

SHELL COLORS IN THE PECULIAR ELLIPTICAL GALAXY IC 1459<sup>1</sup>DUNCAN A. FORBES,<sup>2</sup> AND DAVID B. REITZEL

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## ABSTRACT

The giant elliptical galaxy IC 1459 shows a variety of features normally ascribed to a previous encounter with another galaxy, such as a counter-rotating core, nuclear dust lane and an arm-like feature in the emission-line gas. One notable omission from this list was the presence of stellar shells. Here we present deep CCD imaging of IC 1459 taken in *B*, *V*, and *R* filters covering  $13.5' \times 13.5'$ . After careful model subtraction, we have identified several shells and other fine structure around the galaxy. Shell colors have been measured and are found to be similar to the underlying galaxy. We briefly discuss the origin of the shells and other peculiarities of IC 1459

## 1. INTRODUCTION

Detailed studies of elliptical galaxies reveal them to have a complex nature. Some of their peculiarities have been ascribed to a colorful and sometimes violent past of mergers, accretion and interaction with other galaxies. The merger and interaction simulations that give rise to kinematically distinct cores (KDCs), tidal tails and plumes often produce long-lasting "shells" in the surviving galaxy. After image enhancement, these faint stellar shells are found to be quite common around ellipticals (Seitzer & Schweizer 1990) and yet relatively few studies have been published to date. A variety of mechanisms have been proposed as the origin of shells (see review by Prieur 1990). The most viable are the weak interaction model (Thomson & Wright 1990; Thomson 1991) and the merger models (e.g., Hernquist & Quinn 1988, 1989; Hernquist & Spergel 1992) which range from the accretion of small secondary galaxy to the collision of two disk systems. With further study of shells and the underlying galaxy, we hope to test the competing shell formation mechanisms and better understand the role of mergers/interactions in the evolution of elliptical galaxies.

The giant elliptical IC 1459 reveals many peculiarities. In particular, it is known to possess a fast *counter-rotating* stellar core (Franx & Illingworth 1988), twisted isophotes (Williams & Schwarzschild 1979), a dust lane and patches near the nucleus (Sparks *et al.* 1985; Forbes *et al.* 1994) and an ionized gas disk with a single spiral arm extending from the nucleus ((Forbes *et al.* 1990; Goudfrooij *et al.* 1990). Interestingly, the ionized gas at the core rotates along the major axis in the same direction as the majority of stars in the

galaxy, which is in an opposite direction to that of the stellar core. Enhancement of photographic plates reveals an arc in the outer region (Malin 1985), which appears to be in the same sense as the extended ionized gas structure. Although not included in the catalog of southern shell galaxies by Malin & Carter (1983), here we show that IC 1459 clearly contains several shells over a range of radii, in addition to other fine structures. We have measured the colors of the shells and discuss these in the context of the shell formation models. Analysis of the globular cluster system in IC 1459 will be presented elsewhere (Grillmair *et al.* 1995). At a distance of 30.0 Mpc to IC 1459,  $1''$  equals 0.16 kpc (Bender *et al.* 1992).

## 2. OBSERVATIONS AND DATA REDUCTION

Broadband *B*, *V*, and *R* images of IC 1459 were obtained using the 0.9 m telescope at Cerro Tololo Inter-American Observatory (CTIO) in 1993 October. The Tek 2048 $\times$ 2048 CCD, with a pixel scale of  $0.40''/\text{pix}$ , give a field of view of  $\sim 13.5' \times 13.5'$ . The seeing ( $\sim 1.8''$ ) was similar for images in each filter. Data reduction was carried out using IRAF software. After bias subtraction and flatfielding, there remained a small offset between the two halves of the CCD. This effect was caused by problems associated with the dual amplifier. This effect is reasonably well approximated by a step function which varies perpendicular to the readout direction. This was corrected by measuring the median background around the 20 border pixels for each half, and then subtracting the appropriate amount from half of the image. This gives a smooth transition across the two halves which is indistinguishable from the noise in the sky background. Bad columns were interpolated over using neighboring pixels. The images were then carefully aligned to within a fraction of a pixel and combined with a  $3\sigma$  rejection criterion to exclude cosmic rays. Only those images taken under the best seeing

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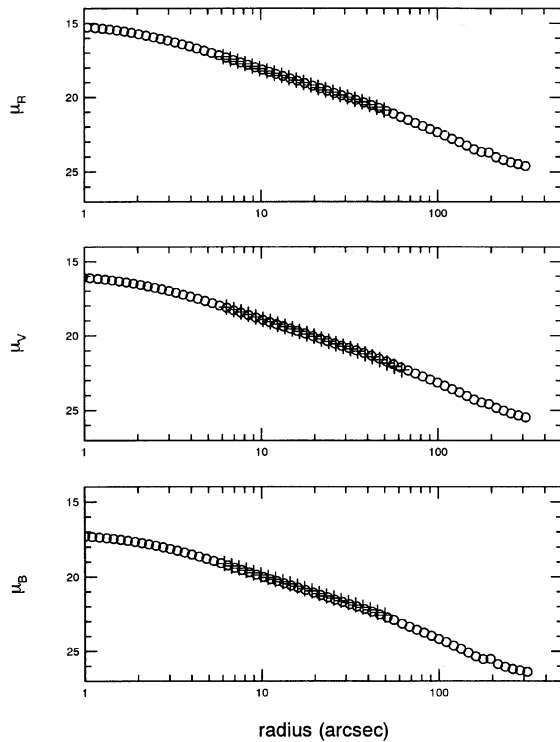


FIG. 1. Surface brightness profiles of IC 1459 in the  $R$ ,  $V$ , and  $B$  bands. Our data (open circles) is shown along with data from the literature (crosses).

conditions were used giving a total of five  $B$  (5700 s), four  $V$  (4500 s) and six  $R$  (6000 s) images.

### 2.1 Modeling

The combined images clearly show much fine structure surrounding the galaxy, as well as numerous foreground stars and globular clusters. In order to better isolate these structures and to search for shells deep within the galaxy, it is necessary to first subtract off a model of the underlying galaxy. Before modeling the galaxy to reveal the shells present, we have first constructed a model for the purpose of sky subtraction and photometric calibration. We used the same technique of ellipse fitting as described by Forbes & Thomson (1992) with the clip parameter set to zero and the brightest stars, globular clusters and galaxies masked out. Sky subtraction was carried out using a method similar to that of Goudfrooij *et al.* (1994), in which the outer parts of the galaxy are fit by a radial power-law in order to accurately determine the sky level. The images were then calibrated using aperture photometry from the catalogs of Longo & de Vaucouleurs (1983) and de Vaucouleurs & Longo (1988). The resulting rms error in the final photometry is  $\pm 0.03$  mag for  $B$  and  $V$ , and  $\pm 0.05$  mag for the  $R$  band. The resulting surface brightness profiles are shown in Fig. 1, along with the measurements of Franx *et al.* for  $B$ ,  $R$ , and Goudfrooij *et al.* for  $V$ . The agreement is good and typically within 0.05 mag of the aperture photometry. Thus we are confident that our data reduction and calibration procedures are consistent with others in the literature.

We then ran a second model to better reveal the presence of shells. Here the brightest pixels in each ellipse are excluded using the clip parameter. This enhances the detection of shells that represent additional light above the underlying galaxy profile. Regions of the galaxy without shells have less than 10% of the typical counts in the shell regions, indicating that the model has successfully subtracted off most of the underlying galaxy starlight. An illustration of the improvement gained by clipping is shown in Fig. 2 of Forbes & Thomson (1992). The central position is fixed throughout the process, based on the position from the first model. The ellipticity and position angle vary out to a radius of  $80''$ , at which point they are fixed to the last value.

### 3. RESULTS

In Fig. 2 (Plate 45) we show the original galaxy image at low contrast. The galaxy appears visually to be a relatively unremarkable elliptical galaxy. There are also numerous globular clusters and faint galaxies in the image. The spiral galaxy IC 5264 is seen to the SW. However, at high contrast much fine structure is seen in Fig. 3 (Plate 46). This includes a conical plume to the NE and a large, sharp-edged shell to the SW. Asymmetries are also seen in IC 5264. These same features are visible in the enhanced photographic plate presented by Malin (1985). His deep 4m plate also reveals an arc feature which extends from the NE to the SW, joining up with the outer SW shell.

By subtracting the clipped model from the galaxy image we have created the residual map shown in Fig. 4 (Plate 47). Here the underlying galaxy starlight has been subtracted off to better reveal the fine structure. As well as the outer shell and plume, this map clearly shows several other shells within the galaxy. They are oriented roughly along the major axis of the galaxy. Additional globular clusters are also apparent in this map. As a test, we have Gaussian smoothed the original galaxy image with  $\sigma=20$  pixels ( $8''$ ). This is similar to the “unsharp masking” technique used by others. Shells are again seen at the same location as in the modeling procedure described above.

We have defined several regions of enhanced light in the residual map which we identify with five distinct shell structures. In order to measure the magnitudes and hence colors of these shells, we have adopted the following procedure. Several boxes of size  $10 \times 10$  pixels were chosen to evenly cover each shell, while avoiding foreground stars, and globular clusters. A median pixel value was found and a surface brightness calculated for each box. We removed the boxes with the lowest signal for each filter, keeping those brighter than surface brightnesses of  $27 \text{ mag arcsec}^{-2}$  in  $B$ ,  $26 \text{ mag arcsec}^{-2}$  for  $V$ , and  $25 \text{ mag arcsec}^{-2}$  for  $R$ . These limits correspond to a few percent of the sky background. The mean values for the remaining boxes were then calculated, and a standard deviation for the color of each shell determined. Boxes with colors more than 2 standard deviations away from the mean were removed, and the mean and standard deviation were recalculated. At the end of this process we checked that the remaining boxes provide a good spatial

TABLE 1. IC 1459 shell parameters.

Shell No.	Radius (arcsec)	Brightness (mag/arcsec <sup>2</sup> )	B-V (mag)	V-R (mag)
1	228	26	$1.0 \pm 0.2$	$0.9 \pm 0.1$
2	107	25	$1.1 \pm 0.3$	$0.9 \pm 0.1$
3	85	26	$1.1 \pm 0.3$	$0.9 \pm 0.2$
4	46	25	$1.0 \pm 0.3$	$1.0 \pm 0.1$
5	45	25	$1.2 \pm 0.2$	$0.9 \pm 0.1$
Galaxy	—	—	$0.9 \pm 0.01$	$0.9 \pm 0.01$

sampling and that no significant trend with surface brightness exists. There is also no obvious trend for color variations within an individual shell.

In Table 1 we list for each shell, the average radial distance from the nucleus, the average surface brightness,  $B-V$  color and one standard deviation,  $V-R$  color and one standard deviation. The galaxy colors represent the average values measured at the same location as the shells in the clipped galaxy model. Shells 2–5 were measured in the residual map as the galaxy starlight clearly dominates for these inner shells. The outermost shell was measured directly from the original image as the contribution from the galaxy at this radius was small. As a consistency check we measured the colors of this shell from the residual map as well and found them to be  $B-V=0.96\pm 0.4$  and  $V-R=1.17\pm 0.3$ , i.e., in reasonable agreement with the values quoted in Table 1.

Although IC 1459 was previously known to exhibit fine

structures (Malin 1985) it was not generally recognized as a shell galaxy of the type catalogued by Malin & Carter (1983). Here we have found that IC 1459 does indeed possess multiple shell structures, which lie mostly along the major axis. The shells are too irregular in their distribution to be described as “type 1” shells (aligned and interleaved) but they bear some resemblance to type 2 shells (partial rings). We have assigned the shells a type 2 classification.

#### 4. DISCUSSION

In Fig. 5 we show a schematic drawing summarizing the main features in IC 1459. The galaxy major axis lies roughly NE–SW. The very inner regions contain an arcsec-scale dust lane that lies NE–SW. Ionized gas is also concentrated on the nucleus, but reveals an extended disk component along the major axis that reaches a radius of  $45''$  (7.2 kpc). At about this radius, we identify shells #4 and #5. The outermost shell (#1) is at an average radius of  $228''$  (36.5 kpc). The effective radius for the starlight from IC 1459 is  $39''$  (6.2 kpc; Bender *et al.* 1992). The spiral galaxy, IC 5264, lies to the SW. Both of these galaxies are located in the Grus loose group along with several other spirals. The environment is thus conducive to mergers, interactions and accretion events.

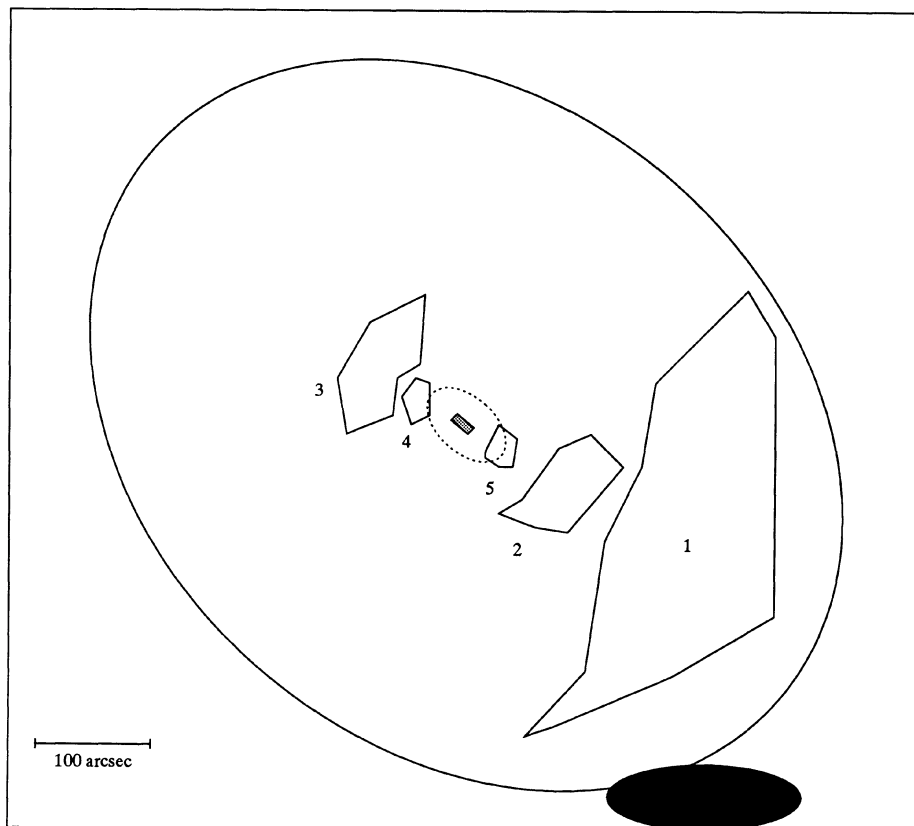


FIG. 5. Schematic diagram of IC 1459 showing the location of the dust lane, ionized gas disk, shells and a nearby spiral galaxy IC 5264.

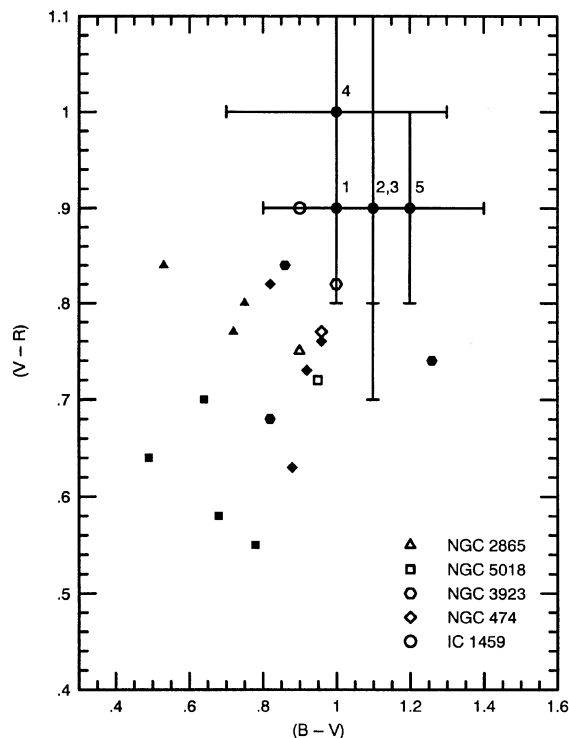


FIG. 6. Two-color diagram. Colors of the host galaxy are given by open symbols and the shells by filled symbols. The shells of IC 1459 are numbered with error bars shown. Errors for shell colors from the literature are not shown but typically range from 0.1 to 0.2 mag.

#### 4.1 Shells in IC 1459

We have measured colors for five of the brightest shells in IC 1459 and find that, within the errors, they have the same color as the underlying galaxy. Assuming that the shells are not dusty, this suggests that the shells are dominated by a late-type stellar population. The similar shell colors suggests either (1) the shells are made of redistributed stars within IC 1459; (2) if the shells consist of stars that were captured from another galaxy they must be of a similar stellar population *or* have had sufficient time to age and redden. The shell colors are shown in Fig. 6 along with the colors of four shell galaxies from the literature (Fort *et al.* 1986; Schombert & Wallin 1987). Shells for three of these galaxies are generally somewhat bluer than the main galaxy. For NGC 474, the colors of the shells are, within the errors, consistent with that of the main galaxy. In this case, Schombert and Wallin concluded that the most likely origin for the shells was “the result of material within the parent galaxy being tidally distorted” by the companion spiral galaxy NGC 470. The *UBV* colors of three shell galaxies have been measured by McGaugh & Bothun (1990). They found Arp 230 and Arp 223 to have shells that were bluer than the main galaxy. For the elliptical galaxy NGC 7010, shell colors were redder than the galaxy with  $B - V \sim 1.2$ .

Shells around ellipticals appear to be quite common (Seitzer & Schweizer 1990); it is therefore important to understand the details of their origin. Three viable models have been proposed to explain the formation of shells: (1) The

capture of a small secondary galaxy. Shells are formed from the disruption of this secondary in the gravitational field of the primary elliptical (e.g., Dupraz & Combes 1986; Hernquist & Quinn 1988, 1989). (2) The collision of two disk galaxies can give rise to long-lived shells in addition to tails and plumes (Hernquist & Spergel 1992). The shells are formed from the stars of both galaxies. (3) Thomson & Wright (1990) and Thomson (1991) have proposed an interaction model for shell formation. In this model the shells are density waves in a postulated thick disk population of dynamically cold stars. The density wave is induced by the interaction with a passing galaxy. We will refer to these models as the accretion, the major merger and the interaction models.

#### 4.2 Other Features of IC 1459

The central few arcseconds of IC 1459 contain perhaps the clearest example known of a rapidly rotating ( $\sim 100 \text{ km s}^{-1}$ ) kinematically distinct core (KDC) in an elliptical galaxy. This component is *counter-rotating* with respect to the main body of stars and contains a significant fraction of the mass  $\sim 10^{10} M_{\odot}$  (Franx & Illingworth 1988). Spectral line analysis suggests that the kinematically distinct component lies in a disk-like structure. A search for a photometric counterpart to this disk, in high resolution *HST* Planetary Camera images, has provided only marginal support for such a disk (Forbes *et al.* 1994).

Simulations indicate that the initial conditions that give rise to shells may also produce a KDC under certain circumstances. For the accretion model, stars from a small elliptical (Balcells & Quinn 1990) or gas from a disk galaxy (Hernquist & Weil 1992; Weil & Hernquist 1993) may sink to the core and be kinematically decoupled from the rest of the galaxy. The major merger model can produce both shells (Hernquist & Spergel 1992) and a kinematically distinct gas core (Hernquist & Barnes 1991). Recently Hau & Thomson (1994) have shown that a retrograde interaction can spin-up a nonrotating halo of an elliptical galaxy, so that an embedded nuclear disk appears as a KDC.

Ionized gas and dust have also been found in IC 1459. Franx & Illingworth (1988) discovered that the ionized gas (as traced by  $[\text{O III}] 5007 \text{ \AA}$ ) counter-rotates with respect to the stellar core, i.e., in the *same* direction as the outer stellar component. Imaging in  $\text{H}\alpha + [\text{N II}]$  shows that the ionized gas is in a disk, which extends about  $45''$  along the major axis, with an arm-like emission feature (Forbes *et al.* 1990; Goudfrooij *et al.* 1990). The “arm” is in the same sense as the outer stellar arc found by Malin (1985). The spatial extent of this ionized gas structure argues that it was formed by some external process.

The  $100 \mu\text{m}$  emission suggests that IC 1459 has a large relative dust content ( $M_{\text{dust}}/L_B$ ) for elliptical galaxies (see Forbes 1991). Some of this dust is concentrated in an arcsecond-scale dust lane which crosses the nucleus (Sparks 1985; Forbes 1994). The short dynamical timescale in this region implies that the dust (and associated gas) play a role in fueling the variable radio core (Slee *et al.* 1994). The orientation

and quantity of dust inferred argue strongly for an external origin.

Using deprojection techniques, Thomas *et al.* (1986) claim that the X-ray gas is cooling (out to a radius of 17 kpc) and depositing a mass of  $0.06 M_{\odot} \text{ yr}^{-1}$  in a cooling flow. In principle a cooling flow could deposit a significant amount of stellar or gaseous material. However, for a sample of ellipticals, Forbes (1991) claims that a cooling flow is *not* a significant source of cool gas or dust. There is no known mechanism for a cooling flow to form a KDC or shells of the type seen in IC 1459.

### 4.3 Evolutionary History

Given that the encounter simulations cannot explore all of the large parameter space required, one must use caution when applying generic simulations to a particular galaxy. With this caveat in mind, we attempt to discuss the shells and other features of IC 1459 in the context of the accretion, the major merger and the interaction models. Unless we invoke multiple encounters, any scenario for the evolutionary history of IC 1459 should be able to explain its peculiarities collectively.

#### (1) The accretion model.

If the dust and gas were accreted in the same encounter that formed the shells, then this would suggest that capture of a gas-rich system such as a spiral galaxy. Shells made from the material of a spiral would initially be bluer than the underlying elliptical starlight. As the shells age they would redden. We would not expect a strong radial color gradient between shells as a spiral galaxy is likely to be fully disrupted on a very short timescale. We find the shells to have essentially the same color as the elliptical with no obvious radial color gradient. In order to remove these signatures from the shells, the accretion model requires that the merger took place at least  $10^8$  yr ago.

Balcells & Quinn (1990) proposed that an accreted compact elliptical on a retrograde orbit, would sink to the elliptical galaxy center forming a KDC. They did not model the infall of a gas-rich system. Simulations which include gas have been produced by Weil & Hernquist (1993). They find that the accreted gas quickly decouples from the stellar component and settles into a disk or ring with a typical size of several kpc after  $\sim 5 \times 10^8$  yrs. The disk of ionized gas in IC 1459 is  $\sim 7$  kpc in radius. For their radial model, with the companion initially tilted at  $45^\circ$  to the orbital plane, they find that the gas forms two components; a kpc-sized disk and a core with a size of a few hundred pc. The disk retains the rotation signature of the accreted galaxy, but torques in the central region cause gas in the core to decouple and counter-rotate with respect to the disk. Subsequent star formation in the high density core gas would produce a counter-rotating stellar core. Thus qualitatively this scenario can produce the salient features of IC 1459. Some details however remain, such as why the currently observed ionized gas at the nucleus rotates along the major axis whereas any gas not used-up in the nuclear starburst should be counter-rotating. It is difficult to imagine how two counter-streaming gas com-

ponents could coexist at the core. Late infall of the second gas component may solve this problem.

#### (2) The major merger model.

The collision of two nearly equal-mass galaxies is related to the accretion model with an extreme mass ratio. Such an encounter has many similarities to that described above. In particular, the core gas decouples and counter-rotates with respect to a kpc-sized disk of gas (Hernquist & Barnes 1991). As with the accretion model, we do not expect to see a large nuclear concentration of gas with the same rotation as the kpc-sized disk. If the gas was driven to the central region after a nuclear starburst such a mechanism must preserve the angular momentum of the gas.

As the stars from both galaxies give rise to the shells, we would expect these shells to have a similar color to the underlying galaxy, as observed. The plumes seen in IC 1459 would support the idea of a violent collision of two large galaxies. Such an encounter would have to occur a few Gyr ago in order for the galaxy starlight to adopt an  $r^{1/4}$  law profile and any tidal tails to have disappeared. Thus IC 1459 may resemble the merging system NGC 7252 (Schweizer 1982) at a more evolved state. An important difference between the two galaxies is that in NGC 7252 the molecular hydrogen content is  $\sim 10^{10} M_{\odot}$ , whereas IC 1459 has  $< 10^7 M_{\odot}$  (Lee *et al.* 1991). Interestingly, the gas content of NGC 7252 matches that of the stellar core in IC 1459, supporting the ideal of a previous nuclear starburst in IC 1459.

#### (3) The interaction model.

The interaction model assumes that the elliptical galaxy contains a pre-existing, thick stellar disk. During the passing interaction with another galaxy a density wave is set up in the thick disk population, which redistributes the stars into stellar shells. This would naturally predict that the shells have essentially the same color as the rest of the galaxy with little or no radial color gradient. The shell morphology is determined by our viewing angle to this disk. We have classified the shells in IC 1459 as "type 2" which indicates that we are viewing the disk close to face-on. To explain the dust and gas disk, mass transfer must have occurred from the passing galaxy. This gas and dust would acquire angular momentum in the same direction as the passing galaxy. From the observed axial ratio of the ionized gas disk (Forbes *et al.* 1990), we estimate an inclination of  $60^\circ$ . It is not clear whether this disk would be at the same inclination as the thick stellar disk within the elliptical.

Hau & Thomson (1994) have modeled a close retrograde encounter involving two elliptical galaxies. In this simulation, the smaller elliptical spins up a previously nonrotating halo which gives the appearance of a KDC. Although their models need to be extended to include a spiral secondary, larger impact parameters and faster relative velocities, it suggests an alternative mechanism for the formation of KDCs.

## 5. CONCLUDING REMARKS

Using deep CCD imaging we have identified several shells and other fine structure in the giant elliptical galaxy IC 1459. Within the errors, the five measured shells have red

colors that are indistinguishable from the underlying galaxy starlight. We have classified the shell system as “type 2”, i.e., partial rings. The shells are oriented along the major axis of the galaxy, as are the small-scale dust lane and ionized gas disk, suggesting that they share a common external origin. We have discussed the peculiarities of IC 1459 in the context of the accretion, major merger and interaction models. All three models offer a viable explanation for the observed features of IC 1459; more data are required to choose one model over another. There would be strong support for the interaction model if the shells were shown to rotate in the same sense as the kinematically distinct core, or if H I mapping revealed signs of a tidal interaction. Measuring the color of

the kinematically distinct component would help to discriminate between a recent starburst event and an old, pre-existing disk. Evidence for two distinct populations of globular clusters would support the merger hypothesis (Ashman & Zepf 1992). Detailed merger and interaction simulations of the IC 1459 system involving gas and stars would also be useful for direct comparison with the observations.

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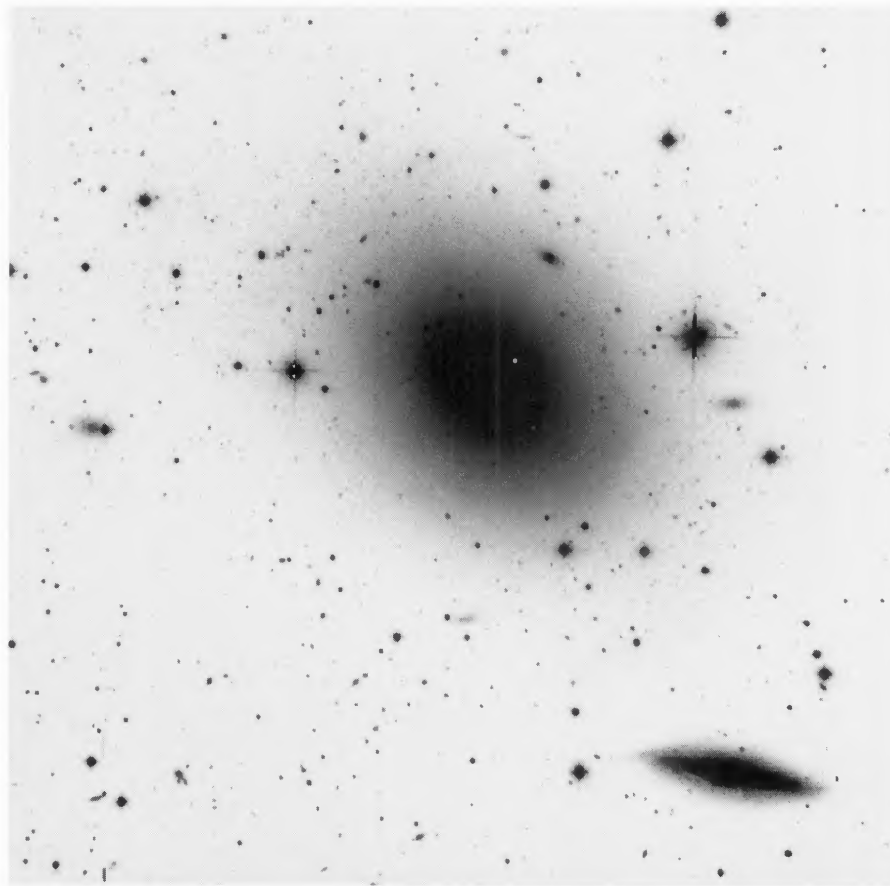


FIG. 2. Original *R* band image of IC 1459 at low contrast. The galaxy looks photometrically normal. A spiral galaxy, IC 5264, can be seen to the SW. North is up and east is left in all plates. The area shown is  $13.5' \times 13.5'$ .

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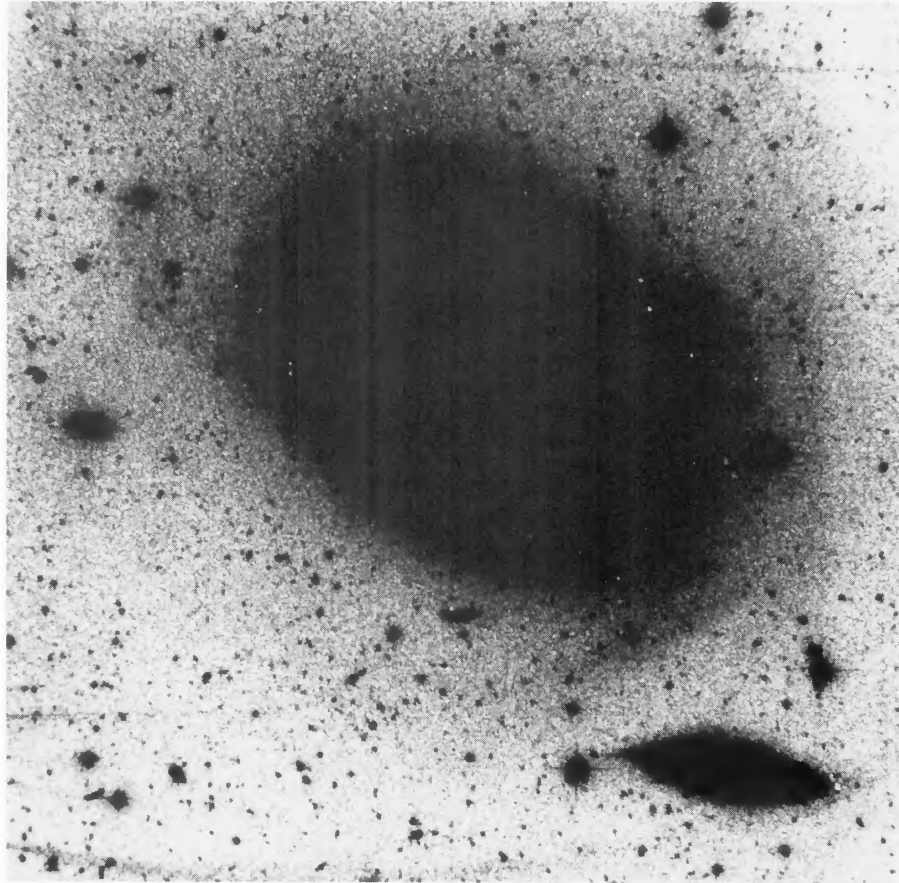


FIG. 3. *R* band image of IC 1459 at high contrast. The galaxy reveals a conical plume to the NE and a shell to the SW.

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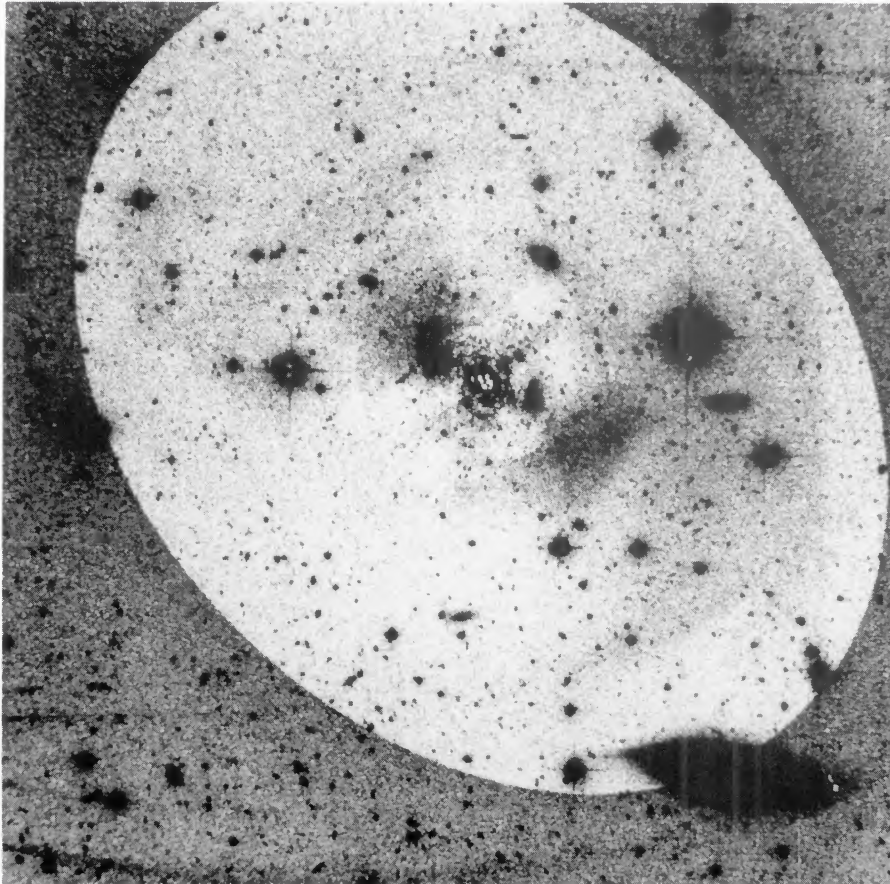


FIG. 4. Residual map of the  $R$  image showing several inner shells in addition to the outer SW shell. The linear features in the lower left corner of the image are not real.

Forbes *et al.* (see page 1577)

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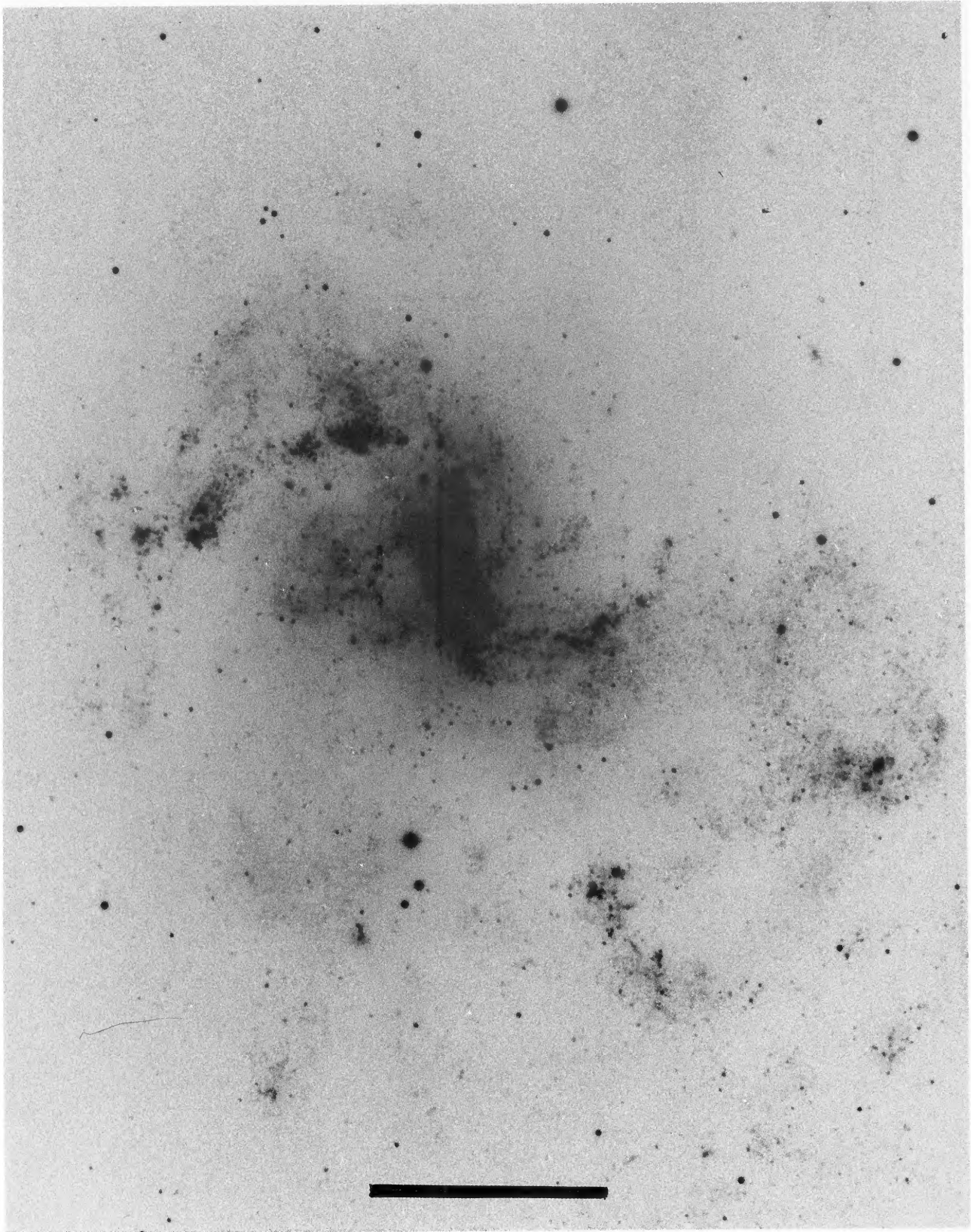


FIG. 1. NGC 1313 as seen in blue light (IIa-O emulsion + GG 385 filter) with the AAT. The suggestion of a spiral structure and rather scattered clouds of stars at some distance from the prominent bar is very reminiscent of the Large Magellanic Cloud. Scale bar is 2' in length. North is at the top and east is to the left in all images.

Ryder *et al.* (see page 1593)