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Gravitational interactions and mergers are shaping and reshaping galaxies throughout the observable Universe. While observations of interacting galaxies at low redshifts yield detailed information about the processes at work, observations at high redshifts suggest that interactions and mergers were much more frequent in the past. Major mergers of nearby disc galaxies form remnants that share many properties with ellipticals and are, in essence, present-day proto-ellipticals. There is also tantalizing evidence that minor mergers of companions may help build bulges in disc galaxies. Gas plays a crucial role in such interactions. Because of its dissipative nature, it tends to get crunched into molecular form, turning into fuel for starbursts and active nuclei. Besides the evidence for ongoing interactions, signatures of past interactions and mergers in galaxies abound: tidal tails and ripples, counter-rotating discs and bulges, polar rings, systems of young globular clusters, and ageing starbursts. Galaxy formation and transformation is clearly a prolonged process, occurring up to the present-day. Overall, the currently available observational evidence points towards Hubble's morphological sequence being mainly a sequence of decreasing merger damage.

Keywords: galaxy interactions; mergers; elliptical formation; bulge formation; starbursts; quasars

1. Introduction

Ever since Hubble (1936) published his famous 'sequence of nebular types' (also known as the tuning-fork diagram), the question has been: what determines the position of a galaxy along this sequence? And why are galaxies at one end of the sequence disc shaped and at the other end ellipsoidal? Was this shape dichotomy imprinted during an early collapse phase of galaxies, or did it arise through subsequent evolution?

Work begun several decades ago by Zwicky (1956), Arp (1966), Alladin (1965) and Toomre & Toomre (1972), among others, has led to growing evidence that gravitational interactions between neighbouring galaxies not only explain some of the most striking 'bridges' and 'tails' observed in disturbed galaxy pairs, but also tend to lead to galactic mergers that often trigger bursts of star formation and clearly represent important phases of galaxy building (Larson 1990; Barnes & Hernquist 1992; Kennicutt *et al.* 1998).

Before reviewing some of the evidence that suggests that interactions and mergers are a significant driver of galaxy evolution, it seems wise to agree on some terminology and point out biases.

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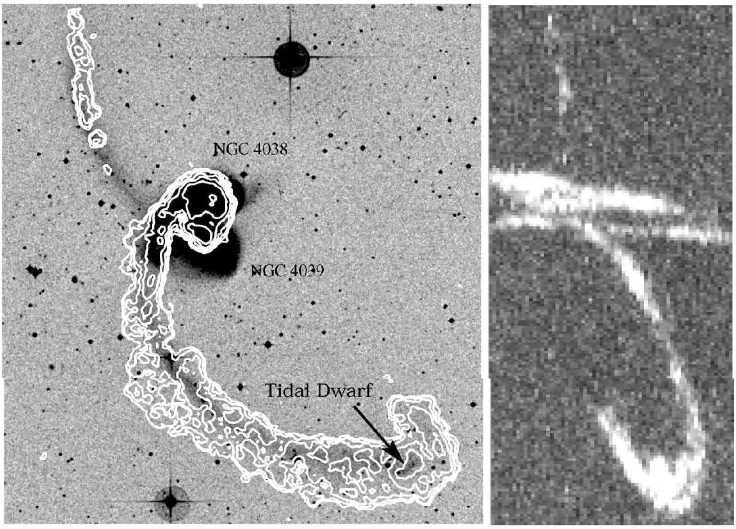

Figure 1. Neutral hydrogen distribution and kinematics of NGC 4038/4039. (Left) HI contour lines (white) superimposed on an optical photograph. (Right) HI position–velocity plot, with declination along y-axis and line-of-sight velocity along x-axis (from Hibbard 2000).

To be called a 'merger', a galaxy pair or single galaxy should at least show clear morphological signatures of an advanced tidal interaction, such as significant distortions, major tails, and ripples or 'shells' (see Schweizer (1998) for a review). A stronger case for merging can usually be made when *kinematic* signatures are also available, such as opposite tail motions, counter-rotating parts, or tail material falling back onto a remnant. As figure 1 illustrates, much recent progress in this area is due to the ability of the upgraded *Very Large Array* to map the line-of-sight motions of neutral hydrogen (HI) in tidal features in great detail (Hibbard 2000).

The main bias in studies of gravitational interactions has been towards major mergers, which involve two galaxies of nearly equal mass. Such mergers are highly destructive and tend to lead to spectacular morphologies, whence they can be observed from the local Universe out to redshifts of $z \approx 2$ and beyond. Minor mergers involving galaxies with mass ratios of, say, $m/M = 0.1$–0.5, are less spectacular and often require verification via some kinematic signature (especially in the remnant phase). Hence, such interactions and mergers have been studied mainly in nearby galaxies and out to $z \lesssim 0.5$. Finally, although satellite accretions leading to mass increases of a few per cent or less may be relatively frequent, they are the most difficult to detect and have been studied only in the 'Local Group', and even there nearly exclusively in our Milky Way Galaxy. Thus, our knowledge of growth through accretions and minor mergers is severely limited.

Because of its dissipative nature, gas plays a disproportionately large role in galaxy interactions. Even at the present epoch, the vast majority of galaxies contain significant amounts of cold gas (Roberts & Haynes 1994). During tidal interactions and mergers this gas tends to be driven towards the centres of galaxies through gravitational torques exerted on it by tidally induced *stellar* bars (see, for example, Barnes & Hernquist 1996). The ensuing shocks and energy dissipation allow the gas to get compressed, leading to intense bursts of star formation, globular-cluster formation, and the feeding of nuclear activity. Starbursts and active galactic nuclei in turn drive galactic winds and jets, which can have profound effects on the chemical evolution of galaxies (Heckman, this issue).

Some of these processes can now be reproduced by modern N-body simulations that include gas hydrodynamics. Barnes (1999) shows a beautiful sequence of two gas-rich disc galaxies merging. Whereas their stars end up in a three-dimensional pile not unlike an elliptical galaxy with considerable fine structure, more than half of the cold gas from the input discs gets funnelled to the centre of the remnant into a region only *ca.* 0.5 kpc in diameter, while the initially warm gas ($T \approx 10^4$ K) gets heated to X-ray temperatures (*ca.* 10^6 K) and forms a pressure-supported atmosphere with similar dimensions to the stellar pile. The time-scale for this transformation from two disc galaxies to one merged remnant is remarkably short: about 1.5 rotation periods of the input discs, or, when scaled to component galaxies of Milky Way size, *ca.* 400 Myr.

The rapidity of this equal-mass merger is due to strong dynamical friction. We should keep this in mind when trying to understand the formation of elliptical galaxies in dense environments. Claims have been made that cluster ellipticals formed in a rapid monolithic collapse because their present-day colours are rather uniform. Yet, experts agree that age differences of $\lesssim 3$ Gyr cannot be discerned from the broad-band colours of galaxies 10–15 Gyr old. A time interval of 3 Gyr may seem short when we struggle with logarithmic age estimates, yet it is long when compared with the merger time-scale. About eight major mergers of the kind simulated by Barnes (1999) could take place one after another during this time-interval, and 12 Gyr later all their remnants would appear nearly the same colour and age. Hence, claims about monolithic collapses and a single epoch of elliptical formation are to be taken with a pinch of salt. There was time for many major mergers of juvenile discs during the first few Gyr after the Big Bang, and most cluster ellipticals could have formed through such mergers without us knowing it from their present-day colours.

The following review of evidence for interactions being a driver of galaxy evolution begins with accretions in the 'Local Group', continues with minor mergers and the damage they inflict on disc galaxies, moves on to major mergers forming ellipticals from wrecked discs, and ends with a brief description of what we have learned from first glimpses of high-redshift mergers.

2. Interactions in the 'Local Group'

There are many signs of recent or ongoing gravitational interactions in the Local Group, including the warped discs of the Milky Way, M 31, and M 33, the Magellanic Stream, and the integral-sign distortion of NGC 205, companion to M 31. However, the details of these interactions are often difficult to establish, and the cumulative effect of interactions not directly leading to mergers remains largely unknown.

Fortunately, there is now—in the Milky Way—some good, detailed evidence for interactions leading to accretions. Three pieces of evidence stand out as particularly reliable among the many that have been claimed.

First and most impressive is the Sagittarius dwarf galaxy, hidden from us behind the Milky Way bulge until its recent discovery by Ibata *et al.* (1994). Located at a distance of 16 kpc from the galactic centre, this dwarf appears very elongated in a direction approximately perpendicular to the galactic plane and is thought to move in a nearly polar orbit with current perigalactic and apogalactic distances of *ca.* 20 kpc and *ca.* 60 kpc, respectively (Ibata & Lewis 1998). Although it may have started out with a mass of as much as $10^{11} M_\odot$ or as little as *ca.* $10^9 M_\odot$ (Jiang & Binney 2000), the dwarf is estimated to currently have a mass of 2×10^8–$10^9 M_\odot$ and an orbital period of *ca.* 0.7–1 Gyr. It will probably disrupt completely over the next few orbits and will then deliver its four globular clusters, one of which appears to be its nucleus (see, for example, Da Costa & Armandroff 1995), to the halo of the Milky Way.

As Searle & Zinn (1978) conjectured, similar accretions of gas fragments and dwarfs may have built this halo over a prolonged period. A second piece of evidence strongly supporting this view is the observed retrograde mean motion of certain subsystems of globular clusters (Rodgers & Paltoglou 1984; Zinn 1993). How could a monolithic collapse possibly have led to a 15% minority of slightly younger halo globulars orbiting in the opposite sense from the majority of old globulars and the disc itself? Accretions from different directions provide a natural explanation.

Most accretions into the halo must have occurred in the first 25–30% of the age of our Galaxy. Colours and inferred minimum ages of halo stars suggest that by 10 Gyr ago such accretions had diminished to a trickle, and since then $\lesssim 6$ Sagittarius-like dwarfs could have been accreted (Unavane *et al.* 1996). Hence, the ongoing accretion of Sgr Dwarf is by now a relatively rare event.

However, a much more massive accretion may still lie in the future. This is suggested by the Magellanic Stream, the third piece of good evidence for a relatively strong interaction involving the Milky Way. This stream of HI extends over 120° in the sky, arching from the Magellanic Clouds through the South Galactic Pole to declination $-30°$, where it was first discovered (Dieter 1965; Mathewson *et al.* 1974). After a long and tortuous history of interpretations, modern models based on a past gravitational interaction between the Large Magellanic Cloud–Small Magellanic Cloud (LMC–SMC) system and the Milky Way are now reasonably successful at explaining the observed morphology of the stream, the high approach velocities near its end, and the existence of a counter-stream on the other side of the Clouds (see, for example, Gardiner & Noguchi 1996). According to such models, the stream and counter-stream represent a tidal tail and bridge drawn from the outer gas disc of the SMC during a close passage to the Milky Way *ca.* 1–1.5 Gyr ago. The prediction is that the LMC–SMC binary will soon break up and the more massive LMC will be the first to merge with the Milky Way in *ca.* 7–8 Gyr (Lin *et al.* 1995).

The LMC's mass is *ca.* 4% of that of the Milky Way, and its visual luminosity twice that of the entire halo. Hence, this future accretion will be a major event, at least an order of magnitude more massive and spectacular than the ongoing Sgr Dwarf accretion. Our descendants can expect significant halo growth, induced star formation, and probably also a thickening of the present thin disc of the Milky Way.

The main message from the above evidence is that—even though most accretions in galaxies outside the Local Group are difficult to detect—they must have occurred primarily early ($z \gtrsim 2$) and must have contributed significantly to the growth and perhaps even morphology of many disc galaxies similar to ours and M 31.

3. Damaged discs

Between small accretions that barely affect disc galaxies and major mergers that wreck discs there must be intermediate-strength interactions and minor mergers that

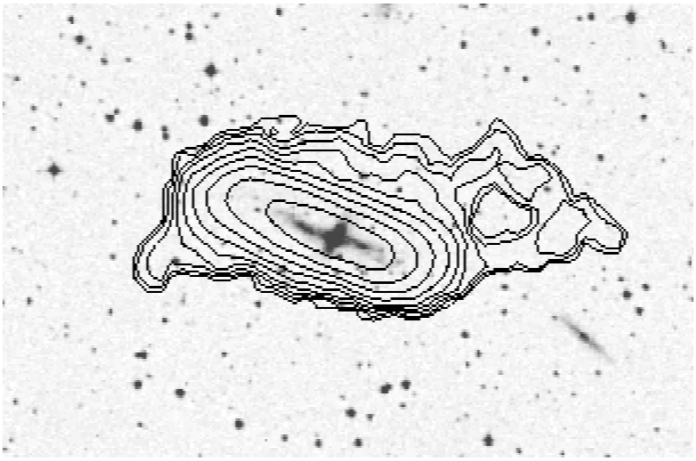

Figure 2. Neutral hydrogen distribution of NGC 4650A, a S0 galaxy with a 'polar ring'. The HI contours are superposed on an optical image of the galaxy (from Arnaboldi *et al*. 1997).

significantly affect discs yet do not destroy them. This immediately suggests three questions:

(1) How fragile are galaxy discs?

(2) Can bulges form through minor mergers?

(3) If so, what fraction of bulges formed in this manner?

Early theoretical worries that accretions of even only a few per cent in mass might disrupt discs (Tóth & Ostriker 1992) have been dispelled by N-body simulations showing that model disc galaxies do survive minor mergers with mass ratios of up to $m/M \approx 0.3$, albeit tilted, warped, slightly thickened, and often with an increased bulge (Walker *et al*. 1996; Huang & Carlberg 1997; Velázquez & White 1999). Hence, galaxy discs are apparently less fragile than once thought, a fact also suggested by observations.

First, note that optical images are not always a reliable indicator of tidal interactions, as the case of M 81 illustrates. Even when displayed at high contrast such images of M 81 paint a rather serene scene of a symmetric grand-design spiral. Yet, the HI distribution is highly asymmetric and dominated by long tidal features whose kinks reveal a strong triple interaction between M 81, NGC 3077, and M 82 (see Yun *et al*. (1994), especially the cover page). M 81 has not only survived this interaction, but probably owes its beautiful spiral structure to it (Toomre & Toomre 1972).

Second, S0 galaxies with polar rings of gas, dust, and young stars increasingly suggest that especially gas-rich discs may well survive minor mergers occurring from near-polar orbits. Such S0 galaxies were long thought to have accreted their ring gas during a fly-by or minor merger (see, for example, Toomre 1977; Schweizer *et al*. 1983). Yet, many of the S0 bodies feature post-starburst spectra, and HI observations show that the gas contents of the polar rings tend to be large and typical of full-grown late-type spirals (Richter *et al*. 1994; Reshetnikov & Combes 1994; Arnaboldi *et al*. 1997), as illustrated in figure 2. Thus it appears that the central S0 galaxies may be remnants of disc companions having fallen into spiral galaxies—now polar rings—nearly over their poles (Bekki 1998). If so, these central S0 bodies represent failed bulges. The crucial point is that two disc systems of not too dissimilar mass apparently *can* survive a merger and—helped by gaseous dissipation—retain their disc identity.

Disc galaxies survive even non-polar minor mergers, as evidenced by a multitude of kinematic signatures. For example, the Sab galaxy NGC 4826 has a gas disc consisting of two nested counter-rotating parts, each of nearly equal mass (Braun *et al*. 1994). The inner component rotates like the stellar disc and bulge, while the outer component counter-rotates (Rubin 1994). The two comparable gas masses suggest that the intruder galaxy was not a mere dwarf a few per cent in mass, but a more massive companion leading to a minor merger.

Whereas similar kinematic signatures are rare among Sb galaxies, they are more frequent among Sa galaxies and nearly the norm among S0 galaxies. From the statistics of counter-rotating, skewedly rotating, and corotating ionized-gas discs one can conclude that at least 40–70% of all S0 galaxies experienced minor mergers (Bertola *et al*. 1992). The fact that the frequency of kinematic signatures of past mergers increases with bulge size strongly suggests that at least major bulges formed through mergers.

Another powerful merger signature correlating with morphological type is the subpopulations of stars counter-rotating in disc galaxies of types S0 to Sb. A well-known example is the E/S0 galaxy NGC 4550, in which half of the disc *stars* rotate one way and the other half rotate the opposite way (Rubin *et al*. 1992). In several Sa and Sb galaxies the split between normal- and counter-rotating disc stars is of the order of 70/30%. Finally, a bulge rotating at right angles to the stellar disc has been observed in the Sa galaxy NGC 4698 (Bertola *et al*. 1999), and bulges counter-rotating to the discs are seen in the Sb galaxies NGC 7331 and NGC 2841 (Prada *et al*. 1996, and F. Prada, personal communication; also see Bottema 1999). N-body simulations suggest that minor and not-so-minor mergers can indeed produce such odd rotations (Thakar & Ryden 1998; Balcells & González 1998).

In short, galactic discs—especially those rich in gas—appear not nearly as fragile as thought only a few years ago. Both observations and numerical simulations suggest that minor mergers do occur in disc galaxies and contribute to bulge building. However, we do not know the exact fraction of bulges that were built in this manner. Also unclear is how unique or varied the possible paths to, say, a present-day Sb galaxy are. Which formed first: the disc or the bulge? And did discs and bulges grow episodically, perhaps even by turns?

4. Ellipticals from wrecked discs

The notion that galaxy collisions are highly inelastic (Alladin 1965) and lead—via dynamical friction and orbital decay—to mergers (Toomre & Toomre 1972) is now well supported by both N-body simulations and observations (see, for example, Barnes 1998). Major mergers clearly do wreck discs and can form giant ellipticals, as first proposed by Toomre & Toomre (1972). What remains controversial is whether *most* ellipticals formed in this manner, and whether those in clusters formed in a systematically different way from those in the field. As described below, there is growing evidence that most giant ellipticals did indeed form through major mergers, and that this occurred earlier on average in clusters than in the field.

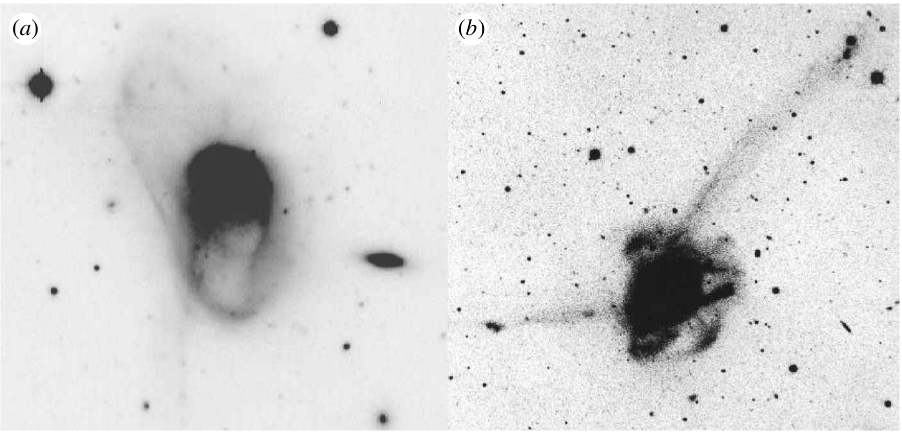

Figure 3. Two recent merger remnants, NGC 3921 (*a*) and NGC 7252 (*b*), with properties marking them as present-day proto-ellipticals (from Schweizer 1996, 1982).

First, the evidence is strong that remnants of *recent* equal-disc mergers are present-day proto-ellipticals. The main theoretical advance has been the inclusion of dark-matter halos and gas in the N-body simulations, leading to efficient mechanisms for outward angular-momentum transport and central density increases (Barnes 1988; Barnes & Hernquist 1996). The model remnants are generally triaxial, violently but incompletely relaxed, and lack rotational support. Their projected isophotes, which are determined mainly by the inclinations of the progenitor discs and the viewing geometry, can range from boxy through boxy-and-discy to rather strongly discy, as observed in real E and E/S0 galaxies (Barnes 1992; Heyl *et al*. 1994). Observationally, recent merger remnants such as NGC 3921 and NGC 7252 (figure 3) feature pairs of tidal tails but single main bodies with relaxed, $r^{1/4}$-type light distributions (Schweizer 1982, 1996; Stanford & Bushouse 1991). Their power-law cores, central luminosity densities, velocity dispersions, and radial colour gradients are typical of giant ellipticals (Lake & Dressler 1986; Doyon *et al*. 1994). Major starbursts, reflected in the integrated-light spectra and in major populations of young star clusters, seem to have converted 10–30% of the visible mass into stars and have nearly doubled the number of globular clusters. Therefore, in all their observed properties such remnants appear to be $\lesssim 1$ Gyr old proto-ellipticals.

Second, recent remnants of disc–disc mergers display several phenomena that connect them also to much older ellipticals. Foremost among these phenomena is the return of tidally ejected material. Model simulations including the effects of massive dark halos predict that most of the matter ejected by two merging discs into tails remains bound and must eventually fall back onto the merger remnant (Barnes 1988). This infall is observed in the HI gas near the base of the tails of NGC 7252 and NGC 3921 (Hibbard *et al*. 1994; Hibbard & van Gorkom 1996) and is presumably shared by the stars. Interestingly, HI absorption in radio ellipticals invariably indicates gas infall (van Gorkom *et al*. 1989). Infalling stars also yield a natural explanation for many of the faint ripples (‘shells’) and plumes observed in elliptical galaxies. As dynamically cold streams of stars fall back into the remnants, they wrap around the centre and form sharp-edged features at their turnaround points (Hernquist & Spergel 1992; Hibbard & Mihos 1995). The high percentage (*ca.* 70%)

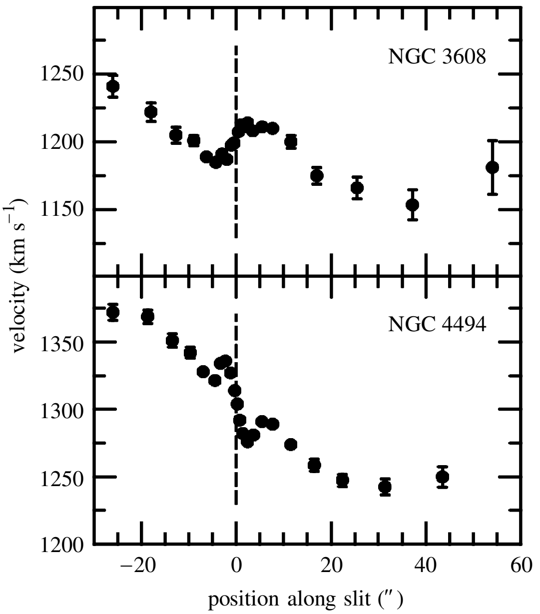

Figure 4. Oddly rotating cores in two elliptical galaxies. Mean stellar velocities are shown as a function of position along major axes. Note counter-rotating core of NGC 3608 and corotating, but kinematically distinct core of NGC 4494 (Jedrzejewski & Schechter 1988).

of field ellipticals featuring such fine structure (Schweizer & Seitzer 1992) and the considerable amounts of material indicated by integrated photometry (Prieur 1990) suggest that most of the observed fine structure cannot be due to mere dwarf galaxies falling in. Instead, such structure is much more likely to be the signature of past major mergers that formed most, or even all, ellipticals.

Third, various unexpected kinematic signatures in giant ellipticals also point towards past mergers of gas-rich discs. About a quarter of all ellipticals show oddly rotating cores, some rotating in the opposite sense of the main body, others at right angles, and still others in the same sense but much faster (figure 4). When studied in detail, such cores appear to be small discs ($r \approx 0.2$–3 kpc) indicative of gaseous dissipation (see, for example, Bender 1996; Mehlert *et al*. 1998). A similar central disc violently forming stars and probably fed by gas returning from the tails is observed in the merger remnant NGC 7252 (Wang *et al*. 1992; Whitmore *et al*. 1993). Model simulations of disc mergers reproduce such odd core rotations quite naturally (Hernquist & Barnes 1991). The existence of distinct kinematic subsystems then argues against ellipticals having assembled from many gaseous fragments and in favour of *two* input discs. Exactly the same message is conveyed by the growing number of ellipticals that—like, for example, NGC 5128 (Schiminovich *et al*. 1994)—possess *two*, often nearly orthogonally rotating, HI discs. Nearly three dozen ellipticals are now known to feature often fragmentary outer gas discs or rings whose kinematics appears decoupled from that of the main body (J. H. van Gorkom, personal communication). Given that the gaseous tails of the remnant NGC 7252 lie in mutually inclined planes, there is strong reason to suspect that these much older ellipticals acquired their outer gas through disc–disc mergers as well.

Fourth, yet another connection between disc mergers and elliptical galaxies is provided by globular star clusters. Although in nearby galaxies most such clusters appear to be very old and seem to have originated in the earliest days of galaxy formation, young globulars have recently been found to form by the hundreds in the vehement starbursts induced by major mergers. Mergers like 'The Antennae', NGC 3921, and NGC 7252 can apparently produce nearly as many young globular clusters as the combined number of old globulars in the component discs, thus approximately doubling the number of clusters in the process (Miller *et al*. 1997; Ashman & Zepf 1998). First spectroscopic evidence shows that, as one would expect, the young globulars have much higher heavy-element abundances than the old ones, being of solar 'metallicity' in the case of NGC 7252 (Schweizer & Seitzer 1998). If major mergers formed most ellipticals, one would therefore expect to find bimodal abundance distributions among their globular-cluster populations (Ashman & Zepf 1992). This is exactly what has been discovered during the past few years. Hubble Space Telescope observations show that at least half of all giant ellipticals feature bimodal cluster distributions (Gebhardt & Kissler-Patig 1999; Kundu 1999). The ratio of second- to first-generation clusters seems to typically range between 0.5 and 1, and the second-generation, metal-rich clusters tend to be more concentrated towards the centres of their host galaxies, as the merger hypothesis predicted.

Bimodal globular-cluster systems, oddly rotating cores, ripples and plumes, and fast outer-halo rotation (Bridges 1999) occur not only in field ellipticals, but also in cluster ellipticals, indicating that giant ellipticals formed via major disc–disc mergers both in the field *and* in clusters.

Merging galaxies and recent remnants show that disc wrecking is an ongoing process. If the wrecks are mainly ellipticals, the latter's ages should vary widely. Measured *UBV* colours and spectral line-strength indices suggest that this is indeed the case, with ages of field ellipticals ranging between *ca.* 2 Gyr and 12 Gyr (Schweizer & Seitzer 1992; González 1993; Faber *et al*. 1995; Davies 1996; Trager *et al*. 2000). In cluster ellipticals, the colours and line strengths vary less and the inferred ages are more uniformly old (De Carvalho & Djorgovski 1992), especially near the cluster centres (Guzmán *et al*. 1992). These observations all agree with the notion that, on average, major mergers occurred earliest in high-density regions now at the centres of rich clusters, significantly later in cluster outskirts where galaxies are still falling in, and at the slowest rate in the field.

5. High-redshift interactions

Observational evidence that interactions and mergers were more frequent in the past has trickled in since the late 1970s and has grown more rapidly since the late-1993 repair of the Hubble Space Telescope. In general this evidence agrees with expectations based on numerical simulations of hierarchical clustering in an expanding Universe dominated by dissipationless dark matter. However, quantitative observations of high-z interactions remain difficult to obtain. As we study objects from $z \approx 0.3$ to *ca.* 1.2, morphological details and kinematic signatures fade, and we are reduced to judging gross morphologies from a few pixels or simply counting galaxy pairs.

Quasars yielded some of the earliest evidence for interactions at higher redshifts ($z \gtrsim 0.2$). When near enough for details to be visible, they are often seen to occur

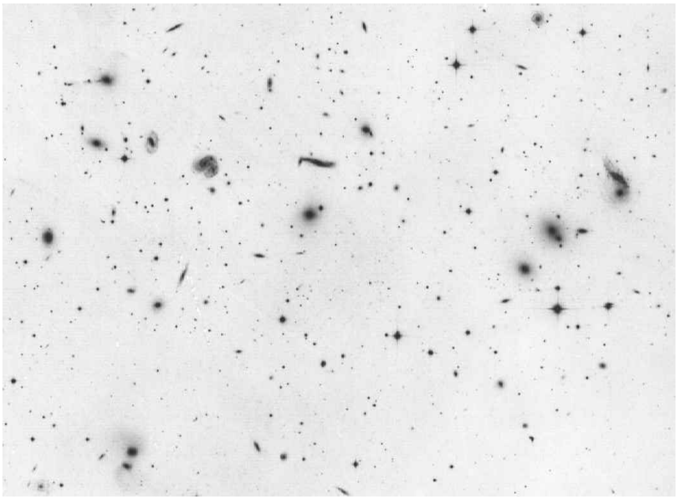

Figure 5. Galaxy interactions and mergers in Hercules cluster. Strongly interacting pair near lower left corner shows giant diffuse tails. Photograph courtesy of Alan Dressler.

in host galaxies that either have close companions or are involved in major mergers (Stockton 1990; Bahcall *et al*. 1997). The quasar OX 169, for example, features at least one tidal tail (probably a pair) and shows a variable Hβ emission-line profile indicative of *two* active nuclei (Stockton & Farnham 1991).

Of special interest is the emerging connection between quasars and infrared-luminous galaxies. At bolometric luminosities above $10^{12}L_\odot$ the so-called ultraluminous infrared galaxies (ULIG) become the dominant population in the local Universe and are 1.5–2 times as numerous as optically selected quasars. When ordered by increasing far-infrared colour temperature, ULIGs and quasars seem to form an evolutionary sequence: ULIGs with low colour temperature are starbursting disc mergers with well-separated components, warm ULIGs appear to be just completing their merging into one object, and the ‘hot’, optically visible quasars shine in peculiar ellipticals that resemble nearby merger remnants (Sanders *et al*. 1988, 1999). Nuclear separations and merger velocities indicate that the ULIG phase lasts *ca.* 200–400 Myr. Hence, extreme starbursts occurring while the nuclei merge and nuclear feeding frenzies climaxing in a quasar phase appear to be natural by-products of elliptical formation through mergers. The peak quasar activity observed around $z \approx 2$ may, then, mark the culmination of major mergers and elliptical formation.

Beyond $z \approx 2$ we have precious little *direct* evidence of interactions and merging. The radio galaxy MCR 0406–244 at $z = 2.44$ may be one of the highest redshift mergers for which there is some detailed structural information. Deep optical Hubble Space Telescope images show a double nucleus and a 30 kpc-size pair of continuum-emitting ‘tails’ suggestive of a tidal origin, while infrared images show two emission-line bubbles indicative of a strong bipolar wind (Rush *et al*. 1997; McCarthy 1999). Hence, at least some mergers at this high redshift may have been similar to local ones and involved pairs of already sizable discs.

The important role played by interactions and mergers is also becoming apparent in galaxy *clusters* of increasingly high redshifts. Despite a widely held prejudice that mergers cannot happen in clusters because of high galaxy-velocity dispersions, both theory and observations show unmistakably that strong interactions and mergers do occur there. In some local clusters ongoing interactions and mergers are obvious. In Hercules at least five major interactions and mergers are visible in the central region alone (figure 5), and even in relaxed-looking Coma 'The Mice' (NGC 4676) provide an example of a major merger occurring on the outskirts. In $z \approx 0.2$–0.5 clusters a fair fraction of the blue galaxies causing the Butcher–Oemler effect (Butcher & Oemler 1978, 1984) have been found to be interacting or merging (Lavery & Henry 1994), while a majority appear to be disturbed gas-rich discs shaken either by high-velocity encounters or minor mergers (Dressler *et al*. 1994; Barger *et al*. 1996; Oemler *et al*. 1997). Most impressive are new Hubble Space Telescope images of the rich cluster MS 1054–03 at $z = 0.83$. Fully 17% of its 81 spectroscopically confirmed members are ongoing mergers, all with luminosities similar to, or higher than, that of a L^* galaxy (van Dokkum *et al*. 1999). These mergers occur preferentially in the cluster outskirts, probably in small infalling clumps, and present 'direct evidence against the formation of ellipticals in a single monolithic collapse at high redshift'.

In order to quantitatively assess the impact of mergers on galaxy evolution, one needs to determine the merger rate (i.e. the number of mergers per unit time and comoving unit volume) as a function of redshift. We can only hope to do this for major mergers, since minor mergers are undetectable at $z \gtrsim 0.5$ and accretions are known only in the Local Group. There are many estimates of the merger rate based on counts of binary galaxies as a function of redshift, and on the assumption that most such binaries will merge in a short time. This assumption is a bit unrealistic, given that even for a much-studied interacting pair like M 51 we do not know whether the presumed merger will occur within 2, 5, or 10 Gyr. Nevertheless, taken at face value several recent estimates based on binary counts suggest a merger rate approximately proportional to $(1 + z)^{3\pm 1}$ (see, for example, Abraham *et al*. 1999), implying an order-of-magnitude increase in mergers at $z \approx 1$ compared with the local rate.

Two estimates of numbers of mergers are relatively reliable and bracket the range of likely rates. First, given that there are around 11 ongoing disc mergers among the 4000+ galaxies of the New General Catalog (NGC) and their median 'age' is *ca.* 0.5 Gyr, there should be about 250 remnants of similar mergers among NGC galaxies *if* the rate has remained constant since high redshifts, and about 750 remnants if, more realistically, the rate declined with time like $t^{-5/3}$ (Toomre 1977). Thus, nearly 20% of all NGC galaxies may be remnants of major mergers, a fraction that agrees remarkably well with the observed number of elliptical and S0 galaxies. Second, if all gas collapsed into discs and all spheroids are due to mergers, then the fractional amount of mass in spheroids—*ca.* 50% when estimated from bulge-to-disc ratios of a complete sample of nearby galaxies—provides an upper limit to the integrated effect of all mergers (Schechter & Dressler 1987). This upper limit emphasizes that at least major mergers cannot have been too frequent, or else they would have destroyed all discs. Especially in late-type, nearly pure-disc galaxies (e.g. M 33 and M 101), most of the assembly must have been gaseous, dissipative, and—after, perhaps, some initial collapse phase—involved mere accretions.

6. Conclusions

This review has highlighted the role that interactions and mergers play in driving galaxy evolution. At present we remain challenged to understand the relative importance of weak and strong interactions, the details of bulge formation, the existence of nearly pure-disc galaxies, and the merger rate as a function of redshift. Yet, some firm conclusions have been reached and are as follows.

1. Gravitational interactions and mergers are forming and transforming galaxies throughout the observable Universe. The vast majority involve gas, dissipation, and enhanced star formation.
2. The close link between mergers, ultra-luminous infrared galaxies, and quasars suggests that—like quasar activity—major merging may have peaked around $z \approx 2$.
3. Major disc–disc mergers form elliptical galaxies with kinematic subsystems, bimodal globular-cluster populations, and remnant fine structure. Such mergers occurred relatively early near the centres of rich clusters, but continue to the present time in rich-cluster outskirts, poorer clusters, and the field.
4. Minor mergers tend to move disc galaxies towards earlier morphological types, creating kinematic subsystems and some bulges (fraction remains unknown).
5. In short, the currently available evidence strongly suggests that Hubble's morphological sequence is mainly a sequence of decreasing merger damage.

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