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FORMATION OF SHELLS IN MAJOR MERGERS

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ABSTRACT

Numerical simulations are used to study the fate of disks in mergers between equal-mass galaxies. Contrary to popular belief, mergers between equal-mass galaxies can form shells, loops, and ripples. Material that was originally in the outer disk of the pre-merger spirals falls into the remnant late in the merger event, long after the inner region of the remnant has relaxed. Thus, its evolution is similar to that of an accreted dwarf satellite that forms shells through "phase wrapping." However, the mechanism described in this letter avoids a number of difficulties with the accretion model; specifically, it can explain the observed correlation between properties of the host galaxies and shell alignments and luminosities. In view of this, we argue that many shell systems may have originated through "major" mergers of comparable-mass galaxies rather than via "minor" mergers or accretions. In particular, the shell elliptical NGC 3923 appears to be a good candidate for shell formation by a major merger.

Subject headings: galaxies: formation — galaxies: interactions

1. INTRODUCTION

A large fraction of all early-type galaxies do not have smooth light profiles but rather show delicate "fine structure," such as plumes, loops, "shells," "ripples," boxy isophotes, and "X-features" (for recent reviews, see Prieur 1990; Barnes & Hernquist 1992). Indeed, the recent survey of Seitzer & Schweizer (1990) suggests that more than a half of all ellipticals and at least a third of all S0's possess shells. It is widely believed that these shells are the stellar remnants from an accretion or merger event. This viewpoint is supported by observations that find a correlation between the presence of sheets and ripples in galaxies and other signatures of galaxy collisions, such as tidal tails, multiple nuclei, and young stellar populations (e.g., Malin & Carter 1983; Schweizer 1980; Schweizer et al. 1990).

Numerical simulations employing restricted methods suggest that the accretion of dwarf companions by more massive galaxies provides a natural mechanism for forming fine structure. As shown first by Quinn (1984), shells can form by the "phase-wrapping" of dynamically cold material on mostly radial orbits in a rigid potential, or by the "spatial wrapping" of debris from thin disks (Hernquist & Quinn 1988). Toomre (1983, cited in Schweizer 1983) emphasized that the encounter delivering the shell-forming matter need not be precisely radial: mass transfers in grazing collisions between galaxies can also produce shells.

Notwithstanding the general acceptance of the accretion model for the origin of shells, a number of lingering difficulties remain. In many ellipticals, shells appear to be aligned with the projected major axis of the galaxy (Prieur 1990). It is not obvious that mergers between small companions and large nonspherical primaries would yield any such correlation (Hernquist & Quinn 1989; see, however, Dupraz & Combes 1986). Shells have been detected deep in the potential wells of some of the best studied cases. The elliptical NGC 3923, for example, has shells within 0.5 effective radii of its center (Fort et al. 1986). It has been argued that this may reflect the action of dynamical friction during a merger between two galaxies of rather different masses. However, the Heisler & White (1990) calculations that include self-gravity fail to verify this conjecture. Finally, in some galaxies the radial distribution of shell luminosities is similar to that of the underlying elliptical (Pence 1986), suggesting that fine structure may indirectly be of *internal* origin (Thomson & Wright 1990).

In principle, many of these problems can be ameliorated if the galaxies encountering one another have similar masses. However, previous analyses suggest that collisions will produce shells only if the galaxies have rather different properties (Hernquist & Quinn 1988). In this paper we critically examine this point of view using simulations of mergers between equal-mass galaxies. Our results demonstrate that shells can indeed form in "major" mergers, contrary to common lore, implying that some shell ellipticals may be relics not of accretion events but of collisions between comparable-mass galaxies. Similar, though less detailed findings have been reported by Barnes (1992) and Hernquist (1992), but these studies were not designed specifically to address the origin of fine structure in mergers.

2. SIMULATIONS

The simulations presented and described here are part of an on-going study of the structure of remnants formed in mergers between various progenitor galaxies. Most of the following discussion relates to one of these calculations, although our general conclusions appear to obtain for all the models we have run so far.

In the simulation primarily referred to here, two identical galaxies with self-gravitating disks and halos merged following

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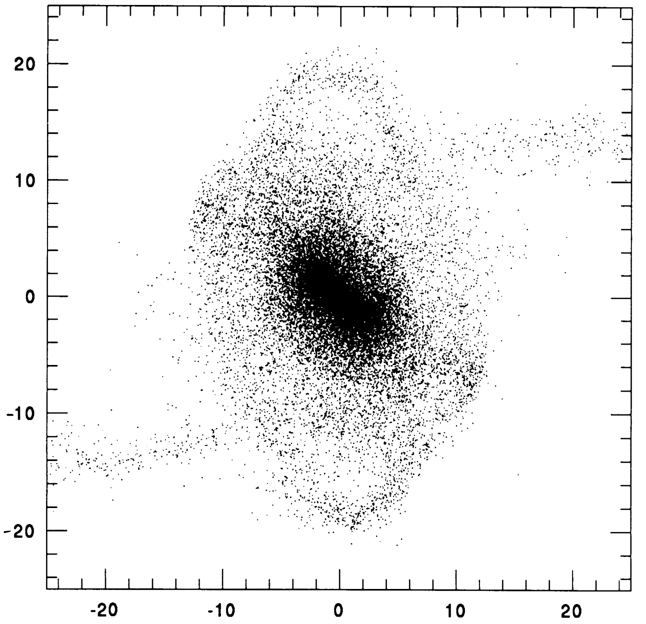

FIG. 1.—Luminous remnant of merger between two equal-mass disk-halo galaxies. The panel measures 25 length units per edge where unit length corresponds to the exponential scale length of each progenitor disk. Scaled to the Milky Way, each edge measures roughly 75 kpc.

a close collision from a parabolic orbit. In a dimensionless system of units with $G \equiv 1$, each galaxy consists initially of an exponential disk with unit scale length and mass and has a vertical density structure $\propto \operatorname{sech}^2 z/z_0$ with $z_0 = 0.2$. The vertical scale-height is constant across each disk, implying a variable Toomre Q-parameter with mean value $\langle Q \rangle \approx 1.5$. Halos are represented by a truncated distribution resembling an isothermal sphere with density structure $\rho \propto \exp(-r^2/r_t^2)/(1 + r^2/a^2)$, with $a = 1$ and $r_t = 10$. The ratio of halo to disk mass in each galaxy is $H:D = 5.8:1$. The plane of each disk initially coincides with the orbit plane and the pericenter separation for the ideal parabolic orbit is 2.5. The encounter is exactly prograde for both disks. This model is identical to Model 1 reported by Hernquist (1992), except for the number of particles used in the simulation. A total of $N = 163{,}840$ particles were employed in the present calculation: each galaxy consists of 81,920 particles divided so that 65,536 represent the disk and 16,384 represent the halo. Even with this large number of particles, we believe that some of the "fine structure" in the merger remnant has been erased by discreteness effects.

The evolution of the merger discussed here is similar to examples presented already by Barnes (1988, 1992) and Hernquist (1992). The much larger number of particles comprising the present disks makes it possible to examine the structure of the luminous remnant in much greater detail than in these earlier studies. Figure 1 shows all disk particles in the remnant at a time $t = 144$ units after the beginning of the encounter. If the progenitors are scaled to properties similar to those of the Milky Way, this corresponds to an elapsed physical time of roughly 2×10^9 yr. Figure 1 shows a view projected onto the orbit plane. Even in this crude depiction, several loops and sharp edges are clearly visible in the particle distribution.

When plotted in phase space, the remnant in Figure 1 exhibits more than 10 clearly defined phase-wraps which can be identified with shells. To highlight the shells we have chosen to "process" the image in Figure 1 to accentuate faint features. Since stars in shells are near the turning points of their orbits, it is convenient to filter out particles with relatively high velocities. Figure 2 shows subsets of particles from each progenitor disk having relatively small radial velocity. As revealed in Figure 2, the remnant is surrounded by a large number of sharp arcs, which we identify with the shells observed around many elliptical galaxies. Aside from the outermost arc, there is a strong tendency for the shells formed in the simulation to align with the projected major axis of the remnant. It is difficult

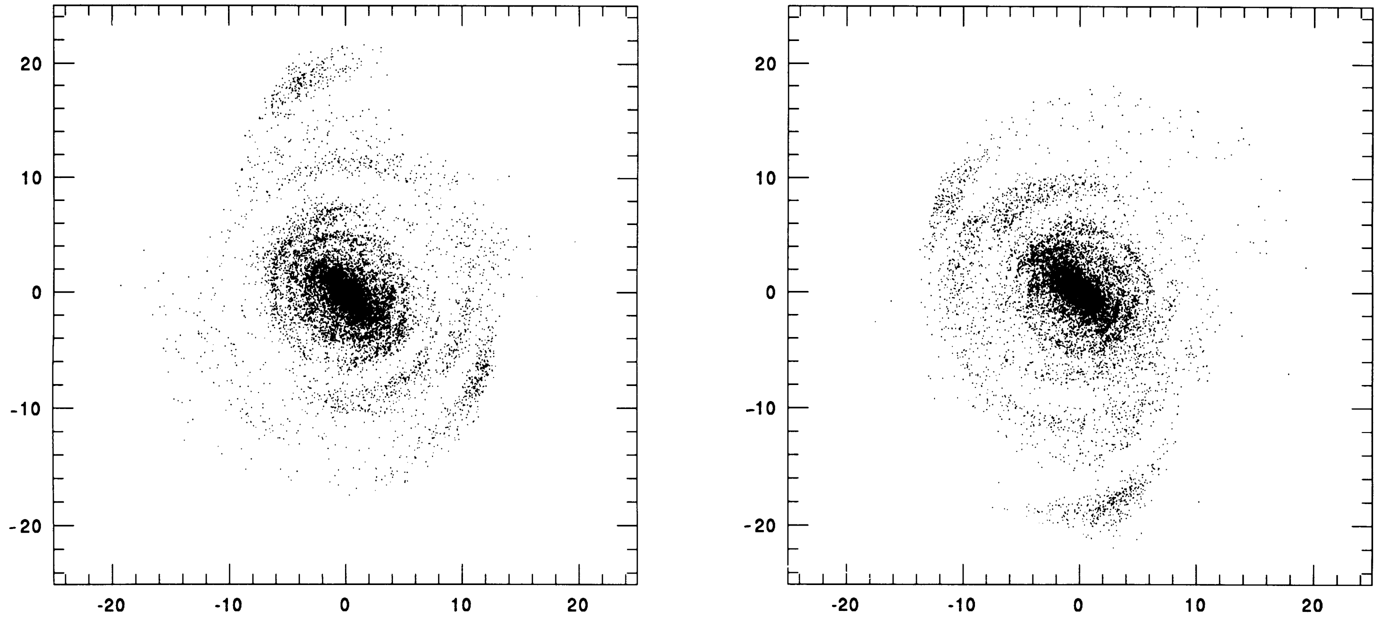

FIG. 2*a* FIG. 2*b*

FIG. 2.—Subsets of particles from each progenitor disk in the remnant. Left panel shows particles from one disk and right panel shows particles from other disk. The scale is identical to that of Fig. 1.

to quantify the number of shells precisely, owing to discreteness noise. By visual inspection of images like Figure 2 and phase-space distributions we estimate that the remnant contains at least 10 and possibly as many as 20 sharp edges. Approximately 25% of all the disk particles satisfy the velocity requirements imposed in Figure 2; thus, major mergers are quite capable of providing sufficient amounts of dynamically cold material to produce even rather large, extensive shell systems.

The images in Figure 2 can be compared to the high definition image of NGC 3923 shown in Figure 3 (Plate L12), kindly provided to us by Peter Quinn. As in the simulation shown in Figure 2, the outermost shell in Figure 3 is not aligned with the major axis of the galaxy. The resemblance is particularly striking if one compares only the particles from one disk, say those in the left panel of Figure 2, with the shells in NGC 3923. Strictly speaking, one should not compare the particle distribution from one of the disks alone with the shells in NGC 3923. However, a remnant similar to that shown in one of the two panels in Figure 2 might result from a less symmetric orbital geometry in which only one disk produces massive tidal tails.

To measure the spacing of the shells shown in Figures 1 and 2, we computed their surface density relative to that of the diffuse matter in the remnant. The result of this procedure is shown in Figure 4. Here, shells were identified by the same procedure used in making Figure 2; i.e., by selecting out particles with relatively small radial velocity. A number of the shells are clearly visible as surface density enhancements in Figure 4. The innermost one we can identify lies at a radius of approximately three length units. The effective radius along the major axis, as determined by binning particles in ellipsoidal shells (Hernquist 1992), is approximately 2.8 length units. Thus, the remnant contains shells at least to within distances of order its effective radius. This compares favorably with many shell galaxies that possess tightly bound shells (Prieur 1990). In fact, NGC 3923 itself is an extreme example of this phenomenon, its innermost shell lying less than 0.5 effective radii from its center. However, the luminosity of the inner shells in NGC 3923 is quite low (Fort 1986), the innermost shell contains only 0.02% of the galaxy's luminosity. Our simulations lack sufficient dynamic range to determine if mergers of galaxies like those described here are capable of accounting for such features.

A final point worth noting from Figure 4 is that the ratio of shell surface density to the surface density of the underlying mass distribution is relatively constant when compared to the overall rapid drop in density. (The mass density is reasonably well-fitted by a model which varies as r^{-4} at large radii [Hernquist 1990, 1992].) Thus, it is possible to account for observed cases in which shell luminosity declines similarly to that of host ellipticals via mergers.

3. DISCUSSION

The ubiquitous nature of galactic fine structure implies that it will not be possible to formulate detailed theories for the evolution of ellipticals and S0's without understanding its origin. Based on mounting observational and theoretical evidence, most astronomers believe that these features are the aftermaths of accretion events or mergers in which a large primary cannibalized a much less massive companion. In either event, the host galaxy would be expected to evolve only modestly as the result of the interaction.

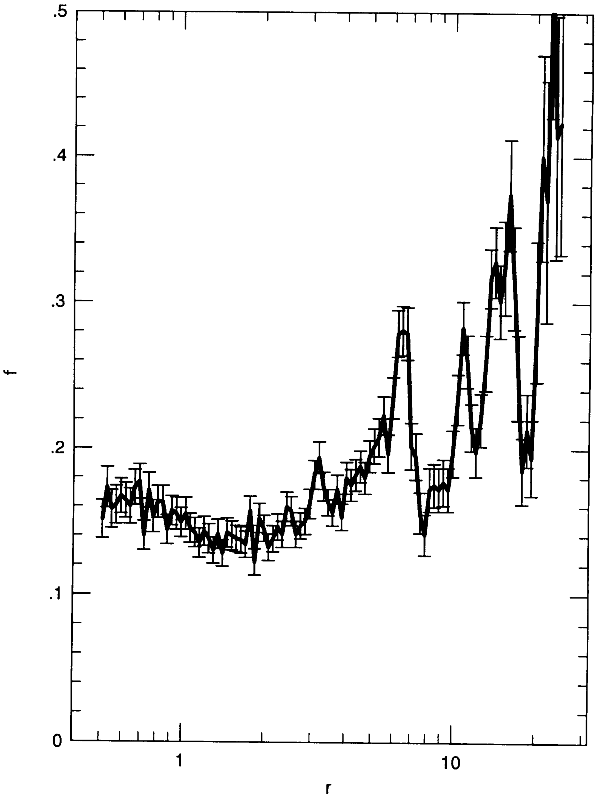

FIG. 4.—Fraction of surface density in shells along a slit aligned with the major axis of the remnant shown in Fig. 1. Error bars indicate level of discreteness fluctuations from binning the particle distributions.

As we argued earlier, the possibility that fine structure can be produced in mergers of comparable-mass progenitors can explain several observed properties of shell galaxies not easily understood within the context of the accretion hypothesis. In particular, our simulations suggest that tightly bound shells can form in major mergers simply owing to the nature of the progenitor disks, unlike in accretion events where one is instead forced to postulate excessive rates of dynamical friction to decelerate the dwarfs supplying the shell-forming material. Our results also show that mergers like those described here can yield shells that are aligned with the major axis of the remnant. At present, however, our coverage of parameter space is insufficient to allow us to determine how this conclusion is affected by variations in, for example, orbital geometry. Finally, since the shells in major mergers are derived from the same material which comprises the host galaxy itself, it is straightforward to account for correlations between the luminosities of the shells and the galaxies in which they are embedded.

Many shell galaxies, of course, do not possess "special" properties like those just enumerated. We suspect that depending upon, e.g., orbital parameters the faint features in these objects could be explained either by accretion events or by major mergers. Without additional data, it may be quite difficult to infer the nature of the progenitors which interacted to produce the structure which is presently observed. These difficulties are complicated by the similarities in stellar populations in dwarf irregular galaxies and the outer regions of disk galaxies.

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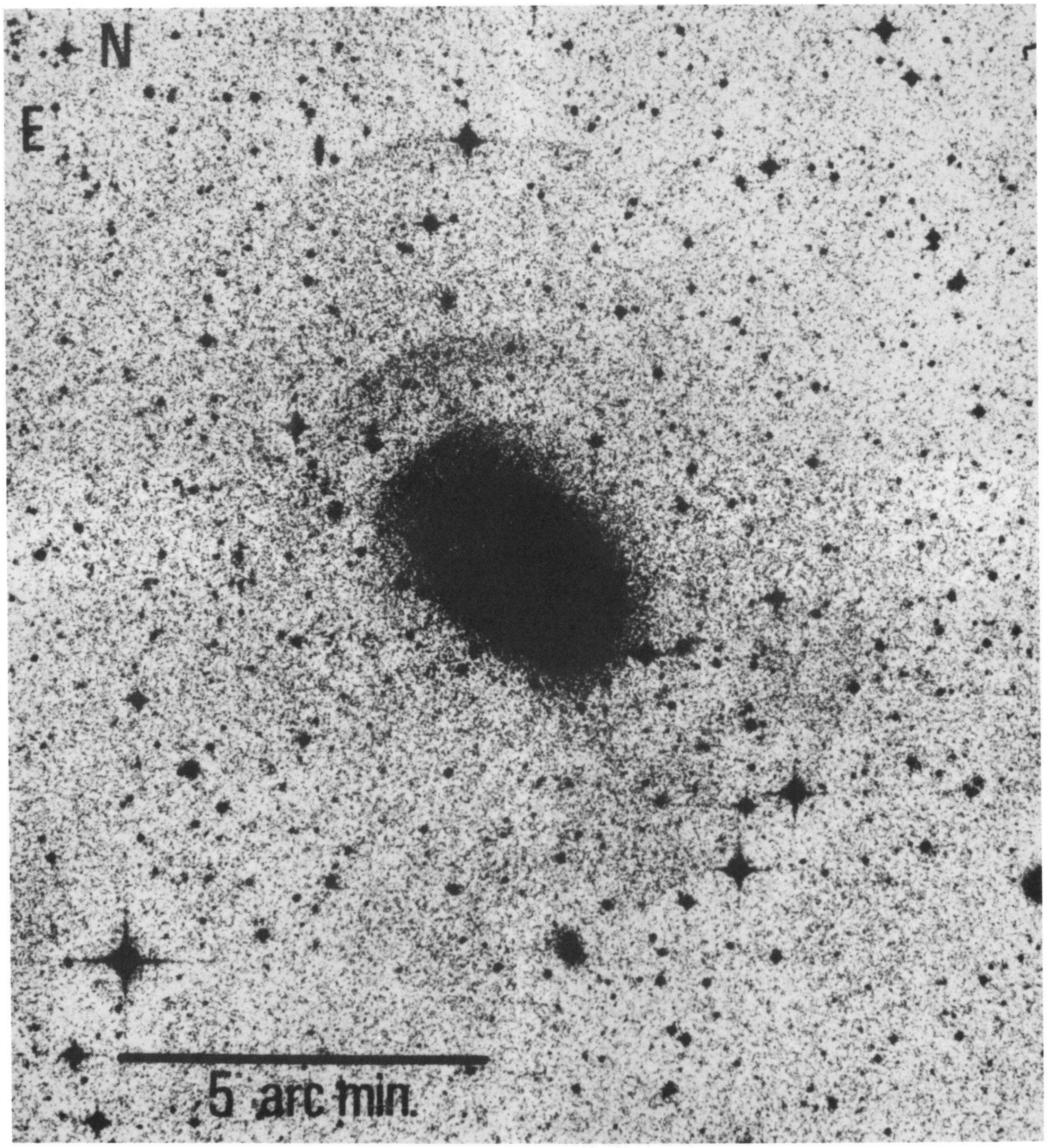

FIG. 3.—Image of NGC 3923 obtained by unsharp masking, showing the outermost shells in this galaxy

The simulations described in this letter demonstrate clearly that the conventional interpretation of shell formation is incomplete and may not be valid in all cases. Our models show that shell systems can also develop during the severe transformation of galaxy Hubble types attending major mergers which completely destroy both progenitors. Thus, the ubiquity of shells may indicate that we live in a dynamically violent universe.

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