Galaxy Transformation by Merging

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Abstract. Theoretical considerations and observational data support the idea that mergers were more frequent in the past. At high redshifts, violent interactions and mergers may be implicated in the origin of Lyman-break galaxies, sub-mm starbursts, and active galactic nuclei. Most stars in cluster ellipticals probably formed at redshifts $z > 2$, as did most of the halo and globular clusters of the Milky Way; these events may all be connected with mergers. But what kind of galaxies merged at high redshifts, and how are these early events connected to present-epoch mergers? I will approach these questions by describing ideas for the formation of the Milky Way, elliptical galaxies, and populations of globular clusters.

1. Introduction

Galaxy merging, once controversial, has become all too respectable. A recent New York Times article claims “The importance of mergers in the evolution of galaxies was one of the insights gained from the northern [Hubble Deep Field] study” (Wilford 1998). But this insight arrived long before HST’s spectacular observations. Theoretical arguments for violent interactions and mergers between galaxies include:

- Hierarchical clustering, in which small objects are progressively incorporated into larger structures (Layzer 1954), is common to many accounts of galaxy formation. In the “core-halo” picture (White & Rees 1978), clustering of dark matter creates galaxy halos which subsequently accumulate cores of baryons, forming visible galaxies.

- Tidal encounters generate short-lived features; a population of binary galaxies with highly eccentric orbits is required to explain the peculiar galaxies observed today (Toomre & Toomre 1972). If these binaries have a flat distribution of binding energies, their merger rate has declined with time as $t^{-5/3}$, and the 10 or so merging galaxies in the NGC catalog are but the most recent additions to a population of about 750 remnants (Toomre 1977).

- The CDM model (Blumenthal et al. 1984) provides a concrete example of galaxy formation in which merging of dark halos is easily calculated and clearly important (Lacey & Cole 1993).
Observations, though until recently limited to redshifts below those probed in the HDF, also indicate rapid merging at high redshift:

- Various counting strategies, mostly limited to $z \lesssim 1$, show the pair density growing like $(1+z)^m$, where $m \simeq 3 \pm 1$ (Zepf & Koo 1989, Abraham 1999).

- Peculiar morphology becomes more common with increasing redshift (van den Bergh et al. 1996). For example, the fraction of irregular galaxies in the CFRS survey increases from about 10% at $z \sim 0.4$ to a third at $z \sim 0.8$ (Brinchmann et al. 1998).

Thus, both theory and observation support the notion that there was “a great deal of merging of sizable bits and pieces (including quite a few lesser galaxies) early in the career of every major galaxy” (Toomre 1977). But the nature of these early mergers is not so clear; were the objects involved dominated by dark matter, by gas, or by stars? And can we learn anything about early mergers by studying present-epoch examples?

2. Signposts of High-Redshift Merging

Merging is hard to prove at redshifts $z \gtrsim 1.5$; cosmological dimming renders tidal tails nearly invisible, while bandshifting effects complicate interpretation of the observations (Hibbard & Vacca 1997). But circumstantial evidence implicates merging in various high-$z$ objects.

2.1. Starburst Galaxies

The most extensively studied high-redshift galaxies are the “Lyman-break” objects at $z \sim 3$, which have rest-frame UV luminosities consistent with star formation rates of $\sim 10 M_\odot \text{yr}^{-1}$ (Steidel et al. 1996b). The actual rates could be several times higher, since much of the UV emitted by young stars may be absorbed by dust (e.g. Heckman 1998). Spectra show gas outflows with velocities of $\sim 500 \text{ km sec}^{-1}$ (Pettini et al. 1998a), atypical of quiescent galaxies but fairly normal for starburst systems. Heavily obscured high-$z$ starbursts have been detected at sub-mm wavelengths (Hughes et al. 1998, Barger et al. 1998). These have IR spectral energy distributions similar to those of ultra-luminous starburst galaxies like Arp 220 and appear to be forming stars at rates of $\sim 10^2 M_\odot \text{yr}^{-1}$.

At low redshifts, luminous starbursts are often triggered by mergers of gas-rich galaxies (Sanders & Mirabel 1996). The gas becomes highly concentrated; H$_2$ surface densities of $10^3$ to $10^5 M_\odot \text{pc}^{-2}$ are typical of nearby starbursts (Kennicutt 1998a), and similar surface densities are indicated in high-$z$ starbursts (Heckman 1998). In the potential of an axisymmetric galaxy, gas becomes “hung up” in a disk several kpc in radius instead of flowing inward. Violently changing potentials in merging galaxies enable gas to shed its angular momentum and collapse to as little as $\sim 1\%$ of its initial radius (Barnes & Hernquist 1996).

Models based on mergers of low-$z$ disk galaxies may not be a good description of high-redshift starbursts. First, compared to nearby starbursts, Lyman-break galaxies have higher peak UV surface brightnesses (Weedman el al. 1998) and seem to be more extended (Pettini et al. 1998b); these differences may be
due to higher gas contents, lower dust extinction, or undetected AGN. Second, disks collapsing at higher redshifts are naturally more compact (Mo, Mao, & White 1998) and thus may form with surface densities characteristic of starbursts. Third, bar instabilities in isolated galaxies can drive rapid gas inflows even without external triggers (Schwarz 1981). Nonetheless, many high-$z$ objects have highly irregular shapes, and deep HDF images reveal faint asymmetric features which may be due to tidal interactions (van den Bergh et al. 1996, Steidel et al. 1996a). Mergers seem to be the “best bet” for high-$z$ starbursts (Somerville, Primack, & Faber 1998), but extrapolation from low-$z$ is only the first step toward testing this conjecture.

2.2. Radio Galaxies

At low redshifts, powerful radio sources are often associated with merger remnants; some 30% exhibit tails, fans, shells, or other signatures of recent collisions (Heckman et al. 1986). But at redshifts $z \gtrsim 0.6$ the most striking morphological feature of powerful radio sources is a near-ubiquitous alignment between the radio lobes and continuum optical emission (McCarthy et al. 1987, Chambers, Miley, & van Breugel 1987). This “alignment effect” seems at odds with the merger morphologies seen at low redshift; one explanation invokes jet-induced star formation (e.g. McCarthy et al. 1987).

Recent observations suggest the alignment effect is compatible with mergers (Stockton 1999). Strong polarization is found in several $z \gtrsim 2$ radio galaxies, implying that the aligned emission is scattered light from an obscured AGN (e.g. Tadhunter, Fosbury, & di Serego Alighieri 1989); in several cases there is good evidence that dust is the primary scattering agent (Knopp & Chambers 1997, Rush et al. 1997). HST imaging of the radio galaxy 0406–244 at $z = 2.44$ reveals a double nucleus and what appear to be tidal debris illuminated by an AGN (Rush et al. 1997).

From a theoretical point of view, merging may be the most efficient way to form powerful radio sources. The engines of such galaxies are probably rapidly spinning black holes (Begelman, Blandford, & Rees 1984). Accretion from a disk is an ineffective way to spin up a black hole, since little of the disk’s angular momentum falls into the hole; on the other hand, two black holes of comparable mass can spiral together to produce a rapidly-spinning hole (Wilson & Colbert 1995).

2.3. Quasars

Evidence that low-redshift quasars frequently occur in interacting systems has been accumulating for two decades (Stockton 1999). Early claims that quasars have close companions are supported by recent studies out to redshifts $z \sim 1$ (Disney et al. 1995, Fisher et al. 1996, Stockton & Ridgway 1998). Even more telling are the tidal tails and other signs of violent interactions in nearby cases (Stockton & Mackenty 1983, Stockton & Ridgway 1991, Bahcall, Kirhakos, & Schneider 1995, Boyce et al. 1996, Stockton, Canalizo, & Close 1998).

The very nature of these interactions makes their detection difficult at high redshifts – there, tidal tails and other signs would be hidden by cosmological dimming and quasar glare. Nor do the low-$z$ observations preclude the possibility that high-redshift quasars may have nothing to do with mergers. A compelling
case that high-z AGN are sparked by mergers probably awaits a theory for the formation of supermassive black holes. All the same, it’s probably no coincidence that the peak in quasar activity at $z \sim 2$ to 3 broadly coincides with other indications of rapid merging reviewed above.

3. Assembling the Milky Way

Complementing the data gathered by looking back to high redshift is information gleaned by “archeological” studies of objects at $z \sim 0$. Mergers of small galaxies probably played an important role in the formation of the Milky Way’s halo (Searle & Zinn 1978); the evidence includes (cf. Gilmore, these proceedings):

1. A “second parameter” – which may (Sarajedini, Chaboyer, & Demarque 1997) or may not (Stetson, VandenBerg, & Bolte 1996) be age – is required to account for variations in globular cluster horizontal branch morphologies.

2. This second parameter is correlated with the shape of a cluster’s orbit; for example, clusters with retrograde orbits have Oosterhoff class I variables (van den Bergh 1993).

3. Halo stars with [$\text{Fe}/\text{H}$] $\sim -1$ have a large range of [$\alpha$/Fe] values (Gilmore & Wyse 1998, Stephens 1999).

4. The outer halo exhibits retrograde rotation with respect to the rest of the galaxy (Majewski 1996).

5. Observations of moving groups in the halo (Eggen 1987, Majewski, Munn, & Hawley 1994).

6. The Magellanic stream (e.g. Mathewson 1985) and other “ghostly streams” of dwarf galaxies and halo globulars (Lynden-Bell & Lynden-Bell 1995).

7. High-latitude A stars in the halo (Preston, Beers, & Sackett 1994).

8. The Sgr I dwarf galaxy, apparently being torn apart by the Milky Way (Ibata, Gillmore, & Irwin 1995).

The variety of stellar populations and abundance patterns (items 1–3) indicate that different parts of the halo have different enrichment histories. Moreover, the strong correlation between Oosterhoff class and orbital direction (item 2) suggests that at least one object with a mass of $\sim 10^{10} M_\odot$ fell in on a retrograde orbit (van den Bergh 1993), and the rotation of the outer halo (item 4) likewise implies a fairly massive retrograde component. Moving groups (item 5) indicate that the stellar halo formed from kinematically distinct components and is not yet well-mixed. Incomplete mixing is also implied by tentative identifications of ghostly streams (item 6), though the interpretation of a stream as the remnant of a single tidally-disrupted galaxy is problematic since multiple dark halos apparently exist in each stream (Kormendy 1990). Streams may instead trace infalling filaments; these may be associated with high-velocity
clouds (Blitz et al. 1999). The A stars at high latitudes (item 7) are too young to have been scattered from the galactic disk and may therefore represent fairly recent acquisitions. Finally, the Sgr I dwarf galaxy (item 8) provides a clear example of halo accretion as an ongoing process.

Two different arguments suggest that the bulk of the halo fell into place long ago. First, most halo stars are old. The halo as a whole shows a well-defined turn-off at $B-V \sim 0.4$, corresponding to ages $\gtrsim 10$ Gyr; only $\sim 10\%$ of the stars appear younger (Unavane, Wyse, & Gilmore 1996). To be sure, this does not rule out recent accretions of objects containing only old stars, but most dwarf galaxies in the local group contain intermediate-age stars as well. Thus, unless the accreted galaxies were unlike those we observe today, most fell in more than 10 Gyr ago.

Second, galactic disks are dynamically fragile; accretion of satellite galaxies can easily ruin a stellar disk. Analytic estimates limit the mass accreted by the Milky Way to less than $4\%$ in the past 5 Gyr (Tóth & Ostriker 1992). N-body experiments show about half the disk heating that analytic work predicts; dark halos absorb much of the damage, and disks may tilt as well as thicken (Walker, Mihos, & Hernquist 1996, Huang & Carlberg 1997, Velázquez & White 1998). Still, accretion events of any size increase the disk's vertical dispersion, $\sigma_z$. Signatures of past mergers may be sought in the $\sigma_z$–age relation; most striking is the jump from $\sigma_z \approx 20$ to $40 \text{ km sec}^{-1}$ which probably marks the transition to the $\sim 10$ Gyr-old thick disk (e.g. Gilmore, Wyse, & Kuijken 1989, Freeman 1993).

Thus it appears that the Milky Way last suffered a significant merger at least 10 Gyr ago; relics of this event include the outer stellar halo and the thick disk. Presumably, the Milky Way’s dark halo was largely in place at this time, since a major merger would have disrupted even the thick disk.

4. Assembling Early-Type Galaxies

While disk galaxies like the Milky Way have had fairly quiet lives for the past 10 Gyr, some elliptical and S0 galaxies have more complex histories. As a group, elliptical galaxies appear to have been shaped by violent relaxation, and almost any plausible account for such violence involves the coalescence of multiple lumps – that is, some sort of merger. But when were these mergers, and what sort of objects were involved?

4.1. Merger Formation

After much debate, it’s clear that elliptical galaxies include some objects formed by fairly recent mergers of disk systems. Support for this position includes:

- The merger origin of ultra-luminous IR galaxies (e.g. Sanders & Mirabel 1996), and the suggestion that such events could build the central regions of elliptical galaxies (Schweizer 1990, Kormendy & Sanders 1992).

- Studies of young merger remnants like NGC 7252 (Schweizer 1982) and models of disk galaxy mergers reproducing such objects (Barnes 1988, Hibbard & Mihos 1995).
Evidence for recent star formation in ellipticals, as indicated by Hβ line strengths (Faber et al. 1994).

Correlations between “fine structures” in elliptical galaxies and residuals in the luminosity–color and luminosity–line strength relations (Schweizer et al. 1990, Schweizer & Seitzer 1992).

These results trace the gradual assimilation of recent merger remnants into the general population of early-type galaxies. Estimated merger ages of nearby field Es and S0s, based on luminosity–color residuals and a color evolution model for disk-galaxy merger remnants, range from ~ 10 Gyr down to 3–5 Gyr, with a handful of younger objects (Schweizer & Seitzer 1992). Complementary evidence from deep photometric surveys indicates that only a third to a half of all field ellipticals were in place and passively evolving by \( z \approx 1 \) (Kauffmann, Charlot, & White 1996, Barger et al. 1999).

Such evidence is scant for cluster ellipticals, which seem to be an older and more homogeneous population. Galaxy clusters are old in two distinct respects: first, cluster galaxies collapsed early; second, dynamical processes run faster in proportion to \( \sqrt{\rho} \). A study of the fundamental plane out to \( z \approx 0.83 \) indicates that most cluster ellipticals have evolved passively since forming the bulk of their stars at \( z \gtrsim 2 \) (van Dokkum et al. 1998).

Counter-rotating or kinematically decoupled “cores” are probably the clearest signs that cluster ellipticals were formed by mergers (Surma & Bender 1995, Mehlert et al. 1998). High-resolution imaging shows that kinematically distinct nuclear components are disks (Surma & Bender 1995, Carollo et al. 1997). These disks typically have high metal abundances (Bender & Surma 1992) and low velocity dispersions (Rix & White 1992); such properties indicate that they formed dissipationally during major mergers (Franx & Illingworth 1988, Schweizer 1990). Merger simulations producing counter-rotating nuclear gas disks back up this hypothesis (Hernquist & Barnes 1991).

The nature of the mergers which formed cluster ellipticals is unclear; often invoked are highly dissipative encounters of gaseous fragments (e.g. Bernardi et al. 1998, Thomas et al. 1999). But the existence of counter-rotating disks in cluster Es indicates that their immediate ancestors can’t have been very numerous or very gassy. If many small objects coalesced, the law of averages would make counter-rotation extremely rare. And counter-rotation is unlikely to arise in essentially gaseous mergers since gas flows can’t interpenetrate.

Relatively few mergers are expected once a cluster has virialized; encounters at speeds higher than about twice a galaxy’s internal velocity dispersion don’t result in mergers (e.g. Makino & Hut 1997). Observations of kinematically distinct disks in cluster galaxies support this expectation, since such disks are unlikely to survive major dissipationless mergers (Schweizer 1998).

In sum, merging apparently began early in proto-cluster environments but tapered off as the clusters themselves virialized, while in field environments merging began later and has continued up to the present. This general picture is broadly supported by semi-analytic treatments of galaxy formation in CDM (Kauffmann 1996, Baugh, Cole, & Frenk 1996). If it is correct then systematic differences between cluster and field ellipticals are expected. The observational status of this prediction is unclear; one study finds field Es are bluer, have lower
Mg$_2$ indices, and higher surface brightnesses than cluster Es of the same luminosity (de Carvalho & Djorgovski 1992), while another study finds essentially identical Mg$_2$–σ$_0$ relations for field and cluster Es (Bernardi et al. 1998).

4.2. **Abundance Ratios**

Relative abundances of α-process elements with respect to Fe are several times higher in elliptical galaxies than they are in the disk of the Milky Way (Worthey, Faber, & Gonzalez 1992, Davies, Sadler, & Peletier 1993). This may constrain the enrichment history; high [$\alpha$/Fe] ratios favor enrichment by SN II on a short timescale, while solar ratios ([α/Fe] = 0) favor enrichment by both SN II and SN Ia on a timescale much longer than 1 Gyr. The high [α/Fe] ratios seen in elliptical galaxies indicate that SN Ia played little role in their chemical evolution; on the face of it, they also imply that ellipticals formed on timescales $\lesssim$ 1 Gyr (e.g. Bender 1997).

Models for chemical enrichment during the formation of elliptical galaxies support this conclusion but illustrate its sensitivity to assumptions about stellar initial mass functions and supernovae yields (Thomas, Greggio, & Bender 1999). With a Salpeter IMF, modest levels of α-process enrichment ([α/Fe] $\simeq$ 0.2) can result from hierarchical collapse with a 1 Gyr star formation timescale; within the uncertainties, mergers of newly-formed (≤ 3 Gyr old) disk galaxies also work, while mergers of present-epoch disks are excluded. But drastic measures seem needed to explain the enrichments of [α/Fe] $\simeq$ 0.5 found in nuclear disks of cluster ellipticals (Surma & Bender 1995, Mehlert et al. 1998). Such high ratios suggest rapid enrichment in starbursts dominated by massive stars; “top-heavy” IMFs are also indicated by optical and IR photometry of ongoing starbursts (e.g. Kennicutt 1998b, p. 71). These arguments must be weighed against the general evidence for a universal IMF (e.g. Elmegreen, these proceedings). Studies of [α/Fe] in post-starburst merger remnants may clarify the issue; significant α-process enrichment would support the case for a top-heavy IMF, while little or no enrichment would support the case against recent disk galaxy mergers.

The hot gas in galaxy clusters, which apparently contains most of the metals in these systems, may further constrain chemical enrichment models for cluster ellipticals. First, the sheer quantity of metals in the intra-cluster medium seems to require a larger fraction of stars becoming supernovae then predicted by a standard IMF (Renzini et al. 1993). Second, the ICM has nearly-solar [α/Fe] ratios consistent with enrichment by both SN II and SN Ia (Ishimaru & Arimoto 1997). If α-process elements were somehow segregated in galaxies, the ICM might be expected to show an excess of Fe, which is not observed (cf. Mushotzky et al. 1996).

4.3. **Globular Clusters**

Young star clusters are observed in star-forming galaxies like the LMC (Elson & Fall 1985) and in intense starburst galaxies (Meurer et al. 1995, Whitmore & Schweizer 1995). These clusters have half-light radii of less than 5 pc, masses of $10^4$ to $10^7$ M$_\odot$, and metal abundances comparable to their parent starbursts. Their luminosity functions follow power laws with slopes of −1.6 to −2, intriguingly close to the mass function of giant molecular clouds (Harris & Pudritz...
However, it’s not entirely clear that cluster luminosity is a good indicator of mass since some range of cluster ages is usually present.

Cluster population correlates with galactic environment as well as morphology (e.g. Harris 1994). In terms of the specific frequency \( S_N \), defined as the number of globular clusters divided by the galaxy luminosity in units of \( M_V = -15 \), ellipticals in rich cluster environments have \( S_N \approx 4 \) to 10, field ellipticals have \( S_N \approx 2 \), and spirals have \( S_N \approx 0.5 \) to 1. Evidence is accumulating that globular cluster populations can be augmented by merger-induced starbursts:

- Ongoing and recent mergers (e.g. NGC 4038/9, NGC 7252, NGC 3921) have populations of blue luminous clusters with ages of less than 1 Gyr (Whitmore & Schweizer 1995, Schweizer et al. 1996, Miller et al. 1997).
- Older remnants (e.g. NGC 3610) have redder and fainter clusters with ages of a few Gyr (Whitmore et al. 1997).
- Predicted specific frequencies in merger remnants increase to \( S_N \approx 2 \) or 3 over \( \sim 10 \) Gyr as the stellar populations fade (Schweizer et al. 1996, Miller et al. 1997).
- Globular clusters in many elliptical galaxies have bimodal or multimodal color (metallicity) distributions (e.g. Harris 1994).

These findings imply that the metal-rich globular clusters in field ellipticals can form during mergers of disk galaxies and subsequently assimilate into existing cluster populations (Ashman & Zepf 1992). This process is illustrated in Fig. 1, which plots specific frequencies of metal rich (\( S^R_N \)) and metal-poor (\( S^P_N \)) globulars. But the metal-poor globulars in cluster ellipticals can’t be explained in the same way (Forbes, Brodie, & Grillmair 1997). Merging of metal-rich systems produces metal-rich clusters; if cluster ellipticals owed their larger globular populations to starbursts in metal-rich material, they would have \( S^R_N \gg S^P_N \), which is not observed. This discrepancy is strongest for cD galaxies, which have \( S^R_N \ll S^P_N \approx 10 \).

The question of high \( S_N \) in cluster ellipticals boils down to this: fewer stars, or more globulars? One way to get fewer stars is to merge galaxies after their metal-poor globular clusters have formed but before they build up substantial disks. For example, the Milky Way as it was \( \sim 10 \) Gyr ago could serve as a building-block for cluster ellipticals; the halo of our galaxy, considered alone, has \( S^P_N \approx 4 \). However, mergers of Milky Way halos or dwarf elliptical galaxies (Miller et al. 1998) still fall short of the high \( S^P_N \) values of cD galaxies and don’t explain the high metallicities of luminous galaxies. Another way to end up with fewer stars is to eject most of the gas after the initial epoch of globular cluster formation; the problem here is that the ejection efficiency must be higher in cD galaxies, which have the deepest potential wells and might be expected to retain the most gas (Harris, Harris, & McLaughlin 1998).

Alternately, the production of globulars may have been more efficient in high-redshift starbursts. Even at low-\( z \), about 20% of the UV emitted by starbursts comes from compact star-forming knots (Meurer et al. 1995); if all these knots survived as clusters, the specific frequency for a pure starburst population would be \( S_N \approx 60 \). Moreover, these knots are concentrated where the surface
Figure 1. Specific frequencies of metal-rich and metal-poor globular clusters in a sample of elliptical galaxies (data from Forbes et al. 1997). The Milky Way (MW) is plotted assuming a ratio of metal-rich to metal-poor clusters $N^R/N^P \simeq 0.2$. The arrows show the result of a merger between two disk galaxies; first the induced starburst forms metal-rich globulars, and then the remnant fades, eventually attaining specific frequencies characteristic of field ellipticals.

densities are highest. It’s likely that net yields of star clusters increase rapidly with increasing gas pressure (Elmegreen & Efremov 1997); “highly crunched gas” (Schweizer 1987) in early starbursts might naturally produce even higher specific frequencies.

If so, then globular cluster systems reflect the starburst histories of their parent galaxies: Large populations of metal-poor globulars are due to efficient cluster production in early, low-metallicity starbursts, while predominantly metal-rich systems (e.g. NGC 5846) formed more recently. Metallicity distributions for globular cluster populations support this idea; giant elliptical galaxies have a range of distributions, often showing multiple peaks between $[Fe/H] \simeq -1.2$ and 0.2 (Harris 1994). This has been interpreted as contradicting merger models and favoring a collapse in “two distinct phases” with bursts of cluster forma-
tion separated by several Gyr (Forbes et al. 1997). But the observed variety of metallicity distributions can arise naturally in a sequence of dissipative mergers if each merger mixes up the available gas and contributes clusters of fairly limited metallicity range to the cumulative population. The final distribution will then be a stochastic sum of a modest number of peaks, in general accord with the observations. Moreover, delays of several Gyr between major starbursts are easily explained by merging, but quite hard to explain as a result of internal events within a single galaxy. This picture for the origin of cluster populations seems ripe for study with the semi-analytic tools for galaxy formation in CDM (Kauffman, White, & Guiderdoni 1993, Cole et al. 1994).

5. Conclusions

A wide range of circumstantial evidence suggests that merging played an important role in galactic evolution long before the present epoch. The key points of the argument can be summed up as follows:

- Starbursts and AGN are signposts of high-redshift mergers; the high incidence of such objects at \( z \approx 2 \) to 4 reflects frequent merging of juvenile galaxies.

- The bulk of the Milky Way’s halo merged more than 10 Gyr ago as part of this activity.

- Cluster ellipticals were formed in dissipative mergers before \( z \approx 2 \); their immediate progenitors were few and only moderately gassy. Early-type galaxies in the field and in small groups have continued forming right up to the present, most recently via dissipative merging of disk galaxies.

- Globular cluster populations in cluster and field ellipticals differ systematically because the former merged first. The metal-rich globular clusters of all ellipticals are relics of their final dissipative mergers.

Peering back to redshifts \( z \approx 5 \) and greater, the familiar Hubble types vanish altogether, and the universe is populated with numerous “subgalaxies” apparently much smaller than present-epoch galaxies. Merging, first between such subgalaxies, and subsequently between more familiar objects, played a key role in assembling the galaxies we know today. Despite the seductiveness of biological metaphors, it may be misleading to say that early-type galaxies are the survivors of an evolutionary process. Rather, early-type galaxies emerged from a merger-dominated environment; in some sense, they are fixed points of merging transformations.

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References

Abraham, R.G. 1999, in Galaxy Interactions at Low and High Redshifts, eds J.E. Barnes & D.B. Sanders (Kluwer, Dordrecht), p. 11
Ashman, K.M. & Zepf, S.E. 1992, ApJ, 384, 50
Bahcall, J.N., Kirhakos, S., & Schneider, D.P. 1995, ApJ, 447, L1
Barger, A.J., Cowie, L.L., Sanders, D.B., Fulton, E., Taniguchi, Y., Sato, Y., Kawara, K., & Okuda, H. 1998, Nature, 394, 248
Barger, A.J., Cowie, L.L., Trentham, N., Fulton, E., Hu, E.M., Songaila, A., & Hall, D. 1999, AJ, 117, 102
Barnes, J.E. 1988, ApJ, 331, 699
Barnes, J.E. & Hernquist, L. 1996, ApJ, 471, 115
Baugh, C.M., Cole, S., & Frenk, C.S. 1996, MNRAS, 283, 1361
Begelman, M.C., Blandford, R.D., & Rees, M.J. 1984, Reviews of Modern Physics, 56, 255
Bender, R. 1997, in The Nature of Elliptical Galaxies, eds. M. Arnaboldi, G.S. Da Costa, & P. Saha (ASP, San Francisco), p. 11
Bender, R. & Surma, P. 1992, AA, 258, 250
Bernardi, M., Renzini, A., da Costa, L.N., Wegner, G., Alonso, M.V., Pellegrini, P.S., Rité, C., & Willmer, C.N.A. 1988, ApJ, 508, L43
Blitz, L. Spergel, S.N., Teuben, P.J., Hartmann, D., & Burton, W.B. 1999, ApJ, 514, 000
Boyce, P.J., Disney, M.J., Blades, J.C., Boksenberg, A., Crane, P., Deharveng, J.M., Macchetto, F.D., Mackay, C.D., & Sparks, W.B. 1996, ApJ, 473, 760
Brinchmann, J., Abraham, R., Schade, D., Tresse, L., Ellis, R. S., Lilly, S., Le Fevre, O., Glazebrook, K., Hammer, F., Colless, M., Crampton, D., & Broadhurst, T. 1998, ApJ, 499, 112
Blumenthal, G.R., Faber, S.M., Primack, J.R., Rees, M.J. 1984, Nature, 311, 517
Carollo, M., Franx, M., Illingworth, G.D., & Forbes, D.A. 1997, ApJ, 481, 710
Chambers, K.C., Miley, G.K., & van Breugel, W.J.M. 1987, Nature, 329, 604
Cole, S., Aragon-Salamanca, A., Frenk, C.S., Navarro, J.F., & Zepf, S.E. 1994, MNRAS, 271, 781
Davies, R.L., Sadler, E.M., Peletier, R.F. 1993, MNRAS, 262, 650
de Carvalho, R.R. & Djorgovski, S. 1992, ApJ, 389, L49
Disney, M.J., Boyce, P.J., Blades, J.C., Boksenberg, A., Cane, P., Deharveng, J.M., Macchetto, F., Mackay, C.D., Sparks, W.B., & Phillipps, S. 1995, Nature, 376, 150
Eggen, O.J. 1987, in The Galaxy, eds. G. Gilmore & B. Carswell (Reidel, Dordrecht), p. 211
Elmegreen, B.G. & Efremov, Y.N. 1997, ApJ, 480, 235
Elson, R.A. & Fall, S.M. 1985, PASP, 97, 692
Faber, S.M., Trager, S.C., Gonzalez, J.J., & Worthey, G. 1994, in Stellar Populations, eds. P.C. van der Kruit & G. Gilmore (Kluwer, Dordrecht), p. 249

Fisher, K.B., Bahcall, J.N., Kirhakos, S., & Schneider, D.P. 1996, ApJ, 468, 469

Forbes, D.A., Brodie, J.P., & Grillmair, C.J. 1997, AJ, 113, 1652

Franx, M. & Illingworth, G.D. 1988, ApJ, 327, L55

Freeman, K.C. 1993, in Galaxy Evolution: The Milky Way Perspective, ed. S.R. Majewski (ASP, San Francisco), p. 125

Gilmore, G. & Wyse, R.F.G. 1998, AJ, 116, 748

Gilmore, G., Wyse, R.F.G., & Kuijken, K. 1989, ARAA, 27, 555

Harris, W.E. 1994, in Stellar Populations, eds. P.C. van der Kruit & G. Gilmore (Kluwer, Dordrecht), p. 85

Harris, W.E., Harris, G.L.H., & McLaughlin, D.E. 1998, AJ, 115, 1801

Harris, W.E. & Pudritz, R.E. 1994, ApJ, 429, 177

Heckman, T.M. 1998, astro-ph/9801155

Heckman, T.M., Smith, E.P., Baum, S.A., van Breugel, W.J., Miley, G.K., Illingworth, G.D., Bothun, G.D., & Balick, B. 1986, ApJ, 311, 526

Hernquist, L. & Barnes, J.E. 1991, Nature, 354, 210

Hibbard, J.E. & Mihos, J.C. 1995, AJ, 110, 140

Hibbard, J.E. & Vacca, W.D. 1997, AJ, 114, 1741

Huang, S. & Carlberg, R.G. 1997, ApJ, 480, 503

Hughes, D.H., Serjeant, S., Dunlop, J., Rowan-Robinson, M., Blain, A., Mann, R.G., Ivison, R., Peacock, J., Efstathiou, A., Gear, W., Oliver, S., Lawrence, A., Longair, M., Goldschmidt, P., & Jenness, T. 1998, Nature, 394, 241

Ibata, R.A., Gillmore, G., & Irwin, M.J. 1995, MNRAS, 277, 781

Ishimaru, Y. & Arimoto, N. 1997, PASJ, 49, 1

Kauffmann, G. 1996, MNRAS, 281, 487

Kauffmann, G., Charlot, S., & White, S.D.M. 1996, MNRAS, 283, L117

Kauffmann, G., White, S.D.M., & Guiderdoni, B. 1993, MNRAS, 264, 201

Kennicutt, R. 1998a, ApJ, 498, 541

Kennicutt, R. 1998b, in Galaxies: Interactions and Induced Star Formation, eds. D. Friedli, L. Martinet, & D. Pfenniger (Springer, Berlin), p. 1

Knopp, G.P. & Chambers, K.C. 1997, ApJ, 487, 644

Kormendy, J. 1990, in The Edwin Hubble Centennial Symposium: The Evolution of the Universe of Galaxies, ed. R. G. Kron (ASP, San Francisco), p. 33

Kormendy, J. & Sanders, D.B. 1992, ApJ, 390, L53

Lacey, C. & Cole, S. 1993, MNRAS, 262, 627

Layzer, D. 1954, AJ, 59, 170

Lynden-Bell, D. & Lynden-Bell, R.M. 1995, MNRAS, 275, 429

Majewski, S.R. 1996, ApJ, 459, L73

Majewski, S.R., Munn, J.A., & Hawley, S.L. ApJ, 427, L37
Makino, J. & Hut, P. 1997, ApJ, 481, 83
Mathewson, D.S. 1985, Proc. Astron. Soc. Australia, 6, 104
McCarthy, P.J., van Breugel, W.J.M., Spinrad, H., & Djorgovski, S.G. 1987, ApJ, 321, L29
Mehlert, D., Saglia, R.P., Bender, R., & Wegner, G. 1998, AA, 332, 33
Meurer, G.R., Heckman, T.M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D.R. 1995, AJ, 110, 2665
Miller, B.W., Lotz, J.M., Ferguson, H.C., Stiavelli, M., & Whitmore, B.C. 1998, ApJ, 508, L133
Miller, B.W., Whitmore, B.C., Schweizer, F., & Fall, S.M. 1997, AJ, 114, 2381
Mo, H.J., Mao, S., & White, S.D.M. 1998, MNRAS, 295, 319
Mushotzky, R., Loewenstein, M., Arnaud, K.A., Tamura, T., Fukazawa, Y., Matsushita, K., Kikuchi, K., & Hatsukade, I. 1996, ApJ, 466, 686
Pettini, M., Kellog, M., Steidel, C.C., Dickinson, M., Adelberger, K.L., & Giavalisco, M. 1998a, ApJ, 508, 539
Pettini, M., Steidel, C.C., Dickenson, M., Kellog, M., Giavalisco, M., & Adelberger, K.L. 1998b, in AIP Conf. Proc. 408, Ultraviolet Universe at Low and High Redshift, ed. W. Waller (AIP, New York), p. 279
Preston, G.W., Beers, T.C., & Schectman, S.A. 1994, AJ, 108, 538
Rush, B., McCarthy, P.J., Athreya, R.M., & Persson, S.E. 1997, ApJ, 484, 163
Sanders, D.B. & Mirabel, I.F. 1996, ARAA, 34, 749
Sarajedini, A., Chaboyer, B., & Demarque, P. 1997, PASP, 109, 1321
Schwarz, M.P. 1981, ApJ, 247, 77
Schweizer, F. 1982, ApJ, 252, 455
Schweizer, F. 1987, in Nearly Normal Galaxies, ed. S.M. Faber (Springer-Verlag, Berlin), p. 18
Schweizer, F. 1990, in Dynamics and Interactions of Galaxies, ed. R. Wielen (Springer, Berlin), p. 60
Schweizer, F. 1998, in Galaxies: Interactions and Induced Star Formation, eds. D. Friedli, L. Martinet, & D. Pfenniger (Springer, Berlin), p. 105
Schweizer, F., Miller, B.W., Whitmore, B.C., & Fall, S.M. 1996, AJ, 112, 1839
Schweizer, F. & Seitzer, P. 1992, AJ, 104, 1039
Schweizer, F., Seitzer, P., Faber, S.M., Burstein, D., Dalle Ore, C.M., & Gonzalez, J.J. 1990, ApJ, 364, L33
Searle, L. & Zinn, R. 1978, ApJ, 225, 357
Somerville, R.S., Primack, J.R., Faber, S.M. 1998, astro-ph/9806228
Steidel, C.C., Giavalisco, M., Dickinson, M., & Adelberger, K.L. 1996a, AJ, 112, 352
Steidel, C.C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K.L. 1996b, ApJ, 462, L17
Stephens, A. 1999, AJ, 117, 000
Stetson, P.B., VandenBerg, D.A., & Bolte, M. 1996, PASP, 108, 560
Stockton, A. 1999, in Galaxy Interactions at Low and High Redshift, eds. J.E. Barnes & D.B. Sanders (Kluwer, Dordrecht), p. 311
Stockton, A., Canalizo, G., & Close, L.M. 1998, ApJ, 500, L121
Stockton, A. & Mackenty, J.W., 1983, Nature, 305, 678
Stockton, A. & Ridgway, S.E. 1991, AJ, 102, 488
Stockton, A. & Ridgway, S.E. 1998, ApJ, 115, 1340
Surma, P. & Bender, R. 1995, AA, 298, 405
Renzini, A., Ciotti, L., D’Ercole, A., & Pellegrini, S. 1993, ApJ, 419, 52
Rix, H.-W. & White, S.D.M. 1992, MNRAS, 254, 389
Tadhunter, C.N., Fosbury, K.R.A.E., & di Serego Alighieri, S. 1989, in BL Lac Objects, eds. L. Maraschi, T. Maccaro, & M.H. Ulrich (Springer, Berlin), p. 79
Thomas, D., Greggio, L., & Bender, R. 1999, MNRAS, 302, 537
Toomre, A. & Toomre, J. 1972, ApJ, 178, 623
Toomre, A. 1977, in The Evolution of Galaxies and of Stellar Populations, eds. B.M. Tinsley & R.B. Larson (Yale Observatory, New Haven), p. 401
Tóth, G. & Ostriker, J.P. 1992, ApJ, 389, 5
Unavane, M., Wyse, R.F.G., & Gilmore, G. 1996, MNRAS, 278, 727
van den Bergh, S. 1993, AJ, 105, 971
van den Bergh, S., Abraham, R.G., Ellis, R.S., Tanvir, N.R., Santiago, B.X., & Glazebrook, K.G. 1996, AJ, 112, 359
van Dokkum, P.G., Franx, M., Kelson, D.D., & Illingworth, G.D. 1998, 504, L17
Velázquez, H. & White, S.D.M. 1998, MNRAS, in press
Walker, I.R., Mihos, J.C., & Hernquist, L. 1996, ApJ, 460, 121
White, S.D.M. & Rees, M.J. 1978, MNRAS, 183, 341
Weedman, D.W., Wolovitz, J.B., Bershady, M.A., & Schneider, D.P. 1998, AJ, 116, 1643
Whitmore, B.C., Miller, B.W., Schweizer, F., & Fall, S.M. 1997, AJ, 114, 1797
Whitmore, B.C. & Schweizer, F. 1995, AJ, 109, 960
Wilford, J.N. 1998, The New York Times, November 24, p. F5
Wilson, A.S. & Colbert E.J.M. 1995, ApJ, 438, 62
Worthey, G., Faber, S.M., & Gonzalez, J.J. 1992, ApJ, 398, 69
Zepf, S.E. & Koo, D.C. 1989, ApJ, 337, 34