Dark Matter in Elliptical Galaxies: 3-Integral Modeling

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Abstract. We describe a method to construct 3 integral axisymmetric models to fit the kinematics of flattened elliptical galaxies. We discuss the case of NGC 4649. A preliminary fit to the major and minor axis kinematics out to $R \approx 1.3R_e$ is obtained with a constant mass-to-light ratio (M/L$_R$=5.2, $H_0 = 50$), a reasonable anisotropic structure of the velocity dispersion tensor and nearly cylindrical rotation.

1. Introduction

In contrast to spiral galaxies, where the geometry and kinematics are well understood (spiral galaxies are rotationally supported disks), ellipticals appear much more complicated to model. They are three-dimensional, pressure supported stellar systems, so that their intrinsic geometry, orbital structure and total gravitational potential can not be determined easily. Except for a few well studied cases, the cold HI gas content present in ellipticals is low enough to escape detection. Therefore, HI rotation curves, the reliable tool to detect dark matter in spirals (see Van Albada, this volume, Morganti et al. 1996) are sadly not available to study the kinematics of early-types. Therefore, kinematical data are derived from the analysis of the (integrated along the line of sight) stellar absorption spectra. The “classical” quantities so derived are the stellar luminosity density distributions, and the mean velocity and velocity dispersion profiles along the line of sight. More recently (van der Marel & Franx 1994, Bender, Saglia & Gerhard 1994) the line of sight velocity distributions (LOSVD) have been measured. This allows to go beyond the first and second kinematical moments and quantify the deviations from Gaussian functions in terms of third and fourth order Hermite polynomial terms h_3 and h_4.

In principle, the stellar dynamical modeling should find the distribution function of the integrals of the motions I and the gravitational potential Φ that best describe these sets of data. In practice, this approach is complicated by a number of problems. The simplest case of spherical geometry faces the anisotropy-potential degeneracy problem (see the extensive discussion in Saglia et al., this volume). Spherical symmetry must be abandoned when flattened, rotating elliptical galaxies are considered. Axisymmetric models based on distribution functions $f(E, L_z)$ of two integral of the motions, the energy E and the angular momentum along the symmetry axis L_z have been extensively studied in the past (van der Marel 1994 and references therein, Dehnen & Gerhard 1993, 1994). These models require large tangential anisotropies to produce even moderately flatted objects. Such large anisotropies produce detectable effects on the LOSVDs, which should appear double-peaked or strongly flat-top, with large negative h_4 (≤ -0.1) values. Fig. 16 of Bender, Saglia & Gerhard (1994) shows that this is not the case: ellipticals have LOSVDs with $\langle h_4 \rangle \approx 0$. Two-integral models can be therefore ruled out (at least for the class of non-disky, normal luminous ellipticals). In general, there is no third integral of the motion in a given axisymmetric potential, so that the class of 3 integral axisymmetric models has not yet received the attention given to the two integral case. The further complication of relaxing the axisymmetric assumption to study triaxial models has been mainly considered in the framework of Stäckel potentials and perfect ellipsoids (de Zeeuw 1985).

In the following the method to construct three-integral axisymmetric models developed by Dejonghe et al. (1996) is summarized (Sect. 2.). Following this approach, we analyze (Sect. 3.) the new accurate kinematical data of the flattened boxy elliptical NGC 4649 and discuss the dynamical results. Conclusions are drawn in Sect. 4.

2. 3-Integral modeling

Dejonghe et al. (1996) developed a method to construct 3-integral axisymmetric distribution functions based on the determination of an *approximate* (see below) third integral I_3. Given the two-dimensional surface brightness distribution $\Sigma(x, y)$ of a (flattened and rotating) elliptical galaxy, a constant mass-to-light ratio is assumed and a three-dimensional axisymmetric density $\rho(x, y, z)$ is derived by deprojecting Σ, using a multi-gaussian expansion (Emssellem, Monnet & Bacon 1993) or a Lucy deprojection algorithm (Binney, Davies & Illingworth 1990). The density ρ is decomposed in spherical harmonics, which allows a straightforward calculation of the relative gravitational potential ψ. Next, the Stäckel potential ψ_S that best approximates ψ is determined. This potential can now be used to compute the *approximate* third integral I_3 as the analytical expression for I_3 known to exist for ψ_S (Dejonghe & de Zeeuw 1988).

The second stage of the algorithm constructs the distribution function $f(E, L_z, I_3)$ that best approximates the data (the two-dimensional surface brightness, the projected mean velocity and velocity dispersion profiles along the major and minor axis, higher order terms h_3 and h_4 if available). Note that the approximate potential ψ_S is used only in the calculation of I_3; in every other step (for example, when determining E), the measured potential ψ is used. The distribution function is decomposed as a weighted sum of components of Fricke type $|E|^p L_z^{2q} 2^{-q} (L_z^2/2 + I_3)^n$. The moments projected along the line of sight of each component are computed analytically. The components and their weighting coefficients are determined by minimizing the χ^2-like quantity constructed from the observational data and the projected moments. Linear constraints are imposed to force $f(E, L_z, I_3) \geq 0$.

Using this procedure, Dejonghe et al. (1996) studied the E4.5 galaxy NGC 4697, showing that 3-integral modeling with constant mass-to-light ratio gives fits to the kinematical data (extending out to $R \leq 0.5 R_e$) of superior quality than 2-integral modeling.

3. The case of NGC 4649

We have applied the method discussed in the previous section to the flattened E2 boxy galaxy NGC 4649. The galaxy was observed as a follow-up of the ESO Key Program "A search for dark matter in elliptical galaxies" (Bertin et al. 1989, Saglia et al. 1993, Bertin et al. 1994). The relevant photometry was taken from Peletier et al. (1990). Major and minor axis spectra were taken with the ESO NTT telescope equipped with EMMI and a 1024×1024 19 μm pixel Thomson CCD detector. With a 28Å/mm grating, a central wavelength of 5150 Å and a slit width of 3 arcsec, a resolution of 90 km/s was achieved. After standard reduction procedures, the spectra were analyzed using the Fourier Correlation Quotient algorithm (FCQ, Bender 1990, Bender, Saglia & Gerhard 1994). Major and minor axis V, σ, h_3 and h_4 profiles were derived out to $R \approx 95'' = 1.3 R_e$.

Figure 1 show the resulting major axis velocity and "total kinetic energy" major and minor axis profiles $\sqrt{V^2 + \sigma^2}$, together with a preliminary best-fit 3-integral model (full line). The properties of the model are illustrated in Figure 2. A reasonable anisotropy structure is obtained, with dominant radial velocity dispersion in the outer parts. The model shows nearly cylindrical rotation. The derived mass-to-light ratio in the R band is $M/L_R = 5.2 M_\odot/L_\odot$, with a distance $D = 26.7$ Mpc ($H_0 = 50$).

4. Conclusions

Axisymmetric, 2-integral models of flattened ellipticals produce large tangential anisotropies, which are ruled out by the observations showing that LOSVDs are not flat-top ($h_4 \approx 0$). We described a method to construct axisymmetric, 3-integral models, based on the definition of an approximate third integral of the motion. We applied the algorithm to study the major and minor axis stellar kinematics of the galaxy NGC 4649 out to $R \approx 1.3 R_e$. A preliminary fit is obtained with a constant mass-to-light ratio (M/L$_R$=5.2, $H_0 = 50$), a reasonable anisotropic structure of the velocity dispersion tensor and nearly cylindrical rotation.

In recent years stellar dynamical studies in the search for dark matter were concentrated on round, massive ellipticals. A part from very few outstanding

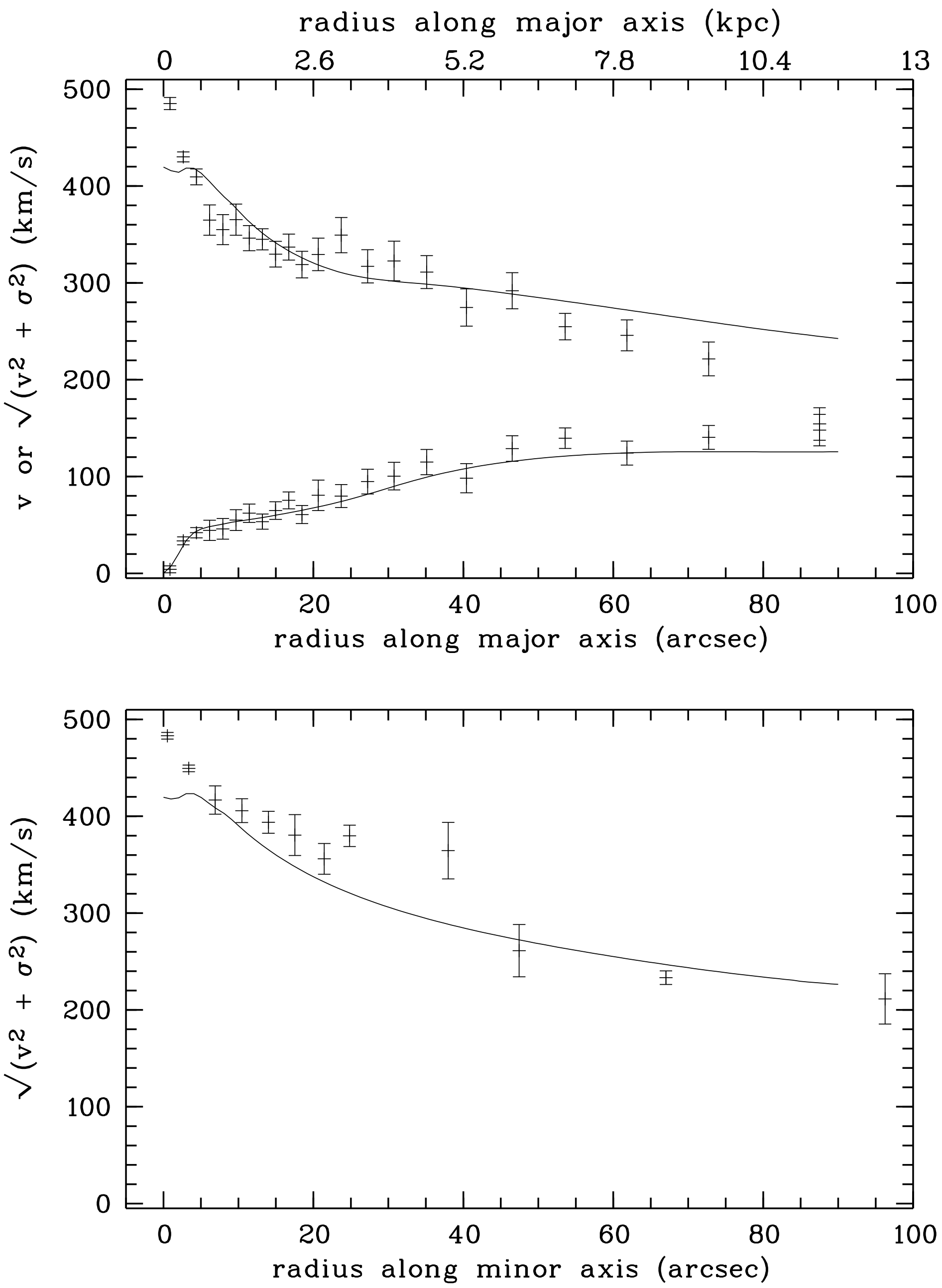

Figure 1. The major (top) and minor axis (bottom) "total kinetic energy" profiles $\sqrt{V^2+\sigma^2}$ of NGC 4649 and the best-fit 3-integral model (full line). The top plot shows also the major axis velocity profile.

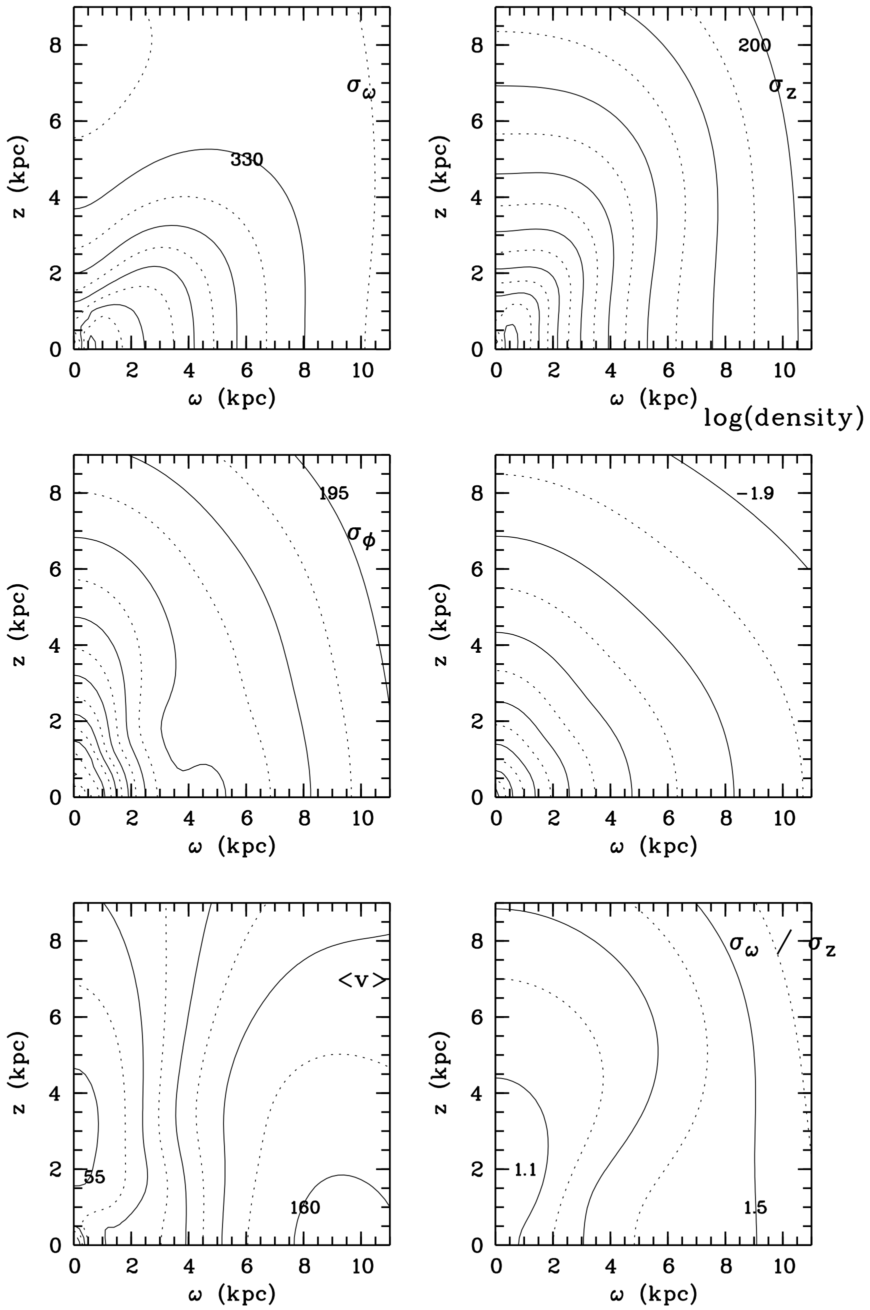

Figure 2. The best-fit 3-integral model of NGC 4649. Upper left, upper right, intermediate left: the contours of equal velocity dispersion components σ_ω, σ_z and σ_Φ respectively in km/s. The spacing is 15 km/s. Intermediate right: The logarithmic isodensity contours in cylindrical coordinates (ω, z). The spacing is $\Delta \log \rho = 0.3$ and ρ is in $M_\odot/pc^3$. Bottom left: the contours of equal mean velocity. The spacing is 15 km/s. Bottom right: The contours of equal σ_ω/σ_z ratio. The spacing is 0.1.

cases, like e.g. NGC 7144 (Saglia et al. 1993), dynamical data indicate only modest amounts of dark matter in these galaxies (c.f. Bertin et al. 1994, Saglia et al., this volume) within typically 2 R_e. An alternative approach, also realized in the framework of the ESO Key Programme, which uses ionized gas disks as tracer of the underlying galaxy potential supports this view (Buson et al. 1993, Zeilinger et al. 1996, Pizzella et al. 1996). The preliminary results of the flattened elliptical NGC 4649 fit in this picture.

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