OVERVIEW: LOW-z OBSERVATIONS

Of Interacting and Merging Galaxies

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Abstract. Gravitational interactions and mergers affect the morphologies and dynamics of galaxies from our Local Group to the limits of the observable universe. Observations of interacting galaxies at low redshifts ($z \lesssim 0.2$) yield detailed information about many of the processes at work. I briefly review these processes and the growing evidence that mergers play a major role in the delayed formation of elliptical and early-type disk galaxies both in the field and in clusters. Low-z observations clearly contradict the notion of a single epoch of E formation at $z \gtrsim 2$; instead, E and S0 galaxies continue forming to the present. The different rates of E and S0 formation inferred from observations of distant and nearby clusters may partially reflect the dependence of dynamical friction on mass: Major, E-forming mergers may tend to occur earlier than minor, S0-forming mergers because the dynamical friction is strongest for equal-mass galaxies.

1. Introduction

Three published figures illustrate the dramatic progress in our understanding of galaxy structure and evolution made during the past six decades. The first of these is Hubble's (1936) empirical "Sequence of Nebular Types" (tuning-fork diagram), which begged the question: What determines the position of a galaxy along this sequence? And, more specifically, why are galaxies at one end of the sequence disk-shaped and at the other end ellipsoidal? The second figure is Toomre's (1977) sketch of "Eleven NGC Prospects for Ongoing Mergers," which illustrated how this puzzling shape dichotomy might result from disk galaxies merging to produce ellipticals (Toomre & Toomre 1972, hereafter TT for short). The third figure is Barnes's (1992, Fig. 9) display of the simulated final passages and merger of two disk galax-

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ies, each represented with its own live halo, disk, and bulge. This figure not only validates TT's earlier hypothesis, but also shows that ellipticals formed via disk mergers bear signatures of the former disks in their fine structure.

The early work by TT and others on gravitational interactions led to many of the broader questions that preoccupy us at present: What dynamical processes drive galaxy evolution? What is the relative importance of tidal interactions, minor accretions, and major mergers in shaping the various types of galaxies? What fractions of stars formed quiescently versus in violent episodes (Schechter & Dressler 1987)? How fast do galaxies assemble? And how has the mix of galaxy types evolved over time?

Although we should not expect this Symposium to yield definitive answers to all these questions, the subject of galaxy interactions is progressing rapidly at present, and the moment seems opportune to review recent advances and chart new courses for addressing these questions.

2. Tidal Interactions

In essence, the tidal nature of galactic "bridges" and "tails" was deciphered during the early 1970s (e.g., TT; for a review, see Barnes & Hernquist 1992). Because of our human preference for the spectacular, there has been a strong observational bias toward studies of near-equal-mass collisions and mergers. Therefore, our knowledge of unequal-mass collisions (say, $m/M \lesssim 0.3$) and of the cumulative effects of weak, relatively distant interactions remains fragmentary. For example, of many galaxy deformations observed in the Local Group, only perhaps the Magellanic Stream (e.g., Gardiner & Noguchi 1996; Lin et al. 1995) and the elongated dwarf galaxy Sgr I (see below) are reasonably well understood. We still do not know the exact causes of the Milky Way's and M33's warps, M31's misaligned bulge, or NGC 205's tidal deformation.

Yet, the eight years since the Heidelberg meeting (Wielen 1990) have brought considerable progress in our general understanding of tidal interactions. Foremost perhaps is a steadily growing appreciation of the many phenomena associated with gas transport and induced star formation, as discussed briefly in §5 below and at length in the reviews by Kennicutt, Schweizer, & Barnes (1998). And certainly a high point has been the discovery of the Sagittarius dwarf, hitherto hidden behind the Milky Way's bulge and the first clear case of accretion observed in our own galaxy (Ibata et al. 1995). This apparently disintegrating companion strongly supports the hypothesis that our halo formed gradually from accreting fragments (Searle & Zinn 1978).

The ability of the *Very Large Array* to now routinely map the H I kinematics of interacting galaxies is rejuvenating the study of these systems.

Because tidal bridges and tails form from the gas-rich outskirts of disk galaxies, they contain H I along their full optically visible extent and often significantly beyond (Hibbard et al. 1994; Hibbard & van Gorkom 1996). The resulting velocity maps contain a wealth of optically inaccessible information and yield kinematic constraints that are invaluable for modeling these systems through N-body simulations (e.g., Hibbard & Mihos 1995). Even the tail lengths alone constrain the ratio of dark to luminous matter in disk galaxies to $M_{\rm d}/M_{\rm l} \lesssim 10$ (Dubinski et al. 1996; Mihos et al. 1998). In the long run, detailed modeling of interacting systems with mapped H I kinematics should yield not only this ratio for individual galaxies, but also the radial variation of it.

Evidence continues to grow that some dwarf galaxies form in tidal tails, as originally proposed by Zwicky (1956). Major clumps of stars and gas have been found in many tails by now (Mirabel et al. 1991; Duc & Mirabel 1994; Hunsberger et al. 1996), and two of these clumps have been shown to probably be self-gravitating entities from their measured H I velocity dispersions (Hibbard et al. 1994).

Many issues remain to be addressed. For example, despite assiduous work by observers and numerical simulators alike, we still do not have any fully successful models for the tidally generated spiral structures of M51 and M81. A new puzzle are the observed displacements between the stars and HI in some tidal tails, occasionally exceeding 2 kpc and perhaps reflecting non-gravitational forces acting upon the gas (Hibbard & van Gorkom 1996; Schiminovich et al. 1995). Finally, although there are many new observations of collisional ring galaxies (for a review, see Appleton & Struck-Marcell 1996), none have addressed yet the interesting issue of the nature of ring-galaxy remnants: Into what kind of galaxies do they evolve?

3. Mergers and the Formation of Ellipticals

The essence of this subject can be encapsulated in the following three questions: (1) What fraction of elliptical galaxies formed via major disk–disk (DD) mergers? (2) Did cluster ellipticals form via such DD mergers, via multiple minor mergers, or in a single collapse? And (3), what is the age distribution of elliptical galaxies?

There is now strong evidence that at least some DD-merger remnants are present-day protoellipticals, as envisaged by TT. My own two favorites are NGC 3921 and NGC 7252. Both feature double tidal tails, but single main bodies of $M_{\rm V} \approx -23$ with $r^{1/4}$-type light distributions indicative of violent relaxation (Schweizer 1996, 1982). Their power-law cores, central luminosity densities, and *UBVI* color gradients are typical of ellipticals, and their central velocity dispersions fit the Faber–Jackson relation for

E's well (Lake & Dressler 1986). Their "E + A" spectra indicate recent ($\lesssim$1 Gyr ago) starbursts of strength $b \approx 10\%$–30%. During these major starbursts, the globular-cluster populations appear to have increased by $\gtrsim$40% in NGC 3921 (Schweizer et al. 1996) and $\sim$80% in NGC 7252 (Miller et al. 1997). Within 5–7 Gyr, both remnants will have specific globular-cluster frequencies typical of field ellipticals. Therefore, in all their observed properties these two remnants appear to be 0.5–1 Gyr old protoellipticals.

A notable success has been the observational confirmation of the theoretical prediction by Barnes (1988) that most of the tidally ejected material must fall back. This phenomenon creates a strong connection between DD mergers and field ellipticals. In NGC 7252, and likely also in NGC 3921, the H I in the lower parts of the tails is observed returning toward the central remnant (Hibbard et al. 1994; Hibbard & Mihos 1995; Hibbard & van Gorkom 1996). It seems hardly coincidental, then, that many E and S0 galaxies feature inclined gas disks (van Gorkom & Schiminovich 1997), H I absorption in radio ellipticals always indicates infall (van Gorkom et al. 1989), and some well-known E and S0 galaxies like NGC 5128, NGC 1052, and NGC 5266 possess *two*, often nearly orthogonally rotating, H I disks (Schiminovich et al. 1994; Plana & Boulesteix 1996; Morganti et al. 1997). There can be little doubt that at least these kinds of field galaxies formed through major DD mergers.

Observations of fine structure in field E and S0 galaxies suggest that not just a few, but *most* of these galaxies formed through that same mechanism (Schweizer & Seitzer 1992). Roughly 70% of the E's and over 50% of the S0's show fine structure (mainly ripples and plumes) indicative of past disk mergers, and recent *N*-body simulations demonstrate that this fine structure is a natural byproduct of tidal material falling back after a major merger (Hernquist & Spergel 1992; Hibbard & Mihos 1995). Photometry of these structures suggests that there is more luminous matter in them than can be accounted for by the proverbial "gas-rich dwarf" that supposedly fell in (Prieur 1990). Therefore, given the high detection rates of fine structure and the limited duration of a significant flux of returning material ($\lesssim$5 Gyr), it seems now likely that the vast majority, and perhaps all, field E and S0 galaxies formed through DD mergers.

For cluster ellipticals the situation is less clear because they are poorer in H I and fine structure. Yet, there are at least three arguments to support the view that these ellipticals formed through DD mergers as well. First, cluster ellipticals are structurally indistinguishable from field ellipticals, for which the evidence for past DD mergers is strong. Second, many cluster ellipticals possess oddly rotating stellar cores, which seem to form naturally in DD mergers (Hernquist & Barnes 1991; Bender 1996) and point toward two, rather than multiple, merged components. And third, the bimodal
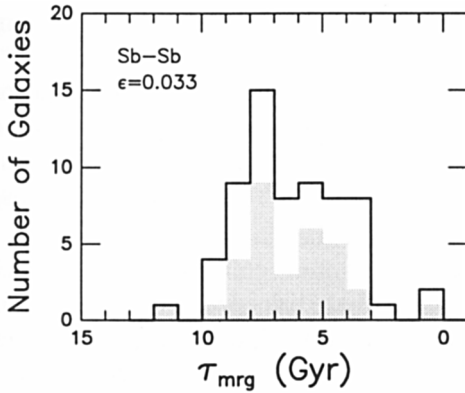
Figure 1. Distribution of merger ages for 65 field E + S0 galaxies. Ellipticals are shaded, age "0" marks present time. Ages are computed for presumed Sb–Sb mergers with star-formation efficiency $\epsilon = 0.033$. Note prolonged period of E + S0 formation suggested by these ages. After Schweizer & Seitzer (1992).

color distributions of globular clusters in cluster ellipticals like M87 and M49 (Whitmore et al. 1995; Geisler et al. 1996) imply a second major cluster-forming event, probably a merger (Ashman & Zepf 1992). Although the remarkably small scatter in the color–luminosity relations of cluster E and S0 galaxies is often taken as evidence against major DD mergers, it may simply be a natural consequence of such mergers having taken place in clusters relatively early (see §6).

If ellipticals did form through delayed DD mergers (Toomre 1977), their formation ages should show a wide spread. The evidence for a significant age spread is increasing, despite the fact that ages of individual E's remain uncertain and often controversial (O'Connell 1980, 1994; Schweizer & Seitzer 1992; González 1993; Faber et al. 1995; Davies 1996). One problem lies in the different possible definitions of "age." In an elliptical galaxy, one must distinguish at least three ages: (1) the true mean age $\langle \tau_* \rangle$ of the stars, (2) the luminosity-weighted mean age $\langle \tau_* \rangle_{\mathrm{lum}}$ of stars, which is what observers using *single*-burst population models for interpretation typically measure, and (3) the merger age τ_{mrg}, reckoned since the merger began or the starburst peaked. In general, $\langle \tau_* \rangle > \langle \tau_* \rangle_{\mathrm{lum}} > \tau_{\mathrm{mrg}}$. Figure 1 shows merger ages for 65 E and S0 galaxies based on *UBV* colors and a simple *two*-burst model of star formation. These formation ages spread over most of the age of the universe. The above model and Kauffmann's (1996) similar calculations also clarify why age-dating ellipticals from spectra is difficult: Because the bulk of stars formed before the final mergers, ellipticals *look* more uniform and old than they really are.

In summary, the combined evidence from low-z observations strongly indicates that *there was no single "epoch of E formation" at $z \gtrsim 2$*, as some have inferred from high-z observations. Instead, this evidence favors the view that E and S0 galaxies continue forming to the present and will do so into the future.

4. Mergers in Disk Galaxies

Although equal-mass mergers are the most spectacular, there must also be unequal-mass ("minor") mergers that affect disk galaxies without completely destroying their disks. Three central questions are: (1) Can bulges form through minor mergers? (2) What fraction of bulges formed in this manner? And (3) how fragile are galaxy disks?

Theoretical work on the fragility of disks is undergoing rapid revisions. As recently as 1992, Tóth & Ostriker argued that disks are very fragile and would be disrupted by any infalling companion more than a few percent the mass of the main disk. Yet, N-body simulations suggest that disk galaxies can survive minor mergers of up to $m/M \approx 0.3$, albeit with increases in bulge mass and a thickened disk (Walker et al. 1996).

Recent observations suggest that the effects of minor mergers on disk galaxies can be surprisingly complex. For example, S0 galaxies with polar rings were thought to have accreted their ring gas during a merger. Yet, new observations show that the H I content of polar rings is often large and typical of late-type disk galaxies, and that many of the S0's feature poststarburst spectra (e.g., Richter et al. 1994; Reshetnikov & Combes 1994). Thus it looks as if it is the central S0 galaxies (rather than the polar rings) that may have formed from a gas-rich companion falling into a spiral galaxy nearly over its poles. If so, these central S0 bodies represent *failed bulges* (Schweizer 1995; Arnaboldi et al. 1997).

Various observations suggest that quite in general early-type disk galaxies may be the remnants of minor mergers. From the statistics of counter-rotating, skewedly rotating, and corotating ionized gas disks, one can conclude that 40%–70% of all S0 galaxies experienced minor mergers (Bertola et al. 1992). The phenomenon of counterrotating gas disks is observed— with decreasing frequency—into Hubble types S0/a, Sa, and Sab.

Another powerful kinematic signature of past mergers are subpopulations of stars counterrotating in disk galaxies of types S0 – Sb. The best known example of this phenomenon occurs in NGC 4550, an E/S0 galaxy with half of its disk stars rotating one way and the other half the other way (Rubin et al. 1992). In the Sa galaxy NGC 4138, the split between normal- and counterrotating disk stars is 75/25% (Jore et al. 1996), while in the Sb galaxy NGC 7217 it is 70/30% (Kuijken 1993). Finally, the whole bulge seems to counterrotate to the disk in the well-known Sb galaxy NGC 7331 (Prada et al. 1996). Some first N-body simulations suggest that minor and not-so-minor dD mergers can indeed produce the counterrotations observed in these systems (Thakar et al. 1997; Pfenniger 1998).

A connection between mergers in disk galaxies and bulge formation is also suggested by fine structure indicative of past mergers observed in

many S0 and Sa galaxies (Schweizer & Seitzer 1988). Even NGC 4594, the "Sombrero," sports a faint fan of luminous material and an opposite tail signaling a not too ancient merger (Malin & Hadley 1997). Our present understanding of the effects of mergers on disk galaxies is then as follows.

Minor mergers do occur in disk galaxies and seem to move them toward earlier Hubble types. It appears that disks, especially those with a significant fraction of gas, are not nearly as fragile as thought just a few years ago. However, we must remember that bulgeless (e.g., M33) and lopsided disk galaxies do constrain the rate of minor mergers. For mergers of $m/M \approx 0.1$, this rate is estimated to be $\lesssim 0.07 - 0.25$ events/Gyr (Zaritsky & Rix 1997). At present, we can merely state that the fraction of bulges built through mergers is clearly >0, but its value remains unknown. A challenge for the future is to determine how unique or varied the possible paths to, say, a present-day Sb galaxy are. Does the disk form first or the bulge, and can each grow episodically and perhaps even by turns?

5. Interaction-Induced Processes

The *IRAS* sky survey opened our eyes to the fact that gas plays a disproportionately large role in interacting and merging galaxies. Due to lack of space, I can here only briefly sketch recent progress in our understanding of the four major interaction-induced processes.

Interaction-induced *starbursts* are fierce episodes of "galaxy building," during which 5%–20% of the luminous matter gets converted from gas into stars over periods of $\sim 10^8$ years. Fueled by molecular gas in quantities of up to $\sim 2 \times 10^{10}\, M_\odot$, these starbursts appear to be self-limiting: the star-formation rate does not exceed $\sim 0.7\, M_\odot\, \mathrm{kpc}^{-2}\, \mathrm{yr}^{-1}$ for stars of 5–100 $M_\odot$. Merger-induced torques tend to drive gas toward the center, where high concentrations of it often dominate the dynamics. These induced concentrations may explain the high central phase-space densities observed in E's.

Globular-cluster formation appears to be a natural by-product of induced starbursts (e.g., NGC 4038/39, 7727, 3921, 7252, 5128, 1275). There is growing evidence that the globulars may form preferentially in high-pressure regions from Giant Molecular Clouds shocked by the surrounding starburst-heated gas. Even at $z \approx 0$, gas-rich DD mergers can apparently about double the number of globular clusters.

Galactic winds are radial 10^2–$10^3\, \mathrm{km\, s}^{-1}$ outflows of gas heated mostly by starburst supernovae. These winds appear "mass loaded" by factors of 3–6. In M82, the Fe-rich wind is estimated to eject $\sim 10^8\, M_\odot$ of gas into the halo over 20–30 Myr. Such winds presumably played a major role in the chemical evolution of early-type galaxies, but details remain unclear.

Nuclear activity often accompanies merger-induced gas inflows. Obser-

vationally, assessing the relative contributions from active galactic nuclei and central starbursts remains a challenging task. About 80% of all host galaxies of low-z QSOs appear to be interacting and 30% appear to be merging. There is evidence that the QSO activity tends to peak shortly before the nuclei of two galaxies merge, and in at least the case of OX 169 the variable Hβ emission-line components suggest the presence of *two* separate engines (Stockton & Farnham 1991).

6.   Interactions and Mergers in Clusters

Clusters are complex environments for galaxy evolution. Two properties of cluster galaxies have led to major questions. First, is the morphology–density relation (Oemler 1974; Dressler 1980) a result of birth or evolution? And second, is the Butcher-Oemler (1978, 1984) effect mainly due to ram-pressure stripping or interactions and mergers? Many astronomers have doubted whether galaxies in clusters can merge because of their high mean relative velocities. If not, why are there so many E + S0 galaxies in clusters?

Yet, there has long been observational evidence for interactions and mergers in clusters, and recently this evidence has grown stronger.

For example, the Hercules Cluster abounds in pairs of interacting disks. The Coma Cluster harbors the well-known DD merger NGC 4676 (TT; Barnes 1998) in its outskirts. And in the Virgo Cluster, systems like NGC 4438/35 show that even $\sim 10^3$ km s^{-1} collisions can strongly affect member galaxies (Combes et al. 1988; Kenney et al. 1995). Clearly, strong tidal interactions and mergers occur in clusters to the present time.

Mergers must have played a major role in shaping the E and S0 galaxies of the Virgo Cluster, especially the most massive ones (as judged by their having Messier numbers). Many of these galaxies feature oddly rotating subsystems (M86, NGC 4365, NGC 4550), ripples (M85, M89), and bimodal globular-cluster populations (M49, M87), all signatures of past disk mergers. This confirms predictions of N-body simulations which have long suggested that "the upper end of the mass spectrum is most strongly affected by the merging process occurring predominantly during the expansion and subsequent collapse of the cluster" (Roos & Aarseth 1982).

There is also growing evidence for interactions and mergers in clusters at $z \approx 0.2$–0.5. Even before the advent of *HST*, groundbased observations suggested that many blue galaxies in Butcher-Oemler clusters are distorted disks or feature excess companions (Lavery & Henry 1988–1994). Observations with *HST* show that a fair fraction of these galaxies are interacting or merging while a majority appear to be disturbed gas-rich disks (Dressler et al. 1994; Couch et al. 1994; Barger et al. 1996). Perhaps the most interesting recent result is that at $z \approx 0.4$ the E population appears to be fully

in place, while there are significantly fewer S0 galaxies and more late-type spirals and Irregulars than at $z \approx 0$ (Oemler et al. 1997).

I believe that a viable scenario for the formation of E and S0 galaxies in clusters is as follows. Major DD mergers occurred relatively early because the dynamical friction is strongest for equal-mass galaxies. These mergers formed the bulk of the ellipticals. Minor mergers took longer on average because of their lesser dynamical friction (deceleration being approximately proportional to mass). They—and perhaps also multiple interactions— slowly transform spirals into S0 galaxies. Presumably, it is the evolving substructure of clusters that allows mergers to occur to the present time.

Finally, field galaxies experienced the same processes, but on a longer time scale because of their lower spatial density. This is why we still see ellipticals forming (NGC 3921, NGC 7252, ULIR galaxies) and why there are fewer S0 galaxies and more spirals in the field than in clusters. If this cluster- and field-evolution scenario is correct in its essence, Hubble's morphological sequence may rank galaxies mainly by the number and mass ratio of mergers in their past history.

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