Deep kinematics and dynamics of edge–on S0 galaxies. I. NGC 3115

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Abstract. As a first step of a program aimed to the detection of dark matter (or radial variations of $M/L$) in early–type galaxies, we report deep spectroscopic observations of the bulge–dominated edge–on S0 galaxy NGC 3115, made at ESO, La Silla, using EFOSC at the 3.6 m telescope and EMMI at NTT. Such observations allow measurements of the rotational velocity out to 1.8 $a_e$ (effective radii) from the galaxy center, where the surface brightness is $\mu_B \approx 24$ mag arcsec$^{-2}$. The rotation curve quickly reaches an asymptotic value, $\langle v_f \rangle \approx 260$ km s$^{-1}$, with only marginal indication of systematic decline within the range of our observations. The line–of–sight velocity dispersion has also been measured; it decreases steeply from a rather high central value and flattens out ($\langle \sigma \rangle \approx 100$ km s$^{-1}$) within our observing range ($a \gtrsim 1.3a_e$).

Models built on these data and simple dynamical arguments show that the $M/L$ of NGC 3115 must thus be increasing from $M/L = 6$ (in solar units) in the inner regions ($\sim a_e$) to at least $M/L \geq 10$ in the outermost regions ($\sim 2a_e$).

Key words: Galaxies: NGC3115; kinematics and dynamics of; lenticular; structure of; dark matter

1. Introduction

Some evidence for the existence of dark matter has now been acquired on all scales, from those of dwarf galaxies up to the richest galaxy clusters. At the same time inflationary theories suggest that dark matter might exist even at cosmological scales. However, at galactic scales, that is at galactocentric distances comparable with the lengths of the effective radii $a_e$, such evidence is still patchy (cf. Kormendy & Knapp 1987). It seems rather firm for dwarf and spiral galaxies, whereas no direct evidence has yet been discovered for early–types (E and S0’s). This happens primarily for three reasons. In the first place, early–type galaxies have little, if any interstellar matter (Knapp 1987), which traces the rotation curve and, indirectly, the dark matter in spirals; the ionized gas in early–type galaxies is mostly confined to the innermost regions, where dark matter is unlikely to be dominant, and all this gas has a very uncertain geometry, which severely limits the interpretation of observations. Cooling flows in ellipticals provide some support for dark matter at very large radii (Fabian, Arnaud & Thomas 1987), but these estimates are fraught with uncertainties (Bertin, Pignatelli & Saglia 1992). Furthermore they apply only to a small and somewhat peculiar subset of all ellipticals, the brightest cluster members, which all happen to be “boxy” galaxies (Bender, et al. 1989, Capaccioli, Caon & D’Onofrio 1992). For the other class of ellipticals, the “disky” E’s, which constitute $\sim 50\%$ of all E’s (Bender et al. 1989), nothing is known.

Bulge–dominated edge–on S0’s (hereafter referred to as BEDOS) provide a convenient laboratory to investigate the presence of dark matter inside the optical regions of early–type galaxies. First of all, bulge dominated S0’s are now believed to be closely related to the class of “disky” ellipticals (Capaccioli 1987, 1990, Capaccioli, Caon & Rampazzo 1990) for which even the equivocal evidence provided by the X–ray coronas is not available. Moreover, the existence of dark matter haloes surrounding S0 galaxies seems to be demanded by those few such objects possessing polar rings (e.g. Sparke 1989 and Arnaboldi et al. 1992). In this respect, the study of BEDOS by direct kinematical mapping along the major axis is greatly simplified for the following reasons:
1. they have a high $v_{\text{max}}/\sigma_v$ ratio (Capaccioli 1979, Davies et al. 1983), which makes the analysis simpler (and more similar to that of spirals);
2. the geometry is known since, as $i \approx 90^\circ$, the apparent axial ratio equals the intrinsic one;
3. the bulge is unlikely to be strongly triaxial (for NGC 3115 and NGC 3379, see Capaccioli et al. 1991);
4. direct observations provide the photometric characteristics and the $M/L$ of the disk (and thus its dynamical relevance), which allow us to subtract its effects;
5. thanks to the “cylindrical rotational field” (i.e. very slow variation of the velocity perpendicularly to the galaxy major axis; cf. Kormendy & Illingworth 1982), we know how to obtain the true rotation velocity of the bulge, without contamination from the disk;
6. lastly, substantial photometric and spectroscopic literature exists, which permits relevant checks and complements modern observations.

A kinematical project involving BEDOS may be simpler than considering directly elliptical galaxies, but it is not altogether simple. In fact, detection of dark matter requires spectroscopic observations at large distances from the centers of galaxies. As a way of comparison, existing models of the mass distribution of the Galaxy (Caldwell & Ostriker 1981, and Bahcall, Schmidt & Soneira 1982) show that, within the solar radius (8.5 kpc, corresponding to $\sim 2.5$ disk scale–lengths), the mass is roughly equally distributed between spheroid, disk, and dark halo. For a similar distribution of matter in early–type galaxies, one should find $\simeq 1/2$ of the total mass in dark matter within $\simeq 1.8$ effective radii $a_e$, the radial range corresponding to the same fraction of the total light in the Milky Way. Spectroscopic observations of stellar lines at these distances from the center of the galaxy are hampered by the faintness of the continuum, which is notoriously already faint enough at $1 \, a_e$: $\mu_e \simeq 22.5 \pm 2$ B-mag arcsec$^{-2}$ for E galaxies and S0 bulges with total luminosity $M_B \lesssim -18$ (Capaccioli & Caon 1991; their Fig. 1).

Kinematical data out to galactocentric distances of $\sim 2a_e$ have now been obtained for the first time as part of a program started at ESO, La Silla, in 1989, and aimed at investigating the dependence of the dynamical behavior of galactic disks on the bulge–to–disk ratios, and the presence and shape of dark haloes in early–type galaxies (Cappellaro, Capaccioli & Held 1989, 1990) through observations of “deep” rotation and velocity dispersion curves in BEDOS and polar ring bulges (Arnaboldi et al. 1992). This program has been made possible by the unique capabilities of the ESO Faint Object Spectrograph and Camera (EFOSC; Melnick, Dekker & D’Odorico 1989) attached to the Cassegrain focus of the ESO 3.6 m telescope. The first target galaxies, NGC 2310, NGC 3115, and NGC 4179, were chosen among the few BEDOS with fairly large angular sizes (distances $\leq 25$ Mpc) with the purpose of minimizing resolution problems.

Here we concentrate on NGC 3115, leaving the remaining objects for a following paper. One reason for this choice is that much work on this “standard” S0 galaxy has already been carried out (see Capaccioli, Held & Nieto 1987, for an extensive photometric mapping, and §2 for references on kinematics and dynamics). In particular, we already know the mass–to–light ratio of the exponential disk of this galaxy (Capaccioli, Vietri & Held 1988) and we have also shown that the dominating bulge is unlikely to be very triaxial (Capaccioli et al. 1991). Another reason is our need to demonstrate, with a good example, the reliability of the EFOSC data, particularly for what concerns the velocity dispersion measurements (see §2), taking advantage of the higher resolution but more expensive results from spectra taken with EMMI at the ESO NTT.

The plan of the paper is as follows. Section 2 details the spectroscopic observations and their reduction, with results doubling the radial extension of the published kinematical measurements in this very well studied galaxy. Major–axis rotation and velocity dispersion curves of NGC 3115 are analyzed theoretically in Sect. 3. Section 4 contains a summary and our conclusions. An Appendix discusses the theoretical method employed for the dynamical analysis, and expands on a few technical details. The relevant data on NGC 3115, mostly taken from Capaccioli et al. (1987), are summarized in Table 1.

2. Spectroscopic observations

2.1. The EFOSC spectra

Five long exposure spectra of NGC 3115 (Table 2) were obtained with EFOSC at the ESO 3.6 m telescope, and recorded with a high resolution RCA CCD (640 $\times$ 1024 pixels; ESO code #8), in binned mode: pixel size = 30$\mu$m, or 0$''$675 on the sky. We chose the ESO Orange 150 grism, with dispersion of 3.9 Å px$^{-1}$ from 5000 to 7000 Å. The 3$''$ $\times$ 1$''$5 spectrograph slit was aligned with the major axis of NGC 3115 (P.A. $= 43^\circ 5$). Although the nucleus of the galaxy was set close to one end of the slit, the other end still viewed a region of the object as bright as $\mu_B \simeq 24.5$, i.e. only $\sim 7$ times fainter than the average night–sky brightness. Therefore we also obtained long exposure spectra of the blank night–sky (by offsetting the telescope by $\sim 20''$), in chronological sequence with the astrophysical exposures.

The raw data were pre–processed by the standard procedures in MIDAS (ESO Operating Manual No. 1) for bias and dark subtraction, and for flat–fielding based on dome and dawn–sky exposures at different count levels. The complex distortion pattern was mapped using the comparison spectra to derive a line–by–line wavelength calibration. We found that the position of the comparison lines drifts over the detector during the night, the amplitude of the displacement being of the order of 1 pixel (equivalent to $\sim 200$ km s$^{-1}$). The consequent frame–to–
frame shift was corrected by matching the position of the night–sky emissions. The drift acted on the zero point of the absolute velocity scale, adding an uncertainty of ±50 km s⁻¹ (r.m.s.) to the systemic velocity. More importantly, it broadened significantly the long exposure spectra of the galaxy, thus introducing a difference with the very short exposure spectra of the template stars (which did not suffer any significant widening by the drift). Repercussions of such a difference on velocity dispersion measurements will be considered below (Sect. 2.4).

A crucial step in the reduction was the night–sky subtraction from galaxy spectra. We used the blank sky exposures since no part of the slit in our spectra of NGC 3115 was free from the galaxy signal. The frames corresponding to the same side of the galaxy major axis were individually sky subtracted, and then averaged with an algorithm correcting for cosmic ray events.

The kinematical data were analyzed with a package (Bender 1990) based on the cross–correlation (CC), at each radial bin, of the continuum–subtracted galaxy spectrum with a template. No differences were found by changing the template stars (spectral classes from G8 to K1).

### Table 1

NGC 3115: catalog data

| Parameter                                | Symbol | Value |
|------------------------------------------|--------|-------|
| Right Ascension (1950.0)                 | α      | 10ʰ 02ᵐ 44ˢ.51 |
| Declination (1950.0)                     | δ      | −07° 28′ 30ʺ7 |
| Morphological type                       |        | S0− (sp) |
| Standard isophotal major diameter        | D₂₅   | 8′63 ± 0′27 |
| Standard axis ratio                      | (b/a)₂₅| 0.51 ± 0.03 |
| Standard position angle                  | P.A.₂₅| 43°5 ± 1° |
| Corrected total magnitude*               | B₂₅   | 9.65 ± 0.1 |
| Observed radial velocity [km s⁻¹]†       | v₀    | 663 |
| Adopted distance [Mpc]                   | Δ     | 10 |
| Scale factor [pc]                        | 1″     | 48.5 |
| Central rotational vel. gradient [km s⁻¹ arcsec⁻¹] | (dv(a)/da)ₐ=0 | > 100 |
| Asymptotic rotational velocity [km s⁻¹]† | ⟨v_r⟩ | 260 |
| Central velocity dispersion [km s⁻¹]†    | σ(0)  | 325 |
| Velocity dispersion at 1ₐ_c [km s⁻¹]†    | σ(ₐ_c) | 105 |

**Spheroid:**
- Effective semi–major axis: aₐ 93″ ± 8″
- Effective semi–minor axis: bₐ 35″ ± 3″
- Corrected total magnitude: (B₂₅)ₐ 9.71 ± 0.1
- Mass–to–light ratio at 1ₐ_c: M/L ≥ 10 [solar=1]†
- Mass–to–light ratio at 2ₐ_c: M/L ≥ 10 [solar=1]†

**Disk:**
- Fractional luminosity: kₐ 0.06 ± 0.01
- Face–on scale length: h 25′.5
- Inclination‡: i 86°
- Mass–to–light ratio: M/L 7 [solar=1]‡

* From Bₐ = 9.75 (Capaccioli et al. 1987) with Aₐ = 0.1 (Burstein & Heiles 1982).
† This paper.
‡ From Capaccioli, Vietri & Held (1988).
aligned with major axis and centered on NGC 3115 nucleus. The spectrum of the galaxy (and of a few template stars) was recorded on the same CCD #8 as above, spatially binned to 30 μm, with resolution FWHM ≃ 1.75 Å (= 2 pix). This material was preprocessed and reduced by the same technique applied to the EFOSC spectra. The systemic velocity, obtained by matching the two sides of the rotation curve opposite to the center, is $v_0 = 663 ± 5$ km s$^{-1}$, in agreement with Rubin, Peterson & Ford (1980). We note explicitly that the coordinate of the velocity center coincides with that of the peak of $\sigma$, in agreement with the symmetry of the velocity dispersion.

The B&C data were not extended enough to solve all problems of the EFOSC spectra. Thus four spectra of one hour each (Table 2) were taken in December 1991 with EMMI, a spectrograph attached to the Nasmyth focus of the ESO 3.5 m New Technology Telescope (NTT). We used grating #6 which gives a dispersion of 28 Å mm$^{-1}$ over the range 4900–5400 Å. The $6''$ long slit was opened to $1''50$, aligned with major axis of NGC 3115. The galaxy nucleus was always set at $100''$ from the NE end of the slit. The spectra of the galaxy (and of two template stars) were recorded on ESO CCD #18, with pixels of 19 μm, with resolution FWHM ≃ 1.4 Å (= 2.6 pix).

The EMMI spectra were again analyzed like the EFOSC spectra, and then co–added. One important difference here is that, due to the relatively longer slit, we performed the blank sky subtraction using the signal at the SW edge of the co–added spectrum. The systemic velocity from the co–added spectrum is $v_o = 647 ± 4$ km s$^{-1}$ (error not including zero point uncertainty).

### 2.3. The rotation curve

Radial velocity measurements for the combined EMMI spectra are plotted in Fig. 1, after folding about the galaxy center and the systemic velocity. The data were also averaged over intervals with amplitude increasing with the galactocentric distance up to a maximum of $\Delta a = 10''$; the r.m.s. deviation about the mean value never exceeds 10 km s$^{-1}$, even in the most distant bin.

![Fig. 1. Radial velocities $v(a)$ measured along the major axis of NGC 3115 and relative to the systemic velocity, plotted against the distance from the center of the galaxy (counted positive on both sides opposite to the center). The sign of the velocities along the SW semiaxis (where $v(a) < 0$) has been changed. Coding for symbols is: EFOSC = filled circles, EMMI = filled diamonds. The solid line, reproducing the plain interpolation of the two data sets, runs quite flat from $a = 50'' \simeq a_e/2$ to $\sim 2a_e$. Representative error bars are also shown.](image)

The off–centered EFOSC spectra were combined using the B&C and EMMI radial velocity curves as a reference, the arbitrariness of the slide fitting technique being minimized by the characteristic run of $v(a)$: a steep central rise followed by a constant plateau. The resulting mean velocities for the EFOSC spectra, plotted in Fig. 1, were binned over 3$''$ radial intervals from $a = 19''6$ and out to 70$''5$, and over 10$''$ intervals out to the record distance of $\sim 2a_e$. The r.m.s. deviations are larger than the internal error estimates from the CC method (both for the radial velocities and for the velocity dispersion measurements). As an upper limit to the uncertainty of the individual measurements we computed the standard deviations of the differences $\Delta v(a) = v_{NE}(a) - v_{SW}(a)$ and $\Delta \sigma(a) = \sigma_{NE}(a) - \sigma_{SW}(a)$, obtaining, in both cases, a value of $\simeq 20$ km s$^{-1}$.

Visual inspection (Fig. 1) shows that the mean curve produced by the EFOSC spectra — which has about the same resolution of the B&C and EMMI curves in the central region (Fig. 2) — runs essentially flat from 20$''$ out to the last observed point, with $\langle v \rangle = 262 ± 9$ km s$^{-1}$ (the quoted uncertainty is the r.m.s. dispersion). Even if the EMMI data are fully consistent, within the er-
Fig. 2. Comparison of our radial velocity measurements (EFOSC = ×, EMMI = +, B&C = ◦) with literature data: Illingworth & Schechter (1982) = filled circles, Rubin et al. (1980) = filled squares (NE side) and diamonds (SW side). The steeper inner gradient shown by our data finds confirmation in the high resolution rotation curve plotted in Kormendy’s (1987); see also Fig. 6.

errors, with the EFOSC data, they suggest that \( v(a) \) decreases slowly with the galactocentric distance as: \( v(a) = (252 - 0.09 \times a) \text{ km s}^{-1} \), for \( a \approx 50'' \). The plain interpolation of the EFOSC and EMMI data, listed in Table 3 and drawn in Fig. 1 as a solid line, runs flat at \( \langle v_f \rangle = 253 \pm 9 \) km s\(^{-1}\) from \( a \approx a_e/2 \) out to \( \sim 2a_e \).

A comparison of our results with the other modern data available in tabular form (Rubin et al. 1980, Illingworth & Schechter 1982) is also given in Fig. 2; note the steep central gradient, the change of slope at \( a \sim 2'' \), and the secondary minimum at \( a \sim 45'' \) of \( v(a) \). It is of interest to remember that in the range of these observations, from \( a \approx 1/5a_e \) to \( \approx 1/2a_e \) along the major axis, the disk is brighter than the bulge (Fig. 3). With respect to preceding studies our result doubles the interval of galactocentric distances over which \( v(a) \) has been found to run constant in NGC 3115.

### 2.4. The velocity dispersion curve

Mean values of the velocity dispersion \( \sigma \) from the EMMI spectra, after folding about the galaxy center and averaging with the same scheme as for the radial velocities, are shown in Fig. 4. The r.m.s. dispersion on \( \sigma \), which is very small at \( a \lesssim 1.4a_e \) (\( \Delta \sigma < 5 \) km s\(^{-1}\)), blows up at larger galactocentric distances (where it is also based on one side of the galaxy only). Therefore we have discarded all data at \( a > 130'' \); the reason for the difference

| \( a'' \) | \( v(a) \) | \( \sigma (a) \) | \( a'' \) | \( v(a) \) | \( \sigma (a) \) |
|-------|-------|------|-------|-------|------|
| 0     | 0     | 302  | 34    | 260   | 118  |
| 1     | 103   | 260  | 37    | 256   | 113  |
| 2     | 135   | 232  | 40    | 250   | 122  |
| 3     | 157   | 220  | 43    | 255   | 107  |
| 4     | 162   | 212  | 46    | 250   | 110  |
| 5     | 172   | 209  | 49    | 243   | 109  |
| 6     | 174   | 204  | 52    | 253   | 118  |
| 7     | 177   | 198  | 55    | 256   | 122  |
| 8     | 186   | 190  | 58    | 257   | 104  |
| 9     | 205   | 172  | 61    | 249   | 107  |
| 10    | 211   | 165  | 64    | 250   | 107  |
| 11    | 217   | 170  | 67    | 252   | 104  |
| 12    | 224   | 167  | 70    | 266   | 97   |
| 13    | 236   | 160  | 80    | 251   | 101  |
| 14    | 244   | 153  | 90    | 252   | 104  |
| 15    | 247   | 153  | 100   | 238   | 104  |
| 16    | 255   | 144  | 110   | 261   | 116  |
| 17    | 249   | 147  | 120   | 250   | 110  |
| 18    | 252   | 151  | 130   | 238   |      |
| 19    | 254   | 144  | 140   | 249   |      |
| 20    | 269   | 132  | 150   | 250   |      |
| 21    | 266   | 129  | 160   | 257   |      |
| 22    | 265   | 124  | 170   | 274   |      |
| 23    | 262   | 119  | 180   | 257   |      |
| 24    | 256   | 123  | 190   | 250   |      |

Fig. 3. Fractional surface density of light for the disk of NGC 3115 along the direction of the major axis. Data have been taken from the photometric study of NGC 3115 by Capaccioli, Held & Nieto (1987).
between radial velocity and velocity dispersion curves is that the rapidly decreasing signal–to–noise (S/N) ratio affects more severely $\sigma$ than $v$ measurements.

The assembly of the measurements from the various EFOSC spectra into a final velocity dispersion curve was made easy by the sharp central cusp (whose spatial coordinate was always found to coincide with that of the corresponding radial velocity curve). The individual determinations of $\sigma(a)$ were co-added and averaged using the same scheme as adopted for $v(a)$. The resulting values $\sigma_a(a)$ were still affected by this convolution, induced by the drift of the spectra across the detector during long exposures. We postulate that the corrected values $\sigma(a)$ depend on the convolved velocity dispersions through the relation

$$\sigma(a) = \left[ \sigma^2_a(a) - s_0^2 \right]^{1/2},$$

where $s_0$ is a constant to be found by comparison with the EMMI and B&C velocity dispersion curves. With $s_0 = 125 \pm 5$ km s$^{-1}$, corresponding to a 20% increase in the instrumental dispersion, we obtained an excellent agreement (Fig. 4 and 5) with the EMMI and B&C curves as well as with the less resolved data of Illingworth and Schechter (1982). Note that the matched values span the interval from $\sigma \approx 100$ to 300 km s$^{-1}$ and that even the central cusp of $\sigma$ is in agreement with the high resolution data plotted in Kormendy (1987) and Kormendy & Richstone (1992); see also Fig. 6. Note also that the EMMI velocity dispersion values are in perfect agreement with the EFOSC data over the entire range, proving that the large and somewhat empirical correction indeed works. An interpolated curve through the two sets of data is sampled in Table 3 and plotted in Fig. 4.

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1 In a preliminary report (Cappellaro et al. 1989, 1990) we simply assumed $\sigma = \sigma_a/1.5$ at all distances, from comparison with Illingworth & Schechter’s (1982).
In any case, we have analysed the effects of the instrumental resolution $\sigma_{\text{inst}}$ and of the signal-to-noise ratio for the EFOSC material. Simulations with our reduction package show that the systematic error on the measured value of the velocity dispersion is $\lesssim 20\%$ for $\sigma > 0.4\sigma_{\text{inst}}$, i.e. for $\sigma > 80$ km s$^{-1}$ in our case. We have also compared the CC package with a Fourier quotient (FQ) package developed and kindly made available to us by Dr. G. Galletta. In agreement with the results of Larsen et al. (1983), we find that CC seems superior to FQ in measuring velocity dispersions, particularly if they are small. The next question is the influence of the signal-to-noise ratio; for decreasing S/N, the measured $\sigma_{\text{obj}}$ is dominated by the noise. Our simulations show that actually, at all $a > 1.3a_e$, the signal of our spectra is such that we cannot reliably measure velocity dispersions which are $\lesssim 100$ km s$^{-1}$. Therefore all values of $\sigma$ at $a > 1.3a_e$ are conservatively discarded.

A comparison of our measurements with the same literature data of Fig. 2 is provided in Fig. 5. Furthermore, comparison with Kormendy & Richstone (1992) is provided in Fig. 6.

3. Theoretical models

The analysis of the data presented above requires fitting the light profiles and the rotation velocity curve with analytical forms. The photometry (Capaccioli et al. 1987) was fitted to the projection of a Jaffe law which, for ease of computation of the potential gradients, was modified as follows:

$$\rho(m^2) = \rho_0 \frac{R_j^4}{m^2(m^2 + R_j^2)}$$  \hspace{1cm} (2)

where

$$m^2 = R^2 + \frac{z^2}{c^2}$$  \hspace{1cm} (3)

with $c$ the intrinsic flattening of the bulge, and $R_j$ a parameter to be fitted. This form of the density distribution has the same asymptotic behavior as Jaffe’s law (Jaffe 1983) for small and large $m$’s, but leads to simpler potential gradients. Figure 7 shows the fit to the observed minor–axis light profile, which represents the pure bulge since NGC 3115 is close to edge–on view. The reduction to the major axis, taking into account the variable flattening of the bulge isophotes (Table 8 in Capaccioli et al. 1987), is also given; the excess light in the observed profile is entirely due to the edge–on disk (Capaccioli, Vietri & Held 1988). The best fitting Jaffe radius for the major axis is $R_j = 92''$, almost coincident with the effective radius of the bulge (Table 1).

An analytical approximation to the observed rotation velocity curve,

$$v_{\text{rot}} = \frac{v_\infty R}{R + R_c}$$  \hspace{1cm} (4)

is shown in Fig. 8, with $v_\infty = 260$ km s$^{-1}$, and $R_c = 2''5$.

The question we are interested in is whether NGC 3115 has dark matter within the radius for which observational data are available. Thus, in a first approximation, we build self-gravitating, constant $M/L$ models, which must satisfy the constraints provided by the photometric and spectroscopic observations.

Models of ellipsoidal systems based on Jeans’ equations (Binney & Tremaine 1987) can be built provided that extra assumptions are introduced to close the system. One reasonable such assumption, discussed by Binney, Davies & Illingworth (1990; hereafter BDI), is that the distribution function depends only on the two classical integrals of motion in an axially symmetric potential, the energy $E$ and the $z$–component of the angular momentum $L_z$. Under such circumstances, the velocity dispersion along the $z$–axis equals that along the $R$–axis, thus closing the system of Jeans’ equations. A variation of the method of BDI is discussed in the Appendix. It shall be borne in mind that all of our models depend also on the accuracy of the assumption that the galaxy is oblate. It is well–known that NGC 3115 has a nearly perfectly edge–on disk (Capaccioli et al. 1988); this, and an argument based on its
resemblance to NGC 3379 (Capaccioli et al. 1991), lead us to expect that such an assumption should be roughly correct. In this case, the apparent flattening of NGC 3115 coincides with its intrinsic flattening, and can immediately be inserted into Eq. 2 and in the computation of the potential gradients.

The effect of the disk is included: it has been modelled as an exponential disk with zero thickness, scale–length \( r_o = 25.5'' \) and \( M/L = 7 \) (Capaccioli, Vietri & Held 1988). Comparison with models without disk shows that its dynamical influence is negligible at all radii, consistent with its accounting for only \( \approx 6\% \) of the total light. For galaxies with massive haloes, the presence of a disk can only make matters worse: in fact, the presence of the disk reduces the bulge contribution in the central parts, and thus also reduces the predicted rotation and velocity dispersion curves in the outer parts, where the disk contribution has died away.

The main result of this analysis is shown in Fig. 9. Here, the observed velocity dispersion along the line of sight is compared to the prediction of the model. Two different curves are presented: the dashed one includes a central mass concentration (black hole as in Kormendy 1987, where the relevant parameters are given), with which the fit to the kinematical data in the innermost regions of the galaxy is improved. The presence of this black hole, whose dynamical importance in the outermost regions is of course negligible, still indirectly affects our modeling, since it reduces the amount of matter needed to fit the observational data, and thus reduces the \( M/L \) of the visible matter, assumed independent of radius. In fact we see that the model without the black hole fits the outer data somewhat better than the model with the black hole. We obtain \( M/L = 6.5 \) in solar units for the model without black hole, and \( M/L = 6 \) for the model with black hole.

However, the most interesting feature of Fig. 9 is that none of the models can follow the roughly flat behavior of the observed velocity dispersion for \( R \gtrsim 0.5 R_J \). It is easy to understand that, given the above assumptions, our data must lead to a physically unacceptable model. In fact, we have no evidence for a decrease in either the rotation velocity or velocity dispersion, while in an isotropic self–gravitating Jaffe model both must decrease over the radial range observed by us. The rotational velocity \( (\equiv (-R\phi/\partial R)^{1/2}) \), which of course is an upper limit to the observed one because of the contribution of the velocity dispersion to the model’s support against self–gravity, is shown in Fig. 8 (dashed line) for the assumed modified Jaffe model with a run of ellipticity as in Table 8 of Capaccioli et al. (1987). It can be easily seen that such rotational velocity decreases, contrary to our evidence. Thus our data alone are sufficient to exclude a self–gravitating model with constant \( M/L \).

On the basis of our models it is less easy to estimate the magnitude of the mass discrepancy in the outer parts. Fig. 9 shows that both curves predict \( \sigma_V^2 = 0 \) for observ-
able radii, $R \simeq 0.8R_J$ for both models. Clearly, such results depend on our assumptions, in particular on having assumed the galaxy to be oblate and $\sigma_z^2 = \sigma_R^2$. It may be possible, by relaxing such constraints, to build a better-fitting model. Still we would like to point out that, from our data, there is a minimum $M/L$ for any model of this galaxy. In fact, we know that, for $R = 180\prime\prime$, it is $v_{rot} \approx 260 \text{ km s}^{-1}$. A minimum $M/L$ model will have from there on $\sigma_z = \sigma_\phi = \sigma_R = \sigma_V = 0$; then the minimum $M/L$ can be estimated by equating, at that galactocentric distance, centrifugal and gravitational accelerations. We obtain ($M/L)_{\text{min}} = 10$ in solar units. It is well-known, however, that the inner rotation curve ($R < 0.5R_J$) can be fitted with $M/L = 6$ (Illingworth & Schechter 1982, Rubin et al. 1980), so that we now find a discrepancy of at least a factor of 2 in $M/L$ while moving from $R \simeq 0.5R_J$ to $R \simeq 2R_J$. It is easy to understand this from Fig. 7, which shows that $L$ changes by only 20% from $R = 90\prime\prime$ to $R = 180\prime\prime$, while the minimum mass $M_{\text{min}}(R) \propto R v_{rot}^2$ doubles over the same range, for our flat rotation curve (Fig. 8).

3. There is a simple argument to show that the disk is not only unimportant from the photometric point of view, but also from the dynamical point of view.

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Appendix

We summarize here the method used to analyze the kinematical data, which is similar to that developed by BDI. We model the galaxy as a modified Jaffe model (MJM, from now on), with density constant on self-similar ellipsoids

$$m^2 = x^2 + y^2 + z^2 \frac{c^2}{e^2}$$

($c$ is the true axial ratio) and density profile

$$\rho = \frac{1}{2\pi^2 c (R_2 + R_1)(m^2 + R_1^2)(m^2 + R_2^2)}$$

where the total mass $M = 1$ and $R_2 \gg R_1$ are two constants. The introduction of a second scale parameter ($R_1$, much smaller than any observed radius) is used to simplify the computation of the gravitational potential.

The model that we are trying to fit to the observational data must satisfy Jeans’ equations. Now we assume that the system that emits the light is oblate and self-gravitating (i.e., it has constant mass-to-light ratio), and has velocity dispersion $v_z^2$ along the $z$-axis equal to that along the $R$-axis, $v_R^2$. The first two assumptions are obvious, the third one is discussed by BDI. Then Jeans’ equations for this model in cylindrical coordinates are

$$\frac{\partial(\rho \sigma_R^2)}{\partial R} + \rho \left(\frac{\sigma_R^2 - v_R^2}{R} + \frac{\partial(\phi + \phi_{\text{ext}})}{\partial R}\right) = 0$$

$$\frac{\partial(\rho \sigma_z^2)}{\partial z} + \rho \frac{\partial(\phi + \phi_{\text{ext}})}{\partial z} = 0$$

Here $\phi$ is the gravitational potential self-consistently engendered by the light-emitting system, and is given for reference below in explicit form in the case in which $c$ is independent of radius, and $\phi_{\text{ext}}$ is the disk potential, computed for an infinitely thin exponential disk (Binney & Tremaine 1987), with the parameters described in Section 4. Clearly, since $\rho$ and $\phi$ are supposed known, these two coupled equations become a system of two unknowns, $\sigma_z^2 = \sigma_R^2$ and $v_R^2$, which can be readily solved numerically.

4. Summary and conclusions

This is the first paper of a series based on deep major-axis spectra of bulge-dominated edge-on S0’s, obtained by using EFOSC in combination with the ESO 3.6m telescope and, in this one case only, EMMI at NTT as a check for our unconventional use of EFOSC. Aim of this series is to report on direct kinematical evidence of dark matter haloes within the optical images of galaxies related to “disky” E’s, i.e. that half of all normal ellipticals which do not offer any other way for probing the occurrence of dark haloes. We summarize briefly our conclusions:

1. We have measured the rotation curve of NGC 3115 out to a galactocentric distance $\approx 2a_c$, where the surface brightness is $\approx 20\%$ of that of the night sky. It increases steeply in the galaxy core, then remains constant (within 10%) at $v_f = 260 \text{ km s}^{-1}$ out to $2a_c$. Similarly, the observed velocity dispersion peaks sharply at the center (with a maximum of $325 \text{ km s}^{-1}$), decreasing outwards till it flattens out at the level of $\approx 100 \text{ km s}^{-1}$; reliable measurements are limited to $a < 1.3a_c$. There is a marginal indication from the EMMI spectra that $\sigma$ decreases for $a \gtrsim 2\prime$.

2. Our simple-minded models, assuming oblateness, constant $M/L$, and $\sigma_z^2 = \sigma_R^2$, predict vanishing velocity dispersions along the line of sight, well within our observed range. We have argued in a qualitative way that fitting our data with $M/L = \text{const}$, is unlikely, even when the aforementioned assumptions are relaxed. Also, we have shown that a simple argument implies that, within our observed range, $M/L$ increases by at least a factor of $\approx 2$, from $M/L = 6$ in the center to $M/L = 10$ at our outermost radius ($1.8a_c$).
The total velocity dispersion $v^2_{\phi}$ thus determined includes contributions from both the rotational velocity and the true velocity dispersion:

$$v^2_{\phi} = v^2_{\phi, rot} + \sigma^2_{\phi}$$

(9)

On the other hand, observations give us $v^2_{\phi, rot}$, which can be subtracted from $v^2_{\phi}$ to yield $\sigma^2_{\phi}$. We now have all the principal components of the velocity dispersion tensor, and can thus project them (see for instance Binney & Mamon 1982) to give $\sigma^2_{V}$, the velocity dispersion along the galaxy major axis, and this can be compared with the observed quantity $\sigma^2_{obs}$. However, we still have the extra freedom of an unknown multiplicative constant, essentially the $M/L$ of the galaxy. In keeping with the spirit of the model, which is self-gravitating and thus ought to reproduce the kinematics of the inner regions of the galaxy, we fix the $M/L$ by demanding that the theoretically determined $\sigma^2_{V}$ fits $\sigma^2_{obs}$ in the inner regions of the galaxy.

Now our model has no free parameters left, and ought to reproduce $\sigma^2_{obs}$ in the whole observable region.

The main difference between our method and that of BDI lies in the fact that we treat the surface photometry as if the light profile were of the Jaffe type everywhere, while they use a Lucy algorithm to deproject the two-dimensional image (or close to this: they have light-emission profiles along a number of PAs). We compensate for this by taking for the axial ratio $c$ not a constant, but the actual observed run with $R$. Since the determination of $c$ in standard packages essentially requires observations along 3 PA’s (we discard the term $\pi c \cos \theta$), this compares reasonably well with BDI, who had data along 7 PA’s. Also, since NGC 3115 is seen edge-on, the axial ratio $c$ is not a free parameter for us, since $c = c_{obs}$. Lastly, BDI do not subtract the observed velocity rotation curve like we do. But since in this case the data for $\sigma^2_{obs}$ and $v_{\phi, rot}$ are coextensive, the method adopted here seemed the most appropriate one.

We give here for reference the gradients of the gravitational potential engendered by the flattened MJM, for the case of constant axial ratio $c$. In these formulae, some simplification is possible through the fact that the density (Eq. 10) can be rewritten as

$$\rho = \frac{1}{2\pi^2 c} \left( \frac{1}{m^2 + R_1^2} - \frac{1}{m^2 + R_2^2} \right)$$

(10)

Such potential is available through well-known implicit formulae (e.g. Binney & Tremaine 1987). We define $R^2 \equiv x^2 + y^2$, take $G = 1$, and omit the algebra, to find

$$\frac{\partial \phi}{\partial R} = -\frac{2R}{\pi (R_2 - R_1)} \left[ X(R_1) - X(R_2) \right]$$

(11)

where

$$X(R_i) = \frac{1}{R_i^2} \left[ g(\tau_1, \tau_2, 1) + g(\tau_2, 1, \tau_1) + g(1, \tau_1, \tau_2) \right]$$

(12)

Here we have defined $\tau_1 < \tau_2$ as the moduli of the solutions of

$$R_i^2 \tau^2 + \left[ (1+c^2) R_i^2 + z^2 + R^2 \right] \tau + R_i^4 c^2 + z^2 + R^2 c^2 = 0$$

(13)

(which, of course, depend on $R_i$), and

$$g(\tau_1, \tau_2, x) = \frac{(1-c^2)^{1/2}}{(\tau_2 - \tau_1)(x - \tau_1)} \left[ \frac{\pi}{2} - \arctan \frac{c}{(\tau_1 - c^2)^{1/2}} \right]$$

(14)

Analogously, we find

$$\frac{\partial \phi}{\partial z} = -\frac{2z}{\pi (R_2 - R_1)} \left[ Y(R_1) - Y(R_2) \right]$$

(15)

with

$$Y(R_i) = \frac{1}{R_i^2 (\tau_1 - \tau_2)} \left[ h(\tau_2) - h(\tau_1) \right]$$

(16)

$$h(\tau) = \frac{\pi}{2} - \arctan \frac{c}{(\tau - c^2)^{1/2}}$$

(17)

and the $\tau$’s are defined as above.

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