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A mass estimate for the companion to the 'Cartwheel' galaxy

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Summary. We have measured the velocity and the velocity dispersion of the elliptical companion to the ring galaxy known as the 'Cartwheel'. The velocity confirms the suggestion of Fosbury & Hawarden that this companion galaxy was the interloper which created the ring structure. The mass inferred from the dispersion is only 5–10 per cent of the mass of the Cartwheel itself derived from the kinematics of the ring. This low mass is insufficient to account for the observed ring by the collisionless kinematic model of Lynds & Toomre. It seems likely, however, that the underlying mechanism is an encounter of the kind suggested by Lynds & Toomre but that the ring is brightened by the star formation induced.

1 Introduction

In their comprehensive study of the Cartwheel galaxy, Fosbury & Hawarden (1977, hereafter FH) were struck by the similarity in appearance of the bright, sharp-edged ring in this galaxy to the structures produced by the two-galaxy encounter modelled by Lynds & Toomre (1976). FH suggested that the morphology of the Cartwheel was due to the passage of the elliptical companion through the centre of the disc, producing a severe ring-like density wave as suggested by Lynds & Toomre. They estimated the age of the ring from its velocity of radial expansion and showed that this agreed with the time since closest approach, as determined from the separation and relative velocity of the two galaxies. We report here a measurement of the velocity dispersion of the elliptical companion from which we can estimate a mass to test the Lynds & Toomre model further.

2 The data and results

The Cartwheel system is shown in Plate 1. The elliptical companion is marked Comp (Galaxy '3' in the notation of FH). Spectra of this galaxy were obtained with the Anglo-Australian telescope using the RGO spectrograph and the IPCS. The 82-cm camera on the spectrograph

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Table 1. Observations and results.

Object	Spectral type	Magnitude m_V	Exposure time (s)	Companion $V_{\odot}$(km s^{-1})	Galaxy* σ(km s^{-1})
SAO 102537	K0 III	8.7	410	8921	97 ± 10
SAO 102576	G8 III	9.0	595	8984	110 ± 11
SAO 110999	G4 III	8.3	600	8951	90 ± 10

*Exposure time 3 × 1000 s.

Note: Spectral types and magnitudes are taken from the SAO Catalog (1966) and from Jaschek, Conde & de Sierra (1964).

and the 1200V grating gave a dispersion of 10 Å mm^{-1}; together with the 1-arcsec slit this produced an instrumental profile with $\sigma < 25$ km s^{-1}. Three 1000-s spectra extending from 5200–5500 Å were obtained. The recession velocity of the system, 9000 km s^{-1}, caused the Mg b triplet to be shifted into this wavelength range. The Fe I 5270 Å feature was also included. Spectra of three late-type giant stars were taken to act as templates in the Fourier quotient analysis. These extended from 5100–5400 Å so as to include the same features as the galaxy spectrum. Neutral-density filters were used to prevent the template stars saturating the IPCS. Details of these spectra are given in Table 1.

The spectra were then corrected for field curvature and sky background, and calibrated in the usual way (e.g. see Davies 1981). The galaxy spectrum was taken to be the sum of the central three 1.4-arcsec increments (1.3 kpc for $H_0 = 50$ km s^{-1} Mpc^{-1}) of the slit. This spectrum was then prepared for analysis by the Fourier quotient method. It was transformed to a logarithmic wavelength scale, with $\delta(\ln\lambda) = 11.3$ km s^{-1}; the low-frequency continuum was fitted by a third-order polynomial and subtracted off, and a cosine bell was applied to 10 per cent of the spectrum at each end. The Fourier quotient technique has been described and tested in detail elsewhere (Sargent *et al.* 1977; Efstathiou, Ellis & Carter 1980; Davies 1981; Kormendy & Illingworth 1982). It has been shown to give reproducible results for velocities and dispersions down to dispersions about 60 per cent of the instrumental resolution, by the use of templates covering a range of spectral types. A Gaussian transform function was fitted to the quotient of the galaxy and star Fourier transforms over the range in wavenumber from 10–250 for each template, and the results are presented in Table 1. The differences in velocity from one template to another entirely reflect the shifts between the star spectra, due to instrumental effects such as different illumination of the spectrograph slit by the star. These problems limit the use of the Fourier technique for measuring absolute velocities.

3 Discussion

We shall adopt the average value of heliocentric velocity and velocity dispersion over the three templates, namely $V_{\odot} = 8952$ km s^{-1} and $\sigma = 99$ km s^{-1}. We take $H_0 = 50$ km s^{-1} Mpc^{-1} and transform quantities from other authors to this value where necessary.

The luminosity–velocity dispersion relation given in table 4 of Davies *et al.* (1983) and a velocity dispersion of 99 km s^{-1} together imply an absolute magnitude $M_B = -19.0$. This is in good agreement with the calibrated spectrophotometry of FH who estimated $M_B = -19.2$. Efstathiou *et al.* (1980) and Schechter (1980) indicate that the average mass-to-light ratio for an elliptical galaxy is 5–10 in solar units. For $M_B = -19.0$ this implies a mass of between $2.5\text{–}5 \times 10^{10} M_{\odot}$. FH commented that the companion galaxy appeared to be of relatively high surface-brightness, so the direct comparison with normal

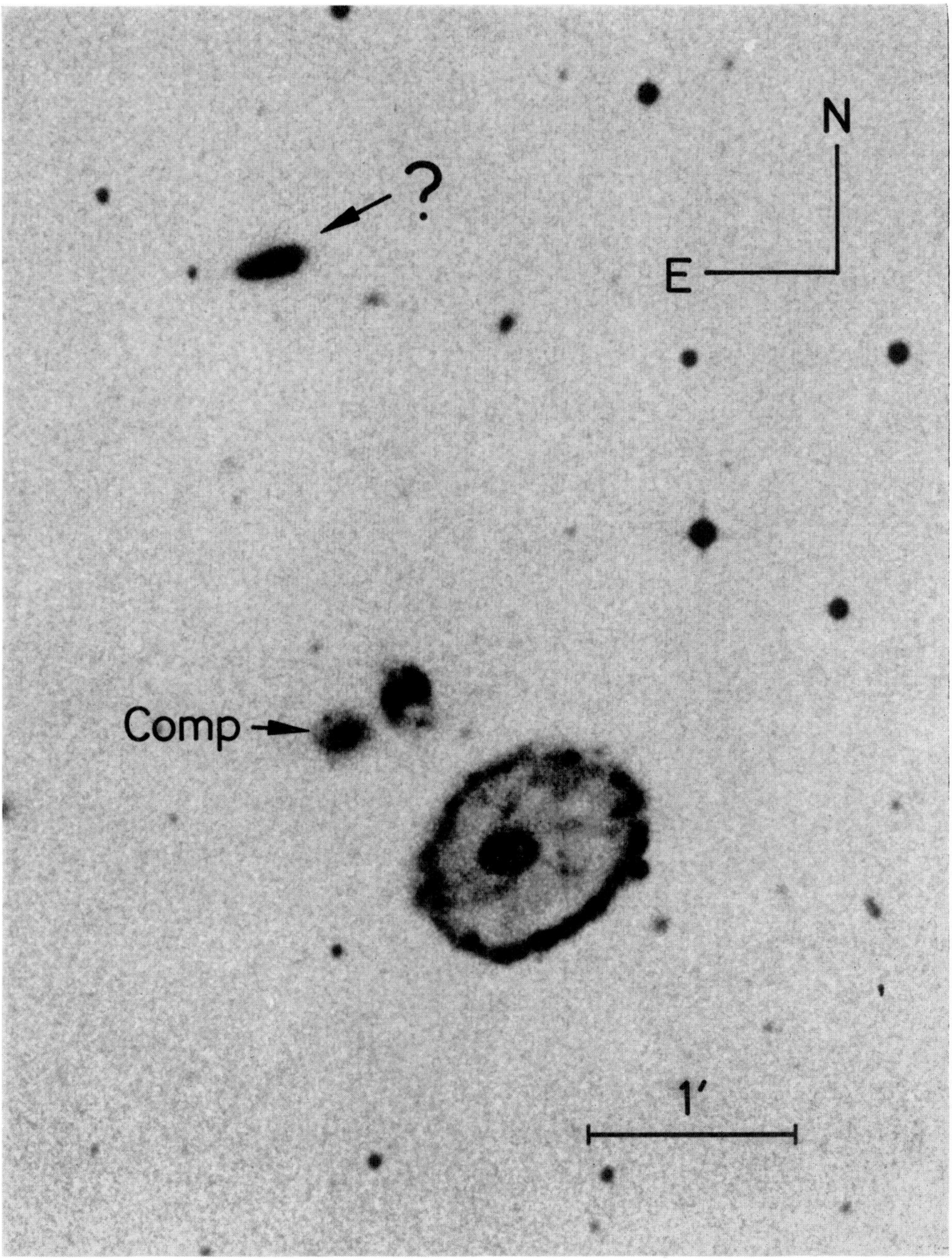

Plate 1. The Cartwheel galaxy together with the suspected interloper studied here, marked 'Comp'; the other candidate interloper is marked '?'. This plate was taken from the SRC-*J* southern sky survey.

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elliptical galaxies may not be strictly appropriate (although the good agreement between the magnitude derived from the velocity dispersion and the spectrophotometric magnitude indicates that the comparison is in fact reasonable).

M32 is a faint elliptical of high surface brightness, velocity dispersion $\sigma = 75\,\mathrm{km\,s^{-1}}$ (Whitmore 1982) and effective radius $R_e = 0.22\,\mathrm{kpc}$ (taking R_e from the *Second Reference Catalogue of Bright Galaxies* (RC2), de Vaucouleurs, de Vaucouleurs & Corwin 1976, and the distance of M32 as 660 kpc, van den Bergh 1975). A crude eye-estimate of the diameter of the companion galaxy from the *ESO-B* and SRC-*J* Southern Sky Surveys suggests that $D_{25} = 0.1-0.2$ times the ring diameter, or 6–12 kpc. Davies *et al.* (1983) suggest that $R_e \approx 1/6\ D_{25}$, indicating that R_e for the companion galaxy is 1–2 kpc. A direct comparison with the mass of M32 using $\sigma^2 R_e$ as a mass estimator gives the mass of the companion as 7–14 times that of M32. Estimates of the mass of M32 range from $4 \times 10^8 M_\odot - 4 \times 10^9 M_\odot$. The lower value is derived from the extremely low velocity–dispersion obtained for the planetary nebulae in M32 (Ford, Jacoby & Jenner 1977), whereas stellar velocity dispersion measurements by Whitmore (1982) and Sargent *et al.* (1977) tend to favour a larger mass. Even with the higher value the mass of the companion is only $3-6 \times 10^{10} M_\odot$.

These two methods of mass determination are not completely independent, but it seems that we are unlikely to be grossly in error if we treat the companion as a normal elliptical and take the mass of the companion galaxy as $4 \pm 2 \times 10^{10}\, M_\odot$ FH estimated the mass of the Cartwheel at $5 \times 10^{11} M_\odot$ from the dynamics of the ring, so the companion has only 5–15 per cent of the mass of the ring galaxy.

To produce the density contrast seen in the ring, the Lynds–Toomre model would require the interloper to have a much greater mass: their model is of a collision between a progenitor of mass 1 and an interloper of mass 2/3. The low mass of the companion galaxy thus suggests three possibilities:

(1) The ring was not caused by an encounter.

(2) The companion galaxy marked on Plate 1 was not the interloper. Another early-type galaxy, marked ? on Plate 1, could have caused the ring. It appears to be two to three times brighter and may therefore be massive enough to have caused the event. Since it is three times further away in projection than the close companion, a much greater time would have elapsed since closest approach; this would then be inconsistent with the age of the ring. Arguments such as these can only be settled when velocity and dispersion data are available for this galaxy.

(3) The close companion was responsible for a stellar density wave in the progenitor but, because of its low mass, this wave was of much lower amplitude than that in the Lynds–Toomre model. The wave could nevertheless have stimulated star formation in the swept-up disc material and produced a stellar population of low mass-to-light ratio, which appears as a sharp-edged ring on the sky-survey films. This last seems by far the most likely of the three possibilities and is supported by the detection by FH of 3×10^6 O stars in the ring. It could be confirmed by taking a CCD frame in the red light of the old stellar population in order to detect a faint ring.

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