-type TFR to hold for S0s. It seems likely, then, from the S0 TFR constructed here, that multiple processes are involved in the formation and evolution of S0s.

1.4 Conclusions

Using I- and H-band photometry and rotation curves derived from stellar absorption line spectroscopy, we have constructed a Tully-Fisher relation for 10 S0s in Coma and 8 S0s in the Virgo Cluster. We combine these results with measurements of 13 S0 galaxies in Coma by Hinz, Rix, & Bernstein (2001). We find a scatter around the H-band relation of $0.97^{+0.51}_{-0.30}$ mag for Coma S0s, $1.33^{+1.28}_{-0.52}$ mag for Virgo S0s, and $1.09^{+0.43}_{-0.30}$ mag for the combined sample. These intrinsic scatter values are larger than the value of ~ 0.7 mag found for a sample of field S0s by Neistein et al. (1999) and larger than the TFR for late-types in these bands, ~ 0.3-0.5 mag. The scatter for the S0s is also greater than is generally predicted by numerical simulations of galaxy formation (Steinmetz & Navarro 1999).

The large scatter in the cluster S0 TFR in comparison to the known late-type relation, together with a small zero-point offset, seems at odds with the idea that S0s are simply former spirals whose star formation has been truncated by tidal stripping. It indicates that S0s are the results of minor mergers and other interactive processes such as slow encounters with other galaxies, multiple encounters, starvation, strangulation, harassment, or some combination of all of these. In this view of S0 galaxies, the class is heterogeneous and produced by differing evolutionary scenarios even within a particular cluster environment.

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