Publ. Astron. Obs. Belgrade No. 86 (2009), 161 - 166 *Contributed paper*

THE PROBLEM OF THE MASS-TO-LIGHT RATIO IN EARLY-TYPE GALAXIES

S. SAMUROVIĆ

Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia
E–mail: srdjan@aob.bg.ac.yu

Abstract. In this contribution I discuss the problem of the mass-to-light ratio in early-type galaxies. The observational evidence based on different and independent techniques suggest that interior to $\sim 3R_e$ (where R_e is the effective radius) from the center of these galaxies dark matter does not play important dynamical role and the mass is dominated by the visible, stellar component. The long-slit spectra observations enable us to deduce the full line-of-sight velocity distribution of a given galaxy, but are limited to $\sim 3 - 4R_e$. Fortunately, the kinematics can also be inferred beyond this limit using planetary nebulae (PNe) and globular clusters (GCs), but the anisotropies of orbits in this approach are not well constrained. I will show that some hints can nevertheless be obtained even using small samples available at this stage. Finally, I will use the X-rays methodology to infer the mass-to-light ratios in different early-type galaxies and to compare the results obtained with the aforementioned techniques while emphasizing the problems inherent in this methodology (e.g. possible lack of hydrostatic equilibrium).

1. INTRODUCTION

In the studies of the problem of dark matter in early-type galaxies the first step is to infer where it is supposed to dominate and this is best established by studying the profile of the mass-to-light ratio of these objects.

The problem of dark matter remains to be one of the most important unresolved problems in cosmology and astronomy. The existence of dark matter in spiral galaxies seems to be well established because in these galaxies there is a cool gas which provides a powerful tool for obtaining rotation curves, that are, for most spirals, nearly flat thus indicating the presence of dark mass in their outer parts – dark haloes (see, e.g., Binney and Tremaine 1987, Persic, Salucci and Stel 1996, Sofue and Rubin 2001, Bahcall, Piran and Weinberg 2004). On the other hand, early–type galaxies (ellipticals and lenticulars) contain little or no cool gas so one cannot use 21-cm observations to trace kinematics of neutral hydrogen out to large galactocentric radii.

The dominant component in early-type galaxies is the old stellar population. Van der Marel (1991) found in his sample of 37 bright ellipticals that the average mass-to-light ratio in the B–band in solar units (it is assumed that solar units are used throughout this work) is: $M/L_B = (5.95 \pm 0.25)h_{50}$ which becomes $M/L_B = 8.33 \pm 0.35$ for $h_0 = 0.70$ (the value of the Hubble constant used in this work).

2. OBSERVATIONAL METHODOLOGIES

The external regions of elliptical galaxies are of special importance because these are regions where dark matter might be expected to dominate luminous matter. The observational methodologies suitable to check whether early-type galaxies do have dark matter haloes are the following:

Stellar kinematics method is based on *the integrated stellar light* and provides a very detailed description of early-type galaxies interior to $\sim 3-4R_\mathrm{e}$ (see for example, Carollo et al. 1995, Statler, Smecker–Hane and Cecil 1996, Kronawitter et al. 2000, Samurović and Danziger 2005, hereafter SD05; review in Samurović 2007a). The great obstacle is the fact that their outer parts are very faint (the isophote at $4R_\mathrm{e}$ encompasses 85% of the total light of a given galaxy, see e.g. Samurović 2007a, Appendix 5), and it is therefore usually difficult to obtain spectra to constrain kinematics at large radii. Using integrated stellar spectra one can determine the full line-of-sight velocity distribution (velocity v, velocity dispersion σ, and Gauss-Hermite parameters h_3 and h_4 which describe asymmetric and symmetric departures from the Gaussian, respectively). Using this methodology, it appears that dark matter (at least in some galaxies) does not dominate in the regions interior to $\sim 3R_\mathrm{e}$.

X–rays, a consequence of the existence of the hot gas at the temperature $T \sim 10^7$ K, found in a large number of massive early–type galaxies (interestingly, not in all, see the case of IC 3370 from SD05) is an extremely useful tool for the study of the mass because the methodology is well known. The present observational situation is interesting: for example, Sivakoff et al. (2004) used the X–ray observations by CHANDRA and assuming hydrostatic equilibrium found that for the X–ray bright galaxy NGC 1600 within $\sim 4R_\mathrm{e}$ dark matter does not dominate. However, two recent studies based on the CHANDRA data by Humphrey et al. (2006) and Fukazawa et al. (2006) used the same methodology (on different samples) on X–ray data to demonstrate the existence of dark matter beyond $\sim 1R_\mathrm{e}$. Usually, two assumptions for hot gas are considered: the hot gas is in hydrostatic equilibrium under the influence of the gravitational potential of the galaxy as a whole, and the gas obeys the perfect gas law. The total mass of the galaxy interior to a given point (Kim and Fabbiano 1995) is:

$$M_T = 1.8 \times 10^{12}(3\beta+\alpha)\left(\frac{T}{1\ \mathrm{keV}}\right)\left(\frac{r}{1000''}\right)\left(\frac{d}{10\ \mathrm{Mpc}}\right)\mathrm{M}_\odot. \tag{1}$$

The total mass-to-light of the galaxy interior to a given point is:

$$\frac{M_T}{L_B} = 1.16 \times 10^{-2}\ 10^{\frac{B}{2.5}}\ (3\beta+\alpha)\ \left(\frac{T}{1\ \mathrm{keV}}\right)\left(\frac{r}{1000''}\right)\left(\frac{d}{10\ \mathrm{Mpc}}\right)^{-1}. \tag{2}$$

Here, B is the B magnitude of galaxy inside radius r, the α parameter is related to the temperature ($T \sim r^{-\alpha}$), β is the slope used in the analytic King approximation model and d is the distance to a given galaxy.

Planetary nebulae (PNe) represent a very promising tool for dark matter research because they are detectable even in moderately distant galaxies through their strong emission lines. For example, Hui et al. (1995) found that the mass-to-light ratio in the central region of a giant elliptical galaxy NGC 5128 is ~ 3.9 and that out to $\sim 5\ R_\mathrm{e}$ it increases to ~ 10 (in the B-band), thus indicating the existence of the dark halo. Romanowsky et al. (2003) observed PNe in three galaxies (NGC 821, NGC 3379 and NGC 4494) and claimed little or no dark matter out to $\sim 3.5\ R_\mathrm{e}$ (if one takes into account a correct value of the effective radius for NGC 3379, see SD05 for details).

Recently, Sluis and Willams (2006) used the Rutgers Fabry–Pérot in order to search for planetary nebulae in NGC 3379 and three other galaxies in order to use the PNe as kinematic tracers of the galaxy potential. They detected 54 PNe in NGC 3379 and found that within $\sim 5R_{\rm e}$ the total mass-to-light ratio in the B–band of this galaxy is ~ 5 implying very low amount of dark matter in the given region (~ 130 arcsec). De Lorenzi et al. (2008) recently modelled NGC 3379 using PNe out to $\sim 7R_{\rm e}$ and found that it may have a dark matter halo but its outer envelope is then strongly radially anisotropic. Méndez et al. (2008) used the 8.2 m Subaru telescope to study the elliptical galaxy NGC 4697. Using the sample of 218 PNe to study this galaxy out to $\sim 5R_{\rm e}$ they found that the observed velocity dispersion is in agreement with the existence of a dark halo plus radial anisotropies and they claim: "the dark matter halo is rather inconspicuous, and it is still unclear how massive it can be".

Globular clusters (GCs) can also be used as tracers of dark matter in the early-type galaxies. Mould et al. (1990) found for two giant elliptical galaxies M49 and M87 from the Virgo cluster that the velocity dispersion profiles of the cluster systems were flat, thus suggesting the existence of an isothermal halo of dark matter in these elliptical galaxies. Grillmair et al. (1994) studied the radial velocities of 47 globular clusters in NGC 1399 in the Fornax cluster od galaxies. Under the assumption that the clusters were on purely circular orbits, they obtained a lower limit on a globally constant mass-to-light (M/L_B) ratio of 79 ± 20 in the B-band. Their result, suggesting that M/L is several times larger than values of mass-to-light ratio determined from the stellar component closer to the core, implies that M/L_B must increase substantially with radius. This result was confirmed in a paper by Samurović and Danziger (2006) who used the observations of NGC 1399 by Dirsch et al. (2003), Richtler et al. (2004) and Dirsch et al. (2004) to find that in spite of the observations that show that the velocity dispersion decreases between 4 and 10 $R_{\rm e}$ there is evidence that dark matter exists beyond $\sim 3R_{\rm e}$ (but does not dominate interior to this distance). Another example is that of M49 (= NGC4472) studied by Côté et al. (2003) who showed that the globular clusters radial velocities and density profiles provide "unmistakable evidence" for a massive dark halo. Pierce et al. (2006) have obtained Gemini/GMOS spectra for 22 GCs associated with NGC 3379 and found that, in contrast to the results of Romanowsky et al. (2003), their results suggest a constant value of the velocity dispersion (out to ~ 200 arcsec) which imply a normal–sized dark matter halo. They do note, however, that due to possible anisotropies they could not rigourously determine the dark halo mass. Samurović and Ćirković (2008a) analyzed the kinematics of NGC 4649 based on the GCs and found that the velocity dispersion of this galaxy can be modelled (using the Jeans equation) with $M/L_B \sim 7$ and that significant amounts of dark matter are not needed even beyond $\sim 3R_{\rm e}$; they also found using standard statistical procedures that tangential anisotropies are most likely present in this galaxy (which is in agreement with the results from the literature).

Weak gravitational lensing enables determination of the dependence of the velocity dispersion on the luminosity of the lensing galaxies and is suitable for studies of dark matter in outer part of distant early-type galaxies. It was found that a Navarro-Frenk-White (NFW) profile provides a good fit to the data (Kleinheinrich et al. 2003). Gavazzi et al. (2007) analyzed 22 early-type lens galaxies, based on deep HST images obtained as part of the Sloan Lens ACS Survey. They found that at $z = 0.2$ interior to one effective radius, about 27% of the mass is in the form of dark matter. The *strong gravitational lenses* can also be used for probing of the galaxy haloes, but only in the inner regions of galaxies (few tens of kiloparsecs) (see, for example, Prada et al. 2003). The Lenses Structure and Dynamics (LSD) Survey gathers kinematic data for distant (up to $z \sim 1$) early-type galaxies that are gravitational lenses (review in Treu et al. 2004). The results of this survey suggest that extended dark matter haloes are detected in the early-type galaxies and that the dark matter contributes 50-75% to the total mass within the Einstein radius.

In general, a serious problem with the determination of the mass (and the mass-to-light ratio) in the early-type galaxies is related to the fact that one does not *a priori* know anything about the orbits of stars in ellipticals which leads to a well known mass-anisotropy degeneracy (see Tonry 1983, see also Binney and Merrifield 1998, Chap. 11.2).

3. RESULTS

It seems obvious from the discusion of different methodologies that the current investigations lead to the conclusion that there is less unambiguous evidence for the dark matter in early-type galaxies than in the case of spirals. The currently popular theoretical cosmological models (such as cold dark matter, CDM, models) predict huge amounts of dark matter in these galaxies, but as it was shown above some recent observations fail to confirm this for particular galaxies at least in regions interior to $\sim 3R_{\rm e}$. Dekel et al. (2005) used numerical simulations to show that dark matter in early-type galaxies in fact exists, but that a careful modelling is needed because radial orbits may dominate. Note that some recent works claim to detect the presence of dark matter in early-type galaxies interior to smaller distances from the galactic center (see, for example, Thomas et al. 2005, Teodorescu et al. 2005, Cappellari et al. 2006, De Rijcke et al. 2006).

In Table 1 the sample of early-type galaxies for which we have the estimates of the total mass-to-light ratio beyond $\sim 3R_{\rm e}$ is given. It is based on the Table 1 from the paper by Napolitano et al. (2005) and on the paper by Samurović (2007b) (the reader is referred to it for details). It is important to stress that the two galaxies have been added to this Table: NGC 4649 (for which the estimates are taken from Samurović and Ćirković 2008b; see also these Proceedings) and NGC 4697 (for which the estimates are taken from Méndez et al. 2008; note that the errors for the mass-to-light ratio were not given). It is obvious that the situation is complex: some galaxies do not require dark matter in their outermost parts (NGC 221, NGC 1700, NGC 4494, NGC 4697 and NGC 3384), some have moderate amounts of dark matter (NGC 821, NGC 3379 and NGC 5128) and some require significant amounts of dark matter (NGC 1399).

It is important to note that the estimates of the mass-to-light ratio between different methodologies may differ: for example for the galaxy NGC 4649 interior to 6 arcmin ($= 4R_{\rm e}$) both X-rays and GCs predict the same mass (and the mass-to-light ratio) profile (see Fig. 1 in Samurović and Ćirković 2008b). At 9 arcmin ($6R_{\rm e}$) the X-ray estimate ($M/L_B \sim 33$) is much higher than that based on GCs ($M/L_B \sim 25$). However both of these estimates differ from the Jeans modelling ($M/L_B \sim 7$, see above). The X-rays estimates given above assume the existence of hydrostatic equilibrium, which is almost universal in interpreting the X-ray profiles. It was suggested that the lack of hydrostatic equilibrium may influence the estimate of the total mass in early-type galxies (see Ciotti and Pellegrini 2004).

Table 1: Sample of early-type galaxies with M/L measurements

Galaxy	Type	D [Mpc]	M_B	R_e [kpc]	R_e [arcsec]	r_{in} [R_e]	Υ_{in}	$\Delta\Upsilon_{in}$	r_{out} [R_e]	Υ_{out}	$\Delta\Upsilon_{out}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
NGC 221	E3	0.9	-16.5	0.2	46	0.1	2.8	0.2	5.6	4.8	2.8
NGC 821	E2	25.5	-20.6	6.2	50	0.5	8.4	0.4	4.8	13.1	3.9
NGC 1399	E1/cD	21.1	-21.4	4.3	42	1.0	8.3	0.8	11.4	45.0	8.0
NGC 1700	E4	52.0	-21.7	3.5	14	0.5	4.0	0.4	4.6	7.8	0.8
NGC 3379	E1	11.2	-20.1	2.0	55	1.0	6.0	1.0	4.0	12.0	1.0
NGC 3384	E5/S0	12.3	-19.8	1.5	25	0.5	4.1	0.4	5.8	7.4	2.2
NGC 4472	E2	17.2	-22.0	8.7	104	0.5	8.0	0.3	4.5	28.5	8.6
NGC 4486	E3/cD	17.0	-21.7	7.8	95	0.5	5.3	0.4	4.8	30.0	4.5
NGC 4494	E1	18.0	-20.7	4.3	49	0.5	3.9	0.4	3.9	5.5	1.7
NGC 4649	E2	15.96	-21.5	7.0	90	1.3	4.8	0.7	6.0	32.8	4.6
NGC 4697	E3	10.5	-20.2	3.4	66	1.0	9.0	?	5.5	9.0	?
NGC 5128	S0	3.84	-21.0	6.6	309	1.0	5.1	1.2	15.1	13.8	3.6
IC 1459	E3	24.2	-20.8	3.9	33	1.0	7.5	2.5	5.0	16.0	2.5

NOTES – Col. (1): Name of the galaxy. Col. (2): Type of the galaxy from HyperLeda catalog. Col. (3): Distance from SBF measurements. Col. (4): Magnitude in the B-band from HyperLeda catalog. Col. (5): Effective radius expressed in kiloparsecs. Col. (6): Effective radius expressed in arcsecs. Col. (7): Inner radius at which the mass-to-light ratio (Υ_{in}) is established. Col. (8): Mass-to-light ratio at r_{in} in the B-band. Col. (9): Error of Υ_{in}. Col. (10): Outer radius at which the mass-to-light ratio (Υ_{out}) is established. Col. (11): Mass-to-light ratio at r_{out} in the B-band. Col. (12): Error of Υ_{out}.

Based on the recent work of Diehl and Statler (2007) the optical and X-ray isophotes for NGC 4649 are very close: for X-rays (based on the CHANDRA observations) ellipticity $\epsilon_X = 0.08 \pm 0.03$ and position angle P.A.$_X = 95 \pm 27$ whereas in the optical domain $\epsilon_{opt} = 0.18 \pm 0.01$ and P.A.$_{opt} = 104.0 \pm 0.4$. This may be interpreted as a support for hydrostatic equilibrium; for NGC 1399 the discrepancy between these two quantities in X-ray and optical domain is much larger: $\epsilon_X = 0.34 \pm 0.04$, $\epsilon_{opt} = 0.10 \pm 0.1$, P.A.$_X = 179 \pm 7$ and P.A.$_{opt} = 107.4 \pm 0.1$. The estimate of the total mass of NGC 1399 based on the X-rays is given in Samurović and Danziger (2006).

All the noted discrepancies (and the physical assumptions which lead to them) must be carefully studied in order to establish correctly mass-to-light profiles in early-type galaxies. Only when these discrepancies vanish will we be able to reach strong conclusions about dark matter in early-type galaxies.

Acknowledgements

This work was supported by the Ministry of Science and Technological Development of the Republic of Serbia through the project no. 146012, "Gaseous and stellar component of galaxies: interaction and evolution".

References

Bahcall, J., Piran, T. and Weinberg, S. (eds.): 2004, Dark Matter in the Universe, second edition, World Scientific Publishing.

Binney, J. J. and Merrifield, M. R.: 1998, Galactic Astronomy, Princeton University Press.

Binney, J. J. and Tremaine, S.: 1987, Galactic Dynamics, Princeton University Press.

Cappellari et al.: 2006, *Mon. Not. R. Astron. Soc.*, **360**, 1126.

Carollo, C. M., de Zeeuw, P. T., van der Marel, R. P., Danziger, I. J. and Qian, E. E.: 1995, *Astrophys. J.*, **441**, L25.

Ciotti, L. and Pellegrini, S.: 2004, *Mon. Not. R. Astron. Soc.*, **350**, 609.

Côté, P., McLaughlin, D. E., Cohen, J. G. and Blakeslee, J. P.: 2003, *Astrophys. J.*, **591**, 850.
De Lorenzi et al.: 2008, *Mon. Not. R. Astron. Soc.*, submitted, preprint `arXiv:0804.3350`
De Rijcke, S., Prugniel, P., Simien, F. and Dejonghe, H.: 2006, *Mon. Not. R. Astron. Soc.*, **369**, 1321.
Dekel, A., Stoehr, F., Mamon, G. A., Cox, T. J. and Primack, J. R.: 2005, *Nature*, **437**, 707.
Diehl, S. and Statler, T. S.: 2007, *Astrophys. J.*, **668**, 150.
Dirsch, B., Richtler, T., Geisler, D., Forte, J. C., Bassino, L. P. and Gieren, W. P.: 2003, *Astron. J.*, **125**, 1908.
Dirsch, B. et al.: 2004, *Astron. J.*, **127**, 2114.
Fukazawa, Y., Botoya-Nonesa, J. G., Pu, J., Ohto, A. and Kawano, N.: 2006, *Astrophys. J.*, **636**, 698.
Gavazzi, R. et al.: 2007, *Astrophys. J.*, **667**, 176.
Grillmair, C. J., Freeman, K. C., Bicknell, G. V., Carter, D., Couch, W. J., Sommer–Larsen, J. and Taylor, K.: 1994, *Astrophys. J.*, **422**, L9.
Hui, X., Ford, H. C., Freeman, K. C., Dopita, M. A.: 1995, *Astrophys. J.*, **449**, 592.
Humphrey, P. J., Buote, D. A., Gastaldello, F., Zappacosta, L., Bullock, J. S., Brighenti, F. and Mathews, W. G.: 2006, *Astrophys. J.*, **646**, 899.
Kim, D.-W. and Fabbiano, G.: 1995, *Astrophys. J.*, **441**, 182.
Kleinheinrich, M., Schneider, P., Erben, T., Schirmer, M., Rix, H-W., Meisenheimer, K. and Wolf, C.: 2003, `preprint astro-ph/0304208`
Kronawitter, A, Saglia, R. P., Gerhard, O. and Bender, R.: 2000, *Astron. Astrophys. Supp.*, **144**, 53.
Méndez, R. H., Teodorescu, A. M., Kudritzki, R.-P. and Burkert, A.: 2008, *Astrophys. J.* in press, preprint `arXiv:0809.5105`
Mould, J. R., Oke, J. B., de Zeeuw, P. T. and Nemec, J. M.: 1990, *Astron. J.*, **99**, 1823.
Napolitano, N. R., Capaccioli, M., Romanowsky, A. J., Douglas, N. G., Merrifield, M. R., Kuijken, K., Arnaboldi, M., Gerhard, O. and Freeman, K. C.: 2005, *Mon. Not. R. Astron. Soc.*, **357**, 691.
Persic, M., Salucci, P. and Stel, F.: 1996, *Mon. Not. R. Astron. Soc.*, **281**, 27.
Pierce, M. et al.: 2006, *Mon. Not. R. Astron. Soc.*, **366**, 1253.
Prada, F. et al: 2003, *Astrophys. J.*, **598**, 260.
Richtler, T. et al.: 2004, *Astron. J.*, **127**, 2094.
Romanowsky, A. J., Douglas, N. G., Arnaboldi, M., Kuijken, K., Merrifield, M. R., Napolitano, N. R., Capaccioli, M. and Freeman, K. C.: 2003, *Science*, **5640**, 1696.
Samurović, S.: 2007a, Dark Matter in Elliptical Galaxies, *Publ. Astron. Obs. Belgrade*, **81**.
Samurović, S.: 2007b, *Serb. Astron. J.*, **174**, 35.
Samurović, S. and Ćirković, M. M.: 2008a, *Astron. Astrophys.*, **488**, 873.
Samurović, S. and Ćirković, M. M.: 2008b, *Serb. Astron. J.*, **177**, 1.
Samurović, S. and Danziger, I. J.: 2005, *Mon. Not. R. Astron. Soc.*, **363**, 769 (SD05).
Samurović, S. and Danziger, I. J.: 2006, *Astron. Astrophys.*, **458**, 79.
Sivakoff, G. R., Sarazin, C. L. and Carlin, J. L.: 2004, *Astrophys. J.*, **617**, 262.
Sluis, A. P. N. and Williams, T. B.: 2006, *Astron. J.*, **131**, 2089.
Sofue, Y. and Rubin, V.: 2001, *Annu. Rev. Astron. Astrophys.*, **39**, 137.
Statler, T., Smecker-Hane, T. and Cecil, G. N: 1996, *Astron. J.*, **111**, 1512.
Teodorescu, A. M. et al.: 2005, *Astrophys. J.*, **635**, 290.
Thomas, J., Saglia, R. P., Bender, R., Thomas, D., Gebhardt, K., Magorrian, J., Corsini, E. M. and Wegner, G.: 2005, *Mon. Not. R. Astron. Soc.*, **360**, 1355.
Tonry, J. L.: 1983, *Astrophys. J.*, **266**, 58.
Treu, T., Koopmans, L. V. E., Sand, D. J., Smith, G. P. and Ellis, R. S: 2004, in the proceedings of IAU Symposium 220 "Dark matter in galaxies", S. Ryder, D. J. Pisano, M. Walker and K. Freeman (eds.), Astronomical Society of the Pacific, 159.
van der Marel, R. P.: 1991, *Mon. Not. R. Astron. Soc.*, **253**, 710.