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PHOTOELECTRIC COLOR MEASUREMENTS OF OUTER RINGS IN GALAXIES[1]

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ABSTRACT

Beam-switched photoelectric measurements of *UBV* colors have been obtained for faint outer rings in four representative galaxies. The data show that rings exist over a range of colors and that the most common rings, which are found in RSB0/a galaxies like NGC 2859, consist largely of older stars. The surface brightness increase within such rings is therefore most plausibly attributed to an increase in the projected stellar density associated with the nonaxisymmetric structure of barred and oval galaxies. The outer ring in the oval galaxy NGC 4736 has a relatively blue $B-V$ color, and this provides an example of an outer ring in which young stars are important. A brief discussion of possible formation mechanisms for outer rings is presented.

Subject headings: galaxies: photometry — galaxies: stellar content — galaxies: structure

I. INTRODUCTION

Outer-ring structures in galaxies are rare (de Vaucouleurs 1975), but when present are often associated with a distinct set of galaxy characteristics. For example, Kormendy (1979) has shown that complete outer rings (R systems in de Vaucouleurs's 1959 notation) and strong bars tend to coexist; the rings therefore might be connected with the nonaxisymmetric gravitational perturbation associated with the bar. Similarly, rings are common in galaxies which show evidence for having oval disks (Kormendy 1979, 1980; Kormendy and Norman 1979). An additional structural correlation was noted by de Vaucouleurs (1975), who pointed out that R rings are most frequently seen in S0/a galaxies. More recently H I 21 cm surveys have revealed that many (but not all) RSB0–RSBa galaxies are H I–rich as compared with typical S0/a systems (Bieging and Biermann 1977; Krumm and Salpeter 1979; Faber, Gallagher, and Knapp 1980). In the few instances where outer rings are found in spiral galaxies, the galaxies tend to be oval; several outstanding examples, including NGC 3504, NGC 4941, and the Seyfert galaxy NGC 1068 are illustrated by Sandage (1961). When high spatial resolution 21 cm line observations are available, as for the oval RSab galaxy NGC 4736 (Bosma, van der Hulst, and Sullivan 1977) or the RSB0/a galaxy NGC 1291 (Mebold *et al.* 1979; Balick 1977), a good case can be made that an H I concentration is associated with the optical ring.

There is, however, as yet no model of galaxy structure which accounts for outer rings. The visual impression that rings are due to a local increase in surface brightness at large galactic radii has been confirmed by photographic surface photometry of several RSB0–RSBa galaxies (de Vaucouleurs 1975; Gallagher 1980), but the cause of this brightness increase is not known. From annular photoelectric photometry and a visual examination of Palomar Sky Survey prints, Kormendy (1977, 1979) suggested outer rings might be blue. This would be consistent with recent star formation which would also account for the knotty appearance of many rings. If young stars exist in sufficient numbers, then rings, like spiral arms, might owe their visibility to the lower mass-to-light ratio of a young stellar population (cf. Schweizer 1976). Studies of gas response in a disk galaxy to bar or oval distortions show these types of perturbations strongly affect the gas distribution and lead to gas concentrations in outer ring like structures which might be ideal sites for star formation (e.g., Roberts, Huntley, and van Albada 1979; Sanders and Tubbs 1980, and references therein). In this case the rings would also be a physical parallel to spiral arms, with the optical light providing a tracer of regions of high gas density. On the other hand, numerical experiments have shown outer rings can be produced purely as a stellar density enhancement associated with a bar, although these structures do not seem to persist (Hohl 1978; Miller 1980). We might then only rarely expect to see rings which are composed primarily of an old stellar population or which exist in gas-poor galaxies.

In this paper photoelectric *UBV* measurements are

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presented for outer rings in a small but representative sample of galaxies. These data allow an approximate determination of the stellar populations within the rings, thereby adding to the observational basis for discussions concerning the evolutionary status of outer rings.

II. OBSERVATIONS

Outer rings of galaxies have low surface brightness, typically 10% or less of the night-sky background. Precise sky subtraction is therefore of critical importance to successful photoelectric measurements. This was accomplished with the KPNO 1.3 m telescope equipped with a chopping secondary mirror which allows the field of view to be quickly and accurately switched between two positions (object and sky) separated symmetrically about the optical axis by up to 15′. The detector was an RCA C31034 A photomultiplier tube, operated in the pulse counting mode in the single channel Kinman Mark II photometer. This photometer has computer-controlled filter wheels, which enabled us to interlace measurements with different filters every few seconds while chopping between object and sky positions at a rate of 1 Hz. Photometry obtained in this way is essentially limited by photon statistics (see a more detailed description in Gallagher, Faber, and Burstein 1980).

Photometric measurements were placed on the *UBV* system through observations each night of approximately a dozen of Landolt's (1973) standard stars. Even though conditions were not ideal during the 1979 February observing run, the transformations and measurements of standards showed reasonable repeatability on the three usable nights, and colors are estimated to be intrinsically accurate to ± 0.03 mag.

Galaxies for this program were chosen to represent a range in outer-ring structure. Integral properties of these galaxies are outlined in Table 1. Here we have followed the notation of de Vaucouleurs (1959) in denoting by R′ a pseudo-outer ring consisting of nearly closed spiral arms. Magnitudes are from de Vaucouleurs, de Vaucouleurs, and Corwin (1976; hereafter RC2), except for NGC 2273 where the 52″ aperture measurements of Huchra (1977) are given. Structural types were determined for all galaxies from blue bandpass photographs with a scale of 10″ mm^{-1} obtained with a single-stage image intensifier on the 2.3 m telescope at Steward Observatory, except for NGC 4736 where the RC2 type is given. Photographs of the program galaxies are provided in Figure 1. The galactic reddening $E(B-V)$ has been estimated for all galaxies by applying the method recommended by Burstein and Heiles (1978) for galactic latitudes greater than 15°.

The results are presented in Table 2. Offsets given in the table in the arc seconds of right ascension and declination from the galaxy center, and positions measured in the rings are shown in Figure 1. These positions were measured relative to either the nucleus or bright stars and were observed by taking advantage of

TABLE 1

PROPERTIES OF PROGRAM GALAXIES

Galaxy	Type	Ring	V_T	$(B-V)_T$	$(U-B)_T$	$E(B-V)$
NGC 2273 . . .	SB(r)ab	R′	(12.29)	(0.98)	(0.44)	0.08
NGC 2859 . . .	RSB0	R	10.72	0.93	. . .	0.00
NGC 3945 . . .	RSBa	R	10.6	0.92	. . .	0.00
NGC 4736 . . .	RS(r)ab	R	8.10	0.75	0.16	0.00

TABLE 2

PHOTOMETRY OF GALAXIES WITH OUTER-RING STRUCTURES

Galaxy	Location	*XY* (in arcsec)	Aperture (in arcsec)	μ_B	$B-V$	$U-B$
NGC 2273 . . .	center	0, 0	23	20.7	1.01	0.44
	ring NE	−39, 38	23	24.0	0.98 ± 0.05	0.56 ± 0.1
NGC 2859 . . .	center	0, 0	23	19.8	1.00	0.58
	bar S	10, −25	23	22.4	0.98	0.54
	gap	−58, 0	23	24.6	0.87 ± 0.06	0.46 + 0.1
	ring S	18, −85	23	24.7	0.94 ± 0.08	0.29 ± 0.15
NGC 3945 . . .	center	0, 0	23	19.6	1.03	0.60
	ring N	0, 125	23	24.8	0.79 ± 0.06	0.18 ± 0.1
	ring SE	−60, −110	23	24.8	0.95 ± 0.08	0.50 ± 0.2
NGC 4736 . . .	center	0, 0	36	20.5	0.93	
	ring S	−50, −300	36	25.2	0.61	

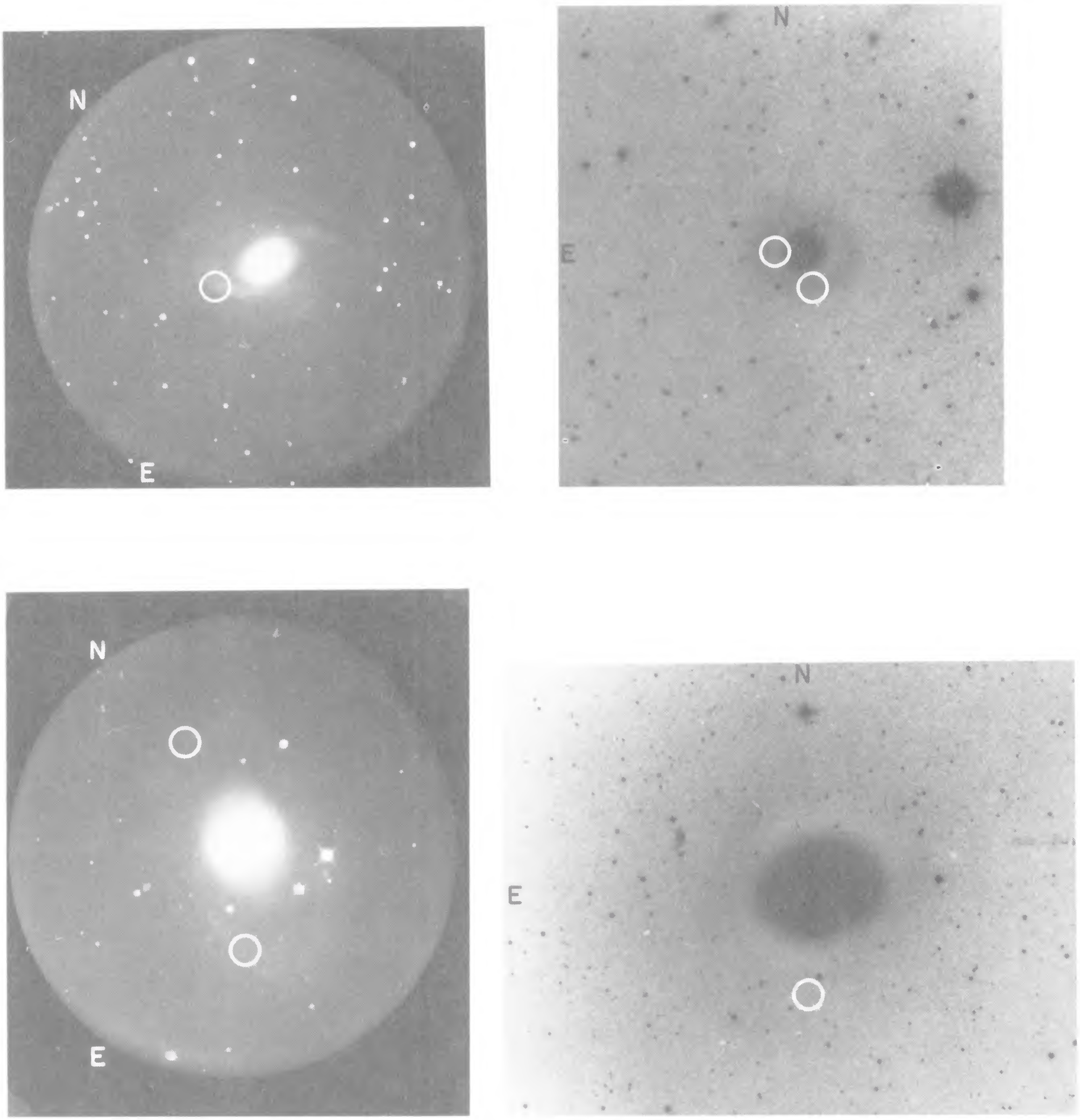

FIG. 1.—Galaxies with typical outer-ring morphologies from the surface photometry program. NGC 2859 and NGC 4736 are reproduced from Palomar Sky Survey blue prints. The NGC 2273 and NGC 3945 illustrations are from *B*-bandpass photographs taken with a one-stage 40 mm image intensifier on the Steward Observatory 2.3 m telescope. The white circles illustrate only the positions which were photometered, and not the aperture size.

the 1.3 m telescope's precision blind-offset capability. Sky reference points were chosen to lie well outside the optical image of the galaxy and to avoid stars visible on the Palomar Sky Survey prints. The object and sky positions are estimated to be accurate to about 5″.

The aperture sizes are nominal values supplied by KPNO and were used only to estimate galaxy surface brightnesses (μ_B mag arcsec^{-2}) given in Table 2. From three centered observations of NGC 2859 taken on different nights, we find that the internal repeatability for both the $U-B$ and $B-V$ colors and V magnitude on a bright object is ± 0.01 mag, as compared with our transformation precisions of ± 0.03 mag. Where the statistical error exceeds ± 0.03 mag, the $\pm 1\ \sigma$ standard deviation as derived from multiple observations is listed in the table.

III. RESULTS

NGC 2273.—In this SBab galaxy weak spiral arms originate from a central bar and nearly close to form a pseudo-outer ring (see Fig. 1); this is perhaps a galaxy with both a bar and ovally distorted disk in which the arms (and thus pseudo-ring) are small pertubations. With our reddening correction the intrinsic colors are in the regime populated by structurally normal Sa galaxies, which suggests that star formation is not widespread. The inclusion of NGC 2273 as number 620 in the Markarian survey of galaxies with blue continua (Markarian and Lipovetskii 1974), and the complex dust lanes seem near the center on our blue image-tube plates indicate that some star formation near the nucleus is possible. However, the photometry reveals little or no color gradient. Denisyuk and Lipovetskii (1974) obtained a nuclear spectrum which shows the nuclear emission line characteristics of a normal spiral, including strong Hα and [N II]. Faber, Gallagher, and Knapp (1980) find NGC 2273 to contain H I from pencil beam measurements made with the NRAO 93 m telescope. For a distance of 39 Mpc ($H_0 = 50$ km s^{-1}Mpc^{-1}), $M_{\rm H\ I} \approx 2 \times 10^9\ M_\odot$ and $M_{\rm H\ I}/L_B \approx 0.1$. These H I parameters are in the normal range for an Sa galaxy. Since NGC 2273 does not support extensive star formation in the disk, the low-amplitude pseudo-ring is therefore most likely due to a density enhancement rather than the effects of star formation. The red colors of this rather normal system provide an interesting contrast to the range of colors which are found for true outer rings.

NGC 2859.—This is probably the best northern example of an RSB0/a-type galaxy (θ galaxy) with a pronounced bar and outer ring. The structure seen both on the Palomar Sky Survey prints and on our image intensifier plates is consistent with the dominant old stellar population implied by the integrated colors: the galaxy has no obvious dust lanes or knots. H I detections have been reported for this system from observations obtained with the Arecibo 305 m and NRAO 93 m telescopes (Bieging and Biermann 1977; Faber, Gallagher, and Knapp 1980), but preliminary data from the Westerbork Radio Synthesis Telescope show that much of the gas may reside in nearby dwarf galaxies (H. van Woerden, private communication). This galaxy therefore does not seem to provide an environment which would be conducive to extensive star formation. Photometric observations were taken at three off-center positions (see Fig. 1). The bar and center measurements have similar colors, but the measurement in the apparent "gap" between the ring and bar is marginally bluer. The ring measurement may be bluer than expected in $U-B$, but the data are rather poor. Note also that we would also expect some color change to be introduced by the normal radial color gradient which is found even in S0 galaxies (e.g., de Vaucouleurs and Corwin 1977). Since the measurement in the gap at $r = 58''$ has nearly the same surface brightness as the ring at $r = 85''$, we can see that the ring is considerably brighter than the extrapolated lens component would be at that radius (cf. de Vaucouleurs 1975). Despite this local rise in surface brightness, if we look only at the more accurate $B-V$ data, there is no significant color change in the ring as compared to the bar or gap regions.

NGC 3945.—A high-quality illustration of this galaxy is given by Kormendy (1979). Dust is present in the galaxy, and knots, which may be star clusters or H II regions, easily can be seen in the southeast part of the ring. Interestingly, despite these optical indications of an active interstellar medium, Faber, Gallagher, and Knapp (1980) obtained at best a weak detection of H I from high-quality 93 m telescope data; NGC 3945 is not H I–rich. The photometric observations are somewhat ambivalent. The southeastern part of the ring, in the region containing the knots, has red colors, but the northern edge of the ring, which is a smooth section, is significantly bluer in $B-V$ and $U-B$ than the center of the galaxy. Clearly more data are needed before we can make any statements about the mean colors of the ring. It is perhaps significant that the ring seems to be sharply bounded near the southeastern knots; maybe this is a dusty region, which might account for the red colors.

NGC 4736.—Outer rings are not common in galaxies with normal spiral structure, but this unusual system has more than its share of interesting features, including a very pronounced oval structure (see discussions in Sandage 1961; van der Kruit 1974, 1976; Bosma, van der Hulst, and Sullivan 1977; Kormendy 1979; Kormendy and Norman 1979). The $B-V$ of the ring is bluer than that of the nucleus or the integrated $B-V$ provided in the RC2. Detailed surface photometry will be required, however, before it can be determined how the ring compares in color with the outer regions of the spiral disk or the gap region between the ring and disk. The presence of H I in the ring near the position where photometry was obtained (Bosma *et al*., and see Fig. 1) and the blue colors are both highly suggestive of a young stellar population; thus this ring probably is a visible indication of active star formation.

IV. DISCUSSION

Our photometric data and the measurements given by Kormendy (1977) show that outer rings do not have the very blue colors associated with dominant young stellar populations and, therefore, are not simply tracers of sites of current star formation in regions of enhanced gas density. Rather, outer rings, like the inner spiral arms in many galaxies (cf. Schweizer 1976; Talbot, Jenson, and Dufour 1979), appear to exist over a range in star-formation rate which extends from very low in NGC 2859 to a modest level in NGC 4736. Thus it seems most probable that rings also primarily result from a stellar density perturbation. Indeed, the most common rings are in SB0/a galaxies with NGC 2859–type morphologies, where young stars are unlikely to be important light contributors, in which case the brightness increase of the ring relative to its surrounding is a measure of the increase in projected stellar density. Even in the ring in NGC 4736, where young stars could be plentiful, the H I distribution and kinematics indicate the ring probably is a result of a density enhancement formed by the oval distortion in the main body of the galaxy (Bosma, van der Hulst, and Sullivan 1977; Bosma 1978; Kormendy 1980).

The close relationship between rings and bars in early-type galaxies or oval disks in spirals is certainly significant, as Kormendy (1979) and Kormendy and Norman (1979) have previously emphasized. It is tempting to presume outer rings are secondary structures resulting from the breaking of axial symmetry in the potential of a galaxy by a bar or oval disk. In general, one can conceive of two classes of possibly interrelated mechanisms which might lead to the appearance of an outer ring. Rings could form in situ, perhaps as a result of repeated episodes of star formation triggered by shocks in a bar or oval-driven gas spiral pattern (cf. Roberts, Huntley, and van Albada 1979; Sanders and Tubbs 1980). This process by itself presumably would lead only to a stellar disk, but it is likely that stars formed near the radius of the bar or oval major axis could not remain in stable orbits (e.g., Sanders and Huntley 1976). Thus a ring structure might build up, whose inner edge is defined by orbital stability and whose outer radius is determined by a radial falloff in star-formation efficiency (cf. Strom 1980). A second possibility is for rings to be primarily produced by rearrangement of a previously existing stellar disk upon the growth of a bar or oval distortion within a galaxy. Although it is still not established whether galaxies evolve from axisymmetric to barred or oval states, it might yet prove feasible for rings to be stationary kinematic phenomena associated with a potential minimum in distorted galaxies (see Freeman 1975; Duus and Freeman 1975; Kormendy 1979, and also the comments in § I).

Whatever process in reality is responsible for outer rings clearly must be able to account for the observed range in stellar populations. A particularly useful constraint is imposed by the red $B-V$ color of the NGC 2859 ring, which if taken alone would suggest most of the ring stars formed more than ~5 billion years ago (Larson and Tinsley 1978). Of course, if blue $U-B$ colors could be confirmed, then the age limits could be considerably relaxed, although it is generally our impression that rings are likely to prove long-lived structures. We also should recognize that if rings are simple kinematic phenomena, then we might expect outer rings to exist in most barred galaxies. This does not seem to be true, which may indicate we are dealing with a more subtle and perhaps transient process. The correlation between the presence of outer rings and high H I content in some SB0/a galaxies also does not comfortably fit into a simple kinematic model. More information is needed before it can be determined which particular conditions favor the production of outer rings in galaxies. The trend from the currently available data, however, supports the view put forth by Kormendy (1979) that ringed galaxies are systems which are experiencing strong internal perturbations. These galaxies therefore are deserving of further study.

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