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IC3328: A "dwarf elliptical galaxy" with spiral structure*

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Abstract. We present the 2-D photometric decomposition of the Virgo galaxy IC3328. The analysis of the global light distribution of this morphologically classified nucleated dwarf elliptical galaxy (dE1,N) reveals a tightly wound, bi-symmetric spiral structure with a diameter of 4.5 kpc, precisely centered on the nucleus of the dwarf. The amplitude of the spiral is only three percent of the dwarf's surface brightness making it the faintest and smallest spiral ever found in a galaxy. In terms of pitch angle and arm winding the spiral is similar to the intermediate-type galaxy M51, but it lacks the dust and prominent H II regions which signal the presence of gas. The visual evidence of a spiral pattern in an early-type dwarf galaxy reopens the question on whether these dwarfs are genuine rotationally supported or anisotropic stellar systems. In the case of IC3328, we argue for a nearly face-on disk (dS0) galaxy with an estimated maximum rotation velocity of $v_{\rm c,max} \approx 55\,{\rm km\,s^{-1}}$. The faintness of the spiral and the small motions within it, suggests that we could be seeing swing-amplified noise. The other possibility is a tidal origin, caused by the near passage of a small companion.

Key words: galaxies: dwarf – galaxies: elliptical and lenticular, cD – galaxies: individual: IC3328 – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: structure

1. Introduction

In this paper we report on the serendipitous discovery of a spiral structure in the Virgo cluster dwarf elliptical IC3328. The presence of spiral structure provides compelling evidence for the disk nature of that particular dwarf galaxy. The observations are described and the light distribution is analysed in Sect. 2. In Sect. 3 we estimate the kinematical properties of the dwarf galaxy from the observed light distribution, assuming a likely value for the mass-to-light ratio and distance. We speculate on the origin of the spiral pattern in Sect. 4. The concluding section deals with the ramifications for the dwarf elliptical taxonomy arising from IC3328.

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2. Photometric evidence for a spiral structure

IC3328 is known as an early-type dwarf galaxy in the Virgo cluster, morphologically classified as dE1,N (Virgo Cluster Catalog 856, Binggeli et al. 1985). The redshift of $v_\odot = 972 \pm 32$ km s^{-1} made this galaxy a probable cluster member and a good candidate for a more refined distance determination based on the Surface Brightness Fluctuations (SBF) method. Candidates for the SBF method should have smooth and symmetric light distributions, and show no obvious dust or star-forming regions.

The first step in applying the SBF method is to determine the mean 2-D surface brightness distribution by suitable averaging and then subtracting it from the galaxy image, leaving just the fluctuating part which arises from the Poisson distribution of the stellar sources, ie. the fluctuations due to unresolved stars in the galaxy. However in the case of IC3328 the residuals were most surprising. The composite of three 400 sec R-band images of IC3328 obtained at the VLT with the FORS1 multi-mode instrument in Service Mode on July 13, 1999 under excellent seeing conditions ($0.6''$) is shown in the left panel of Fig. 1. The surface brightness "fluctuations" obtained after subtracting the mean is shown in the right panel.

Clearly "fluctuations" is not the right word to describe the exceptionally regular spiral whose amplitude is so low that it remained invisible in the original exposure. The spiral structure is confined to the inner $30''$ of the galaxy which has an isophotal radius of $r_{R,27}$=80$''$. It appears that we have discovered the real nature of IC3328: a seemingly dust-free disk galaxy with unusually faint spiral structure.

The initial analysis of the light distribution in IC3328 followed the traditional route, based on standard IRAF procedures. The nuclear offsets determined by fitting ellipses to the light distribution were perfectly normal (top panels of Fig. 2). The first signs of unusual behaviour came from the ellipticity and position angle variations of the ellipse fits. The coherent wiggles at smaller radii ($r < 30''$) suggested interesting, but low level structure, which could be seen as a spiral pattern in the contour maps.

Contour maps, and in particular the smoothed contour maps reconstructed from the ellipse fits are powerful tools for revealing faint structure, but are not immediately suitable for quantitative analysis of the light distribution. The presence of a smooth

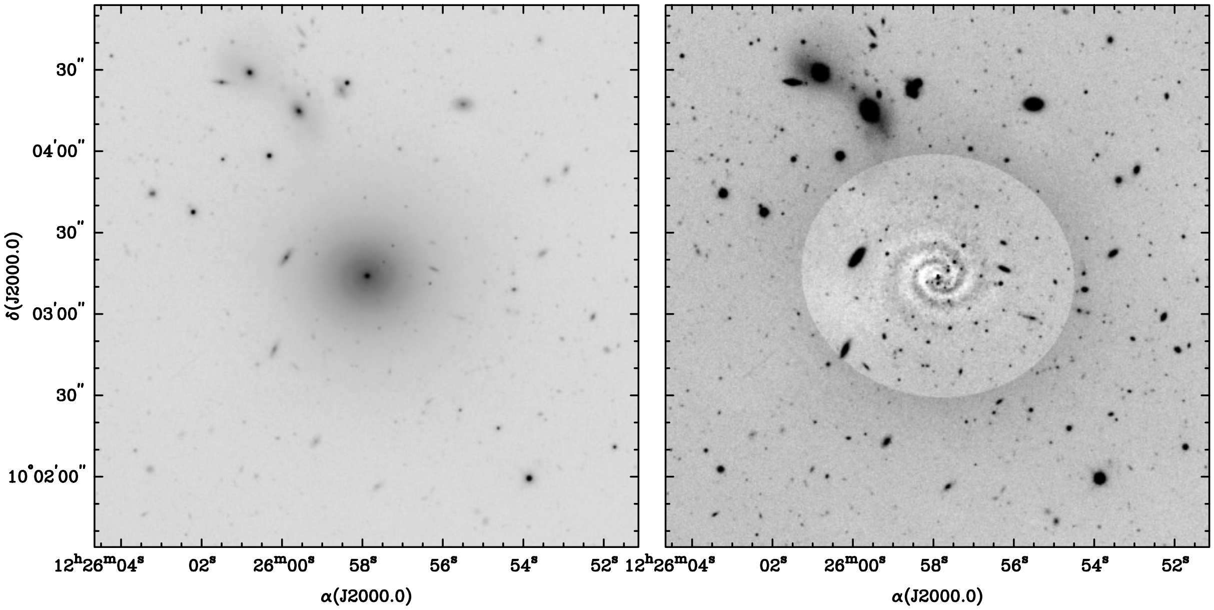

Fig. 1. The deep R-band CCD image of IC3328 (left panel) illustrates the overall morphology of this as dE1,N classified galaxy: a smooth radially decreasing light distribution with a centrally located nucleus. After the subtraction of the axis symmetric component, the residual image (right panel) reveals a prominent 2-armed spiral structure with a possible central bar.

spiral indicates that we are dealing with a disk or a disk embedded in a spheroidal mass distribution. The most straight-forward analysis consists of guessing the orientation of the disk and expanding the deprojected light distribution in a Fourier series in the azimuthal angle θ:

$$I(r,\theta) \;=\; I_0(r) + I_1(r)\cos[\theta-\theta_1(r)] \\ +\; I_2(r)\cos 2[\theta-\theta_2(r)] + \cdots \;.$$

The amplitude of the two-armed spiral, $I_2(r)$, is quite sensitive to changes in inclination, and less so to the position angle; a wrong inclination will produce modulations in the amplitude. An inclination of $25\overset{\circ}{.}2$ (which corresponds to the ellipticity $e = 0.095$), and the position angle of $82\overset{\circ}{.}5$ produced the smoothest two-armed component. The amplitude and phase of this spiral is shown in Fig. 3. The fractional amplitude of $3-4\%$ is extremely low.

The one-armed, or $\cos\theta$ terms become important close to the center ($< 5''$).

In the interval $5'' < r < 30''$ the phase $\theta_2(r)$ is well approximated by a straight line. Such a phase variation corresponds to a two-armed logarithmic spiral inclined at $12\overset{\circ}{.}1$ to a circle. The angular winding of the arms is $430°$. In these respects IC3328 resembles a Sb or Sbc galaxy very similar to M51 (Danver 1942; Kennicutt 1981), but without obvious gas, dust or bright H II regions.

The surface brightness profile derived from $I_0(r)$ is shown in Fig. 4. It can be approximated by two straight lines (exponentials), with the cross-over occuring at $r \simeq 30''$, which is also the place where the spiral pattern ends. The end of the spiral can be seen in the flattening of the phase in Fig. 3. The R surface brightness profile has the same characteristics as the B profile,

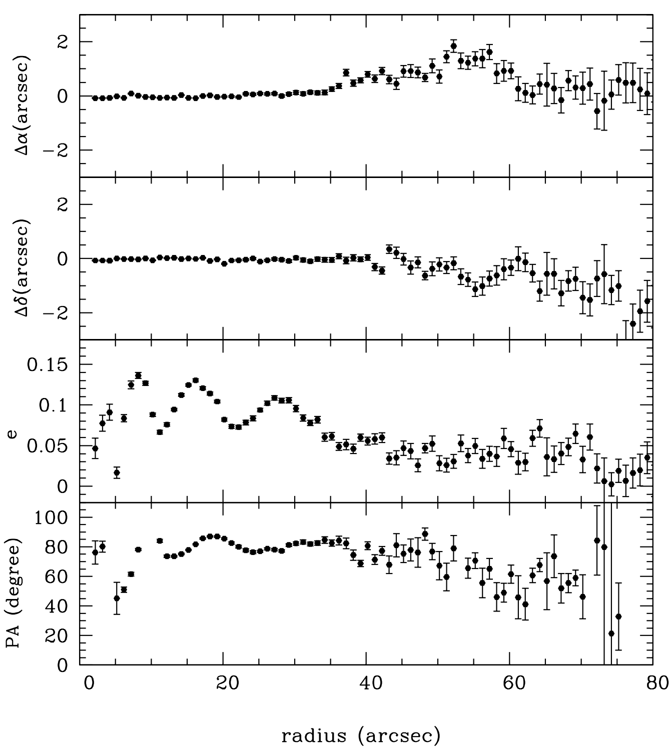

Fig. 2. The coordinate offset $\Delta\alpha$ and $\Delta\delta$ between the nucleus and the center of isophotal ellipses, ellipticity, and position angle (counterclockwise from north) shown as functions of radius.

which has been classified as type IIIb by Binggeli & Cameron (1991, hereafter BC91).

The total apparent magnitude, R_T, computed from $I_0(r)$ is 13.17. The half light radius $r_{\rm eff} = 15\overset{\prime\prime}{.}9$, and the mean sur-

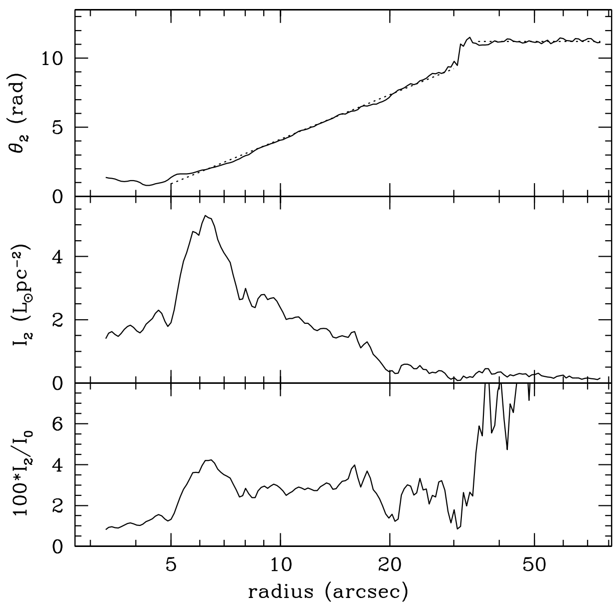

Fig. 3. Azimuthal phase (top panel) and amplitude (central panel) of the spiral as a function of radius. The logarithmic spiral approximation is shown by the sloping dotted line. The fractional amplitude of the spiral is plotted in the bottom panel.

face brightness within the effective radius $\langle\mu\rangle_{\rm eff} = 21.17$ mag arcsec^{-2}. The best-fitting line (exponential) of the inner part has a central surface brightness of $\mu^{\rm exp} = 19.95$ mag arcsec^{-2} and a scale length $r^{\rm exp} = 8.''7$.

3. Dynamics

In order to estimate the dynamical time scales associated with the spiral pattern we need to know the distance to and the velocities within IC3328.

There are two distance estimates for IC3328. The first comes from the radial velocity which coincides with the mean velocity of the Virgo cluster. It agrees well with the preliminary SBF distance of 15.5 Mpc (Jerjen et al. in preparation). At this distance $1''$ corresponds to 77.5 pc.

The only kinematic data available for IC3328 to date is a measurement of the central velocity dispersion of $\sigma_{\rm c} = 27\,{\rm km\,s^{-1}}$ (Peterson & Caldwell 1993). In the absence of a proper velocity field determination we have to resort to the light distribution and estimates of the mass-to-light ratio, M/L.

The square of the rotational velocity, $V_{\rm c}^2$, can be determined from $2\pi G\mu r$, where $\mu(r)$ is the projected surface mass density. On a logarithmic scale these two quantities are related by a convolution (Kalnajs 1999). Fig. 5 shows the relation between the two quantities in the case when $M/L = 1$. The two $V_{\rm c}^2$ curves correspond to the limiting cases where the projected surface density comes from a flat or a spherical mass distribution. Fig. 5 also makes it clear that the value of M/L around the peak $2\pi G\mu r$ is what really matters.

Assuming $M/L = 1$ gives a maximum disk rotation velocity, $V_{\rm c,max} = 44\,{\rm km\,s^{-1}}$. A better estimate of $55\,{\rm km\,s^{-1}}$ comes from the average mass-to-light ratio for globular clusters

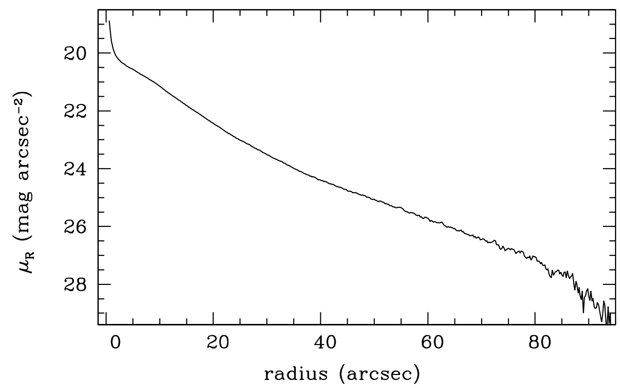

Fig. 4. The R-band surface brightness profile of VCC0856 exhibits a distinct bi-linearity, characteristic for a type IIIb profile (see BC91). The transition occurs at $r \approx 30''$ precisely where the spiral fades out.

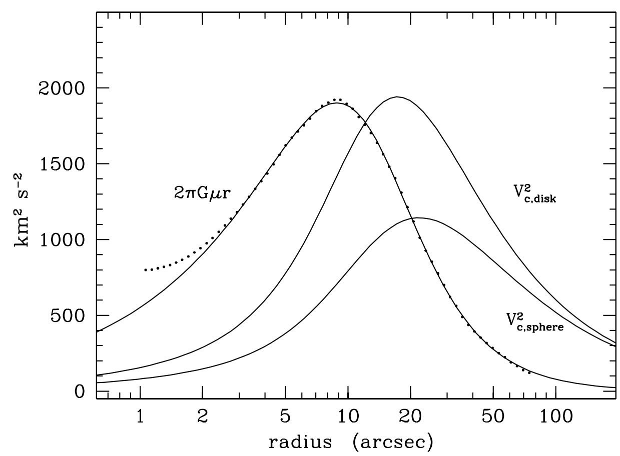

Fig. 5. A plot of $2\pi G\mu r$ and the two rotation curves, $V_{\rm c,disk}^2$ and $V_{\rm c,sphere}^2$, produced by it. The surface density $\mu(r)$ was obtained from $I_0(r)$ by assuming the $M/L = 1$ (in solar units). The $2\pi G\mu r$ curve is a Nuker profile fit to $2\pi G I_0(r) r$, shown by the dots.

$(M/L)_R = 1.6$, based on the quantities $(M/L)_V = 2.5$ (Pryor & Meylan 1993) and $(V-R)_0 = 0.47$ (Peterson 1993). Such a value does not clash with $\sigma_{\rm c} = 27\,{\rm km\,s^{-1}}$.

The best option would be to measure the rotation curve. Then one could use the above arguments to obtain the actual M/L ratio of IC3328.

The estimated peak rotation velocity of $55\,{\rm km\,s^{-1}}$ occurs around 1.4 kpc, which means that the angular rotation rate there is $39\,{\rm km\,s^{-1}}$ kpc^{-1}, a value comparable to the $25\,{\rm km\,s^{-1}}$ kpc^{-1}measured near the Sun. Thus IC3328 has had ample time to settle into an equilibrium.

4. Spiral structure

The presence of the spiral implies the presence of a disk. If what we see is a nearly face-on disk then the small spiral amplitude is quite unusual. We can estimate the mean displacements and velocities that are needed to produce the observed density contrast.

A density wave is created by coherent oscillations of stars around their equilibrium orbits. Because the spiral is tightly wrapped, the largest contribution comes from the radial displacements, δr, whose phases are rapidly varying functions of the equilibrium position r. If we write the phase as $\exp\{i[\alpha \ln(r) - 2\theta]\}$, then a little bit of algebra shows that the change in surface density, $\delta\mu$ satisfies the relation

$$|\frac{\delta\mu}{\mu}| \simeq |\alpha\frac{\delta r}{r}|$$

when $\alpha \gg 1$. For our spiral $\alpha = \frac{2}{\sin 12\overset{\circ}{.}1} = 9.5$, which means that when $\frac{\delta\mu}{\mu} \simeq 0.03$, $\frac{\delta r}{r} \simeq 0.003$, a very small number indeed!

In a similar spirit we can estimate the velocities, δV, associated with such displacements. The radial displacements will oscillate with a frequency typically less than the natural radial frequency κ, which in turn is roughly $\sqrt{2}$ times the mean angular rotation rate Ω. Hence $\frac{\delta V}{V_c} \simeq 0.005$, or $0.3\,\mathrm{km\,s^{-1}}$.

These small numbers can be increased by reducing the disk light contribution and attributing it to a spheroid. Even a ten-fold reduction would produce fractional displacements of 3%, and velocities of only $3\,\mathrm{km\,s^{-1}}$. Such low velocities are unlikely to lead to shocks in any neutral gas that may be present in the disk, and therefore to any star formation that would signal the presence of gas.

By reducing the disk light contribution we also reduce the importance of the spiral's self-gravity and increase the likelihood of a tidal origin. Fig. 6 shows several possible perturbers. When the self-gravity becomes negligible, one can rule out even a distant passage of a big perturber like NGC4380, since the tidal distortions will not propagate to the center. That leaves close passages by the fainter objects, such as the two VCC dwarf galaxies, as possible cause of the spiral seen in IC3328.

The other plausible scenario is that most of the light does come from the disk and we are seeing swing amplified noise (Toomre & Kalnajs 1991). The gain of the swing amplifier is not large enough to amplify the $\sqrt{N}$ stellar density fluctuations to the observed 3% level, but a small amount lumpy gas could provide the necessary leading perturbations which then are amplified by a factor of $10-30$ as the shear transforms them into a trailing spirals (Toomre 1981). Huchtmeier & Richter's (1986) upper limit of $\approx 6\cdot 10^7 M_\odot$ for the H I content of IC3328 does not rule out this possibility.

5. On the taxonomy of dwarf elliptical galaxies

Dwarf galaxies come in two basic brands: dwarf ellipticals (dEs) and dwarf irregulars (dIrrs). The common view is that dEs are spheroids and dIrrs are disks. In the case of irregulars, the disk nature is clearly indicated by the typical rotation pattern found in HI radio data (at least for dIrrs more luminous than $M_B = -12$). Owing to the absence of gas and hence the lack of an easily accessible kinematic tracer, the situation is less clear for dEs. The basic evidence for their spheroidal nature is purely statistical: the flattening distribution of this dwarf type is very similar to the one shown by normal ellipticals, which is distinctly different from disk galaxies (Ryden & Terndrup 1994; Binggeli & Popescu 1995). Supporting evidence for the spheroidal nature of dEs comes from spectroscopy. The measurements so far clearly show a lack of rotation (Paltoglou & Freeman 1987; Bender & Nieto 1990; Bender et al. 1991).

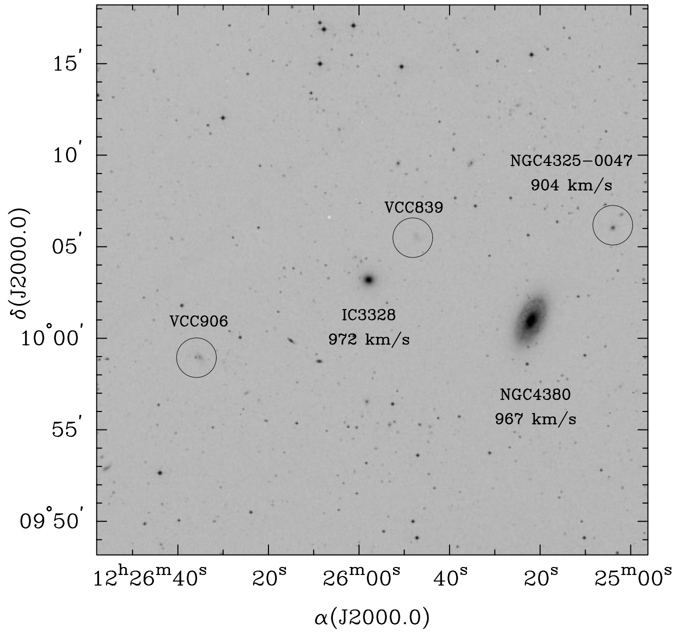

Fig. 6. A DSS-II image centered at IC3328 showing the galaxy distribution within a 15 arcmin squared field. The bright spiral galaxy NGC4380 is at a distance of 9.1 arcmin or 46 kpc to the West. Slightly further away is the faint galaxy NGC4325-0047. Furthermore, there are the two hardly visible, low surface brightness dwarf galaxies VCC839 (dE0:) and VCC906 (dE:) indicated by circles. Heliocentric velocities are given if available.

However, there are strong indications suggesting that at least *part* of the dwarf galaxies classified "dE" might be genuine disk galaxies:

(1) There is a general photometric kinship between dEs and low-luminosity late-type galaxies (dIrrs and spirals of type Sd and Sm); e.g. both have roughly exponential surface brightness profiles (e.g. Lin & Faber 1983; Binggeli & Cameron 1993). Coupled with the general morphology-density relation of dwarf galaxies (Einasto et al. 1974; Binggeli et al. 1987), this has fostered the idea that a significant fraction of the dwarf ellipticals might be the dead ends of evolved irregulars and low-luminosity spirals (Lin & Faber 1983; Kormendy 1985; Ferguson & Sandage 1989; see Ferguson & Binggeli 1994 for a broader discussion). In case of a sufficiently soft evolutionary mechanism such as ram pressure stripping, a dwarf galaxy could indeed have preserved its disk structure while loosing its gas.

(2) Sandage & Binggeli (1984), in their morphological work on Virgo cluster dwarfs, introduced the class of dwarf S0 galaxies. Objects classified dS0, while being much rarer than dEs and confined to a bright magnitude range, are characterized either by a hint of a two-component (S0-like) structure, or some other peculiar feature like boxyness, bar-like feature, or extreme flattening (see also BC91). The flattening distribution of dS0s is typical for disk galaxies (Binggeli & Popescu 1995).

(3) More evidence for the structural diversity of dEs is provided by Ryden et al. (1999). From an isophotal analysis of a sample of Virgo cluster dEs and dS0s these authors found the same range and frequency of “boxy” versus “disky” distortions from ellipticity as in normal ellipticals (e.g. Bender et al. 1989). Clearly, some of these early-type dwarf galaxies will be disk galaxies, or at least have a disk component embedded.

The fourth and latest indication for a disk in a dE of course is the spiral in IC3328. Despite its classification as dE, this galaxy clearly is a mis-classified dS0. We would like to emphasize that IC3328 does not resemble a “dwarf spiral”, a new galaxy type proposed by Schombert et al. (1995), as it lacks a bulge and shows no obvious signs of gas and dust.

It is very likely that more dS0s will be identified among the bright round dEs in the future by means of a careful study of the 2-D light distribution.

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