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DYNAMICS OF INTERACTING GALAXIES

Joshua E. Barnes

Institute for Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Lars Hernquist[1]

Department of Astronomy, University of California, Santa Cruz, California 95064

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1. INTRODUCTION

Interacting galaxies encompass a tremendous range of phenomena—indeed, if events during galaxy formation are counted, there are probably few galaxies that were not shaped by interactions or even outright mergers (e.g. Toomre 1977, Efstathiou 1990). In order to keep our subject from completely overrunning the bounds of a single article we focus on the dynamics of interacting galaxies as observed in our own epoch. Even within this focus, there are many interrelated topics—including star formation, nuclear activity, and galactic morphology—which continually tempt reviewers to depart on inviting tangents. While exploring some of these byways, this article makes no pretense at a *complete* coverage of the subject. A more observationally oriented review of galactic collisions has been presented by Schweizer (1986), while earlier numerical work has been summarized by White (1983b). Galactic interactions have featured prominently in recent conferences—the proceedings edited by Wielen (1990) and by Sulentic et al (1990) together present a wider range of viewpoints on this subject than we could hope to encompass here. It is fortunate that excellent reviews of some related topics have recently

[1] Alfred P. Sloan Foundation Fellow.

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appeared. In particular, the reader is referred to Sellwood (1987) for simulation techniques, to Soifer et al (1987) for infrared-luminous galaxies, to Kormendy & Djorgovski (1989) and to de Zeeuw & Franx (1991) respectively for the observations and dynamics of elliptical galaxies, and to Osterbrock (1991) for the observational status of active galaxies.

Figure 1 presents a few well-known interacting systems, arranged roughly in order of increasing violence. M 51's dramatic spiral is very likely of tidal origin, but how secure would this inference be without the other signs of tidal damage to both galaxies? Next, we see gas being transferred from NCG 3808 to its smaller, spindle-like companion, where it may eventually form a polar ring. The "Cartwheel," on the other hand, is evidently the result of a direct hit by one of this galaxy's two small companions. NGC 4038/9, the "Antennae," originated in a close encounter of two comparable disk galaxies; several 10^8 yr later extensive tidal tails

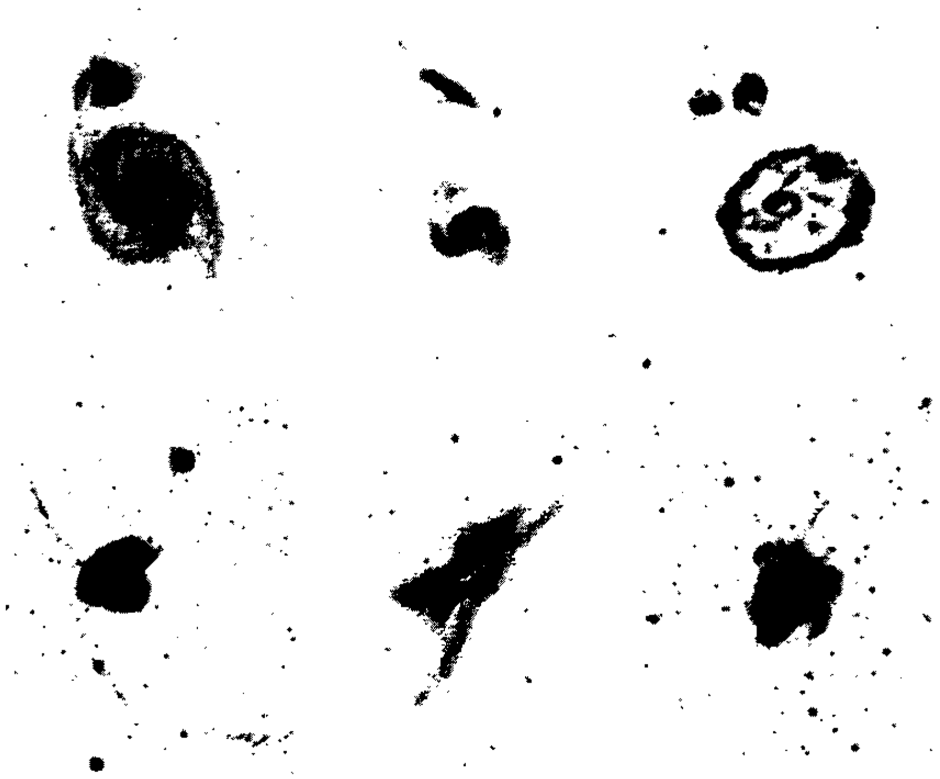

Figure 1 A child's garden of galactic collisions (Barnes et al 1991). Top row shows galaxies interacting with smaller companions; on the left is the "grand design" spiral M 51, in the middle is NGC 3808, and on the right is the "Cartwheel" galaxy. Bottom row shows more violent interactions; on the left are the "Antennae," in the middle is NGC 520, and on the right is NGC 7252.

have developed and the galaxies have apparently returned for a second passage. Two intertwined disk galaxies evidently make up NCG 520, which was once classified as a single irregular galaxy; CO observations indicate the presence of a substantial amount of molecular gas coincident with the dust lane crossing the face of this object. Finally, NGC 7252 is a merger remnant $\sim 10^9$ yr old; it exhibits a relaxed body with a de Vaucouleurs' luminosity profile, a messy, irregular envelope, and a pair of extended tidal tails as a legacy of the two disk systems destroyed in its making.

The outline of this review is as follows. Numerical methods for modeling galactic interactions are discussed in Section 2. Next, Section 3 describes the signatures written on interacting galaxies by tidal forces. Events which add mass to a galaxy are the focus of Section 4, and major mergers between systems of comparable mass are discussed in Section 5. The many forms of activity triggered or induced by galactic interactions are the subject of Section 6. Finally, Section 7 discusses these galaxies' return to normality and related cosmological issues, and Section 8 lists some outstanding questions.

2. METHODS

Simple estimates imply that relaxation times of galaxies are many orders of magnitude longer than a Hubble time (e.g. Binney & Tremaine 1987). Consequently, the dynamics of stars in galaxies is well-described by the collisionless Boltzmann equation

$$\frac{\partial f}{\partial t}+\mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{x}}-\nabla\Phi\cdot\frac{\partial f}{\partial \mathbf{v}}=0, \qquad 1.$$

where $f = f(\mathbf{x}, \mathbf{v}, t)$ is the distribution function normalized so that $f d\mathbf{x} d\mathbf{v}$ is the number of stars in the phase-space volume $d\mathbf{x}d\mathbf{v}$ centered on the point $(\mathbf{x}, \mathbf{v})$. The potential, Φ, includes the self-consistent field generated by the stars as well as the gravitational influence of dark matter and gas. While the nature of the dark matter remains enigmatic, observational constraints suggest that it too obeys Equation 1.

N-Body Methods

In the purely stellar-dynamical limit, the interaction of galaxies is a well-posed problem, in the sense that the evolution is determined entirely by the collisionless Boltzmann equation. Unfortunately, we don't know how to obtain relevant analytic solutions to this equation, except in the limit of weak interactions (e.g. Weinberg 1986, 1989) or for rather special systems (e.g. Sridhar & Nityananda 1990), so numerical methods must be used. Rather than solve the collisionless Boltzmann equation with a finite-difference technique in six dimensions, a Monte-Carlo approach is employed. The initial $f(\mathbf{x}, \mathbf{v})$ is used as a probability distribution function to pick phase-space coordinates $\mathbf{x}_i$ and $\mathbf{v}_i$ for particles $i = 1, \dots, N$; these particles are then integrated along the characteristic curves of Equation 1:

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i, \tag{2}$$

$$\frac{d\mathbf{v}_i}{dt} = -\nabla\Phi_i. \tag{3}$$

Despite the enormous simplification entailed by Equations 2 and 3, the evolution of interacting galaxies is quite costly to compute, owing mainly to the difficulty of calculating the self-consistent potential. In practice, the mass in real galaxies is much more finely divided than in any computer model, so the model's self-consistent potential is much noisier than that of actual galaxies. This gives rise to an unwanted diffusion in phase space which can alter the structure of simulated galaxies on uncomfortably short time scales.

Broadly speaking, the various known algorithms for computing the potential of a system of N particles can be categorized as either "action-at-a-distance" or "field" methods. The former explicitly treat interactions between individual particles while the latter do so only indirectly through the contributions of particles to the global gravitational field. The simplest action-at-a-distance technique is *direct summation.* A common expression for the gravitational potential at the location of particle i is

$$\Phi(\mathbf{r}_i) = -G \sum_{j \neq i} \frac{m_j}{[|\mathbf{r}_i - \mathbf{r}_j|^2 + \varepsilon^2]^{1/2}}, \tag{4}$$

where ε is the "softening parameter." Direct summation is flexible but has an asymptotic cpu cost per step scaling as $\sim O(N^2)$, limiting its practical use to small-N systems. Nevertheless, some early investigations of the dynamics of mergers were performed using this algorithm (e.g. White 1978, 1979, 1980; Gerhard 1981; Quinn 1982) and much larger simulations with $N > 10{,}000$ may ultimately be feasible on special-purpose machines (e.g. Sugimoto et al 1990).

A variety of methods have been proposed to reduce the cost of computing the self-consistent potential. For some problems, it is expedient to neglect self-gravity altogether and evolve the system in a potential which is known a priori, such as in test-particle methods (e.g. Schwarzschild 1979, Quinn 1984), the restricted three-body method (e.g. Pfleiderer &

Siedentopf 1961, Toomre & Toomre 1972), or semi-restricted N-body codes (e.g. Lin & Tremaine 1983, Quinn & Goodman 1986, Hernquist & Weinberg 1989). Generally speaking, however, the dynamics of interacting galaxies will not be represented faithfully without including self-gravity (Barnes 1988).

The majority of the known self-consistent methods have historically not been useful for studying systems with small filling factors in three dimensions such as interacting and merging galaxies. [We refer the reader to the excellent monographs by Sellwood (1987) and Hockney & Eastwood (1988) for a discussion of the limitations of grid methods.] An exception is the technique known as the "hierarchical tree" method (Appel 1985, Jernigan 1985, Barnes & Hut 1986) which recently has had a significant impact on the study of colliding galaxies. All variants of this technique are effectively gridless and retain the essential ingredients of the action-at-a-distance formulation. Particles are processed similarly to direct summation, but the potential from distant groups of particles is approximated using low-order multipole expansions. If the required operations are performed using tree-structured data the cpu cost per step scales as $\sim O(N \log N)$. In fact, it is possible to reduce the cost even further to $\sim O(N)$ by using tree-structured data in the context of a field representation of the potential (Greengard & Rokhlin 1987, Greengard 1988). A distinct approach used in "expansion codes," relies on the use of basis function expansions to compute the potential from the known density field sampled by the particles (Aarseth 1967; Clutton-Brock 1972a,b; van Albada & van Gorkom 1977; Villumsen 1982, 1983; White 1983a; McGlynn 1984; Bontekoe & van Albada 1987).

As emphasized by Sellwood (1987), the choice of method is largely dictated by considerations of efficiency. Contrary to claims which persist in the literature, action-at-a-distance and field methods suffer from comparable degrees of relaxation for the same spatial resolution and particle number (Hernquist & Barnes 1990, Hernquist & Ostriker 1992). Therefore, there is no objection in principle to using direct methods to evolve collisionless systems, provided that a sufficiently large N can be used to suppress relaxation effects to the extent required.

Gas-Dynamic Methods

While present-day galaxies typically contain less than 10% of their luminous mass in this form, gas is critical to our understanding of galactic phenomena such as starbursts and active galactic nuclei, because it can dissipate and form stars. Galactic gas obeys the ordinary conservation laws for a compressible fluid (e.g. Landau & Lifshitz 1959). However, given our present level of understanding of the interstellar medium of even our own galaxy, the dynamics of galactic gas is ill-posed. Because of cooling and feedback from supernovae, interstellar gas is highly inhomogeneous and comprises several distinct phases (McKee & Ostriker 1977). We lack the computational hardware and theoretical knowledge to model the different phases simultaneously, and some compromises must necessarily be made.

One strategy, used to advantage by some workers, is to focus on global issues where the detailed small-scale structure of the gas is probably not crucial. In the limit where the gas can be represented as a continuous medium, its equations of motion can be solved either by finite-difference algorithms or by particle-based techniques. A promising example of the latter is the method known as smoothed particle hydrodynamics (SPH; e.g. Lucy 1977, Gingold & Monaghan 1977, Monaghan 1992). Since SPH is Lagrangian, it does not suffer from grid-based limitations on spatial resolution or global geometry and is especially well-suited for studying interacting systems. In addition, SPH can be generalized so that it is adaptive in both space and time (Hernquist & Katz 1989); these refinements offer significant advantages when dealing with large density contrasts (Hernquist 1989a, Barnes & Hernquist 1991).

A phenomenological treatment is sometimes useful in the opposite extreme when the gas is modeled as a set of discrete clouds (e.g. Negroponte & White 1983). In the "sticky-particle" method, particles representing the gas evolve similarly to collisionless particles but undergo inelastic collisions amongst themselves, thereby dissipating kinetic energy. Computationally, this approach is simpler than those which solve the equations of motion for continuum gas, but requires a number of ad hoc parameters whose relationship to actual physical processes is problematic. Given our ignorance of the true state of interstellar gas it is difficult to argue for or against one of the two extremes embodied by, e.g. the SPH or sticky-particle formalisms.

3. TIDAL TRAUMAS

Although the peculiar appearance of galaxies in a few double and multiple systems had been noticed much earlier, it was Zwicky (1956, 1959) who first called attention to the enormous variety of extended structures seen in such objects. Zwicky described these features as "clouds, filaments and jets of *stars* which are ejected massively from galaxies in collision" by "large scale tidal effects." Many astronomers, however, were skeptical that certain remarkably narrow appendages could be blamed on tidal forces (e.g. Gold & Hoyle 1959, Vorontsov-Vel'yaminov 1961), and Zwicky himself suggested that "electromagnetic actions . . . contribute to the internal viscosity of stellar systems."

Bridges and Tails

Bridges and *tails* are common in interacting disk galaxies. The former often appear to link large galaxies to small companions, while the latter stretch far away from the galaxy causing the perturbation. That "old-fashioned gravity" could extract these narrow structures was illustrated by Pfleiderer & Seidentopf (1961), Pfleiderer (1963), Yabushita (1971), Clutton-Brock (1972a,b), Toomre & Toomre (1972; hereafter TT), Wright (1972), and Eneev et al (1973). These calculations generally treated each galaxy as a point mass surrounded by a disk of test particles—a simple numerical method, but adequate for the job. Only close, relatively slow passages—parabolic or even sub-parabolic—readily produce convincing bridges and tails; faster passages produce smaller disturbances. As TT noted, such slow passages would naturally result between pairs of galaxies which, bound gravitationally since formation, have fallen together for the first time along extremely eccentric orbits.

With varying degrees of success, the calculations reproduced bridges and tails as thin, curving ribbons yanked from disks by violent tidal forces. Such features are clearly *relics* of recent collisions rather than signs of ongoing interactions. The most impressive examples arise in direct passages where the orbital angular speed of the companion temporarily matches that of the stars within the disks, creating a quite broad resonance.

The tidal hypothesis gained additional credibility from TT's deliberately simple models of four well-known interacting systems. Further studies of these and other galaxies continue to support the tidal picture. For example, Schweizer (1978) and Schombert et al (1990) have reiterated Zwicky's claim that bridges and tails are composed largely of stars drawn from a population very similar to that of the disks from which they extend. Kinematic studies of interacting galaxies (e.g. Tully 1974; van der Hulst 1979a,b; Combes et al 1980; Marcelin et al 1987) have revealed velocity fields quite consistent with tidal models (Toomre 1978).

Early test particle models raised many questions which could only be addressed with self-consistent calculations. One such question concerns effects of self-gravity in structuring tidal bridges and tails. Once launched, such features develop in an essentially *kinematic* manner (TT), and deep exposures of NGC 4038/9 by Schweizer (1978) reveal thick tails consistent with free expansion both parallel and perpendicular to the direction of extension. On the other hand, self-gravity may create small-scale structure within tails. Zwicky (1956) noticed a concentration of luminosity near the end of the southern tail of NGC 4038/9 and speculated that such objects might evolve into dwarf galaxies. Schweizer (1978) reported clumps of gas and young stars in the tidal tails of other interacting systems, and Mirabel et al (1991) describe a beautiful system with at least nine distinct knots spread along a total extent of 350 kpc. Models indicate that dwarf galaxies formed in this manner can incorporate considerable gas from the disks but very little material from the halos of their parent galaxies, and so should have unusually low M/L ratios (Barnes & Hernquist 1992).

Another such question concerned the conjecture that tails extracted from disks might be unable to climb out of deep halo potential wells (e.g. White 1983b). This raised the possibility that the long observed tails could contradict the large masses proposed for invisible halos. However, encounters between self-consistent disk/halo models indicate that galaxies with halos of four times the mass of their luminous components can nonetheless produce tails as long as those of NGC 4038/9 (Barnes 1988). Since the energy required to climb out is provided by falling in, mere length is probably not an effective constraint on halo masses.

Wavelike Tidal Spirals

Self-gravity plays an important role in structuring the *inner* disks of some interacting galaxies. TT noted that galaxies with bisymmetric spiral patterns often have close companions, and suggested that these spirals have a tidal origin. N-body models of galactic disks abundantly illustrate the development of tidally excited spirals (Toomre 1981, Noguchi 1987, Barnes 1990). In a shearing, self-gravitating disk of stars, perturbations can grow by factors $\gg 10$ while swinging around to become trailing spiral patterns (Goldreich & Lynden-Bell 1965, Julian & Toomre 1966). Such "swing amplification" occurs because the shearing of the spiral pattern temporarily matches the epicyclic motions of individual stars, permitting a modified form of Jeans instability to develop (e.g. Toomre 1981). This mechanism can amplify tidal perturbations in situ, rapidly bringing forth a trailing spiral over much of the disk. The calculations show that such spirals, although manifested as density waves as well as material arms, do not survive long but wind up tightly over a few rotation periods.

Several groups have attempted to reproduce the inner spiral structure of M 51 with tidal interaction models (Hernquist 1990, Howard & Byrd 1990, Sundelius 1990). Perturbations strong enough to generate the large-scale tidal features originally modeled by TT and Toomre (1978) also give rise to a "grand-design" spiral density wave in the inner disk. At present, however, none of the calculations offer a really convincing reconstruction of M 51's spiral structure; better models of the pre-encounter disk of NGC 5194 are probably required.

Cartwheel Galaxies

Some, although by no means all, galaxies with pronounced rings (e.g. Few & Madore 1986) appear to be the result of collisions. As shown in simple N-body simulations (Lynds & Toomre 1976, Theys & Spiegel 1977), rings develop when a companion galaxy makes a close and nearly normal-incidence passage through the plane of the victim, exciting large epicyclic oscillations in the target disk. Initially, all these oscillators are in phase, but since their periods increase with mean radius, the oscillations drift out of phase and orbits crowd together radially to produce an expanding ring. Indeed, kinematic studies of several ring galaxies find velocities consistent with the collision model (e.g. Fosbury & Hawarden 1977, Few et al 1982). Even the "folded ring" galaxy Arp 144, once interpreted as a collision between a galaxy and an intergalactic H I cloud (Freeman & de Vaucouleurs 1974), is now known to include *two* bodies with infrared colors typical of evolved stellar populations (Joy et al 1988).

To be sure, not all ring-making collisions are described by the simplest models. The system studied by Taylor & Atherton (1984) exhibits a rather complex velocity field. More remarkable yet is the extreme range of velocities, exceeding 1000 km/s, observed in the messy H II ring of Arp 118 (Hippelen 1989); many features of this system are nicely reproduced by a test particle calculation, but the M/L ratios implied seem uncomfortably high. The "Cartwheel galaxy" itself presents a modest puzzle or two; the putative companion does not seem massive enough to produce the very strong ring observed (Davies & Morton 1982), and the spoke-like features giving this galaxy its name are not well understood. Self-consistent three-dimensional models might help account for all these systems (e.g. Appleton & James 1990).

Only head-on collisions leave the bulge of the victim at the center of the ring; if the perturber is somewhat off-center, the bulge can be yanked to one side, producing an empty ring (Lynds & Toomre 1976). More off-center passages, although presumably more common, may not retain their ring-like appearance for as long as a direct hit; the resulting morphology changes smoothly from a ring to an open tidally-induced spiral as the pericentric separation is increased (Toomre 1978). Ring-like shapes resulting from off-center passages are more common than generally thought. One example is the very extended H I tail of M 51 (Appleton et al 1986), which presents an almost circular outline beautifully illustrated in VLA maps (Rots et al 1990).

Damaged Ellipticals

Tidal interactions involving elliptical galaxies are more subtle than those involving spirals, since encounters in rich clusters tend to be fast and disturbed ellipticals produce diffuse sprays of stars instead of narrow filaments. Nonetheless, a number of interacting ellipticals have been identified by their luminosity profiles (Kormendy 1977), distorted and off-center isophotes (e.g. Lauer 1986), and peculiar kinematics (e.g. Borne & Hoessel 1988).

The effects of hyperbolic encounters on the luminosity profiles of spherical galaxies have been studied both analytically (e.g. Knobloch 1978) and numerically (e.g. Dekel et al 1980; Aguilar & White 1985, 1986; McGlynn 1990). Such encounters do *not* tidally truncate the target; on the contrary, they promote stars to loosely-bound orbits, creating extended halos with $\rho \propto r^{-4}$ density profiles, closely following a de Vaucouleurs law (e.g. Jaffe 1987). Aguilar & White (1986) found that stars which have not yet phase-mixed produce transient, outward-moving luminosity excesses. These results provide a natural explanation for the distended profiles of galaxies with nearby companions (Kormendy 1977).

Photometric decomposition techniques provide further evidence of interactions among elliptical galaxies (e.g. Hoessel et al 1985; Lauer 1986, 1988). In these reductions a smooth, concentric luminosity model is simultaneously fit to each galaxy in the field; the residuals reveal nonconcentric isophotes and elongated features referred to as "dynamical friction wakes." These studies find little evidence for *strong* interactions among most multiple-nucleus cluster galaxies, in general accord with the view that such systems are either optical doubles or extremely fast, plunging encounters (Merritt 1984, Tonry 1984). Some points of confusion remain; Hoessel et al (1985) report that only those pairs with velocity differences smaller than their internal dispersions show signs of interaction, while Lauer (1988) sees evidence for interactions in pairs with velocity differences in excess of 1000 km/s.

Surface photometry and long-slit velocity data of several interacting elliptical galaxies have been used to construct semi-restricted 3-body models (Borne 1988, Borne et al 1988, Balcells et al 1989). These models do a fairly convincing job of reproducing the tidally disturbed morphology and "U-shaped" velocity profiles (e.g. Borne & Hoessel 1988) of their subjects, but it is difficult to assess their claimed uniqueness since they do not seem to be overconstrained by the data. Fully self-consistent models including dark halos are probably needed to reliably predict the future evolution of these systems.

An interesting exception to most of the rules for interacting ellipticals are "dumbbell" systems (e.g. Valentijn & Casertano 1988). These are comparable pairs of giant elliptical galaxies with projected separations of $\sim 10h^{-1}$ kpc, found at the centers of some rich clusters. The distorted morphologies and relatively small pairwise velocity differences observed in these objects imply that many are bona fide interacting systems. Tremaine (1990) suggested that dumbbell galaxies are the last stage in the merger of rich clusters, each containing a D or cD galaxy. This proposal provides a reasonable account of many features of dumbbell systems, including their morphology, separations, velocity differences, and overall frequency. Rix & White (1989) have constructed self-consistent equilibria for dumbbell galaxies and used *N*-body calculations to show that at least some of these models are free from violent dynamical instabilities; it is not clear if systems with extensive common envelops can also turn out to be stable or if real dumbbell systems can get themselves into such slowly evolving states.

4. ACQUISITIONS & ACCRETIONS

Galaxies can acquire material from passing companions via mass transfer or accrete much less-massive neighbors, such as satellites, suffering only relatively minor damage. Although individual events like these add only a modest amount of mass to large galaxies, their consequences can have a significant effect on observable properties of galaxies and provide indications as to the frequency and import of galaxy collisions.

Shells and Other Fine Structures

Beginning with Arp's (1966) classic study of peculiar galaxies, "fine structures," such as "shells," "ripples," "plumes," boxy isophotes, and "X-features" have been detected in an ever-larger fraction of S0's and ellipticals (Malin & Carter 1980, 1983; Schweizer 1980). Indeed, in the most recent survey by Seitzer & Schweizer (1990), 32% of their S0's and 56% of their E's possess shells and $\sim 10\%$ and $\sim 30\%$ of their entire sample have X's and boxy isophotes, respectively. The actual percentage of all galaxies exhibiting such fine structure is rather uncertain, owing to the difficulty of determining if the faint features detected are bona fide. This complication is especially acute for later-type disks, which often possess diffuse spiral patterns that mimic these structures, e.g. shells. However, there are observational indications that at least shells exist in some Sa's and Sb's (e.g. Schweizer & Seitzer 1988).

Simulations employing restricted methods support the view that the accretion of material by large galaxies provides a natural explanation for the origin of fine structures. Shells can form either by the "phase-wrapping" of debris on nearly radial orbits (Quinn 1984) or by the "spatial-wrapping" of matter in thin disks (Hernquist & Quinn 1988). Contrary to Quinn's (1984) hypothesis, the shell-forming material need neither reside initially in a thin disk nor be on precisely radial orbits. Shells can be produced during the accretion of spheroidal companions by larger galaxies, provided that the total phase-space volumes they occupy are sufficiently different (Dupraz & Combes 1986; Hernquist & Quinn 1988), and in nonradial collisions through mass transfer, eliminating concerns that an improbable encounter geometry would be needed to produce them (Toomre 1983, Hernquist & Quinn 1988).

These various studies have also shown that other types of fine structure develop in encounters which simultaneously produce shells. Plumes consisting of debris on unbound or weakly-bound orbits occur frequently in shell-forming collisions (Hernquist & Quinn 1988). Moreover, material accreted by nonspherical potentials can produce X-structures and features that appear boxy in projection (Hernquist & Quinn 1989).

In spite of the general acceptance of the accretion model, a number of difficulties remain. The numerical studies mostly ignore self-gravity and the consequences of dynamical friction. While the self-gravity of the victim does not appear crucial to the issue of whether or not fine structures will form (Barnes 1989, Heisler & White 1990, Salmon et al 1990), it is impossible to predict, e.g. the radial distribution of shells formed by a close collision without including dynamical friction (Dupraz & Combes 1987). Indeed, if the accretion scenario is correct, it appears that dynamical friction probably played a significant role in structuring some of these objects since many contain extremely tightly bound shells. Self-consistent calculations by Heisler & White (1990) indicate that the disruption of satellites can indeed inject material onto tightly bound orbits, populating inner shells. However, even these models are not sufficiently detailed to explain objects such as NGC 3923, which contains more than 20 shells distributed regularly around the galaxy.

As noted by Thomson & Wright (1990), the restricted simulations are deficient in other regards. In some galaxies, the intensity of shells increasingly far from the galaxy drops similarly to that of the elliptical, suggesting that these shells may be of *internal* origin. Accordingly, Thomson & Wright have put forward an alternate model in which shells are induced in a thin disk component of an elliptical by a tidal encounter with another galaxy. The existence of such disks in ellipticals is problematic, but the inability of restricted calculations like those of Hernquist & Quinn (1988) to explain the radial luminosity of shell systems reemphasizes the need for more physical models.

It should also be noted that boxy or X-shaped structures need not arise through accretion events; these features simply reflect phase-mixed populations of stars in certain kinds of orbits which may have been created by a variety of processes (Binney & Petrou 1985). An example is provided by the recent work of Merritt & Hernquist (1991) who show that dynamical "bending" instabilities produce remnants which are photometrically similar to ellipticals having boxy isophotes and weak X-structures. These models do not display shells, however, so a strong correlation between all these various features would support the view that they are of external origin.

Polar Rings

Many S0 galaxies possess rings of gas-rich material that appear to be kinematically distinct from the galaxy proper (e.g. Schweizer et al 1983, Athanassoula & Bosma 1985). The recent survey by Whitmore et al (1990) implies that $\sim 0.5\%$ of all S0s have *polar rings*; i.e. rings of gas, dust, and young stars with axes aligned perpendicular to the major axis of the disk. The actual fraction of S0s with such features may be even larger when observational selection effects and ring lifetimes are taken into account.

Searches for similar features in elliptical galaxies have met with mixed success. Obscuring dust lanes (e.g. Bertola 1987) and diffuse, extended disks and rings of gas are seen in many ellipticals (e.g. van Gorkom et al 1986, Lake et al 1987, Kim et al 1988, Schweizer et al 1989), but few ellipticals with rings as substantial as those of classical polar rings in S0s are known. A notable exception is the galaxy AM2020-5050 (Whitmore et al 1987), which is classified as Hubble type E4. However, this object rotates rapidly and appears somewhat intermediate between an elliptical and a S0 galaxy.

Since these rings often appear kinematically distinct from their hosts, it is generally assumed that they are of external origin. Two scenarios have been proposed for the formation of polar rings: accretion of gas-rich dwarfs (e.g. Athanassoula & Bosma 1985) and capture of material from a passing galaxy by mass transfer. An example of the latter is NGC 3808, where a stream of material can be seen linking a large disk galaxy to an S0 of comparable luminosity as shown in Figure 1. Unfortunately, neither scenario has been tested in detail. Theoretical studies of polar rings have instead focused mainly on determining the equilibrium states accessible to material on closed orbits in axisymmetric and triaxial potentials. These calculations have shown that the "settling time," which is the time for gas in an axisymmetric or triaxial potential to settle into steady state, is small compared to the age of the universe (Tohline et al 1982; Steiman-Cameron & Durisen 1982, 1988; Habe & Ikeuchi 1985, 1988; Varnas et al 1987), and so there is sufficient time for accreted gas to form polar rings.

However, all these studies are limited by their neglect of self-gravity and time-dependent effects and their use of unrealistic initial conditions. The first two difficulties will likely be overcome by Lagrangian codes, such as TREESPH (Hernquist & Katz 1989) which explicitly include gravitational forces between mass elements. Some preliminary steps in this direction have already been taken by Rix & Katz (1991). The role of initial conditions in ring-forming events is not likely to be elucidated without resort to calculations that treat the dynamics of galaxy collisions and mergers in detail, including dynamical friction and dissipation. Such models may eventually determine why rings are most common in S0 galaxies, largely avoiding other galactic types, and also explain why fine structures such as shells should be more common than rings if all result from accretion of external matter.

Sinking Satellites

As emphasized by Ostriker & Tremaine (1975) and Tremaine (1981), dynamical friction will cause the orbits of satellites around massive galaxies to decay. Eventually, the victims will be destroyed tidally and/or cannibalized by the primary galaxy. Using Chandrasekhar's treatment of dynamical friction, Tremaine showed that galaxies like the Milky Way have probably accreted a non-negligible amount of mass in the form of discrete objects over a Hubble time. Although it is difficult to make precise estimates of this effect, owing to the absence of a complete theory of galaxy formation and large-scale structure, Tremaine's simple argument implies that galaxies do not age peacefully in isolation, even if they do not experience a strong encounter with a neighbor of comparable mass.

In the limit of weak encounters, perturbation theory can be used to compute torques on satellites and predict their decay paths (Tremaine & Weinberg 1984, Weinberg 1986, Statler 1988). More generally, there is little alternative to numerical simulation, particularly if the details of the tidal disruption of the companion and/or the self-consistent response of the primary to large perturbations are of interest. Numerical studies have included the orbital decay of satellites around spherical galaxies (Lin & Tremaine 1983, White 1983a) and disks (Quinn & Goodman 1986, Quinn et al 1992). The results are supported by quasi-analytic calculations, implying that simulations yield reliable decay rates (Hernquist & Weinberg 1989). However, existing studies have typically approximated the self-consistent response of the primary, complicating their interpretation. For example, while Quinn et al (1991) include the self-gravity of primary disks, they ignore the self-consistent response of the halo. As emphasized by Barnes (1988), orbital decay in composite systems involves a complex interplay amongst the various components. Fully self-consistent calculations by Hernquist (1992b) support this claim and show that the torque on a satellite near a disk is derived in roughly equal measure from the disk and halo; provided, of course, that galaxies possess dark matter halos similar to those inferred in external spirals.

Technical issues aside, it seems likely that a variety of apparently disparate phenomena may be blamed on satellite accretions. Some ellipticals contain cores that are kinematically distinct from the surrounding galaxies (e.g. Efstathiou et al 1982, Franx & Illingworth 1988, Franx et al 1989, Jedrzejewski & Schechter 1988, Wagner et al 1988, Bender 1990a). One possible explanation for these peculiar velocity fields was first proposed by Kormendy (1984) who argued that the central rotation of NGC 5813 is a consequence of the accretion of a spinning dwarf galaxy. This idea was tested by Balcells & Quinn (1990) using N-body simulations. In their models, angular momentum is transferred from the orbit of the dwarf to the primary by gravitational torques during a merger. If the satellite's orbit is retrograde, the angular momentum deposited can partly cancel the primary's original rotation and even reverse it near the center where the rotation curve is rising. Following mergers from retrograde orbits, therefore, the central regions of the primary can display distinct velocity fields from the outlying regions. Although this specific scenario is not the only way to produce kinematically decoupled cores, the general idea that angular momentum deposited by satellite accretions can "organize" the shapes and velocity fields of elliptical galaxies seems promising (e.g. Quinn et al 1990).

Satellite mergers may also alter structure of disk galaxies (for a review, see Hernquist 1991). The self-consistent models of Quinn et al (1991) indicate that decaying satellites can excite transient warps in the outer parts of disks that may be sufficiently long-lived to explain some stellar warps in external spirals. Moreover, dynamical heating by these satellite accretions produce disturbed, featureless disks possessing little or no large-scale spiral structure (Hernquist 1989a,b), reminiscent of amorphous galaxies (Sandage & Brucato 1979). Tidal debris from cannibalized satellites may account for a number of peculiar features in our Galaxy, including its two-component system of globular clusters (e.g. Freeman 1990), retrograde halo stars, and the Magellanic Stream (e.g. Lin & Lynden-Bell 1982).

More generally, the consequences of satellite accretions are important for theories of the formation of galaxies and large-scale structure. Schweizer (1990) has proposed that the bulges of spiral galaxies may be relics of past accretion events. A similar suggestion has been made for thick disk components of external, edge-on systems (for a discussion, see Quinn et al 1991). Such processes may be responsible for many aspects of galactic structure that were once attributed to events at the time galaxies were born. If so, then it is impossible to relate the observed properties of galaxies to cosmological models without considering late and on-going evolutionary effects. Indeed, as noted recently by Toth & Ostriker (1992) the existence of cold, thin disk components in spiral galaxies limits the rate of satellite accretion in cosmological models. Whether or not these constraints can be applied to test actual scenarios for the formation of large-scale structures remains to be seen.

5. MERGERS

Mutual tidal capture of two disk galaxies during a close, planar passage was illustrated by Holmberg (1941), using an optical analog computer to perform N-body integrations. However, these calculations were part of an investigation into the origins of galaxy clustering, and Holmberg elsewhere (perhaps reluctantly) rejected the idea that repeated tidal encounters would cause galaxies to merge. Thus Zwicky (1959) seems to have been the first to propose that very close encounters might lead to "considerable disruption of both systems [or] total mutual capture." This possibility was also mentioned by Alladin (1965) in his analytic study of fast—in other words, hyperbolic—encounters of spherical galaxies. But an appreciation of the terrible strength of inelastic effects in slower encounters remained largely lacking, although TT estimated that the relative orbit of NGC 4038/9 had decayed from $e = 0.8$ to $e = 0.5$ as a result of the most recent passage, and that even more severe orbital decays seemed necessary to account for the half-dozen objects which they described as each resembling "a single luminous ball, from which protrude several tentacles or filaments."

Evidence for violent tidal friction was thereafter sought in self-consistent simulations. At the same time, evidence began to collect that disk galaxies might be surrounded by massive dark halos (Ostriker & Peebles 1973); it was noted that such halos would increase the merger cross-sections of visible galaxies (e.g. Toomre 1977). The simplest N-body simulations modeled the encounter of a pair of spherical galaxies. As White (1978) pointed out, these experiments are perhaps best viewed as reproducing the dynamics of dark halos.

Spherical Systems

N-body models illuminated the mechanisms responsible for rapid orbital decay. In head-on collisions, decay results from the gravitational compression arising when the two galaxies nearly coincide; this compression causes a slightly greater axial force to be felt between them as they try to separate than they experienced at corresponding distances during their approach (Toomre 1974, van Albada & van Gorkom 1977, White 1978, Miller & Smith 1980). By stirring up the material in each galaxy at the expense of their orbital energy, this mechanism brings about the rapid merger of even the most centrally concentrated systems in only a few passages. In off-axis collisions, the collective response is dominated by those particles which orbit within their respective galaxies in the same direction as the two galaxies pass each other (White 1978, 1979; Roos & Norman 1979; Villumsen 1982, 1983). Such particles are again promoted onto less-bound orbits, receiving both binding energy and angular momentum from the relative motion of the two galaxies, and producing broad tail-like structures. Orbital decay is more rapid if the victim galaxies rotate internally in the same direction as their passage, since more of their constituents then match the angular speed of the perturber (White 1979).

All in all, it seems unlikely that any bound pair of galaxies can forever escape merging. In some cases the decay time-scale may be quite long, and it can become difficult to delineate the conditions leading to an eventual merger (e.g. Navarro 1989). However, White (1978) found that parabolic encounters between identical spherical galaxies with half-mass radii greater than their pericentric separation generally lead to rapid capture and merger on the subsequent orbital passage.

Fluctuating gravitational fields during the merging process tend to transfer binding energy between different components of the system, but such fluctuations damp down before a complete redistribution takes place. This *incomplete* violent relaxation only partly erases the original ordering of material in binding energy; the centers and outskirts of merger remnants remain dominated by particles from the respective centers and outskirts of the victim galaxies. Thus radial population gradients present in the progenitors may well survive the merging process (White 1980, Quinn et al 1990).

After a merger, the remnant relaxes progressively outward on a time scale comparable to the local crossing time. Outside the relaxed region at any typical instant is material falling back onto the remnant for the first time on long-period, loosely-bound orbits. Still further out lie bound particles which have yet to attain apogalacticon, and at even greater radii are those which have become unbound during the merger. Multiple passages before merger generate more complicated structures since each passage launches a fresh outward surge of loosely-bound mass. The amount of material that escapes depends on the structure of the victim galaxies as well as the parameters of their encounter. In general the escaping stuff comes from the outskirts of the original galaxies; truncated victims such as King (1966) models generally lose only a few percent of their mass after merging in parabolic encounters.

The material that does not quite escape eventually phase-mixes to form an extended envelope around the body of the remnant. Simple arguments based on continuity of the energy distribution imply that this envelope will have a $\rho \propto r^{-4}$ density profile (Jaffe 1987, White 1987, McGlynn 1990). Insofar as such a density profile provides a fair approximation, in projection, to the outer parts of a de Vaucouleurs law, the continuity of the distribution function may help explain why de Vaucouleurs profiles are frequently produced in mergers, as well as in other situations involving violent relaxation (e.g. van Albada 1982, McGlynn 1984).

To the extent that the small amount of mass lost can be neglected, the overall scale of a merger remnant may be estimated by a straightforward energy argument (Hausman & Ostriker 1978, White 1983b). The simplest version describes the merger, following a parabolic encounter, of two identical galaxies; in this case the total mass and binding energy of the remnant are just twice the mass and binding energy of a single victim. Then the gravitational radius ($r_g \equiv GM^2/|U|$), mean velocity dispersion, and characteristic surface density of the remnant must be respectively double, equal, and half the corresponding values for the victims. Note, however, that these relations are only valid for the remnant as a whole; energy conservation alone does not predict the *central* properties of merger remnants, nor how different components become distributed in multi-component remnants.

The cores of merger remnants are constrained by Liouville's theorem, since a system with a de Vaucouleurs profile extending all the way to the center requires an infinite peak in its phase-space density (May & van Albada 1984). Thus if the victim galaxies have finite cores, the remnant they produce must also have a finite core. In practice, mergers of spherical isotropic galaxies seem to produce only a modest decrease in the maximum coarse-grained phase-space density (e.g. Melott 1982, Farouki et al 1983). Remnants generally have core radii comparable to those of the victim galaxies, but their central densities and velocity dispersions are often higher, contradicting the homology assumptions invoked in some early theoretical discussions.

Mergers of spherical galaxies produce remnants with fairly simple shapes and kinematics (White 1983b). Head-on encounters result in prolate remnants with anisotropic velocity dispersions, whereas if the encounter is not quite head-on, the result is a slowly-tumbling triaxial object. Encounters with a pericentric separation $R_p \gtrsim 0.5R_h$, where R_h is the victim half-mass radius, generally result in nearly-oblate remnants with figures supported largely by internal rotation. This last outcome might appear to dispute the notion that slowly-rotating elliptical galaxies are formed by mergers—since it may seem unlikely that progenitors falling from separations of ~ 1 Mpc would frequently pass within only ~ 1 or 2 kpc of each other on their first plunge. However, hierarchical clustering generally favors rather close encounters (Aarseth & Fall 1980). In addition, extended dark halos take up much of the orbital angular momentum, an effect left only implicit in the early single-component studies.

Disk/Halo Systems

Dark matter has been included in more recent models of merging disk systems to support approximately flat rotation curves, to help prevent violent bar instabilities, and to otherwise make the simulations more realistic. Mergers between equally-matched disk/halo galaxies were presented by Gerhard (1981), Farouki & Shapiro (1982), Negroponte & White (1983), and Barnes (1988, 1992); in addition, Gerhard (1983a,b) and Barnes (1989) discussed models in which several disk/halo galaxies merge sequentially. Over the past decade, the particle number N has increased by two orders of magnitude, but perhaps the most significant difference between the latest models and their predecessors is the scale of the halos modeled. In the earlier calculations, halos of approximately the same mass and radial extent as the visible disks were employed, obviously insufficient to maintain flat rotation curves out to the radii seen in some galaxies. Halos used in some recent calculations have four or more times the mass and several times the radial extent of the luminous components.

The dynamics of encounters between such galaxies are largely governed by the interactions of their extended dark halos; consequently even passages in which the *visible* components completely miss each other at first can lead to rapid orbital decay. Roughly speaking, a pair of spherical, interpenetrating dark halos interact as if they were single-component systems: the orbital angular momentum of the two halos is transferred to internal degrees of freedom, imparting spin and creating broad tidal tails. More tightly bound components, such as embedded disks and/or bulges, are not much braked by the tidal forces retarding the dark matter; instead, these components lose orbital angular momentum mostly by interacting with their *own* surrounding halos, once the latter have been decelerated (Barnes 1992). It is the interaction between such extended dark halos that brings two galaxies to a "screeching halt" and subsequent merger while the luminous tails extracted from their disks are still well-defined and visibly incriminating (Barnes 1988).

As in mergers of spherical systems, the incomplete violent relaxation of disk/halo models only blurs the original ordering in binding energy; the tightly-bound components which contained most of the luminosity in the original galaxies will be found near the center of the merger remnant. Luminous material dominates the central regions of merger remnants precisely because the dense luminous parts of the infalling galaxies remain largely undisturbed until they finally encounter each other and merge within a now-common envelope of halo material (Barnes 1988). This ends any worry that mergers between galaxies with larger dark halos might mix up the dark and luminous components, producing diffuse, extended remnants with extremely low surface brightnesses.

Thus even if the two galaxies originally encountered each other on a parabolic orbit, the luminous regions typically find each other only after their relative orbit has become more tightly bound. As a result, the luminous stuff tends to have a substantially higher velocity dispersion in a disk/halo remnant than it did in the initial galaxies (Farouke & Shapiro 1982). In parabolic mergers of composite bulge/disk/halo systems, the velocity dispersions of those particles belonging to the bulges are $\sim$40% higher in the final remnant than in the initial galaxies (Barnes 1988). It seems likely, as Farouki & Shapiro already noted, that this effect might well remove Ostriker's (1980) objection that disk-galaxy merger remnants should have markedly lower velocity dispersions than elliptical galaxies of the same total luminosity. What is more, actual observations indicate that merger remnants have velocity dispersions consistent with normal ellipticals of the same luminosity (Lake & Dressler 1986).

A more interesting challenge to the simple slogan that "merging disk galaxies make ellipticals" comes from the expected core radii—or equivalently from the peak coarse-grained phase-space densities—of merger remnants. Central disk phase-space densities are lower than the peak phase-space densities of many lower-luminosity ellipticals (e.g. Carlberg 1986, Vedel & Sommer-Larsen 1990). Moreover, the violence needed to convert a pair of dynamically cold disks to a hot, spheroidal remnant must swirl a good deal of vacuum together with the disk phase fluid, further lowering the coarse-grained phase-space density (e.g. Barnes 1992). Thus merging disk galaxies cannot form the cores of ellipticals unless they contain either substantial preexisting bulges or else sufficient interstellar material to build such cores dissipatively (e.g. Kormendy 1989).

The shapes and kinematics of the remnants of disk/halo galaxy mergers are much more complex and diverse than those produced by mergers of spherical systems, but certain generalizations can still be made (White 1983b). Just as for spherical systems, mergers from high angular momentum orbits tend to produce oblate, rapidly-rotating remnants, while those resulting from head-on encounters are prolate. But this is more true for the halos of remnants than for their luminous contents; orbital decay tends to leave the latter with but a small part of the orbital angular momentum they possessed originally. In many of the numerical experiments, the final encounters of the most tightly-bound components are observed to be nearly head-on, producing remnants with nearly prolate centers supported largely by particles on box orbits (Barnes 1990).

Remnants with rapidly rotating luminous components *can* result from direct or nearly direct encounters which allow the spin and orbital angular momenta of the original disks to reinforce each other. Such remnants have nearly oblate figures and owe much of their flattening to rotational support (Negroponte & White 1983). The significant streaming motions in these remnants are due to the many particles in direct minor-axis tube orbits. Highly flattened remnants can also be produced by nearly retrograde encounters, but here the comparable numbers of particles on direct and retrograde minor-axis tube orbits give the resulting objects little, if any, net streaming motion (Barnes 1992).

Encounters between more inclined disks tend to produce rounder, more slowly-rotating remnants with more luminous material on major-axis tube orbits. In some cases the initial spins of the disks are "remembered" in the sense that circulation about the major axis in one direction is favored over circulation in the other direction (Barnes 1992); such differential population of the various orbit families can result in large misalignments between the spin and minor axes (Levison 1987). Recent studies of elliptical galaxies suggest that most have small kinematic misalignments, while a minority have spin vectors nearly parallel to their major axes (Franx et al 1991); if substantiated, this may still prove a serious obstacle to the production of ellipticals by mergers of inclined disk galaxies.

Finally, some experiments yield merger remnants with intrinsic axial twists or rapid figure rotation (Gerhard 1983a,b; Barnes 1992). The long-term stability of such configurations remains an open question; effects related to the diffusion of chaotic orbits, for example, may only show up on time scales so long that they are completely obscured by the "particle noise" in the potentials of existing N-body models.

Gas Dynamics in Merging Disk Galaxies

If pressure forces are small, the gas in interacting galaxies follows the same trajectories as the stars, but shocks can transfer momentum between parcels of gas and thereby drive it off the stellar track. Long ago, Spitzer & Baade (1951) suggested that global shocks could sweep the gas from spiral galaxies during fast interpenetrating collisions, producing gas-poor disks resembling S0 galaxies, but this idea did not survive revised estimates of collision rates. Unless the encounter geometry is just right, the fraction of gas removed by direct impacts cannot be large. But tidal forces in *slow* passages can perturb the gas and stars alike over most of an entire disk, and if large-scale shocks develop in the gas, its flow may diverge markedly from that of the intermixed disk stars.

Self-consistent models of interacting gas-rich spirals (Negroponte & White 1983, Barnes & Hernquist 1991, Noguchi 1991) suggest that the most common result of such tidal perturbations is indeed *not* to eject the interstellar material but to drive a large fraction of it close to the center of each galaxy. One (but not the only) way this can happen is for the perturbed stellar disk to form a bar (e.g. Noguchi 1987); gravitational torques between the bar and the shocked gas rob the latter of its angular momentum and so allow it to flow inward (Barnes & Hernquist 1991; see also Noguchi 1988, Combes et al 1990). If the encounter is a close one, the shocks generated are extremely strong and a substantial fraction of the gas in the disk can flow inwards on a dynamical time scale. This inward-driven gas typically collects in a rotating ring or "blob" with dimensions, scaling the models back to reality, of $\lesssim 1$ kpc (e.g. Barnes & Hernquist 1991).

Only when two galaxies undergo a final, nearly head-on collision will hydrodynamic forces between these newly-built gas blobs come into play. Such final encounters result from orbital decay in bound pairs of galaxies. In the present context, the central gas blobs lose orbital angular momentum to the surrounding stellar stuff. Their eventual coalescence cancels out much of their residual spin about different axes. Thus experimental merger remnants are often left with massive central gas clouds containing $\gtrsim 50\%$ of the gas initially spread throughout the victim disks. The linear dimensions of these clouds, corresponding to a few hundred pc, are comparable to the spatial resolution of the calculations; more detailed simulations are needed to model the structure of these central concentrations.

The ultimate fate of gas in merging galaxies will be still more difficult to predict. Observations discussed in the next section imply that compression in large-scale shocks and in the dense gas clouds may convert a substantial fraction of the gas to stars on a $\sim 10^8$ yr time scale (e.g. Larson 1987). It seems likely that energy released by stellar or nonthermal activity could blow out most of the remaining gas, producing the "super-winds" seen in some IR-luminous galaxies (e.g. Baan et al 1989, Heckman et al 1990). Such outflows may well strip merger remnants of their cool interstellar gas, create the x-ray coronae around some ellipticals (e.g. Forman et al 1985, Fabbiano 1989), or even transport metals back to the intercluster medium. However, these possibilities have not been convincingly demonstrated in numerical simulations.

If the time scale for star formation significantly exceeds the remnant's central dynamical time scale, the gas may settle into a relatively thin central disk like the one in NGC 7252 (Schweizer 1982). Such a disk has been reported in a numerical model of merging spiral galaxies (Hernquist & Barnes 1991). Because the gas must lose so much angular momentum to arrive where we find it, the small amount of spin it retains may not be well-correlated with the rotation of the merger remnant as a whole. Indeed, both NGC 7252 and the above-mentioned model contain *counter-rotating* gas disks, spinning in the opposite direction from the rest of the remnant.

Subsequent star formation would leave a compact stellar disk (e.g. Schweizer 1990) with kinematics unlike the rest of the galaxy, perhaps resembling the "kinematically decoupled" cores found in elliptical galaxies (e.g. Bender 1990a and references therein). Counter-rotating systems can be produced by purely stellar-dynamical mergers (Kormendy 1984, Balcells & Quinn 1990), and apparent counter-rotation may also result from projection effects in triaxial systems with streaming motions (Statler 1991). However, the line profiles of some systems indicate that their disks are dynamically "cold" (e.g. Bender 1990b, Rix & White 1992); such disks were probably assembled in gaseous form as described here.

6. ACTIVE GALAXIES

Observationally, it has long been known that there may be a link between interactions and unusual forms of energy generation in galaxies. Baade & Minkowski (1954) argued that the radio source in Cygnus A consists of "... two galaxies in actual collision." However, it was widely believed that objects like Cygnus A were anomalous and that most galactic activity was produced by explosions or other violent events within isolated galaxies. Only during the past decade have observations challenged this long-standing prejudice (for a discussion, see Balick & Heckman 1982).

Attempts to establish a definitive causal relationship between galactic activity and interactions have evoked considerable controversy. Statistical analyses are typically plagued by the lack of reliable "control samples" against which the active galaxies should be compared. This problem is especially acute for cosmologically distant sources since it is not easy to identify the morphological types of the galaxies (e.g. Stockton 1990). Detailed studies of individual objects, on the other hand, provide direct evidence as to the import of interactions in select cases, but provide little basis for generalization. Even so, such case studies seem more persuasive than statistical analyses in view of the difficulties associated with establishing definitive control samples.

Global Starbursts

In a classic paper, Larson & Tinsley (1978) demonstrated that the peculiar galaxies in the Arp (1966) atlas tend to be bluer, on average, than their isolated counterparts. The best fits to their data invoke intense bursts of star formation throughout the peculiar galaxies to account for their anomalous colors. These findings have been corroborated by many subsequent studies, including those of Joseph et al (1984), Kennicutt et al (1987), Bushouse (1987), Telesco et al (1988), and Laurikainen & Moles (1989). There is even evidence for induced star formation *between* colliding galaxies (e.g. Thronson et al 1989). However, it should be emphasized that not all interacting pairs display this behavior (Keel et al 1985, Bushouse 1986, Kennicutt et al 1987, Bushouse et al 1988, Solomon & Sage 1988).

Thus, the *observational* link between encounters and enhanced star formation seems quite compelling. A likely explanation is that interactions accelerate star formation as gas is compressed in shocks and cloud-cloud collisions (e.g. Young et al 1986). However, the severity of these effects undoubtedly depends on the orientations of the disks and the orbital geometry, so a starburst is not guaranteed in all collisions.

Theoretical work on this issue remains ambiguous. Using numerical simulation, Noguchi & Ishibashi (1986) and Olson & Kwan (1990) argue that star formation is enhanced during galaxy interactions through increased collisions between molecular clouds in disks; a finding disputed by Mihos et al (1991). In reality, the connection between cloud-cloud collisions and star formation is poorly understood. While the numerical simulations do demonstrate that large-scale shocks develop in the gas as it is compressed by tidal perturbations, no existing method possesses the dynamic range needed to translate the measured effect into a reliable star formation rate.

Infrared-Luminous Galaxies

The most extreme examples of starbursting objects are those where the peculiar emission is generated mainly in the nucleus (for a summary of the observations, see Soifer et al 1987). Spectacular examples of this phenomenon were revealed by the *IRAS* survey: sources with infrared luminosities up to $10^{13} L_{\odot}$—the brightest of which invariably possess features typical of merging galaxies (e.g. Soifer et al 1984a,b; Allen et al 1985; Joseph & Wright 1985; Sanders et al 1986; Armus et al 1987; Sanders et al 1988a,b; Kleinmann et al 1988). CO observations of these objects indicate that they often contain large quantities of gas in their nuclei. For example, Mrk 231, Arp 220, and NGC 3256 appear to contain nuclear gas masses in excess of $10^{10} M_{\odot}$, confined to their inner few hundred parsecs (e.g. Scoville et al 1986; Sargent et al 1987, 1989).

There seems little doubt that mergers are somehow responsible for the activity in at least the brightest *IRAS* objects (e.g. Sanders et al 1988a,b; Sanders 1992). This hypothesis is supported by numerical experiments which indicate that mergers between disks of comparable mass can create substantial nuclear gas concentrations (Negroponte & White 1983, Noguchi 1991, Barnes & Hernquist 1991). Gas accumulates in the center of each galaxy prior to the merger and eventually the two gas concentrations sink to the center of the ensuing remnant by dynamical friction. An observed example of such an event may be Arp 220, which appears to contain a double-Seyfert nucleus (Norris 1988, Diamond et al 1989, Graham et al 1990; but see Smith et al 1988). There are indications that many and perhaps even all of the ultraluminous *IRAS* objects possess double nuclei and that the intensity of the emission is correlated with the proximity of the nuclei (Sanders 1992). Indeed the apparent dearth of single-nucleus luminous infrared galaxies is somewhat unexpected—numerical experiments indicate that the double-nucleus phase is rather short-lived (e.g. Barnes & Hernquist 1991)—and there is no obvious mechanism that would shut off the IR emission once the nuclei have merged.

Seyfert Galaxies

The most common AGN in the local universe are those which were first studied in detail by Seyfert (1943; for a discussion, see Osterbrock 1991). Unlike radio ellipticals, Seyferts are associated with late galaxy types but, like radio galaxies, are more common in the field than in rich clusters (e.g. Dressler et al 1985). A variety of studies hint that Seyferts tend to be found in galaxies interacting with nearby companions (e.g. Adams 1977, Dahari 1984, Kennicutt & Keel 1984, Keel et al 1985, MacKenty 1989), a proposal which has evoked controversy owing to difficulties with control samples (Fuentes-Williams & Stocke 1988). Nevertheless, there now appears to be a general consensus that at least some types of Seyfert activity are correlated with galaxy collisions (Osterbrock 1991).

There are also many indications that mergers, in addition to transient encounters, are related to Seyfert activity. Some Seyferts display multiple nuclei and tidal tails, characteristic of merger events (Fricke & Kollatschny 1989, Kollatschny & Fricke 1989). It is probably also significant that a large fraction of Seyferts in MacKenty's (1990) sample are amorphous or otherwise disturbed. Numerical simulations by Hernquist (1989a,b; 1992a) demonstrate that the accretion of small satellites by gas-rich disks lead to rapid nuclear inflows of gas and leave remnants that have distorted, but mostly featureless disks. As in mergers of comparable-mass galaxies containing gas, these inflows can be driven by large-scale stellar bars, excited by the decaying satellite. Moreover, this effect can operate even if stellar bars are not generated during a merger (Hernquist 1989a,b). In some cases, the tidal field of the satellite "squeezes" gas orbits in the disk, leading to rapid dissipation as streamlines intersect. If the gas is self-gravitating it can fragment, and the blobs of gas left over will sink to the center of the disk by shedding angular momentum to surrounding stars via dynamical friction. It is natural to suppose that events such as these can simultaneously trigger Seyfert activity and leave remnants with global morphologies similar to those of the galaxies in MacKenty's sample. However, the fate of the central gas in the models is problematic and there is little hard observational evidence to support an evolutionary connection between starbursts and Seyfert activity (e.g. De Robertis & Shaw 1988).

A variety of models suggest that transient encounters can also drive gas to the centers of galaxies (e.g. Byrd et al 1987; Noguchi 1987, 1988; Lin et al 1988). However, these calculations either ignore the effects of dissipation or are not fully self-consistent. Judging from the simulations of Barnes (1988) and Barnes & Hernquist (1991) it is not inconceivable that the violent interactions needed to provoke nuclear inflows of gas would lead to mergers and complete destruction of the disks involved. The remnants of such events do not resemble Seyferts but are instead similar to the elliptical and peculiar galaxies which harbor starbursts and radio sources. These issues will not be resolved until detailed parameter surveys are available which include the full self-gravity of all components. It should also be noted that not all Seyfert activity is triggered by interactions and that some other fueling mechanism, such as bar-induced inflow (Simkin et al 1980), may be more widespread than encounters of galaxies.

QSOs and Quasars

There is considerable indirect evidence to support the conjecture that quasar activity is triggered by galaxy collisions. Studies of the morphological structure of quasar hosts by several groups (e.g. Gehren et al 1984, Hutchings et al 1984, Malkan et al 1984, Smith et al 1986) indicate that a large fraction of these galaxies are disturbed. Among low-redshift quasars, 70% or more have nearby companions (French & Gunn 1983, Heckman et al 1984, Vader et al 1987, Hutchings et al 1989), some possess features reminiscent of tidal tails (Stockton 1978, MacKenty & Stockton 1984, Stockton & Ridgway 1991), and still others appear to be linked to neighboring galaxies by bridges or display evidence for multiple nuclei (Stockton & MacKenty 1987, Hutchings et al 1988, Block & Stockton 1991). In addition, there are compelling arguments indicating that many of the more luminous *IRAS* galaxies are, in fact, "buried quasars," or systems which will eventually evolve into quasars (e.g. Sanders et al 1990). As noted above, the brightest of these systems are invariably associated with mergers.

In general, theoretical studies on the relevance of mergers to quasar activity mainly comprise wishful thinking. While calculations like those by Negroponte & White (1983), Noguchi (1988), and Barnes & Hernquist (1991) demonstrate that tidal forces can drive gas into the nuclei of interacting galaxies, they do not predict the ultimate fate of the gas and so cannot determine if an AGN will develop. Moreover, it is not clear if the galaxy models used by these workers, which are analogues of present-day disks, are even reasonable caricatures of quasar hosts. Nevertheless, if collisions between galaxies and an abundant supply of gas are necessary ingredients for forming quasars, then it is expected that AGN should be more abundant at high redshifts than in the local universe since interactions were more frequent then and, presumably, more free gas was available than today (e.g. Yee & Green 1984, 1987; Roos 1985).

Radio Galaxies

The most convincing observations linking interactions with radio activity in ellipticals are studies by Heckman et al (1986) and Vader et al (1989) implying that many radio galaxies are the products of recent mergers. These objects display structural irregularities often associated with merger candidates, including dust lanes, tails, bridges, shells, and double nuclei (see also Schweizer 1980, van Albada et al 1982, de Ruiter et al 1988, Smith & Heckman 1989). Others display stellar disks that may be debris from a merger (e.g. Gonzalez-Serrano & Perez-Fournon 1989). Moreover, some show evidence of recent or ongoing star formation and unusually high levels of infrared emission, suggesting that they are relatively young. It is quite natural, therefore, to speculate that these galaxies formed by mergers of disk progenitors which also triggered the observed activity.

The numerical studies reviewed in Section 5 indicate that merger remnants are morphologically similar to elliptical galaxies and that if the galaxies involved are gas-rich a substantial fraction of the gas may fall into the nuclei of merger remnants. In this regard, it is interesting to note that the kinematics of radio ellipticals are quite similar to those of normal ones (Heckman et al 1985, Smith et al 1990) and that many merger candidates exhibit $r^{1/4}$ law luminosity profiles (e.g. Schweizer 1982, Wright et al 1990). The calculations lack sufficient dynamic range to determine the evolution of the gas on scales much smaller than 100 pc, but a variety of phenomenological arguments suggest that the gas should continue to fragment and contract on smaller scales and may eventually form a black hole or be accreted by an existing one (Begelman et al 1984, Norman & Scoville 1988, Scoville & Norman 1988, Shlosman et al 1989).

7. COSMOLOGICAL CONNECTIONS

With the discovery that collisions and the peculiar behavior they induce generally represent but short episodes in the life of a galaxy came the recognition that for each spectacularly interacting system we see, there must be many that have gone through such phases in the past (e.g. TT). This realization encourages a search for evidence that galactic interactions have been at work in creating some of the structures we observe today; a search which might logically begin by examining how the scars of violent encounters fade with time.

Aging Merger Remnants

Intermediate-age merger remnants are expected to be plentiful, and the most youthful examples not difficult to find; Toomre (1977) listed a half-dozen ongoing mergers with but a single conspicuous center each. One of the best-studied of these is NGC 7252 (Schweizer 1982). This galaxy, shown in the last panel of Figure 1, sports a pair of well-defined tidal tails which extend from a single, messy-looking ellipsoidal body. Photometrically, it exhibits an $r^{1/4}$-law luminosity profile with numerous loops, ripples, and plumes superimposed (e.g. Schweizer 1990). Strong Balmer lines indicate the presence of a substantial number of A-type stars in the main body of the system. Raw materials for star formation are present in the form of a central counter-rotating disk of ionized gas (Schweizer 1982) and in a substantial amount of molecular material (Dupraz et al 1990).

NGC 7252 is naturally explained as the merger of two comparable disk galaxies. Age estimates based on the kinematics of the tails and on the colors of the main galaxy indicate that this merger took place less than 10^9 yr ago (Schweizer 1982). Self-consistent simulations, while not specifically intended to model NGC 7252, show that pairs of merging disk/halo galaxies may come to resemble this system. By the stage roughly corresponding to the present epoch, material from the tidal tails is falling back into the galaxy on two fairly cold and organized streams; spatial and phase-wrapping of this material can produce shells, loops, and plumes (Barnes 1992) much like seen in NGC 7252. Likewise, models including gas dynamics indicate that counter-rotating or otherwise distinctive gas kinematics should be fairly common in mergers of comparable disk galaxies (Hernquist & Barnes 1991).

Further examples are not wanting; NGC 3921 (Schweizer 1978, 1990), Mrk 231 (Hamilton & Keel 1987), and ESO 341-IG04 (Bergvall et al 1989) all exhibit extended tails, $r^{1/4}$ luminosity profiles, shells and other fine structures, and Balmer absorption spectra; these systems seem similar in age and gas content to NGC 7252. On the other hand, NGC 6776 (Sansom et al 1988) features but one well-defined tidal tail and seems to be poor in gas, dust, and young stars; this system may well have originated in a merger between an elliptical and a smaller, early-type disk galaxy.

Older merger remnants apparently lurk among those elliptical and S0 galaxies with fine structures—such as ripples, plumes, boxy isophotes, or X-shapes. Schweizer et al (1990) find that such galaxies tend to have stronger Hβ absorption and weaker CN and Mg indices than average galaxies of the same luminosity; they propose that the galaxies responsible for these correlations are merger remnants with ages greater than $\sim 10^9$ yr but considerably less than 10^{10} yr. Boxy elliptical galaxies are also louder than average in the radio *and* X-ray bands (e.g. Bender et al 1989), and Bender (1988) and Nieto & Bender (1989) have suggested that these galaxies are merger remnants with intermediate ages. The increasingly large fraction of elliptical galaxies that exhibit ever-fainter scars of past interactions lends much support to the idea that merger remnants blend into the population of normal ellipticals as they age.

Sites of Interactions

Evidence that galactic mergers play a significant cosmological role comes from a simple demographic argument presented by TT and refined by Toomre (1977). Out of the ~ 4000 galaxies in the NGC catalog, there are at least a dozen which are either close pairs of disk galaxies strongly interacting or recent merger remnants with prominent double tails. Adopting a nominal age of 5×10^8 yr for these objects, Toomre (1977) concluded "we should expect to find roughly 250 old relics of mergers among the NGC systems alone, *provided* that the present rate of those intense encounters is at all typical of the 10–15 billion years that galaxies have existed." In fact, the present merger rate probably *underestimates* the average rate over the past $\sim 10^{10}$ yr. The pairs we find in violent interactions and mergers today presumably spent most of the last 10^{10} yr loitering near apogalacticon, and have only recently fallen back together (TT). Almost any reasonable assumption for the distribution of binding energies for an ensemble of such pairs yields a merger rate that declines with time (e.g. Toomre 1977).

Besides the relatively isolated pairs which appear to account for most of the objects listed by Toomre (1977), violently interacting galaxies are also found in other settings. Galaxies in compact groups frequently exhibit strong tidal distortions (e.g. Rose 1979, Hickson 1982) and kinematic peculiarities (Rubin et al 1991). Numerical simulations indicate that such groups experience on the order of one merger per crossing time as a result of low-velocity encounters (e.g. Barnes 1989). This view gains further support from observations indicating that $\sim 6\%$ of compact group members have colors characteristic of recent merger remnants (Zepf & Whitmore 1991). Such mergers might not be as easily recognized as those involving isolated pairs since the tidal forces of other group members tend to shred extended tidal tails. It remains difficult to estimate how many merger remnants are being produced in compact groups, largely because characteristic lifetimes are not well known for many of these systems (e.g. White 1990).

Rich clusters provide another possible setting for interactions and mergers. Initially, attention focused on "cannibalism" as a mechanism for forming the extremely luminous galaxies found at the centers of rich regular clusters (Lecar 1975, Ostriker & Tremaine 1975, White 1976). In these early models, dynamical friction was invoked to bring massive galaxies into the core of the cluster, where they would merge to form a D or cD galaxy. However, more detailed studies showed that the victim galaxies would be shorn of much of their halo mass by the cluster's tidal field, and therefore would not spiral in rapidly enough to contribute much more than $\sim 10\%$ of the luminosity of the central giant (Merritt 1985 and references therein; see also Malumuth & Richstone 1984). This result has been substantiated by observational studies (Tonry 1984; Merritt 1984; Lauer 1986, 1988) which show that most of the "secondary" nuclei in cD galaxies are merely passing through with velocities typical of the cluster as a whole. Such high-speed collisions also occur elsewhere in rich clusters and their effects can be studied using analytic approximations (e.g. Gerhard & Fall 1983); in general, however, it seems unlikely that these collisions cause significant damage to a large number of galaxies or contribute a substantial amount of stripped luminosity to a cluster-wide background.

Galactic interactions may have played a more important role during the formation of rich clusters. Within the context of "hierarchical clustering" models for the growth of large-scale structure (e.g. White & Rees 1978, Peebles 1980), rich clusters are expected to form by the amalgamation of smaller ones. Before collapsing, such a system probably resembles a hierarchical federation of compact groups. Such systems are favorable sites for violent interactions since most of the galaxies reside in pockets of substructure with relatively high densities and low velocity dispersions, and a glance at a photograph of the Hercules cluster reveals many interacting galaxies. A toy model for the dynamical evolution of a hierarchy of 128 core/halo galaxies illustrates how such a system passes through stages resembling irregular clusters before relaxing to form a regular, centrally concentrated cluster with a substantial population of merger remnants (Barnes 1992). It remains to be shown that more realistic initial conditions can produce enough mergers to account for the elliptical populations of rich regular clusters without also depositing more than 10–15L_* in a central star-pile (Tremaine 1990).

These considerations suggest a plausible explanation for the overall correlation between spatial density and types of galaxies described by Dressler (1980). In this view, merger remnants are formed in regions of intermediate density which are undergoing gravitational collapse, and are "caught up by the subsequent growth of larger-scale structure" (e.g. Aarseth & Fall 1980, Barnes 1989). Thus the *products* of interactions are found in the regions of higher density than the regions where interactions are now taking place. If so then rich clusters are rubble-heaps containing nearly a Hubble time worth of galactic collisions.

Mergers and Morphology

The above arguments imply that at least a fair fraction of elliptical galaxies acquired their present forms as a result of mergers. But merging is only one process shaping galaxies, and the origin of ellipticals is only a part of the larger problem of the formation and evolution of all galaxies. For example, elliptical galaxies share many properties with the bulges of disk galaxies; it seems unlikely that this is a coincidence. Indeed, the success of numerical simulations in producing elliptical-like merger remnants can be partly attributed to the presence of fairly substantial bulges in the victim disk galaxy models. Are bulges merely ellipticals which have subsequently acquired disks, or are the central parts of ellipticals instead merged bulges dressed in the remains of their attendant disks?

Purely collisionless mergers are constrained by conservation of phase-space density; if they are to produce remnants with small cores, the victims must have had small cores to begin with. But mergers of gas-rich galaxies could develop cores of much higher phase-space densities through dissipative processes. This is indeed what appears to be happening in many starburst galaxies, and the central concentrations of gas found in these galaxies have characteristic masses and scales consistent with the cores of ellipticals. The simulations indicate that galactic collisions can "bring *deep* into a galaxy a fairly *sudden* supply . . . of interstellar material" (TT). Core formation from this material has many features in common with "dissipative collapse" pictures for galaxy formation (e.g. Kormendy 1989), but two new wrinkles need to be stressed. First, merging galaxies in our neighborhood offer a glimpse of the formation of spheroidal systems in general. Second, the large collapse factors invoked in the dissipative picture may require strong gravitational torques exerted during a merger-like process to get rid of excess angular momentum of the gas.

If this approach to galaxy formation is fruitful, then models of galactic mergers including gas dissipation and star formation might be expected to reproduce the color and metallicity profiles of elliptical galaxies (e.g. Franx & Illingworth 1990) as well as their kinematic properties. Although such models will probably have a number of free parameters reflecting our relative ignorance about the process of star formation, it need not follow that their realization would teach us nothing about events leading up to the formation of real galaxies. On the other hand, real galaxies also have features that may prove difficult to account for in any numerical model feasible with present-generation computers.

Recent observations suggest that nearby galaxies may harbor black holes with masses of $10^{6.5}$ to $10^{9}M_{\odot}$ (e.g. Kormendy & Richstone 1992). The formation of such massive black holes is attended by a substantial release of energy which would presumably manifest as an active galactic nucleus. As noted above, there is considerable circumstantial evidence linking nuclear activity to violent interactions and mergers. If massive black holes turn out to be common features of galactic spheroids then it seems plausible that spheroidal systems and their central holes were formed as a result of mergers between gas-rich galaxies. This hypothesis has the potential to link galactic activity at redshifts of $z \sim 2$ with the formation of bulges and elliptical galaxies (e.g. Roos 1985, Carlberg 1990).

Perhaps one of the greatest puzzles associated with a "dissipative merger" picture for spheroid formation is the origin of globular clusters. Van den Bergh (1990) has argued that the number of globular clusters in a galaxy is well-correlated not with *total* luminosity but rather with the luminosity of the spheroidal component alone. Mergers of disk galaxies, however, are expected to produce remnants with fewer globular clusters per unit luminosity than typical ellipticals. In fact, the specific frequency of globular clusters in elliptical galaxies seems to be somewhat environment dependent, and field ellipticals are perhaps no richer in globulars than typical disk galaxy merger remnants. But still unexplained are the tremendous numbers of globular clusters in galaxies like M 87 (e.g. Harris 1988); if such galaxies formed as the result of mergers, their progenitors may well have systematically differed from present-epoch disk galaxies in other respects besides globular cluster content (e.g. Efstathiou 1990).

8. FURTHER QUESTIONS

Most astronomers would agree that galaxies interact and that gravity plays the leading role in the dynamics of such encounters. At present, however, there is considerable controversy over the significance of interactions in shaping galaxies. The point of view adopted in this article is that interactions provide important examples of galaxy transformations.

Numerous questions remain: How much satellite accretion can disk galaxies stand? How much has occurred? What signatures exist in our galaxy? What are realistic parameters for merger progenitors and remnants? What range of remnant dynamics and orbital structure are permitted by the merger process? What distributions of axial ratios, minor-axis rotation, and nonelliptical isophote shapes are expected of mergers? Does long-term dynamical evolution play a role? How does gas lose angular momentum during interactions and mergers? How will a multiphase ISM behave? What effects will star formation have? What photometric, kinematic, and enrichment signatures of starburst events should we look for in older merger remnants? What controls the rate at which a monster is fed? What are the relative contributions of starbursts and nonthermal sources to *IRAS* galaxies? To powering "superwinds"? Can "buried quasars" break through? And continue to shine after? Why were QSOs more common at $z \simeq 2$? Why were they so much *brighter*? Do a few, some, or most E galaxies have central black holes? What is the origin of the density-morphology relationship? How often are compact groups formed in evolving loose groups? How much merging took place in the evolution of rich clusters? How much substructure survives in regular clusters? Where do cD galaxies come from? How does the merger rate change over time? Can galaxies long survive the merging of their halos? What is the relation between bulges and ellipticals? What determines the specific frequency of globular clusters?

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