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Interactions and Mergers of Cluster Galaxies

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Abstract

The high-density environment of galaxy clusters is ripe for collisional encounters of galaxies. While the large velocity dispersion of clusters was originally thought to preclude slow encounters, the infall of smaller groups into the cluster environment provides a mechanism for promoting slow encounters and even mergers within clusters. The dynamical and star-forming response of galaxies to a close encounter depends on both their internal structure and on the collisional encounter speed—fast encounters tend to trigger modest, disk-wide responses in luminous spirals, while slow encounters are more able to drive instabilities that result in strong nuclear activity. While the combined effects of the cluster tidal field and ram pressure stripping make it difficult for individual cluster galaxies to participate in many merger-driven evolutionary scenarios, infalling groups represent a natural site for these evolutionary processes and may represent a "preprocessing" stage in the evolution of cluster galaxies. Meanwhile, the efficiency of tidal stripping also drives the formation of the diffuse intracluster light in galaxy clusters; deep imaging of clusters is beginning to reveal evidence for significant substructure in the intracluster light.

1.1 Interactions of Cluster Galaxies

The importance of collisions in the life of cluster galaxies can be seen through a simple rate argument. A characteristic number of interactions per galaxy can be written as $N \approx n\sigma\upsilon t$, where n is the number density of galaxies in a cluster, σ is the cross section for interactions, υ is the encounter velocity, and t is the age of the cluster. If $\sigma = \pi r_p^2$, where r_p is the impact parameter, and $\upsilon = \sqrt{2}\sigma_\upsilon$, then for a cluster like Coma we have

$$N \approx 4 \left(\frac{n}{250\ \mathrm{Mpc}^{-3}}\right)\left(\frac{r_p}{20\ \mathrm{kpc}}\right)^2\left(\frac{\sigma_\upsilon}{1000\ \ \mathrm{km\ s}^{-1}}\right)\left(\frac{t}{10\ \mathrm{Gyr}}\right).$$

While very crude, this calculation shows that it is reasonable to expect that over the course of its lifetime in the cluster, a typical galaxy should experience several close interactions with other cluster members.

While interactions should be common in clusters, they will also be fast. Because the characteristic encounter velocity is much higher than the typical circular velocities of galaxies, these perturbations will be impulsive in nature. Simple analytic arguments suggest that both the energy input and dynamical friction should scale as υ^{-2} (Binney & Tremaine 1987), so that a fast encounter does less damage and is much less likely to lead to a merger than are the slow encounters experienced by galaxies in the field. A common view has arisen, therefore, that slow interactions and mergers of galaxies are a rarity in massive clusters (e.g., Ostriker 1980), and that much of the dynamical evolution in cluster galaxy populations is driven by the effects of the global tidal field (e.g., Byrd & Valtonen 1990; Henriksen & Byrd 1996). Combined with the possible effects of ram pressure stripping of the dense interstellar mediuum (ISM) (Gunn & Gott 1972) or hot gas in galaxy halos ("strangulation"; Larson, Tinsley, & Caldwell 1980), a myriad of processes, aside from galaxy interactions themselves, seemed available to transform cluster galaxies.

However, the abandonment of individual collisions as a mechanism to drive cluster galaxy evolution has proved premature. More recent work on the dynamical evolution of cluster galaxies has emphasized the importance of fast collisions. Moore et al. (1996) and Moore, Lake, & Katz (1998) have shown that *repeated* fast encounters, coupled with the effects of the global tidal field, can drive a very strong response in cluster galaxies. For galaxy-like potentials, the amount of heating during an impulsive encounter scales like $\Delta E/E \sim r_p^{-2}$, such that distant encounters impart less energy. However, this effect is balanced by the fact that under simple geometric weighting the number of encounters scales as r_p^2, so that the total heating, summed over all interactions, can be significant. While this simple argument breaks down when one considers more realistic galaxy potentials and the finite time scales involved, in hindsight it is not surprising that repeated high-speed encounters—"galaxy harassment"—should drive strong evolution. However, the efficacy of harassment is largely limited to low-luminosity hosts, due to their slowly rising rotation curves and low-density cores. In luminous spirals, the effects of harassment are much more limited (Moore et al. 1999). This effect leads to a situation where harassment can effectively describe processes such as the formation of dwarf ellipticals (Moore et al. 1998), the fueling of low-luminosity AGNs (Lake, Katz, & Moore 1998), and the destruction of low-surface brightness galaxies in clusters (Moore et al. 1999), but is less able to explain the evolution of luminous cluster galaxies.

Even as the effects of high-speed collisions are being demonstrated, a new attention is focusing on slow encounters and mergers in clusters. The crucial element that is often overlooked in a classical discussion of cluster interactions is the fact that structure forms *hierarchically*. Galaxy clusters form not by accreting individual galaxies randomly from the field environment, but rather through the infall of less massive groups falling in along the filaments that make up the "cosmic web." Observationally, evidence for this accretion of smaller galaxy groups is well established. Clusters show ample evidence for substructure in X-rays, galaxy populations, and velocity structure (see, e.g., reviews by Buote 2002; Girardi & Biviano 2002) . These infalling groups have velocity dispersions that are much smaller than that of the cluster as a whole, permitting the slow, strong interactions normally associated with field galaxies. Imaging of distant clusters show populations of strongly interacting and possibly merging galaxies (e.g., Dressler et al. 1997; van Dokkum et al. 1999), which may contribute to the Butcher-Oemler effect (e.g., Lavery & Henry 1988). Even in nearby (presumably dynamically older) clusters, several notable examples of strongly interacting systems exist (e.g., Schweizer 1998; Dressler, this volume), including the classic Toomre-sequence pair "The Mice" (NGC 4476) located at a projected distance of $\sim$5 Mpc from the center of the Coma cluster. Interactions in the infalling group environment may in effect represent a "preprocessing" step in the evolution of cluster galaxies.

While the observational record contains many examples of group accretion and slow en-

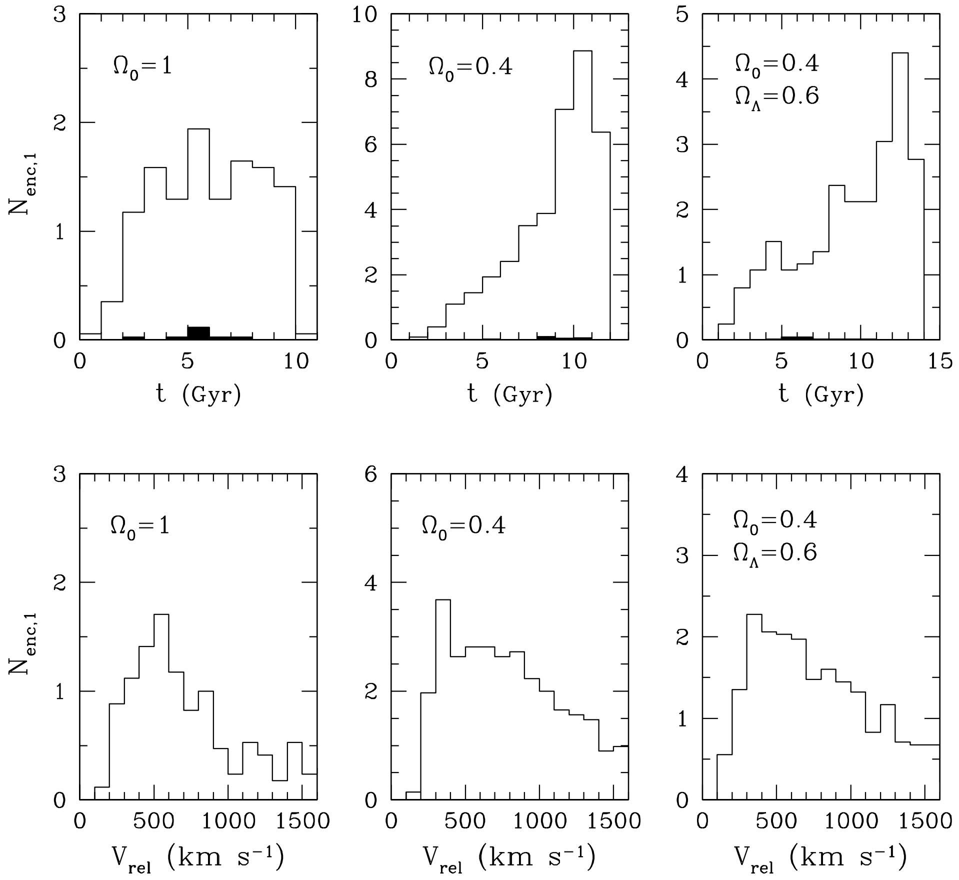

Fig. 1.1. Top: Number of close encounters per galaxy per Gyr in a simulated $\log(M/M_\odot) = 14.6$ cluster under different cosmologies. Bottom: The distribution of galaxy encounter velocities in the simulated clusters. (From Gnedin 2003.)

counters, numerical simulations are also beginning to reveal this evolutionary path for cluster galaxies. Modern *N*-body calculations can follow the evolution of individual galaxy-mass dark matter halos in large-scale cosmological simulations, allowing the interaction and merger history of cluster galaxies to be probed. Ghigna et al. (1998) tracked galaxy halos in an $\Omega_m = 1, \log(M/M_\odot) = 14.7$ cluster and showed at late times ($z < 0.5$) that, while no mergers occurred within the inner virialized 1.5 Mpc of the cluster, in the outskirts the merger rate was $\sim$5%–10%. Similar models by Dubinski (1998) confirmed these results, and showed more intense activity between $z = 1$ and $z = 0.4$. Gnedin (2003) expanded on these works by studying the interaction and merger rates in clusters under different cosmological models (Fig. 1.1). In $\Omega_m = 1$ cosmologies, the encounter rates in clusters stays relatively constant with time as the cluster slowly accretes, while under open or Λ-dominated cosmologies, the interaction rate increases significantly once the cluster virializes, as the galaxies experience many high-speed encounters in the cluster core. The distribution of velocities in these encounters shows a large tail to high encounter velocities, but a significant fraction of encounters, largely those in the cluster periphery or those occurring at higher redshift, before the cluster has fully collapsed, occur at low relative velocities ($v_{\rm rel} < 500$ km s^{-1}). Clearly, not *all* interactions are of the high-speed variety!

In summary, clusters are an active dynamical environment, with a multitude of processes available to drive evolution in the galaxy population. Disentangling these different processes continues to prove difficult, in large part because nearly all of them correlate with cluster richness and clustercentric distance. Indeed, seeking to isolate the "dominant" mechanism driving evolution may be ill motivated, as these processes likely work in concert, such as the connection between high-speed collisions and tidal field that describes galaxy harassment. What is clear from both observational and computational studies is that slow encounters and mergers of galaxies can be important over the life of a cluster—at early times when the cluster is first collapsing, and at later times in the outskirts as the cluster accretes groups from the field.

Finally, it is also particularly important to remember two points. First, clusters come in a range of mass and richness: not every cluster is as massive as the archetypal Coma cluster, with its extraordinarily high velocity dispersion of $\sigma_v = 1000$ km s^{-1}. In smaller clusters and groups, the lower velocity dispersion will slow the encounter velocities and make them behave more like field encounters. Second, as we push observations out to higher and higher redshift, we begin to probe the regime of cluster formation, where unvirialized dense environments can host strong encounters.

1.2 Lessons from the Field ...

To understand the effects of interactions and mergers on cluster galaxies, we start with lessons learned from the study of collisions in the field environment. In §1.3, we will then ask how the cluster environment modifies these results. In this discussion, we focus largely on two aspects of encounters: the triggering of starbursts and nuclear activity, and the late-time evolution of tidal debris and possible reformation of gaseous disks.

The role of galaxy interactions in driving activity and evolution of field spirals has been well documented through a myriad of observational and theoretical studies. Models of interactions have demonstrated the basic dynamical response of galaxies to close encounter (e.g., Toomre & Toomre 1972; Negroponte & White 1982; Barnes 1988, 1992; Noguchi 1988; Barnes & Hernquist 1991, 1996; Mihos & Hernquist 1994, 1996). Close interactions can lead to a strong internal dynamical response in the galaxies, driving the formation of spiral arms and, depending on the structural properties of the disks, strong bar modes. These non-axisymmetric structures lead to compression and inflow of gas in the disks, elevating star formation rates and fueling nuclear starburst/AGN activity. If the encounter is sufficiently close, dynamical friction leads to an eventual merging of the galaxies, at which time violent relaxation destroys the dynamically cold disks and produces a kinematically hot merger remnant with many of the properties found in the field elliptical galaxy population (see, e.g., Barnes & Hernquist 1992).

Observational studies support much of this picture. Interacting systems show preferentially elevated star formation rates, enhanced on average by factors of a few over those of isolated spirals (Larson & Tinsley 1978; Condon et al. 1982; Keel et al. 1985; Kennicutt et al. 1987). Nuclear starbursts are common, with typical starburst mass fractions that involve a few percent of the luminous mass (Kennicutt et al. 1987). More dramati-

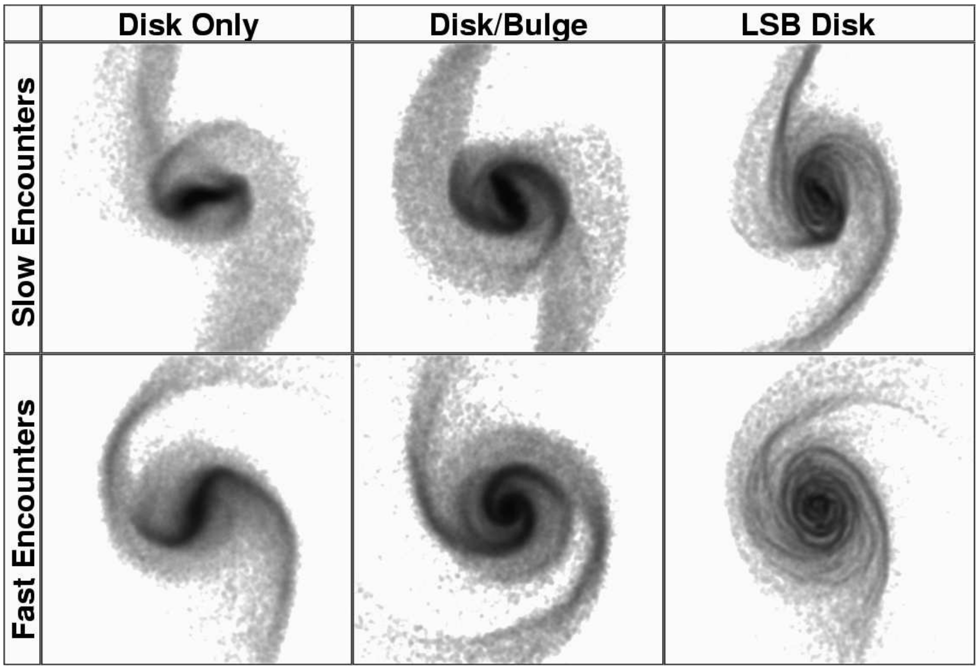

Fig. 1.2. The morphological response of galaxies to a close encounter. The galaxy models are viewed one rotation period after the initial collision. Top panels show the response to a slow, parabolic encounter, while the bottom panels show the response to fast encounters. The left columns show the response of a pure disk system, the middle panels show a disk/bulge system, and the right panels show a low-density, dark matter dominated disk.

cally, infrared-selected samples of galaxies reveal a population of interacting "ultraluminous infrared galaxies," where star formation rates are elevated by 1–2 orders of magnitude and dust-enshrouded nuclear activity is common (Soifer et al. 1984; Lawrence et al. 1989). These systems are preferentially found in late-stage mergers (e.g., Veilleux, Kim, & Sanders 2002) and have been suggested as the precursors of luminous quasars (Sanders et al. 1988). This diversity of properties for interacting systems argues that the response of a galaxy to a close interaction is likely a complicated function of encounter parameters, galaxy type, local environment, and gas fraction.

Can we isolate the different determining factors to understand what drives the strong response in interacting systems? Numerical modeling of interactions has shown that gaseous inflow and central activity in an interacting disk is driven largely by gravitational torques acting on the gas—not from the companion galaxy, but by the developing non-axisymmetric structures (spiral arms and/or central bar) in the host disk (Noguchi 1988; Barnes & Hernquist 1991; Mihos & Hernquist 1996). This result argues that the structural properties of galaxies play a central role in determining the response to interactions. In particular, disks that are stable against the strong growth of disk instabilities will experience a weaker response, exhibiting modestly enhanced, disk-wide star formation (unless and until they ultimately merge). This stability can be provided by the presence of a centrally concentrated bulge (Mihos & Hernquist 1996) or a lowered disk surface density (at fixed rotational speed;

Mihos, McGaugh, & de Blok 1997). In contrast, disk-dominated systems are more susceptible to global bar modes and experience the strongest levels of inflow and nuclear activity (see § 1.3).

Interacting and merging galaxies also show a wide variety of tidal features, from long thin tidal tails to plumes, bridges, and other amorphous tidal debris. The evolution of this material was first elegantly described by the computer models of Toomre & Toomre (1972) and Wright (1972). Gravitational tides during a close encounter lead to the stripping of loosely bound material from the galaxies (see Fig. 1.3); rather than being completely liberated, the lion's share of this material ($> 95\%$) remains bound, albeit weakly, to its host galaxy (Hernquist & Spergel 1992; Hibbard & Mihos 1995). Material is sorted in the tidal tails by a combination of energy and angular momentum—the outer portions of the tails contain the least bound material with the highest angular momentum. At any given time, material at the base of the tail has achieved turn-around and is falling back toward the remnant. Further out in the tail, material still expands away, resulting in a rapid drop in the luminosity density of the tidal tails due to this differential stretching. As a result, the detectability of these tidal features is a strong function of age and limiting surface brightness; after a few billion years of dynamical evolution, they will be extremely difficult to detect (Mihos 1995).

In mergers, the gas and stars ejected in the tidal tails fall back onto the remnant in a long-lived "rain" that spans many billions of years (Hernquist & Spergel 1992; Hibbard & Mihos 1995). In the merger simulation shown in Figure 1.3, this fallback manifests itself as loops of tidal debris that form as stars fall back through the gravitational potential of the remnant. Tidal gas will follow a different evolution, as it shocks and dissipates energy as it falls back. The most tightly bound gaseous material returns to the remnant over short time scales and can resettle into a warped disk (Mihos & Hernquist 1996; Naab & Burkert 2001; Barnes 2002). Such warped H I disks have been observed in NGC 4753 (Steiman-Cameron, Kormendy, & Durisen 1992) and in the nearby merger remnant Centaurus A (Nicholson, Bland-Hawthorn, & Taylor 1992). Over longer time scales, the loosely bound, high-angular momentum gas falls back to ever-increasing radii, forming a more extended but less-organized distribution of gas outside several effective radii in the remnant. Many elliptical galaxies show extended neutral hydrogen gas, sometimes in the form of broken rings at large radius, perhaps arising from long-ago merger events (e.g., van Gorkom & Schiminovich 1997).

The ultimate fate of this infalling material is uncertain, but may have important ramifications for interaction-driven galaxy evolution models. If efficient star formation occurs in this gas, such as that observed in the inner disk of the merger remnant NGC 7252 (Hibbard et al. 1994), this may present a mechanism for building disks in elliptical galaxies. If the amount of gas resettling into the disk is significant, in principle the remnant could evolve to become a spheroidal system with a high bulge-to-disk ratio, perhaps forming an S0 or Sa galaxy (e.g., Schweizer 1998).

1.3 ... Applied to Clusters

In clusters, a number of environmental effects may modify the dynamical response and evolution of interacting galaxies described above. First, the relative velocities of interacting systems tend to be higher, although, as argued earlier, many low-velocity encounters still occur within smaller groups falling in from the cluster periphery. Second, the global tidal field of the cluster must also play a role in the evolution of interacting systems, strip-

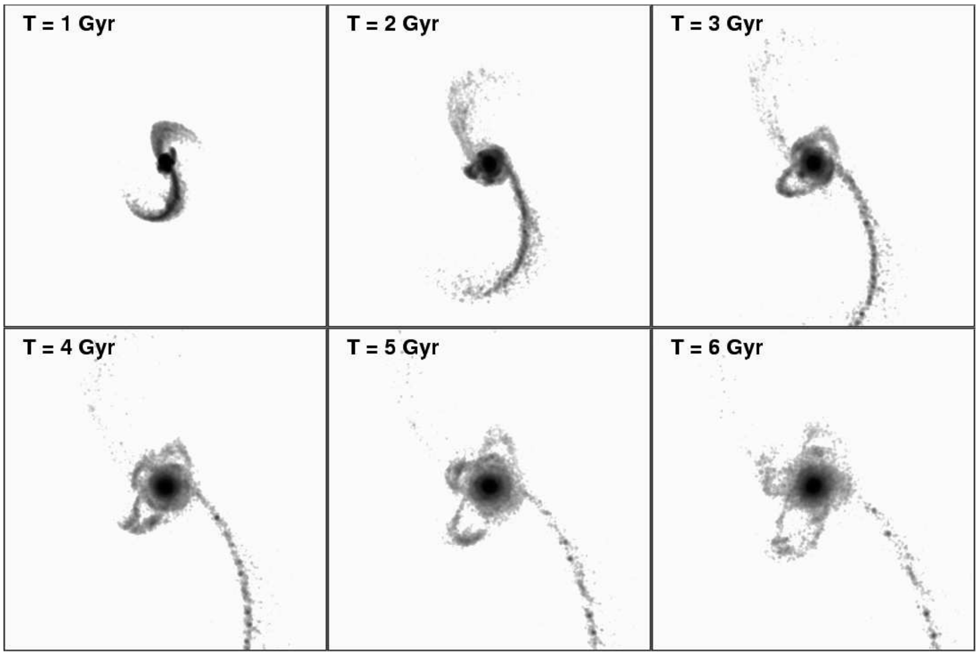

Fig. 1.3. Evolution of the tidal debris in an equal-mass merger of two disk galaxies occurring in isolation. Each frame is approximately 0.9 Mpc on a side. Note the sharpness of the tidal debris, as well as the loops that form as material falls back into the remnant over long time scales.

ping away the loosely bound tidal material and potentially adding energy to bound groups. The hot intracluster medium (ICM) can act to further strip out low-density ISM in galaxies, particularly the diffuse tidal gas ejected during collisions.

The most obvious difference between interactions in the field and in the cluster environment is the collision speed of the encounter. While slow interactions are able to drive a strong dynamical response in disk galaxies, faster encounters result in a perturbation that is much shorter lived and less resonant with the internal dynamics of the disk. Figure 1.2 shows the different response of galaxies to slow and fast collisions. In each case, the galaxies experience an equal-mass encounter inclined 45° to the orbital plane and with a closest approach of six disk scale lengths. Three structural models are used for the galaxies. The first is a pure disk system where the disk dominates the rotation curve in the inner two scale lengths; the second is identical to the first, but with a central bulge with bulge-to-disk ratio of 1:3. In both these models, the disk-to-halo mass ratio is 1:5.8. The third system is identical to the first, but with the disk surface density lowered by a factor of 8; this system represents a dark matter dominated, low-surface brightness (LSB) disk galaxy. In the slow collision, the galaxies fall on a parabolic (zero-energy) orbit with a velocity at closest approach that is approximately twice the circular velocity. The fast collision takes place with a hyperbolic orbit with an encounter velocity of twice that of the parabolic encounters.

Notable differences can be seen in the dynamical response of the galaxy models, particularly in the growth of global bar modes. During slow encounters, both the disk and disk/bulge galaxy models develop dramatic bars and spiral arms, which can drive strong inflow and central activity. The lowered surface density of the LSB model results in a weaker self-gravitating response (Mihos et al. 1997); a very small, weak bar is present, but the overall response is one of a persistent oval distortion, which would be much less able to drive gaseous inflow. In contrast, the response of the fast encounters depends more strongly on the structural properties of the galaxy. The pure-disk model develops a relatively strong bar mode, while the disk/bulge system sports a two-arm spiral pattern with no central bar. These results are similar to those shown in Moore et al. (1999), who modeled high-speed encounters of disk galaxies of varying structural properties. The LSB model, on the other hand, lacks the disk self-gravity to amplify the perturbation into any strong internal response. However, the vulnerability of LSBs lies not in their internal response to a *single* encounter, but rather in their response to *repeated* high-speed collisions in the cluster environment (Moore et al. 1998).

Because the star-forming response of a galaxy is intimately linked to its dynamical response, we can use these results to guide our expectations of starburst triggering mechanisms in cluster galaxies. Because of their stability toward high-speed encounters, luminous, early-type spirals should experience modestly enhanced, disk-wide starbursts. Low-luminosity, late-type disks will be more susceptible to stronger inflows, central starbursts, and AGN fueling; even the LSBs will succumb to the effects of repeated encounters and the cluster tides (Moore et al. 1996), which drive a much stronger response. As a result, these high-speed, "harassment-like" encounters are effective at driving evolution in the low-luminosity cluster populations (Moore et al. 1996; Lake et al. 1998), but if harassment is the whole story in driving cluster galaxy evolution, it is hard to explain strong starburst activity in *luminous* cluster spirals at moderate redshift. On the other hand, the slower collisions expected in infalling substructure are able to drive a stronger response regardless of galaxy type.

Aside from driving stronger starbursts in interacting cluster galaxies, slow collisions also heat and strip galaxies more efficiently than do high-speed encounters. They also raise the possibility for mergers among cluster galaxies, and the potential for merger-driven evolutionary scenarios. However, unlike slow collisions in the field, cluster galaxies must also contend with the effects of the overall tidal field of the cluster. How will this affect the evolution of close interactions, in particular the longevity and detectability of tidal debris, and the ability for galaxies to reaccrete tidal material? To address this question, Figure 1.4 shows the evolution of an equal-mass merger (identical to the merger shown in Fig. 1.3) occurring in a cluster tidal field. The cluster potential is given by an Coma-like Navarro, Frenk, & White (1996) profile with total mass $M_{200} = 10^{15} M_{\odot}$, $r_{200} = 2$ Mpc, and $r_s = 300$ kpc. The binary pair travels on an orbit with $r_{\rm peri} = 0.5$ Mpc and $r_{\rm apo} = 2$ Mpc, and passes through periclustercon twice, at T $\approx$ 1 and 4 Gyr.

The tidal field has a number of effects on the evolution of this system. First, the merger time scale has been lengthened—the cluster tidal field imparts energy to the galaxies' orbits, extending the time it takes for the system to merge (by $\sim$50% for this calculation). In this case, the encounter is close enough that the galaxies do still ultimately merge, but it is not hard to envision encounters where the tidal energy input is sufficient to unbind the galaxy pair. This raises the interesting possibility that infalling pairs may experience the close, slow collisions that drive strong activity, yet survive the encounter whole without merging.

The most dramatic difference between field mergers and those in a cluster is in the evolution of the tidal debris. In the field, most of the material ejected into the tidal tails remains

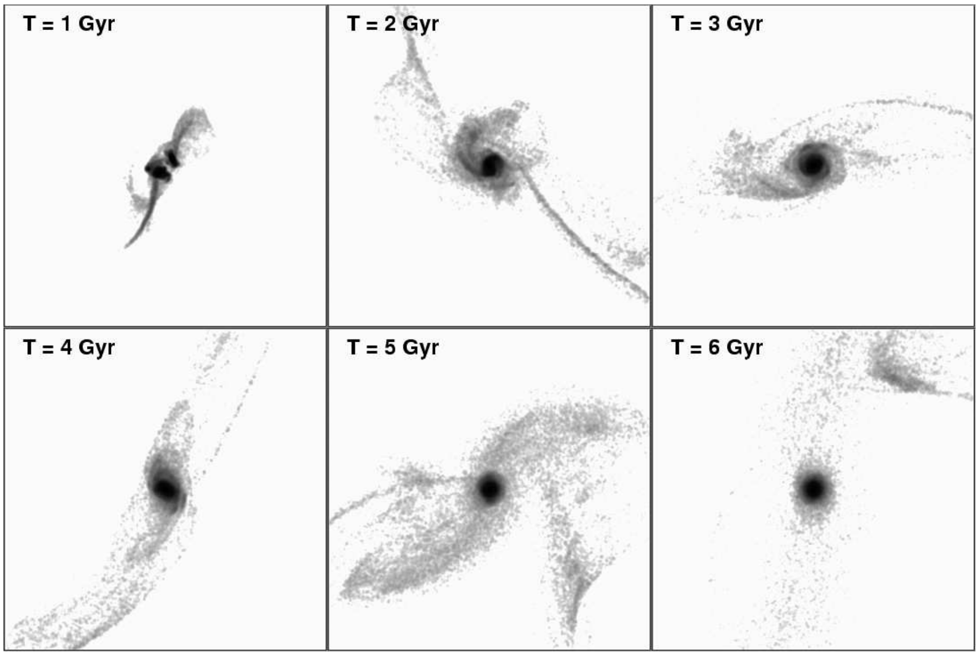

Fig. 1.4. Evolution of an equal-mass merger, identical to that in Fig. 1.3, but occurring as the system orbits through a Coma-like cluster potential (see text). Note the rapid stripping of the tidal tails early in the simulation; the tidal debris seen here is more extended and diffuse than in the field merger, and late infall is shut off due to tidal stripping by the cluster potential.

loosely bound to the host galaxy, forming a well-defined tracer of the tidal encounter. In the cluster encounter, the tidal field quickly strips this loosely bound material from the galaxies, dispersing it throughout the cluster and adding to the diffuse intracluster starlight found in galaxy clusters. This rapid stripping of the tidal debris is clear in Figure 1.4: shortly after the first passage the debris becomes very extended and diffuse and is removed entirely from the system after the subsequent passage through the cluster interior. In this encounter, 20% of the stellar mass is stripped to large distances (> 50 kpc), fully twice the amount in a similar field merger.

This rapid stripping has a number of important ramifications. First, these tidal tracers are very short-lived; identifying a galaxy as a victim of a close interaction or merger will be very difficult indeed shortly after it enters the cluster potential. The tidal features we do see in cluster galaxies are likely signatures of a very recent interaction, such that interaction rates derived from the presence of tidal debris may underestimate the true interaction rates in clusters. Second, the rebuilding/resettling of gaseous disks in interaction/merger remnants will be severely inhibited, as both cluster tides and ram pressure stripping act to strip off all but the most bound material in the tidal debris, leaving little material able to return. Finally, this stripping will contribute both to the intracluster light and to the ICM, as gas and stars in the tidal debris are mixed in to the diffuse cluster environment. We discuss these processes in the following sections.

1.4 Galaxy Evolution: Mergers, Elliptical, and S0 Galaxies

In the field environment, interactions and mergers of galaxies are thought to be a prime candidate for driving evolution in galaxy populations. Major mergers of spiral galaxies may lead to the transformation of spirals into ellipticals (e.g., Toomre 1978; Schweizer 1982): the violent relaxation associated with a merger effectively destroys the galactic disks and creates a kinematically hot, $r^{1/4}$-law spheroid, while the concurrent intense burst of star formation may process the cold ISM of a spiral galaxy into the hot X-ray halo of an elliptical. These processes are not totally efficient, however, and leave signatures behind that identify the violence of the merging process: diffuse loops and shells of starlight, extended H I gas, significant rotation in the outskirts of the remnant, and dynamically distinct cores (see, e.g., the review by Schweizer 1998). While it is an open question as to what fraction of ellipticals formed this way, it is clear that at least some nearby field ellipticals—Centaurus A being a notable example (Schiminovich et al. 1994)—have had such violent histories.

Mergers have also been proposed as a mechanism to drive the formation of S0 galaxies. In this case, the scenarios are varied. For S0s with very large bulge-to-disk ratios, reaccretion of gas after a major merger (either from returning tidal material or from the surrounding environment) may rebuild a disk inside a newly formed spheroid. In unequal-mass mergers of disk galaxies, disk destruction is not complete, and the resulting remnant retains a significant amount of rotation (Bendo & Barnes 2000; Cretton et al. 2001) and may be identified with a disky S0, particularly if a significant amount of cold gas is retained by the system to reform a thin disk (Bekki 1998). Finally, minor mergers between spirals and their satellite companions can significantly heat, but not destroy, galactic disks (Toth & Ostriker 1992; Quinn, Hernquist, & Fullagar 1993; Walker, Mihos, & Hernquist 1996), while simultaneously helping to "sweep the disk clean" of cold gas via a gravitationally induced bar driving gas to the nucleus (Hernquist & Mihos 1995). The resulting disks have many similarities to disky S0s (Mihos et al. 1995): thickened disks, little or no spiral structure, cold gas, or ongoing star formation. These different scenarios vary mainly in the proposed strength of the interaction—from major to minor mergers—and it has been proposed that this parameter may, in fact, determine the ultimate morphological classification of galaxies all the way from early-type ellipticals to late-type spirals (e.g., Schweizer 1998; Steinmetz & Navarro 2002).

Applying these arguments to cluster populations, it seems that building cluster ellipticals through a wholesale merging of spirals within the established cluster environment is a difficult proposition. Clusters ellipticals are an old, homogeneous population showing little evolution since at least a redshift of $z \approx 1$ (e.g., Dressler et al. 1997; Ellis et al. 1997). Within the cores of massive clusters, merging has largely shut off due to the high velocity dispersion of the virialized cluster (Ghigna et al. 1998). The accretion of merger-spawned ellipticals from infalling groups may still occur, and these will be hard to identify morphologically as merger remnants—the combination of cluster tides and hot ICM will strip off any tell-tale tidal debris and sweep clean any diffuse cold gas in the tidal tails (recall Fig. 1.4) or low-density reaccreting disk. However, the small scatter in the color-magnitude relation and weak evolution of the fundamental plane of cluster ellipticals (see, e.g., the review by van Dokkum 2002) argues that such lately formed ellipticals likely do not contribute to the bulk of the cluster elliptical population. This does not mean that mergers have not played a role in the formation of cluster ellipticals. In any hierarchical model for structure formation, galaxies form via the accretion of smaller objects. Luminous cluster ellipticals may well have formed from mergers of galaxies at high redshift, in the previrialized environment of the protocluster. However, at these redshifts ($z \gg 1$), the progenitor galaxies are likely to have looked very different from the present-day spiral population.

Unlike the rather passive evolution observed in cluster ellipticals, much stronger evolution is observed in the population of cluster S0s. The fraction of S0s in rich cluster has increased significantly since a redshift of $z \approx 1$, with a corresponding decrease in the spiral fraction (Dressler et al. 1997). Can the same collisional processes that have been hypothesized to drive S0 formation in the field account for the dramatic evolution in cluster S0 populations? S0 formation scenarios that rely on reaccretion of material after a major merger (disk rebuilding schemes) seem difficult to envision wholly within the cluster environment. While mergers are possible in infalling groups, the combination of tidal and ram pressure stripping will shut down reaccretion and ablate any low-density gaseous disks that have survived the merger process. For example, it is unlikely the H I disk in Centaurus A (Nicholson et al. 1992), likely a product of merger accretion, would survive passage through the hot ICM of a dense cluster. Satellite merger mechanisms trade one dynamical problem for another—because the mergers involve bound satellite populations there is no concern about the efficacy of high-speed mergers, but, instead, the issue is whether or not satellite populations can stay bound to their host galaxy as it moves through the cluster potential. And, of course, this mechanism relies on the very *local* environment of galaxies, which does not explain why S0 formation would be enhanced in clusters.

None of the proposed merger-driven S0 formation mechanisms appear to work well deep inside the cluster potential. On the other hand, these processes should operate efficiently in the group environment, where the encounter velocities are smaller and cluster tides and the hot ICM do not play havoc with tidal reaccretion. The group environment may create S0s and feed them into the accreting cluster, but if there is wholesale transformation of cluster spirals into S0s in the cluster environment, it needs to occur via other mechanisms.

Other cluster-specific methods for making S0 galaxies have been proposed, including collisional heating and ram pressure stripping of the dense ISM (Moore et al. 1999; Quilis, Moore, & Bower 2000) and strangulation, the stripping of hot halo gas from spirals (Larson et al. 1980; Bekki, Couch, & Shioya 2002). While these models, by design, explain the preferential link between clusters and S0 galaxies, they are not without problems themselves. While the effects of ram pressure stripping on the extended neutral hydrogen gas in cluster galaxies is clear (e.g., van Gorkom, this volume), its efficacy on the denser molecular gas is unclear. For example, the H I deficient spirals in the Virgo cluster still contain significant quantities of molecular gas (e.g., Kenney & Young 1989), while studies of the molecular content of cluster spirals show no deficit of CO emission (Casoli et al. 1998). If the molecular ISM survives, it is unclear why star formation should not continue in these disks. Strangulation models suffer less from concerns of the efficacy of ram pressure stripping, since it is much easier to strip low-density halo gas than a dense molecular ISM, although it must be noted that there currently is little observational evidence for hot halos in (non-starbursting) spiral galaxies. In addition, neither of these methods leads to the production of a luminous spheroid—the S0s that might be produced in these ways would have low bulge-to-disk ratios.

Ultimately, S0s are a heterogeneous class, from bulge-dominated S0s to the disky S0s seen in galaxy clusters, and it should not be surprising that a single mechanism cannot fully account for the range of S0 types (e.g., Hinz, Rix, & Bernstein 2001). Whether there is a systematic difference between cluster and field S0s is unclear, an issue fraught with selection and classification uncertainties. What is clear is that, even in clusters, S0s often show evidence for accretion events, similar to that observed in the field S0 population (see, e.g., , the discussion in Schweizer 1998). It is likely that many of these S0s were "processed" via mergers in the group environment before being incorporated into clusters.

1.5 Tidal Stripping and Intracluster Light

As galaxies orbit in the potential well of a galaxy cluster, stars are tidally stripped from their outer regions, mixing over time to form a diffuse "intracluster light" (ICL). First proposed by Zwicky (1951), the ICL has proved very difficult to study—at its *brightest*, it is only $\sim$1% of the brightness of the night sky. Previous attempts to study the ICL have resulted in some heroic detections (Oemler 1973; Thuan & Kormendy 1977; Bernstein et al. 1995; Gregg & West 1998; Gonzalez et al. 2000), verified by observations of intracluster stars and planetary nebulae in Virgo (Feldmeier, Ciardullo, & Jacoby 1998; Ferguson, Tanvir, & von Hippel 1998; Arnaboldi et al. 2002). While the ICL is typically thought of as arising from the stripping of starlight due to the cluster potential, in fact the role of interactions between cluster galaxies in feeding the ICL is quite strong. Galaxy interactions significantly enhance the rate at which material is stripped; as illustrated in Figure 1.4, the strong, local tidal field of a close encounter can strip material from deep within a galaxy's potential well, after which the cluster tidal field can liberate the material completely. Interactions, particularly those in infalling groups, act to "prime the pump" for the creation of the ICL.

The properties of the ICL in clusters, particularly the fractional luminosity, radial light profile, and presence of substructure, may hold important clues about the accretion history and dynamical evolution of galaxy clusters. Material stripped from galaxies falling in the cluster potential is left on orbits that trace the orbital path of the accreted galaxy, creating long, low-surface brightness tidal arcs (e.g., Moore et al. 1996), which have been observed in a few nearby clusters (Trentham & Mobasher 1998; Calcáneo-Roldán et al. 2000). However, these arcs will only survive as discrete structures if the potential is quiet; substructure will dynamically heat these arcs, and the accretion of significant mass (i.e., a cluster merger event) may well destroy these structures. If much of the ICL is formed early in a cluster's dynamical history, before the cluster has been fully assembled, the bulk of the ICL will be morphologically smooth and well mixed by the present day, with a few faint tidal arcs showing the effects of late accretion. In contrast, if the ICL formed largely after cluster virialization, from the stripping of "quietly infalling" galaxies, the ICL should consist of an ensemble of kinematically distinct tidal debris arcs. Clusters that are dynamically younger should also possess an ICL with significant kinematic and morphological substructure.

Early theoretical studies of the formation of the ICL suggested that it might account for anywhere from 10% to 70% of the total cluster luminosity (Richstone 1976; Merritt 1983, 1984; Miller 1983; Richstone & Malumuth 1983; Malumuth & Richstone 1984). These studies were based largely on analytic estimates of tidal stripping, or on simulations of individual galaxies orbiting in a smooth cluster potential well. Such estimates miss the effects of interactions with individual galaxies (e.g., Moore et al. 1996), intermediate-scale substructure (Gnedin 2003), and priming due to interactions in the infalling group environment. As a result, these models underpredict the total amount of ICL as well as the heating of tidal streams in the ICL. Now, however, cosmological simulations can be used to study cluster

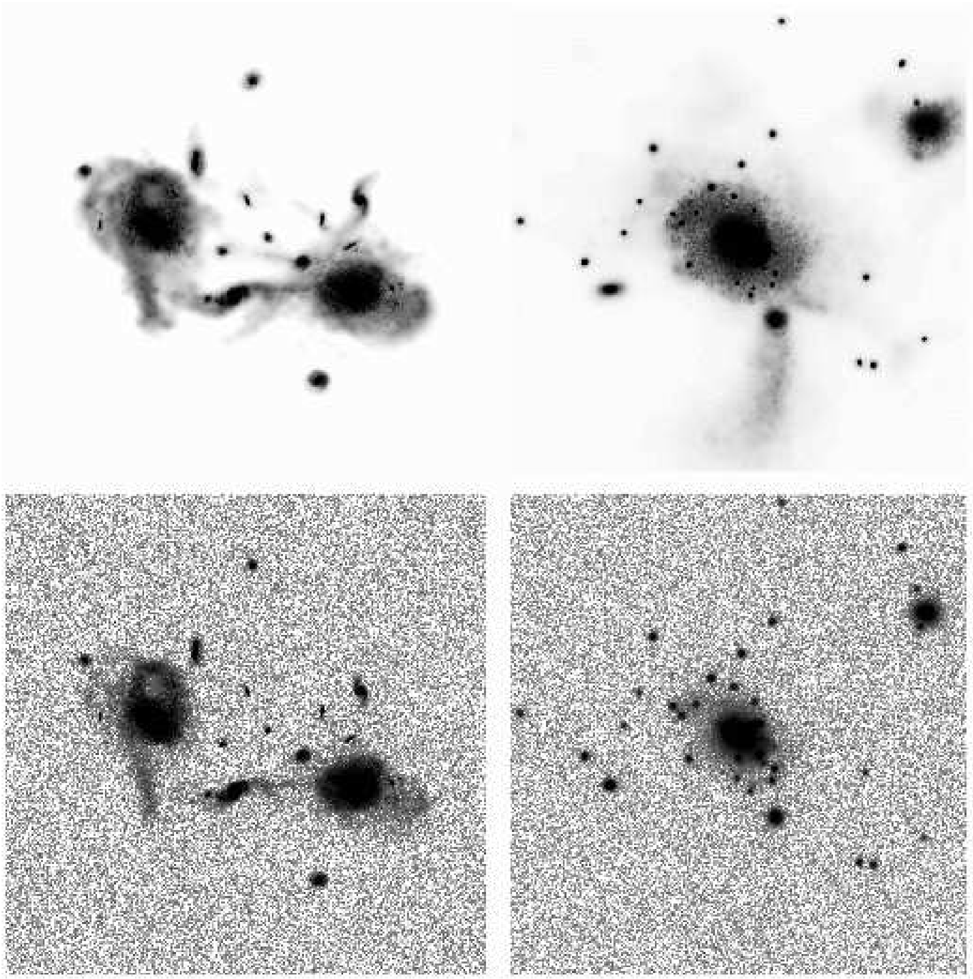

Fig. 1.5. Visualizations of the cluster simulations of Dubinski (1998). Top panels show the distribution of luminous starlight, with the faintest contours corresponding to a surface brightness of $\mu_V \approx 30$ mag arcsec^{-2}. Bottom panels show the effect of adding noise characteristic of current observational limits. Left panels show the cluster early in collapse (at $z = 2$), while right panels show the virialized cluster at $z = 0$.

collapse and tidal stripping at much higher resolution and with a cosmologically motivated cluster accretion history (e.g., Moore et al. 1998; Dubinski, Murali, & Ouyed 2001).

One example of the modeling of ICL is shown in Figure 1.5. These images are derived from the N-body simulations of Dubinski (1998), who simulated the collapse of a $\log(M/M_\odot) = 14.0$ cluster in a standard cold dark matter Universe. Starting from a cosmological dark matter simulation, the 100 most massive halos are identified at a redshift of $z = 2.2$ and replaced with composite disk/bulge/halo galaxies, whereafter the simulation is continued to $z = 0$ (see Dubinski 1998 for more details). To quantify the diffuse light in these cluster models, we assign luminosity to the stellar particles based on a mass-to-light ratio of

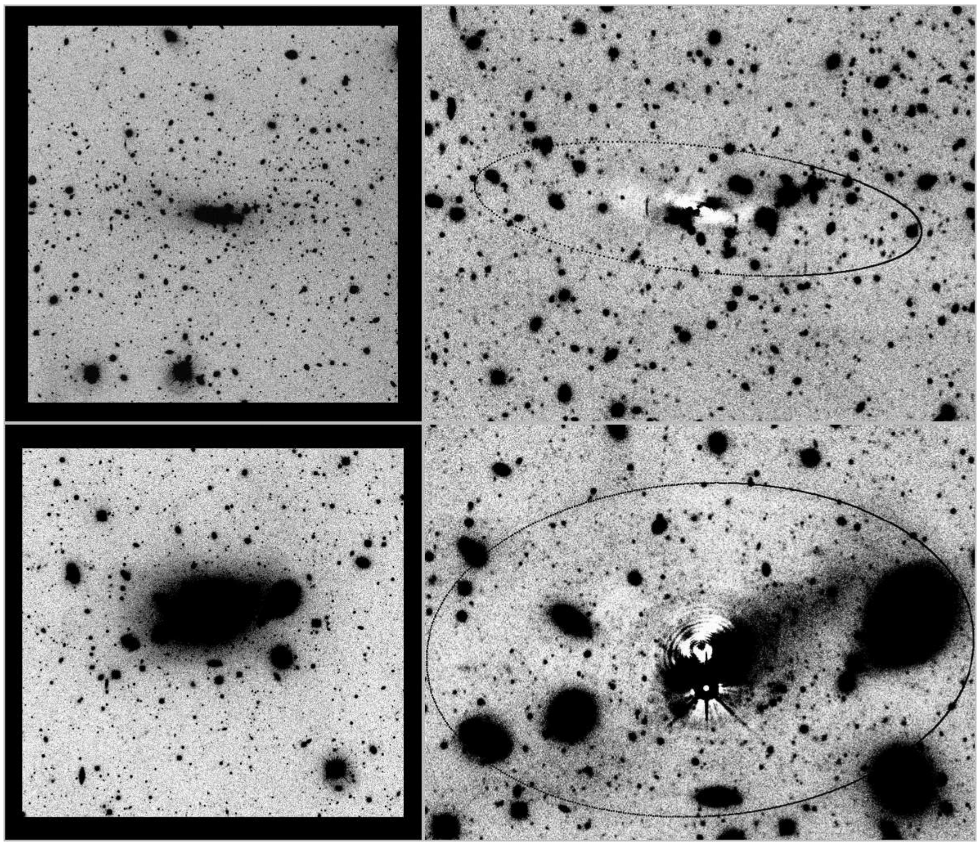

Fig. 1.6. Deep imaging of cD clusters from Feldmeier et al. (2002). Top panels show Abell 1413; bottom panels show MKW 7. The left panels show the full $10' \times 10'$ view of the cluster, while the right panels show a close up of the clusters once a smooth elliptical fit to the cD cluster envelope has been removed. The oval shows the radius inside which the model has been subtracted.

1. The top panels show the cluster at two different times. On the left, the cluster is shown early in the collapse, at $z = 2$, where it consists of two main groups coming together. The right panels show the cluster at $z = 0$, when the cluster has virialized and formed a massive cD galaxy at the center. In each case, the lowest visible contour is at a surface brightness of $\mu_V \approx 30$ mag arcsec^{-2}. The bottom panels show the effects of adding observational noise typical of our ICL imaging data (discussed below) and illustrate the difficulties in detecting this diffuse light.

In the early stages of cluster collapse, material is being stripped out of galaxies and into the growing ICL component. This material has a significant degree of spatial structure in the form of thin streams and more diffuse plumes, much of it at observationally detectable surface brightnesses. At later times this material has become well mixed in the virialized cluster, forming a much smoother distribution of ICL and substructure that is visible only at much fainter surface brightnesses, well below current levels of detectability. Along these

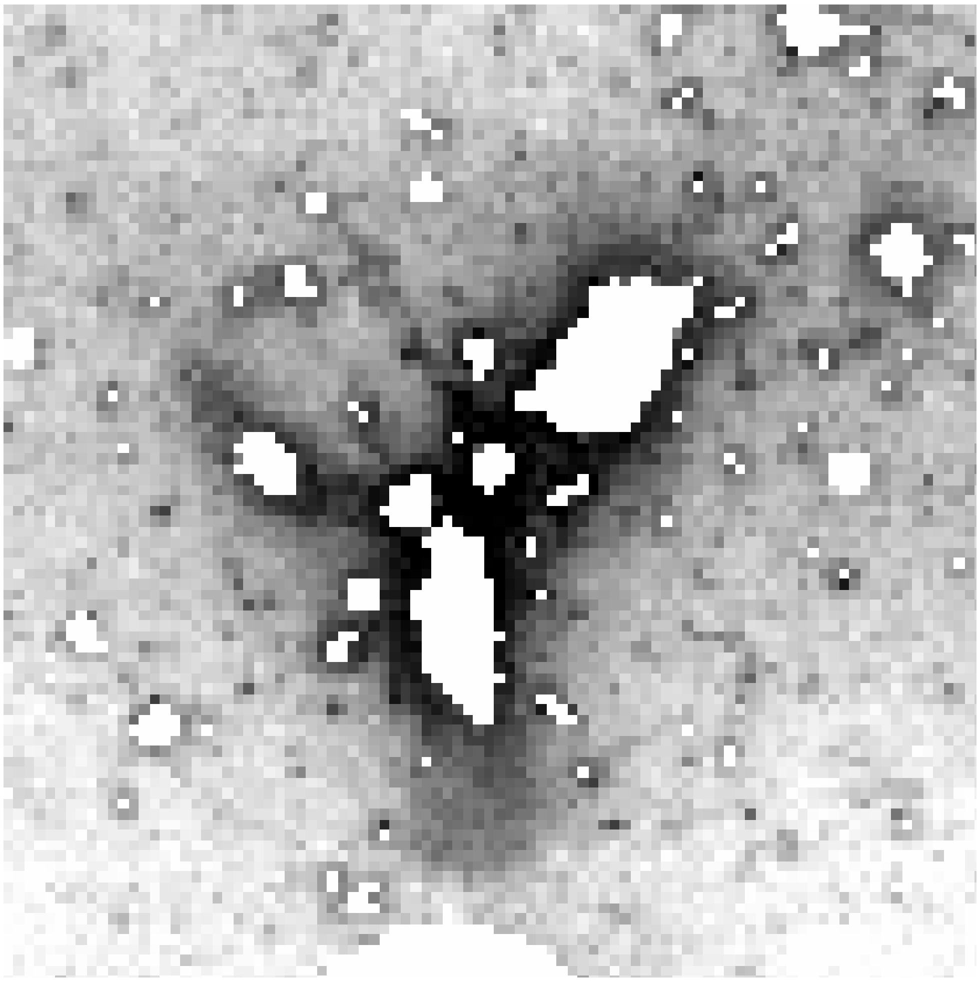

Fig. 1.7. The ICL in Abell 1914 (from Feldmeier et al. 2004).

lines, the degree of ICL substructure may act as a tracer of the dynamical age of galaxy clusters.

Indeed, galaxy clusters do show a range of ICL properties. We (Feldmeier et al. 2002, 2004) have recently begun a deep imaging survey of galaxy clusters, aimed at linking their morphological properties to the structure of their ICL. As the detection of ICL is crucially dependent on reducing systematic effects in the flat fielding, we have taken significant steps to alleviate these issues, including imaging in the Washington M filter to reduce contamination from variable night sky lines, flat fielding from a composite of many night sky flats taken at similar telescope orientations, and aggressive masking of bright stars and background sources (see Feldmeier et al. 2002 for complete details). With this data, we achieve a signal-to-noise ratio of 5 at μ_V = 26.5 mag arcsec^{-2} and a signal-to-noise ratio of 1 at μ_V = 28.3 mag arcsec^{-2}. We have targeted two types of galaxy clusters thus far: cD-dominated Bautz-

Morgan class I clusters (Feldmeier et al. 2002) and irregular Bautz-Morgan class III clusters (Feldmeier et al. 2004).

Figure 1.6 shows results for the cD clusters Abell 1413 and MKW 7. Similar to the clusters studied by Gonzalez et al. (2000; see also Gonzalez, Zabludoff, & Zaritsky 2004), the cD galaxies are well fit by a $r^{1/4}$ law over a large range in radius, with only a slight luminosity excess in the outskirts of each cluster. In each case, we search for ICL substructure by using the STSDAS `ellipse` package to subtract a smooth fit to the cD galaxy extended envelope. In the case of Abell 1413, we see little evidence for any substructure in the ICL; the small-scale arcs we observe are likely to be due to gravitational lensing. MKW 7 shows a broad plume extending from the cD galaxy to a nearby bright elliptical, but little else in the way of substructure.

In contrast, we see evidence for more widespread ICL substructure in our Bautz-Morgan type III clusters. Figure 1.7 shows our image of Abell 1914, binned to a resolution of $3''$ after all stars and galaxies have been masked. Here we see a variety of features: a fan-like plume projecting from the southern clump of galaxies, another diffuse plume extending from the galaxy group to the east of the cluster, and a narrow stream extending to the northeast from the cluster center. The amount of substructure seen here is consistent with an unrelaxed cluster experiencing a merger, similar to the features seen in the unrelaxed phase of the model cluster shown in Figure 1.5. We see similar plumes in other type III clusters, suggesting that the ICL in these types of clusters does reflect a cluster that is dynamically less evolved than the cD-dominated clusters of Feldmeier et al. (2002).

While these studies point toward significant substructure in the ICL of galaxy clusters, imaging surveys continue to be hampered by systematic effects. With so much of the ICL substructure present only at surface brightnesses fainter than $\mu_V > 28$ mag arcsec^{-2}, issues of flat fielding, scattered light, and sky variability become severe. An interesting alternative is to use the significant numbers of intracluster planetary nebulae now being found in emission-line surveys of nearby galaxy clusters (Feldmeier et al. 1998; Arnaboldi et al. 2002). These studies have very different detection biases than deep surface photometry and have the potential to probe the ICL down to much lower surface densities. Planetary nebulae offer an added bonus: as emission-line objects, follow-up spectroscopy can determine the kinematics of the ICL, giving yet another view of the degree to which the ICL is dynamically relaxed (Dubinski et al. 2001). An interesting analogy can be made between the search for kinematic substructure due to tidal stripping in galaxy clusters and the search for kinematic substructure due to tidally destroyed satellites in the Milky Way's halo (e.g., Morrison et al. 2002). In both cases, kinematic substructure can be used to trace the dynamical accretion history of the system. With the advent of multi-object spectrographs on 8-m class telescopes, new and exciting opportunities now exist for studying this substructure in the diffuse starlight of galaxy clusters.

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