Case Studies of Mass Transfer and Star Formation in Galaxy Collisions

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Abstract.
The amount, timing and ultimate location of mass transfer and induced star formation in galaxy collisions are sensitive functions of orbital and galaxy structural parameters. I discuss the role of detailed case studies and describe the results for two systems, Arp 284 and NGC 2207/IC 2163, that have been studied with both multiwaveband observations, and detailed dynamical models. The models yield the mass transfer and compressional histories of the encounters and the "probable causes" or triggers of individual star-forming regions.

1. Introduction: The Case for Case Studies

There are two general approaches to the study of the complex effects of galaxy collisions. The first is statistical, such as the study of particular properties of a reasonable sample of interacting galaxy systems, or a grid of numerical models covering some range of initial conditions. The second approach is the case study, the detailed investigation of a particular collisional system.

The first approach is the path more frequently followed, in the literature. A great deal can be learned from observations of the global properties of many systems, which are easier to acquire (individually), than the high sensitivity, high resolution, multi-wavelength data needed for a good case study. In the realm of simulations, the statistical approach also has many attractions. For example, in many regions of parameter space the model outcomes are quite sensitive to collision parameters, so converging on the correct parameters can be a prolonged task. (At the same time, such sensitivities can go a long way toward guaranteeing the uniqueness of a successful model.)

One of the greatest successes of the statistical approach (spurred by IRAS results) in the last two decades is an understanding of how gas is redistributed in major mergers, and how ultra-luminous, super-starbursts result. Insights obtained from numerical models (e.g., Barnes and Hernquist 1972) also played a crucial role.

Statistical studies also provide important inputs to the topics of mass transfer and induced star formation (SF) in galaxy collisions. Even aside from studies of luminous major merger remnants, there has been much work on the questions of whether and by how much SF is enhanced by interactions. The early color analysis of Larson and Tinsley (1978), suggested color dispersion enhancement,

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rather than bluer colors. The nuclear spectrophotometry by Keel et al. (1985, also Kennicutt et al. 1987) suggested enhancement of nuclear SFRs.

More recently, Bergvall et al. (2003 and earlier work cited therein) find no difference in the broadband colors of sample of 59 interacting systems relative to a control sample of 38 galaxies. They do find a moderate increase in central SF and far-infrared emission in the interacting sample. They argue that earlier work, claiming greater enhancements was biased towards IR luminous merger remnants, in contrast to their sample. Barton, Geller & Kenyon (2003a, and Barton Gillespie, Geller & Kenyon 2003b) obtained B and R band photometry and optical spectroscopy of 190 galaxies in pairs and compact groups. They also found enhanced core SF, and a number of post-starburst, as well as starburst cores. In addition they found an anti-correlation between galaxy separation and SF, and suggested starbursts were preferentially triggered at closest approach, decaying thereafter.

These statistical studies shed the most light on nuclear SF, suggesting that it has a short duty cycle, and perhaps requires a relatively strong disturbance to funnel the gas fuel inward (Keel 1993). In this symposium we have seen some beautiful observations of SF in tidal structures. The statistical studies suggest that such SF does not add up to a very large amount. This echos the result of the statistical study of Schombert, Wallin & Struck-Marcell (1990) on the colors of tidal bridges and tails. Yet, in tails it is the nature, rather than the quantity of SF that is of interest. Case studies with more details on the SF history, as well as instantaneous rates in individual SF regions are needed to address the many unanswered questions.

The processes of tidal or splash mass transfer are very hard to study either individually, or statistically. We can observe the amount of gas between or outside the interacting galaxies, but how much has been transferred already, and how much will yet be pulled out? The statistical question can be addressed with models, but there have been few such studies. Wallin & Stuart (1992) gave us a survey and analysis of 1000 restricted 3-body encounters with mass transfer from a particle disk around the primary. These models evenly sampled a number of collision parameters, and quantified dependences, such as inclination, some of which had been known since Toomre and Toomre 1972 (see Struck 1999, Sec. 4.1). Howard et al. (1993) published a nice atlas of 86 N-body simulations (with rigid halos) of the effects of encounters on (2-d) disks. I produced a small model grid to study the hydrodynamics of colliding gas disks (Struck 1997).

Statistical studies show us the big picture, and give the average answer to big picture questions, but often leave us wondering about the specific mechanisms. Case studies provide detailed answers to some of those questions, but they require a large amount of high quality observational data, and a substantial modeling effort to interpret it. As yet, not many have been published. However, we can now optically resolve individual star clusters in nearby interacting systems, map tenuous gas distributions, and we have the computer power to do the modeling, so it is a great time for case studies. I will justify that statement with two examples.

2.   Case 1: Arp 284 (NGC 7714/15)

Bev Smith and I have been working for some years on this beautiful system (see Figure 1, and Smith & Wallin 1992, Smith et al. 1997, Struck & Smith 2003).
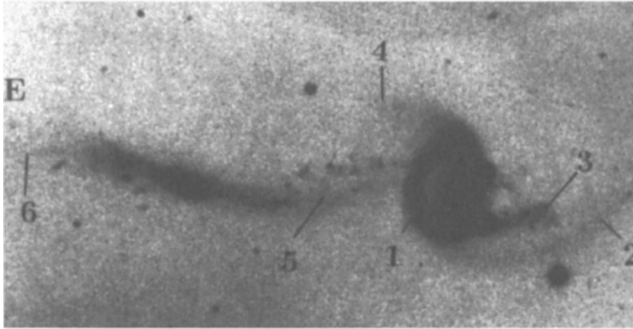

Figure 1.   Arp atlas image of NGC 7714/15 (Arp 284, NGC 7714 is on the right) from Struck & Smith (2003). Feature 3 is the inner SW tail discussed in the text.

It is an asymmetric collisional ring galaxy, with a substantial bridge connecting it to a nearly edge-on companion, and it also contains some distinctive tidal tails. It has a variety of features that make it an especially interesting 'case' for the study of induced SF and mass transfer. The primary has a prototypical starburst nucleus, but their is little evidence for recent SF in the ring wave, in contrast to most gas-rich collisional ring systems (see Appleton and Struck-Marcell 1996). The companion has a post-starburst spectrum. There are intriguing knots of recent SF in one of the countertails, and roughly in a line on the north side of the bridge. More than half of the gas mass is located outside the main disks, in the bridge and tails (Smith et al. 1997). In the bridge, there is an offset between the center line of the old stars, and that of the gas.

Lançon et al. (2001) have published detailed spectral evolutionary models of HST observations, so we have a good picture of the SF history of the nucleus of NGC 7714. In a word, this history seems to be characterized by repetitive bursts. Unfortunately, high resolution HST spectra are not available for extra-nuclear regions, or for the companion. (A. Lançon is working to obtain VLT data, however.)

We have recently published N-body hydrodynamic (SPH) models of this system that can account for nearly all of the observed morphological and kinematic features (Smith & Struck 2003). Successful models require a high inclination collision, which is somewhat prograde for galaxies. Such an orbit allows the simultaneous production of a complete ring, and the tails.

In terms of mass transfer we found that we could indeed fling a large fraction of the gas out of the two disks in such model collisions, and without unusual initial conditions, like especially extended gas disks. Specifically, our models put a somewhat larger gas fraction than observed into the great HI loop to the north, somewhat less than observed in the bridge, and a good deal in the companion countertail. This last feature is not isolated in the observations, except as a slight

eastern extension of the companion disk. The models suggest that it lies behind both the companion disk and the bridge, and cannot be easily distinguished.

Interestingly, we found that the bridge consists of several superposed, but dynamically distinct components. In addition to the two usual tidal components stretching from the near side of each galaxy towards its companion, there is also the superposed countertail of NGC 7715, and the remnants of an old tail winding around from the far-side of NGC 7715 to the primary (NGC 7714). Mass transfer onto the primary from this old bridge started before closest approach. Some of the early transfer material was incorporated into the primary disk, or in a plane very close to it, and subsequently flung out (again!) as the inner SW countertail. This feature, and the fact that the location and mass of some of the bridge components are very sensitive to initial collision parameters, illustrate the intricacies of mass transfer that can be found in detailed case studies.

Our models include simple feedback prescriptions that can tell us something about induced SF. The gas compression history can also suggest SF phenomena even when we don't really have enough particles to fully resolve them. Examples of the latter include the result that the (star-forming) inner SW countertail of NGC 7714 may consist of mass transferred material that has been compressed in the primary disk. Similarly, the models show that the old bridge component is overrun and shocked by a newer bridge component. This might account for the line of young star clusters on the north side. The feedback model further suggests that the companion experienced a starburst at closest approach, consistent with its post-starburst spectrum. It also suggests multiple bursts have occurred in the core of the primary, in agreement with the spectral synthesis results.

However, the exact timing and number of these bursts are not completely predictable. The models suggest that they could be driven by compressions from the (m=0) ring wave component of the disturbance, and fed by inward mass transfer resulting from the spiral component. On the other hand, repetitive starbursts in the gas-rich core are driven by the feedback terms even without an external disturbance. (This result derives from control runs and other unpublished modeling.) It is likely that the gas density in the core or its susceptibility to SF was less than in the models.

3.   Case 2: NGC2207/IC2163

I have been working on this galaxy with the 'ocular' galaxy collaboration (see Elmegreen et al. 1991, 1995a,b, 2000, 2001, Kaufman et al. 1997). The Hubble Heritage image of this graceful pair has been often reproduced. The models suggest that it has been one of the gentlest close interactions known. They further suggest that the companion approached from slightly above the primary (in the west), interacting with its outer edge, and then moving slightly below and to the north and then east of the primary. The encounter is retrograde relative to the primary, so its optical disk is not greatly perturbed, though its larger HI disk is.

The encounter is prograde and nearly in-plane relative to the companion, which is estimated to be about 60-80% of the mass of the primary. Encounters that strongly torque the disk produce long tidal tails, and also the transient ocular (eye-shaped) morphology from material that loses angular momentum
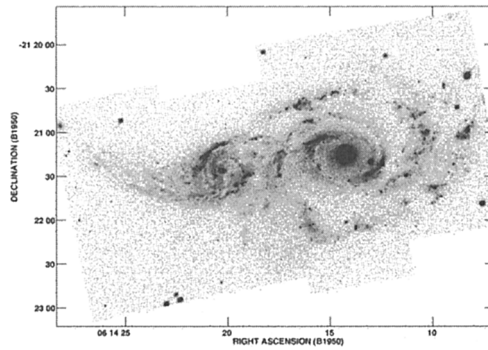
Figure 2.   NGC 2207/IC 2163 from Elmegreen et al. (2001); NGC 2207 is on the right.

(Elmegreen et al. 1991). This system is a prototypical example of that process of disk rearrangement. In addition, the models suggest that there is some moderate mass transfer from the companion to the primary, both presently and earlier in a glancing interaction on the west side. They also suggest that the collisional perturbation did not produce the spirals in the primary; they were almost certainly pre-existing.

Observationally, the recent star formation in this system is mostly extended (and beautiful!) with no excess in the galaxy cores. Specifically, the young star clusters are concentrated in the long spiral arms. In the companion, the young clusters are concentrated on the rim of the ocular. The tidal tail is younger and shorter than many we have seen at this symposium and is not presently the site of active SF. The models, projected into the future, indicate that it will grow!

The feedback models yield a bit more SF in the core of the primary than observed, but otherwise with the same widely distributed SF in the primary, and concentration of SF in the ocular and tidal tail of the companion. The models suggest some interesting patterns in the SF in the primary over the course of the interaction, but these must be further analyzed.

4.   Conclusions

What have we learned from these and other published case studies, and how do they complement the statistical studies? In the area of mass transfer, the generally good agreement between model and observational gas distributions in two very different cases - Arp 284 (extreme gas removal from the disks) and NGC 2207 (little perturbation of the primary disk) - is very encouraging. These general results also agree with expectations derived from exploratory model grids. The more detailed comparisons to observation in these two systems give us confidence that hydrodynamic models can quite accurately reproduce details of collisional morphology and kinematics on scales of about a few kpc. This could motivate further checks of model predictions, e.g., a metallicity study of the countertails of NGC 7714 to see if there is evidence of differences that might be expected if the inner tail gas came from the companion. Such specific predictions are not possible without detailed modeling of individual systems.

In terms of SF, case studies are required to model modes of SF that are either unique to a specific system, or nearly so. Possible examples from the cases above include the inner SW tail of NGC 7714 and, the line of SF regions on the northern edge of the Arp 284 bridge. Less unique examples, but still with system specific characteristics include the absence of SF in the NGC 7714 ring, SF in the rim of the IC 2163 ocular, and the scattered SF in the NGC 2207 disk.

The bulk of interaction induced SF in the universe occurs in merger remnants and the cores of unmerged collision partners. Statistical studies are ideal for studying the mean characteristics of this type of SF, and case studies would contribute little if this SF has a large stochastic component. However, understanding anomalous SF, like the examples of the previous paragraph, may be essential to understanding the formation of globular clusters and tidal dwarfs. These are minority populations, but still very interesting. In fact, answering the questions of how tidal dwarfs and globulars form, and also understanding the sytematics of wave induced SF in disks will require many detailed case studies.

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