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STELLAR POPULATIONS IN SHELL GALAXIES

STACY S. MCGAUGH AND GREGORY D. BOTHUN
Department of Astronomy, University of Michigan, Ann Arbor, Michigan 48109

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ABSTRACT

UBV surface photometry of the shell galaxies Arp 230, NGC 7010, and Arp 223 is presented. We find all to be the result of mergers. In Arp 230, the merger of two spirals induced a burst of star formation which has declined in strength since the collision. The remnant seems likely to become elliptical. NGC 7010 has very red shells, perhaps redder than the galaxy itself. Evolution of the stellar content of these shells may be important. Arp 223 has shell colors which are slightly bluer than the main body of the galaxy, consistent with an origin in an Sb. Our data indicate that the timescale since the interaction is typically $\approx$ 1 Gyr. Moreover, those ellipticals that have been formed by mergers should have complex stellar populations with a component formed in the collision. This extra component might be detectable by the methods of empirical population synthesis, at least to some age limit, making it possible to investigate the relative numbers of ellipticals formed in this manner by methods other than morphology.

I. INTRODUCTION

Distinguishing between the various mechanisms proposed for the occurrence of extended shells around early-type galaxies (e.g., Arp 1966, Schweizer 1980) is essential to the interpretation of both their statistical frequency and formative process (Malin and Carter 1983; Schweizer and Seitzer 1988). This is especially important in light of arguments that imply a rather high merger rate leading to the suggestion that many or *all* ellipticals and bulges were formed by mergers between disk galaxies (Barnes 1989 and references therein). Despite what they may tell us about some aspects of galaxy formation, shells remain poorly understood in terms of the stellar population of which they are composed. Understanding this is crucial in distinguishing between different formation mechanisms.

Theoretical work on shells generally falls into two categories: the merger hypothesis, whereby material accreted from a companion forms the shells (e.g., Quinn 1984; Huang and Stewart 1985; Dupraz and Combes 1986; Hernquist and Quinn 1988, 1989), and gas dynamical theories, which invoke star formation in gas intrinsic to the galaxy (e.g., Fabian, Nulsen, and Stewart 1980; Williams and Christiansen 1985; Umemura and Ikeuchi 1987; Loewenstein, Fabian, and Nulsen 1987). As a corollary to the merger scenario, Wallin and Struck-Marcell (1988) have developed models in which shell-like structure is formed in the disks of S0s by collisional encounters during the evolution towards a merger. Nulsen (1989) has shown analytically that shell features can form as a result of shearing in any population which is initially confined to a small volume of phase space.

These theories make specific predictions that are testable. In merger scenarios a population external to the primary galaxy forms the shells; this should result in a color difference between the shells and the rest of the galaxy. Shell galaxies are usually giant ellipticals or S0s while the cannibalized galaxies are less massive, being either late-type galaxies or former physical companions. Hence merger models anticipate shells which are bluer than the main body of the galaxy to the extent that low mass galaxies are intrinsically bluer than those of high mass. Projecting the results of merger simulations onto the plane of the sky results in a plateau shaped luminosity profile (Hernquist and Quinn 1988). In contrast, the features predicted by Wallin and Struck-Marcell (1988) to occur in the disks of S0s should have more symmetric profiles and colors identical to the surrounding disk. Thus, such features should be distinguishable from shells of external origin, even in systems where both might be present.

Gas dynamical theories invoke recent star formation, and such shells should be considerably bluer than the rest of the galaxy (assuming a normal IMF). Umemura and Ikeuchi (1987) suggest that since outer shells are the more recently formed, they should be bluer than inner shells. This is also implicit in the blast wave theory of Williams and Christiansen (1985). Furthermore, Williams and Christiansen compute the radial-luminosity profile they expect for shells formed by their mechanism. This profile has a sharp outer edge but varies smoothly inward. Other gas dynamical theories predict shell profiles which are likely indistinguishable from merger predictions. This makes shell geometry a less useful discriminator than color.

To date, observations are most consistent with the merger hypothesis. Merger simulations account very well for the observed morphology of shell systems (Malin, Quinn, and Graham 1983; Quinn 1984), though dynamical friction must be invoked to explain the presence in some galaxies of shells at very small radii (Pence 1986; Prieur 1988a). McGaugh (1985) argued that the sharp inner as well as outer edges of the shells were inconsistent with the blast wave scenario. Fort *et al.* (1986) modeled the observed radial profiles of the shells and found them to be consistent with the predictions of merger simulations. As for the colors of the shells, Carter, Allen, and Malin (1982) found that one shell of NGC 1344 was bluer than the rest of the galaxy in $B-J$, though their data indicate that it might be redder in $B-V$. Fort *et al.* (1986) found the shells of NGC 5018 and NGC 2865 to be bluer than the main bodies of those galaxies, but found no color difference in NGC 3923. Pence (1986) reached the same conclusion for that galaxy and also for NGC 3051. In the well-studied case of Arp 227 (NGC 474), McGaugh (1985) found marginal evidence for a color difference, Schombert and Wallin (1987) found no difference, and Prieur (1988b) found significant differences. We attribute these results to differences in the analysis methods used. In particular, Schombert and Wallin made no attempt to subtract out the background galaxy light. In those studies where a color difference in the shells was detected, they were found to be slightly bluer, consistent with a merged population but not with recent star formation. However, a number of studies find no color difference.

It is important to understand this in terms of the stellar population that compose the shells. Some merger remnants may have come from red galaxies. Dupraz and Combes (1986) and Hernquist and Quinn (1988) note that compact spheroidal galaxies can form shells as well as dynamically cold disks. However, dEs are bluer on average than their giant brethren, having a mean $\langle B-V \rangle = 0.72$ (Caldwell and Bothun 1987). Furthermore, their colors are less subject to fading (due to a reduced population of upper main-sequence stars) than are those of disks. Thus the stellar population of some shell systems remains a mystery, and it is possible that these structures are intrinsic to the galaxies. To investigate the origin and stellar population of the shells, we have extended the observational baseline into the ground-based ultraviolet where the color differences between shells and the host galaxy should be most pronounced. Our observations are discussed in Sec. II and the analysis is described in Sec. III. Results are presented in Sec. IV and their significance is discussed in Sec. V.

II. OBSERVATIONS AND REDUCTION

Observations were made with the McGraw Hill 1.3 m telescope on six nights (of which three were photometric) in August 1988. A Thomson CCD was used in direct mode, giving an image scale of 0.48″ per 23 μm pixel. This CCD is a quiet ($7e^-$ rms read noise), frontside illuminated device which derives its ultraviolet sensitivity from a metachrome-2 coating. Photometric transformations were derived from observations of Landolt (1983) standard stars covering a wide range of color. The solutions have very small color terms, implying that the U filter suffers no serious red leak.

Objects were chosen from Table II of Malin and Carter (1983). We sought to cover a wide range of morphological types, and so selected Arp 230 (peculiar), Arp 223 = NGC 7585 (S0), and NGC 7010 (E). The primary limitation we faced was the small field of view ($3.2' \times 4.6'$) of the direct mode, and so the above galaxies were also chosen because they fit within this small field with room left for sky determination. Available reducing optics do not transmit below 4000 Å so it was necessary to use the direct mode in order to obtain U data. Each galaxy was observed for 3600 s in U, 1800 s in B, and 900 s in V on each of the three useful nights.

Standard CCD reduction procedures were employed; these include bias and dark subtraction and flatfielding. These were accomplished using the software packages BARF and IRAF. Twilight flats were compared to flats derived from the median of all image frames from a given filter. No significant differences were found. Determination of sky levels show that all frames are flat to 0.1% or better. This, plus the darkness of the sky in U and B, make this project possible. After sky subtraction, the images for each galaxy in each filter were registered and combined to increase signal to noise and remove cosmic rays. The program PROF in the GASP package was used to fit elliptical isophotes to the luminosity profile of the galaxies. PROF is an iterative ellipse fitting routine which treats the center, position angle, and ellipticity of each ellipse as free parameters. These ellipses were also used to determine the differential color profiles of the galaxies. A useful check on the zero points determined from the standard stars was made by comparing the luminosity and color profiles determined for each galaxy with data from different nights. Excellent agreement was found among all independent datasets. Also, our data for Arp 223 is in agreement with the published photometry of Schombert *et al.* (1990).

III. ANALYSIS

The technique of two-color mapping (Bothun 1986) was initially employed to search for color differences in each galaxy. This revealed only the general color gradient already seen in the differential color profiles—the shells did not stand out as being very different in color from the surrounding galaxy. This could be due either to the shells being the same color as the host galaxy, or to the background galaxy light dominating the shell light. Since shells are typically very low surface brightness features ($\mu_B \approx 25$ mag arcsec^{-2}), the latter is likely to be true except at large radii. Thus it is necessary to remove the galaxy background to get the true shell colors (e.g., Fort *et al.* 1986).

Two kinds of subtraction methods were employed here. The first involved empirical models built from the ellipses generated by PROF. The shells were masked and not included in the ellipse fitting. Masking out the shells also meant masking out a significant amount of galaxy light, and profiles fit to these data lacked sufficient signal to constrain all three ellipse parameters simultaneously. The best subtractions (of the many we tried) were made by fixing the ellipse center and the position angle at that of the last ellipse fit to high signal, unmasked galaxy light. The second subtraction method smoothed the data over scales larger than the shell features after first editing out stars with IMEDIT in IRAF. Boxcars and median filters of 10–40 arcsec were tried. The best results came for those of 20–30 arcsec. This method obviously does a poor job near the centers of the galaxies, but is quite good at intermediate to large radii where most of the shells are found. Some over-subtraction results, but this should not affect the measured colors as each filter is treated in the same manner. Overall, the median filter was found to produce the most robust results.

Colors and surface brightnesses for features in all galaxies are listed in Table I. The various features are identified in the

TABLE I. Shell data.

Galaxy	Feature	$B-V$	$U-B$	$\mu(B)$
Arp 230	A	0.67 ± 0.03	0.31 ± 0.10	25.5
	B	0.53 ± 0.02	0.25 ± 0.15	24.9
	C	0.52 ± 0.06	0.01 ± 0.10	24.8
	D	0.48 ± 0.06	-0.11 ± 0.07	24.4
	E	0.54 ± 0.05	-0.35 ± 0.20	24.5
	F	0.47 ± 0.04	...	24.2
	Center	0.89 ± 0.01	0.03 ± 0.02	20.5
	East plume	0.35 ± 0.01	-0.29 ± 0.02	21.0
	West plume	0.48 ± 0.01	-0.50 ± 0.02	21.1
	Southern extension	0.66 ± 0.07	0.02 ± 0.10	25.8
NGC 7010	A	1.44 ± 0.11	0.29 ± 0.25	26.4
	B	1.34 ± 0.03	0.19 ± 0.30	25.8
	C	1.11 ± 0.04	0.36 ± 0.20	24.9
	D	1.03 ± 0.25	...	25.5
Arp 223	A	0.76 ± 0.03	0.13 ± 0.07	24.7
	B	0.99 ± 0.03	0.26 ± 0.10	25.0
	C	0.89 ± 0.08	0.17 ± 0.13	24.8
	D	0.84 ± 0.07	0.00 ± 0.12	24.7
	E	0.63 ± 0.07	...	25.4
	F	0.76 ± 0.10	...	26.1
	G	0.81 ± 0.06	0.09 ± 0.15	26.4
	H	0.80 ± 0.10	...	25.9

background subtracted images [Figs. 1(d), 4(b), and 6(b)]. The listed values were determined in contiguous 5 pixel ($\approx 2.5''$) square apertures placed to cover as much of each feature as possible while avoiding regions where stars had been edited out. The different galaxy subtraction methods yield consistent colors for most features. Errors are estimated by comparing the results of the various schemes. Uncertainty in the background subtraction is the dominant source of error, but we found no indication of systematic errors such as color trends with smoothing scale. Surface brightnesses are more sensitive to the subtraction method than are colors; these values should be treated as estimates only.

IV. RESULTS FOR INDIVIDUAL GALAXIES

a) Arp 230

Arp 230 is classified only as a peculiar galaxy (Arp 1966). It has the prototypical shell morphology, appearing elliptical in deep photographs with interleaved shells aligned along the major axis [Fig. 1(a)]. However, it is not elliptical, as can be seen in Fig. 1(b), which is scaled to reveal the interior structure. There is a strong dust lane aligned along the putative minor axis, and two plumes extend out from the center roughly parallel to this. Several small loops appear beyond the tips of the plumes. The center of the galaxy is heavily reddened, as can be seen in Fig. 1(c). This is a gray-scale image of the $B-V$ color produced by dividing the B frame by the V frame. It also shows that the plumes are much bluer than the rest of the galaxy. Figure 1(d) is the background subtracted image. A 50 pixel median filter has been used to create a smoothed image which was subtracted from the original. The sharp-edged shells remain as does the interior structure. The shells are labeled from outer to inner, in the order merger simulations imply they would form (which is opposite to the formation order implied by gas dynamical theories).

The morphology of this galaxy strongly suggests that it is the result of a collision between two spirals. Schweizer (1983) classifies it as such. The overall colors are those of a late-type spiral, ruling out the possible involvement of an elliptical in this merger. The luminosity profile (Fig. 2) is not well fit by any standard law, though it is consistent with a de Vaucoulers profile. Figure 3(a) is a color–color diagram. The differential color profile of this galaxy (determined with the ellipses fit by PROF) is shown without error bars. The errors of these points are quite small, being limited only by the zero points and the intrinsic signal-to-noise. Therefore the scatter in these points is real. This is not surprising considering Fig. 1(c): many ellipses include both the blue plumes and the dust lane. Points redward of $B-V=0.7$ probably suffer some reddening from the dust lane (see the reddening vector). At large radii there is a general red to blue color gradient. The center of the galaxy is the reddest point on the graph, consistent with the heavy reddening seen in Fig. 1(c). The two plumes are very blue. The shells are bluer in $B-V$ than the main body of the galaxy, and cover a wide range in $U-B$.

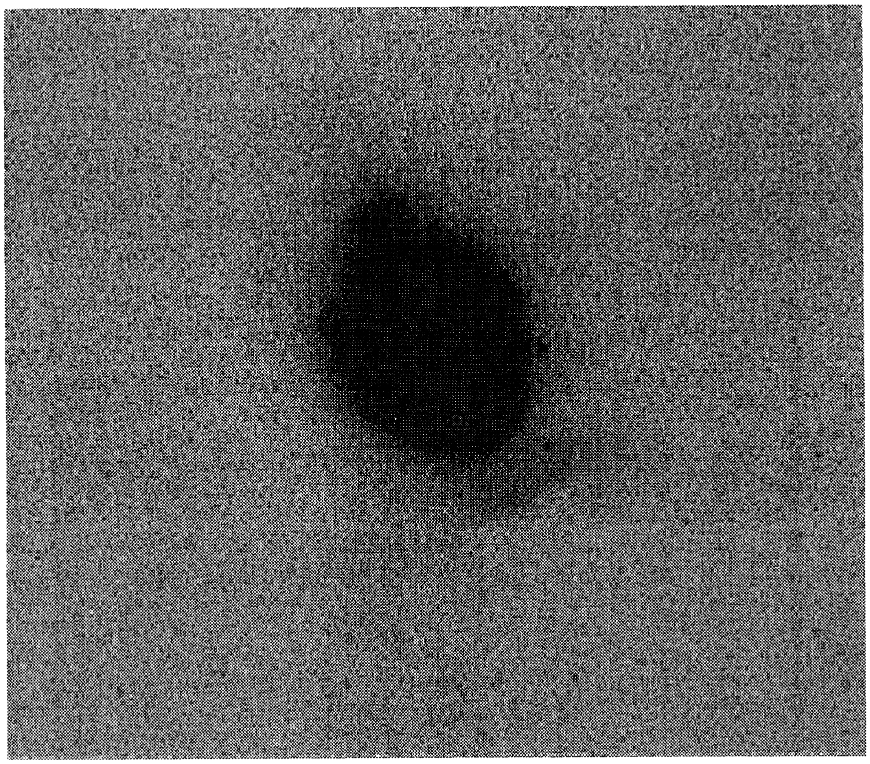
If this system is indeed the result of the merger of two spirals, as color and morphology imply, it is possible that some star formation could have been induced by the collision. Thronson, Bally, and Hacking (1989) have searched the *IRAS* database for shell galaxies to see if these merged systems show any indications of such an effect. Their results are negative: shell galaxies have infrared colors and far-infrared-to-blue flux ratios similar to those of normal galaxies of the same Hubble type. In the particular case of Arp 230, the infrared colors are again those of a late-type spiral, consistent with the optical colors. Using our measured B magnitude with the infrared flux reported for this object by Thronson *et al.* we derive a flux ratio $\log(F_{\rm IR}/F_B) = 2.7 \pm 0.1$. This is high (average Sc $= 2.2$), which we attribute in large part to the unusual geometry of the dust lane which suppresses much of the blue light that would normally be received from the center of the galaxy. The measured $60/100\,\mu$ flux ratio for Arp 230 is 0.41 ± 0.01, a value which is consistent with dust heating by older A, F, and G stars (see Bothun, Lonsdale, and Rice 1989).

With this in mind, the interpretation of the positions of the shells in the color–color diagram becomes very clear. Larson and Tinsley (1978) modeled the effect of a burst of star formation on the $U-B$, $B-V$ colors of a galaxy, and showed that it would first become much bluer in both colors, then fade in $U-B$ faster than in $B-V$ after the burst had ceased. Figure 3(b) is the color–color diagram of Arp 230 with the tracks of Larson and Tinsley [from their Fig. 2(a)] superimposed. These tracks show the outer envelope of colors reached by very strong bursts of star formation. The shells appear to be material which participated (though were not wholly formed) in a burst of star formation which has now ceased. Their colors have faded more rapidly in $U-B$ than in $B-V$, consistent with the evolutionary tracks of Larson and Tinsley. Indeed, the dynamically oldest outermost shell has faded the most, and each subsequent shell has faded less. This implies that the dynamical processes which form the shell may terminate star formation in the shell, either because the gas does not follow the stars or because the gas density in the shells quickly drops below the threshold for star formation (Kennicutt 1989).

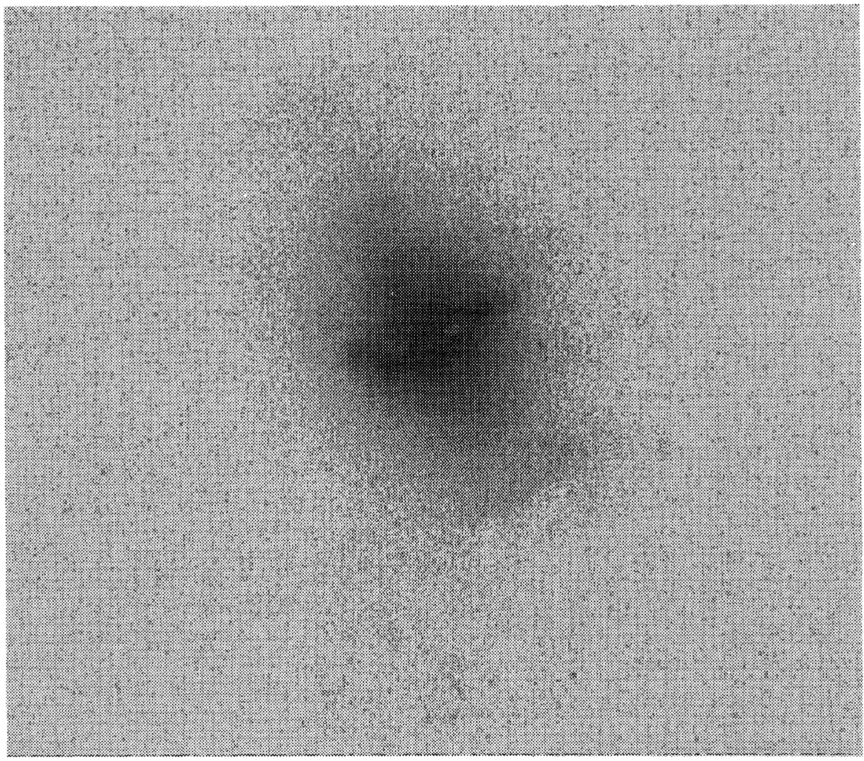
The colors of the shells can be used to gauge the time since the star burst and hence the age of the merged system, providing a quantitative observational measure of the timescale for shell formation. The outermost shell (shell A) has a color that would result from a strong burst and an age of 1–2 Gyr. The color of shell B implies an age of 0.5–0.7 Gyr. The colors of the inner shells lie closer to tracks of weaker bursts at younger ($\leqslant 0.3$ Gyr) ages, implying that the strength of the burst decreased with time.

To the accuracy that they are determined, these ages are not particularly sensitive to metallicity. The primary effect of metallicity would be in the U band via the blueward extent of the horizontal branch and line blanketing. Shifting the $U-B$ colors of the shells does not alter the interpretation. Though the majority of the shell material is expected to be old stars, the vigorous young population dominates at the observed wavelengths. Indeed, Carter *et al.* (1988) found that substantial numbers of A stars were present in the nuclear spectra of 20% of a large sample of shell galaxies, which they interpret as the result of star formation associated with the shell-forming merger event. Note that this sample is a subset of the Thronson *et al.* sample previously discussed. That no indication of star formation is present in the infrared implies that this type of activity (dust heating by massive stars) has died out by the time the shells become visible. If such star formation episodes are common, they may contribute to the population of very metal-rich stars in elliptical galaxies, relaxing the requirement that these be formed during the epoch of galaxy formation.

The shell ages are somewhat more consistent with the dy-



(a)



(b)

FIG. 1. Arp 230: (a) North is up, east is to the left. Area displayed is approximately 3.2′×2.8′. (b) Logarithmically scaled to reveal inner structure. Also note faint extension to the south. (c) Color gray scale. Bluer regions are darker. Note strong central dust lane and blue plumes. (d) Image produced by subtracting median filtered replica. Shells are labeled from outer to inner. Bulges along the minor axis are the plumes; holes near the center are due to the dust lane.

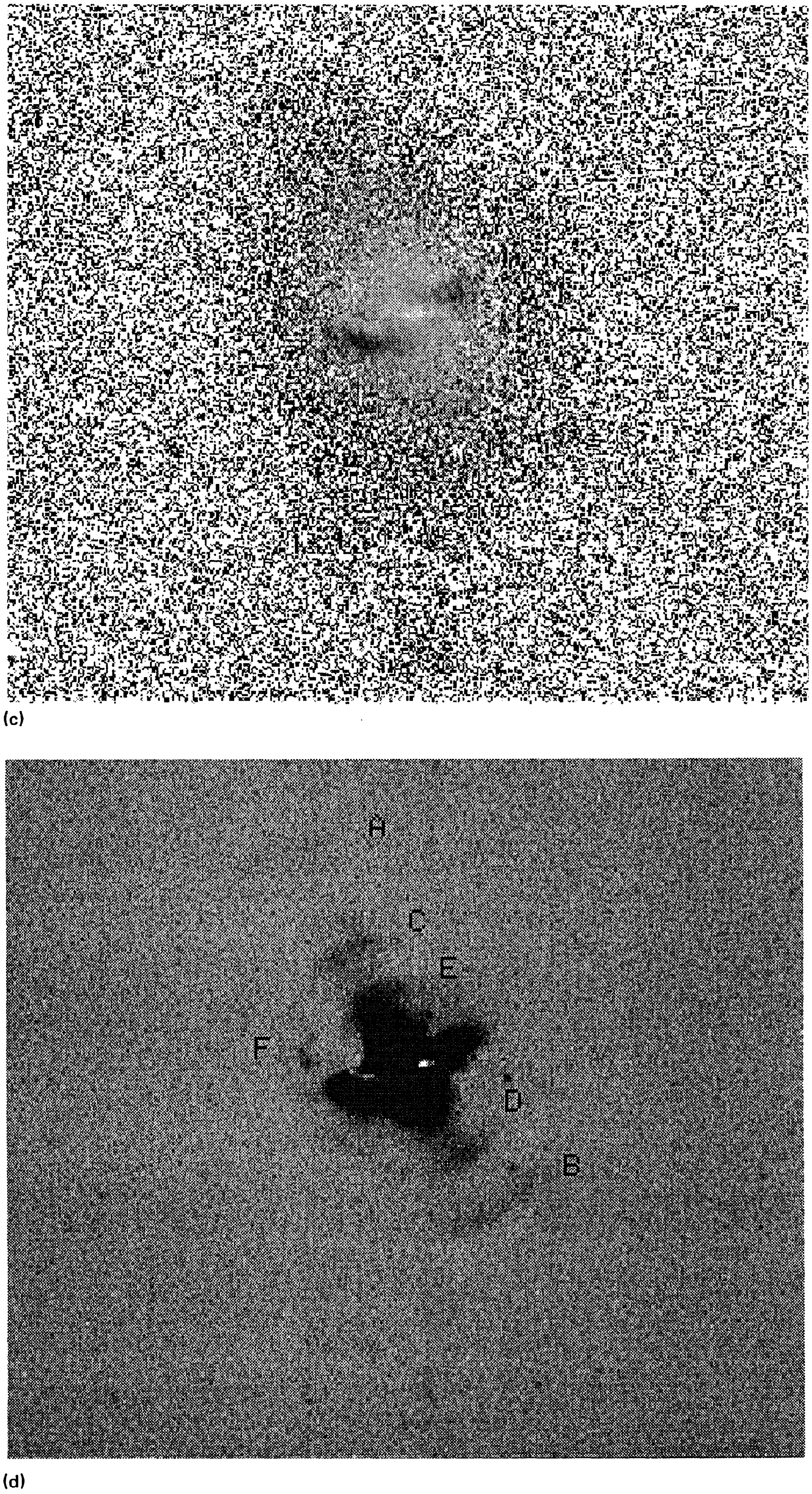


FIG. 1. (continued)

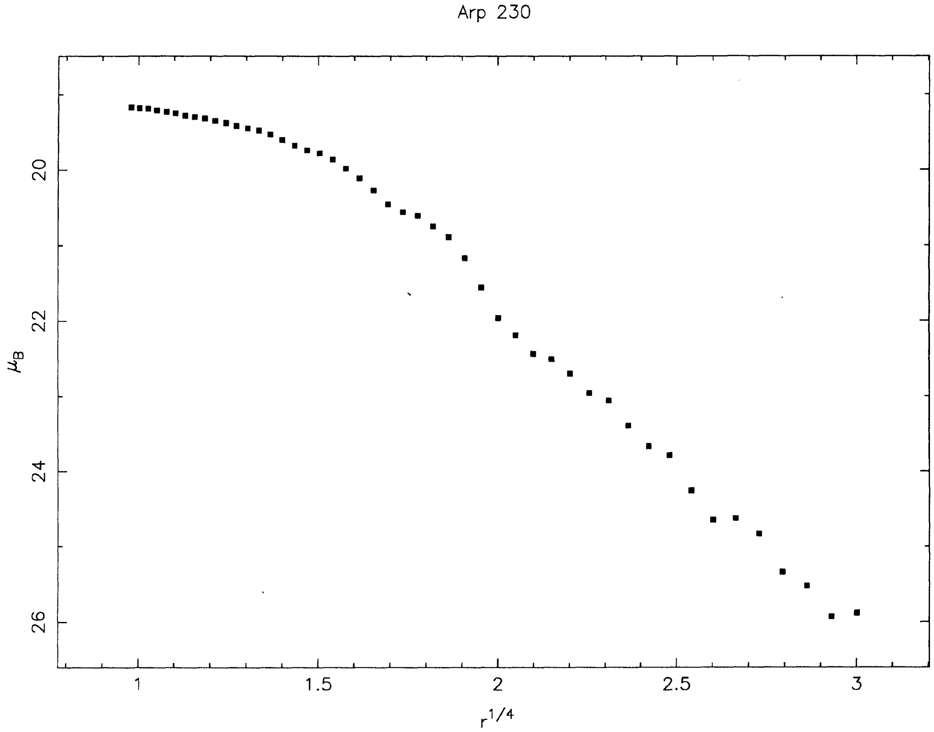


FIG. 2. Luminosity profile of Arp 230 showing disturbed de Vaucouleurs profile.

namical models of Hernquist and Quinn (1988) than with those of Dupraz and Combes (1986). In the simulations of Hernquist and Quinn, shells form on timescales of $\approx 10^8$ yr and endure for a few Gyr. Shell formation proceeds more slowly in the simulations of Dupraz and Combes, with shell systems lasting as long as a Hubble time. Since the observable endurance of a shell system is difficult to quantify, and since the present data give no indication of the number of shells which the Arp 230 system might produce in the future, the distinction between these models is marginal.

The bulk of the evidence strongly suggests that Arp 230 is a recently merged pair of spirals. Its shells were formed as a result of this merger. Had these shells been formed by gas dynamical processes within the galaxy, the outermost shell would be the youngest and bluest, opposite the observed trend. The appearance and profile of Arp 230 suggest that it may become elliptical, as in the case of NGC 7252. Notably lacking are the long tails seen in this galaxy. In 1–2 Gyr, such tails may have had time to disperse. Or, it may be that the plumes of Arp 230 are beginning to form these structures. If so, this process occurs in reverse order to that suggested by Dupraz and Combes. It might be that the plumes [or inner ring, as Schweizer and Ford (1985) call it] are the remnants of the spirals' disks. Detailed velocity maps are required to sort this out. It could also be that the low surface-brightness extension to the south of the Arp 230 is a tidal tail, as Schweizer and Ford suggest, though its morphology is far from typical for such features (i.e., it is much too wide). Another possibility is that the precursor galaxies may have lacked sufficiently massive dark halos to form narrow tidal tails (Barnes 1988).

It appears that sharp-edged shell features can form even in the merger of two nearly equal-mass disk systems. Merger simulations always assume large mass ratios so that the primary potential can be treated as unperturbed and that of the companion can be ignored. This computational convenience now seems unnecessary to shell formation. Nulsen (1989) has shown analytically that shell-like features can form in any integrable potential. From this example, it seems unlikely that the integrability of the potential is any more of a requirement for shell formation than is a large mass ratio. This means that shell features may be formed as a result of encounters from a larger volume of parameter space than has previously been assumed.

b) NGC 7010

NGC 7010 is a true elliptical with prototypic shell morphology [Fig. 4(a)]. Its shells are broad, plateau shaped, and quite low in surface brightness (see Table I). Figure 4(b) shows the galaxy after subtraction of a smoothed (50 pixel median filter) replica. Figure 5 is the color–color diagram for this galaxy. The differential color profile trends from red in the center to blue further out, consistent with a metallicity gradient in the galaxy. Again, the scatter in these points is real. In this case, the isochromes are unlikely to vary significantly from the isophotes, as this is a very subtle effect in true ellipticals (Boroson and Thompson 1987). Rather, we believe that this scatter results from the material of a merged companion which is spread unevenly throughout the galaxy. As has been discussed, theories of shell formation predict blue shells. It is surprising, then, that these shells are as red or redder than the rest of the galaxy. While the faintness of these shells and the rapidly changing galaxy background (and hence uncertain background subtraction) make for large uncertainties, there is no indication of systematic error which would result in very red shells in this one case. Indeed, that our method reveals both red and blue

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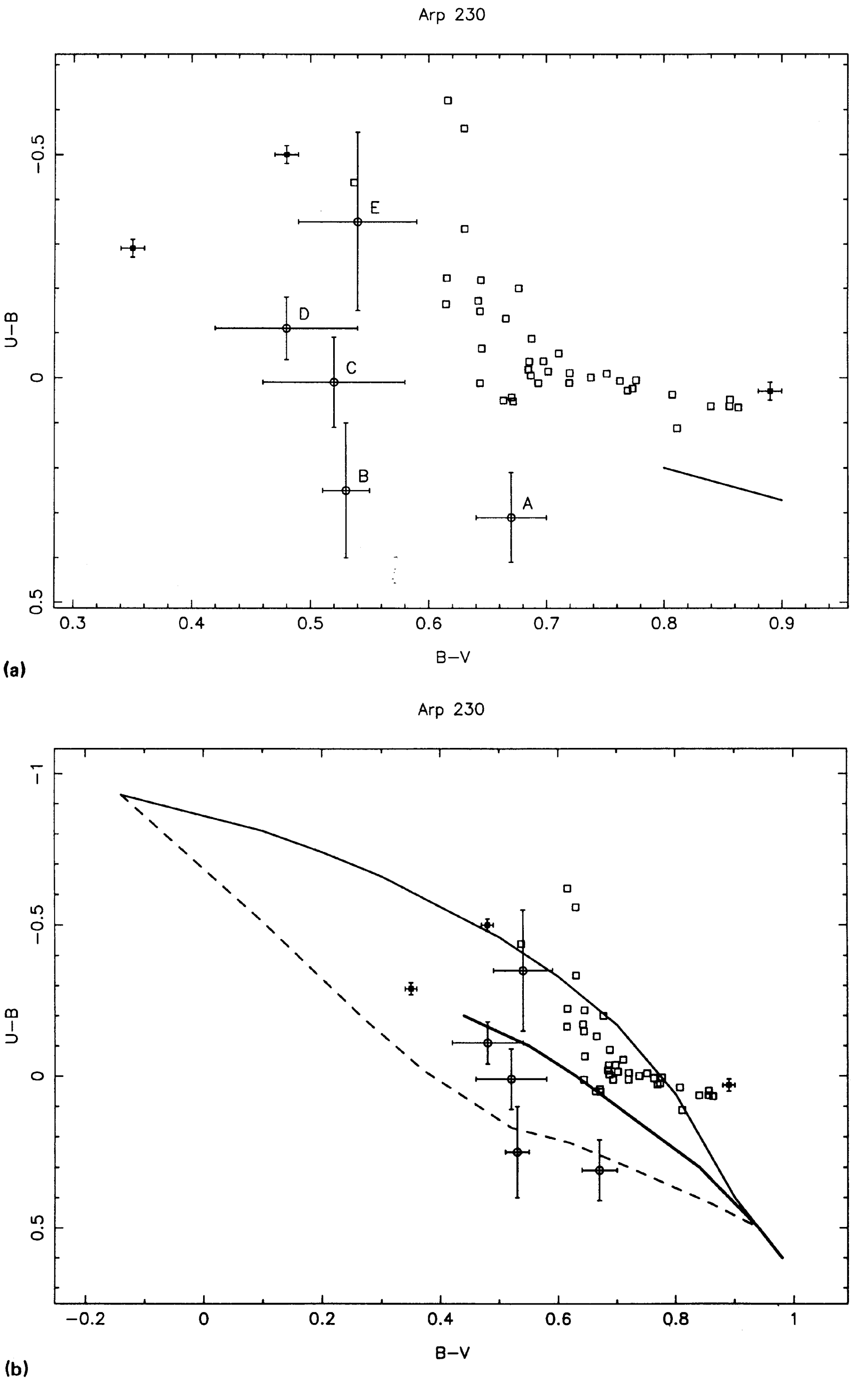


FIG. 3. Arp 230 color–color diagram. (a) Open squares are the differential color profile of the galaxy. Open circles are the shells labeled as in Fig. 1(d). Filled squares are the center and inner plumes of the galaxy. The solid line shows the slope of the reddening vector; its length corresponds to a reddening $E(B-V)=0.1$. (b) The evolutionary tracks of Larson and Tinsley (1978) superimposed on the Arp 230 data [from their Fig. 2(a)]. The heavy solid line is the standard galaxy track. The upper solid line is the locus of different burst strengths. The dashed line is the evolutionary track after the cessation of a strong burst. See Sec. IV*a*.

shells indicates that there is no systematic bias. Since this galaxy is a third of our sample, and other galaxies are also observed to have red shells, it is important to understand how this can occur.

It is possible that the merged companion was originally red. Some S0s this red are known, but are very rare and therefore cannot explain the incidence of red shells in the limited sample of shell galaxies with good color measurements. It is highly unlikely that the merger of two giant ellipticals could form shells. It may be possible that some shells are features intrinsic to these galaxies. If so, they cannot be the result of recent star formation unless an unusual IMF is invoked, as has been suggested for cooling flows (Fabian *et al.* 1982). Instead, they must be formed of a population similar to the rest of the galaxy. If this is the case, a new theory is required that uses this population to form shells. The work of Nulsen (1989) provides a mechanism whereby this might happen, but provides no clue as to how the necessary initial conditions (that the shell material occupy a restricted volume of phase space) could be met by the intrinsic population.

There is yet another possibility to be considered. Merger

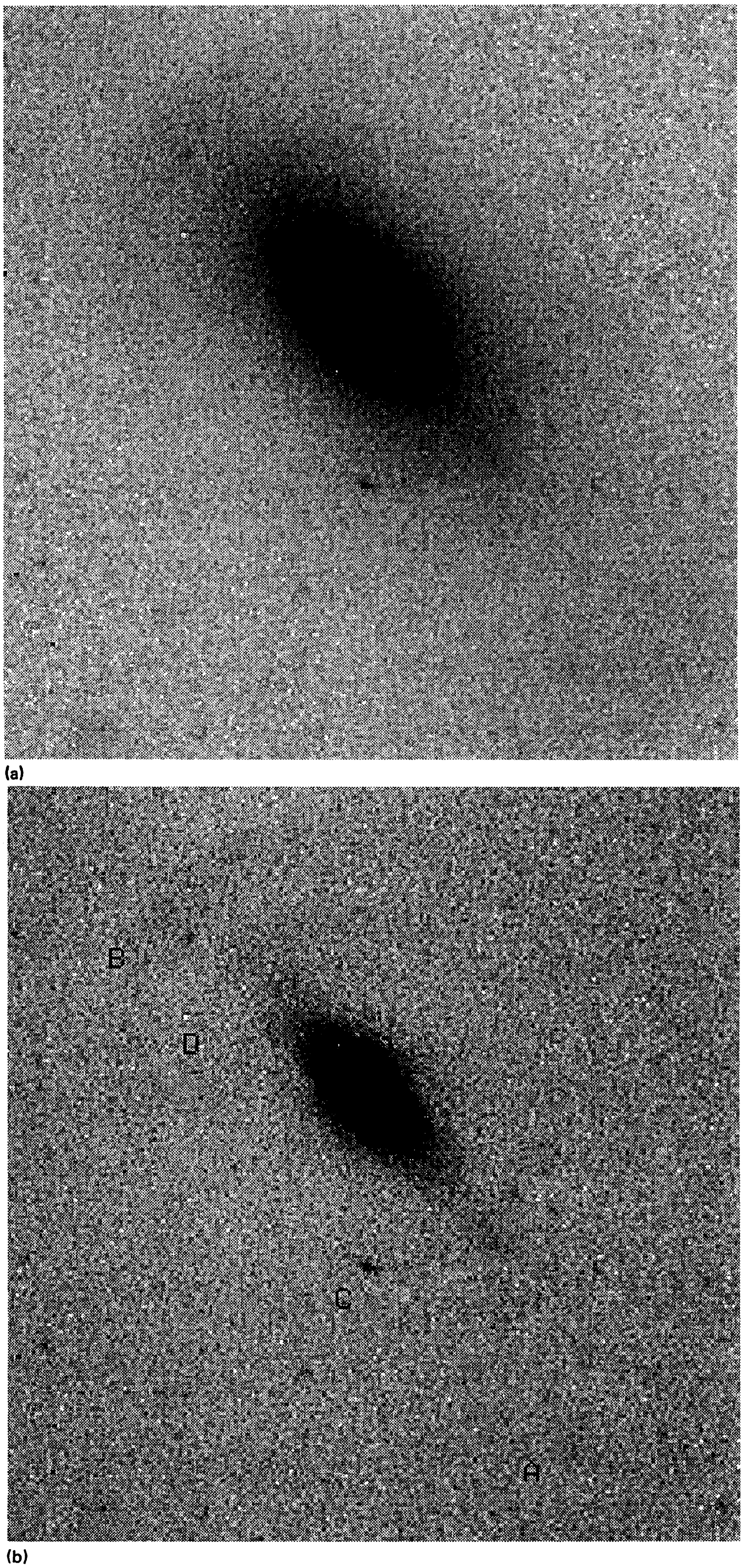


FIG. 4. NGC 7010. (a) North is up, east is to the left. Area displayed is approximately 2.5′ × 2.6′. (b) Image produced by subtracting median-filtered replica. Shells are labeled from outer to inner.

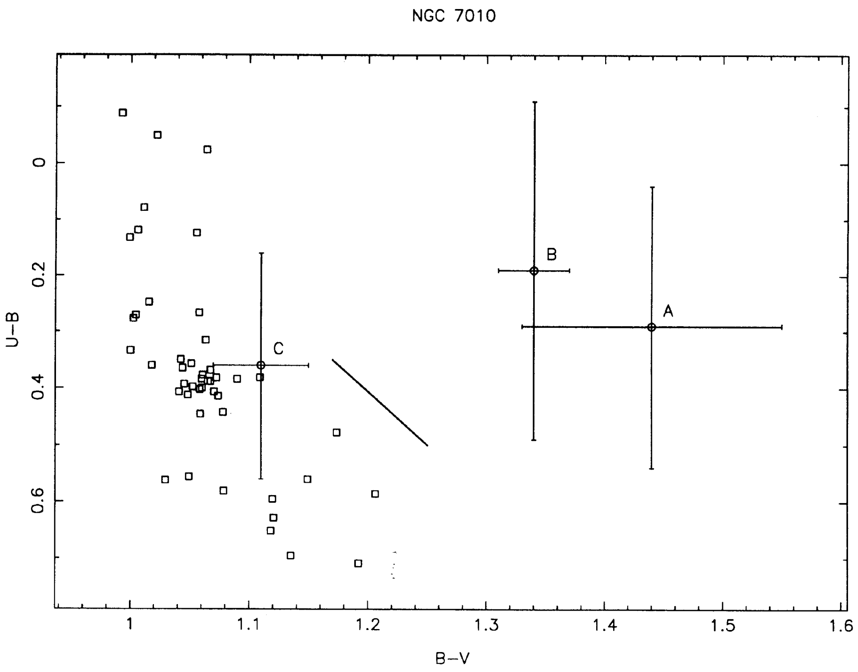


FIG. 5. NGC 7010 color–color diagram. Squares are the differential color profile of the galaxy. Circles are the shells labeled as in Fig. 4(b). The solid line is parallel to the vector of changing metallicity (Tinsley 1980).

simulations form shells by phase wrapping dynamically cold material (Quinn 1984). Published simulations use perfectly cold sheets (Quinn, Hernquist, and Quinn) or introduce a minimal velocity dispersion which is uniform throughout the disk (Dupraz and Combes). But real disks have a range of velocity dispersions. We suggest that the phase wrapping process may preferentially select the dynamically colder components for inclusion in the shells. This means that preferentially younger material will be selected, effectively weighting the mass function towards higher mass stars. This is yet another reason to expect blue shells, at least initially. But as the population evolves, the shells could become very red, due to the evolution of these massive stars toward the AGB, especially if further star formation is suppressed. Stars of $\geqslant 2\,\mathscr{M}_\odot$ will evolve on the relevant timescale of a few times 10^8 yr. The AGB branch is expected to dominate such an intermediate age population (Renzini and Buzzoni 1986). Barbaro and Olivi (1986) calculate that the inclusion of this AGB branch can redden a population by roughly 0.20 in $B-V$ and 0.05 in $U-B$ for a normal IMF. This effect would be even more pronounced if the shell-forming mechanism initially weights the mass function towards higher mass stars.

This scenario makes some obvious predictions about the infrared colors of the shells and luminosity indicators like the calcium triplet. Pence (1986) found no differences in the absorption features of the shells and galaxy in NGC 3923 (which also has red shells), but the signal to noise is low and the calcium triplet in particular is contaminated by a strong night sky line. Considering the difficulty of this project, the brightness of the night sky and poor sensitivity of currently available detectors at infrared wavelengths make such observations technically impossible.

There is marginal evidence in the NGC 7010 data to support this scenario. The AGB branch will affect $B-V$ more strongly than $U-B$; the observed shell colors vary widely in $B-V$ at nearly constant $U-B$. There is a weak trend in $B-V$ with shell position: the older, outer shells are redder, consistent with the above scenario. However, even if this is the case for NGC 7010, it is the result of a rather specific evolutionary history and we do not suggest that this is the cause of all red shell systems. Rather, we stress that the stellar evolution and star-formation history of the shell material can have an important effect on shell colors.

c) Arp 223

Arp 223 (NGC 7585) is an S0 galaxy with a bulge-to-disk ratio of 2:1 (in the V band). The disk is present and distinct from the shells. Thus the shells did not cause this galaxy to be classified as an S0, though they may have affected its detailed classification as an $S0_1(3)$/Sa (Sandage and Tammann 1981). Schweizer and Seitzer (1988) have pointed out that shells are not uncommon in S0s. Unlike Arp 230 and NGC 7010, which are isolated, Arp 223 has two companions: NGC 7576 and NGC 7592. These are 10.7′ = $109h^{-1}$ and 15.7′ = $160h^{-1}$ kpc projected distance from Arp 223 respectively. NGC 7576 has a radial velocity of 3723 km s^{-1}, similar to that of Arp 223 (3502 km s^{-1}) (de Vaucouleurs, de Vaucouleurs, and Corwin 1976). Thus it is close enough to have had a recent encounter with Arp 223, but is itself a normal spiral with no hint of the effects of a recent interaction visible on the POSS-I prints. NGC 7592 is a disturbed and lopsided spiral, having one heavy arm and a faint outer arm that points towards Arp 223. However, this galaxy has a velocity of 7440 km s^{-1}. Thus it seems unlikely that either of these galaxies were involved in the event which formed the shell system around Arp 223.

This shell system is not regular (Fig. 6). Features are labeled in Fig. 6(b), which is the result of subtracting a replica made with a 50 pixel median filter. Figure 6(c) is the result of passing Fig. 6(b) through a 3 pixel median filter to enhance the appearance of faint features. In addition to shells, Arp 223 possesses a number of radial spokes and loops, and a

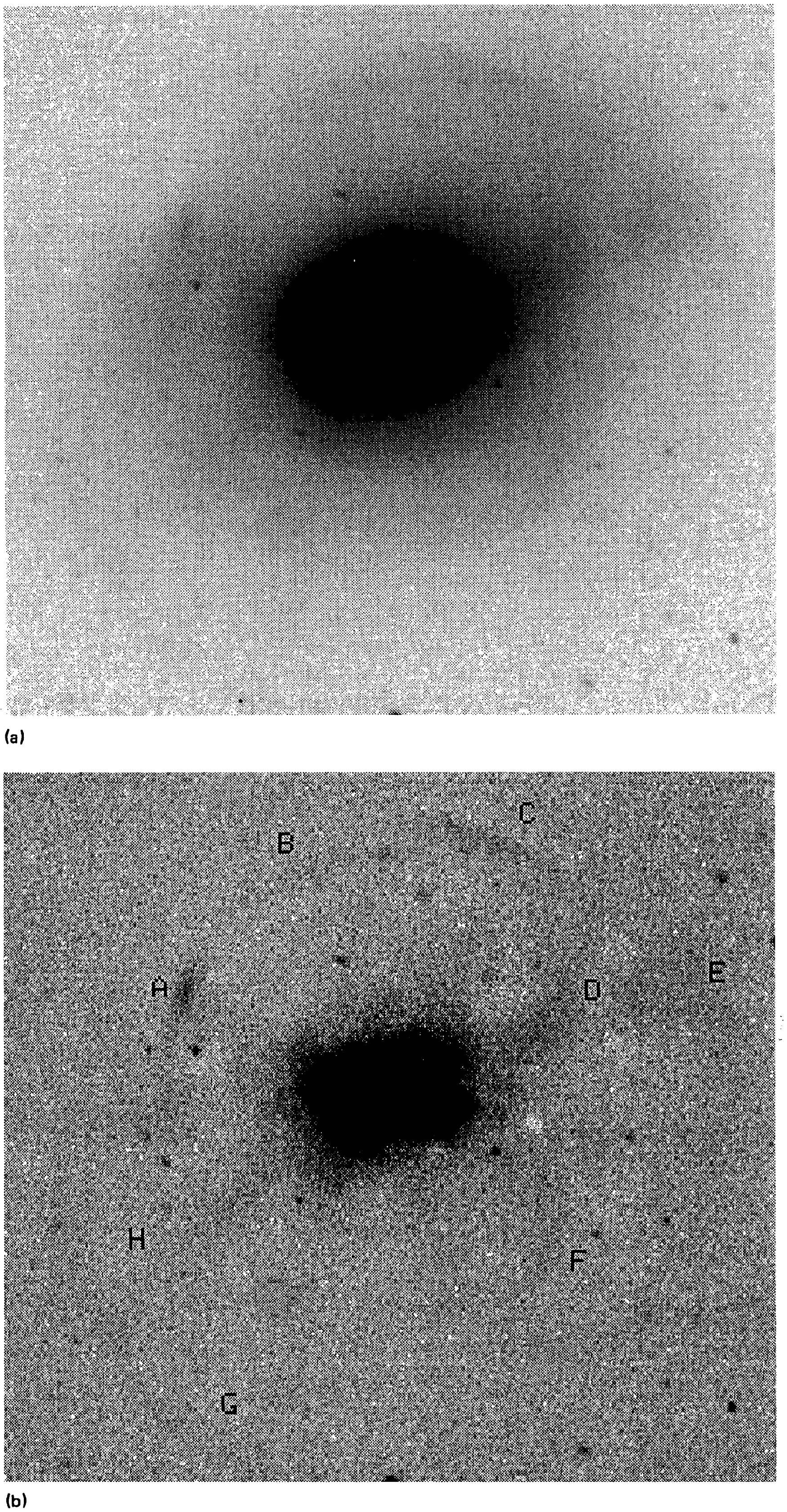
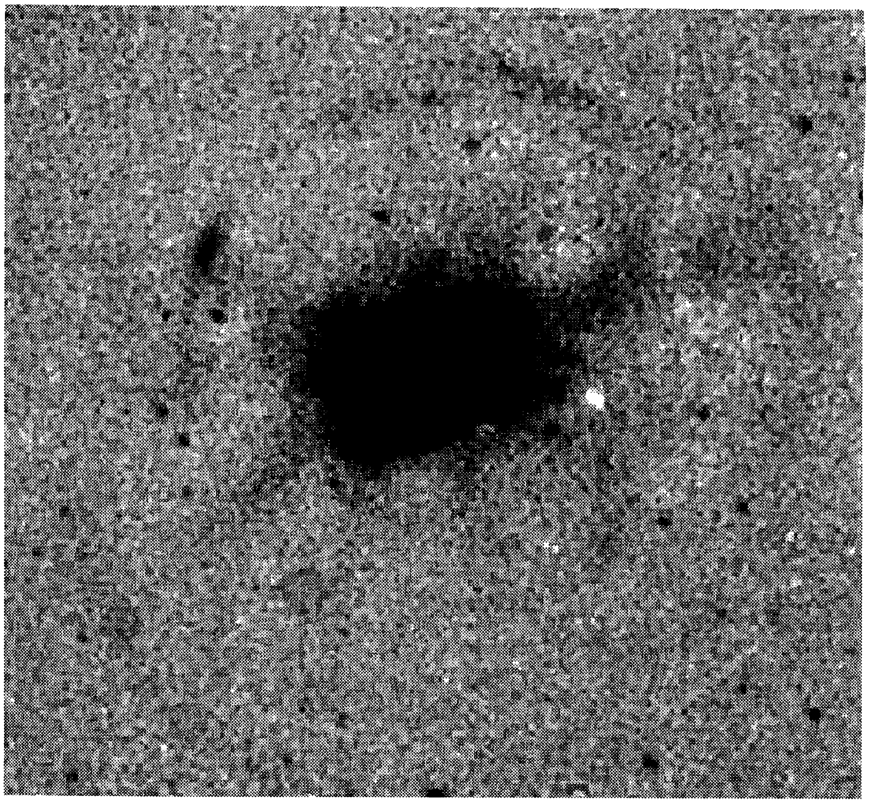


FIG. 6. Arp 223 (NGC 7585) (a) North is up, east is to the left. Area displayed is approximately $3.2' \times 2.9'$. (b) Image produced by subtracting median-filtered replica. Features are labeled clockwise from the brightest shell. (c) Median filter of (b) to better display faint structure.



(c)

Fig. 6. (continued)

faint outer "arm" (feature G). Figure 7 is the color–color plot for Arp 223. The differential color profile of the galaxy runs from red in the center to blue further out, again consistent with a metallicity gradient. Most of the scatter in the profile seems to come where the spokes become important. Most features are distinctly bluer than the galaxy (A, D, E, F, G, and H). These features are not so blue as to be the result of recent star formation. Instead, an external population is clearly indicated for this material, as anticipated by merger simulations. The mean color of the shells is roughly

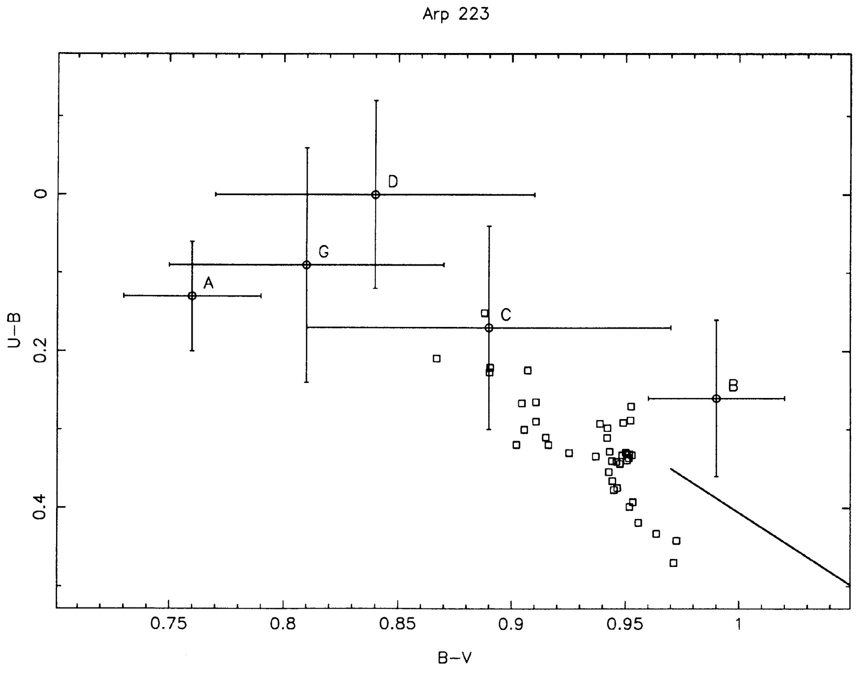


Fig. 7. Arp 223 color–color diagram. Squares are the differential color profile of the galaxy. Circles are the various features labeled as in Fig. 6(b). The solid line is parallel to the vector of changing metallicity (Tinsley 1980).

that of an Sb galaxy. If a later type than this is responsible for the shells, a few Gyr must be allowed for evolution to reach these colors. However, the chaotic morphology seems consistent with the infall of a relatively warm disk.

The color of feature C is consistent with such an origin, but is also consistent with an internal origin. The collisional model of Wallin and Struck-Marcell (1988) can produce such structures in route to a merger. These authors expect symmetric profiles, but this feature is plateau-shaped indicating that it too has an external origin. Feature B is quite red. It too is plateau- shaped, indicating that it is not likely to be of internal origin. Since compact spheroids can form shells, it may be that this particular shell had its origin in the bulge of the accreted galaxy. Published simulations do not include a bulge component, so the fate of this population is unclear.

V. CONCLUSIONS

Our observations strongly support the merger hypothesis of shell formation. Gas dynamical processes which invoke star formation to make shells are not present in the galaxies studied. The color progression found among the shells is opposite that predicted by gas dynamical theories, but is well matched by the merger model when stellar evolution is taken into account.

In the case of Arp 230, we have found clear evidence for the formation of shells as a result of a merger between two disk galaxies, releasing the constraint of large mass ratios usually imposed in merger simulations. The collision led to a burst of star formation which is now fading or over. The shell material participated in this star-forming event, but star formation had ceased by the time of complete shell formation. This allows an approximate color age of 1–2 Gyr to be determined. The remnant seems likely to become an elliptical galaxy. Ellipticals formed in this manner should have complicated stellar populations with a component formed in the collision. This might be detectable by the methods of empirical population synthesis, at least to some age limit, making it possible to investigate the relative numbers of ellipticals formed in this manner by methods other than morphology.

The NGC 7010 system morphology and shell profiles are consistent with the shells consisting of externally accreted phase wrapped material. However, the shells are very red. This is interpreted to be the combined result of stellar evolution and phase wrapping which leads to the preferential exclusion of low mass stars from the shell features. Modeling involving realistic disks with multiple velocity dispersion components and a bulge component is needed to further investigate this situation. Such models should also track the evolution of the resultant shell population, and test how shell profiles evolve to see if shells become thinner with time (as expected for phase space conservation of sheetlike material) or if they spread out as material with a finite, differential velocity dispersion diffuses away from the sheet. If possible, the dynamical fate of gas and dust should also be investigated. We have suggested that gas, if present at all in the shells, is at too low a surface density to form stars. While not important to the interpretation of colors here, it is conceivable that projection effects within shells could make dust reddening significant, or it may be that, due to collisions, dust does not follow the stars into shell structures at all.

The shells of the Arp 223 system are distinctly bluer than the main body of that galaxy, as anticipated by the merger model. Roughly an Sb galaxy is indicated as the source of the shell material. Though the statistics of shell colors is poor, relatively few systems have such a simple interpretation, and even in this case there are complications. This reinforces the need for models which make quantitative predictions about observables like color as well as morphology.

Finally, we caution that we need to improve our understanding of the formation of shells before the statistics of their occurrence can be used to draw conclusions about merger rates. In particular, the timescales over which shells form and disperse need to be better quantified. Our work provides marginal evidence in favor of shorter ($\approx 10^9$ yr) timescales typical of the models of Hernquist and Quinn, but by no means excludes the longer timescales of Dupraz and Combes. Also, the full range of events that can lead to shell formation need to be considered. If a significant number of galaxies have been formed as the result of collisions, there is a pressing need to identify a quantitative, nonmorphological observable signature for distinguishing these galaxies from the normal galaxy population. Our color analysis techniques may offer such a scheme and we encourage their extension to other shell systems.

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REFERENCES

Arp, H. (1966). Astrophys. J. Suppl. **14**, 1.

Barbaro, G., and Olivi, F. M. (1986). In *Spectral Evolution of Galaxies*, edited by C. Chiosi and A. Renzini (Reidel, Dordrecht), p. 283.

Barnes, J. E. (1988). Astrophys. J. **331**, 699.

Barnes, J. E. (1989). Nature **338**, 123.

Boroson, T. A., and Thompson, I. B. (1987). Astrophys J. **93**, 33.

Bothun, G. D. (1986). Astron. J. **91**, 507.

Bothun, G., Lonsdale, C., and Rice, W. (1989). Astrophys. J. **341**, 129.

Caldwell, N., and Bothun, G. D. (1987). Astron. J. **94**, 1126.

Carter, D., Allen, D. A., and Malin, D. F. (1982). Nature **295**, 126.

Carter, D., Prieur, J.-L., Wilkinson, A., Sparks, W. B., and Malin, D. F. (1988). Mon. Not. R. Astron. Soc. **235**, 813.

de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. (1976). *Second Reference Catalog of Bright Galaxies* (University of Texas, Austin).

Dupraz, C., and Combes, F. (1986). Astron. Astrophys. **166**, 53.

Fabian, A. C., Nulsen, P. E. J., and Stewart, G. C. (1980). Nature **287**, 613.

Fabian, A. C., Nulsen, P. E. J., and Canizares, C. R. (1982). Mon. Not. R. Astron. Soc. **201**, 933.

Fort, B. P., Prieur, J.-L., Carter, D., Meatheringham, S. J., and Vigroux, L. (1986). Astrophys. J. **306**, 110.

Hernquist, L., and Quinn, P. J. (1988). Astrophys. J. **331**, 682.

Hernquist, L., and Quinn, P. J. (1989). Astrophys. J. **342**, 1.

Huang, S., and Stewart, P. (1985). Astron. Astrophys. **153**, 189.

Kennicutt, R. C. (1989). Astrophys. J. **344**, 685.

Landolt, A. U. (1983). Astron. J. **88**, 439.

Larson, R. B., and Tinsley, B. M. (1978). Astrophys. J. **219**, 46.

Lowenstein, M., Fabian, A. C., and Nulsen, P. E. J. (1987). Mon. Not. R. Astron. Soc. **229**, 129.

Malin, D. F., and Carter, D. (1983). Astrophys. J. **274**, 534.

Malin, D. F., Quinn, P. J., and Graham, J. R. (1983). Astrophys. J. Lett. **272**, L5.

McGaugh, S. S. (1985). S. B. thesis, Massachusetts Institute of Technology.

Nulsen, P. E. J. (1989). Astrophys. J. **346**, 690.

Pence, W. D. (1986). Astrophys. J. **310**, 597.

Prieur, J.-L. (1988a). Astrophys. J. **326**, 596.

Prieur, J.-L. (1988b). Ph.D. thesis, Université de Toulouse.

Quinn, P. J. (1984). Astrophys. J. **279**, 596.

Renzini, A., and Buzzoni, A. (1986). In *Spectral Evolution of Galaxies*, edited by C. Chiosi and A. Renzini (Reidel, Dordrecht), p. 195.

Sandage, A., and Tammann, G. A. (1981). In *Revised Shapley-Ames Catalog of Bright Galaxies* (Carnegie Institution of Washington, Washington, DC).

Schombert, J. M., and Wallin, J. F. (1987). Astron. J. **94**, 300.

Schombert, J. M., Wallin, J. F., and Struck-Marcell, C. (1990). Astron. J. **99**, 497.

Schweizer, F. (1980). Astrophys. J. **237**, 303.

Schweizer, F. (1983). In *The Internal Kinematics and Dynamics of Galaxies*, IAU Symposium No. 100, edited by E. Athanassoula (Reidel, Dordrecht), p. 319.

Schweizer, F., and Ford, W. K. (1985). In *New Aspects of Galaxy Photometry*, edited by J.-L. Nieto (Springer, New York), p. 235.

Schweizer, F., and Seitzer, P. (1988). Astrophys. J. **328**, 88.

Tinsley, B. M. (1980). Fund. Cos. Phys. **5**, 287.

Thronson, H. A., Bally, J., and Hacking, P. (1989). Astron. J. **97**, 363.

Umemura, M., and Ikeuchi, S. (1987). Astrophys. J. **319**, 601.

Wallin, J. F., and Struck-Marcell, C. (1988). Astron. J. **96**, 1580.

Williams, R. E., and Christiansen, W. A. (1985). Astrophys J. **291**, 80.