Elliptical galaxies as gravitational lenses

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ABSTRACT

Following Hjorth & Kneib (1997) we study the properties of a simple density distribution useful for modeling elliptical galaxies acting as gravitational lenses. The model closely corresponds to a model based on a physical scenario of violent relaxation and is analytic in its gravitational lensing properties for any ellipticity in the projected (surface) mass density. Besides the ellipticity, it has one free shape parameter which, for a wide range of values, yields a projected density profile similar to the $R^{1/4}$ law. As an illustration we apply the model to the quadruple lens system HST 14176+5226 in which the lens is an elliptical galaxy at $z = 0.81$. The four lensed images probe the mass distribution out to 1.5 times the half-light radius. We find that no model in which mass follows light is consistent with the observational constraints. Adding a more extended dark halo with a slightly larger ellipticity and a slight misalignment is however capable of reproducing the observed configuration and intensity ratios. This means that the mass-to-light ratio increases with radius. The inferred ellipticity is not nearly as large as that claimed based on models using a singular isothermal sphere for the lens. We predict the central stellar velocity dispersion which in conjunction with the measured effective radius and surface brightness implies a (passive) luminosity evolution of 0.9 ± 0.2 mag since $z = 0.8$ by comparison with the Fundamental Plane for the Coma cluster.

1. Model

The density distribution studied by Hjorth & Kneib (1997) is

$$\rho(r) = \frac{\rho_0}{(1 + r^2/a^2)(1 + r^2/s^2)}; \qquad s > a. \tag{1}$$

This distribution describes a spherical system with scale radius s. In the centre $\rho \approx \rho_0/(1 + r^2/a^2)$ which describes a core (core radius a) with central density ρ_0. The core is not strictly isothermal in which case $\rho \sim (1 + r^2/a^2)^{-3/2}$ (Binney & Tremaine 1987) but in the transition region ($a \lesssim r \lesssim s$) $\rho \sim r^{-2}$ as for the isothermal sphere. In the outer parts the density falls off as $\rho \sim r^{-4}$, as is usually required for elliptical galaxy models (Hjorth & Madsen 1991).

The density distribution can be rewritten as

$$\rho(r) = \frac{\rho_0}{(1 + (\eta\xi)^2)(1 + \xi^2)}; \qquad \eta > 1 \tag{2}$$

with $\xi \equiv r/s$ and $\eta \equiv s/a$. Thus s acts as a scale parameter and η is a shape parameter. An equivalent family of mass models was recently introduced independently by Merritt & Valluri (1996) who used them as a starting point in an investigation of the orbital properties of triaxial stellar systems.

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In its functional form, the proposed model is very similar to other popular analytic models of elliptical galaxies, such as the Jaffe (1983) model, the modified Jaffe model (van Albada, Bertin, & Stiavelli 1995), the Hernquist (1990) model, and the generalisations of the Jaffe and Hernquist models (Dehnen 1993; Tremaine et al. 1994). Each of these models have particular (analytic) advantages and draw-backs, but are in general equally valid for describing elliptical galaxies. The advantage of the model introduced here is that its lens properties are analytically tractable, i.e., the projected gravitational potential and first and second order derivatives can be computed in a straightforward manner.

The projected density is

$$\begin{aligned}\Sigma(R) &= 2\int_R^\infty \frac{\rho(r)r}{\sqrt{r^2-R^2}}\mathrm{d}r \\ &= \Sigma_0 \frac{as}{s-a}\left(\frac{1}{\sqrt{a^2+R^2}} - \frac{1}{\sqrt{s^2+R^2}}\right) \qquad (3)\end{aligned}$$

with

$$\Sigma_0 = \pi\rho_0 \frac{as}{s+a}. \qquad (4)$$

This model is the two-component pseudo-isothermal elliptical mass distribution suggested by Kassiola & Kovner (1993) useful in lensing studies (Kneib et al. 1995, 1996, 1997; Natarajan & Kneib 1997). For a vanishing core radius it reduces to

$$\Sigma(R) = \Sigma_0 \frac{a}{R}\left(1 - \frac{1}{\sqrt{1+s^2/R^2}}\right); \qquad \eta \to \infty \qquad (5)$$

which is the model proposed by Brainerd, Blandford & Smail (1996) for modeling galaxy-galaxy lensing. In this special case, a becomes a simple amplitude scaling parameter and s is the half-mass radius, r_h.

In Fig. 1 we show that for $\eta = 10, 200, \infty$ excellent fits to the $R^{1/4}$ law are obtained. The residuals from the $R^{1/4}$ law are very similar to the model proposed by Hjorth & Madsen (1991) based on violent relaxation. In general the scaling parameter s is related to the half-mass radius, R_e, by $R_e \approx 3s/4$.

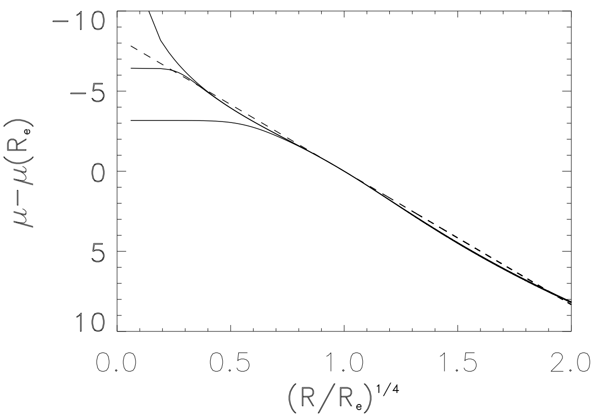

Fig. 1.— Surface-brightness profile ($\mu(R) \equiv -2.5\log\Sigma(R)$) for the model given by eq. (2) for $\eta = 10, 200, \infty$ (solid curves) compared to the $R^{1/4}$ law (dashed curve).

2. Elliptical surface mass distribution and gravitational lensing

An elliptical projected mass distribution with ellipticity $\epsilon \equiv (A-B)/(A+B)$, where A and B are the semi major and minor axes respectively, can be introduced by substituting $R \to \tilde{R}$, with

$$\tilde{R}^2 = \frac{X^2}{(1+\epsilon)^2} + \frac{Y^2}{(1-\epsilon)^2}, \tag{6}$$

where X and Y are the spatial coordinates along the major and minor projected axes, respectively. With this definition of the ellipticity, the quantity $e \equiv 1 - B/A$ is related to ϵ through $e = 2\epsilon/(1+\epsilon)$. The main advantage of the class of elliptical mass distributions introduced by Kassiola & Kovner (1993),

$$\Sigma = \Sigma_0 \left(1 + \frac{\tilde{R}^2}{a^2}\right)^{-\nu} ; \quad \nu = 1/2 \times \mathrm{j}; \quad \mathrm{j} \in \mathcal{N}, \tag{7}$$

(and thus $\Sigma(\tilde{R})$ discussed in this paper) is that the potential as well as its first and second partial derivatives can be expressed analytically to derive deflections, time delays etc. for *any* ellipticity.

3. Application: Modeling the lens HST 14176+5226=CFRS 14.1311

3.1. Observations of the GL system

To illustrate one possible use of our suggested surface-mass distribution we model the quadruple gravitational lens system HST 14176+5226 (Ratnatunga et al. 1995). The lens is an elliptical galaxy at $z_l = 0.81$ and the source is presumably a blue $z_s = 3.4$ AGN (Crampton et al. 1996). In the F814W band the ellipticity is $e = 0.32 \pm 0.01$ ($\epsilon = 0.19 \pm 0.01$). The effective radius has been determined to $1''.200$ (Ratnatunga et al. 1995), compared to the Einstein radius of $1''.6$.

We have performed aperture photometry and profile fitting of the galaxy. Applying the long exposure-time correction (Hill et al. 1997) we find $I_C = 19.64$ (which translates into $M_B = -23.08$ or a luminosity of $L_B/L_{B\odot} = 2.5 \cdot 10^{11}$) and a half-light radius $R_e = 1''.23$ in very good agreement with Ratnatunga et al. (1995).

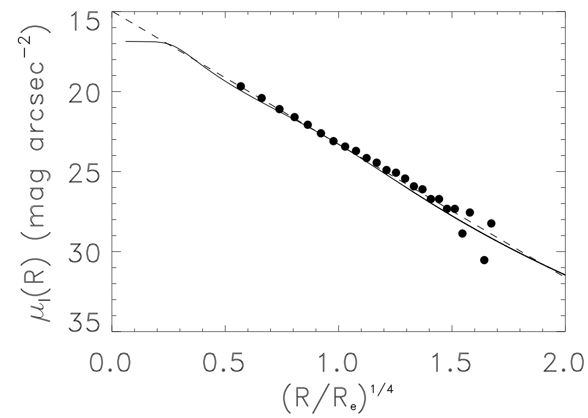

Fig. 2.— Surface-brightness profile for HST14176+5226 with the $R^{1/4}$ law (dashed line) and the $\eta = 200$ model (solid curve) overplotted.

The surface-brightness profile is shown in Fig. 2 and is well-fit by an $R^{1/4}$ law as well as an $\eta = 200$ model. We may thus test whether mass follows light in this galaxy using our model.

3.2. Lens modeling

Following the precepts of Kneib (1993) and Kneib et al. (1996) we will try here to model the mass distribution of this GL system in a consistent way to take into account all the available constraints. Namely, we have 4 image positions and intensity ratios, the position of the lens, its ellipticity, its orientation and its surface brightness profile, which can be converted into a stellar mass profile assuming a typical E galaxy and a constant mass-to-light ratio with radius. Using our model it can be parametrised with the following set of parameters: $e = 0.37 \pm 0.02$, $\theta_0 = 53.8 \pm 2$, $a = 0.07$ kpc, $s = 13.5$ kpc, $R_e = 1.''23$.

By only changing the M/L ratio of the stars it is found that *no* model can reproduce the image positions and intensities of the 4 images – even when allowing for the observed uncertainties in the parameters and observables. This clearly demonstrates *the existence of an extra matter component in this system that does not follow the light profile.*

We then try to model the mass of this system by the sum of the stellar mass and the dark mass. We find that the orientation and ellipticity of the matter distribution is consistent with the geometrical distribution of the light, except for a ∼10 deg misalignment, but the ellipticity is not much larger than the ellipticity of the light (which was not the case in the Ratnatunga et al. (1995) model). However *the profiles of the luminous and dark matter are distinct.* The dark matter is more extended. The mass distribution is well constrained at the location of the multiple images and somewhat model dependent elsewhere (very central part and outer part). We see that the dark matter is more extended than the light, and that the mass-to-light ratio increases with radius. Thus we have detected a significant amount of dark matter out to a radius of 1.5 R_e. This result is in agreement with Kochanek's (1995) evidence for dark matter in MG 1654+134 at a radius of about 0.6 R_e.

3.3. Stellar velocity dispersion and the Fundamental Plane

By building a consistent model, we can now derive the stellar velocity dispersion of the E lens galaxy. Making the simplifying assumption that the velocity tensor is isotropic, the stellar line of sight velocity dispersion of the stars σ_{P*} is computed as

$$\sigma^2_{P*}(R) = \frac{2G}{\Sigma_*(R)} \int_R^\infty \frac{M_{*+\mathrm{dark}}(r)\rho_*(r)}{r^2} \sqrt{r^2 - R^2}\mathrm{d}r. \tag{8}$$

Using this velocity dispersion, the effective surface brightness and radius we can compare with the Fundamental Plane (FP) at Coma (Jørgensen, Franx, & Kjærgaard 1993),

$$\log R_e = 1.203 \log \sigma + 0.352 \langle \mu_B \rangle_e - 9.310. \tag{9}$$

Taking out the surface-brightness dimming we find that the galaxy is brighter by 0.89 mag relative to Coma ($z = 0.024$). The uncertainty in this value is a combination of uncertainty in σ (10 %), intrinsic uncertainty in the FP (0.16 mag), and photometric calibration of the magnitude of the galaxy (0.1 mag). We thus find passive evolution of 0.9 ± 0.2 mag since $z = 0.8$ from one E lens galaxy. This is consistent with the findings of Schade, Barrientos, & López-Cruz (1997) ($\Delta\mu \approx -z$ for cluster and field E's) but slightly on the high side compared to the FP studies in Gunn r of Jørgensen et al. (1997).

4. Discussion and conclusion

The model studied in this paper is essentially motivated by the observed light profiles of elliptical galaxies, but also by theoretical considerations of violent relaxation scenarios for self-gravitating systems in general. While $R^{1/4}$ law models with elliptical potentials have previously been used to model E galaxies this is the first to accommodate any ellipticity.

The first test in applications to individual E galaxy lenses is to see if mass follows light, i.e., if the observed distribution of light is able to produce the observed lensing profile. We have used this to present the first direct evidence from lensing that mass does not follow light in an isolated E galaxy. This is also shown to be the case for the E lens galaxy of UM673 (Hjorth, Kneib, & Jørgensen 1997). Kochanek (1995) reached a similar conclusion in MG 1654+134 but in this system the light profile of the galaxy was not used. Likewise, Falco, Lehár, & Shapiro (1997) in their models of the lens in MG0414+0534 did not model the system with an $R^{1/4}$ law and furthermore did not know the redshift of lens.

As in the case of HST14176+5226 discussed in this paper, the model may also be a good description of the dark-matter halo based on theoretical considerations (Hjorth & Madsen 1991) and numerical simulations where it it shown that dark-matter halos are well-described by the Hernquist profile (Cole & Lacey 1996) which is similar to this model and E galaxy light profiles.

We find that the dark halo of HST14176+5226 compared the the luminous matter is (i) slightly more elliptical ($e = 0.42$ vs. 0.32) (ii) misaligned by 9 degrees and (iii) more extended. These results are consistent with the findings of Buote & Canizares (1994,1996,1997) for NGC 720 and with the current picture of formation of E galaxies in triaxial dark matter halos based on numerical simulations (Dubinski 1994; Warren et al. 1992) in which the extended dark matter halos are on average more elliptical than observed galaxies and the misalignment is a results of the triaxial shape of the dark halo.

The fact that this model, which is more faithful to observations and theory than the isothermal sphere models, yields much more physically plausible results, shows that the use of isothermal sphere models for elliptical galaxies may be an oversimplified description. In particular we do not find the very flattened DM distributions usually inferred, also in the case of HST14176+5226 (Ratnatunga et al. 1995).

Finally, we have shown that one lens provides a very accurate constraint on galaxy evolution by establishing the highest redshift FP (Jørgensen et al. 1997).

The numbers presented in this contribution are preliminary. The final numbers can be found in Hjorth & Kneib (1997) along with a more detailed account of this work.

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