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Polar Ring Galaxies and the Tully-Fisher relation: implications for the dark halo shape

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Abstract. We have investigated the Tully-Fisher relation for Polar Ring Galaxies (PRGs), based on near infrared, optical and H I data available for a sample of these peculiar objects. The total K-band luminosity, which mainly comes from the central host galaxy, and the measured H I linewidth at 20% of the peak line flux density, which traces the potential in the polar plane, place most polar rings of the sample far from the Tully-Fisher relation defined for spiral galaxies, with many PRGs showing larger H I line-widths than expected for the observed K band luminosity. This result is confirmed by a larger sample of objects, based on B-band data. This observational evidence may be related to the dark halo shape and orientation in these systems, which we study by numerical modeling of PRG formation and dynamics: the larger rotation velocities observed in PRGs can be explained by a flattened polar halo, aligned with the polar ring.

1. Introduction

Polar Ring Galaxies (PRGs) are peculiar objects composed of a central spheroidal component, the host galaxy, surrounded by an outer ring, made up of gas, stars and dust, which orbits nearly perpendicular to the plane of the gas-poor central galaxy (PRGC; Whitmore et al. 1990). Previous papers (Arnaboldi et al. 1995, 1997; Iodice et al. 2002a, 2002b, 2002c) found that even where the morphology of the host galaxy resembles that of an early-type system, PRGs show many similarities with late-type galaxies. The PRGs are characterized by a large amount of neutral hydrogen (H I), always associated with the polar structure (Schechter et al. 1984; van Gorkom et al. 1987; Arnaboldi et al. 1997), and by a gas-to-total luminosity ratio in the B-band typical of late-type galaxies.

By exploring the properties of the host galaxy and ring in the optical and NIR, for a sample of PRGs, Iodice et al. (2002a, 2002b, 2002c) found that the connection with spirals is tighter. The Tully-Fisher relation (TF) is the most important scaling relation for disks (Tully & Fisher, 1977): this is an empirical relationship between the disk rotational velocity (V_{rot}) and its absolute luminosity (L), where $L \propto V_{rot}^4$, approximately. In the past few years, several studies have asserted the validity of the TF relation for some classes of disk galaxies which show different photometric and kinematical properties with respect to "classical", high-surface-brightness spiral galaxies (Matthews, van Driel & Gallagher 1998a, 1998b; McGaugh et al. 2000; Chung et al. 2002). These latest developments indicate that the TF relation is probing a very close liaison between the dark halo parameters and the total quantity of baryons in galaxies: the dark halo, which is responsible for the H I linewidth and the flat rotation curve in the outer regions of a disk, is tuned to the total amount of baryons in the luminous component.

In PRGs, the H I linewidth (ΔV) measures the dynamics along the meridian plane, which is dominated by the dark matter, while the baryons are nearly equally distributed between the host galaxy and the polar ring. We wish to investigate the position of the PRGs in the $\log(\Delta V) - L$ plane, and study via N-body simulations of 3-D systems whether the dark halo shape may influence their position in the $\log(\Delta V) - L$ plane, with respect to the TF relation of bright disks. The question of the dark halo shape is important *i)* to constrain dark matter models, through cosmological simulations (Navarro, Frenk & White 1996, 1997; Bullock et al. 2001) which predict the distribution of the halo shapes and the universal radial dependence of the dark matter distribution; *ii)* to give hints on the nature of dark matter (see Combes 2003 as a review); and furthermore *iii)* the dark halo properties in PRGs can give important constraints on the formation scenarios for these peculiar objects, which is still an open issue (see Iodice et al. 2002a, 2002c, and references therein).

2. Observations

New near-infrared J, H and Kn images are available for a sample of PRGs (Iodice et al. 2002a, 2002b, 2002c), which are selected from the PRGC, and for ESO 235-G58. The B band magnitude is known for many PRGs (Van Driel et al. 2002, 2003; Gallagher et al. 2002), and the H I integrated line profile data were obtained from several published hydrogen observations of PRGs, carried out by e.g. Richter et al. (1994), van Gorkom et al. (1987), van Driel and collaborators (2000, 2002, 2003), with several radio telescopes.

To derive the TF relation for normal disk galaxies, we will use the very large and detailed dataset available in the I-band from Giovanelli et al. (1997). We estimate the B band magnitude for spiral disks in the sample from Giovanelli et al. using the observational relation between morphological type index and the $B-I$ colours (de Jong 1996).

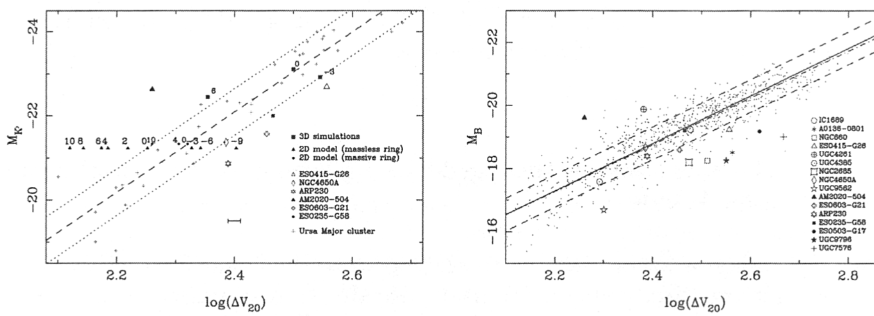

Figure 1. *Left Panel* – Absolute magnitude in the K band vs. the measured H I linewidth at 20% of the peak line flux density (ΔV_{20}), for PRGs of the selected sample, compared with a sample of spiral galaxies from Verheijen (2001), and with the results from 3-D simulations and 2-D models (for massless rings and rings that are as massive as the host galaxy), see also Bournaud & Combes (2003). The long-dashed line is a linear interpolation of the TF relation for spiral galaxies, and the short-dashed lines show the width at 15% of the peak of the statistical distribution of spiral galaxies. For both models, the flattening of the halo is indicated next to each circle (massless ring) or triangle (very massive ring): a positive x number indicates that it is an Ex halo with an equatorial flattening, while $-x$ corresponds to an Ex halo flattened toward the polar plane. The results from the 3-D models shown in this plot are those computed for the accretion scenario (Reshetnikov & Sotnikova 1997); our values for ΔV_{20} vs. M_K are very similar when one considers the merging scenario (Bekki 1998). *Right Panel* – Absolute magnitude in the B band vs. the linewidth at 20% of the peak line flux density (ΔV_{20}), for 15 PRGs. Data for disk galaxies (dots) are from Giovanelli et al. (1997). Absolute magnitudes have been normalized to the same value of H_0 for PRGs and disk galaxies (75 km s^{-1} Mpc^{-1}). A linear interpolation of the TF relation is shown for these disk galaxies (solid line), 81% of which lie inside the dashed lines that are computed at 25% of the peak of the statistical distribution of spiral galaxies. The long-short dashed line is obtained for unbarred disks, seen nearly edge-on ($i \geq 80°$). From Iodice et al. (2003).

2.1. PRGs and the TF Relation for Spiral Galaxies

In Fig. 1 we show the K-band TF relation for a sample of spiral galaxies studied by Verheijen (2001). The values of M_K and $\log(\Delta V_{20})$ for PRGs are also shown on this plot. Our and Verheijen's data sets have very similar photometric properties and limiting magnitudes. We see that five PRGs lie near to the high-velocity boundary of the TF relation, or show larger velocities (for a given luminosity) than disk galaxies. Only the PRG AM2020-504 shows a lower rotation velocity for its K-band absolute magnitude.

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In the B-band, the tendency of PRGs to have larger velocities with respect to the TF is confirmed for a larger sample of PRGs compared with data for 787 disk galaxies (Giovanelli et al. 1997). In Fig. 1, we see that two PRGs lie at lower velocities than those predicted by the TF for spiral galaxies, two objects lie on the TF relation, and twelve PRGs either lie on the high velocity boundary of the TF relation or show much larger velocities. Van Driel et al. (2003) also find that most kinematically confirmed PRGs show larger H I profile widths than bright spiral galaxies, at a given luminosity.

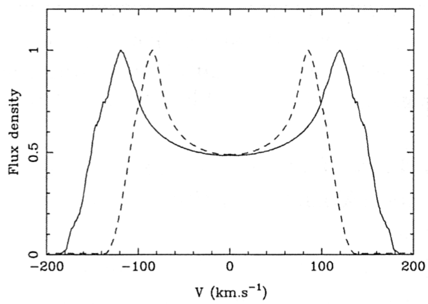
3. The PRG positions in the $\log(\Delta V) - L$ plane and their implications for the dark halo

Observing higher or lower velocities with respect to the linear TF of disk galaxies is relevant for the discussion on the dark halo shape. Via analytical models and simple assumptions about the mass distribution, either luminous or dark, we can estimate where the PRGs ought to lie in the $\log(\Delta V) - M_{K/B}$ plane (Fig. 1), with respect to the TF relation for disk galaxies. If there were no dark matter, and the gravitational potential were oblate in the same sense as the flattened host galaxy, the polar ring would acquire an eccentric shape. When the polar ring and the host galaxy are both seen edge-on, which is close to being the case for most of our PRGs, the net effect will be that the line-of-sight (LOS) polar ring velocities are reduced. In the logarithmic, scale-free, potential case, a simple formula gives the expected velocity ratio between the major and the minor axis components as:

$$\epsilon_v = 1 - \frac{v_{minor}}{v_{major}} = \epsilon_\rho \simeq 2\epsilon_\Phi \tag{1}$$

from Gerhard & Vietri (1986), where ϵ_ρ is the flattening (1-axis ratio) of the density distribution and ϵ_ϕ is the potential flattening. Therefore we would expect PRGs to have on average lower velocities with respect to what would be measured in the equatorial plane.

This implies that when the polar structure is eccentric, the observed LOS velocities in ΔV_{20} are the smallest, i.e. those from the particles in the polar regions, see Fig. 2. Thus the observed ΔV_{20} depends on both the mean velocity along the ring, and the ring eccentricity. On the contrary, Fig. 1 shows that the majority of PRGs have larger velocities than expected in the $\log(\Delta V) - M_{K/B}$ plane. Therefore we need to investigate how these velocities can be produced, and how they may depend on the intrinsic properties of the dark galaxy halo. We computed a series of N-body models of the formation of PRGs (Bournaud & Combes 2003). Our 3-D and 2-D simulations of PRGs show different positions in the TF plane depending on the shape of their dark halos. When the halo is oblate and flattened towards the host galaxy, the observed velocity in the polar ring are then smaller, and PRGs lie on the left-hand of the TF relation for bright disks. When the dark halo is flattened towards the polar ring plane, the observed velocities as larger, shifting the PRGs to the right-hand side of the diagram as in Fig. 1 (see also Iodice et al. 2003).



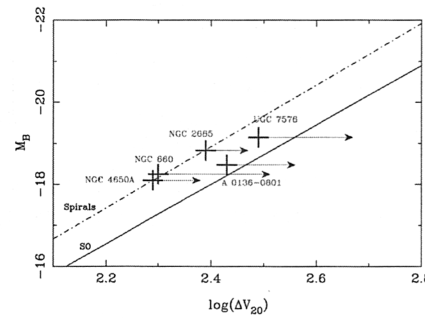


Figure 2. *Left panel* – Simulated H I profiles for circular and eccentric polar rings seen edge-on. Solid line: H I profile computed for a circular ring, extending from 10 to 15 kpc. Dashed line: H I profile computed for an eccentric ring, with the same radial extension and radius, and ellipticity 0.35. The values of $\log(\Delta V_{20})$ are 2.51 for the circular ring and 2.38 for the eccentric ring. This difference is in agreement with the set of values for ΔV_{20}, at a given total K or I band luminosity, obtained from PRG numerical models. *Right panel* – TF relation for S0 galaxies (data from Mathieu et al. 2002) and PRGs. The TF for spiral galaxies is plotted as a dashed line. Large crosses show the position of the central component in five PRGs. From Iodice et al. (2003).

4. Discussion

In the $\log(\Delta V) - M_{K/B}$ planes shown in Fig. 1, most PRGs have larger H I rotation velocities than standard spiral galaxies, at a given K or B-band luminosity of the stellar component. Our N-body simulations have suggested that a likely explanation for this effect is a flat dark halo, whose main plane is aligned with the host galaxy meridian plane, preventing the polar ring from becoming eccentric. The question arises if other effects, i.e. non-homogeneities in the TF relations for spirals, caused by bar and/or non edge-on disks, or larger M/L ratios, can produce similar results and therefore be alternative explanations for the high velocities observed in PRGs.

Can the offset between the TF relation for bright spirals and PRGs be caused by the PRGs being less luminous than spirals at a given velocity? No, it cannot: as shown in Fig. 2 the host galaxies in 5 PRGs fall on the TF relation for bright spirals, which indicates 1) that the M/L ratio of this component is different from those of standard S0s, and 2) a luminous-to-dark matter content ratio similar to those of standard bright disks. Gerhard et al. (2001) showed that elliptical galaxies follow a TF relation in the $\log(\Delta V) - M_*$, where M_* is the total mass in the luminous component, which is shallower than the relation for spiral galaxies, even when the maximal M/L_B is adopted to compute the total stellar masses. This led Gerhard and collaborators to infer that elliptical galaxies have slightly lower baryonic mass than spiral galaxies of the same circular velocity, and that their dark halos are denser than halos of spiral galaxies with the same L_B. How much more massive must the dark halo be, to account for the velocities observed in polar rings? The observed value of ΔV_{20} depends largely on the dark halo shape and the ring eccentricity, while it varies only as the square root of the total mass (and depends even less on the dark mass). Thus, a large amount of dark matter is needed when the halo is not polar: it ranges from factor 2 for a spherical halo, to a factor 3.5/4 for an oblate/prolate halo. Such a massive halo would cause a large offset of the host galaxy from the TF relation of bright disks, which is not observed.

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