The dynamics of the dE galaxy FS76: bridging the kinematic dichotomy between Es and dEs.¹

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ABSTRACT

We present major and minor axis kinematics out to ≈ 2 half-light radii for the bright ($M_B = -16.7$) dwarf elliptical (dE) FS76, a member of the NGC5044 group. Its velocity dispersion is $46 \pm 2$ km/s in the center and rises to $70 \pm 10$ km/s at half-light radius. Beyond 1 $R_e$ the dispersion starts to fall again. The maximum rotation velocity is $15 \pm 6$ km/s, about the value expected for an oblate isotropic rotator with the same flattening as FS76 (i.e. E1). Hence, FS76 is the first dE discovered so far that is not flattened predominantly by anisotropy. There is a discontinuity in the radial velocity profile at ± 1″, corresponding to a kinematically peculiar core with a radial extent of 0.25 kpc. The reversed outward trend of the velocity dispersion is interpreted as evidence for a truncated dark halo and hence for the occurrence of tidal stripping.

Using dynamical models we estimate the total mass within a sphere of 1 kpc ($\approx 1.5 R_e$) to be between 1.2 and 3.4 $\times 10^9 M_\odot$ at the 90% confidence level, corresponding to $3.2 \leq (M_\odot/L_\odot)_B \leq 9.1$. These values are consistent with predictions based on CDM cosmological scenarios for galaxy formation.

Subject headings: dwarf ellipticals – kinematics and dynamics of galaxies

1. Introduction

Dwarf ellipticals are of particular interest because they dominate in numbers the nearby universe and in CDM scenarios they are supposed to be dark matter dominated systems. Due to their very faint surface brightness levels that make long slit spectroscopy a very daunting task, the kine-
matics of dEs have so far been left largely unexplored. Up to now, the central velocity dispersions of only a few tens of dEs have been determined (Peterson & Caldwell 1993). Furthermore, the projected velocity and velocity dispersion profiles of only 6 dEs can be found in the literature. These are the Virgo dEs VCC351 and IC794, the Fornax dE (Bender & Nieto 1990; Mateo et al. 1991; Bender et al. 1991; Carter & Sadler 1990; Held et al. 1990, 1992)

None of the dEs in this sample are flattened by rotation. The ratio of the observed \( v/\sigma \) to the theoretical estimate for an oblate, isotropic rotator \( (v/\sigma)^* = (v/\sigma)_{\text{obs}}/(v/\sigma)_{\text{theo}} \) gives an indication of the relative importance of rotation in flattening a galaxy. All dEs in this sample have \( (v/\sigma)^* < 0.4 \) and hence are supported by anisotropy. This finding introduced a dichotomy in the otherwise linear sequence of increasing rotational support with decreasing luminosity for ellipticals. The issue of a photometric dichotomy between Es and dEs however has been resolved. It is now known that the surface brightness profiles of both Es and dEs can be well approximated by a Sersic profile \( I(r) = I_0 \exp(-(r/r_0)^{1/n}) \) and that both types form a single sequence in \((n, M_B), (I_0, M_B)\) and \((r_0, M_B)\) diagrams (Jerjen & Binggeli 1998).

A comprehensive review on the subject is given by Ferguson & Binggeli (1994). Recently Ryden et al. (1999) pointed out that dEs have the same range and frequency of boxy and disky isophotes as normal Es.

The class of dEs is a key factor in understanding galaxy formation. In CDM cosmology scenarios, dEs form from average-amplitude density fluctuations (Dekel & Silk 1986). Supernova-driven winds are thought responsible for expelling their gas and reshaping the galaxies. This scenario successfully predicts the observed scaling relations between mass, velocity dispersion and luminosity but fails to reproduce the observed clustering properties of dEs. Alternatively, Moore et al. (1998) argue that dEs can also form out of late-type galaxies that are stripped of their disk material and dark matter by galaxy harassment. Their simulations yield objects that are qualitatively similar to bright, non-nucleated dEs. The latter are known to have the same clustering properties as late-type spirals (Ferguson & Binggeli 1994), strengthening the idea of an evolutionary link between both types of objects. A better knowledge on the internal dynamical structure of dEs is urgently needed to test these formation scenarios. In a case study on the dE FS76, first results of an ongoing ESO Large Programme on physical properties of a sample of dwarfs ranging from dE0 to dS0 are reported. FS76 is a member of the NGC 5044 group. VRI photometry and deep, high resolution major and minor axes kinematics are presented. These data show that FS76 is the fastest rotating dE recorded so far and bridges the kinematic dichotomy between Es and dEs. We argue that its outward declining velocity dispersion is the result of a compact dark halo.

2. Observations and data reduction

The observations were carried out in the period May 9-16, 2000 at the 8.2 m telescope Kueyen (VLT-UT2) using FORS2, both for the imaging and the spectroscopy. It is classified as a round dE, possibly a compact elliptical (cE). Major (PA=46\(^\circ\)) and minor axis (PA=136\(^\circ\)) long-slit spectra were obtained with the FORS2 grism GRIS_{1028z+29} in the wavelength region \(\lambda\lambda 7900 - 9300\AA\) achieving an instrumental broadening of \(\sigma_{\text{Instr}} = 30 \text{ km/s} \). Total integration time was 5 h for each position angle. The spectra were obtained at typical seeing conditions of 0.7\" - 0.8\" FWHM. The standard data reduction procedures were performed with ESO-MIDAS \(^4\) (the details of the observations and data reduction will be given in a subsequent paper (Dejonghe et al. 2001)). All spectra were rebinned to a linear wavelength scale (rectifying the emission lines of the arc spectra to an accuracy of \(\approx 1 \text{ km/s} \) FWHM). We also obtained spectra of 9 giant stars in the late G to early M spectral range as velocity templates. In addition, we obtained V, R and I images during a period of excellent seeing (\(\approx 0.3'' - 0.4'' \) FWHM).

Ellipses were fitted to the isophotes of the calibrated VRI images in order to derive surface brightness, position angle and ellipticity profiles together with the Fourier coefficients that quantify the deviations of the isophotes from a pure elliptic shape. Errors on all quantities were estimated using the bootstrap method. Sersic profiles

\(^4\)ESO-MIDAS is developed and maintained by the European Southern Observatory
were fitted to the V, R and I band growth curves. The derived photometric characteristics of FS76 can be found in Tables 1 and 2. The kinematic parameters – the mean rotation velocity $v_p$ and the velocity dispersion $\sigma_p$ – were obtained by fitting Gaussians to the line-of-sight velocity distributions (LOSVDs). The best fit was obtained with a K11 template. Template mismatch was found to be negligible with this star spectrum. The resulting mean velocity and velocity dispersion profiles for major and minor axes are presented in Figure 1.

3. Results and discussion

The analysis of the surface photometry confirms the picture of FS76 being a normal dwarf elliptical. No photometric peculiarities were noted. There is only a modest amount of isophote twisting (the PA varies slowly between $30^\circ$ and $50^\circ$ over a radial region of $10''$). FS76 is not nucleated and its nucleus (defined as the brightest pixel) is coincident with the geometric center of the outer isophotes. Work on the Virgo cluster by Sandage et al. (1985), has shown that only 20% of all dEs of comparable intrinsic brightness are non-nucleated. No significant deviations from ellipses were detected in the isophotes. A heliocentric velocity of $2734 \pm 4$ km/s was derived from the spectra which confirms FS76 as a member of the NGC5044 group ($v_{NGC5044} = 2704 \pm 33$ km/s). Using a distance modulus of $-32.78$ ($H_0 = 75$ km/s/Mpc) for the NGC5044 group we derive $M_B = -16.7$ mag for FS76. The galaxy closely follows the relations between the Sérsic parameters and absolute magnitude found to be valid for Es and dEs (but not for cEs) and also falls among the bright dEs in a central surface brightness versus absolute magnitude diagram with $m_B(0) = 19.15$ mag. We can therefore positively exclude a cE-type nature of FS76 and classify it as dE1.

The velocity dispersion profiles of both axes agree remarkably well. A central value of $\sigma_p = 46 \pm 2$ km/s is derived. The velocity dispersion rises outward to about $70 \pm 10$ km/s at half-light radius ($R_e$). Beyond $1R_e$ the profile declines to about $50$ km/s at a radial distance of $2R_e$. The maximum rotation velocity along the major axis is $15 \pm 6$ km/s. A discontinuity in the radial velocity profile at $\pm 1''$, indicates the presence of a kinematically decoupled core. The rotation velocity profile shows a distinct asymmetry. There is a hint of this asymmetry in the velocity dispersion profile as well. A small velocity gradient is also present along the minor axis. This immediately excludes another alternative, i.e. that we are seeing a disk galaxy almost face-on, because such an object would have a much lower surface brightness, would lack minor-axis rotation and have a much smaller velocity dispersion.

The ratio of the rotation velocity to the velocity dispersion can be used as an indicator for the importance of rotation in flattening a stellar system. Using equation (4-95) of Binney & Tremaine (1987), the expected ratio for an isotropic E1 galaxy is $v_p/\sigma_p = 0.41$. Another theoretical estimate yields $v_p/\sigma_p = \pi \sqrt{2((1-\epsilon)^{-0.5} - 1)/4} = 0.35$ (e.g. Sparke & Gallagher (2000)). The observed ratio of the peak velocity to the central velocity dispersion is $(v_p/\sigma_p)_{obs} = 0.33 \pm 0.15$, corresponding to an anisotropy parameter $(\epsilon/\sigma)^* \approx 0.9$, the highest value obtained so far for a dE. Moreover, the best fitting dynamical model (see section 4) learns that the radial pressure drops only very little towards the rotation axis (the radial velocity dispersion $\sigma_r$ varies only by a few km/s if one moves from the equatorial plane towards the rotation axis) and therefore pressure differences play only a minor role in flattening this galaxy. Thus, the observed kinematics and detailed dynamical models unambiguously show that FS76 is indeed flattened by rotation and not by pressure anisotropy. This suggests that at least in some dEs rotation plays a major role. Of the 6 galaxies in our present sample, which includes also very flattened objects, of which the kinematics have been analyzed (Dejonghe et al. 2001), this is the only one that is rotationally flattened. Hence, if we add also the dEs for which spatially resolved kinematics have been published and interpret small-number statistics, the current sample of dEs suggests that probably not more than 10% of all dEs are flattened by rotation.

4. The dynamical modeling

The derived kinematics together with the reported results from the surface photometry argue in favor of an almost round though slightly triaxial object, viewed approximately along its intermedi-
ate axis. For the modeling purposes we assumed a spherical gravitational potential with the stellar body seen edge-on. The total spatial density was taken to be the spatial density of the luminous matter (obtained by deprojecting the surface brightness profile), multiplied with a constant or outwardly rising function, corresponding respectively to a constant or outwardly rising $M/L$. The gravitational potential follows from Poisson’s equation. The orbital structure is described by the distribution function (DF) $F(E, L, L_z)$, a function of binding energy $E$, angular momentum $L$ and the component of the angular momentum along the rotation axis $L_z$. This DF can be obtained by fitting a dynamical model directly to the spectra (De Rijcke & Dejonghe 1998). Thus, all kinematic information in the spectra is used, the shape of the LOSVD is not biased towards a Gaussian and each model can be given an absolute likelihood (the $\chi^2$ serves as a goodness of fit). By trying a wide variety of mass distributions, the range of models that are compatible to the data can be determined, yielding reliable $M/L$-estimates.

We fitted about 100 models to the spectra, with mass distributions varying between constant $M/L$ and models with steeply outwardly rising $M/L$ (consisting of up to 50% of dark matter inside 1 kpc). The total mass within a sphere of 1 kpc ($\approx 1.5 R_e$) is found to be between 1.2 and $3.4 \times 10^9 M_\odot$ at the 90% confidence level. This corresponds to $3.2 \leq (M/L)_B \leq 9.1$. Although a model with constant $(M/L)_B = 5.6$ cannot be ruled out, the best fitting model has an outwardly rising $M/L$ ($(M/L)_B = 6.0$ at 1 kpc). This model remains isotropic out to 0.25 kpc and becomes slightly tangentially anisotropic at larger radii (the radial dispersion is about 40 km/s while the tangential dispersion is 65 km/s). Analysis of the distribution function revealed that the kinematically decoupled core is indeed due to a fast rotating, isotropic stellar component with a radial extent of 0.25 kpc (contrary to the case of NGC7097 where analysis of the distribution function indicated that the counter-rotation is not related to a compact group of stars (De Bruyne et al. 2001)). The DF for orbits in the equatorial plane is plotted in Figure 2.

Dekel & Silk (1986) have derived scaling relations between the luminosity $L$, radius $R$ and total mass $M$ of elliptical galaxies. Their simple model of galaxy evolution is based on two premises: (i) dEs lose significant amounts of gas in a supernova-driven wind and are surrounded by a dark halo that dominates their dynamics and (ii) the observed relation $L \propto R^4$ between luminosity and radius holds for all ellipticals. They predict that fainter dEs are more dark matter dominated ($M/L \propto L^{-0.37}$) and have smaller velocity dispersions ($\sigma \propto L^{0.19}$). The derived relation between mass and radius ($M \propto R^{2.5}$) happens to correspond to what is predicted by CDM cosmological models. Hence, obtaining reliable $M/L$ estimates for dEs has important repercussions on cosmology. FS76 closely follows the $L \propto R^4$ and $\sigma \propto L^{0.19}$ sequences (we’re using the central velocity dispersion for comparison). Dekel & Silk predict $(M/L)_B \approx 3$, somewhat lower than what we find. This is likely the result of the outwardly rising velocity dispersion profile. Overall, we can say that our results for FS76 are in reasonable agreement with the predictions of the standard CDM cosmological scenarios for galaxy formation.

5. The compact halo of FS76

A peculiarity of FS76 is the reversed outward trend of its velocity dispersion: it rises from 46 km/s in the center to about 70 km/s at half-light radius and then declines to approximately 50 km/s at 2 half-light radii. This feature is present on both sides of major axis and minor axis. If radial anisotropy is responsible for the falling velocity dispersion at large radii, one would see a high velocity dispersion in the center since there the line of sight is almost parallel to the radial orbits, something which is not observed. Moreover, our dynamical models show no sign of a rapidly changing anisotropy at the radius where the reversed trend sets in: they remain slightly tangentially anisotropic. We also find that dynamical models with rapidly rising $M/L$ have too high a velocity dispersion at large radii. Therefore we consider this to be strong evidence that the halo, which according to our modeling is likely to be present, must be compact and thus of comparable extent as the luminous matter, indicating that, at least for this dE, the light is not ‘the top of the iceberg’. This would fit into the scenario suggested by Moore et al. (1998) where dark matter dominated disk galaxies are transformed into baryon dominated dEs. The kinematically peculiar core
we observe may be a consequence of gas that is driven towards the center by the torques induced by tidal interactions, followed by star-formation. Moreover, FS76 is a bright non-nucleated dE. This species of dEs is clustered the same way as spirals, which led Ferguson & Binggeli (1994) to suggest a possible evolutionary link between these dEs and late-type galaxies. An $M/L$ in the range 3 to 8 is predicted from this scenario, consistent with our findings.

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Fig. 1.— The major (triangles) and minor axis (circles) kinematics of FS76. Lower panel: the mean projected velocity $v_p$, top panel: the projected velocity dispersion $\sigma_p$. The linear scale (in kpc) is shown at the top axis. The vertical dashed lines measure distances of one and two half-light radii. The horizontal dashed line in the lower panel marks the systemic velocity of FS76.

Fig. 2.— The DF of FS76 for equatorial plane orbits in turning-point space, i.e. the phase-space density of stars on orbits with a given pericenter distance $r_{\text{peri}}$ and apocenter distance $r_{\text{apo}}$. The contours are spaced 0.25 logarithmic bins apart. $r_{\text{peri}}$ has the same sign as the angular momentum, $L_z$. The peculiar core consists of stars around the locus of circular orbits with radius $\approx 0.2$ kpc ($\approx 1''$). Mark also the paucity of stars on radial orbits with apocenter distances larger than 0.7 kpc ($4''$). At all radii, there are more stars on orbits with positive $L_z$ than with negative $L_z$, producing the bulk rotation of the galaxy.
Table 1

EXTINCTION CORRECTED \( (m^0_T) \) APPARENT MAGNITUDES AND COLORS, EFFECTIVE SURFACE
BRIGHTNESSES \( (\mu)_e^0 \) AND HALF-LIGHT RADII \( R_e \) OF FS76.

| V   | R   | I   | V–R | V–I | R–I |
|-----|-----|-----|-----|-----|-----|
| m^0_V | 15.44 | 14.84 | 14.35 | 0.60 | 1.09 |
| (\mu)_e^0 | 29.60 | 20.03 | 19.60 |       |     |
| R_e (\arcsec) | 4.29  | 4.35  | 4.47  |       |     |
Table 2
Parameters of the V, R and I band Sérsic profiles: the extrapolated central surface brightness \( m_0 \), the scale-length \( r_0 \) and the exponent \( n \).

|   | \( m_0 \) | \( r_0 \) (\arcsec) | \( n \) |
|---|---------|----------------|------|
| V | 16.63   | 0.21           | 1.97 |
| R | 16.05   | 0.21           | 1.98 |
| I | 15.63   | 0.22           | 1.98 |