Polar rings and the 3D-shape of dark matter

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Abstract. Polar ring galaxies (PRG) are unique to give insight on the 3D-shape of dark matter haloes. Some caveats have prevented to draw clear conclusions in previous works. Also the formation mechanisms need to be well known. All available information on the topic is reviewed, and criteria are defined for an ideal PRG system, in the hope of removing the ambiguities and make progress in the domain.

1. Introduction

Polar ring galaxies are clearly multi-spin systems, with two almost perpendicular spins. The primary object is usually an early-type galaxy, poor in gas, lenticular or elliptical. The polar ring is generally younger, akin to late-type galaxies, with large amount of HI gas, young stars with blue colors. The frequency of PRG, once corrected from selection biases and projection effects, has been estimated to \( \sim 5\% \) (Whitmore et al. 1990).

Recently, the Galaxy Zoo project in the Sloan data-base has been searched to find new PRG; Finkelman et al. (2012) identified and observed 16 candidates at slightly higher redshift than Whitmore et al. (1990). PRG at even higher redshifts were identified with HST images by Reshetnikov (1997). Moiseev et al. (2011) have built a catalogue of 275 PRG candidates from the Galaxy Zoo project.

These new candidates are a promise for the determination of the 3D-shape of dark matter halos. However, to be able to relate the dark matter of the PRG to dark matter in spiral progenitors, it is necessary to study the PRG formation scenarios.

1.1. The ideal polar ring galaxy

The polar material should have a large extent, with a large HI gas radius, to measure the rotation curve as far as possible from the center and probe the dark halo.

The polar ring should be as wide as possible, and even become a polar disk, with young stars and ionised gas yielding the H\( \alpha \) rotation curve.

The mass of the polar system should be small enough that the PR material can be considered as test particles in the host potential, and not perturb the shape of the original halo.

1.2. Diversity of results

All previous studies (e.g. Whitmore et al. 1987, Sackett & Sparke 1990, Sackett et al. 1994, Reshetnikov & Combes 1994, Combes & Arnaboldi 1996, Iodice et al. 2003) agree only on one conclusion, that PRG are indeed embedded in a dark halo.
But they conclude to very different 3D-shapes: almost spherical halo for Whitmore et al. (1987), flattened along the equatorial plane of the host (Sackett et al. 1994), or flattened along the polar-ring plane (Combes & Arnaboldi 1996). The latter was supported for a large number of PRG by Iodice et al. (2003), through a study of the Tully-Fisher diagram.

2. Formation of polar rings

At least three formation mechanisms have been proposed: (1) the accretion scenario, where two interacting galaxies exchange mass (Schweizer et al. 1983; Reshetnikov & Sotnikova 1997); (2) the merging scenario (Bekki 1997, 1998; Bournaud & Combes 2003); (3) the cosmic formation scenario, where the PRG form through the misaligned accretion of gas from cosmic filaments (Maccio et al. 2006; Brook et al. 2008).

Some might be even more complex, with two perpendicular PRG, as in the ESO 474-G26 system (Reshetnikov et al. 2005). The two perpendicular rings are formed with stars from each separated companion. In each case, detailed numerical simulations can constrain the formation scenario (cf Figure 1).

![Figure 1. Simulations of the polar ring formation in AM 1934-563, compared with the observations. Stellar particles are in red, gas clouds in blue. An incomplete ring has just formed. From Reshetnikov et al. (2006).](image)

2.1. Tidal accretion versus merging scenario

Tidal accretion of gas from a companion flying by in an hyperbolic orbit has been shown to be more likely to form the PRG observed (e.g. Bournaud & Combes 2003). The process is able to form inclined polar rings, such as NGC 660 or NGC 3718, revealing intermediate and inclined cases suggesting continuity with warps. When simulating series of different encounters, with statistics over geometry, initial spin angles, orbital energy, angular momentum or mass ratios, the tidal accretion scenario is 3-5 times more likely than minor mergers to form PRG final remnants. Very massive PR can form through tidal accretion up to 100% of the host mass.
In particular, the prototype N4650A appears more a case for tidal accretion, then minor merger. There is a test to disentangle the two possibilities: in case of a minor merger, the stars from the swallowed companion are dispersed all around, while the gas settles in a polar ring through dissipation. Then in the final remnant, a halo of old stars should be detected around the main galaxy. This is not the case for NGC 4650A, where the polar ring contains $8 \times 10^9 M_\odot$ of HI gas and $4 \times 10^9 M_\odot$ of young stars, formed after the event.

Polar ionized gas disks allow the determination of metallicities and abundances to constrain the formation scenario. In IC5181, Pizzella et al. (2013) demonstrate that the polar gas is likely to come from a donor, the tidal accretion reproducing better the age, metallicity and [alpha/Fe] data of the object.

The system AM2020-504 involving a rare PRG around an elliptical galaxy, favors also the accretion from a donor galaxy and not cold gas accretion. It is surrounded by a group of nearby galaxies, with about the same velocity. The ring is young and blue, with relaxed rotation and a warp. The polar ring follows the metallicity-luminosity relation for normal spiral galaxies and has an O/H gradient across the ring (Freitas-Lemes et al. 2012).

AM 1934-563 is part of a triplet galaxy, the primary disk has a rotational velocity compatible with a spiral galaxy on the Tully-Fisher relation. The polar ring has a small mass and therefore could be an ideal case. The numerical simulations (cf Figure 1) favors the tidal accretion scenario from a gas-rich companion (Reshetnikov et al. 2006). This scenario was however discussed by Brosch et al. (2007) with new long-slit spectroscopic data. They found the stellar component rotating as a solid body contrary to the gas component in the primary disk, and the gas in the polar ring rotating slower that in the primary. They favor the cold accretion scenario, with dark matter flattened along the primary.

UGC 9796 is a gas-rich PRG, with $5 \times 10^8 M_\odot$ of HI in the polar ring. It is surrounded by a group of gas-rich galaxies. The ring is inclined by $25^\circ$ from polar, and warps away from the minor axis of the host, as is reproduced in simulations (Cox et al. 2006).

### 2.2. Late gas infall, or dark matter infall with resonance

Without any interaction or merger, polar rings can form through gas infalling from cosmic filaments (Katz & Rix 1992, Semelin & Combes 2005, Brook et al. 2008, Snaith et al. 2012). Contrary to the tidal accretion scenario, dark matter is also infalling from filaments, in even larger quantity than gas. The stability problem, with respect to infalling angles, is the same as in the merging scenario.

In the cosmological simulations by Maccio et al. (2006), gas was accreted from cosmic filaments at almost a right angle from the plane of the host, and all the gas settled in the polar ring, while stars were only in the host. Several small companions in the filament were also accreted as minor mergers. At the end, the global dark matter halo was quite round in the visible part.

In the more targeted simulations by Brook et al. (2008), cf Figure 2, accretion first formed the host. After a sudden change of filaments and orientation, accretion occurs then along the polar system, with both gas and dark matter. After 1.5 Gyr, the interaction between the two disks destroys the PRG. During the life-time of the PRG, the velocity curve is about the same in both equatorial and polar planes, contrary to most observations.
Figure 2. Composite image of the polar ring simulation and comparison with NGC 4650A (right) from Gallagher et al. (2002). The simulated polar disk (left) is imaged by assigning the colors blue, green, and red to three mock HST bands at 450, 606, and 814 nm, as done in the observations. The final product is superimposed onto an HST background. From Brook et al. (2008).

The fact that some PRG are polar disks more than polar rings supports the formation through (misaligned) cosmic accretion (Spavone et al. 2010), while the presence of a true ring supports the tidal accretion. Snaith et al. (2012) develop in more details the cosmic accretion studied by Brook et al. (2008); they look in particular at the dark matter when the polar disk is progressively formed out of matter infalling from a cosmic filament. They find that the dark matter is aligned with the polar system.

To be complete, we can also mention another scenario to form PRG, but which is certainly rarer: the resonance phenomenon. In a spiral galaxy, embedded in a triaxial dark matter halo, slightly tilted orbits precess with a retrograde slow pattern. They could resonate with the tumbling retrograde triaxial halo, if the latter does tumble. When dark matter is accreted, the halo pattern speed tends to zero, and passes across the resonance, which levitates the orbits in a polar ring. The polar ring would then contain two equal-mass counter-rotating stellar disks (Tremaine & Yu 2000). This mechanism has been invoked also to explain counter-rotating disks in the equatorial plane (Evans & Collett 1994).
3. Observational tests

3.1. Tully-Fisher for PRG

The number of individual PRG where detailed kinematics is resolved is very small. However, it is possible to have more statistics, with a global velocity measurement, through the HI spectrum of the PR. More than a dozen have been displayed in a Tully-Fisher (TF) diagram, like in Figure 3 (Iodice et al. 2003). The surprise is that most of them reveal a higher rotational velocity in the polar ring, than expected from their TF location. While as predicted by simulations, the velocity of the PR should be lower than in the equatorial plane. Indeed, there is no circular orbits in a PR system. In addition, the velocity of the PR is measured when the matter is at apocenter, since in general, for selection effects, both components polar and equatorial are seen nearly edge-on. When dark matter is spherical or flattened along the host, the observed velocity for PR should be the smallest. And the more dark matter is added in the halo, the more eccentric are the PR orbits. Simulations show that the polar rings are indeed significantly elongated perpendicular to the host potential well, even when massive enough to be self-gravitating.

The surprising result could be a consequence of the perturbed host systems, in color or luminosity, due to the accretion event. However, when the TF of the hosts is compared with the TF of the polar rings, it is possible to rule out this possibility. The equatorial velocity is indeed lower than the polar velocity.

The main implication of the TF diagram for PRG is that most of PRG require dark matter aligned along the polar disk, and not along the host. Only 2 cases, where the ring is light, can be explained with the sole visible baryonic mass flattened along the host. With collisionless dark matter, both merging and tidal accretion scenarios produce either spherical haloes, or halos flattened along the host. A secondary accretion event of gas and dark matter is then required. There could be also some dark baryons, in the form of gas. Their dissipative character will re-create some halo flattened along the PR. The metallicity of the gas could disentangle the scenarios.

Note that an alternative solution to dark matter has been developed in the form of modified gravity (MOND, e.g. Milgrom 2010). Recently, it has been shown that in this model, the expected rotational velocity in the PR is always larger than in the host (Lüghausen et al. 2013).

3.2. Molecular gas in polar rings

HI-21cm emission is essential to have PR rotation curves. But PRG are rare and often at high redshift. Only the molecular gas could then be detected, and ALMA opens large perspectives.

CO emission has been detected in NGC 660 (Combes et al. 1992), in the polar rings of NGC 2685 and NGC 4650A (Watson et al. 1994), in the spindle galaxy NGC 2685 with interferometry (Schinnerer & Scoville 2002), or in the inner PR, in the center of NGC2768 (Crocker et al. 2008). In addition, ten PRG have a global CO spectrum (Galletta et al. 1997).

We have recently undertaken the CO search in the best candidates of Moiseev et al. (2011). Five have been detected, and will be mapped with the IRAM interferometer (Combes et al. 2013). Their TF position is indicated in Figure 3.
4. 3D-shapes of haloes

Dark matter haloes could be triaxial. How can we probe their shape already in the galaxy planes? Tests have been made of their axisymmetry, with HI orbits versus velocity widths (Merrifield 2002). If the HI orbits were non-circular, more scatter would be expected in the Tully-Fisher relation. But this is not observed. The comparison of the morphology and kinematics of the ring in IC2006 has also concluded to axisymmetry (Franx et al. 1994). Flattening is only expected in the direction perpendicular to the plane.

A first method is the flaring of the HI plane. The ideal would be to measure simultaneously the shape of the flare (in edge-on galaxies), and the HI velocity dispersion, perpendicular to the plane (in face-on galaxies). Since this cannot be done, the HI dispersion is assumed to be constant, $\sigma_z(\text{HI}) \sim 10\, \text{km/s}$, as in some face-on galaxies. Then the shape of the flare in $z$ is a function of the density of dark matter in the plane. Given the rotation curve, and the total dark matter, it is possible to deduce the flattening. One caveat is to identify all baryons in the plane, since some dark baryons can exist there, especially at large radii (e.g. Kalberla 2004).

The method produced a large diversity of results in the literature, as shown in Figure 4 (O’Brien et al. 2010, Peters et al. 2013). Either a constant velocity dispersion is assumed, or a model is designed to derive it. One of the problems is that the vertical force depends on the halo in the extreme outer parts (cf Olling 1995, Becquaert & Combes 1997). Through the HI flaring model, the dark matter halo in the Milky Way has been derived prolate in shape (Banerjee & Jog 2011).

The results of various methods are also compared in Figure 4. The PR method assumes dark matter aligned with the host, and the HI-flaring method assumes a constant velocity dispersion of 10 km/s. Other methods are the shape of X-ray isophotes,
the use of tidal streams in the Milky Way (Helmi 2004), or the galaxy-galaxy lensing (see Arnaboldi’s review, this meeting). Whether the halo is truncated or not makes a lot of difference, it could be truncated at the end of the HI rotation curve, or much farther out (Bland-Hawthorn et al. 1997).

Other methods have been proposed in the past, like the extension of tidal tails to constrain the dark matter shape and concentration (Dubinski et al. 1996, Springel & White 1999, Dubinski et al. 1999). Tidal dwarfs can also constrain the extension of dark matter haloes (Duc et al. 2004, Bournaud et al. 2003).

Figure 4. Histogram of halo flattening, according to the three main methods used in the literature: (F) flaring gas-layer, (P) polar-rings and (X) X-ray isophotes. There is also an estimation from tidal streams in the MW, and a statistical galaxy-galaxy lensing estimation.

5. Conclusions

Polar rings are very useful objects to probe the 3rd dimension in dark halo shapes, but there are caveats. More statistics are needed, to disentangle all formation scenarios: mergers, tidal accretion, cosmic accretion of gas and dark matter. It is possible that the PRG formation itself modifies considerably the dark matter shape. Light polar rings are therefore ideal. Molecular gas tracers open new perspective, since they allow to gather more PRG at high redshifts. The flaring method is complementary, however with assumptions on vertical dispersions or on the dark matter radial extent. Warps complicate the derivation; as for polar rings, they can be explained by late accretion of dark matter and gas.

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