NGC 5128 AS AN ISOTROPIC ROTATOR

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ABSTRACT

NGC 5128 is a well-studied elliptical galaxy with an excellent kinematic data set for planetary nebulae which has been modelled up till now only by solving the Jeans equation for spherical systems. As a first approximation beyond spherical symmetry we model the galaxy as an axisymmetric system flattened by rotation with isotropic velocity distribution. We propose a new version of such an isotropic rotator having cuspy density profile with NFW-like behavior. The solutions of the Jeans equations for a single component of such form do not reproduce the data well: the rotation curve rises too slowly with radius and the velocity dispersion profile drops too fast. The data are well fitted however by a system built with two components: a more compact, flattened, less massive, fast-rotating and cold ‘bulge’ and an extended, almost spherical, more massive, slow-rotating and hot ‘halo’. This picture agrees well with the results of recent N-body simulations of galaxy mergers which tend to produce oblate rotating spheroids. The total mass of the system is estimated to be $(9.1 \pm 3.5) \times 10^{11}$ solar masses and the mass-to-light ratio is only $26 \pm 17$ solar units.

Subject headings: methods: data analysis – galaxies: elliptical and lenticular, cD – galaxies: individual (NGC 5128) – galaxies: fundamental parameters – galaxies: kinematics and dynamics – dark matter

1. INTRODUCTION

NGC 5128 (Centaurus A) is a well-studied nearby elliptical galaxy (for a review see Israel 1998) with an excellent kinematic data set of 780 planetary nebulae (PNe) with measured velocities (Peng, Ford, & Freeman 2004). The data extend out to about 16 effective radii allowing us to probe the dynamics of the galaxy not only in the usual inner part but well beyond the distribution of light. Peng et al. found that the zero velocity curve deduced from the data departs from the minor axis and concluded that the galaxy must be triaxial. However, they modelled the PNe kinematics only via the spherical Jeans equation.

Since the rotation is much stronger along the major axis than the minor axis it is reasonable to consider, as a first approximation beyond spherical symmetry, an axisymmetric model in which the galaxy is an oblate spheroid flattened by rotation. This conjecture is strongly supported by the results of recent simulations of dissipational mergers of disks where oblate systems are the most frequent outcomes (Cox et al. 2006). In addition, the observed rotation along the minor axis could be at least in part due to contamination from a merger remnant (now visible as the spectacular dust lane and gas ring along the minor axis of the galaxy) with its own population of PNe not in equilibrium with the rest of the galaxy (Sparke 1996). The measured kinematics of both neutral (Schiminovich et al. 1994) and ionized (Bland, Taylor, & Atherton 1987) hydrogen in this region shows that the NW side of the ring is approaching while the SE one is receding, like the PNe along the minor axis.

A number of analytic potential-density pairs for axisymmetric systems can be found in the literature. Miyamoto & Nagai (1975) and Satoh (1980) proposed a family of generalized Plummer models that can describe axisymmetric galactic systems with a combination of random motions and rotation. The disadvantage of these models is that their density distributions possess cores and therefore are unlikely to reproduce well the density profiles of elliptical galaxies (Mamon & Loks 2005a, b). Other models that could be generated from the well-known potentials by rescaling the cylindrical coordinates tend to produce non-physical negative densities along the rotation axis (Binney & Tremaine 1987).

In this work we propose a new potential generating a cuspy axisymmetric density distribution with an NFW-like (Navarro, Frenk, & White 1997) asymptotic behavior. We use this model in solving the Jeans equations assuming isotropic velocity distribution and finding the projected rotation velocity and dispersion profiles. The solutions are then fitted to the data for PNe in NGC 5128. The new model allows us to consider for the first time different inclinations and flattenings and constrain the mass of the galaxy without the assumption of spherical symmetry.

2. A NEW ISOTROPIC ROTATOR

We propose to approximate the (positive) axisymmetric potential of the galaxy with a formula

$$\Phi(R, z) = \frac{GM}{b + (1/2)f_1 + (1/2)f_2}$$

with

$$f_1(R, z) = (R^2 + z^2)^{1/2}$$

$$f_2(R, z, a, b) = \{R^2 + [a + (b^2 + z^2)^{1/2}]^2\}^{1/2}$$

where $R$ and $z$ are the standard cylindrical coordinates, $M$ is the total mass of the system, while $a$ and $b$ are constants with the dimension of length. The form of the potential was motivated on one hand by the Hernquist (1990) model and on the other by the way suggested by Miyamoto & Nagai (1975) and Satoh (1980) to flatten Plummer potentials. The formula for the density distribution following from the potential \( \Phi \) via the Poisson
Jeans equations (Binney & Tremaine 1987) \[ \text{w mean rotational velocity and velocity dispersion are then line of sight. The projected surface density distribution, angle between the equatorial plane of the galaxy and the major axis of the galaxy, Y centered on the models with b/a \approx 1 are flattened, fast rotators with little random motion (spiral galaxies), while those with b/a \gg 1 are almost spherical systems dominated by random motions with little rotation (elliptical galaxies). An interesting intermediate case is when b/a is of the order of a few; such systems are only moderately flattened and possess similar amount of random and ordered motion.}

We denote the velocities along the three cylindrical coordinates R, \( \theta \) and \( z \) respectively by \( u = v_R \), \( v = v_\theta \) and \( w = v_z \). Their variances are related by the set of Jeans equations (Binney & Tremaine 1987)

\[
\frac{\partial}{\partial R}(\rho(u^2)) + \frac{1}{R}(\rho(\langle u^2 \rangle - \rho(v^2))) = \rho\frac{\partial}{\partial R}\Phi \tag{2}
\]

\[
\frac{\partial}{\partial z}(\rho(w^2)) = \rho\frac{\partial}{\partial z}\Phi. \tag{3}
\]

We assume that the only streaming motion in the galaxy is the rotation so \( \langle u \rangle = \langle w \rangle = 0 \), \( \langle v \rangle \neq 0 \) and the residual velocity components around the mean are isotropic everywhere in the system: \( \langle u^2 \rangle = \langle w^2 \rangle = \langle v^2 \rangle - \langle v \rangle^2 \).

For comparison with observations the quantities discussed above have to be projected along the line of sight and on the plane of the sky. We express the projected quantities in terms of Cartesian coordinates \( X, Y \) and \( L \) centered on the models with \( X \)-axis along the projected major axis of the galaxy, \( Y \) along the minor axis, and \( L \) along the line of sight. The inclination angle \( i \) is the angle between the equatorial plane of the galaxy and the line of sight. The projected surface density distribution, mean rotational velocity and velocity dispersion are then given respectively by

\[
\mu(X,Y) = \int_{-\infty}^{+\infty} \rho \ dL \tag{4}
\]
\[
V(X,Y) = \frac{1}{\mu} \int_{-\infty}^{+\infty} \nu \rho(\nu) \ dL \tag{5}
\]
\[
\sigma^2(X,Y) = \frac{1}{\mu} \int_{-\infty}^{+\infty} \rho(w^2) \ dL \tag{6}
\]

where \( \nu = X \cos i/[X^2 + (Y \sin i - L \cos i)^2]^{1/2} \) is the direction cosine.

3. THE DATA

The data comprise 780 spectroscopically confirmed PNe from Peng et al. (2004, including the earlier data set of Hui et al. 1995) with positions and velocities measured with high accuracy so that the velocity errors can be neglected in the further analysis. Plots of velocities versus positions do not show any outliers which suggests that the data set is not contaminated by any background or neighboring systems and all PNe can be considered as members of the galaxy.

The data were transformed using the symmetries of the axisymmetric system so that all PNe have positive \( X, Y \) positions. It was assumed that the minor axis of the optical image of the galaxy is the projected rotation axis and the major axis has \( PA = 35^\circ \) (Dufour et al. 1979). The PNe were then ordered by their position along the major axis (\( X \)) and binned with \( n = 78 \) objects per bin. This resulted in 10 data points for both line-of-sight rotation velocity and dispersion at mean \( (X,Y) \) values in the bin. The dispersions \( \sigma \) were estimated using the standard unbiased estimator and assigned sampling errors of size \( \sigma/\sqrt{2(n-1)} \). The mean velocities were assigned standard errors of the mean \( \sigma/\sqrt{n} \). The velocity moments estimated from the data are plotted in Figure 1 as a function of \( X \). The moments are measured close to the major axis since mean \( Y < s' \) for all ten data points.

The velocity dispersion profile presented in Figure 1 shows remarkable similarity to those of regular clusters of galaxies (e.g. Lokas & Mamon 2003; Lokas et al. 2006; Wojtak & Lokas 2007) and theoretical predictions for objects with NFW-like density distributions and isotropic orbits (Lokas & Mamon 2001). The situation with rotation velocity is less clear: the innermost point falls well below zero velocity expected in the center, which we suspect to be due to the contamination from the dust lane-related merger remnant.

4. THE MODELS

The data shown in Figure 1 were fitted with the projected solutions of the Jeans equations (5)-(6) assuming
that the potential in the galaxy is given by formula (1) and the density follows from it via Poisson equation. Our approach here is rather unorthodox compared e.g. to Binney, Davies, & Illingworth (1990) where the distribution of light was used to constrain potential. However, since population gradients are present in the galaxy it is not obvious that mass follows light in this component. In addition, the distribution of light in NGC 5128 is difficult to estimate along the minor axis where it is obscured by the prominent dust lane. We therefore proceed as if no information was available on the stellar mass. In principle, the density \( \rho \) in equations (2)-(6) refers to the tracer (PNe) whose kinematics we study. We do not estimate it from the distribution of PNe since their number is low and sampling not uniform, it does not have to follow the light either. In any case, the distribution of the tracer is not critical to the modelling because it partially cancels out due to the way it enters equations (1)-(6). For simplicity we suppose here that PNe follow the total density.

Both rotation velocity and dispersion data can be fitted simultaneously by simple \( \chi^2 \) minimization since they are very weakly correlated (as can be shown by Monte Carlo sampling from nearly Gaussian distributions analogous to the one described by Lokas & Mamon 2003). The adopted distance to the galaxy was \( D = 3.84 \pm 0.35 \) Mpc (Rejkuba 2004) so that \( i' \) corresponds to 1.12 kpc.

In the case of single-component models the best fit with \( \chi^2/N = 25.9/16 \) is found for \( i = 30^\circ \) (with \( i = 0^\circ \) corresponding to the edge-on view), but similar quality fits are found for a wide range of inclinations, only the ratio \( b/a \) of the best-fitting parameters decreases systematically with inclination, since the galaxy then has to have more rotation to make up for the projection effects.

The best-fitting solutions for \( V \) and \( \sigma \) corresponding to the \( i = 30^\circ \) case with \( a = 4.4', \) \( b = 10.0' \) and \( M = 7.3 \times 10^{11} \) M\(_\odot \) are plotted in Figure 1 as dashed lines. The quality of the fits is not satisfactory, the best solution for the rotation velocity rises too slowly with radius and the dispersion profile drops too fast. In addition, when the data for rotation velocity and dispersion are fitted separately good fits are obtained, but for rather different parameter values. While the rotation curve is well reproduced by a low-mass model with \( b/a \approx 1 \), the dispersion profile needs higher mass and \( b/a \gg 1 \). It is therefore reasonable to expect that both data sets would be better reproduced by two-component models.

In the case of two-component models the first component is parametrized by the scalelengths \( a, b \) and the total mass \( M = M_1 \), the second by analogous quantities \( c, d \) and \( M_2 \). The parameters of the best-fitting models for different inclinations are listed in Table 1. The quality of the fits is now acceptable (\( \chi^2/N > 1 \) only because of the discrepant inner-most velocity data point). Again the \( b/a \) ratio decreases with growing inclination and similar quality fits are obtained for a wide range of inclinations.

The best fit with \( \chi^2/N = 17.3/13 \) is found for \( i = 50^\circ \). The solutions for this case are plotted in Figure 2 (as solid lines). The density profiles of the two components and the total density distribution are compared in Figure 3. The surface distribution \( \mu(X,Y) \) of both components is presented in Figure 4. The picture emerging from these results is that the velocity distribution of PNe in NGC 5128 can be well reproduced by a more compact, less massive and faster rotating flattened component with \( b/a \approx 1 \) together with a more extended, more massive and slowly rotating almost spherical component with \( d/c \approx 1 \). The compact component contributes mostly to the inner part of the rotation curve while its contribution to the dispersion is small. On the other hand, the extended component contributes to the rotation mostly in the outer parts but dominates in the dispersion. The two components can be interpreted as the traditional stellar bulge and dark matter halo in elliptical galaxies. The comparison between the surface density distribution of the more compact component and the light distribution in NGC 5128 (Dufour et al. 1979) shows that the latter (well approximated by the de Vaucouleurs profile with an effective radius of 5') is somewhat less extended, especially along the major axis. Note that the results do not change significantly if we assume that only one (the more compact) instead of both components contribute to the tracer.

The best-fitting total mass of both components is \( M = M_1 + M_2 = (9.1 \pm 3.5) \times 10^{11} \) M\(_\odot \) where the 1\( \sigma \)

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**Table 1**

| \( i \) | \( a \) | \( b \) | \( M_1 \) | \( c \) | \( d \) | \( M_2 \) | \( \chi^2/N \) |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 0   | 2.2 | 2.7 | 1.1 | 2.2 | 3.7 | 8.2 | 19/13 |
| 10  | 2.5 | 4.0 | 1.4 | 1.2 | 15.7 | 7.8 | 18/13 |
| 20  | 2.8 | 4.1 | 1.5 | 1.6 | 15.5 | 7.6 | 18/13 |
| 30  | 3.9 | 4.3 | 1.5 | 1.1 | 15.2 | 7.4 | 17/13 |
| 40  | 5.3 | 4.1 | 1.6 | 1.1 | 14.9 | 7.3 | 17/13 |
| 50  | 8.0 | 3.4 | 1.7 | 1.6 | 14.3 | 7.4 | 17/13 |
| 60  | 9.2 | 2.8 | 0.3 | 2.7 | 11.1 | 9.1 | 18/13 |
| 70  | 9.2 | 1.9 | 0.0 | 10.2 | 7.6 | 10.1 | 21/13 |

**Note.** — The inclination \( i \) is in degrees, the scalelengths \( a, b, c \) and \( d \) in arcmin and the masses \( M_1 \) and \( M_2 \) in \( 10^{11} \) M\(_\odot \).
error (dominated by the sampling errors of velocity moments) was estimated from the $\Delta \chi^2$ statistics by Monte Carlo sampling of the parameter space and marginalizing over the remaining parameters. Adopting the luminosity of the galaxy (de Vaucouleurs et al. 1991) $L_V = (3.45 \pm 0.88) \times 10^{10} L_\odot$ (where the 1σ error includes the error in the estimate of the total apparent brightness as well as the distance) we get the mass-to-light ratio $M/L = 26.3 \pm 16.9 M_\odot/L_\odot$. The mass-to-light ratio for the more compact component is a few times lower, $M/L = 4.9 M_\odot/L_\odot$, consistent with stellar values, which confirms that this component indeed corresponds to the light distribution in the galaxy.

Our mass and $M/L$ estimates are somewhat larger than those found by Peng et al. (2004) by solving the Jeans equation for spherical systems. Within 80 kpc Peng et al. estimate the total mass to be $5-6 \times 10^{11} M_\odot$ while at the same distance we find $M = 6.6 \times 10^{11} M_\odot$. The values agree within our mass error which was found to be larger than 30 percent.

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5. CONCLUSIONS

The total mass-to-light ratio estimated here is rather low, in concordance with the results claiming the dearth of dark matter by Romanowsky et al. (2003), but in disagreement with the high $M/L$ values found from the analysis of dispersion profiles of satellites of isolated elliptical galaxies by Prada et al. (2003) and the results of N-body simulations (e.g. Marinoni & Hudson 2002). As discussed by Mamon & Lokas (2005b) and Dekel et al. (2005) the disagreement can be weakened by considering radially anisotropic, tidally affected stellar orbits and different density profiles. Note however, that the results of Romanowsky et al. as well as and the proposed remedies were based on or trying to explain the velocity dispersion profiles of PNe strongly decreasing with radius, while in NGC 5128 the dispersion decreases in the outermost bin by no more than 30 percent with respect to the central value.

The new analysis of the PNe data for NGC 5128 in the framework of axisymmetric systems presented here points to the existence of a flattened, rotating component whose mass distribution follows the light distribution in the galaxy except for the equatorial plane where it is more extended. The need for the presence of such a disk-like component in elliptical galaxies to explain their line-of-sight velocity distribution has been postulated by Naab & Burkert (2001) based on N-body simulations of mergers. The model of NGC 5128 proposed here provides further evidence for the extended rotating component in elliptical galaxies.

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