Do the low PN velocity dispersions around elliptical galaxies imply that these lack dark matter?

Gary A. Mamon*, Avishai Dekel† and Felix Stoehr*

*Institut d’Astrophysique de Paris (UMR 8111: CNRS & Univ. P. & M. Curie), Paris, France
†Racah Institute of Physics, Hebrew University, Jerusalem, Israel

Abstract. While kinematical modelling of the low PN velocity dispersions observed in the outer regions of elliptical galaxies suggest a lack of dark matter around these galaxies, we report on an analysis of a suite of \textit{N}-body simulations (with gas) of major mergers of spiral galaxies embedded in dark matter halos, and find that the outer velocity dispersions are as low as observed for the PNe. The inconsistency between our dynamical modelling and previous kinematical modelling is caused by very radial stellar orbits and projection effects when viewing face-on oblate ellipticals. Our simulations (weakly) suggest the youth of PNe around ellipticals, and we propose that the universality of the PN luminosity function may be explained if the bright PNe in ellipticals are formed after the regular accretion of very low mass gas-rich galaxies.

INTRODUCTION

Although it is generally accepted that spiral galaxies are embedded in dark matter halos, the presence and amount of dark matter in elliptical galaxies is still uncertain.

The classical way to infer the mass distribution of a gravitational system is by analyzing its internal kinematics. For an unordered system such as an elliptical galaxy, the more mass there is, the higher the velocity dispersions. Mathematically, this is expressed through the Jeans equation \(\nabla P = -\nabla \Phi\), where \(P\), \(\Phi\) and \(\nu\) are the dynamical pressure, gravitational potential and (number or luminosity) density of the tracer, which in spherical symmetry becomes:

\[
\frac{d}{dr} \left( \nu \sigma^2 \right) + 2 \beta(r) \frac{\nu(r) \sigma^2(r)}{r} = -\nu \frac{GM(r)}{r^2},
\]

where \(M\) is the mass, \(\sigma\) the radial velocity dispersion, \(\beta = 1 - \sigma^2/(2 \sigma^2)\) the velocity anisotropy (zero for isotropic systems) and \(\sigma\) the tangential velocity dispersion. The modelling is complicated by projection effects and by the intrinsic mass/anisotropy degeneracy in the Jeans equation.

Alas, stellar velocity dispersions in elliptical galaxies are difficult to measure (through absorption-line spectroscopy) beyond 2 half-light (effective) radii (\(2 R_e\)). Planetary nebulae (hereafter, PNe) happen to provide a discrete indicator of the gravitational potential that extends up to 5\(R_e\), and therefore helps constrain the mass profiles of ellipticals. Measured velocity dispersions of PNe around ellipticals turn out to be low and decreasing with radius (Ciardullo et al. 1993; Méndez et al. 2001; Romanowsky et al. 2003, but see Teodorescu, in these proceedings), and refined kinematical analyses lead to a lack of dark matter around elliptical galaxies (Romanowsky et al.). This conclusion is at odds with the predictions of the standard hierarchical scenario in which elliptical galaxies are the products of mergers of spiral galaxies of comparable mass (Springel et al. 2001).

Do the low PN velocity dispersions force us to revise our general understanding of the formation of elliptical galaxies? In this contribution, we gain considerable insight through an analysis of dynamical \textit{N}-body simulations of galaxy mergers.

THE LINE-OF-SIGHT VELOCITY DISPERSION PROFILES OF MERGER REMNANTS

We use a series of 10 simulations (Cox et al. 2005) of equal mass mergers of disk+bulge+gas+dark matter halo spiral galaxies, with different orbital parameters, bulge/disk ratio, gas fraction and feedback efficiency.

Figure 1 shows snapshots of one of the mergers, illustrating the tidal tails and bridge formed during the closest approach, after which the galaxies separate and merge at second passage, while the tidal tails expand outwards. The final remnant, viewed here edge-on is oblate.

Figure 2 shows the line-of-sight velocity dispersion of the 10 merger remnants, together with the stellar and PNe dispersions of Romanowsky et al. and Méndez et al. Interestingly, the stellar line-of-sight velocity dispersions of the dark matter-embedded merger remnants are as low
FIGURE 1. Snapshots of the merger of equal mass spiral galaxies (see Cox et al. 2005). The lighter zones in the central regions of the galaxies represents the young stars formed during the simulation, while the remaining smooth greyscale are the old stars.

FIGURE 2. Line-of-sight velocity dispersion vs. projected radius, normalized to the effective radius (from Dekel et al. 2005). The merger remnants are viewed from three orthogonal directions at two late times after the merger. Lower solid, dashed, and upper solid curves show the dispersions from all stars, young (< 3 Gyr) stars, and dark matter, respectively. The 1σ scatter is marked by shaded or hashed areas or a thick bar. For comparison, are shown the stellar (crosses, Jedrzejewski and Schechter 1989; Binney et al. 1990; Bender et al. 1994; Statler and Smecker-Hane 1999) and PN (circles, Méndez et al.; Romanowsky et al.) velocity dispersions of galaxies NGC 821, 3379, 4494 and 4697. The errors are 1σ. Thin curves refer to the earlier models (Romanowsky et al.) with (upper) and without (lower) dark matter.

FIGURE 3. Radial (3D) profiles (Dekel et al. 2005) of velocity anisotropy, for the dark matter (nearly constant solid), young stars (dashed), old stars (dotted) and all stars (rising solid curves), respectively.

WHY DID KINEMATICAL AND DYNAMICAL MODELLING PRODUCE INCONSISTENT RESULTS?

One can criticize the relevance of these simulations to understanding the kinematics of PNe around elliptical galaxies as these are not thought to be subject to recent (few Gyr) mergers of equal mass spiral galaxies. However, the low velocity dispersions are also found in mergers of spirals with mass ratio 3 (which are much more frequent) and these low velocity dispersions are long lived if one lets the remnant evolve for many Gyr more.

If the merger simulations analyzed by Dekel et al. are relevant, then how can dark matter-rich spirals make elliptical-like merger remnants similar to the observed elliptical galaxies, while kinematical modelling of the PN motions around ellipticals imply little or no dark matter (Romanowsky et al. 2003)?

There are several reasons for the inconsistency between the kinematical and dynamical analyses. First, the orbits of the outer stars turn out to be quite radial, with $\beta \approx 0.5$ (Fig. 3 from Dekel et al. and also Domínguez-Tenreiro et al. 2004; Abadi et al. 2005), which decreases the observed velocity dispersions, since the dispersion
Figure 4. Mass-to-light ratio at the virial radius, relative to that derived from isotropic NFW modelling, as a function of observed line-of-sight stellar velocity dispersion at 2 (right) and 5 (left) $r_e$. From Mamon and Łokas (2005).

Figure 5. Ratio of Jeans mass (i.e., the mass from the stationary spherical Jeans equation [1] — with the velocity dispersions replaced by rms velocities to take streaming motions into account), to true mass averaged over the 10 simulated merger remnants, and in spherical shells.

at a fixed projected radius depends (Mamon and Łokas 2005) on the mass profile outside that radius and the overall anisotropy profile. This radial stellar anisotropy arises because the stars selected to lie far from the center in the remnant must have come from the inner regions right after the closest approach, and were thrown out on elongated orbits in tidal tails (see Fig. 1). This is illustrated in Fig. 4, which shows that for the stellar anisotropy of the merger simulations (upper curves: ‘Nav04-0.18’) the mass inferred at the virial radius with the recent representation (Navarro et al. 2004) of $\Lambda$CDM density profiles is 2.4 times what would be inferred for an isotropic “standard” NFW (Navarro et al. 1996) dark matter model (Mamon and Łokas 2005). Although the best fit models found in the kinematical analysis are moderately radially anisotropic (Romanowsky 2005, private communication), our equal mass merger leads to even stronger radial anisotropy, and unequal mass major mergers lead to even stronger anisotropy.

Second, the galaxy modelled in detail by Romanowsky et al., NGC 3379, appears circular and its PN system shows no rotation (Ciardullo et al.; Romanowsky et al.) and may well be an oblate elliptical viewed face-on (Statler and Smecker-Hane 1999), which would lead to roughly 10% lower velocity dispersions (Dekel et al.).

Moreover, the galaxy may not be stationary, contrary to the assumptions of all kinematical modelling. However, Fig. 5 indicates that the spherical stationary Jeans equation (1) recovers well the true mass profile, so that the merger remnants can be modelled as stationary and spherical systems (at the meeting, we incorrectly reported a 40% deficit in the mass estimated by the stationary spherical Jeans equation).

Are the PNe Observed in Elliptical Galaxies Young?

There are several reasons to believe that the PNe observed in elliptical galaxies are young objects, although each explanation comes with its caveat:

1. in the latest model of PN evolution (Marigo et al. 2004), the brightest PNe are 1 or so Gyr old, comparable to our young stars — however, the universality of the bright-end of the PN luminosity function (Ciardullo et al. 1989), between old ellipticals and young spirals, suggests otherwise (see below);
2. the young stars in the simulations formed during the merger from the gas particles, have lower velocity dispersions than the older stars (dashed vs. solid curves in Fig. 2) — however, the effect is of order of 10%, and the old stars fit the observed PNe velocity dispersions as well as the young stars;
3. the reduced kurtoses, $h_4$, of the line-of-sight velocity distribution of the young stars are larger than for
the old stars and more similar to the \( h_4 \) parameters measured in the two galaxies with publicly available PN velocity data, while the \( h_4 \) values for the old stars are closer to the measurements from spectral absorption lines (see Fig. 6) — however, the match is not excellent.

None of these reasons is compelling. One clever reconciliation (Ciardullo et al. 2005 and Ciardullo, in these proceedings) between the observed universality of the PNLF between young spirals and old elliptical galaxies and the recent Marigo et al. model linking the bright-end PNLF with the age of the PNe is to suppose that the progenitors of the bright PNe in ellipticals are binary systems (blue stragglers) of fairly old stellar mass stars rather than much younger 2\( M_\odot \) single stars.

Alternatively, it may be possible to reconcile PNLF universality and the Marigo et al. PN model if one supposes that the bright PNe in ellipticals are caused by recent (1 Gyr) accretion of very low mass galaxies that go through a starburst as they are tidally squeezed by the gravitational potential of the elliptical. Contrary to any model driven by major mergers, for which 1 Gyr old starbursts will be as stochastic as is the merging process, the rate of accretion should vary little with galaxy type, luminosity and perhaps even environment.

Both scenarios ought to be tested quantitatively in the context of evolutionary models for the PN luminosities, stellar masses and galaxy spectra. The mass accretion rate can be obtained (Salvador-Solé et al. 1998) through the extended Press-Schechter formalism (e.g. Lacey and Cole 1993). Will there be sufficient blue stragglers in ellipticals to produce the universality of the PNLF? And, on the other hand, will the rate of accretion of small galaxies be large enough to produce sufficient bright PNe and not too large to make elliptical galaxies bluer than they are observed to be?

**ACKNOWLEDGMENTS**

We thank Ryszard Szczerba and Grazyna Stasińska for helping GAM attend this superbly organized meeting and another outstanding Polish astronomer, Ewa Łokas, who collaborated on work that led to Fig. 4, as well as T. J. Cox for his beautiful simulations.

**REFERENCES**

- R. Ciardullo, G. H. Jacoby, and H. B. Dejonghe, ApJ, 414, 454–462 (1993).
- R. H. Méndez, A. Riffeser, R.-P. Kudritzki, M. Matthias, K. C. Freeman, M. Arnaboldi, M. Capaccioli, and O. E. Gerhard, ApJ, 563, 135–150 (2001).
- A. J. Romanowsky, N. G. Douglas, M. Arnaboldi, K. Kuijken, M. R. Merrifield, N. R. Napolitano, M. Capaccioli, and K. C. Freeman, Science, 301, 1696–1698 (2003).
- V. Springel, S. D. M. White, G. Tormen, and G. Kauffmann, MNRAS, 328, 726–750 (2001).
- T. J. Cox, P. Jonsson, J. R. Primack, and R. S. Somerville, MNRAS (2005), submitted, arXiv:astro-ph/0503201.
- A. Dekel, F. Stoehr, G. A. Mamon, T. J. Cox, and J. R. Primack, Nature (2005), in press, arXiv:astro-ph/051622.
- R. Jedrzejewski, and P. L. Schechter, AJ, 98, 147–165 (1989).
- J. J. Binney, R. L. Davies, and G. D. Illingworth, ApJ, 361, 78–97 (1990).
- R. Bender, R. P. Saglia, and O. E. Gerhard, MNRAS, 269, 785–813 (1994).
- T. S. Statler, and T. Smecker-Hane, AJ, 117, 839–854 (1999).
- R. Domínguez-Tenreiro, A. Sáiz, and A. Serna, ApJ, 611, 1.5–L.8 (2004).
- M. G. Abadi, J. F. Navarro, and M. Steinmetz, MNRAS (2005), submitted, arXiv:astro-ph/0506659.
- G. A. Mamon, and E. L. Łokas, MNRAS (2005), in press, arXiv:astro-ph/0405941.
- J. F. Navarro, E. Hayashi, C. Power, A. R. Jenkins, C. S. Frenk, S. D. M. White, V. Springel, J. Stadel, and T. R. Quinn, MNRAS, 349, 1039–1051 (2004).
- J. F. Navarro, C. S. Frenk, and S. D. M. White, ApJ, 462, 563–575 (1996).
- P. Marigo, L. Girardi, A. Weiss, M. A. T. Groenewegen, and C. Chiosi, A&A, 423, 995–1015 (2004).
- R. Ciardullo, G. H. Jacoby, and H. C. Ford, ApJ, 344, 715–725 (1989).
- R. Ciardullo, S. Sigurdsson, J. J. Feldmeier, and G. H. Jacoby, ApJ, 629, 499–506 (2005).
E. Salvador-Solé, J. M. Solanes, and A. Manrique, ApJ, 499, 542–547 (1998).
C. Lacey, and S. Cole, MNRAS, 262, 627–649 (1993).

Do the low PN velocity dispersions around elliptical galaxies imply that these lack dark matter?