Part 3. Ejection and Outflow Collisions between Galaxies

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The Evolution of Tidal Debris

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Abstract. Galaxy interactions expel a significant amount of stars and gas into the surrounding environment. I review the formation and evolution of the tidal debris spawned during these collisions, and describe how this evolution depends on the large scale environment in which the galaxies live. In addition to acting as a long-lived tracer of the interaction history of galaxies, the evolution of this material – on both large scales and small – has important ramifications for galactic recycling processes, the feeding of the intracluster light and intracluster medium within galaxy clusters, and the delayed formation of galactic disks and dwarf galaxies.

1. The Physics of Tidal Tails

The large-scale dynamical evolution of tidal debris is governed largely by simple gravitational physics. As first elegantly shown in simulations by Toomre & Toomre (1972) and Wright (1972), the tidal forces acting on spiral galaxies during a close encounter, coupled with the galaxies' rotational motion, draw out long slender "tidal tails" of gas and stars. An example of this process is shown in Figure 1. As the galaxies pass by each other on the first passage, tidal forces give disk material sufficient energy to escape the inner potential well. The symmetric nature of tidal forces means that streams are torn off both the near side and far side (with respect to pericenter) of the disks; the near side material forms a tidal "bridge" between the disks (which typically does not physically connect, depending on orbital geometry) while the far side material forms the tidal tails. The formation of tidal tails is a strong function of the orbital geometry – tidal tails are strongest in prograde encounters where the spin and orbital angular momentum vectors are (even moderately) aligned, while retrograde encounters yield weak tails at best. The length of the tidal tails is further pronounced due to the orbital decay of the merging pair (e.g., Barnes 1988), which causes the galaxies to "fall away" from their tails as they merge together.

Once launched, tidal tails are not in simple expansion. Figure 2 shows the kinematic structure of the tidal tails shown in Figure 1, observed 0.5 Gyr after the merger is complete. Most of the material remains bound to the remnant on loosely bound elliptical orbits, with only the relatively small fraction at the tip of the tails being unbound. The radial velocity curve shows this orbital structure well: the loosely bound outer portion of the tails are still expanding, while material at the base of the tails has already reached apocenter and has started falling back in towards the merger remnant. This velocity structure

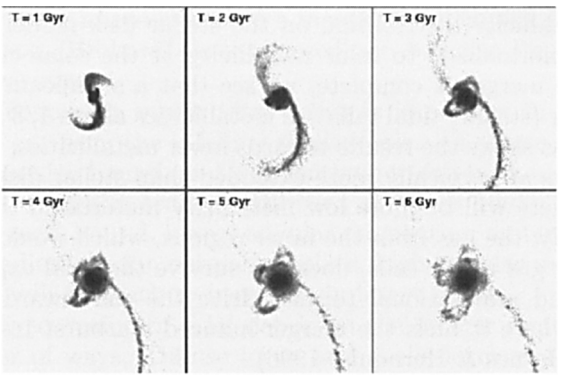

Figure 1. Evolution of the tidal debris in an equal-mass merger of two disk galaxies. Each frame is approximately 0.9 Mpc on a side.

results in a continual stretching of the tidal tails – they are long-lived and do not simply expand away, although their surface brightness drops rapidly due to this dynamical evolution (Mihos 1995). One important caveat to this description is the depth of the galaxies' potential well: a deep potential well provided by extended dark matter halos will result in less unbound material and a more rapid fall-back of the tidal debris to the parent galaxy (Dubinski et al. 1996, 1999; Springel & White 1999).

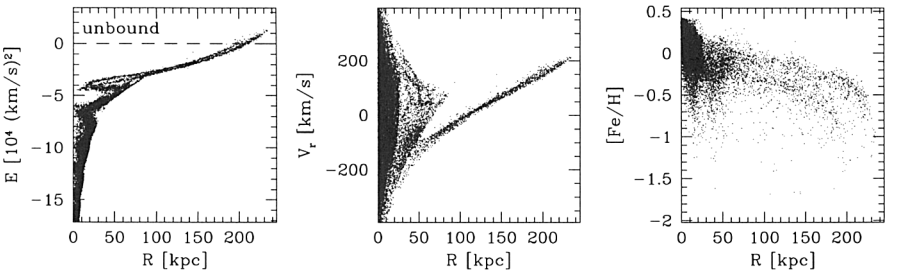

Figure 2. The structure of the tidal debris from Figure 1, shown 0.5 Gyr after the merger is complete. Left: energy structure, middle: velocity structure, right: metallicity distribution (see text).

The material forming the tidal tails comes from a wide range of initial radii in the progenitor disks. During close passages, tidal forces are effective at dredging up material from the inner disk and expelling it into the tidal debris. In the simulation shown in Figure 1, scaled to Milky Way sized progenitors, the extended tidal tails are formed from material originally outside the solar circle, while the loops and shells which fall back in the first Gyr after the merger include a significant amount of material from the solar circle and inwards. This "tidal dredge-up" means that tidal debris will be moderately metal rich, since it is not simply the outer parts of the disks involved. To demonstrate this effect,

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we imprint a metallicity distribution on the stellar disk model of d[Fe/H]/dR $= -0.05$ kpc^{-1}, normalized to solar metallicity at the solar circle. Observed 0.5 Gyr after the merger is complete, we see that a significant amount of the debris in the outer (stellar) tidal tails has metallicities above 1/3 solar. A similar exercise for the gas skews the results towards lower metallicities, for a number of reasons. Gas disks are typically more extended than stellar disks; for a similar radial gradient there will be more low metallicity material in the gas than the stars. Additionally, the gas from the inner regions, which would have provided higher metallicity gas in the tails, does not survive the tidal expulsion process; instead shocks and gravitational torques drive the gas inwards to the center of the remnant where it fuels the merger-induced starburst instead (Mihos & Hernquist 1996; Barnes & Hernquist 1996).

2. Galactic Recycling

While on large scales the evolution of tidal debris is largely a gravitational phenomenon, on smaller scales a variety of mechanisms can drive structure formation within the tidal tails. Overdensities can form in the tidal tails either through gravitational collapse of small scale instabilities in the progenitor disks (Barnes & Hernquist 1992) or by cooling and fragmentation of structure in the tidal expelled gas (Elmegreen et al. 1993). This has led to the suggestion that dwarf galaxies may form within the tidal debris of merging galaxies. Observations have detected a number of discrete, often star-forming, sources in the tidal debris of interacting galaxies (e.g., Duc, these proceedings); whether or not these are truly bound objects destined to become dwarf galaxies remains to be seen.

We can use simulations of interacting galaxies to make predictions for the properties of any tidally spawned dwarfs. Coming from material stripped from their progenitor disks, they should have moderate metallicities and travel on loosely bound, highly eccentric orbits (Hibbard & Mihos 1995). They are unlikely to have significant amounts of dark matter, since the kinematically hot dark matter will not collapse into the shallow potential wells (Barnes & Hernquist 1992) formed from small-scale instabilities in the tails. Finally, these tidal dwarfs may well show different generations of stellar populations, as they arise in a mixed medium of old stellar disk material and young stars formed from the gaseous tidal debris.

The dynamical stretching of the tidal debris means that it should be hard for these condensations to grow continuously. On small scales, bound structures can form, but continual accretion onto these structures will be limited by shear in the surrounding material. In this context, it is important to make a cautionary note about claims that large, tidally spawned HI complexes are often found preferentially at the end of optical tidal tails. Dynamically it is unclear why this would be – HI tails often extend much further out than the optical tails do, and there is no clear reason why the "end of the optical tails" should be a dynamically important spot. It is more likely that many of these objects are the result of projection effects. Tidal tails are curved, and a sightline which passes along the tangent point to a curving tail will not only give the appearance of marking the end of the tail, but also will project along a large column of HI,

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artificially giving the impression that a massive HI complex lives at the end of a tidal tail (see e.g., Hibbard, these proceedings, but also Bournaud et al. 2003 for an alternative view).

The other context in which tidal debris is important in galactic recycling is the return of gas from the infalling tidal debris. As shown in §1, material in the tidal tails remains bound, and will continue to fall back to the remnant over many Gyr. The return is ordered (Hibbard & Mihos 1995); the first material to return is the most bound, lowest angular momentum material, which will fall back to small radius. As the remnant evolves, high angular momentum, loosely bound material will fall back to increasingly larger radius.

This long-lived "rain" of tidal debris on the merger remnant manifests itself in a number of ways. Diffuse loops and shells form as the stars fall back through and wrap around the remnant, while the infalling gas can dissipate energy and settle into a warped, rotating disk (Mihos & Hernquist 1996; Naab & Burkert 2001; Barnes 2002), such as those found in the nearby elliptical galaxies NGC 4753 (Steiman-Cameron et al. 1992) and Centaurus A (Nicholson et al. 1992). The most loosely bound tidal material forms less-well organized structures outside of a few effective radii as it falls back, and may be the source of the extended HI gas found in shells and broken rings around many elliptical galaxies (e.g., Schminovich & van Gorkom 1997). More speculatively, if the returning gas can efficiently form stars, this process provides a mechanism for rebuilding stellar disks. For example, the gaseous disk inside the merger remnant NGC 7252 is rapidly forming stars (Hibbard et al. 1994), and may ultimately result in a kiloparsec-scale stellar disk embedded in the $r^{\frac{1}{4}}$ spheroid formed in the merger. If significant amount of tidal material exists to reform a stellar disk, it may even be possible for the remnant to eventually evolve towards a bulge-dominated S0 or Sa galaxy (e.g., Schweizer 1998).

3. Tidal Debris in Clusters

Many dynamical avenues are available to drive tidal evolution in cluster galaxies. The most obvious is the cluster potential itself, particularly for galaxies whose orbit takes them close to the cluster center (e.g., Henriksen & Byrd 1996). More recently, the importance of repeated, fast collisions in stripping cluster galaxies has been emphasized by Moore et al. (1996, 1998). However, because of the large velocity dispersion within galaxy clusters, conventional wisdom held that strong interactions and mergers between cluster galaxies were rare (Ostriker 1980).

More recently, a greater understanding of the nature of hierarchical clustering is changing this view. While slow encounters are rare for an individual galaxy falling into a well-established environment (e.g., Ghigna et al. 1998), many galaxies are accreted onto clusters from within the small group environment. Clusters show ample evidence for substructure in X-rays, galaxy populations, and velocity structure (see, e.g., reviews by Buote 2002; Girardi & Biviano 2002). Interactions within infalling groups can be strong – witness, for example, the classic interacting pair "the Mice" (NGC 4676), found in the outskirts of the Coma cluster. Clearly strong interactions can and do occur during the evolution of clusters, either early as the cluster forms, or late as groups are accreted from the field.

The effects of the cluster potential on the evolution of tidal debris during a slow encounter can be dramatic. To illustrate this, Fig 3 shows the evolution of the same merger shown in Fig 1, except this time occurring in a Coma-like cluster potential. The orbit of the galaxy pair in the cluster carries it within 0.5 Mpc of the cluster core, with an orbital period of $\sim$ 3.5 Gyr. As the galaxies merge, the very loosely bound material forming the tidal tails is now subjected to the large scale tidal field of the cluster, and is very efficiently stripped out of the galactic potential altogether.

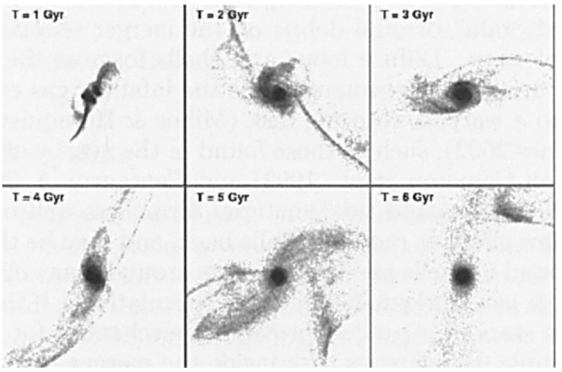

Figure 3. Evolution of an equal-mass merger, identical to that in Fig. 1, but occurring as the system orbits through a Coma-like cluster potential (see text). Note the rapid stripping of the tidal tails early in the simulation; the tidal debris seen here is more extended and diffuse than in the field merger, and late infall is shut off due to tidal stripping by the cluster potential.

An extremely important facet of this kind of encounter is the enhanced efficiency of the tidal stripping. This is shown in Figure 4, which shows the fraction of material stripped to large radius ($r > 35$ kpc, or approximately 5 R_e in the simulation) in the field and cluster versions of the simulations, as well as in a single disk galaxy on the same cluster orbit. The combination of the local and cluster tides causes significant stripping – encounters of galaxies in small infalling groups effectively "prime the pump" for the cluster tides to do their work. Indeed, the *individual* disk galaxy is hardly tidally stripped at all, suggesting that estimates of tidal stripping based on the tidal radius of individual galaxies falling into a cluster potential may significantly underestimate the effect.

The combined effects of galactic and cluster tides not only raise the efficiency of tidal stripping, they also result in particularly *deep* stripping. That is, the stronger galactic tides can strip material out from deep in the galaxies' potential well, which is then vulnerable to the gentler but long-lived cluster tides that liberate it entirely. As a result, the stripped material will be relatively high in metallicity, coming from the inner parts of the disk, and has a mean metallicity of [Fe/H]=-0.25, with a significant spread. This has important consequences for studies of the intracluster light (ICL), particularly in terms of

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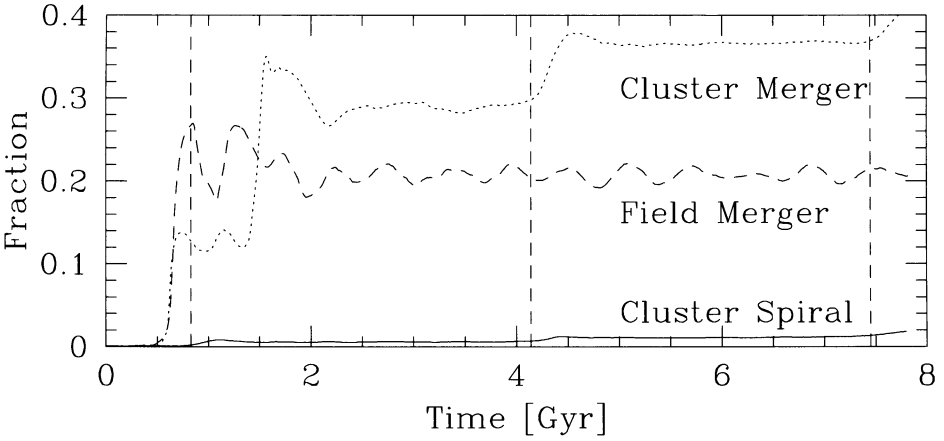

Figure 4. Material stripped to large radius ($r > 35$ kpc) for the isolated merger, the cluster merger, and a isolated spiral orbiting in the cluster potential. Cluster peri passages are shown as dashed lines. Note that most of the tidal material in the isolated merger remains bound to the remnant, while it is unbound in the cluster merger.

searches for individual intracluster stars which are sensitive to the metallicity of the population (e.g., Durrell et al. 2002).

In terms of galactic recycling, the cluster has the effect of essentially shutting down various recycling paths. The ability for tidal tails to grow large tidal dwarfs may be extremely limited, as the cluster tides rapidly disperse the tidal material. The hot intracluster medium may also act to heat the tidal gas, making it difficult to form stars. If any dwarfs or, on smaller scales, star clusters do form in the tidal debris, they will be rapidly stripped from their hosts, perhaps contributing to the populations of cluster dwarfs or intracluster globular clusters.

The cluster will also shut down reaccretion from the tidal tails spawned during a merger. The combination of cluster tides and ram pressure stripping from a hot intracluster medium will "sweep clean" the tidal debris and any low density gas that might remain in the remnants. For example, the diffuse HI disk in the merger remnant Centaurus A (Nicholson et al. 1992) is unlikely to survive any passage through the hot ICM of a dense cluster. Models for forming S0 galaxies from mergers of galaxies followed by reformation or survival of a gaseous disk (e.g., Bekki 1998, or see the discussion in Schweizer 1998) seem difficult to envision in the dense cluster environment. However, the S0 classification is a very diverse one, and the mechanism which gives rise to disky cluster S0's may well be quite different than the merger mechanisms hypothesized to give rise to bulge-dominated S0's in the field environment.

4. The Formation of Intracluster Light

As galaxies orbit in the cluster environment, they are subject to tidal stripping from a variety of sources – interactions with individual galaxies, with groups of

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galaxies, or with the global cluster potential itself (see, e.g., the discussion in Gnedin 2003). Over time, this stripped starlight builds up the diffuse intracluster light found in clusters of galaxies. The properties of this ICL – its luminosity, morphological structure, metallicity, and kinematics – and their correlation with cluster properties can help unravel the dynamical history of cluster collapse, accretion, and evolution. To date, theoretical work has largely focused on tidal stripping from individual galaxies orbiting in an evolved cluster potential (e.g., Merritt 1983; Richstone & Malamuth 1983; Moore et al. 1996; Calcáneo-Roldán et al. 2000) and ignored two important effects: preprocessing in groups, and heating by substructure (Gnedin 2003). Full cosmologically-motivated simulations are needed to study the phenomenon in detail (e.g., Dubinski et al. 2001; Napolitano et al. 2003; Mihos et al. 2004).

An example of these models is shown in Figure 5 (from Mihos et al. 2004). In this simulation, we have excised a cluster from a flat ΛCDM cosmological simulation and traced it back to $z = 2$. At that point we identify dark matter halos more massive than 10^{11} $M_{\odot}$, destined to end up in the $z = 0$ cluster, and replace them with composite (collisionless) disk/halo galaxy models. The simulation is then run forward to the present day to examine the formation of tidal debris and the ICL. In essence, this simulation follows the contribution to the ICL from luminous galaxies, rather than from the stripping of low mass dwarfs. In this simulation, we see significant kinematic and spatial substructure at early times; at late times much of this substructure has been well mixed into a diffuse intracluster light. However, at low surface brightnesses, significant substructure remains even at $z = 0$.

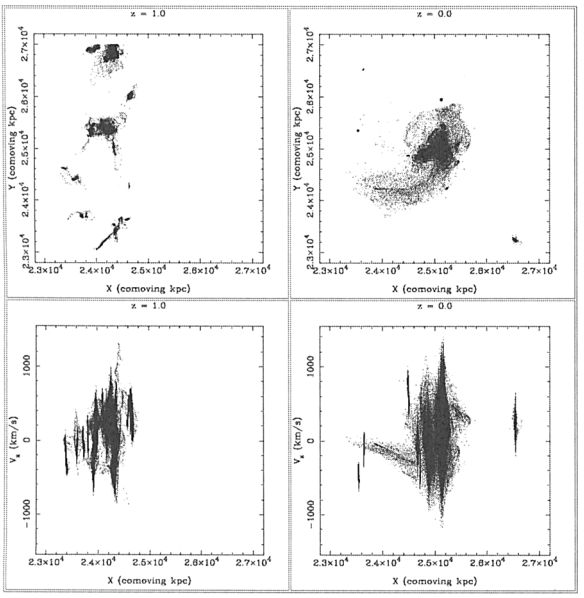

Figure 5. Morphological (top) and kinematic (bottom) structure of the intracluster light in a simulated galaxy cluster. Left panels show the cluster at $z = 1$, while the right panels show $z = 0$. From Mihos et al. (2004).

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Detecting this ICL has proved difficult, as at its *brightest*, the ICL is only ∼1% of the brightness of the night sky. Efforts to detect this ICL include deep surface photometry to look for the diffuse ICL (e.g., Uson et al. 1991; Bernstein et al. 1995; Gonzalez et al. 2000; Feldmeier et al. 2002), as well as imaging of individual stars and planetary nebulae in nearby clusters (Ferguson et al. 1998; Feldmeier et al. 1998; Arnaboldi et al. 2002). Recently, these surveys have begun to reveal interesting substructure in the ICL, often in the form of diffuse arcs or streaks of material from tidally stripped galaxies (Trentham & Mobasher 1998; Gregg & West 1998; Calcáneo-Roldán et al. 2000).

To quantify the prevalence and properties of ICL as a function of cluster properties, we have begun a deep imaging survey of clusters using the KPNO 2m (Feldmeier et al. 2002, 2004). We target a variety of clusters, from cD-dominated Bautz-Morgan Type I clusters to Type III clusters which are typified by a more irregular distribution of galaxies. Examples from this survey are shown in Figure 6. The massive cD cluster Abell 1413 is marked by regular distribution of diffuse light, well-fit by a $r^{\frac{1}{4}}$ distribution over a large range of radius, with only a moderate excess at large radius and little substructure. In contrast, Abell 1914 shows a variety of features: a fan-like plume projecting from the eastern clump of galaxies, another diffuse plume extending from the galaxy group to the north of the cluster, and a narrow stream extending to the northwest from the cluster center. We see similar behavior in other Abell clusters we have surveyed.

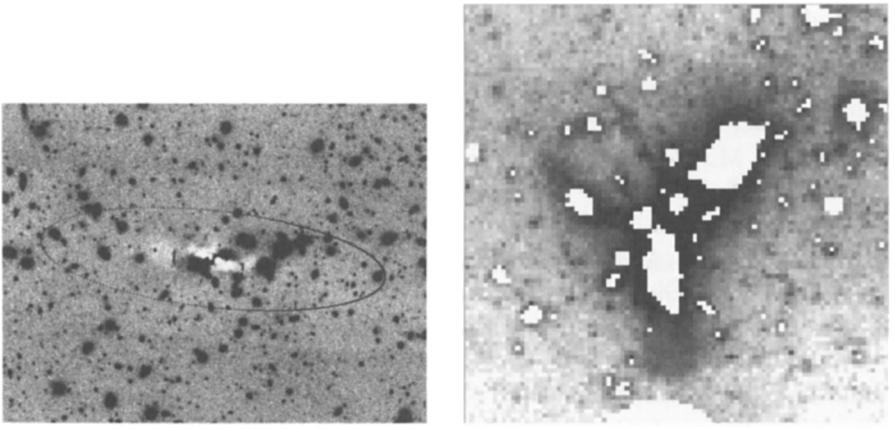

Figure 6. Left: the cD cluster Abell 1413, after subtraction of a smooth $r^{\frac{1}{4}}$ law (the extent of which is shown by the ellipse). Very little substructure is seen. Right: the Bautz-Morgan Type III cluster Abell 1914, showing a rich variety of substructure. North is to the left; east is down. (From Feldmeier et al. 2002, 2004)

Although the sample size is small, these results are consistent with the expectations that substructure in the ICL is correlated with the dynamical state of the cluster as a whole. As clusters are assembled, the ICL is built up though the significant tidal stripping that occurs during interactions within the accreting groups, and between galaxies and substructure within the cluster. Does the total

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amount of ICL also correlate with Bautz-Morgan cluster type? Examining ICL measurements from a variety of sources, Ciardullo et al. (this conference) find only a weak dependence – the ICL fraction rises as expected from Type III to Type II clusters, but Type I (cD-dominated) clusters show fractionally less ICL than do the Type II's. However, the drop in the Type I's is likely due to the difficulty in distinguishing the ICL from the diffuse envelope of the cD galaxy itself; indeed, such distinction may not even be well motivated, since the cD envelope itself likely is formed from tidally stripped material. Including the luminosity of the cD envelope in the ICL budget would raise the fractional amount of ICL in Type I clusters and bring the trend in line with expectations from the dynamical models for generating ICL in clusters.

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