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Dynamical modelling of gas flows and dark matter in barred galaxies

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The streaming motions and the associated gas shocks in the bar region are determined by the potential in the inner parts of galaxies. This signatures of non-circular motions can break the disk-halo degeneracy and be used to obtain the contribution of the dark halo to the potential. In this paper we give a short review on the current understanding of the dark matter content in the inner parts of barred galaxies using dynamical modelling. We give an overview of the main differences among the models and the main results presented by each of the groups. The main result, common to all the modelling carried out up to now, is the fact that the gravitational field in the inner region is mostly provided by the stellar luminous component. The bar pattern speeds found by the different groups are consistent with fast rotators, and the best fit M/L ratios obtained are compatible with M/L ratios derived from current population synthesis models.

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1. Introduction

The idea is simple, the non-circular velocities that characterise gas streaming motions in the bar region allow us to determine the necessity for a dark halo in the inner parts of spiral galaxies. The gas shocks in the bar region are determined by the shape of the potential in the inner parts. Therefore, the non-circular features of the velocity field can help us to break the disk-halo degeneracy.

Few studies have been done addressing the dark matter contribution in the inner parts using this approach: The fluid dynamics approach with the work by Weiner et al. (2001) on the modelling of NGC 4123; Pérez (2003) and Pérez et al. (2004) on the study of the dark matter content of 5 barred galaxies (NGC 5505, NGC 7483, NGC 5728, and NGC 7267); and the sticky-particle approach by Rautiainen et al. (2004) modelling the dynamics of ESO 566-24 and Salo et al. (1999) who modelled NGC 4214. Petipas et al. are involved in a project of modelling the gas dynamics of a large number of barred galaxies to compare it to the BIMA Survey of Nearby Galaxies (SONG), results are still unpublished.

A controversial point at the moment is the loss of angular momentum by the disk embedded in a dark halo. It has been argued that a heavy halo will slow down a bar by dynamical friction (i.e. Weinberg et al., 1985; and Debattista & Sellwood, 2002); therefore bars embedded in a heavy halo would have to be slow rotators. However, the few directly measured pattern speeds seem to indicate that they are fast rotators (where the ratio between the corotation radius, R_{CR}, and the bar semi-major axis, R_{bar}, lies between 1.0 and 1.4), implying the existence of a sub-dominant halo in the inner parts. However, it might be dangerous to constrain the dark matter halo using the bar pattern speed; Tremaine & Ostriker (1999) explain the fact that the bars rotate fast by arguing that the angular momentum transfer from the disk to the halo would spin the latter up, flattening the inner halo. Since bars are coupled to the halos they should also rotate rapidly. In this way one obtains a fast bar embedded in a massive dark halo. Recent numerical simulations show that the pattern speed of a bar embedded in a heavy halo may not change for many bar rotations depending on the angular momentum absorbed by the halo (Athanassoula, 2002; Valenzuela & Klypin, 2003). Due to this on-going debate we will not discuss here the studies which base their determination of the dark matter contribution to the potential on the bar pattern speed.

2. The modelling

Different gas modelling flavours have been used by the groups. Fluid dynamical methods: Weiner et al. used a Eulerian grid code while Pérez et al. used a 3-D N-body/SPH. Sticky-particle methods: chosen by Rautiainen et al. and Salo et al.. To test the effect of using different methods on the results we run the SPH code using the potential derived from NGC 4123 with very similar results as those of Weiner et al., reassuring us that the results were not dependent on the fluid-dynamical algorithm chosen (Pérez et al., 2003). To derive the potential *H*-band images are used by all the groups with the exception of the Weiner et al. group who chose the *I*-band image to derive the potential. We discuss in detail the differences derived from using different bands in the gas flows. The M/L ratio is kept constant throughout the disk, and simulations were run for a range of M/L ratios for all the groups, except for Pérez et al. who made use of population synthesis

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Table 1: Galaxy parameters

Name	Distance (Mpc)	h_R (kpc)	V_{flat} (km s^{-1})	Morph. type (from RC3)	Comments	Reference
NGC 4123	22.4	3.2	130	SBc	inner ring	Weiner et al., 2001
ESO 566-24	45.0	2.3	190	SBb	four-armed, outer ring	Rautiainen et al., 2004
NGC 4214	32	–	200	SBa	outer, inner, and nuclear ring	Salo et al., 1999
NGC 7267	44.7	2.5	117	SBa	four-armed, outer ring	Pérez et al., 2004
NGC 5505	57.1	1.9	143	SBab	”	”
NGC 7483	65.8	11.0	277	SBa	inner and outer ring	”
NGC 5728	37.2	5.4	239	SBa	”	”
IC 5186	65.5	2.5	155	SBab	”	”

models and different optical colours to obtain 2-D M/L ratio maps (different M/L were also tested). The scale-height (h_z) is treated similarly in all the studies; constant h_z with either an exponential or a $sech^2$ covering a similar range of h_z. There are some differences in the additional mass components and the details of the derivation of the potential but no big differences are expected in the results. The fact that Pérez et al. used a 3-D code while the other two groups used a 2-D should produce minor differences; basically, the radial forces will be slightly more smoothed out (for the same potential) in the 3-D code. And, of course, all the groups explored a range of pattern speeds in the modelling. The structural parameters for all the galaxies are summarised in Table 1.

The modelled gas dynamics is then compared to the observed kinematic information (e.g. Fig. 1). To better constrain the models one should compare the models to 2-D kinematic information. Fabry-Perot H_α velocity fields are chosen by all the authors apart from Pérez et al. who use 1-D velocity field from long-slit spectroscopy (future work will include integral field kinematic information).

3. Results and discussion

The main result from these studies is that the gravitational field in the inner region is mostly provided by the stellar luminous component (less than 20% is provided by the dark halo). It is interesting to notice the fact that the M/L ratios obtained from population synthesis models are the best fit results in the Pérez et al. paper. All the studies manage to reproduce well the velocity fields and the morphologies of the modelled galaxies. However, for NGC 5505 and NGC 7267 no steady flow is reached in the simulations, possibly reflecting the fact that for these galaxies the stellar distribution is not in a sufficiently stationary state to allow a rigid potential approximation. A discussion about this result is presented in Pérez et al. (2004).

Regarding the pattern speed of the bar, Weiner et al., Pérez et al., and Salo et al. found the best fit for fast rotators (with R_{CR}/R_{bar} between 1.1 and 1.4). Rautiainen et al. finds a $R_{CR}/R_{bar} = 1.6 \pm 0.3$; although slower a bar than the other studies, the result is not incompatible with a fast rotator. As already mentioned, one has to be very careful when using the pattern speed to conclude anything about the mass of the halo since if the halo velocity dispersion is increased then the slowdown rate of the bar decreases (Athanassoula, 2002).

Weiner et al. analysed the possible halo shapes. They found that their results were consistent with a low density NFW type halo as well as with an isothermal halo. However, this NFW halo

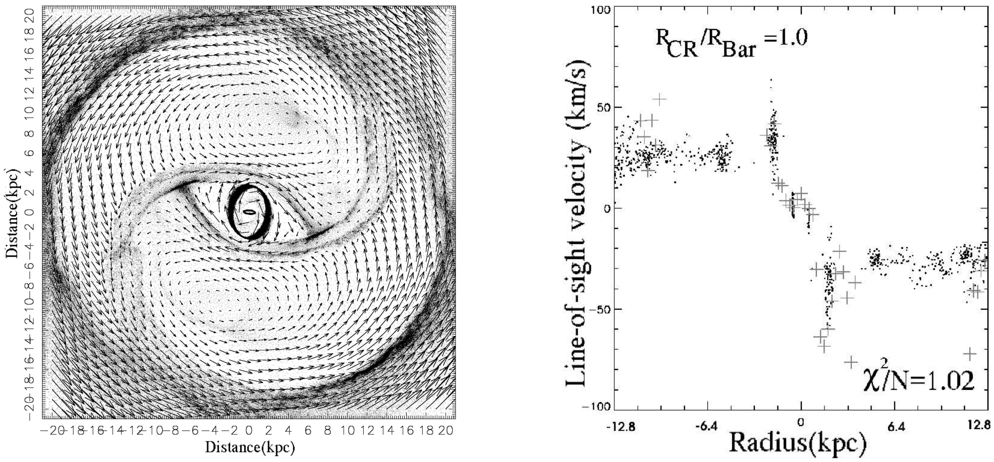

Figure 1: Example of the velocity field and comparison with the observed kinematics of one of the modelled galaxies (NGC 7483). Left panel: The gas distribution and velocity field for the mass distribution derived from the composite H, I-band image of NGC 7483, at 4 bar rotations and for $R_{\rm CR}/R_{\rm bar}$=1.0. The length of the vectors is proportional to the velocity in the frame rotating with the bar. Right Panel: Line-of-sight velocity curve along the major axis for the NGC 7483 with $R_{\rm CR}/R_{\rm bar}$=1.0, after 4 bar rotations. The dots represent the gas particles and the overlaid gray crosses the observed major axis line-of-sight velocity curve. The modelled velocity curve agrees very well with the observed data. Figures taken from Pérez et al (2004).

must be much less dense than predicted by the relations between halo concentration and mass found in CDM simulations.

The derived $({\rm M/L})_{\rm H}$ = 1.2 for ESO 566-24 is compatible with a $B-I \approx 2.25$ from stellar populations (close box model and a Salpeter IMF with a flatter low mass end; Bell & de Jong., 2001). This value is in agreement with the observed colour (Buta el al. 1991). The $({\rm M/L})_{\rm H}$ = 0.75 derived for NGC 4214 gives a $V-I$ = 0.98, with the same parameters as before for the stellar populations. The observed $V-I$ is 1.15 ± 0.03. The derived average $({\rm M/L})_{\rm H}$ = 0.8 from Pérez et al. was obtained using population synthesis models with similar parameters. NGC 4123 gives a best fit value $({\rm M/L})_I$ of 2.25 corresponding to a $V-I$ = 1.13,with the same parameters as before. The observed $V-I$ is 1.12. The best fit M/L ratios found by the different groups are compatible with M/L ratios derived from population synthesis models.

The modelled systems do not seem to be exceptional barred galaxies in any way (see Table 1). Are the strengths of the bars systematic in any way? The definition adopted by the different groups for the bar strength takes into account both the radial and the tangential forces (i.e. Combes & Sanders, 1981). The strength of the bar, or $Q_T(R)$ parameter, of the modelled galaxies ranges from 0.1 to 0.6, basically covering all possible bar strengths.

In summary, all the studies involving numerical simulations of barred galaxies conclude that the gravitational field in the inner region is mostly provided by the stellar luminous component. But are barred galaxies different to unbarred galaxies in their dark halo distribution? A study of the Tully-Fisher relation of barred galaxies (Courteau et al., 2003) shows that barred and unbarred galaxies behave similarly and are likely to have, on average, comparable fractions of luminous and dark matter at a around 2.2 disk scale-lengths. In principal, there is no obvious indication to conclude that there is a distinction in the dark matter content between unbarred and barred high surface brightness galaxies.

The standard cold dark matter cosmology (CDM) predicts halos that are dark matter dominated inside the optical radius (Navarro et al. 1996). The results presented here suggest that either the halos have lower scale density (or radius) than the CDM cosmology predictions since the dark halo is sub-dominant in the inner parts. This result is in agreement with the mass in spiral galaxies being distributed according to the inner baryon dominance regime, where there is a characteristic radius at which the luminous matter accounts for the all the mass distribution while for larger radii the dark halo starts signifi cantly contributing to the circular velocity (Salucci & Persic 1999).

The issue of morphological type vs bar pattern speed needs still to be further investigated, as well as the the transfer of angular momentum among the different components. In the future, the 'maximality' of barred galaxies plus their structural parameters such as the strength of the bar and the pattern speed could be used used to constrain the shape of a non-spherical dark halo.

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