VI

MERGERS

OBSERVATIONAL EVIDENCE FOR MERGERS

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Theory has long suggested that dynamical friction between colliding galaxies must lead to mergers. The problem for observers has been to find which galaxies are mergers. I shall first review the available evidence for mergers in various kinds of galaxies, then propose a tentative classification scheme for mergers, and finally discuss mergers in giant ellipticals and their relation to the evolution and perhaps even the formation of ellipticals.

I shall here define merger more restrictively than did Toomre (1977), who in his list of "eleven prospects for ongoing mergers" included pairs of interacting galaxies that can still be discerned separately, such as NGC 4038/39 (the "Antennae") and NGC 4676 (the "Mice"). Even NGC 3256, where it is already difficult to distinguish the two interacting disks, I shall not yet call a merger. Rather, with few exceptions, I shall consider systems where the two participants have merged into one single remnant, even though their individual debris, such as tidal tails, may still be visible. This restricted definition of merger would leave only three candidates in Toomre's list. Here, I shall describe or at least mention over two dozen such mergers.

1. MERGERS IN cD GALAXIES

The large extent of cD envelopes (>100 kpc) and the existence of dynamical friction suggest strongly that cluster galaxies which cross the envelopes will eventually fall in and merge (Ostriker & Tremaine 1975). The direct observational evidence for the occurrence of this process is, however, meager. Various observations of colors and color gradients in cD galaxies have been used to claim support for the theory; yet such claims seem inconclusive because we know little about the meaning of color differences and gradients even in nearby, normal ellipticals. Large core radii have also been quoted as evidence for mergers in cD's. However, they are ill determined observationally and it is not even clear that merging, which seems to occur nonhomologously, ought to lead to bloated cores (White 1978; Schweizer 1981).

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 319–329.

It seems to me that two promising pieces of observational evidence in favor of mergers in cD galaxies are (1) the presence of multiple nuclei and (2) the existence of asymmetric envelopes. Hoessel (1980) found that 28% of brightest cluster galaxies have multiple nuclei, and derived merger rates from this number. Some of the "nuclei," however, may be other, superposed cluster members: Minkowski (1961) found a velocity spread of 1400 km/s among the three "nuclei" of NGC 6166. Hence, a careful statistical study of multiple nuclei ought to include velocity measurements and corrections for foreground and background contamination. Asymmetries in cD envelopes have been noted by various authors (e.g., van den Bergh 1977). Since they indicate deviations from symmetric equilibrium configurations, they are probably transient and may be the result of interactions with cluster galaxies or of mergers.

2. THREE WELL ESTABLISHED MERGERS

NGC 1316 (= Fornax A) is a classical Morgan D galaxy, which means it has an elliptical-like body embedded in an extensive envelope. Figure 1b shows this envelope and two major protruding filaments discovered by Arp. Schweizer (1980) interpreted them as the tails of small disk galaxies that fell in ~1 Gyr ago. The case for a merger there rests also

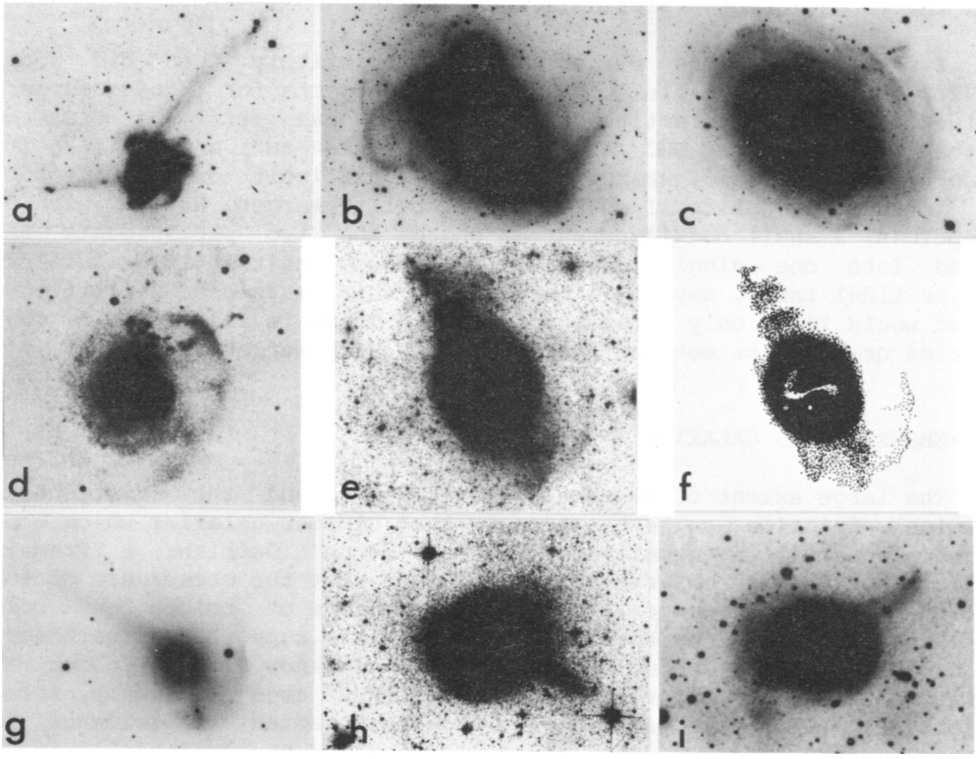

Figure 1. Tails and ripples in mergers: (a) N7252; (b) N1316 tails and (c) ripples; (d) N3310; (e) + (f) N5128; (g) N7135; (h) M89; (i) N5018.

on the presence of (1) a highly inclined gas disk that rotates much faster than the stars and (2) "ripples," which are the arc-like features shown in Fig. 1c (enhanced photographically by unsharp masking). These ripples pervade the main body, consist of moderately old stars, and are a frequent signature of infallen disks, as we shall see. The small galaxy just to the north in Fig. 1b is NGC 1317, a normal barred spiral seen nearly face-on; it seems unlikely to have caused the tails and ripples because it looks quite unperturbed itself.

NGC 5128 (= Cen A) is probably the best known case of a recent merger, even though it was widely regarded to be an explosive galaxy until a few years ago. The general change of opinion has been caused by Graham's (1979) observation that the gaseous disk rotates fast, as found by the Burbidges in 1959, whereas the stellar body rotates barely at all. The fast rotation of the gas excludes nuclear ejection as its source, and the slow rotation of the spheroid excludes the possibility that the gas was shed by the stars. The most likely remaining source for the gas seems to be infall from outside of the galaxy, and models based on the assumption that a small gas-rich companion fell in have indeed been successful at modeling the observed warp of the gaseous disk (see comments after the paper by K. Taylor). Luckily for my contention that ripples are signatures of infallen disks, NGC 5128 features some ripples, too. On the deep photograph by Cannon (1981) shown in Fig. 1e, they appear as luminous steps in the faint NE and SW extensions, much as they were seen and sketched by Johnson (1963), here Fig. 1f. (After this Symposium, J.A. Graham showed me a beautiful new photograph, on which the ripples can be seen around the whole periphery of the galaxy.) Finally, the curved filament that emerges from the SW extension and turns northward may be either the remaining tail of the captured disk galaxy or, perhaps, just another ripple. Whatever they are, the various appendices of NGC 5128 seem to be part of the mess associated with the merger of two galaxies.

NGC 7252 is a particularly well established merger because of the lucky coincidence of five characteristics (Schweizer 1982): (1) It has two long tails (Fig. 1a) indicative of a strong interaction between two disk galaxies of about equal masses. (Such interactions produce only one tail per disk; see NGC 4038/39 and Toomre & Toomre 1972.) (2) The galaxy is so isolated that there is no external source for the observed tidal perturbations. (3) The tails move in opposite directions relative to the nucleus, as required by any tidal model. (4) Despite the two tails, there is one single body and nucleus. (5) Spectroscopy of the gas in the body reveals two surviving motion systems, which cause velocity reversals in the rotation curve. Apparently, two large disk galaxies began merging 1.0 Gyr ago, the time being calculated from the tail lengths divided by the velocities. The result is a single, rather symmetric, though messy looking remnant with an A-star-type spectrum and a respectable $M_V = -22.8$ (H_0=50). Ripples again pervade the body. The mean surface brightness follows an $r^{1/4}$ law quite closely, indicating that the remnant has a structure similar to an elliptical, presumably because it relaxed violently (Lynden-Bell 1967). Obviously, this merger of two disks has been very nonhomologous, and I believe it provides a first solid piece of evidence for the delayed formation of some ellipticals envisaged by the Toomres (1972).

3. A TENTATIVE CLASSIFICATION OF MERGERS

Before discussing individual candidate mergers, it seems useful to establish a rough classification for them. One possible scheme is to order them by the combined Hubble types of the merged components. To simplify matters, assume that there are only three structural types of galaxies: E = ellipticals, D = disks (incl. S0's), and G = gas clouds (incl. Irr's). If one distinguishes the more massive and less massive components by capital and small letters, respectively, and combines them in this order, the resulting classification has nine classes: Ee, Ed, Eg, De, Dd, ..., Gg. Figure 2 (to the right) represents these classes by boxes arranged in a square; their dimensions are roughly proportional to the fractions of galaxy types in the field. Written into the boxes are the names of merger candidates, e.g., NGC 1316 and 5128 as types Ed, and NGC 7252 as DD (where I use two capital letters to indicate that the disks were of roughly equal masses). We now describe the various classes in turn.

	e	d	g
E	N 750 I5250	N 596, 1316, 3923, 5018, 5128, M89	N42-78
D	?	N3310, 4650A, 7135, Arp 230, Smith 60, AM 0044-2437 Equal disks (DD): N3921, 6052, 7252. N2685 ↔	?
G	?	?	II-Zw40

Dd mergers predominate in the field, where ~80% of all galaxies are disks. Among their most telling signatures are tidal tails, ripples (see §4), and motions in crossed planes. They display an amazing variety of forms, some resembling NGC 7252, and others not at all. NGC 3921, e.g., is a close kin in most respects (Schweizer 1978); its two long tails suggest that here, too, two similarly massive disks have just completed merging. NGC 6052 (= Mrk 297) may be a third example of a DD merger, although it has not yet run to completion; it features two nuclei and motion systems, and has been interpreted as a probable collision of two late-type spirals (Alloin and Duflot 1979). Certainly, its tremendous burst of star formation is compatible with this view, and I would guess that the stubs extending north- and southward are two beginning tails. NGC 3310 has a totally different appearance; it was first noted by Walker and Chincarini (1967) for its nucleus, which is offset from the rotation center, and the "bow and arrow" signature shown in Fig. 1d. Its beautiful inner spiral arms are associated with a strong density wave (van der Kruit 1976). Balick and Heckman (1981) found a sharp and unique (among 20 observed Sb galaxies) drop in metallicity within 1 kpc from the center and suggested a merger; a small, low-metallicity galaxy would have fallen in 100 Myr ago, depositing fresh gas, displacing the nucleus, and generating the density wave. It seems to me that the strongest signatures in favor of a recent Dd merger there are the bow and arrow, which I would reinterpret as the ripple and tail of the small

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disk intruder. Many more such mergers of unequal mass may have taken place in nearby spirals, but may remain unknown because of the rapid (<2 Gyr) disappearance of all tracers. Finally, let me mention a recently discovered class of probable Dd mergers: S0 galaxies with polar rings or disks, such as NGC 2685 (Schechter & Gunn 1978), NGC 4650A (Laustsen & West 1980) which clearly is an edge-on old disk with a polar ring rather than a prolate elliptical (Schechter, private comm.), A0136-080 that Rubin, Whitmore, and I have been studying, and a half dozen others. They all have two crossed disks, of which one is massive and old, whereas the other seems to consist of the debris of a small victim (disk?) galaxy.

Ee mergers are hard to catch for two reasons. First, ellipticals being rare in the field, Ee interactions are $(\text{rare})^2$. Second, because of their hot nature, interacting ellipticals produce faint, diffuse fans that dissipate rapidly, rather than bright, narrow tails. The only two candidate EE mergers that I know of are NGC 750/751 and IC 5250, both still distinctly double and hence not mergers in the restricted sense.

We postpone the discussion of Ed mergers until §4. Of the remaining six classes, Gg is perhaps the most interesting. The type example there is II Zw 40, a classical "isolated extragalactic H II region" discussed by Sargent and Searle. Recently, Baldwin et al. (1982) have shown that it has two tidal tails (the "fan jets S and SE" noticed by Zwicky), probably consists of two gas-rich dwarfs in collision, and seems to have many kins among other isolated H II regions. Given the brief duration and visibility of these events, large numbers of Gg remnants must exist. Among the Eg's, the elliptical NGC 4278 (see G. Knapp and M.H. Ulrich, this volume) is considered prototypical, although I suspect that an intruding small disk cannot be excluded as an alternative to a gas cloud. The Ge, Gd, and Dg classes have no known members yet, presumably because massive gas clouds are scarce and small gas clouds are difficult to detect when falling into large disks. Finally, small ellipticals punching through larger disks can temporarily create ring galaxies, but we do not yet know of any case where an eventual De merger seems likely.

4. MERGERS IN ELLIPTICALS

Ed mergers receive currently much attention, and for good reason since they tell us something about the evolution of ellipticals. The discovery of a "jet" and "shells" in M89 (Malin 1979; here Fig. 1h) and of "giant shells" in four more normal ellipticals (Malin and Carter 1980) has made it clear that such tails and ripples, as I prefer calling these structures, are common in giant ellipticals. We know already that tails are tidal structures, but what are the ripples? Based on their frequent association with tails in merging galaxies (Fig. 1), Schweizer (1980, 1982) suggested that they result from disk mergers. This empirical conclusion is now getting theoretical support from model calculations by P. Quinn (see this volume) and by A. Toomre.

The models suggest that ripples are the distorted remains of a disk galaxy accreted by an elliptical. The top two rows of Figure 3, kindly provided by Toomre, illustrate the accretion process. In this simplified calculation, a disk of 2000 noninteracting test particles (top row, time zero) is "dropped" (in the direction of the arrow) into a fixed Plummer potential of characteristic radius a (marked by the dashed circle) from an initial distance 4a. The orbiting disk gets bent and stretched by differential gravity, and wraps itself around the center of the potential (t=20-80). As the wrapping progresses over several revolutions (second row, scale slightly reduced and 6000 disk particles), more and more "ripples" appear wherever the distorted disk surface is seen nearly edge-on. They last for over ten initial orbital periods and resemble the ripples observed in ellipticals to a surprising degree: The bottom row of Fig. 3 shows NGC 3923 first unmasked, then masked unsharply by Malin to emphasize the faint ripples, and Frame t=300 of the above model sequence rotated by 180° and mirrored. Note that the model has not been matched to the galaxy in any detail and that it shows "ripples" from more than half of all possible viewing directions. Further model calculations by Toomre suggest that even part of a disk, torn off during a close E-D encounter, suffices to produce ripples in the elliptical.

To determine the frequency of ripples, I have photographed 28 bright field ellipticals ($-19.5 > M_B > -22$) with the CTIO 4-m telescope. I find that 15 of them show ripples, though mostly not as spectacular ones as NGC 3923 does. Among the ellipticals with newly discovered ripples are NGC 596, well known for its strong isophotal twist (Williams 1981) and relatively fast rotation in the core (Schechter & Gunn 1979); IC 3370, with crossed "streamers" forming an X and ripples filling two opposite quadrants of this X; and NGC 5018, a "true" elliptical (i.e.,

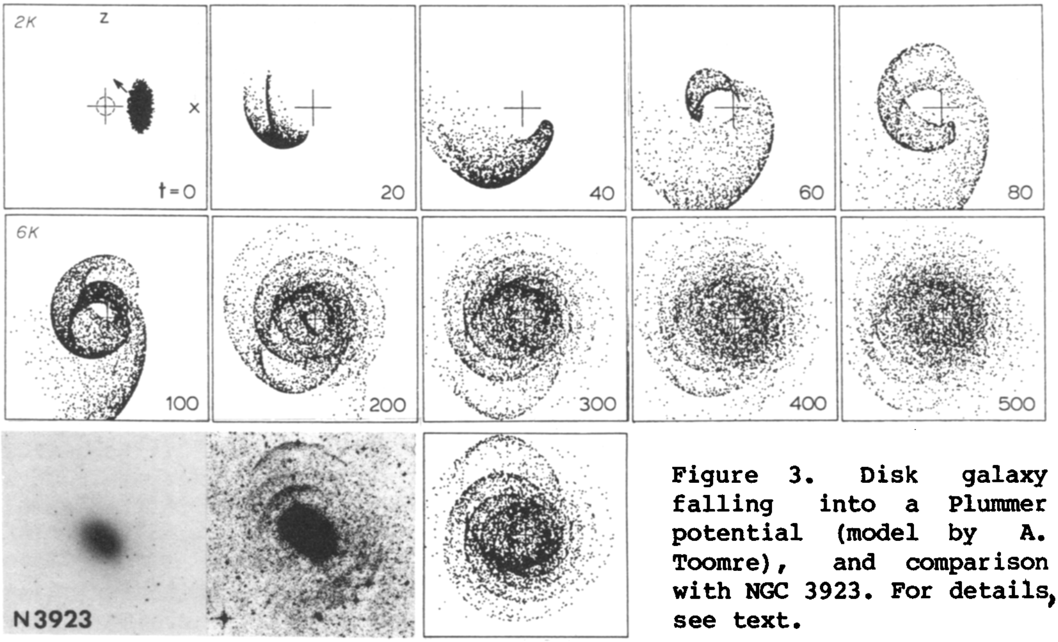

Figure 3. Disk galaxy falling into a Plummer potential (model by A. Toomre), and comparison with NGC 3923. For details, see text.

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classified as E by both de Vaucouleurs and Sandage), yet featuring dust, ripples, and two tail-like filaments (Fig. 1i).

The conclusions from all this work on Ed and other mergers are: (1) One quarter to one half of the bright field ellipticals show signs of having accreted disks or parts of disks recently. (2) If ripples last $\lesssim 2$ Gyr, as the model calculations suggest, then a typical bright field elliptical accretes at least 2-5 (parts of) disks over a Hubble time. After correction for higher interaction rates in the past (Toomre 1977) and aspect dependance, this number may increase to 4-10 (parts of) disks accreted over the age of the Universe. (3) This accretion process must have tended to reduce the number of disk galaxies and increase the luminosities of bright ellipticals. And (4), in at least one case, NGC 7252, we seem to witness the delayed formation of an elliptical from two merged disks. In a more speculative vein, this work also suggests that (a) random accretion of disks may have led to the slow apparent rotation of bright ellipticals; (b) varying admixtures of disk stars may explain the varying UV brightnesses of ellipticals; (c) disk wrapping may be an efficient mechanism for gas "removal" from ellipticals; and (d) ellipticals in clusters may be accreting disks also (M89 in Virgo did it).

To facilitate further work, Table 1 (next page) gives a list of currently known candidate mergers with their characteristics (isolation, ripples, tails, velocity anomalies, etc.) and types.

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Table 1: CANDIDATE MERGERS

Name	Other name	Decl.	Isol.	Ripples	Tails	Veloc.	Other features	Type	Note
N1316	For A	-37°		x	x	x		Ed	1
N5128	Cen A	-43	x	x	(x)	x		Ed	1
N7252	Arp 226	-25	x	x	x	x		DD	1
N 596		-7°		x	x	(x)	isophotal twists	Ed	2S
N1344		-31	x	x			dust	Ed	2M
N2685	Arp 336	+59	(x)			x	inner disk	Dd,Dg	2
N3310	Arp 217	+53	x	x	x		strong dens. wave	Dd	2
N3509	Arp 335	+5	x		x			Dd	2
N3921	Arp 224	+55			x		sloshing isoph.	DD	2
N3923		-29	(x)	x			dust	Ed	2M
N4552	M89	+13		x	x			Ed	2M
N4650A		-41				x	S0 disk + ring	Dd	2
N5018		-19		x	x		dust	Ed	2S
N6052	Mrk 297	+21	x		(x)	x	two nuclei	DD	2*
N7135		-35	x	x	x			Ed,Dd	2
AM 0044-2437		-25				x	two rings	Dd	2
Arp 230		-14	x	x	x		N5128-type dust	Dd,Ed	2
Smith 60		-34	x		x	x		Dd,Ed	2
N750/51	Arp 166	$+33^{\circ}$	(x)		x			EE,ED	3*
N1395		-23		x	(x)		isophotal twists	Ed	3M
N3585		-27	x		x			Ed	3S
N3656	Arp 155	+54	x	x	(x)		N5128-type dust	Dd,Ed	3
N4194	Arp 160	+55	x	x	x			Dd?	3
N7585	Arp 223	-5		x	(x)			Dd,Ed	3
N7727	Arp 222	-12	(x)	(x)	x			Dd	3
I1575	Arp 231	-4		x				Dd,Ed	3
I3370		-39	x	x			Crossed streamers	Ed	3S
I4797		-54		x				Ed	3M
I5250		-65			x			EE,ED	3*
ESO 293-IG37		-42	(x)	(x)	(x)			Dd	3
ESO 341-IG04		-38	x		x			Dd,Ed	3B
II Zw 40		+3	x		x			GG,DD	3*

Notes: 1 = established merger; 2 = probable m.; 3 = candidate m.; B = discovered by Bergvall; M = Malin (1979, or with Carter 1980); S = from Schweizer's survey; * = two component galaxies are still discernible.

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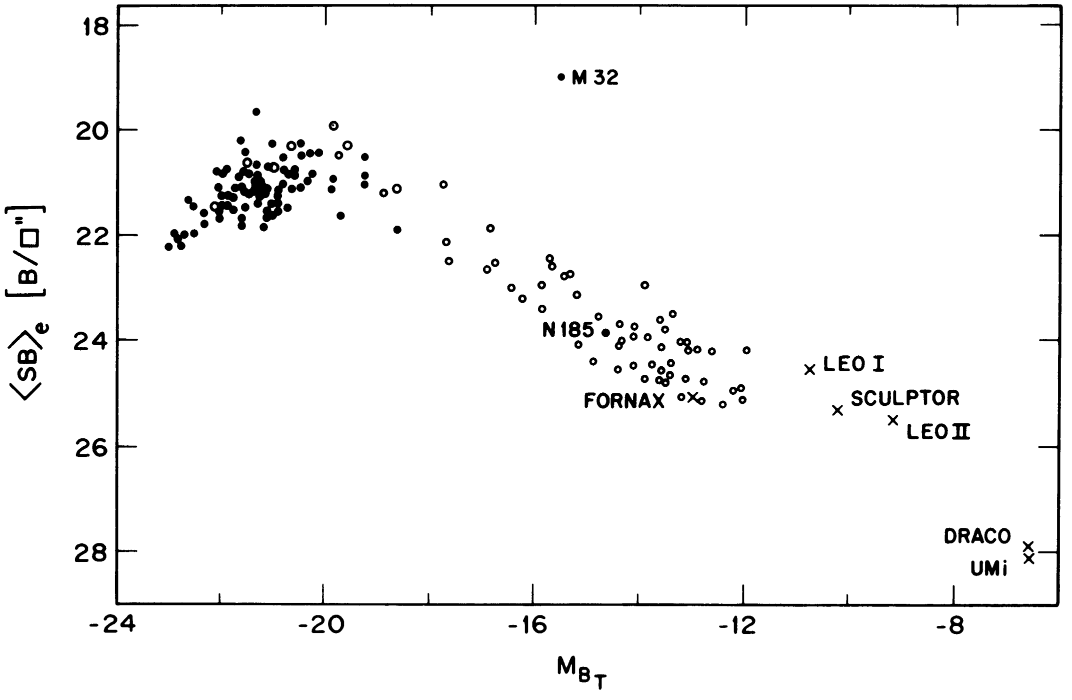
DISCUSSION

RICHSTONE : Kirk Borne and I had a first try at reconstructing NGC7252 as a wreck of two disks using a numerical restricted three-body technique. The spatial match isn't perfect and can probably be improved. The match to the rotation curve is better. I would like to make three comments :
a) It does become elliptical
b) It has a rather high V/σ for a luminous elliptical
c) It is an isolated system with considerable angular momentum. If galactic angular momentum comes from tidal torque, where is the object that supplied the torque in this case ?

SANDAGE : You leave me with the impression that all E galaxies are formed by merging disks. Your evidence in this case is the transient ripples in the outer envelopes. If E galaxies are secondary structures rather than primary, then the fundamental distinction between disk and spheroidal galaxies at the time of formation would be in doubt. Hence many of the ideas of formation via collapse with and without dissipation would be wrong. As your conclusion is based on the outer ripples,the following question arises : how many of your E galaxies with ripples are in the field, and how many are in groups or clusters ? If any are in the field, is there not a problem with the rate of mergers of field disks in the past 10^9 years, given the present low density of neighbors and the low mean random velocities ?

SCHWEIZER : I have made two specific claims : (1) In NGC7252, we seem to be witnessing the formation of one future giant elliptical from the merger of two disks ; and (2) between 1/4 and 1/2 of all giant ellipticals in the field have accreted disks in the past 1-2 Gyr. This accretion is an evolutionary process, and I have avoided making statements concerning how and when these field ellipticals were formed. The conclusion that they accreted 4-10 disks or parts of disks in the past is, however, difficult to avoid. In answer to your question, about half of my field ellipticals are as isolated as one can find, which means they have no neighbor within 500 kpc projected distance. Even in the "field", galaxies are often in pairs or very loose groups ; the crossing time for 500 kpc at v = 250 km/s is only 2 Gyr. It is well known that the observed number of interacting galaxies is significantly larger than one would expect from random encounters with the low mean random velocities that you advocate ; this implies that either these velocities are higher or, more likely, the majority of galaxies are members of multiple systems, just like stars are.

SANDAGE : I do not understand your answer in terms of binary galaxies. You state that the age of these ripples (or shells) is only 10^9 years. Hence they will not occur again in any given rippled galaxy because the companions no longer exist. Since less than 25 % of the field disk galaxies have companions now, I don't see how you can get a present fraction of 25 % of E's which have ripples and thus, according to you, recently merged,unless you believe that at the end of the next 10^9 years, the % will be much less (i.e. will be at the present frequency of binary field disk galaxies which is certainly much less than 10 %).



That E galaxies are generic to the Hubble sequence and are not due to secondary processes as you suggest, follows from the continuity of properties of effective surface brightness, effective radius, cut-off radius, and central density over more than 10^6 in intensity from $M_B = -23$ to $M_B = -8$. The evidence for this continuity in effective surface brightness is shown in the diagram which is from a study of Virgo cluster E galaxies (open circles) supplemented with field galaxies (closed circles) and with 7 local group spheroidals. The Virgo cluster data is from work done with Bruno Binggeli of Basel and Massimo Tarenghi of ESO.

SCHWEIZER : It seems mysterious to me how you can draw conclusions concerning the formation of ellipticals from your graph, unless you claim to understand the maximum that occurs at $M_B = -20$ and the differing slopes on either side. Furthermore I note that all field galaxies lie on one side of the maximum and most cluster galaxies on the other. This diagram, which is not understood at all, cannot compete with signatures such as the rails and ripples, which we understand and know how to model.

SIMKIN : The interesting rotation curve you showed for NGC7252 has the same structure as that found in the gas of 3 of the 5 cD radio galaxies I have measured. If it is a sign of recent mergers then it must persist

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much longer than any morphological signs of such a merger, since none of these cD galaxies show any "shells", "tails", or double nuclei.

OORT : Is there a satisfactory interpretation of the ripples ?

SCHWEIZER : Peter Quinn will give us more details about the models in a moment and will show a movie. Let me add that if ripples are distorted and wrapped-around disks, then spectrograms taken with a long slit across the ripples should show velocity "jumps" at the ripples. These local deviations from the velocity of the underlying elliptical should have opposite signs on opposite sides of the nucleus. Bosma (priv. comm.) has some evidence for such jumps at the innermost ripple in NGC 1316 in one slit position, but does not know yet for the ones further away.

DRESSLER : Fornax A certainly cannot be a prototype of how bright ellipticals are formed. It fails to satisfy the Faber-Jackson relation -its central velocity dispersion is much too low for its luminosity (220 km/sec instead of $\sim$ 350)- and its V/σ (as determined by Bosma) places it above the oblate line in the V/σ - ellipticity diagram. These results are extremely atypical of luminous ellipticals.

SCHWEIZER : I have claimed only that Fornax A swallowed one or two small disks recently. One ought to consider how such infalls might affect the measured velocity dispersion : the line profiles must be composite, i.e., formed by two different stellar population types with different velocity dispersions. It is not clear to me how Fourier programs derive velocity dispersions from such composite, presumably non-Gaussian line profiles.

RUBIN : In two pairs of interacting spirals which I have studied, the rotation curves fall to zero (and below) in all galaxies. On the basis of these observations as well as your own, I would suggest that steeply falling rotation curves are a diagnostic for interacting galaxies.

SCHWEIZER : I agree.