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The *z*-structure of the disc of NGC 3115

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Summary. We have analysed the photometric observations of the edge-on disc of NGC 3115 presented by Capaccioli, Held & Nieto. By deprojection of the observed major axis light profile, it is shown that, outside the central region where the disc fades ($R<20''$), the face-on surface brightness is accurately described by the usual exponential law, with a scale-length $\alpha_c^{-1}=1.2$ kpc, and an extrapolated central value $\mu_0=21.7$ *B*-mag arcsec^{-2}. The deprojected scale-height in the *z*-direction is not constant with the galactocentric distance *R*. Its linear flare-up at $R\simeq75''$ suggests that the disc ceases to be self-gravitating at this radius, which implies $M/L_B=7$ (same as for the bulge). The radial dependence of $\langle V_z^2\rangle^{1/2}$ is also deduced; the mean value (~25 km s^{-1} for $R>75''$), rather high for a disc with no gas, suggests that, in the past, the disc of NGC 3115 possessed a fair amount of gas.

1 Introduction

While the *z*-structure of the disc of spirals has been extensively investigated (van der Kruit & Searle 1982, and references therein), little is yet known about their analogues in S0s. Recently, Capaccioli, Held & Nieto (1987) have derived the following photometric and structural properties of the disc of the classical edge-on S0 galaxy NGC 3115:

(a) The integrated *B*-luminosity is 5 per cent of the total luminosity of the galaxy; adopting B_T^0 (NGC 3115)=9.40, $M_{B,\odot}=5.48$, and a distance of $\Delta=\delta\times10$ Mpc ($1''$ equivalent to 48.5 pc$\times\delta$), then $L_B(\text{disc})=1.35\times10^9\,L_{B,\odot}\times\delta^2$.

(b) The major axis light profile (Fig. 1) is only roughly exponential from $R\simeq20''$ (1 kpc$\times\delta$) over the observed range (to $R=135''$ or 6.8 kpc$\times\delta$), with a mean scale-length $\alpha^{-1}=18\farcs1$ ($=0.9$ kpc$\times\delta$).

(c) The innermost profile is perturbed by the presence of dust lanes and possibly drops inside $R\simeq10''=0.5$ kpc$\times\delta$.

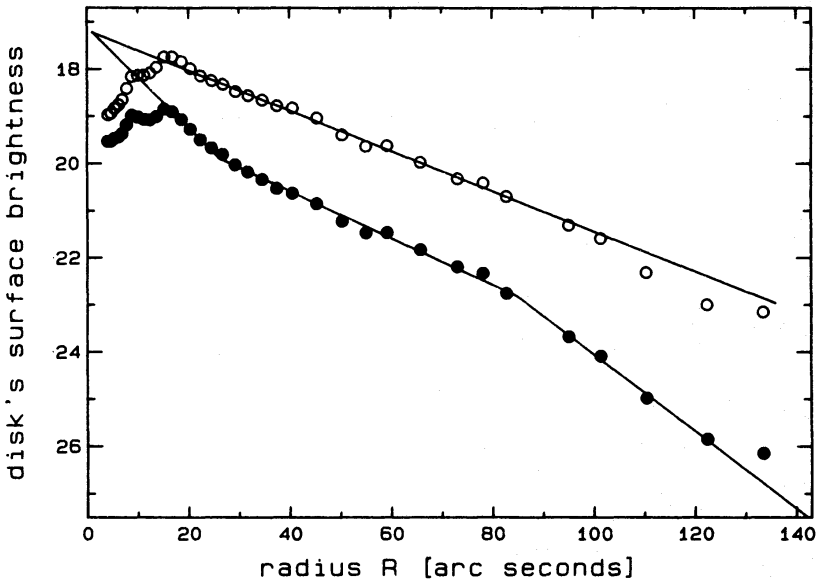

Figure 1. Closed circles represent the observed light profile of the disc of NGC 3115 along the major axis. The overimposed broken line is the interpolation used in the numerical integration. Open symbols give the light profile of the disc reduced to a constant scale-height $z_0=1''$. The linear fit (solid line) corresponds to an exponential with a scale-length $\alpha_c^{-1}=25''.5$.

(d) Over the observed interval ($5''<R<100''$), the light profiles normal to the disc's major axis are definitely parabolic, $\mu(R,z)=\mu_0(R)[1+z^2/Z_0^2(R)]$.

(e) The disc's scale-height z_0 increases steadily with galactocentric distance inside $R\simeq 40''(=2\,\mathrm{kpc}\times\delta)$ and outside $R\simeq 80''(=4\,\mathrm{kpc}\times\delta)$, while it flattens up in the intermediate range (Fig. 2).

(f) There is a hint of spiral arms in the range $70''<R<100''$, already noted by Strom *et al.* (1977).

We give here a dynamical interpretation of the structure of this disc, taking advantage of the featureless flat rotation curve (Rubin, Peterson & Ford 1980) which simplifies the modelling of the overall potential field.

2 Photometric analysis

The major-axis light profile of the disc of NGC 3115 has been integrated along the z-axis to compare it with those of face-on spiral galaxies. The light distribution, $\mu_c(R)=\mu_0(R)-2.5\log Z_0(R)$, corresponds to an edge-on disc with constant scale-height $Z_0=1''$ (Fig. 1); it is exponential from outside the central 'hole' to $R=100''$, with a scale-length $\alpha_c^{-1}=25''.5$ (or $1.25\,\mathrm{kpc}\times\delta$). Note that, if the linear trend of $Z_0(R)$ in the range $75''<R<100''$ is extrapolated to $R=135''$ (where Z_0 would be $16''$), $\mu_c(R)$ is exponential to the last observed point.

Incidentally, the smoothness and linearity of $\mu_c(R)$ over a region ($20''<R<100''$), where the bulge's surface brightness varies by $\simeq 5$ mag, add confidence to the model of the bulge adopted by Capaccioli *et al.* (1987): it seems unlikely that the 'true' light profile of the disc and modelling errors should conspire to give a linear $\mu_c(R)$. The same argument rules out any major role of the dust (if present). One might then argue that the observed flaring of the disc is due to the presence of a slight outer warp. But the high degree of symmetry of the scale-height as measured in four quadrants of the disc requires an unlikely, near perfect alignment of the disc's apparent major-axis and the tilt axis of the warp. Since we observe this same symmetry in two more cases (Capaccioli *et al.* in preparation), also the face-on warp hypothesis can be ruled out.

The face-on surface intensity of light, $I(R)$, is given by inversion of the usual Abel-type integral equation (neglecting internal absorption). In the interval $20'' < R < 100''$, it is accurately approximated by $I(R) = I_0 K_0(\alpha_c R)$, where K_0 is a modified Bessel function. The extrapolated peak value, $I_0 = 141 \times L_{B,\odot}\ \mathrm{pc}^{-2}$, is fixed by equating the total luminosity, $2\pi I_0 \alpha_c^{-2}$, to the observed one, $L_B(\mathrm{disc})$.

Spatial deprojection of the disc scale-height (to the second order in the disc inclination) is given by

$$z_0^2(R) = -\frac{\pi R \psi(R)}{(d/dR)\displaystyle\int_R^{+\infty} [\Psi(t)/Z_0^2(t)][t\,dt/(t^2-R^2)^{1/2}]} \qquad (1)$$

where $\Psi(R) = 10^{-0.4\mu_0(R)}$ is the observed light surface brightness along the disc major axis, and $\psi(R)$ is the usual deprojected light-density in the disc plane ($z=0$). The deprojected scale-height, z_0, does not differ significantly from the observed one, Z_0 (Fig. 2).

In conclusion, the disc of NGC 3115 looks similar to those of spirals (de Vaucouleurs 1959) in the behaviour of the light profile, which is close to an exponential $[I(R) = I_0 K_0(\alpha_c R)]$. On the other hand, this disc differs from spirals in that it has a very short scale-length $\alpha_c^{-1} = 1.2\ \mathrm{kpc} \times \delta$ (but with the 'standard' extrapolated face-on peak surface brightness $\mu_0 = 21.7$ *B*-mag arcsec^{-2}; Freeman 1970), a small total mass $M(\mathrm{disc}) = 1.35 \times 10^9 \times (M/L_B)\, M_\odot \times \delta^2$, and a scale-height, z_0, which is not constant.

3 Dynamical analysis

We now turn our attention to the disc scale-height z_0. Since both self- and external gravity may be important, the usual expression for the first moment of the Vlasov equation along z (Spitzer 1942)

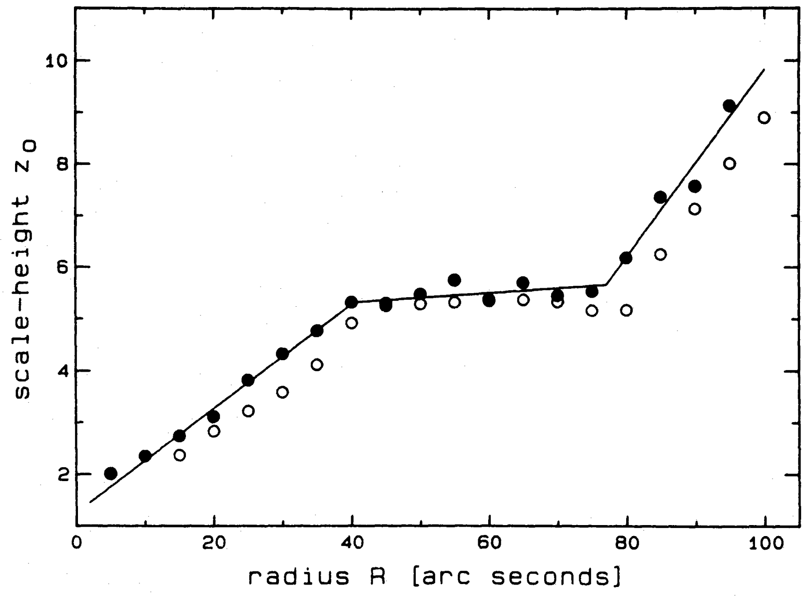

Figure 2. Closed circles are average measurements of the scale-height z_0 of the disc of NGC 3115 at various galactocentric distances. Typical errors of the individual data points are $\Delta z_0 \simeq \pm 1''$. The schematic interpolation used in the text is plotted as a solid line. Deprojected values of z_0 are also shown as open circles.

must be modified by adding the external gravity,

$$\frac{d^2 \ln \varrho(R,z)}{dz^2} = -\frac{4\pi G\varrho}{\langle V_z^2\rangle} - \frac{V_{\rm rot}^2}{\langle V_z^2\rangle}\,\frac{1/q_\phi^2}{R^2+R_0^2}, \tag{2}$$

where ϱ is the mass density distribution of the disc, and $\langle V_z^2\rangle^{1/2}$ the disc dispersion velocity, supposed independent of z. Guided by the extreme flatness of the rotation curve, we assume the external potential to be $\Phi=\frac{1}{2}V_{\rm rot}^2 \ln(R_0^2+R^2+z^2/q_\phi^2)$. The potential's flattening, q_ϕ is a weakly varying function of R. The observed flattening of the bulge is at least $b/a=0.7$ and at most $b/a=0.4$; thus, the error we make on $\langle V_z^2\rangle^{1/2}$ by taking $q_\phi=1$ will be at most of a factor of 1.5 (note that the potential is rounder than the density distribution). The observations (Rubin *et al.* 1980) give $V_{\rm rot}\simeq 300\ {\rm km\ s^{-1}}$, constant in the range $20''<R<100''$, and $R_0=18''$. The solution of equation (2) is $\varrho(R,z)\simeq\varrho_0(R)(1-z^2/z_0^2)$, where

$$z_0^2 \equiv \frac{H_0^2}{1+H_0^2/2\sigma^2}, \qquad H_0^2 \equiv \frac{\langle V_z^2\rangle}{2\pi G\varrho_0(R)}, \qquad \sigma^2 \equiv \frac{\langle V_z^2\rangle}{V_{\rm rot}^2}\,(R^2+R_0^2), \tag{3}$$

is given to the lowest order in z^2: the presence of the underlying bright bulge limits the observations to $|z|<2z_0$, preventing measurement of the higher order terms in the Taylor expansion of $\mu(R,z)$.

Whether the z-structure of the disc is determined by self-gravity or by the external gravity depends upon the relative importance of the two terms on the rhs of equation (2). Balance occurs at $R=R_{\rm c}$, where

$$(R_{\rm c}^2+R_0^2)\varrho_0(R_{\rm c}) = \frac{V_{\rm rot}^2}{4\pi G} = (R_{\rm c}^2+R_0^2)\varrho_0(0)\ \exp\,(-\alpha_{\rm c} R_{\rm c}); \tag{4}$$

the last equality holds for an exponential disc. Outside $R_{\rm c}$, external gravity dominates, and the disc scale-height increases linearly (equation 3) provided $\langle V_z^2\rangle$ is almost independent of R. *A priori*, we do not know the behaviour of $\langle V_z^2\rangle$ with R, but, by analogy with spirals (van der Kruit & Searle 1982), we may expect the scale-height to remain constant wherever self-gravity dominates. In other words, we suggest to identify $R_{\rm c}$ with the flare-up point of the disc scale-height. Inspection of Fig. 2 gives $R_{\rm c}\simeq 75''$, with which $\Sigma_0=10^3\,M_\odot\ {\rm pc^{-2}}\times\delta^{-1}$, a value often quoted for the galactic disc (Bahcall, Schmidt & Soneira 1982). The corresponding $M/L_B=7\times\delta$ is quite reasonable and almost identical to the mass-to-light ratio of the entire galaxy within the same isophote (Rubin *et al.* 1980).

One can also solve equation (4) for $R_{\rm c}$ assuming a value of M/L_B. For $M/L_B\leqslant 10$, then $R_{\rm c}\leqslant 100''$. This strengthens the confidence in our interpretation of the flare-up shown in Fig. 2, and suggests that it is the same phenomenon discussed for spirals by van der Kruit & Searle (1982), but not detected by them.

Our estimate of M/L_B is independent of which fraction of the rotation curve is due to any 'spherically distributed' dark matter, and of the value of $\langle V_z^2\rangle^{1/2}(R_{\rm c})$ (equation 4). In turn, $\langle V_z^2\rangle^{1/2}$ is independent of M/L_B outside $R_{\rm c}$; in fact, if self-gravity is negligible, equation (3) yields $z_0^2\simeq 2\sigma^2\equiv 2(R^2+R_0^2)\langle V_z^2\rangle/V_{\rm rot}^2$. Comparison with Fig. 2 then gives $\langle V_z^2\rangle^{1/2}\simeq 25\ {\rm km\ s^{-1}}$. This figure is again typical for spiral galaxies (Mihalas & Binney 1982).

The radial run of $\langle V_z^2\rangle$ depends on the way M/L_B varies with radius. Fig. 3 shows $\langle V_z^2\rangle^{1/2}(R)$, formally computed from equation (3) for a set of constant values of M/L_B, including our best estimate.

In summary, the above analysis shows that, even if fairly light, the disc of NGC 3115 is most likely self-gravitating inside $R\simeq 75''$, and has $M/L_B\simeq 7\times\delta$. In the intermediate range $40''<R<75''$ the disc scale-height is constant, as it is for most spirals. The mean value of $\langle V_z^2\rangle^{1/2}\simeq 25\ {\rm km\ s^{-1}}$

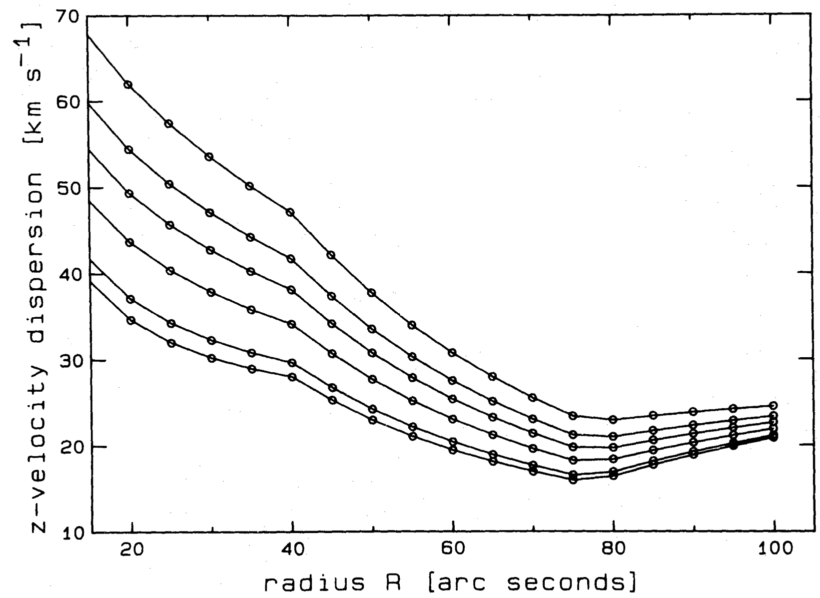

Figure 3. z-velocity dispersion computed from equation 3 for M/L_B(disc)=0, 1, 4, 7, 10, 15 (curves from bottom to top).

appropriate for this range (Fig. 3), again agrees with those of normal spirals. Note that the asymptotic value of $\langle V_z^2\rangle^{1/2}$ is not significantly reduced by assuming $M/L_B=0$ (bottom line in Fig. 3), but it might be increased by a factor of ~1.5 if the potential's flattening q_ϕ were taken into account. However, inside $R=40''$, the disc scale-height decreases almost linearly, contrary to ordinary spirals where it is still constant inside $R\simeq\frac{3}{2}\alpha^{-1}$ (van der Kruit & Searle 1982). Since we have argued that the external gravity is not dominant for $R<75''$, then $z_0^2\simeq H_0^2=\langle V_z^2\rangle[2\pi G\varrho_0(R)]^{-1}$, which implies that the inward decrease of z_0^2 must be due to an insufficiently rapid increase of $\langle V_z^2\rangle$ with respect to ϱ_0. Why this should be so, is not clear. It is clear, however, that the thinning of the disc in the region $20''<R<40''$ is not related to the presence of a central hole, if any: the total surface density (i.e. the surface brightness, $\mu_c(R)$, corrected for the varying disc scale-height; Fig. 1) is still accurately exponential in this range.

Lastly, we remark that the stellar disc of NGC 3115 seems very stable against spiral arm formation. We have computed Toomre's (1964) Q parameter, with the radial velocity dispersion $\langle V_r^2\rangle^{1/2}$ taken as $\langle V_r^2\rangle^{1/2}=2\langle V_z^2\rangle^{1/2}$ (appropriate for the galaxy; Mihalas & Binney 1982). It is easily seen that $Q>Q_{\rm crit}\simeq3$ for all $M/L_B\leq15$, where $Q_{\rm crit}$ is the threshold value for spiral activity to take place (Toomre 1981). This is in contrast with the spiral arms found by Capaccioli *et al.* (1987) in the region $70''<R<100''$ of the disc of NGC 3115.

4 Discussion

In summary, we have determined the mass-to-light ratio at R_c and the value of the vertical velocity dispersion appropriate to the outer part of the disc of NGC 3115. These results are dependent on the assumption that the flare-up of the disc's scale-height occurs where external gravity begins to dominate over self-gravity.

The disc of NGC 3115 has many properties in common with spiral galaxies. It is exponential, even in the region where it is unlikely to be self-gravitating ($R>R_c\simeq75''$). Its extrapolated central mass density, $\Sigma_0=980\,M_\odot\,{\rm pc}^{-2}\times[1(1/7)(M/L_B)]$, is appropriate to a normal galaxy such as ours. The value of $\langle V_z^2\rangle^{1/2}$ is reasonable everywhere (Fig. 3). The z-structure shows a clear constant scale-height region, just like ordinary spirals, with a thickness ($z_0\alpha_c \simeq \frac{1}{5}$, $40'' < R < 75''$), well within the range of values in table 2 of van der Kruit & Searle (1982).

On the other hand, there are some properties which make the disc of NGC 3115 dissimilar from those of ordinary spirals. First, it has a low total mass, $M = 9.5 \times 10^9 M_\odot$, and, as a consequence of the 'normality' of Σ_0, a short scale-length $\alpha_c^{-1} = 1.2$ kpc. Secondly, the scale-height in the innermost region ($R < 40''$) is not constant, linearly decreasing with radius.

The existence of a 'normal' range of values for $\langle V_z^2 \rangle^{1/2}$ is also somewhat surprising. The usual mechanism for accelerating stars in the discs of spiral galaxies is through encounters with giant molecular clouds (Spitzer & Schwarzschild 1951). But there is no trace of gas in NGC 3115, which is not even an *IRAS* source. It is tempting to take this fact as an indirect evidence that, some time in the past ($\sim 10^9$ yr; Larson, Tinsley & Caldwell 1980), this S0 galaxy, formerly known as a standard E7 galaxy (Hubble 1930), may have had a significant gaseous disc, unless one favours more exotic proposals such as encounters with massive ($\sim 10^6 M_\odot$) black holes (Lacey & Ostriker 1986). Two-dimensional colour distributions should help in determining whether the disc and bulge populations share the same evolutionary history. This work is in progress.

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