Dark Matter in Elliptical Galaxies: breaking the anisotropy-potential degeneracy.

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Abstract. We have addressed the problem of the anisotropy-potential degeneracy by constructing a large number of spherical models with self-consistent (Jaffe) and dark halo (logarithmic) potentials, based on distribution functions producing a variety of anisotropy profiles. We have used these models to analyze the velocity dispersion and h_4 profiles of the E0 galaxy NGC 6703, showing that self-consistent, constant M/L ratio models give significantly worse fits to both profiles than models with a dark halo. The anisotropy and the gravitational potential of a spherical galaxy can be estimated by a simple "recipe" method from the measured logarithmic derivative of the velocity dispersion and h_4 profiles. Data for a sample of bright round ellipticals indicate that anisotropy is low and that dark matter is not yet dominant inside $R \approx 2R_e$.

1. Introduction

As discussed in Saglia et al. (this volume), the study of the dynamics of elliptical galaxies is complicated by many problems: the unknown geometry and the related projection effects, the lack of cold gas as kinematical tracer, the unknown stellar orbital structure. In the following we discuss one of these problems: the anisotropy-potential degeneracy. When modeled with the Jeans equations, the projected stellar velocity dispersion σ of a spherical galaxy can be fit by different choices of orbital structure and gravitational potential. The central increase of σ of the galaxy M87 can be interpreted as evidence for the presence of a black hole with an isotropic stellar orbital structure, or, alternatively, as a strong increase of radial orbits in the self-consistent potential of the galaxy (Binney & Mamon 1982). The flat σ profiles in the outer parts of giant ellipticals can indicate the presence of a massive diffuse dark halo with isotropic or radial orbital structure, or, alternatively, they can be reproduced with a constant mass-to-light ratio and an increasingly tangential velocity dispersion tensor (Saglia et al. 1993).

This degeneracy can be broken with the measurement of the line-of-sight velocity distributions (LOSVDs; Gerhard 1993, Merritt 1993). For example, if radial orbits are causing the central increase of σ in M87, one expects to measure flat-top LOSVDs in the very center, where projected large velocities can be seen, and pointed LOSVDs outside the center, where radial orbits project to low velocities. If tangential orbits are causing the flat σ profiles of the outer regions of bright ellipticals, one should measure double-peaked or flat-top LOSVDs, resulting from the superposition of the two streams rotating in opposite direction. One useful way to parametrize the shapes of the LOSVDs is the Hermite decomposition (van der Marel & Franx, Gerhard 1993), where the symmetric deviations from a gaussian profile are measured by the amplitude of the fourth order terms h_4. LOSVD shapes have been measured with good accuracy out to $0.5R_e$ for a large number of galaxies (Bender, Saglia & Gerhard 1994). Data reaching larger radii ($R \approx 2-3R_e$) are now being accumulated by Carollo et al. 1995, Statler, Smecker-Hane & Cecil 1996, Rix (this book) and ourselves.

In this line of research, we have developed a set of theoretical tools (Jeske 1995, Gerhard et al. 1996, Jeske et al. 1996) and started an observational program (Saglia et al. 1996) to investigate the problem of dark matter in elliptical galaxies and their orbital structure. In the following we present some first results. In Sect. 2. we describe the survey of spherical models we have constructed to cover the variety of anisotropy profiles of (round) ellipticals. In Sect. 3. we show the result of fitting these models to data for NGC 6703. In Sect. 4. we describe a "recipe" approach to estimate the anisotropy and the potential of a round elliptical. In Sect. 5. we draw our conclusions.

2. A survey of spherical models

We constructed a database of ≈ 1000 spherical non-rotating models based on quasi-separable distribution functions $f(E,L) = g(E)h(x)$ (Gerhard 1991), complemented with some models of the Osipkov (1979) and Merritt (1985) family. We tested a number of *circularity functions* $h(x)$, where $x = L/(L_0 + L_c(E))$ is the *circularity*, E is the energy, L is the total angular momentum, $L_c(E)$ the angular momentum of the circular orbits of energy E and L_0 is a scaling parameter. This allowed us to derive a large variety of anisotropy profiles β, from extreme tangentially to extreme radially anisotropic and cover the possible variety present in elliptical galaxies (Fig. 1). The function $g(E)$ was determined using the Lucy (1974) - Richardson (1972) algorithm, by requiring that the model density $\rho = \int f d^3v$ followed the Jaffe (1983) density profile. The models were computed in the self-consistent Jaffe potential and in the logarithmic potential of a dark halo. The line-of-sight velocity distributions (LOSVDs) were computed as a function of the projected radial distance, decomposed in Hermite polynomials and used to determine the projected velocity dispersion σ and h_4 profiles. A full discussion of the models and the computation technique can be found in Gerhard (1991), Jeske (1995) and Gerhard et al. (1996).

3. The case of NGC 6703

We observed the E0 galaxy NGC 6703 with the 3.5 telescope of Calar Alto and the Boller & Chivens longslit twin spectrograph with a 36 Å/mm grating, a Tektronix CCD with 1024×1024 24 μm pixels and the wavelength range 4760-5640 Å. The instrumental resolution obtained using a $3.6''$ wide slit was 85 km/s. We collected 1.5 hrs of observations along the major axis and 16 hrs

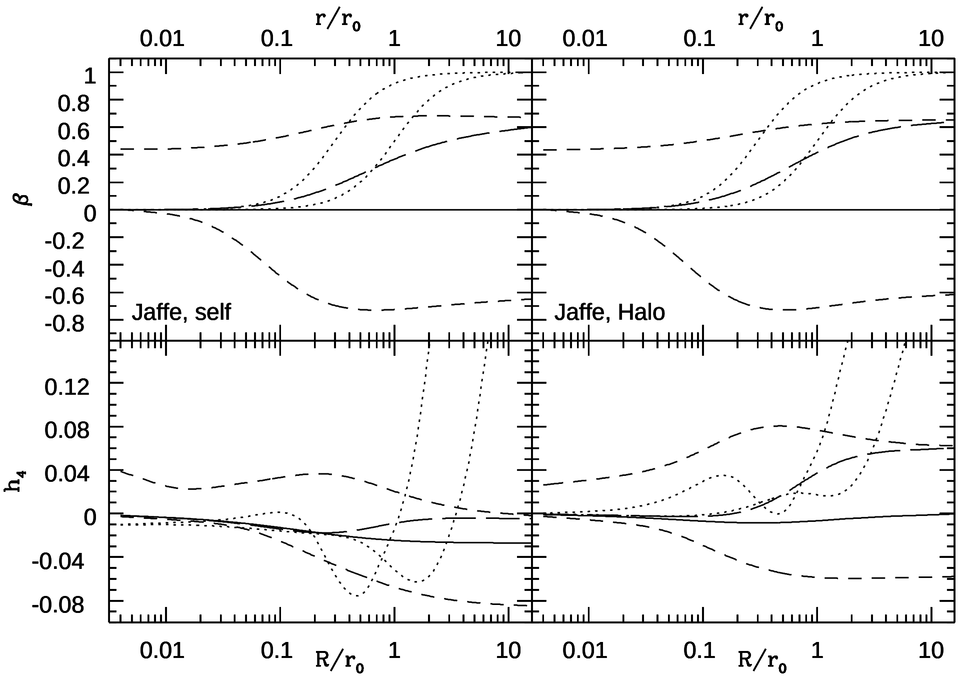

Figure 1. Anisotropy parameter β and the LOSVD parameter h_4 for representative Jaffe models (dashed lines) in self-consistent (left) and halo (right) potentials. The isotropic model (solid) and two Osipkov-Merritt models (dotted lines) are also shown.

perpendicular to the major axis and shifted from the center. The analysis of the data was carried out following the steps described by Bender, Saglia & Gerhard (1994).

We fitted the photometry, the velocity dispersion and h_4 profiles using the set of models described in Sect. 2.. Fig. 2 shows the results. Even though the galaxy shows a rather fast declining velocity dispersion profile, the self-consistent model gives a significantly worse fit than the model with a dark halo. The halo model shown in Fig. 2 gives $M = 1.5 \times 10^{11} M_\odot$ inside $R = 79'' = 13.8$ kpc (D=36 Mpc with $H_0 = 50$ km/s/Mpc), with $M/L_B = 5.8 M_\odot/L_\odot$, a factor 1.7 larger than what is found for the self-consistent case. Dark halo models with masses from $\approx 20\%$ smaller to $\approx 30\%$ larger can also fit the data. The anisotropy profile derived from the fit is mildly radial for $R \leq 50''$ and is less determined in the outer parts (see discussion in Gerhard et al. 1996).

Data of similar quality have been collected for a sample of 15 bright round elliptical galaxies using the Calar Alto 3.5m telescope and the NTT at ESO and are now under analysis (Saglia et al 1996).

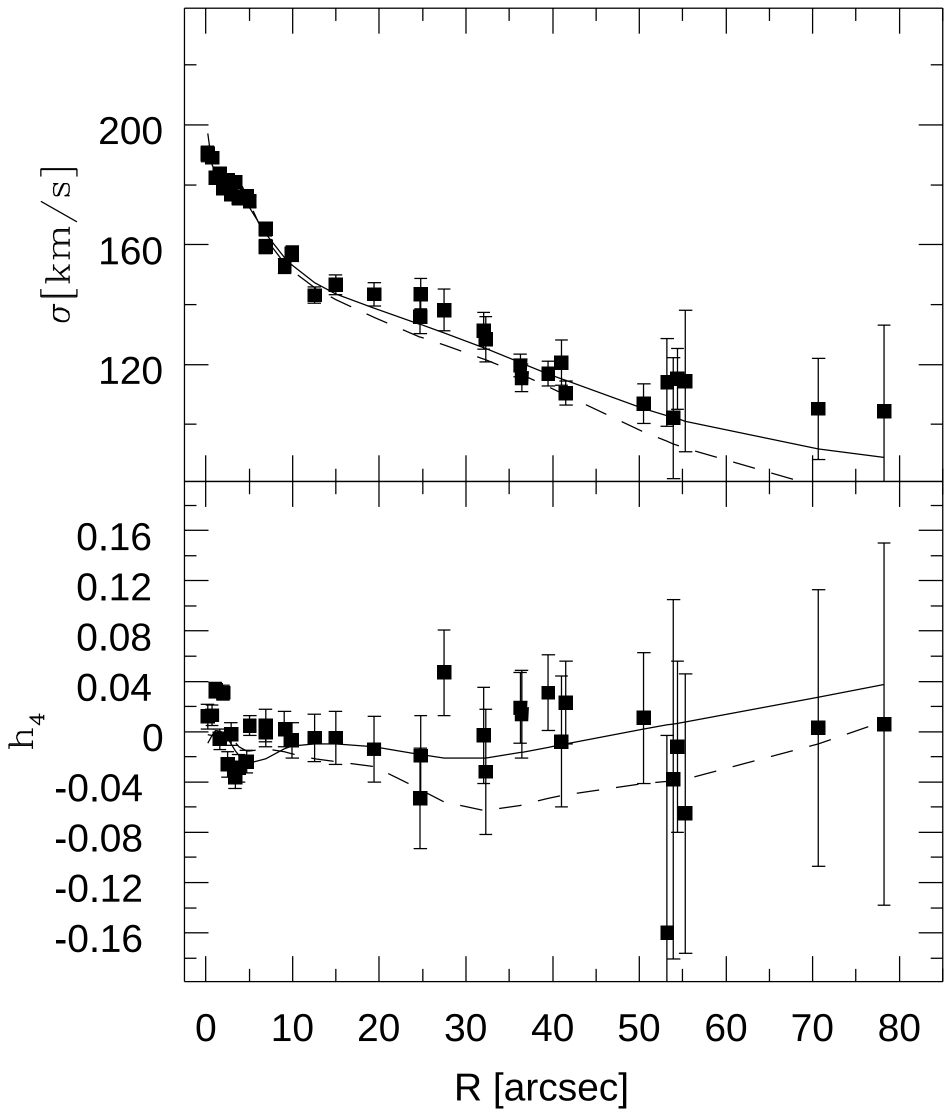

Figure 2. Dynamical models (full line: a model with a dark matter halo, dashed line: a self-consistent model) for the kinematics of NGC 6703, compared to projected σ and h_4 profiles (squares with error bars).

4. A recipe to derive β and Φ

Using the database described in Sect. 2., we constructed the contours of constant anisotropy β at given projected radius R/R_e as a function of the h_4 value and of the logarithmic derivative of the projected velocity dispersion $\xi = d\ln\sigma^2/d\ln r$ (Jeske 1995). These plots can be used to derive simple mass estimates for round galaxies where h_4 and ξ profiles have been measured as follows. One can approximate the projected luminosity density $I(R)$ and velocity dispersion profiles $\sigma(R)$ of a round elliptical locally as power laws: $I \sim R^{-q}$ and $\sigma \sim R^{-s}$, with $s = \xi/2$. Writing down the Jeans' equations, one finds that the mass inside of the sphere of radius R can be expressed as $M(R) = f(q,s,\beta)R\sigma^2(R)/G$, with $f(q,s,\beta) = \frac{q+s+1-2\beta}{1-\beta(q+s)/(q+s+1)}\frac{\Gamma((q+s+1)/2)\Gamma(q/2)}{\Gamma((q+s)/2)\Gamma((q+1)/2)}$ (Jeske et al. 1996). From the contour diagrams, at each radius one can derive two estimates of $\beta(r)$ and thus $M(R)$, one for the self-consistent and the other for the halo case. The comparison with the radial dependence predicted in the two cases allows one to check which of the two potentials describes the galaxy best.

We applied this procedure to a sample of 12 round ellipticals (Saglia et al. 1996), where we measured σ and h_4 profiles out to $R \approx 2R_e$. Mean σ, h_4 and ξ profiles were derived scaling the σ to the central values and the radii with R_e (Fig. 3, top left and right plots). Using the relation between h_4 and the mean derived gradient ξ (Fig. 3, bottom left), the plots in Jeske (1995) and the above equation, we estimated the (dimensionless) mass inside $1, 1.5, 2R_e$ in the halo and in the self-consistent potential and compared it to the expected radial dependence in the two cases (Fig. 3, bottom right).

Within the error bars the derived masses in the self-consistent case fall on top of the dotted curve representing the expected radial mass profile. The derived masses in the halo potential fit the corresponding mass profile (full line) less well, but – given the error bars – are also not far off. We conclude from this that dark matter is not yet dominating the dynamics inside $\approx 2R_e$. Fig. 3, bottom left, also implies a nearly isotropic orbital structure, with $\beta \approx 0$.

5. Conclusions

Because of a degeneracy between the unknown anisotropy and gravitational potential, the mass profile of an elliptical galaxy cannot be determined from the velocity dispersion profile alone. The results of analyzing a large set of spherical dynamical models indicate, however, that this degeneracy can be overcome if accurate σ and h_4 profiles can be measured. We discuss the case of NGC 6703, an E0 galaxy with a rather steeply declining σ profile and $h_4 \geq 0$. We show that even in this "non-optimal" case our modeling detects the presence of a dark halo and constrains the anisotropy structure, finding a mild radial anisotropy. A simple "recipe" method allows one to estimate the anisotropy and the mass at a given radius from the measured h_4 profile and the logarithmic derivative of the σ profile. Data for a sample of bright round ellipticals show that anisotropy is low and that dark matter is not yet dominant inside $R \approx 2R_e$.

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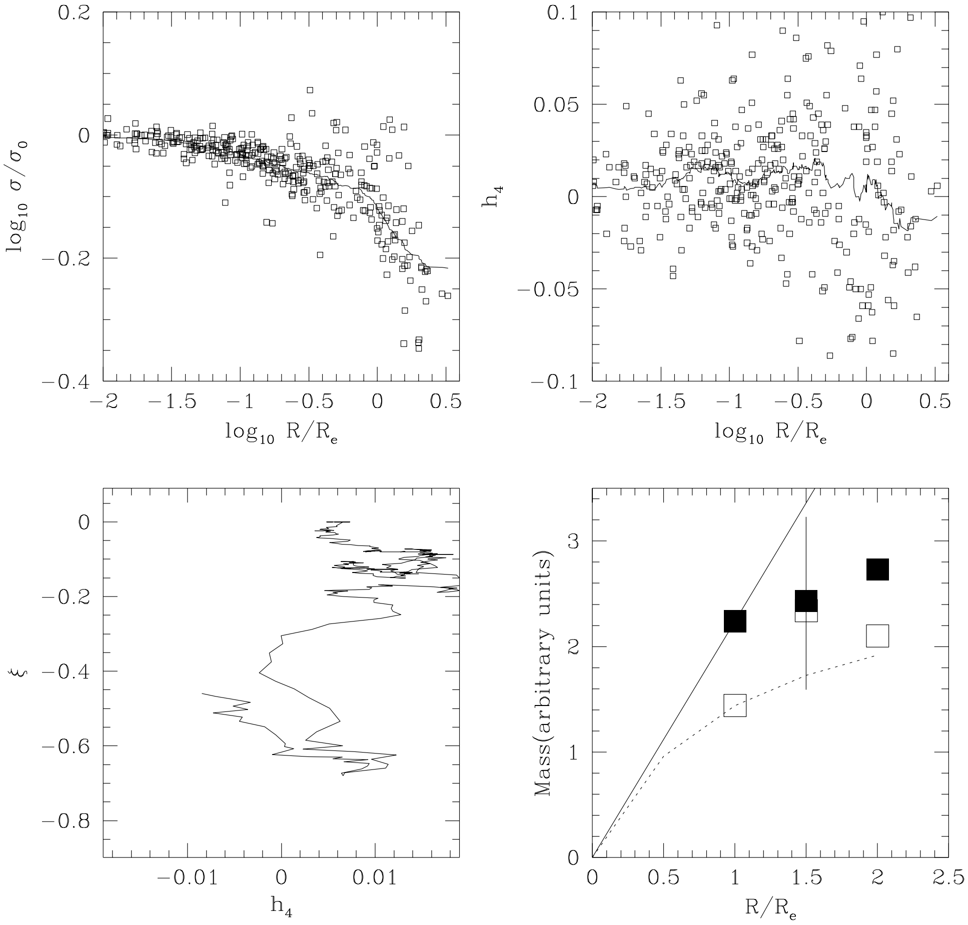

Figure 3. The mean scaled σ (top left, full line) and h_4 (top right, full line) profiles of a sample of 12 round ellipticals (squares) as a function of the scaled distance from the centers. The bottom left plot shows the relation between the mean h_4 and the mean gradient ξ. The bottom right plot shows the (dimensionless) mass profiles derived in the halo (filled squares) and in the self-consistent potential (open squares). The full and dotted lines show the mass profiles expected in the halo and in the self-consistent potential respectively.

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