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A COUNTERROTATING CORE IN IC 1459¹

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ABSTRACT

The radio elliptical IC 1459 is shown to have a massive rapidly *counterrotating* stellar core. Along the major axis a strong peak in the rotational velocity is observed at a distance of 2" (0.3 kpc) from the center. The velocity reaches $170 \pm 20 \text{ km s}^{-1}$. The rotational velocity in the outer parts rises to $45 \pm 8 \text{ km s}^{-1}$, but in the *opposite* sense to the rotation of the center. Along the minor axis, no significant rotation is measured, neither in the center nor in the outer parts. Line profiles derived from cross-correlated spectra along the major axis in the core show a clear asymmetry. Ionized gas rotates around the minor axis in the same sense as the outer part of the galaxy. The other properties are typical of normal ellipticals. The galaxy has a regular color gradient and line strength gradient. The mass of the counterrotating component is estimated to be $\sim 10^{10} M_{\odot}$. We postulate that such a core could form, following the merger of two galaxies, either by the tidal disruption of the victim or through a starburst-like event.

Subject headings: galaxies: interactions — galaxies: internal motions — galaxies: nuclei

I. INTRODUCTION

Some of the most energetic phenomena in the universe occur within the nuclei of galaxies. Yet little is known about the structure of the cores of galaxies—primarily because of the small scales involved. Only a few nearby galaxies can be studied in detail, e.g., M31 and M32. Strikingly, both are found to have rapidly rotating nuclei (see, e.g., Kormendy 1988; Tonry 1987).

For more distant galaxies nuclear characteristics such as those measured in M31 and M32 become unobservable. Yet it is becoming apparent that interesting kinematical and structural data can be obtained about the nuclei of some galaxies, primarily of some giant ellipticals. The core of M87 is one such case (see, e.g., Merritt 1987 for a summary). For NGC 5813 the unusual structural and kinematic properties of the core (Efstathiou, Ellis, and Carter 1982) led Kormendy (1984) to characterize the galaxy as a core within a core. The structure of the center of NGC 5813 could result from a high-density nucleus (from a low-luminosity elliptical or disk galaxy bulge) falling into the large low-surface brightness core of the giant elliptical. This indicated that core properties could also lead to some further hints as to the processes that contribute to galaxy formation and evolution.

It is this continuing interest in the nuclei of galaxies and the comparative rarity of such data that prompted us to report a new and fascinating result for the giant elliptical IC 1459.

IC 1459 was one of the first ellipticals with a well-established photometric twist (Williams and Schwarzschild 1979). IC 1459 is an E3 giant elliptical ($B_T = 11.0$; $M_B = -21.6$ for $H_0 = 50$

$\text{km s}^{-1} \text{ Mpc}^{-1}$) that is distinguished by several features. First, there is some dust absorption in the central 10" as noted by Sparks *et al.* (1985) from an asymmetry in the color image. Although it is listed in the *IRAS Point Source Catalog*, its emission is not exceptional (Jura *et al.* 1987). Second, it is a compact radio source, with a brightness of 1.2 Jy at 2.7 GHz (Sadler 1984). Third, Malin (1985) has published a deep photograph of the galaxy, showing faint wisps or arms in the outer parts of the galaxy, suggestive of an interaction.

This galaxy was studied as part of a program started by the authors to determine the shapes of ellipticals, along the lines described by Binney (1985). The program requires surface brightness distributions and minor and major axis kinematic data to be collected for a sample of ellipticals. The results for IC 1459 were unusual and so striking that we decided to present them before the full program was completed. A full account will be given elsewhere (Franx, Illingworth, and Heckman 1988).

In short, what we find is that IC 1459 has a core that rotates in the opposite sense to the body of the galaxy. The data, tests, and implications of this result are expanded upon below.

II. KINEMATICS OF STARS AND GAS

Long-slit spectra were taken along the major and minor axes of IC 1459 with spatial resolutions ranging from 1"2 to 3" at several different telescopes, namely the CTIO 4 m telescope with the 2D-Fruitti photon counting system, and the ESO 2.2 m and 3.6 m telescopes with an RCA CCD. Conditions were not optimum, but the data have adequate S/N to derive satisfactory kinematic profiles. The position angles (P.A.) used were derived from *B* and *R* CCD surface photometry. We adopted a mean P.A. of 39° ($10'' < r < 50''$), since the P.A. of the major axis varies from 32° at $5''$ to 42° at $60''$ from the center.

The data reduction was carried out with the IRAF long-slit package (Valdes 1986). Stellar rotational velocities V_{rot} and velocity dispersions σ were determined using an approach

¹ Partly based on observations made at the European Southern Observatory, La Silla, Chile.

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similar to the Fourier quotient method (e.g., Sargent *et al.* 1977). In a special mode (equivalent to the cross-correlation method; cf. Tonry and Davis 1979) the broadening was fixed, and only the velocity and line strength allowed to vary. In general, all methods give the same velocities, if the line and instrumental profiles are symmetric.

The spectra were centered around the 5170 Å Mg triplet; no strong emission lines occur in the galaxy in the wavelength interval used for the fits. Velocity profiles and dispersion profiles for the minor and major axis are given in Figure 1. *Note the pronounced peak in the rotation curve along the major axis, and the reversal of V_{rot} at around 10" from the center.* The amplitude of the central rotation varied from exposure to exposure, depending on the seeing, slit width, and wavelength resolution. The data shown in the core are an average of those with good seeing and resolution. Further out along the major axis V_{rot} rises to $45 \pm 8 \text{ km s}^{-1}$ for $20'' < r < 40''$. No significant rotation was found on the minor axis (formally a not significant $12 \pm 8 \text{ km s}^{-1}$ for $10'' < r < 30''$). However, in these minor axis data, the mean velocity in the core is larger than that at larger radii. While small and not very significant, this effect was found in all exposures, although it differed in amplitude. It may result from the nucleus not being centered in the slit, although it is surprising that the sense was the same in each case.

From these results we conclude that the main body and the core of the galaxy have opposite angular momentum and rotate around axes which both project onto the photometric minor axis to within $\sim 15^\circ$.

The Fourier method gives rotational velocities in the center which are a factor of 2 lower than the cross-correlation velo-

cities. Systematic effects like galaxy-star mismatch or an asymmetry in the instrumental profile cannot produce such an effect. This effect could arise if the cross-correlation peaks are asymmetric and are such that the asymmetries reverse across the nucleus. This proved to be the case. A careful evaluation of the highest resolution data showed that the line profiles in the core of IC 1459 were asymmetric. The line profiles were derived from the cross-correlation spectra with a method similar to the "CLEAN" method used in radio astronomy (Högbom 1974). We "CLEANed" the cross-correlation spectrum with the autocorrelation spectrum of the *template* as the response function (i.e., the "antenna pattern" or the point response function). The main purpose of this technique is not to enhance resolution but to find a nonnegative solution for the line profile. A more extensive discussion is given in Franx, Illingworth, and Heckman (1988). Averages of line profiles east and west of the center are presented in Figure 2. Clearly the profiles have asymmetric peaks and are mirror images of one another, indicating a rapidly rotating component (with $V_{\text{rot}} \approx 300 \text{ km s}^{-1}$). Note that the cross-correlation method gives higher weight to the peaks and so will result in a more accurate estimate of the rotation of a narrow-lined, peaked component than the Fourier fitting method which gives velocities nearer to the mean.

It is also noteworthy that the velocity dispersion, which is derived using the Fourier fitting approach, remains high, and in fact increases, into the core even as the rotation increases. The gradient in the central 2" might be due to unresolved rotation. Ignoring the asymmetry in the line profiles, we obtain a corrected central σ of 300 km s^{-1} . Since the line profiles are

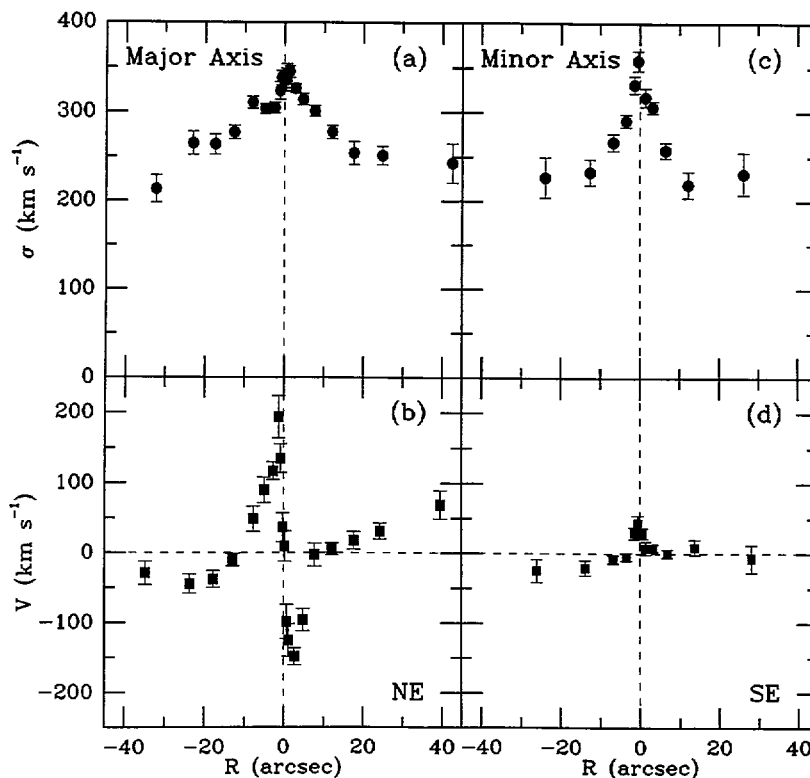


FIG. 1.—The stellar velocity dispersion and radial velocity profiles of IC 1459 along the major axis (a, b) and along the minor axis (c, d). The radial velocities were calculated with the cross-correlation method. The systemic heliocentric velocity used was 1720 km s^{-1} . The dispersions were determined with the Fourier Fitting technique. Positive radii lie to the east. For $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the scale is $0.17 \text{ kpc arcsec}^{-1}$.

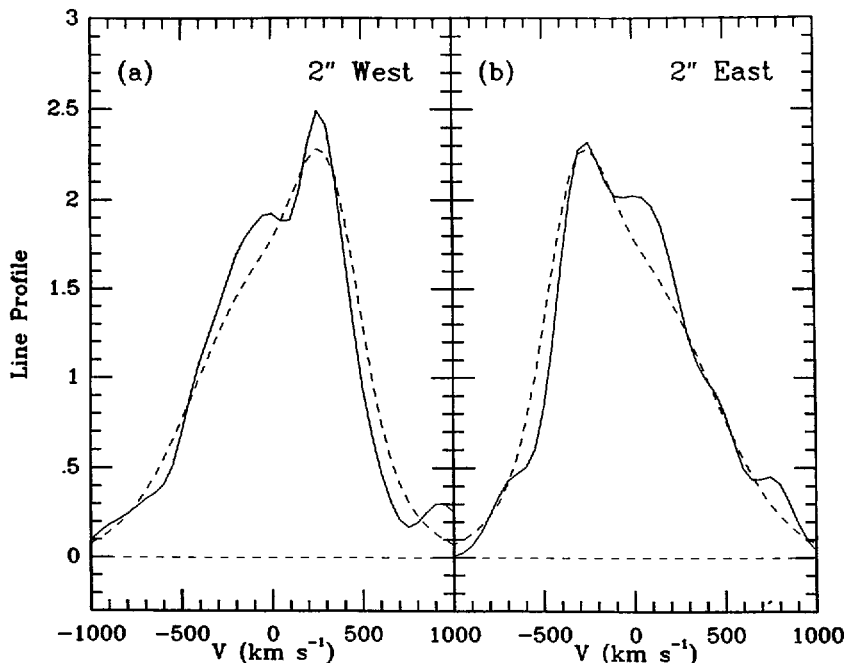


FIG. 2.—The line profiles west (a) and east (b) of the nucleus. The dashed lines are model fits. The line profiles are noisy, with amplitude errors of 10%–15% at the $\sim 200 \text{ km s}^{-1}$ resolution of the data and therefore appear more resolved than is probably the case.

asymmetric, the real value will probably lie between 300 and 350 km s^{-1} . The most straightforward interpretation of these data and the profiles in Figure 2 is that we have a two-component core, one of narrow linewidth and high rotation, and the other of high dispersion and low rotation, with this latter component being dominant.

Accordingly, we have modeled the line profiles in the core with a summation of two components: one extended component with a low V_{rot} and a high σ , and a compact counterrotating component with a high V_{rot} and a low σ . The luminosity distributions were Hubble-like power laws. The line profile of each component was assumed to be a Gaussian. The model fit to the line profiles is good, being consistent with the errors in the profiles (see Fig. 2). The V_{rot} of the compact component peaks at 300 km s^{-1} in the model, with an uncertain but clearly small σ of $\sim 100\text{--}150 \text{ km s}^{-1}$. This component is cold and disklike, with a $V_{\text{rot}}/\sigma \approx 2\text{--}3$ that is much greater than that found in ellipticals or bulges. The fractional contribution to the line profile is small for this cold component, being no more than 25% anywhere. The hot component in the model has a central σ of 350 km s^{-1} . This simplistic model demonstrates only that a plausible two-component structure can result in asymmetries consistent with those measured. The model is neither unique nor complete.

Weak [O III] 5007 \AA emission is also present on several spectra. The radial velocities of the gas along the major and minor axes are plotted in Figure 3. Note that the gas rotates in the same direction as the outer stellar component. The zero point was set using the night sky 5577 \AA line, and the absorption line systemic velocity. The rotation curve is regular, with a peak of about 350 km s^{-1} on the major axis, though some asymmetries are present. These may arise, for example, from dust absorption or nonuniform distribution of the gas. While some residual rotation is measured along the minor axis, the projected rotation axis is clearly close to the photometric minor axis.

It is particularly interesting to note that the gas extends into the core, since the 5007 \AA line flux peaks strongly in the center, dropping to 10% of its central value by $4''$. Thus, *the stars and the gas are counterrotating within the same volume in the core.*

III. PHOTOMETRY AND STELLAR POPULATION

B and R CCD frames of IC 1459 were taken with the CTIO 0.9 m telescope, and the ESO 1.5 m telescope. We are grateful to Mario Mateo for supplementary data from the 0.9 m telescope and to Reynier Peletier for the data from the ESO 1.5 m telescope. These photometric data were analyzed with an ellipse fitting program similar to the Grasp package (Davis *et al.* 1985). The resulting intensity profiles were calibrated with the B aperture data of Burstein *et al.* (1987) and the $B\text{--}R_J$ colors of Sandage (1975).

Figure 4 gives the B surface brightness profile, and the $B\text{--}R_J$ color along the major axis, for the best seeing data ($\approx 1''.1$ FWHM). In the center the profile rises less steeply than the best-fitting $r^{1/4}$ law. The core appears to be resolved. After application of the seeing corrections calculated by Kormendy (1985) we obtain a core radius $r_c \approx 1''.4$ and a central surface brightness of $\mu_B \approx 16.4$.

The $B\text{--}R_J$ color profile shows a color gradient of 0.14 mag per decade in radius with no unusual behavior in the center. This gradient is typical of that for ellipticals (see, e.g., Peletier *et al.* 1988). We have determined the line strengths of the Mg lines in our spectra. The Mg_2 index, as defined by Burstein *et al.* (1984) drops from 0.27 in the center to 0.17 in the outer parts. Although not many line strength gradients have yet been published, available data on other galaxies (Gorgas and Efsthathiou 1987; Davies and Sadler 1987) show similar profiles. Since the counterrotating component contributes $\sim 25\%$, or less, of the luminosity of the high-dispersion component, the constraints placed on its stellar population by these data are

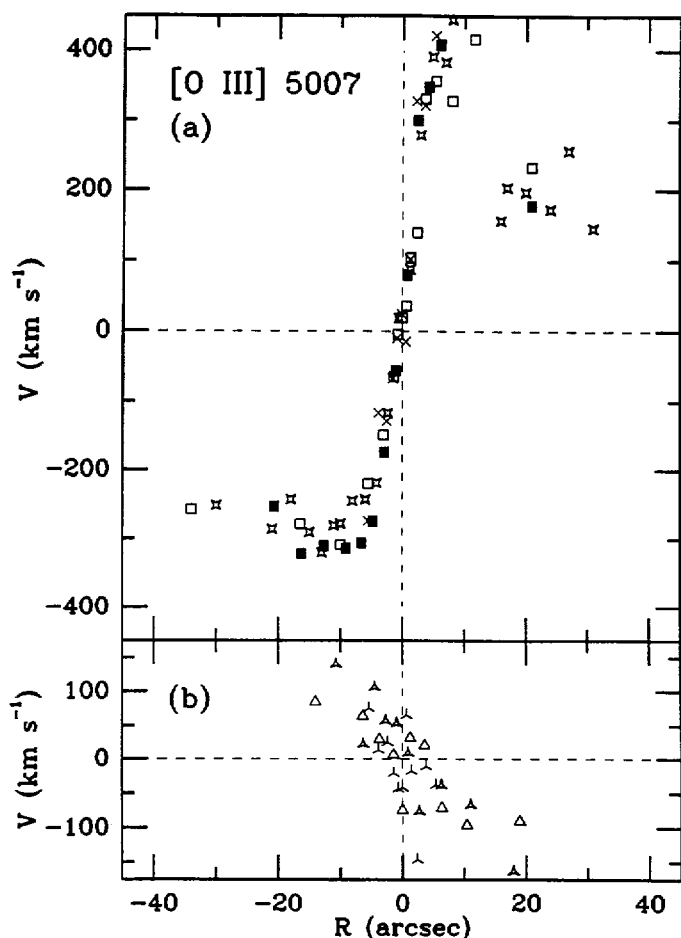


FIG. 3.—The rotational velocity of the gas from the [O III] 5007 Å line along the major (a) and minor (b) axis. The systemic velocity used was 1720 km s^{-1} . Different symbols denote data from different spectra. Positive radii lie to the east.

modest; they do indicate, however, that the core population is not significantly different from the cores of other ellipticals.

IV. DISCUSSION

IC 1459 contains a cold component in its core that rotates in the *opposite* sense to that of the main body of the galaxy. In other properties, this galaxy appears normal. The core satisfies the relations found by Kormendy (1985) for the nuclei of a large sample of galaxies. The photometry is characteristic of a regular elliptical, with a normal color gradient. Only in that this galaxy has some dust in the center, an isophote twist of 10° and distortions in the outer parts is IC 1459 to be distinguished in appearance from the mainstream of ellipticals. The M/L within the core is not unusual at $7 (M/L_B)$; using $\sigma = 300 \text{ km s}^{-1}$, $r_c = 1.4$, $\mu_B = 16.4$, and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, but this constraint is weak given the low spatial resolution of these data. An order-of-magnitude estimate based on a fractional contribution of 20% indicates that the cold component has a luminosity $M_B \approx -17.5$ within a radius $4r_c$, and a mass $\approx 10^{10} M_\odot$ for $M/L_B = 7$. The velocity dispersion gradient (à la M87), the core rotation, and the mass involved suggest that higher spatial resolution data could be of considerable interest.

The presence of two dynamical components in the center

suggest a merger event, wherein a smaller galaxy has fallen into the giant elliptical. The luminosity estimated above would suggest a small disk or a low-luminosity elliptical as the victim (since the victim must have had $M_B \leq -17.5$). If the smaller galaxy has a dense core it can remain intact and form a core within a core (cf. Kormendy 1984). However, we do not see any evidence of a separate component in the surface photometry, color, or line strengths. Furthermore, V_{rot} and V_{rot}/σ are unusually high for the core of either an elliptical or disk galaxy. This suggests that we are observing the disrupted core of the victim. The small galaxy would have been disrupted near the core of the larger galaxy where the tidal forces were strongest. The remains of the victim were spread throughout the center of the host, thereby losing its physical identity, while leaving a kinematic imprint. The angular momentum of the remnant material would be the *orbital* angular momentum of the victim, not its intrinsic angular momentum. This is a natural way of obtaining a cold component, such as we see in IC 1459, which is rotating with a velocity comparable to the circular velocity of the hot component.

Another interesting fact is that the gas rotates in the same sense as the body of the galaxy. As such it could not have arisen from the same merger event as the counterrotating core.

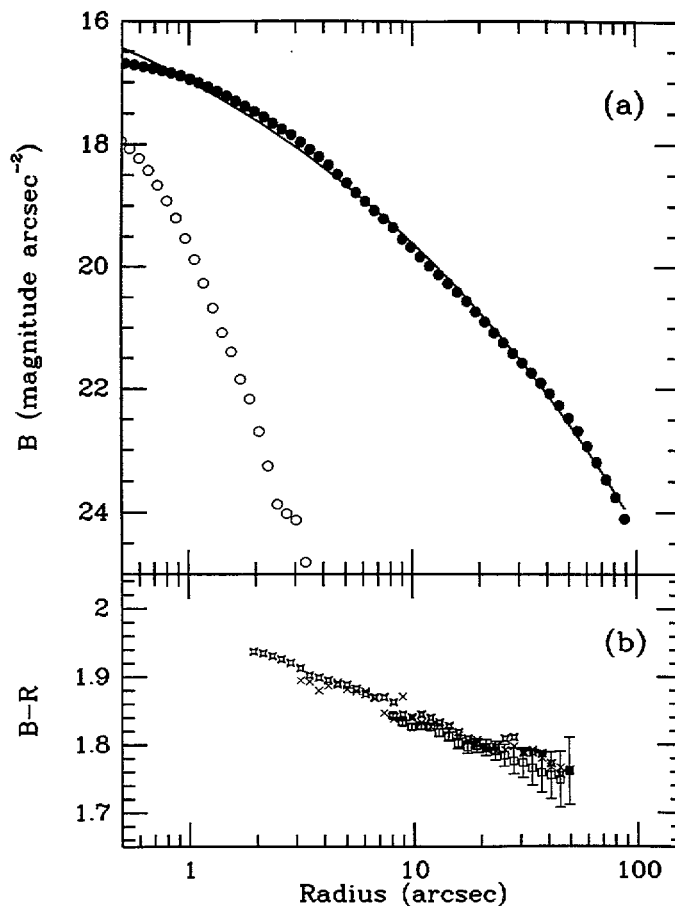


FIG. 4.—The surface brightness profile in $B \text{ mag arcsec}^{-2}$ (a) and $B-R$, color profile (b) as a function of major axis radius. The open symbols give the seeing profile derived from a star in the field. The best fitting $r^{1/4}$ law is shown. Different symbols denote different CCD data sets. The error bars are those resulting from $\pm 5\%$ uncertainty in the sky background.

A plausible alternative to the merger/sinking core picture is that the counterrotating component resulted from star formation within the core from gas that had settled to the center. This gas must also have been counterrotating, and hence acquired through a merger event. Such a starburst-like event (involving some $10^{10} M_{\odot}$ of gas; cf. Scoville *et al.* 1986, who found $10^{10} M_{\odot}$ gas within 0.75 kpc in Arp 220) must result in a population that now meets the photometric and kinematic constraints. As before, the gas currently seen throughout the body of the giant elliptical must have resulted from another interaction.

While this system most likely formed through a merger, it is interesting to explore the possibility that the galaxy formed in a single collapse. If galaxies acquire their angular momenta by tidal torques, then we might expect misalignment between the angular momenta of the centers and the outer parts (Binney 1986; Barnes and Efstathiou 1987). If this were the case, then

counterrotation may be quite common. However, such a process would not explain the clear coexistence of two components as shown by the asymmetry of the line profiles in the center, nor, in all likelihood, the high rotational velocity.

It is interesting to note that this is more than just a stellar dynamical curiosity. It is likely to be one of the clearest signatures of a merger or acquisition of a companion that we have. Such cores, counterrotating or not, may be quite common since most available data does not have the spatial resolution, nor, in many cases, the *velocity resolution* to detect such components.

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