Polar Ring Galaxies and Warps

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Abstract. Polar ring galaxies, where matter is in equilibrium in perpendicular orbits around spiral galaxies, are ideal objects to probe the 3D shapes of dark matter halos. The conditions to constrain the halos are that the perpendicular system does not strongly perturb the host galaxy, or that it is possible to derive back its initial shape, knowing the formation scenario of the polar ring. The formation mechanisms are reviewed: mergers, tidal accretion, or gas accretion from cosmic filaments. The Tully-Fisher diagram for polar rings reveals that the velocity in the polar plane is higher than in the host plane, which can only be explained if the dark matter is oblate and flattened along the polar plane. Only a few individual systems have been studied in details, and 3D shapes of their haloes determined by several methods. The high frequency of warps could be explained by spontaneous bending instability, if the disks are sufficiently self-gravitating, which can put constraints on the dark matter flattening.

1 Polar rings formation scenarios

Polar Ring Galaxies (PRG) are composed of an early-type host, surrounded by a gaseous and stellar perpendicular ring which has the characteristic of a late-type galaxy: large HI amount, young stars, blue colors. If the polar ring is in equilibrium, it could provide clues on the 3D-shape of dark matter in the host galaxy. For that, the polar ring must not be too massive, in order to keep the initial gravitational potential unperturbed; or in any case, we must know the formation mechanism of the polar rings, to be able to generalise the results to normal haloes. The probability to have a PRG has been estimated to ∼ 5% from the observations (Whitmore et al 1990).

Several mechanisms have been proposed in the literature to form polar ring galaxies, that can be gathered into two kinds: merger between two galaxies, of which one at least is gas rich, or mass accretion by the original host galaxy. The

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first kind can be a major merger between two perpendicularly oriented systems, or the disruption of a small companion on a polar orbit (the debris align then on the polar ring). The second kind can be either gas transfer between two galaxies, in an hyperbolic passage, or gas accretion from cosmic filaments in a polar ring by the host. In all cases, the bulk of the stars in the polar plane form after the event, from the gas settled in the polar plane.

1.1 Merger scenario

The collision scenario has first been simulated by Bekki (1997, 1998). Bournaud & Combes (2003) have explored the geometrical parameters of the collision to determine the stability of the final system, and the actual probability to form a PRG from such a merger. The mechanisms are perfectly able to form polar rings, and even double rings (see the ESO 474-G26 system in Figure 1, Reshetnikov et al 2005a). However the parameter space is smaller than for accretion, so the majority of PRGs must not have been formed through mergers.

![Image of ESO 474-G26](image)

**Fig. 1.** The double ringed galaxy ESO 474-G26: **Left:** The V-band image of the Galaxy **Right:** The result of the simulated formation of this system through a merger of two spiral galaxies of comparable masses, at t=700 Myr. From Reshetnikov et al (2005a).

1.2 Tidal accretion scenario

The tidal accretion scenario, proposed by Schweizer et al (1983) and first simulated by Reshetnikov et al (1997), was long thought to form only very light polar rings, since the donor galaxy exchange only part of its mass, before leaving the interaction scene. When the geometrical parameters are explored, they are able to form quite inclined polar ring, such as the prototype NGC 660, which makes the continuity with highly warped systems (see also NGC 3718, Krips et al 2005). From the statistics of initial conditions, the accretion scenario was estimated to be 3-5 times more likely to form polar rings (Bournaud & Combes 2003). The configuration of
particular systems tends to orient towards this accretion scenario, which provides the best fit, (see for instance AM1934-563, Reshetnikov et al 2005b).

Very massive polar rings can form through accretion, with polar components of comparable mass (or even larger) to the host component. The prototype NGC 4650A is a good case for accretion, since no stellar halo is detected around the galaxy. Such a stellar halo is expected in the merging scenario to come from the dispersed stars from the destroyed satellite. The polar component is quite massive, $8 \times 10^9 M_\odot$ of HI gas and $4 \times 10^9 M_\odot$ in stars.

### 1.3 Gas accretion from cosmic filaments

The formation of polar rings could also occur without any interaction or merger, through gas infalling from cosmic filaments, with inclined angular momentum (Katz & Rix 1992, Semelin & Combes 2005). This scenario has been simulated by Maccio & Moore (2005): the gas is acquired from a filament of $\sim 1$ Mpc long, and is essentially cold gas accretion, with small impact parameter. This kind of cold gas accretion might be the more realistic way by which galaxies get their gas (e.g. Keres et al 2005). One case happens to be quite similar to the prototype NGC 4650A, where the stars are essentially in the host and gas in the polar plane; several small companions are also found all along the filament. Dark matter is quite round in the visible part after the infall of gas.

### 1.4 Late dark matter infall with resonance

An alternative scenario, requiring no external gas accretion or merger for PRG formation, has been proposed by Tremaine & Yu (2000). It assumes that a disk galaxy lies in the symmetry plane of a triaxial dark matter halo. The dark halo tumbles with a retrograde pattern speed with respect to the disk. When this tumbling slows down, through dark matter infall, the stars in the disk could get trapped in a vertical resonance with the halo. Indeed, a stellar orbit slightly tilted with respect to the plane, precess at a slow retrograde rate, and when the resonance progressively reaches stars at larger and larger radii, the stars are propelled into the polar plane. With this mechanism, the polar ring would contain two equal-mass counter-rotating stellar disks. This mechanism also explains the splitting of the stars in two counter-rotating streams in the disk, when the tumbling halo slows down from retrograde, to zero and then prograde (Evans & Collett 1994).

This mechanism however has not been confirmed in observations, when velocity fields of the stars in the polar ring have been studied (e.g. Swaters & Rubin 2003). The stellar kinematics in NGC 4650A for instance does not reveal counter-rotation. A flat rotation curve in observed in the polar ring, which confirms that it is more a full plane than a ring. With the help of large telescopes, it is possible to have now much more precise and accurate kinematical information on the remote polar ring, as shown by the new VLT-FORS2 data on NGC 4650A (Iodice et al 2005). The detailed stellar kinematics on the major and minor axis of the host galaxy reveal a flat velocity dispersion, with a slight drop in the center, and will allow in
the near future a better determination of the gravitational potential and its 3D shape.

2 Tully-Fisher diagram for PRGs

Since a complete velocity field is difficult to obtain for many PRGs, a single Tully-Fisher allows to gather more statistics (Iodice et al 2003). The position of 15 polar rings revealed quite surprising in such a plot, since the HI total widths of the gas in the polar plane is clearly larger than expected from the normal spiral TF relation. Because of the superposition of the two perpendicular systems, the orbits are expected to be non-circular in the polar rings. In general, and for obvious selection effects, both components are seen nearly edge-on. Then the maximum velocity in projection in the ring is coming from the top of the ring, corresponding to the largest distance from the center of the galaxy. The observed velocity is then expected to be lower than circular, and then lower than the maximal velocity observed in the host galaxy plane. This is already the case in absence of dark matter, or if the dark matter is spherical. If the dark halo is flattened and oblate, parallel to the host disk, this effect will be accentuated, and the HI width in the polar plane expected even lower.

But the contrary is observed. Is this due to the fact that the host component is also perturbed, and does not fall on the TF relation? Figure 2 shows the TF diagram for the PRGs where a detailed velocity width have been obtained in the two perpendicular components. It shows that the host galaxy obeys the normal TF relation, while there is a large difference of velocity between the two perpendicular planes, the velocity being larger in the polar ring.

The only solution to the problem is to assume that the dark matter halo is oblate and aligned with the polar ring itself. In this case, the orbits in the host are then non-circular, and we observe the maximum velocity when the matter is farther from the center, and lower than circular. In the polar plane, the orbits will be circular, and larger than in the host plane. It does not help to assume that the dark halo is prolate, keeping the orbits circular in the host.

Is there a formation scenario able to explain that most PRGs have their dark matter halo flattened along the polar disk? With dissipationless dark matter, both merging and accretion scenarios produce either spherical haloes, or halos flattened along the host. However, if a large fraction of the dark matter around galaxies is dissipative (dark gas), it will settle in the polar plane, and it is possible to account for the flattening along the polar disk.

3 3D shapes of haloes

3.1 Axisymmetry

Pure CDM simulations predict triaxial shapes for collapsed structures, so that the haloes are not axisymmetric even in the plane of the baryonic galactic disk. The axisymmetry in galactic disks have been checked through the orbits of the baryons,
and in particular the HI gas, with low velocity dispersion. Of course, inclination effects have to be taken into account, as well as flaring, warps or other distortions, due to the spiral, bars or ring features in the galaxy disks.

The result of these investigations is that galaxies are actually axisymmetric in their planes, with a very low upper limit for the eccentricity: below 0.1 with the isophote shape versus HI velocity widths method (Merrifield 2002), or even less than 0.045, when using near-infrared data to avoid extinction (Rix & Zaritsky 1995). On special cases, the limit can be better, eccentricity of the order of 0.012 in potential in the very regular early-type galaxy IC2006 with an HI ring (Franx et al 1994). This axisymmetric shape of galactic haloes is confirmed by the low scatter observed for the Tully-Fisher relation.

### 3.2 Flattening

As for the flattening, pure CDM haloes are predicted rather flattened in numerical simulations; they are half oblate and half prolate, with axis ratios of the order of $c/a = 0.5, b/a = 0.7$. It is interesting to note that the dark haloes are predicted more flattened than observed elliptical galaxies; the distribution peaks at E5 (while elliptical galaxies peak at E2 ($c/a = 0.8$)) cf Dubinski & Carlberg (1991).

However, when the dissipative infall of gas is taken into account, the dark matter haloes are concentrated, through adiabatic contraction, and are also forced to an oblate shape, the prediction now becomes in average: $c/a = 0.5, b/a > 0.7$. 

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**Fig. 2.** TF relation for spirals (dashed line), S0 galaxies (solid lines) and 5 PRGs, where the velocity curve is known in both perpendicular components. Large crosses show the position of the central host galaxy and the arrow shows the offset in log($\Delta V_{20}$) between the velocities in the host galaxy equatorial plane and in the polar ring for each system. From Iodice et al (2003).
Mass Profiles and Shapes of Cosmological Structures

This depends a lot on the actual physics of baryons. When the cooling is taken into account, the dark haloes are obtained much rounder, since the baryons are more concentrated to the center, in the simulations of Kazantzidis et al (2004). These predictions are roughly compatible to the flattening observed statistically by weak lensing measurements (Hoekstra et al 2004), where the average ellipticity of the haloes is 0.33, if the dark matter is assumed aligned with the baryons.

3.3 Results of various methods

Method of HI flaring

One of the methods most frequently used is the flaring of the HI planes: the thickness of the gaseous layers is a function of the velocity dispersion, perpendicular to the plane and of the gravity restoring force towards the plane, which depends on the mass contained within the HI layer. The z-velocity dispersion is not known in the edge-on galaxies where the HI thickness can be measured, but it is assumed the same as in similar face-on galaxies, where it is measured to be about constant with radius, and around 10km/s. The thickness that can be derived by this method is sensitive to the radial distribution of the dark matter and mainly to its extension or truncation at large radius, which is not known precisely. Olling (1995, 1996), and Becquaert & Combes (1997) found quite flattened halos for NGC 224, 891, 3198, 4013 and 4244 (see Merrifield 2002). From an NFW profile of the dark matter halo in the outer parts (density in \( r^{-3} \)) Narayan et al (2005) find as the best fit a spherical shape. From the flaring also, Kalberla (2004) favors a model where most of the dark matter is in the disk.

Polar rings

As was shown above, the polar ring method is potentially powerful, but many more systems should be studied in details. There is evidence for substantial dark matter, relatively flattened, although more along the polar plane than along the host plane. Only the case of NGC 4650A is reported in Figure 3.

X-ray isophotes

To determine the amount and the flattening of dark matter in elliptical galaxies, the method of the shape of X-ray isophotes have been used (e.g. Buote et al 1998, 2002). The method relies on the comparison between the observed ellipticities and orientations of X-ray isophotes, with those expected if the gravitating mass traces the same shape as the stellar light. This method was applied to two isolated E4 ellipticals (NGC 720 and NGC 3923), and one isolated S0 galaxy (NGC 1332). The results were dark matter ellipticities between 0.4 and 0.6, and the indication in NGC 720 that the dark matter is flatter than the stellar distribution (cf Fig 3).

Tidal streamers in the dark halo of the MW

Most Sagittarius streams are too young to constrain the shape of the Milky Way dark halo. Either oblate or prolate, with c=0.6 are compatible with the
data. Only one older stream and its kinematics give a prolate shape of 0.6 Helmi (2004a,b). A more spherical fit is found by Johnston et al (2005).

![Fig. 3. Distribution of total mass flattening (axis ratio q=c/a) as a function of morphological types, for the few galaxies studied in the literature, either by the polar ring, X-ray isophotes or flaring HI plane techniques. Galaxies are marked by their NGC number, except for the Milky Way. For the latter, the recent result from tidal streamers has been adopted.](image)

4 Warps and constraints on dark matter

Warps in stellar disks are very frequent (e.g. Reshetnikov & Combes 1998). If the disk is self-gravitating, spontaneous bending instabilities can explain these warps (Revaz & Pfenniger 2004). The disks are unstable to bending, if the z-velocity dispersion is below Araki limit $\sigma_z/\sigma_r = 0.293$. If the optical disk warps have all to be explained through this instability, then the fraction of dark matter in the disk should be above a certain threshold, according to the flattening assumed for the spheroidal halo. For a typical galaxy as the Milky Way, the dark matter should be equally distributed in the disk and the spheroidal halo (Revaz & Pfenniger 2004).

5 Conclusions

The kinematical observations of polar rings are precious tools to probe the 3D shape of dark haloes. Their Tully-Fisher diagram until now reveal that most PRGs have their dark matter flattened in the polar planes. More detailed data on more systems are required to confirm this result, which would imply that dark baryons could play a role in their formation. Small stellar warps that are present in most spiral disks put constraints in the dark matter flattening, if it is assumed that they are excited by bending waves. Large gas warps might be a phenomenon akin to polar rings, formed through late accretion of external gas. The frequency
of these phenomena confirm the important role of late gas accretion in galaxy formation.

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