

Galaxy Collisions - Dawn of a New Era

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Summary. The study of colliding galaxies has progressed rapidly in the last few years, driven by observations with powerful new ground and space-based instruments. These instruments have been used for detailed studies of specific nearby systems, statistical studies of large samples of relatively nearby systems, and increasingly large samples of high redshift systems. Following a brief summary of the historical context, this review attempts to integrate these studies to address the following key issues. What role do collisions play in galaxy evolution, and how can recently discovered processes like downsizing resolve some apparently contradictory results of high redshift studies? What is the role of environment in galaxy collisions? How is star formation and nuclear activity orchestrated by the large scale dynamics, before and during merger? Are novel modes of star formation involved? What are we to make of the association of ultraluminous X-ray sources with colliding galaxies? To what degree do mergers and feedback trigger long-term secular effects? How far can we push the archaeology of individual systems to determine the nature of precursor systems and the precise effect of the interaction? Tentative answers to many of these questions have been suggested, and the prospects for answering most of them in the next few decades are good.

1.1 Introduction: Some Past Highlights and Current Issues

1.1.1 Early Days

The study of galaxy collisions is not an ancient one; Erik Holmberg, Fritz Zwicky, and a few others did quite a bit of work relevant to colliding galaxies before the 1950s, but that decade opened and closed with two landmark papers. Thus, we can justify taking it as the first decade of general interest in the subject, and view the earlier work as pioneering. The first of the two papers, by Spitzer & Baade (1951), revived Zwicky's suggestion that collisions would be frequent within dense galaxy clusters, and considered what would happen in direct collisions between two galaxies. Specifically, they correctly argued that the stellar distribution might be only moderately disturbed, while strong shock waves could push the interstellar gas out of the galaxies. Their primary conclusion was that this

process could account for the scarcity of late-type spiral galaxies with substantial ongoing star formation in clusters. For the first time galaxy collisions were seen to have an important role in galaxy evolution.

The second landmark paper was Zwicky’s review of his extensive imagery of morphologically peculiar galaxies, together with arguments that many of these peculiarities were caused by tidal forces in collisions (Zwicky, 1959). At the time, Zwicky’s theory seemed doubtful, since collisions between the widely separated “island universes” were deemed improbable. Moreover, his arguments were generally semi-quantitative, and so, not compelling.

In the middle of this first decade Baade & Minkowski (1954) suggested that one of the most prominent members of the newly discovered class of radio galaxies, Cygnus A, was in collision. Thus, we already have the first hints of many of the most important themes in this field, including: the generation of unique tidal morphologies, induced nuclear activity, induced star formation, the important role of collisions in galaxy evolution, and the dependence of these effects on the clustering environment. In this review I will focus on the last few items - induced star formation, galaxy evolution, and environmental effects - and say relatively little about the first two and many other related topics.

In the second decade, much of the work was of a more detailed, and sometimes indirect nature, which I cannot review here (see e.g., Struck 1999). The major exception to this generalization was publication of Arp’s pictorial atlas of more than 300 peculiar galaxies (Arp, 1966). Arp derived the atlas objects from the Palomar sky survey. In the following decades this atlas became the standard ‘field guide’ for workers in this field. The Arp galaxies were arranged in categories somewhat like Zwicky’s, but with many more examples, and excellent photographic images. One psychological effect of so many images may well have been to make the peculiar galaxies seem less like freakish rarities, and more like zoological families in need of explanation.

1.1.2 The 1970s

Toomre & Toomre (1972) took a giant step toward these explanations. Their numerical models were not the first, and were simple by modern standards, but they were more extensive than previous efforts. They were able to account for many of the Arp atlas forms in detail, thereby making a strong case for the collisional origins theory. They also made a number of important predictions for observation, such as that strong tidal waves would lead to enhanced star formation and gas transfer to nuclear regions, which could fuel nuclear activity. These would become dominant themes in subsequent work.

However, Toomre and Toomre’s models did not directly account for the ‘messiest’ objects in the Arp atlas (see examples in Figure 1). Alar Toomre returned to these objects in his contribution to the seminal Yale galaxies conference (Toomre, 1977). He pointed out that the earlier models had not included the effect of Chandrasekhar’s dynamical friction (Chandrasekhar, 1943), and showed that the effect would draw the colliding galaxies into a merger. He further considered how merger remnants would evolve, and how they would appear

Fig. 1.1. Multiwaveband images of several well-known merger remnants (courtesy D. B. Sanders and I. F. Mirabel): a) NGC 4038/39 (Arp 244, “The Antennae”), b) NGC 7252 (Arp 226, “Atoms for Peace”), c) IRAS 19254-7245 (“The Super-Antennae”), d) IC 4553/54 (Arp 220). An optical image shown in greyscale, HI (21 cm) surface intensity shown by contours, and K band (2.2 mm) shown in insets. Scale-bar represents 20 kpc in each case; see Sanders & Mirabel (1996) for details.

observationally. This led him to some radical conclusions for that time, that mergers between comparable large spiral galaxies could lead to the formation of elliptical galaxies, and that reasonable extrapolation of the statistics of such collisions suggested that a large fraction of ellipticals could be formed this way. The debate still continues on many aspects of this scenario, but it immediately had an important effect. Toomre had opened the door to the possibility that collisions were the dominant factor in the evolution of an important class of galaxies. Collisions were more than just a means of accounting for rare freaks, or a specialized process peculiar to the environment of dense clusters.

Other important developments in the 1970s included the work of Larson & Tinsley (1978), who suggested that Arp atlas galaxies had a wider range of optical colors and star formation rates (SFRs) than the more normal Hubble atlas (Sandage, 1961) galaxies. Extension of that work suggested that infrared colors would provide even more sensitive indications of varying SFRs (Struck-Marcell & Tinsley, 1978). Ever increasing evidence that galaxies (and groups and clusters) possessed massive dark halos (see Sofue & Rubin (2001) for a history of rotation curve studies) completely changed our understanding of what a galaxy is. The ten-fold increase of galaxy masses and sizes in the new picture provided an explanation of why collisions could be common, despite the great separations of the visible parts of galaxies. Their cross section were much larger than previously thought, and collision partners were born bound together in larger entities.

1.1.3 The 1980s and Early 1990s

This period saw expansion of the field into many new directions, with a number of major developments that defined the current epoch. One of the highest points was the discovery of ultraluminous far-infrared galaxies (ULIRGs) with the observations of the IRAS satellite (see reviews of Soifer, Houck, & Neugebauer 1987 and Sanders & Mirabel 1996). This discovery set off a gold rush of studies of these objects, as illustrated by the papers of the 1986 Pasadena meeting (Lonsdale Persson, 1986) and the 1989 Alabama meeting (Sulentic, Keel, & Telesco, 1989), and which continues to some degree up to the present. A primary focus of most ULIRG papers has been the relative role of nuclear starbursts versus active nuclei in generating the huge emissions. This is a difficult question to answer because both are usually buried deeply in the gas and dust of the merger remnant; most observational techniques give only indirect clues. While elucidating the connection between starburst and nuclear activity is very important, the

ULIRGs and their somewhat less luminous cousins, the LIRGs, offer a wealth of other information on questions of galaxy evolution.

A second focus of ULIRG studies was the determination of what sort of remnant would ultimately emerge from a major merger. ULIRGs could be seen as the missing link in Toomre's theory of elliptical formation from major mergers. They are recent mergers with prodigious amounts of star formation, which might eventually either consume or heat and disperse the gas, as required by the theory. The fact that the old star surface brightness profile approximated the de Vaucouleurs profile characteristic of ellipticals in the inner regions of some ULIRGs, despite the presence of tidal distortions in the outer parts, gave further support to the theory.

This was generally a period of rapid development of numerical models. It began with the publication of the first fully self-consistent three-dimensional models of galaxy collisions followed through the merger (see review of Barnes & Hernquist 1992). In these models the galaxies were of comparable size and consisted of a single spheroidal component, i.e. like two elliptical galaxies without dark haloes. They showed that mergers occurred much more quickly than expected, as orbital energy was efficiently channeled into internal collective modes. They also revealed the rapid appearance of a de Vaucouleurs surface density profile in some major merger remnants. This profile can be viewed as a kind of meta-stable state, resulting from the prompt relaxation of collective modes. Its appearance in ULIRGs indicated agreement between observations and models, and provided more support for the ellipticals from mergers theory.

By the end of this period the state of the numerical art had advanced to self-consistent merger models of galaxies with stellar disk, gas disk, and dark halo components (Barnes & Hernquist, 1992). These models showed that different galaxy components behaved somewhat differently during the (major) merger process, with dynamically hot halo components generally merging more quickly than the disk components. Even more exciting from the point of view of ULIRG studies, the models showed that a fraction of the gas carried much of the angular momentum out into extended tidal structures, while the rest of the gas fell into a small volume in the remnant center. This mass of highly compressed gas could readily fuel ULIRG superstarbursts.

This period did not see many models of mini or micro mergers, in part because ULIRGs and major mergers were the focus, but also because adequate numerical resolution of small companions was difficult. Another lacuna of modeling in this period was realistic gas dynamics; most models used either an isothermal equation of state for the gas or 'sticky particle' algorithms with phenomenological collision rules between particles representing gas clouds. Cooling, heating and stellar feedback processes were not generally included, (but see e.g., Appleton & Struck-Marcell 1987b).

Alongside the major thrusts of merger studies several quiet revolutions occurred in this period. One of these was based on the sensitive mapping of atomic hydrogen in galaxies generally, as well as collisional systems, by many observers using the Westerbork array, and later the VLA (Very Large Array of the National Radio Astronomy Observatory). These observations first made clear that

the gas disks of typical disk galaxies were much larger than the stellar, and then as one might have expected, that these extended gas disks were more strongly affected by collisional encounters than the inner stellar disks. It soon became clear that such observations were essential for determining the full extent of tidal tails and bridges. HI mapping also provides a map of the line-of-sight velocities of the gas. Kinematic maps provide us a view in a third dimension of the six dimensional position-velocity space, and this information is usually crucial to the success of models of individual systems, thereby to detailed tests of collision theory. The accomplishments of the VLA were summarized at a recent symposium (Hibbard, Rupen, & van Gorkom, 2001), and a valuable legacy of that meeting was the creation of the HI Rogue’s Gallery website of colliding galaxy HI maps by J. Hibbard (www.nrao.edu/astrores/Hirogues/).

Another discovery that can be described as revolutionary is that tidal interactions can induce the formation of a bar component out of disk material. This was shown by the numerical models of Noguchi (1987), and studied in detail by Athanassoula (see review of Athanassoula (2004) and references therein). This result is important because bars transfer angular momentum outward in the disk, and so can drive gas into the central regions before merger. The bar can also drive spiral density waves. Both the increased central gas concentration and the bar/spiral waves can induce star formation.

We will examine the question of SF induced before merging in more detail below. However, we should note here that Keel, Kennicutt and collaborators carried out an extensive program of H α imagery and spectra of both collisional systems and of a control sample (Keel et al. 1985, Kennicutt et al. 1987). They found indications of enhanced SF in the collision sample, and particularly of SF enhancements in galaxy cores which were kinematically disturbed. On larger scales, Schombert, Wallin, & Struck-Marcell (1990) observed the broad band colors of a sample of tidal bridges, plumes and tails, and found that while SF in these structures was not especially strong, it did continue after their formation. This is somewhat surprising given the great extent of many of these structures, which would seem to imply diminished gas densities and SF.

In his continuing studies of putative merger remnant-to-elliptical systems, Schweizer also discovered large, young star clusters or dwarf galaxies formed in tidal tails, most notably in the “Antennae” system (Schweizer, 1983). These discoveries would inspire a great deal of new work in the 1990s and the present decade. More generally, Schweizer’s detailed, multi-waveband studies of specific merger remnants, whose appearance suggested that they were on the road to becoming ellipticals, advanced Toomre’s merger theory (see Schweizer (1998) and references therein).

As a final example of quiet revolutions of the 1980s I would include the extensions to dynamical friction theory by Tremaine & Weinberg (1984), and the application of the new theory to the evolution of galactic bars (Weinberg, 1985). The classical Chandrasekhar (1943) theory was too idealized to account for the frictional effects in major mergers, and even more so in the case of a “sinking satellite” orbiting outside of, but interacting with the disk of the primary galaxy. The Tremaine and Weinberg theory included the collective effects not accounted

for in the classical theory, and is able to account for the rapidity of major mergers seen in numerical models.

Even beyond these revolutionary examples the tapestry of colliding galaxy studies also grew with the addition of more new threads in this period. These included studies of many specific types of collisional system, such as: colliding ring galaxies (see review of Appleton & Struck-Marcell 1987a), polar rings (see review of Sparke 2002), ocular ovals (Elmegreen et al., 1991), and shell galaxies (e.g., Hernquist & Quinn 1988). Numerical modeling demonstrated how these distinctive morphologies could be produced in collisions, and thus confirmed earlier conjectures on the broad scope of collision theory. In addition, distinctive morphologies were generally found to be the result of a relatively narrow set of collision parameters. Examples in each class can be viewed as a set of related natural experiments, seen at different times and with slightly different initial parameter values, which have the potential to provide much insight into difficult or obscure collision processes (e.g., hydrodynamic or SF processes).

1.1.4 Key Issues Up to the Present

The 1990s saw continued rapid expansion of the field, driven in part by new ground and satellite-based instrumentation, and by rapidly increasing computer power. It is very difficult to summarize the accomplishments of that decade briefly. Queries to NASA’s Astrophysical Data System show that the number of literature papers with abstracts containing the words “galaxy” and “collision” grew very rapidly with each decade: 27 (1950s), 75 (1960s), 326 (1970s), 826 (1980s), 1413 (1990s). Similar increases in the number of studies in the related fields of galaxy formation and galaxy evolution at high redshift make the task even more difficult. In this review we will focus our attention on key issues relating to star formation and galaxy evolution.

It is clear that over the second half of the 20th century this field has gone from bare beginnings to a considerable maturity, providing answers to some of its most important questions and early paradoxes. Yet many questions remain, including some that have been common threads through the whole history of the subject, and which are connected to the deepest questions in astrophysics. For reference in the rest of this review, I list here some of the most important ones.

1. How do collisions and interactions affect galaxy evolution overall? More precisely, what are the relative roles of major and minor mergers in building galaxies? This question is related to that of how galaxies form, since major mergers are very important in hierarchical build-up models, and negligible in monolithic collapse models of galaxy formation.

2. How does the answer to the previous question depend on environment? How do collisions differ in cluster, group, or nearly isolated environments? Some partial answers to these questions have been known for a long time. For example, collisions between field galaxies are very different from those between cluster galaxies because the latter have typical relative velocities of thousands of km/s versus velocities of hundreds of km/s in the former case. High velocity collisions

can remove interstellar gas and produce moderate tidal distortions, but are unlikely to result in merger, while mergers are generally inevitable in the lower velocity collisions in groups. Research over the last few decades has provided a great deal of information on these questions, and it has become clear that environment plays a very large role in determining the nature of collisions that can occur, and the relative importance of galaxy collisions versus other evolutionary processes (like gas sweeping in dense clusters).

3. How do the large-scale dynamics of collisions and interactions orchestrate star formation (SF) and nuclear activity, which are inherently small scale processes? The clear answer from the 1980s is that activity is induced by dumping a great deal of gas into the central regions of major merger remnants. Major mergers may be the way to make most of the stars in a significant fraction of early type galaxies, but they are a rare event in the world of galaxy collisions, and the question remains for other types of collision. Related questions include: when do galactic winds and fountains result from interaction induced SF, and what feedback role do they play in the subsequent SF?

4. To what degree do mergers trigger long-term (more than 1.0 Gyr) secular processes? Examples include the long-term effects of collisionally induced bar components, and the fallback of large scale tidal structures.

5. How far can we push the archaeology of individual systems? Do enough clues remain to determine the morphology of the precursor galaxies, and decipher the details of the interaction up to the present?

In the remainder of this review we will consider how developments in the last decade and the near future help to answer these questions. The first three sets of questions include the key questions of this review. The last two push beyond its scope, and I will not treat them in any detail, despite their intrinsic interest.

1.2 Induced Star Formation and Winds

1.2.1 Star Formation Processes in Interactions

Star formation induced by galaxy collisions appears similar to SF in isolated galaxies in several ways. Before merging it is often concentrated in spiral waves or bars, and tidal tails often look like extensions of the spirals. Both before and after merger it is often concentrated in nuclear starbursts. These can be orders of magnitude stronger than core bursts in isolated galaxies, but they can appear qualitatively similar.

However, there are theoretical reasons to think that the nature of collisionally induced SF is very different from that in isolated disks. In isolated star-forming disks there is evidence that SF, and gas disk structure, are self-regulated by energy and momentum feedbacks from young SF regions (e.g., Kennicutt 1989). The self-regulation processes work to maintain a gas surface density close to the threshold for local gravitational instability throughout the disk. SF is usually concentrated in grand design or flocculent phase waves, which compress the gas, pushing its density over the stability threshold. Thus, isolated gas galaxy disks

are likely examples of self-regulated, non-equilibrium steady states, at least in regions where the rotation curve is essentially flat (Note that the details of the self-regulatory processes are not well understood. See Struck & Smith (1999) for a self-consistent model in the case of strong global SF. See Zhang (2003) for a discussion of how spiral waves may be maintained for relatively long periods.)

Collisions upset steady state disks, even if they don't tear regions in them apart, as occurs in the case of direct collisions between two gas disks (e.g., Struck 1997), or major mergers (e.g., Barnes & Hernquist 1996, Mihos & Hernquist 1996). The waves in these disturbed disks are of a different nature than those in steady disks. For example, tidal tails are material, rather than phase waves, and in most cases induced spirals and bars have mixed material and phase aspects. Induced waves can have a very different combinations of Fourier modes than steady waves. For example, odd numbered, asymmetric modes are evidently more common.

Compressions in steady spirals can push the gas above instability thresholds and drive SF, but the degree of compression is limited by the passage time through the wave (e.g., half the epicyclic period). In material waves, compressed gas elements can move together, and maintain their compression for longer periods. Beyond this, gas clouds can be partially separated from their original surroundings, and launched like collisionless stars over substantial distances, to interact with other clouds from very different radial positions in the initial disk. This tidal mixing can sometimes involve substantial relative velocities, and may play a great role in induced SF. This point has not been studied in any detail, probably because of the difficulty in obtaining observational evidence of the mixing.

Tidal mixing is similar to collisional splash effects, where direct collisions between gas disks drive gas out of both disks, and both disks experience later fallback. Both effects are analogous to splash and mixing effects in water waves. Tidal tails are breaking waves in galaxies.

These examples highlight how detailed studies of SF in colliding galaxies can advance our understanding of SF processes in general, as well as allow us to study modes that simply don't occur in quasi-steady isolated disks. These modes are likely to be very important in the early stages of galaxy buildup. We will return to the subject of high redshift galaxies below.

1.2.2 Observational Samples of Star Formation Before Merger

Given these theoretical motivations, let us consider observational results. In Sec. 1 we discussed the discovery of ULIRG super-starbursts in gas-rich, major mergers in the 1980s. Generally, no such strong signal of enhanced SF has been found in pre-merger interactions. Since in most interactions there is no wholesale gas compression like that found in major merger remnants this is not surprising. The questions remain, however, do interaction induced disturbances lead to substantial SF enhancements, and if so, where, when and how? These questions were raised by Toomre & Toomre (1972) and Larson & Tinsley (1978). They have been the focus of much interest in observational studies in many wavebands of

both individual systems and samples of systems (see Sec. 7 in the review of Struck 1999).

The common conclusion was that there is an average SF enhancement in interacting systems, and that this could be result of a modest starburst in most cases. However, SF is not obviously enhanced in all interactions, and may be suppressed in some. The galaxy samples studied in the 1980s and 1990s were not generally large enough to provide strong enough statistical results to be definitive, let alone to tease out details of the relevant processes. The larger samples tended to contain systems from a wide range of pre-merger or merger stages (like the the Larson and Tinsley Arp Atlas sample), and so, could be dominated by the merger-burst effect. On the other hand, samples of specific types of interaction (e.g., the ring galaxy sample of Appleton & Struck-Marcell 1987a) or specific stages (e.g., the Bushouse 1987 violently interacting sample) tended to be small. Interactions are rare in the present day, and specific types are therefore doubly rare!

Fig. 1.2. Image of the Arp 89 system (NGC 2648, from Arp (1966). It is an example of systems studied by Keel (1993). The companion has one of the strongest nuclear SFRs in the sample.

Nonetheless, interesting clues came out of many of these studies. An important example is the Keel (1993) spectroscopic study of SF correlations in a sample of 75 Karachentsev spiral pairs (see Figure 2 for an example system). This work built on a decade of earlier work by Keel, Kennicutt and collaborators (Keel et al. 1985, Kennicutt et al. 1987). Keel found that the current SFR (as measured by $H\alpha$ equivalent width) did not depend much on the projected separation of the two galaxies, nor on whether a galaxy experienced the collision as prograde or retrograde. These results seem to defy the intuitive notion that strong perturbations at closest approach should drive strong responses, which could result in enhanced SF (but see Keel & Borne 2003). In prograde encounters the companion orbits in the same sense as the galaxy's spin, and so the encounter is prolonged, undoubtedly resulting in more disturbance, e.g., tidal tails. Thus, it was surprising that Keel did not find a spin/orbit effect in the SF.

What Keel did find was SF enhancement in systems with disturbed kinematics or in galaxies with large regions of solid body rotation. Disturbed kinematics was measured by the largest difference between the measured velocity and that of a mean symmetric rotation curve. Such kinematic disturbances can be seen in barred galaxies. However, Keel's sample did not include many barred galaxies. Keel also found that both disk and nuclear SF enhancements were linked to kinematic disturbance, which at first sight seems to be another mysterious result.

Keel considered some of the theoretical mechanisms proposed to account for induced SF in light of his observational results. He found contradictions between several of the observational results and the predictions of models on the enhance-

ment of collisions between massive gas clouds. The correlation of enhanced SF with the size of solid-body rotation regions lead him to favor gravitational instability processes, since such regions are very susceptible to these instabilities.

Recently, Barton and collaborators (Barton, Geller, & Kenyon 2000, Barton Gillespie, Geller, & Kenyon 2003) re-examined these questions with a larger sample of 502 galaxy pairs and groups drawn from Harvard redshift surveys. In contrast to Keel they found a significant anti-correlation between SF (again measured by $H\alpha$ equivalent width) and separation of the galaxies. The two samples have comparable ranges of separation and equivalent width. Although Barton et al.'s SF-separation anticorrelation is statistically strong, it does appear to be strongly influenced by the approximately two dozen sample galaxies with equivalent widths greater than or about equal to 50. Given the relative sample size, we would expect to find only about 3-4 such systems in Keel's sample. Indeed, there are 4. Thus, it appears that the effect is too weak to have been easily detected in a sample much smaller than Barton et al.'s. Barton et al. speculate that the cause of this anticorrelation is driven gas inflow before merger in some systems.

Barton and collaborators find a second anticorrelation between SF and line of sight velocity separation between the two galaxies in each pair. This is in accord with the intuitive notion that slower passages induce stronger collisional responses. Among their pairs and groups they find a very strong anti-correlation between SF and galaxy density, which they interpret as a symptom of the well-known density-morphology relation in groups and clusters. And finally, Barton Gillespie, Geller, & Kenyon (2003) have compared their observations and models of $H\alpha$ equivalent width and B-R broad band color, taking careful account of reddening effects. They find a significant correlation between burst population age and separation. They attribute this correlation and post-starburst spectral indicators in some systems to starburst triggering at closest approach, and subsequent aging as the galaxies move to apogalacticon.

On the other hand, Bergvall, Laurikainen, & Aalto (2003) have recently questioned the whole notion that there are statistically significant SF enhancements before merger. They examined the UVB broad band colors of a sample of 59 interacting or merging systems, and compared to a control sample of 38 isolated galaxies. They find no significantly greater scatter in the colors of Arp atlas galaxies relative to controls, in contrast to the Larson and Tinsley result, and no evidence for a significant enhancement in global SF in their interacting sample relative to the control. They do find evidence for a modest enhancement, by a factor of 2-3, in the central SF of their interacting sample. Given the previous result this implies a diminution of the average extra-nuclear disk SF in the interacting sample. Keel (1993) found no such distinction between net and nuclear SF enhancement in his sample.

On the face of it, Bergvall et al.'s primary result about the lack of SF enhancement in interactions seems to contradict many previous studies. However, these studies also find that the effect is weak if we exclude merger remnants, and the Barton et al. papers in particular suggest that we may need a sample of at least several hundred galaxies to find it. Given Bergvall et al.'s sample size, their work may not provide strong evidence for the complete absence of an effect, and

they may even be a bit pessimistic in their estimate that the frequency of strong, triggered starbursts in interacting systems is of order 0.1%. Recent very large surveys of galaxy properties, like the Sloan Digital Sky Survey (SDSS) and the Two Degree Field (2dF) survey, could provide the answers, and indeed, a couple of analyses based on these surveys have been published recently.

Fig. 1.3. Specific star formation rates for 3 subsamples of Sloan Digital Sky Survey galaxies, selected according to absolute SFR in the ranges: 0-3, 3-10, and $> 10 M_{\odot} \text{ yr}^{-1}$ (courtesy B. Nikolic). See Nikolic, Cullen, & Alexander (2004) for details.

Nikolic, Cullen, & Alexander (2004) selected nearly 12,500 pair systems with companions within 300 kpc of the primary from the SDSS. This is a volume-limited, low redshift sample with SFRs determined from SDSS (extinction and aperture corrected) $H\alpha$ data, supplemented by IRAS data. They also reject very close pairs, i.e., most merger remnants. They find that “the mean projected star formation rate is significantly enhanced for projected separations less than 30 kpc.” (see Figure 3). Like Barton et al. they find an anticorrelation between SF and the pair velocity difference. Despite its statistical significance they also found the the SF-separation anticorrelation is relatively weak, in accord with previous studies.

With such a large sample, they were able to look at subsamples, for example, subsamples consisting of two late-type disks, two early-type disks, or mixtures. The anticorrelation is present in all three subsamples, with some indication that it extends to larger radii in the late-type subsample. Nikolic, Cullen and Alexander also presented SFRs normalized by galaxy mass, and show that the magnitude of the normalized SF-separation relation depends on how the normalization is performed.

Lambas et al. (2003) carried out a similar pair study with 1258 pairs from the 2dF survey, and found anticorrelations of SF with separation and velocity like those in the Nikolic et al. study.

Bergvall, Laurikainen, and Aalto noted that “the interacting and in particular the merging galaxies are characterized by increased far infrared luminosities and temperatures that weakly correlate with the central activity.” This result, in turn, agrees with much evidence that many specific types of interacting galaxy have enhanced far-infrared emission. For example, M51 type systems (e.g., Klimanov & Reshetnikov 2001) on one hand, and the collisional ring galaxies (Appleton & Struck-Marcell, 1987a) on the other hand, both show modestly enhanced IRAS fluxes relative to the late-type disk norms.

Fig. 1.4. Some examples of LIRG systems in B and I wavebands. Note the scale bars and the change of scale between rows. From Arribas et al. (2004), courtesy S. Arribas.

For a broader perspective, one can turn the table and ask about the nature of galaxies with enhanced infrared emission (and usually radio continuum emission as well). We have discussed ULIRGs above, and noted that they are primarily merger remnants, and so not of interest in the present context. Luminous Infrared Galaxies (LIRGs or LIGs) and Very Luminous Infrared Galaxies (VLIRGs or VLIGs) are variously defined as galaxies with far-infrared luminosities in the approximate range $3 \times 10^{10} - 10^{12} L_{\odot}$, and have not been studied as intensively (see examples in Figure 4). However, it appears that a large fraction of these objects are pre-merger, collisional systems with a relatively strong starburst in the core of at least one of the galaxies (see e.g., Young et al. (1996), Gao & Solomon (1999), Corbett et al. (2003), Arribas et al. (2004) and references therein). Based on statements like that of Bergvall et al. in the previous paragraph, and the rarity of LIRGs (like the ULIRGs), it seems likely that they are the same as, or more obscured relatives of, the few starburst galaxies that seem to be responsible for the weak SF enhancement found in optical pair samples.

In sum, optical studies show that interactions lead to only a very small SF enhancement before merger, on average. Given that core starbursts are likely to have quite short durations (unless they have prolonged driving, e.g., Struck 2005), it is natural to interpret this as the result of random sampling of a common process with a short duty cycle. The LIRG studies suggest another possibility, that a small minority of galaxies (the LIRGs) are responsible for the general weak enhancement, and that these galaxies are near the end of the road to merger, though not yet merged. The latter clause is supported by the fact that the few starbursts in pair samples generally have small separations and velocity separations, and this is also true for many LIRGs. In this alternative view, SF is not significantly enhanced in the early stages of interaction despite strong morphological disturbances. Also there is a more continuous increase in SF as merger is approached, an idea suggested in some of the LIRG studies. Gao and Solomon, in particular, have suggested that the phase structure of galactic ISM changes through the merger process, with an increase in the molecular phase in the final pre-merger stage (Gao & Solomon 1999, also see Gao & Solomon 2004 for similar results concerning molecular abundance changes through core starburst evolution). We will return to this discussion in Section 2.5.

1.2.3 Detailed Case Studies

Because it is difficult to directly translate projected galaxy separations into true separations, and directly divine the stage along the path to merging, it is difficult to use limited observations (in any waveband) to determine which of the viewpoints of the previous paragraph is correct. (Although it might be possible to estimate the separation and evolutionary stage statistically in the large samples.) There are two other ways to test evolutionary hypotheses. The first is to confront it with theory and the results of numerical simulations, which we will consider below. The second is by assembling a large library of careful case studies of specific systems. Such studies require a panchromatic array of spatially resolved and kinematic observations, which can provide strong constraints

on numerical models. They also require system specific models, which closely match all available observations, and thereby provide a clear determination of the interaction stage (see discussion in Struck 2004). Given the prolonged debate on whether the nearby M51 system is the result of one or two close encounters, this is not necessarily an easy task (see review of Struck 1999), though in either case it is clear that the system is not yet near the end of the merger road.

With a library of detailed case studies one could hope to graph SFR (or specific SFR per unit mass or gas mass) versus interaction stage to resolve the issues above. The “interaction stage” would require careful definition, however.

Detailed color and spectral synthesis modeling can in fact yield constraints, if not yet unique solutions, for the SF history of some nearby well-studied systems, e.g., the Magellanic Clouds (Zaritsky & Harris 2004, Javiel, Santiago, & Kerber 2005), M51 (Bastian et al. 2005, Bianchi et al. 2005), M82 (De Grijs 2001, De Grijs, O’Connell, & Gallagher 2002) and Arp 284 (Lançon et al., 2001). From such cases, one can add a few points to the hypothetical SFR-interaction stage plot.

1.2.4 Modes of Star Formation

Detailed case studies are also a primary tool for studying a number of specialized modes of SF, some of which have received a good deal of attention in recent years. These include: the formation of super star clusters (SSCs), SF in tidal bridges and tails, and SF in induced disk waves. Except perhaps in the last case, these modes do not usually dominate the SF in interacting systems, but they may involve physical processes unique to collisional environments, and produce especially interesting products like dwarf galaxies and halo globular clusters.

Tidal Dwarf Galaxy Formation

We have already mentioned early studies of SF in tidal tails in Section 1, but there has been a great of recent work. Work in this area has been energized by the possibility that, not only massive star clusters, but actual dwarf galaxies might be formed out of material in tidal tails (Figure 5). If so, this could be a means of forming dwarf galaxies at the present time, and in observable environments. In the introduction to a recent paper Duc, Bournaud, & Masset (2004) review much of the literature of the last decade, and additionally a section of the proceedings of a recent IAU symposium is also dedicated to the topic (Duc, Braine, & Brinks, 2004). These two sources provide a good entry points to the literature.

Fig. 1.5. Arp atlas image (Arp 1966) of the Arp 105 system. This system contains a probable tidal dwarf galaxy at the end of the long tidal tail in the north. See Duc et al. (1997) for details.

We should begin by noting that the tidal dwarf formation has been controversial, and difficult to prove (or disprove). Most tailed galaxies do not have an

obvious luminous SF region at the end of their tails. To date, only a few examples of dwarfs forming in tails have been studied in detail, so it is not clear how rare is that circumstance, nor what is the general nature of SF in tails. In fact, there are a number of difficulties in finding these objects, and confirming that they are dwarf galaxies in formation. Sometimes the tail is viewed edge-on, and if it is curved in the vicinity of the candidate dwarf a good deal of material that is not physically connected can be superposed along the line-of-sight, including multiple SF regions (e.g., Duc et al. 2000). This can lead to large overestimates of the mass and extent of the tidal dwarf candidate, leading, in turn, to a bias for such systems in the candidate list. Determining whether a tidal dwarf candidate is truly a gravitationally bound object, and will persist as a distinct entity is also challenging, if only because of the resolution limits of observations of HI and molecular gas in these small objects.

Discussions of this latter question have been entwined with those concerning two early theories for the formation of tidal dwarfs. Barnes & Hernquist (1992) suggested that they could form as a result of gravitational instabilities in tails consisting of collisionless stars, while Elmegreen et al. (1991) argued for the dominance of gas dynamical processes in regions of enhanced turbulence (i.e., enhanced velocity dispersion). One of the difficulties in the modeling is that some density concentrations may not be persistent, and the models are not generally able to follow their evolution for very long times, or with sufficient particle resolution (but see the high resolution model of Hibbard & Barnes 2004). Another problem in confronting these theories to observation is that since gas disks are more extensive than stellar disks, all tidal dwarf candidates are likely to contain a large fraction of gas, so it is not possible to find a case of assembly by gravitational means alone. Based on new simulations, Duc, Bournaud, & Masset (2004, and references therein) argue that only if the parent galaxy has an extensive dark halo is it likely that large amounts of gas will accumulate at the end of a tidal tail, and that this is the most efficient route to forming true tidal dwarfs with masses in excess of $10^9 M_{\odot}$. These authors also find that the gas accumulation process is primarily kinematic, with self-gravity playing only a minor role. It will be interesting to see how these new ideas develop in the next few years.

Massive and Super Star Cluster Formation

Fig. 1.6. HST image of young star clusters in the merging Antennae galaxies, from Whitmore et al. (1999, courtesy of B. Whitmore).

One of the greatest contributions of the Hubble Space Telescope to extragalactic astronomy was to resolve individual star clusters in relatively nearby galaxies and allow us to take the census the cluster populations in them. As a result of such studies it has become clear that a large fraction of new stars in colliding galaxies are formed in clusters (see Figure 6). This is difficult to

quantify, but has been estimated at 50-100%. The characteristics of the most massive of these clusters, the super star clusters with estimated masses in the range $10^5 - 10^8 M_{\odot}$, are just what we would expect from young clusters, so it appears that we are now able to study the formation and development of globular clusters at a variety of stages by direct observation. These studies have given rise to a considerable literature, which extends far beyond the topic of this review, so we only describe a few of the relevant highlights.

In a summary of a recent conference on this topic, O'Connell (2004) emphasized the universality of the properties of young cluster populations, despite a huge range of formation environments and scales. These properties include a nearly universal power law mass function, which evolves naturally with time to the exponential function of old globulars. The number of clusters and the maximum cluster luminosity in a star-forming region both scale with total SFR. Most cluster populations have a very small range of formation ages. This is especially true of populations in galactic nuclei, but in colliding galaxies with widely spread SF regions there can be distinct populations, each with small age spreads (e.g., Alonso-Herrero et al. 2002). The spatial structure of super star clusters also appears to be universal. The stellar initial mass function is universal, at least at the high end where it can be determined.

It is worth emphasizing the range of environments where super star clusters and their somewhat less massive relatives are found in colliding galaxies. Of course, starburst nuclei are primary locations and M82 (De Grijs 2001, Melo 2005) is probably the most famous example. M51 (Bik et al. 2003, Bastian et al. 2005) is also very interesting. At the other extreme we have globular cluster populations of intermediate age (i.e., of order a few Gyr) around merger remnants. In the ongoing merger in the Antennae system, clusters are scattered at many locations in the bodies of the galaxies (Whitmore & Schweizer, 1995). Massive young clusters are found in many tidal tails, though interestingly Knierman et al. (2003) make a suggestion, based on their study of 6 tail regions, that they either have a population of massive young clusters or a tidal dwarf, but not both. This conjecture certainly merits further observational and modeling study. Massive cluster populations are also found in ring galaxies like the Cartwheel (Appleton et al., 1996) and ocular waves like IC 2163 (Elmegreen et al., 2000). It seems very likely that the mid-infrared detectors on the Spitzer Space Telescope will find massive cluster populations in more environments that are hidden from Hubble and ground-based telescopes.

What do these environments have in common and what's the physics behind massive cluster formation? O'Connell (2004) summarizes the prevailing view that the formation of SSCs requires high gas pressures, of order 10^4 times those of the interstellar medium in the solar neighborhood, and that these high pressures must extend through a region of size greater than 1 kpc (also see Schweizer 1998). Strong turbulence also pervades the formation region. O'Connell emphasize that the energetic environment inside a forming massive cluster must be truly extraordinary.

It is likely that all of the colliding galaxy environments noted above are able to achieve the high pressures and turbulence that the theory says are necessary

to form the super star clusters. This is not entirely clear in the case of disk waves and tidal tails. However, in the former case the process may be aided by feedback effects from the first stars to form. In the case of tails it may simply be that some achieve the requisite conditions and form massive clusters, and others do not. We have much to learn yet about these processes.

Finally, O’Connell notes a couple examples of nuclear starbursts where the super star clusters are much more massive than the other clusters, and so, the mass function is discontinuous. He speculates there may be a special formation mode for these cases, though the nature of that mode is not clear. As in the case of tidal dwarf formation there are competing mechanisms, and one of these may dominate only in the exceptional cases. These mechanisms again include the formation of massive progenitor clouds triggered directly via gravitational instability, or indirectly in dense environments assembled by large scale gravitational instability. They may also include hydrodynamic effects like cloud crushing that occurs when giant clouds experience an abrupt pressure increase after impacting large-scale shocks or other high pressure regions (Jog & Solomon 1992, Braine et al. 2004, Bekki et al. 2004). The combination of these processes could probably generate discontinuous cluster mass functions, but at present, this is only speculation.

A few more exotic ideas have also been discussed recently. Scannapieco, Weisheit, & Harlow (2004) have suggested that strong winds from young galaxies could have shocked their dwarf companions, stripping gas and compressing it to form globular clusters. Burstein et al. (2004) also suggest that globulars might form in dwarf companions. Their argument is based on a hierarchical clustering model of galaxy formation as applied to the cluster populations in the Milky Way and M31. On the other hand, Hibbard, Vacca, & Yun (2000) have found several examples of systems where winds seem to have swept the gas out of parts of tidal tails, without the production of massive star clusters.

ULXs

Ultraluminous X-ray sources (ULXs) are defined as having X-ray luminosities of order $10^{39} - 10^{41}$ ergs per s^{-1} , which extends beyond the luminosities of the well-studied high mass X-ray binaries, but is still much less than a typical active galactic nucleus. X-ray sources of this luminosity have been detected in galactic nuclei for two decades, but the arcsecond resolution of the Chandra Observatory has facilitated their discovery and definition as a class of objects (see reviews of Mushotsky 2004a, van der Marel 2004, Ward 2003).

Estimates indicate that they may be a quite common constituent of the nuclei of normal galaxies. However, their nature remains somewhat mysterious. There are two leading theories. The first is that they are indeed an extension of the high mass ($\simeq 10M_{\odot}$) binary phenomenon, but with highly super-Eddington accretion rates and beamed emission (e.g., Begelman 2002, King 2004, King & Dehnen 2005, Liu, Bregman, & Irwin 2005). The second is that these are in fact black hole accretion systems of intermediate mass between stellar black holes and active nuclei, e.g., masses $\gg 100 M_{\odot}$ (e.g., Hopman et al. 2004, Krolik 2004,

Miller, Fabian, & Miller 2004, Miller 2005). There are strong arguments for both models. For the most luminous ULXs the stellar mass explanation is strained. For the most rapidly variable ones the source size and mass is limited from above. Since the luminosity bounds of the class are ad hoc, it is certainly possible that the class includes both kinds of source. Gutiérrez & López (2005) also present a cautionary tale of how apparent ultraluminous sources can in fact be background sources.

Fig. 1.7. Smoothed greyscale X-ray image of the Arp 284 system from Chandra Observatory data, with luminous point sources numbered. Contours showing the optical outline are derived from the Digital Sky Survey image. See Smith, Struck, & Nowak (2005) for details.

A number of galaxies are now known to contain enough ULXs to allow the construction of luminosity functions, and these luminosity functions are found to scale with total SFR or a combination of SFR and galaxy mass (e.g., Swartz et al. 2004). Over the last 5 years ULX populations have been found in several colliding galaxies, including M82 (Fiorito & Titarchuk 2004, Matsumoto et al. 2004, Portegies Zwart, Dewi, & Maccarone 2004 and references therein), the Antennae, the Cartwheel ring galaxy, and the ring-tailed Arp 284 system (Figure 7). The ULXs are widely spread across the Antennae (Fabbiano et al. 2004, Miller et al. 2004). They are found in the outer ring and an X-ray bridge of the Cartwheel (Gao et al. 2003, Wolter & Trinchieri 2004). In Arp 284, most are associated with tidal features, especially a prominent tail, but with one of the brightest known contained in the ring (Smith, Struck, & Nowak 2005). Some of these ULXs are associated with star-forming regions, and so they provide another locator and probe of such regions that is not easily obscured.

The environment of these “tidal ULXs” can be less confused than that of many nuclear ULXs. A few are associated with super star clusters. Models can often provide a good deal of information about the dynamical history of specific tidal structures, and thus, about the formation environment of the ULXs. The discovery of any specific phenomenology in these environments could provide useful information on the nature of ULXs. However, at present the number of cases studied is too small to allow any firm conclusions beyond the association between collision morphologies and the occurrence of ULXs.

1.2.5 Summary and Theory

Clearly, there has been a vast amount of work on interaction induced SF in the last few decades, and we have only been able to skim through it above. Is all of this work leading to a comprehensive understanding of the phenomenon? Perhaps not quite yet, but we may be getting close to that goal. The question can be broken down into several separate questions. First of all, do we understand the general physical processes, and do we understand enough about how

they work to account for the general observational systematics? Secondly, do we understand these processes well enough to reproduce their effects in numerical models, both comprehensive models of specific systems, and models of SF in particular dynamical processes?

Numerical Models

We'll begin by considering recent numerical models and some aspects of the last question. Star and star cluster formation take place on scales that are orders of magnitude smaller than those typically resolved in simulations of galaxy collisions. However, separate models of the process on those small scales are beginning to advance our understanding greatly. Because of this, and the fact that much of the dynamics on the intermediate scales is essentially scale-free turbulence, we may be able to develop reasonably accurate SF formulations, without needing to resolve the scales on which it occurs. However, to date, relatively simple SF prescriptions have been used in galaxy collision models. Moreover, these prescriptions have been based on several different ideas about the dominant SF triggering process. Three of the most popular are: 1) a simple density-dependent SFR, 2) triggering by strong compressions in cloud-cloud collisions or large-scale shock waves, or 3) triggering by gravitational instability above a threshold density (or surface density or pressure).

With regard to the first of these, the Schmidt Law, in which the SFR is proportional to a low power of the gas density, surface density, or the gas density divided by a local dynamical time has been surprisingly resilient. Mihos, Bothun, & Richstone (1993) used it (and isothermal particle hydrodynamics) to model collisions between two disk galaxies, and Mihos & Hernquist (1994) used it to model the Cartwheel ring galaxy. In both cases they found that the models gave about the “relative intensity and morphology of induced star formation.” Later, Mihos & Hernquist (1996) found that with this formulation mergers between disk galaxies with bulges could produce burst SFRs a hundred times larger than those of isolated galaxies. They also explored how the presence of a bulge component affected the merger SFR. Given the simplicity of the prescription the results are impressive. However, Cox et al. (2005) have recently shown that the amount of SF in mergers may have been overestimated in earlier models, because this quantity depends on how conservation conditions are implemented in the SPH algorithm.

Phenomenological cloud collision models for gaseous dissipation in galaxies go back to the 1970s. The obvious disadvantage of such models is that interstellar gas clouds are transient, ever-changing structures, and not the coherent entities implicitly assumed when equating them with the ‘sticky’ (i.e., dissipative) particles of a numerical model. On the other hand, it is a straightforward way to model the cloud collisions and shock encounters which occur in many types of collision. In models of polar ring galaxies (Bekki, 1997), models of starbursts in multiple mergers (Bekki, 2001), and in other applications, Bekki has used a hybrid particle model. In his models there is dissipation from cloud collisions, but a probabilistic Schmidt Law is used to convert selected gas particles to stars.

The local gas density is computed for each gas particle and used in the Schmidt Law.

Recently, Barnes (2004) has proposed a rather sophisticated phenomenological model, in which SF depends on the amount of energy dissipation in shocks. He argues that with this prescription he is able to produce a much better model of the Mice system (NGC 4676) than with a Schmidt Law. This is one of the few significant comparisons of different formulations in models of the same system. Barnes also notes that Schmidt Law models are quite insensitive to details of the interaction, while shock induced SF is very sensitive, and could be checked observationally.

Threshold instability models have been used frequently in the areas of galaxy formation and multiphase models of galaxy disks in recent years. This author has used such a model with feedback and gas with a continuous range of thermal phases in studies of direct collisions between two gas disks and their reformation (Struck, 1997). More recent work on disk collisions with many more particles has been carried out by Springel & Hernquist (2005). Cox et al. (2005) have recently presented an efficient effective equation of state approach to handling the thermal physics.

I have also used this type of SF formulation in detailed N-body hydrodynamic models of a couple of specific systems with extensive observational data (Struck & Smith 2003, Struck 2005). Both the spatial distribution of SF and the history of net SF fit the observational constraints, though the constraints on the SF history are not stringent. At low threshold densities this type of formulation is probably much like the Schmidt Law, since the SF will occur in regions with the most particles (i.e., high density). With a high threshold density, a violent process like shock compression and subsequent cooling will be needed in many cases to drive SF, more like the Barnes model.

In the end we see that many different numerical treatments can simulate induced SF reasonably well, and so none are immediately falsifiable. The answer to the question posed at the beginning of this discussion is yes, we can reproduce observations, but not because the models represent the underlying physical processes especially faithfully. The universality of those processes, and their highly interconnected properties, allow modelers to use simple formulations on large scales. Stringent tests of feedback prescriptions may eventually come by fitting the mass fraction and distribution of warm-to-hot phases in the interstellar gas. However, this will take much more realistic modeling of the thermal physics, and the stellar initial mass function, than is currently the norm.

Detailed observational studies on kiloparsec scales in various environments may provide insight into how sensitive SF is to compression and dynamical timescales. Spitzer Space Telescope observations in the mid-infrared have the ability to see through obscuring dust and provide a complete SF census on these scales in nearby galaxies, so the prospects are exciting in the next few years.

Squeezing Out Stars

All of the models described above, form stars by compressing gas (albeit in more or less finely tuned ways). This recalls the Kennicutt (1989) observational result on the universality of the Schmidt Law over a range from isolated galaxies with modest SFRs to ULIRGs. Apparently, the first law of induced SF is - it's just the (large-scale) compression. More precisely, it appears that large-scale compression drives a turbulent cascade, which enhances star-forming compressions on the small scales (e.g., Krumholz & McKee 2005, and references therein). Because of the universality of the cascade, this process doesn't necessarily depend much on the details at the large and small scales.

In the case of ULIRGs the spectacular response is the result of spectacular angular momentum transport and compression in the major merger. For rapid or distant encounters the most that can be achieved are relatively small compressions in bars and waves. It is worth recalling that basic tidal forces stretch along the line of galaxy centers and compress in the perpendicular directions. For an approximately two-dimensional disk this means (very roughly!) stretching in one dimension and compressing in one dimension. Alternately, in terms of a simple impulsive torque, it means that angular momentum is added to one side of the disk (stars are pulled ahead in their orbits), and subtracted from the other side (stars are pulled back). Thus, net compression across the disk is roughly balanced by stretching or torque-induced rarefaction. In either case, the global effects are modest for small amplitude disturbances, implying little induced SF, as observed in such cases. On the other hand, in strong disturbances, the torque-induced decelerations of the gas orbital motion, and subsequent compression of a significant fraction of the gas, may be enough to induce a strong starburst, regardless of the fate of the rest of the gas.

LIRGs seem to be a heterogeneous class, but they include interacting galaxies that are separated by about 1-2 diameters of the larger. In such cases the tidal effects are nonlinear. In addition, the gravitational forces within each disk will be augmented by dark matter from the other galaxy's halo, which is coextensive with the disk. (In fact, the importance of this effect must be estimated quantitatively, but generally it will become important at the separations cited.) The resulting global compressions can account for the SF enhancement. It appears that such cases play an important part in creating the observed anti-correlation between SFR and the separation of the two galaxies.

In sum, it appears that the general systematics of induced SF can indeed be accounted for, to first order, as the direct result of compression. The consequence of this, that we can learn little more about SF physics from large scale studies, is disappointing. On the other hand, it means that colliding galaxy model results are not sensitive to many details of the SF/feedback formulation, and that there is little point in trying to extend numerical resolutions to very small scales. (However, we will eventually have much higher observational and modeling resolutions, which would allow the study of the cloud turbulent cascade, and the full effects of the non-equilibrium interaction environment. The point is that modest resolution improvements will not help much.)

We conclude with a brief mention of some possible exceptions or refinements to the “it’s just compression” rule. The first might be found in the environment of core starbursts. If these are triggered by strong shocks, or with a sensitive threshold, then they may turn on rapidly. If, instead, they obey the Schmidt Law they will turn on more slowly if the central gas mass and density accumulate slowly. Generally, current spectral synthesis techniques are not able to provide SF histories that are accurate enough to distinguish. That is, except in a few nearby starburst cores, where the evidence seems to favor rapid turn-on of local density concentrations (because of the small age spreads within these concentrations, e.g., Harris et al. 2004). Similarly, the study of core burst turnoff might be enlightening. There seem to be regions in the core of M82 where the cloud system is disrupted, SF is turned off, but pressures and gas densities remain high (Mao et al. 2000 and references therein). The existence of such regions may necessitate at least a caveat in the Schmidt formulation.

We might be able to derive more information by studying SF within and behind density waves in disks. Spiral waves are ubiquitous, but ring waves produced in direct galaxy collisions are simpler. Asymmetric rings produced in slightly off-center collisions are the most interesting because they are still simple, but the wave amplitude varies continuously with azimuth. This is an excellent environment for confronting threshold versus continuous theories, at least if the compression in part, but not all, of the ring exceeds the threshold. To date, there is some evidence in support of thresholds, but not without complications ranging from incompletely known obscuration to unknown details of the collision parameters. The primary example is the Cartwheel ring with large variations of SFR and cluster populations around the ring, but with uncertainty about the details of the collision, and no old star component in the ring to provide independent information about wave amplitude as a function of azimuth (Appleton & Struck-Marcell 1996). With its relatively high resolution and ability to see through much obscuration, the Spitzer space telescope could resolve these ambiguities in carefully chosen systems.

There are many more examples of how to get beyond the simple compression law and the first-order theory of induced SF, and such work should become increasingly important in this field.

1.3 Environmental Effects

We have seen that the study of galaxy collisions is a relatively young, but rapidly maturing field. Thus, it is understandable that most progress to date has been in understanding the most spectacular collisions, ULIRG/major mergers, and the nature of some of the closest systems which can be studied in detail. Most of the latter occur in quite small groups like our own local group. However, studies of collisions in other environments date back to Spitzer & Baade (1951), and their number has been increasing recently.

Fig. 1.8. Arp (1966) atlas image of Arp 120 (NGC 4438), a Virgo cluster system in collision, with a starburst galactic wind, and likely also experiencing environmental effects. See Boselli et al. (2005) and Kenney & Yale (2002) for details.

1.3.1 Cluster Bustle

At the opposite end of the spectrum from the local group environment is that of massive, dense clusters of galaxies. It will suffice for our purposes to briefly note the different processes in this environment relative to that of local groups. These differences include: high speed collisions, galaxy 'harassment', ram pressure stripping, 'strangulation,' and induced slow collisions (see Figure 8).

Spitzer & Baade (1951) first suggested that high velocity collisions in galaxy clusters might have little effect on the stellar components, but could blast away the overlapping parts of gas disks. This is because the typical random galaxy velocities in clusters of up to several thousand km/s, are not only highly supersonic for the intercluster gas, but are in excess of normal disk escape velocities. Generally, we expect a moderation of tidal gravitational effects, but in some cases a drastic increase in hydrodynamic effects.

High-speed collisions may have weak gravitational effects, but encounters are much more common in the cluster environment. Thus, in the aggregate, tidal effects are not negligible in clusters. The cumulative effect of many weak (high-speed or distant) galaxy-galaxy interactions in clusters, as well as perturbations from the cluster potential, and possibly from intermediate scale sub-structure is called 'harassment' (see Moore et al. 1996, Moore et al. 1999). In recent high resolution numerical studies of the growth of moderate clusters, Gnedin (2003a,b) has shown how this process can secularly erode galaxy halos, thicken moderate mass stellar disks and truncate SF, and destroy small disks.

Ram pressure stripping (RPS) by the intra-cluster medium can have somewhat similar effects on disks. RPS is an interesting subject, with a number of recent developments, and worthy of a review of its own. Thus, it is beyond the scope of this review, except for a few comments. First of all, long time residents of dense galaxy clusters were probably stripped long ago, so RPS is most relevant to gas-rich galaxies falling into the intra-cluster medium for the first time. X-ray satellites have provided much evidence that the infall of galaxy groups into clusters and cluster-cluster mergers are still common events (Mushotsky, 2004b). Once the intra-group medium is stripped in such interactions, individual disk galaxies are vulnerable to RPS. RPS of spheroidal galaxies has been studied for 30 yrs., but in the last 10 yrs. a small literature on stripping of disk galaxies has blossomed.

The outermost parts of gas disks are stripped promptly, and slower interactions continue for some time. Slow viscous interactions at the edge of disks moving face-on into the intra-cluster medium has recently been studied in detail by Roediger & Hensler (2005). The three-dimensional dynamics in tilted cases have been modeled in several recent papers (Abadi, Moore & Bower 1999, Vollmer et al. 2000, Vollmer et al. 2001, Schulz & Struck 2001). Schulz and

Struck, in particular, pointed out that if the gas disk is not promptly stripped, it can nonetheless be displaced relative to the stellar disk and the halo center. The displaced gas disk experiences tidal compression (perpendicular to the disk plane) and asymmetric torques in the tilted case, which generate spiral waves. The waves transfer some gas and much angular momentum outwards, where it is stripped. The remaining gas, with less angular momentum, compresses radially, which “anneals” it against further stripping. The various compressions should induce SF. The tidal forces and induced SF are much like those in galaxy collisions. Thus, after the stripped material is gone, it could be difficult to discern whether excess SF is the result of RPS, a minor merger, or harassment. In fact, since these processes could work simultaneously, the question may be academic.

Vollmer and Schulz and Struck emphasized another aspect of stripping: some of the removed material can later fall back onto the disk. This can occur either when the galaxy moves into regions of lower intra-cluster medium densities, where the levitating pressure is reduced, or when gas clouds move into the disk ‘shadow’ where the pressure is also reduced. In either case we would expect effects akin to those of mass transfer in galaxy collisions.

Strangulation is a weaker cousin of RPS. It is the process of removing the potential feedstock of disk SF, gas in the galactic halo, usually via RPS (Larson, Tinsley, & Caldwell, 1980). The feedstock could include gas blown out of the disk by supernovae or stellar or galactic winds, it could include gas tidally removed from companions, or primordial gas falling into the halo for the first time. This process is likely to be most important in the young universe, when there is still much gas outside of galaxy disks, but it also hampers gas recycling from dying populations in cluster galaxies.

1.3.2 Cluster Slow Dance

A final process that may be very important in cluster environments is induced slow encounters in infalling groups. Recent studies of the Butcher-Oemler effect (see review of Pimbblet 2003), which is an excess of blue galaxies in clusters at redshifts of less than 1, provide evidence that many of the blue galaxies are mergers or interacting (also see Zabludoff et al. 1996, Hashimoto & Oemler 2000, Ellingson et al. 2001, Goto 2005). It seems unlikely that high speed interactions could be responsible for this effect. Mihos (2004) has emphasized that large-scale cluster formation models show that slow interactions continue to occur even in large clusters, and are quite common during cluster formation. He also notes that slow encounters can occur in groups or small clusters with modest velocity dispersions falling into large clusters (also see Poggianti et al. 2004).

This is an interesting phenomenon that has not been much investigated. Mihos notes that a number of different processes may be involved and it may be impossible to disentangle them. For example, tidal forces from the cluster potential could perturb orbits in the infalling group inducing interactions, and intracluster medium annealing could induce increased SFRs. Personally, I suspect these are secondary processes.

At least for galaxies that fall through the cluster core the primary process may well be gravitational shocking, which depends directly on the cluster potential rather than indirectly or on the derivative of the potential (tidal forces). Consider the relatively simple example of a galaxy group containing about 30-100 galaxies, falling into a large dense cluster. Cold dark matter structure formation models predict a common density profile across the range of structures from galaxy halos to the dark halos of large clusters, and observational tracers (e.g., intracluster starlight, see Feldmeier et al. 2002 and references therein) show good agreement with profile functions derived from these simulations, like the popular NFW profile (Navarro, Frenk, & White, 1997). Then it is reasonable to assume our example group and cluster have similar density profiles, though not necessarily with the central cusp of the NFW profile.

The observations also suggest that the central density decreases slowly with mass in dark matter halos. We might, for example, model our large cluster after Abell 2029, whose mass profile was studied in detail by Lewis, Buote, & Stocke (2003). They find a mass of about $9.2 \times 10^{13}/h_{70} M_{\odot}$ contained within a radius of $260/h_{70}$ kpc, yielding a central density of $0.0052 M_{\odot}/\text{pc}^3$. As an example of a group, on the other hand, we can take a 'poor' group like those studied by Zabludoff & Mulchaey (1998). These groups have virial masses of about $7 \times 10^{13}/h_{70} M_{\odot}$ within radii of about $300/h_{70}$ Mpc. The authors estimate that 80-90% of the virial mass is in the group halo, so the mean group halo density is about $0.0022 M_{\odot}/\text{pc}^3$. These numbers are meant to be representative, not precise. Group parameters, e.g., in compact versus poor groups, could easily range over factors of a few. Nonetheless, the message is clear that passing through the cluster core would substantially increase the instantaneous group halo mass.

Moreover, the time to pass through the core is of the same order as the group dynamical time. We can estimate the former by dividing the core radius above by a typical cluster velocity of about 2000 km/s; the result is about 300 Myr. The free fall time at the edge of our example group is about 200 Myr. Therefore there is time for group galaxies to be pulled into a much denser and compact configuration. For roughly comparable group and cluster halo core densities, galaxies could be pulled in to roughly half their previous distance from the core, increasing the galaxy density by nearly an order of magnitude and their collisions by about a factor of 100 (density squared).

Like stars in clusters that pass through the galactic disk, when the group leaves the cluster core, and gravity is reduced, the galaxies will fly outward. (This is also like collisional ring galaxies.) However, collisions between galaxy halos are stickier than those between cluster stars. During the compression period, along near parallel but converging trajectories on the way down, encounters are likely, and there is time for dynamical friction to dissipate relative orbital energy. The result would frequently be a fairly slow interaction and eventual merger.

Considering all the various ways that clusters accelerate galaxy evolution, one can view life for average galaxies in small local groups as more or less a holding pattern, or at least a matter of slow maturation. Evolution doesn't begin in earnest until they fall in a larger group or cluster; the classic tale of youth leaving the farm for the big city.

1.4 Interactions and Galaxy Evolution

Galaxy collisions drive galaxy evolution, but how much compared to other processes like the passive conversion of gas to stars in isolated galaxy disks or compared to other dynamical processes like ram pressure stripping? Also, how does the role of collisions change with cosmological epoch?

To begin, we note that it has become quite clear that at least some massive galaxies and massive disk galaxies, in particular, formed very early, and had already attained a respectable age by redshifts of 1-2 (see review of Spinrad 2004). From a practical point of view, this means that observations must push to very high redshifts to see big evolutionary changes. We will come back to what has been seen in a moment. This fact has also been taken as evidence that at least some galaxies formed in a rapid monolithic collapse, rather than building up steadily in a prolonged sequence of mergers.

1.4.1 Models of Structure Buildup

What do theory and cosmological structure formation simulations lead us to expect? Currently, hierarchical build-up, Λ CDM models (i.e., models with cold dark matter plus “ Λ ” dark energy) in the “concordance cosmology” are the dominant paradigm. This picture suggests the occurrence of many mergers of small building blocks in the earliest stages, and continuing mergers thereafter. Moreover, recent analysis shows that it is possible to form some massive galaxies, including disk galaxies, at early times in these models (Nagamine et al., 2005).

Thus, part of the solution to the paradox of early massive galaxy formation is that fully nonlinear Λ CDM models do not yield exactly the same results as simple, analytic hierarchical structure formation models. Early massive disk galaxies may be a roughly 2σ outcome of the simulations, but that may be sufficient to account for the observations.

From another point of view, the early formation of massive disks allows for the possibility that major mergers form elliptical galaxies at early times, i.e., accounts for ellipticals containing only old stellar populations within the merger theory (see discussion in Schweizer 2005).

To return to the Λ CDM paradigm, another thing the simulations show us is that when substantial entities merge, not all their substructure is erased. In fact, the absence of hundreds of dwarf satellites around the Milky Way has been cited as a problem for this kind of model (e.g., Klypin et al. 1999). However, RPS in the hot halo, tidal disruption, and collisions with the galactic disk may have destroyed many of the leftover building blocks. Indeed, digesting the leftovers may be an important secondary evolutionary process, operating alongside the primary hierarchical merging process.

Thus, the picture of sequential buildup of galaxies via successive major mergers in the simplest hierarchical models is not the only one in which collisions and mergers are crucial. In more realistic models minor mergers and the accretion of numerous small companions play important roles. Such lesser collision events are probably very common in groups and clusters. As in solar system formation,

“core accretion” may be as important as monolithic collapse and hierarchical buildup.

1.4.2 Observations of Evolution

Let us return to observation. As in the case of induced SF discussed above, there are two approaches - study of the statistical properties of large samples, or study of individual objects in detail. In the last decade there have been a great many surveys to provide data for the first type of analysis (see the overview of Irion 2004). These include Hubble Space Telescope projects like the Medium Deep Survey, the Hubble Deep Fields North and South, and most recently GOODS (the Great Observatories Origins Deep Survey), carried out in collaboration with the Chandra Observatory and the Spitzer Space Telescope (see special issue of the *Astrophysical Journal Letters*, Jan, 10, 2004), and GEMS (Galaxy Evolution from Morphology and Spectral energy distributions, e.g., Bell et al. 2005).

The science and observing techniques of deep field survey and high redshift studies in general are well beyond the scope of this review. This is also not the place to consider the many different classes of high redshift galaxies in any detail. These topics have become the subject of wide interest and a burgeoning literature. However, specific products of these studies, like the merger rates, the cosmic star formation rate and mean morphological statistics as a function of redshift, can provide information on the history of galaxy collisions.

Merger Rate versus Redshift

The differing predictions of the different models of galaxy formation, and the interest in the role of major mergers/ULIRGs, have motivated a continuing interest in the merger rate as a function of redshift. For example, the CNOC cluster galaxy redshift project has reported quite modest evolution in the merger rate at redshifts less than 1 (see Patton et al. 2002 and references therein). Specifically, Patton et al. examined a sample of 4184 galaxies, found 88 galaxies in close pairs, and derived a merger rate of $(1+z)^{2.3\pm 0.7}$.

This result of low (and not rapidly changing) merger rate is confirmed by several other recent studies, including the Caltech Faint Galaxy Redshift Survey (Carlberg et al., 2000). Moreover, Lin et al. (2004) report initial results of the DEEP2 survey, in which they find a merger rate of $(1+z)^m$ with exponent of $m = 0.51 \pm 0.28$ assuming mild luminosity evolution, or $m = 1.6 \pm 0.29$ assuming no luminosity evolution, since $z = 1.2$. They note that this implies only 9% of L_* galaxies have undergone major mergers over this redshift interval. Using deep infrared observations from the Subaru telescope Bundy et al. (2004) found that the fraction of close pairs (which usually define the merger rate in these studies) increases “modestly” to only about $7 \pm 6\%$ at $z \simeq 1$. This is less than that found by typical optical studies, and they note that the optical studies may be “inflated” by unrepresentative “bright star-forming regions.”

Going in the other direction, Lavery et al. (2004) find a very rapid increase in the number of colliding ring galaxies with redshift. Head-on ring galaxy collisions

generally result in merger, so if the rings represent a small randomly chosen fraction of all mergers, this would imply a very rapidly evolving merger rate. On the other hand, if the number of ring galaxies increases much more rapidly with redshift than other types of merger, one wonders why?

For reference, we note that Xu, Sun, & He (2004) recently used data from the 2MASS near infrared survey to estimate the local merger rate; they found the fraction of close major merger pairs to be $1.70 \pm 0.32\%$. For completeness, we note that at the time writing, merger rates based on the Sloan Digital Sky Survey or the 2dF survey have not been published, though an initial atlas of SDSS merger pairs has (Allam et al., 2004). In the coming years it will be very interesting to see statistically significant estimates of the merger rate extended to well beyond $z = 1$.

Cosmic Star Formation

Estimates of the mean SFR as a function of redshift are usually based on color or emission line indicators (as opposed to the morphology used to estimate merger rates in the pair surveys). In recent years there have been surveys in a variety of wavebands. Cram (1998) carried out a novel radio continuum survey and found a local SFR of about twice the optical $H\alpha$ value - $0.025 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. He found a value about 12 times greater at $z \simeq 1$. An analysis based on the 2dF survey also found an strong increase ($\propto (1+z)^b$, with $b < 5$) back to $z \simeq 1$, and a more moderate increase at redshifts of 1-5 (Baldry et al., 2002). Analyses based on SDSS data come to similar conclusions (Glazebrook et al., 2003; Brinchman et al., 2004). The HST STIS Parallel Survey found an SFR at $z \simeq 1$ of $0.043 \pm 0.014 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, based on [OII] emission (Teplitz et al., 2003), which is lower than most of the previous results.

The CADIS survey found SFR decreased by about a factor of 20 between redshift 1.2 and the present, and the authors note the agreement of their extinction corrected results with far infrared results (Hippelein et al. 2003, also see the Herschel Telescope survey of Glazebrook et al. 2004). Results from the Gemini Deep Deep Survey indicate that the SFR was about 6 times higher at $z = 2$ than at present (Juneau et al., 2005). One of the most dramatic changes in SFR was the factor of 30 found in a GALEX (Galaxy Evolution Explorer satellite) ultraviolet survey between $z = 1$ and the present (Schiminovich et al., 2005). Ultraviolet luminous galaxies may not very representative of the cosmic SFR, but they could be related to colliding galaxies.

The newest and deepest surveys indicate that SFR declines from a peak at moderate redshifts to lower values at the highest redshifts. Bundy et al. (2004) identify and study 54 galaxies in the Hubble Ultra Deep field and conclude that the SFR at $z = 6$ is about 6 times less than at $z \simeq 3$. Heavens et al. (2004) come to similar conclusions about the general history of SF on the basis of an analysis of SDSS and other surveys. Juneau et al. (2005) describe the situation as a cosmic starburst at $z \simeq 2$.

Very recently, survey results have revealed the phenomena of “downsizing,” wherein the most massive galaxies form first, and most of the SF takes place

in progressively smaller galaxies as time goes on (e.g., Poggianti et al. 2004, Bouche & Lowenthal 2005, Juneau et al. 2005, Le Borgne et al. 2005, Shapley et al. 2005). Bundy, Ellis & Conselice (2005) argue (based in part on GOODS data) that downsizing also proceeds from early to late Hubble types, and that merging plays a key role. The implication is that there is a mass dependence in the merger rate at any given epoch.

These new cosmic SFR results provide very interesting inputs to the story of galaxy evolution. However, the relation of these results to interactions and mergers remains to be clarified. Actually, the same is true of the merger rate results, which are not sensitive to many minor mergers or other interaction phenomena.

Morphology versus Redshift

For an outsider the phenomenology of high redshift galaxies, which is much constrained by detection techniques, is a daunting jungle of jargon. Moreover, the relation between increasingly elaborate simulations of structure formation and the observations is complex. With rapid advances on both fronts, and increased efforts in analysis and synthesis, we can expect much more clarity in the coming decade (see review of Spinrad 2004 for a lucid current discussion). For the present we focus on a few simple questions. Are we directly observing galaxy evolution, i.e., the changing appearance (build-up) of galaxies with redshift? Are collisions and mergers an important part of this evolution?

Fig. 1.9. Conselice et al. (2004) sequence of “low density objects” at varying redshifts, illustrating the development of Hubble type galaxies. (Courtesy C. Conselice)

There is much new evidence in favor of an affirmative answer to both questions (see commentary of Conselice 2004, with further details on GOODS data in Conselice et al. 2004). To say it a bit more emphatically, these papers and those referenced within them suggest that we may be beginning to acquire the observations that directly show the buildup of typical Hubble sequence galaxies (see Figure 9).

There is much information to be found in the literature on the properties of individual high redshift objects (individual galaxies and clusters). We cannot review this literature here, and refer the reader to the review of Spinrad (2004). Instead, let us return to the subject of massive, or at least luminous, galaxies at high redshift, and in particular, the interesting classes of extremely red galaxies and submillimeter galaxies (or SCUBA galaxies, after the detector on the James C. Maxwell Telescope). The latter are very infrared luminous, high redshift objects (e.g., Conselice, Chapman, & Windhorst 2003, Genzel et al. 2004, Swinbank et al. 2004, Pope et al. 2005). Until recently, only a few were known, but recent deep searches are beginning to detect a substantial number (Greve et al. 2004, Smail et al. 2004, Wang, Cowie, & Barger

2004). It appears that most of these objects are either dust obscured quasars or high redshift LIRGs or ULIRGs, with perhaps about 2/3 being the latter (Conselice, Chapman, & Windhorst 2003, Neri et al. 2003, Smail et al. 2004, Swinbank et al. 2004). As with their local counterparts, the LIRGs and ULIRGs are generally mergers or mergers-in-progress (see Georgakakis et al. 2005).

It appears that the submillimeter LIRGs are much more common than present day LIRGS, and that they generate a substantial fraction of the IR background (e.g., Genzel et al. 2004, Wang, Cowie, & Barger 2004). They have typical redshifts of 2-3, and thus, coincide with the peak of the cosmic SFR. They may be well represented among the most luminous galaxies in that peak, but the evidence is preliminary. These results are beginning to provide direct evidence that major mergers, if not hierarchical buildup, were major contributors to galaxy evolution and the cosmic star formation rate at these redshifts.

The submillimeter galaxies may be related to another high redshift class, the Lyman Break Galaxies (Shu, Mao, & Mo, 2001). However, few of the latter are detected as the former (Chapman et al. 2000, but note the outstanding exception Westphal-MMD 11 discussed in Chapman et al. 2002). The deep ISO (Infrared Space Observatory) ELAIS survey also found a number of ULIRGs at $z < 1$ (Rowan-Robinson et al., 2004). These objects may bridge the gap between local ULIRGs and SCUBA galaxies. Recent observations with the Spitzer Space Telescope show that SCUBA galaxies are generally detectable at 24 microns, but with a wide range of mid-infrared colors (Frayser et al., 2004). Spitzer observations also promise to delineate active nuclei from starburst powered submillimeter galaxies (Ivison et al., 2004). All of this work should contribute substantially to our understanding of the “ULIRG rate” as a function of redshift (see the review of the cosmic evolution of luminous infrared galaxies by Sanders 2004).

Before submillimeter galaxies were discovered, observers were already very interested in “extremely red objects” at high redshift. Naively, one might expect to find more and more blue galaxies at high redshift, and as described above, this is generally the case. In this context, finding very red galaxies is surprising. On the other hand, with a knowledge of dust-enshrouded starbursts in ULIRGs, maybe this is not so surprising, but are EROs ULIRGs? Recent studies suggest not, but rather many of them may be the already (at typical redshifts of $> 1-2$) old, red progenitors of present-day early type galaxies (e.g., Franx et al. 2003, Förster Schreiber et al. 2004, Yan & Thompson 2003, Yan et al. 2004, Yan, Thompson, & Soifer 2004 Bell et al. 2005).

Redness and age are relative terms. The typical age of the stellar populations in these galaxies may be about 1 Gyr, which locally would not be described as an old, red population. However, at the high redshifts where these galaxies are found, the age of the universe when the light was emitted was only a few Gyr or less.

Nonetheless, a fraction of the extremely red objects may be ULIRGs. Yan & Thompson (2003) in an HST study of the morphology of a sample at redshifts of about 1-2, estimate that about $17 \pm 4\%$ of the objects are mergers or interactions. However, for the majority dominated by older stellar populations we will have to seek merging and interacting progenitors at still higher redshifts.

In conclusion, the above paragraphs describe the great advances that have been made in recent years in studies of galaxy evolution at high redshift. This work is impressive, but it is still hampered by resolution, sensitivity and statistical limitations. There are hints that mergers and interactions are important at all stages, but there is a great deal more work to do before we understand the details.

1.5 Archaeology

As discussed in several places above, models of particular classes of collision have gotten quite sophisticated at this stage in the development of the field. However, in the case of specific systems this generalization is true only for systems that have experienced only one close encounter, or where the time between encounters is so long that the signatures of the first encounter have been largely erased. The one notable exception to this caveat is the M51 system, which may well be the result of two close encounters (see discussion in Struck 1999).

There are wave and tidal morphologies characteristic of cases with two close passes separated by a time interval of order the mean internal dynamical (e.g., rotational) time in the primary disk. Struck-Marcell & Lotan (1990) demonstrated this explicitly in the case of colliding ring galaxies, and it is quite clear in a number of merger models. It also seems likely that a number of objects in the colliding galaxy atlases require two close encounters to explain their morphology (e.g., the M51 types).

Another kind of double encounter that has so far received only exploratory attention is the case when a galaxy falls into a group and has close encounters with more than one group member.

The study, and ultimately the classification, of double encounter morphologies and merger remnant systematics is one that could advance a long way in the next decade. There are no insurmountable technical difficulties preventing advancement, though a great deal of numerical effort will be required. Not only would a large number of simulations have to be run, but they would have to be fully self-consistent models. The ability to decipher two stages of development in colliding systems would represent a substantial advance in galaxy archaeology.

1.6 Coming Attractions

For the patient reader, it should be clear from the above that this field has had a very exciting first fifty years or so. It must be admitted that this is in large measure due to outside influences. Like all other parts of astronomy, the study of galaxy collisions has ridden the breaking waves of the vast technological advances in detectors, satellite engineering, and computational resources. The subject has received further boosts from the enormous interest in parallel areas of study within the fields of galaxy evolution and star formation, and has

contributed back to those areas. Never again will so many new, information-rich wavebands be opened. On the other hand, wide scientific frontiers remain to be explored with the aid of continuing increases in observational sensitivity, resolution, computational power, and synergistic interactions with allied fields.

In the last few sections I have attempted to clarify where we stand on the key questions posed at the end of Section 1. The first group of questions concerned the role of galaxy collisions within the overall picture of galaxy formation and evolution. Toomre's work in the 1970s held out the possibility that collisions and interactions were a dominant process, and that possibility has energized the field for most of the time since. However, there have always been counter-arguments. One of the strongest in the present era is the modest increase in the merger rate with redshift found in deep surveys. On the other hand, the relations between cosmic SFR or ULIRG numbers and redshift tell a different story. Downsizing may be an important part of the resolution between the different stories. Presently, we only see a hazy outline of the full portrait of the relation between galaxy morphology and redshift. Progress has been rapid in these areas, and we can expect a great deal more in the next decade or two. For optimistic theorists the answers are already available (if not yet fully extracted) from large-scale numerical models of structure formation.

The second group of key questions concerned the role of environment on collision dynamics and evolutionary processes. Although the study of galaxy collisions in groups and clusters has been around since Spitzer and Baade's work, it is being reborn in the present era. There is currently a great deal of interest in groups and clusters among observers, with new tools to facilitate that work. The theory and modeling side of this area is more complicated than that of binary collisions and mergers because of the interaction between several strong dynamical processes (e.g., ram pressure stripping, group/cluster direct or tidal effects, etc.). Nonetheless, it is also reasonable to expect significant advances in this area on decadal timescales.

The third group of questions concerned the orchestration of SF and nuclear activity by large-scale interaction dynamics. In the recent past it seemed likely that progress in this area would be hindered by the interplay of a number of complex dynamical processes. It now appears that this view was overly pessimistic. Due to the universal properties of turbulent interstellar gas, it now seems that wherever you compress cool gas you will enhance SF (in quantifiable ways). Thus, large-scale orchestration is mostly about gathering and compressing gas; feedback effects are mostly about heating and dispersing gas. There are more complexities than this, but the big picture does not appear impossibly complicated. Work in the coming decades should provide a much firmer foundation for this scenario, and a much better understanding of the exceptional cases.

So the reviewer's crystal ball conveys a bright outlook for answers to the first three groups of key questions. The glass gets more murky when we ask the last couple of questions. The fourth group of questions concerned secular effects and the fifth was about the archaeology of individual systems. Of course we can model long-term processes on the computer with ever more precision. However,

as discussed in several contexts above, it is hard to compare to observation either statistically or in individual cases.

That said, I would expect more progress from statistical studies, even though that will require the relatively slow accumulation of good datasets on numerous systems, for example acquiring large libraries of faint tidal structures in numerous galaxies. That slow work is not likely to be taken up by professional astronomers, but with the increasing availability of moderate sized telescopes and sensitive CCD detectors, it could become the realm of serious amateurs or robot astronomers.

It seems possible that the majority of key questions discussed above will be resolved within the next 50 years. However, new phenomena will be discovered, and more detailed understandings will be demanded. Recent, and possible near-future, examples support the point. As an example, consider the exotic forms or products of SF, like the ULX sources, and the possibility that some of these X-ray sources are intermediate mass black holes formed in dense, young star clusters. It will take a lot more observational work to explicate this phenomenon, and probably new theoretical insights to explain it. We could use several more Chandra observatories!

There are also still a few wavebands that remain largely unexplored, including low-frequency radio waves, very high-energy gamma rays (new more sensitive Cherenkov telescope arrays are presently coming on line), and gravitational waves of many frequencies. Equally exciting is the prospect that within a few decades our understanding of galaxy disk hydrodynamics may advance to point that we understand both the small scale, relatively short time, weather changes occurring in isolated disks, and the longer term climate changes wrought by various types of collisions and interactions. However, there is a great deal of work to be done before goal is achieved.

1.7 Acknowledgements

I am very grateful to my research collaborators for teaching me much about colliding galaxies and related topics. I want to thank Bev Smith, in particular, for making a number of helpful suggestions on this manuscript. I'd also like to acknowledge support from a NASA Spitzer GO Cycle 1 grant.

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