Mergers and Galaxy Assembly

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Abstract. Theoretical considerations and observational data support the idea that mergers were more frequent in the past. At redshifts $z = 2$ to 5, violent interactions and mergers may be implicated by observations of Lyman-break galaxies, sub-mm starbursts, and active galactic nuclei. Most stars in cluster ellipticals probably formed at such redshifts, 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 are present-epoch mergers useful guides to these early collisions? I will approach these questions by describing ideas for the formation of the Milky Way, elliptical galaxies, and systems of globular clusters.

INTRODUCTION

Why is it so plausible that galactic mergers and tidal interactions were more frequent in the past? Several theoretical reasons come to mind:

- Hierarchical clustering, in which small objects are progressively incorporated into larger structures [1], is common to many accounts of galaxy formation. In the "core-halo" picture [2], 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 [3]. 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 [4].
- The CDM model [5] provides a concrete example of galaxy formation in which merging of dark halos is easily calculated and clearly important [6].

Observations, though not always reaching the redshift range emphasized in this meeting, also imply rapid merging at high redshift:

- Various counting strategies indicate that the pair density grows like $(1+z)^m$, where $m \simeq 3 \pm 1$ [7,8].

- Peculiar morphology becomes more common with increasing redshift [9]. For example, the fraction of irregular galaxies in the CFRS survey increases from about 10% at $z \sim 0.4$ to a third at $z \sim 0.8$ [10].

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" [4]. 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?

SIGNPOSTS OF HIGH-REDSHIFT MERGERS

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 [11]. But circumstantial evidence implicates merging in various high-z objects.

Starburst Galaxies

The most extensive and unbiased sample of high-redshift galaxies are the "Lyman-break" objects at $z \sim 3$, which have rest-frame UV luminosities consistent with star formation rates of $\sim 10^1 \, \mathrm{M_\odot \, yr^{-1}}$ [12]. The actual rates could be several times higher, since much of the UV emitted by young stars may be absorbed by dust (eg. [13]). Spectra show gas outflows with velocities of $\sim 500 \, \mathrm{km \, sec^{-1}}$ [14], atypical of quiescent galaxies but fairly normal for starburst systems. Heavily obscured high-z starbursts have been detected at sub-mm wavelengths [15,16]. These have IR spectral energy distributions similar to ultra-luminous starburst galaxies like Arp 220 and appear to be forming stars at rates of $\sim 10^2 \, \mathrm{M_\odot \, yr^{-1}}$.

At low redshifts, luminous starbursts are often triggered by mergers of gas-rich galaxies [17]. The gas in such systems is highly concentrated; $\mathrm{H_2}$ surface densities of 10^3 to $10^5 \, \mathrm{M_\odot \, pc^{-2}}$ are typical of nearby starbursts [18], and similar surface densities are indicated in high-z starbursts [13]. In the potential of an axisymmetric galaxy, gas becomes "hung up" in a disk several kpc in radius (Frenk, these proceedings) 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 [19].

But models based on mergers of low-z disk galaxies may not apply to high-redshift starbursts [20]. First, bar instabilities in isolated galaxies can drive rapid gas inflows without external triggers [21]. Second, disks forming at higher redshifts are more compact [22] and thus may already have the surface densities associated with starbursts. Third, the starbursts in Lyman-break galaxies occur on scales of several kpc (Weedman, these proceedings), whereas inflows concentrate gas into much smaller regions. Nonetheless, these objects also have irregular morphologies suggestive of mergers, and deep HDF images reveal faint asymmetric features which may be due to tidal interactions [9,23]. Mergers seem to be the "best bet" for high-z starbursts, but something more than naive extrapolation from low-z is needed to test this conjecture.

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 [24]. 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 [25,26]. This "alignment effect" seems at odds with the merger morphologies seen at low redshift; one explanation invokes jet-induced star formation (eg. [25]).

Recent observations suggest the alignment effect is compatible with mergers [27]. Strong polarization is found in several $z \gtrsim 2$ radio galaxies, implying that the aligned emission is scattered light from an obscured AGN (eg. [28]); in several cases there is good evidence that dust is the primary scattering agent [29,30]. 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 [30].

From a theoretical perspective, merging may even be *necessary* to form powerful radio sources. The most plausible engines for such galaxies are rapidly spinning black holes (Blandford, these proceedings). Accretion from a disk can't spin up a black hole unless the accretion phase lasts ~ 0.1 Gyr; on the other hand, two black holes of comparable mass can coalesce to produce a rapidly-spinning hole [31].

Quasars

Evidence that low-redshift quasars frequently occur in interacting systems has been accumulating for two decades [27]. Early claims that quasars have close companions are supported by recent studies out to redshifts $z \sim 1$ [32–34]. Even more telling are the tidal tails and other signs of violent interactions in nearby cases [35–39].

The very nature of these interactions makes their detection difficult at higher redshifts – tidal tails and other signs are hidden by cosmological dimming and quasar glare. Nor does the low-z evidence preclude the possibility that high-redshift quasars may have nothing to do with mergers. However, the peak in quasar activity at $z \sim 2$ to 3 seems to broadly coincide with other indications of extensive merging activity reviewed above. Given the observational difficulties, a compelling case that this high-z activity is driven by mergers probably awaits a theory for the formation of supermassive black holes.

ASSEMBLING THE MILKY WAY

Complementing the data gathered by looking back to high redshift is information gleaned by "archeological" studies of objects at $z \sim 0$. The oldest components of the Milky Way provide evidence that mergers of small galaxies played an important role [40]:

1. A "second parameter" – which may not be age [41] – is required to account for variations in the stellar content of globular clusters.
2. This second parameter is correlated with orbital direction; clusters with retrograde orbits have Oosterhoff class I variables [42].
3. Halo stars with [Fe/H] ~ -1 have a large range of [α/Fe] values [43,44].
4. The outer halo exhibits retrograde rotation with respect to the rest of the galaxy [45].
5. The halo is not completely well-mixed, as indicated by observations of star streams and moving groups [45–47].

Items 1–3 indicate that different parts of the halo have different enrichment histories, items 2 & 4 imply that some part of the halo fell in on a retrograde orbit, and item 5 is direct evidence for the gradual dissolution of fragments after merging.

Halo accretion is clearly an ongoing process, as shown by the discovery of the Sgr I dwarf galaxy [48] and by observations of high-latitude A stars [49]. But two different arguments suggest that the *bulk* of the halo fell into place long ago.

First, halo stars are old. The halo as a whole shows a well-defined turn-off at $B-V \sim 0.4$, corresponding to ages $\gtrsim 10\,\mathrm{Gyr}$; only $\sim 10\%$ of the stars appear younger [50]. 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 [51]. N-body experiments show less disk heating than the analytic work predicts; dark halos absorb much of the damage, and disks may tilt as well as thicken [52–54]. Still, accretion events of any size increase the disk's vertical dispersion, σ_{z}. Significant structure is seen in the σ_{z}–age relation; most striking is the jump from $\sigma_{\mathrm{z}} \simeq 20$ to $40\,\mathrm{km\,sec^{-1}}$ which marks the transition to the ~ 10 Gyr-old thick disk [55].

In sum, the Milky Way last suffered a significant merger at least 10 Gyr ago; relics of this event include the outer stellar halo and possibly 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.

ASSEMBLING CLUSTER ELLIPTICALS

Galaxy clusters are old in two distinct respects: first, cluster galaxies probably collapsed early; second, dynamical processes run faster in proportion to $\sqrt{\rho}$. Thus clusters should contain remnants of many high-redshift mergers. Archeological evidence from nearby clusters provides important clues to these mergers.

Merger Formation

After some controversy, it's generally accepted that elliptical galaxies can be formed by fairly *recent* mergers of disk galaxies. Support for this position includes:

- Studies of proto-elliptical merger remnants like NGC 7252 [56] and models of disk galaxy mergers reproducing such objects [57,58].
- Hβ line strengths in some ellipticals indicating recent star formation [59].
- "Fine structures" in elliptical galaxies correlating with residuals in luminosity–color and luminosity–line strength relations [60,61].

These results enable us to trace the gradual assimilation of recent merger remnants into the larger population of field ellipticals. But such evidence is not available for cluster ellipticals, which seem to be a more homogeneous population (eg. [62]). Studies of the fundamental plane out to $z \simeq 0.8$ indicate that cluster ellipticals evolve passively and probably formed the bulk of their stars at $z \gtrsim 2$ [63]. Thus cluster ellipticals are unlikely to show the signs which betray aging merger remnants in the field.

Counter-rotating or otherwise decoupled "cores" are probably the clearest signs that cluster ellipticals were formed by ancient mergers [64,65]. High-resolution imaging shows that kinematically distinct nuclear components are usually *disks* [64,66]. Such disks typically have high metal abundances [67] and low velocity dispersions [68]. These properties indicate that they formed dissipationally during major mergers [69,70]; merger simulations producing counter-rotating nuclear gas disks back up this hypothesis [71].

The nature of the mergers which formed cluster ellipticals is unknown; often invoked are highly dissipative encounters of gaseous fragments. But the existence of counter-rotating disks indicates that the penultimate participants 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.

Once formed, kinematically distinct disks would be easily disrupted by dissipationless mergers [72]. Thus observations of such structures in cluster galaxies imply that few mergers occur once a cluster has virialized. This is entirely plausible on dynamical grounds since encounters at speeds higher than about twice a galaxy's internal velocity dispersion don't result in mergers [73].

Abundance Ratios

In elliptical galaxies, α-process elements are more abundant with respect to Fe than they are in the disk of the Milky Way [74]. This may constrain the timescale for star formation in ellipticals, since α-process elements are produced in SN II, which explode on a short timescale, while Fe is also produced in SN Ia, which explode after $\sim 1\,\mathrm{Gyr}$. Indeed, [Mg/Fe] $\simeq 0.5$ for the nuclear disks in cluster ellipticals [64,65]. High α-process abundances indicate that SN Ia played little role in enriching these galaxies; on the face of it, they also imply that cluster ellipticals formed on timescales $\lesssim 1\,\mathrm{Gyr}$ (eg. [75]).

High abundances of α-process elements with respect to Fe are also seen in X-ray observations of the diffuse gas in galaxy clusters (eg. [76], but see [77]). The large amounts of metals in cluster gas require remarkably high SN rates which may not be possible with a Salpeter IMF [78]. These results undermine the argument that high α/Fe ratios imply short enrichment timescales, since abundances in the cluster gas presumably represent integrated metal production over $\sim 10\,\mathrm{Gyr}$. The abundance patterns of cluster ellipticals are clearly inconsistent with mergers of present-day spirals, but do not preclude mergers of moderately gas-rich galaxies containing substantial stellar disks.

Globular Clusters

Young star clusters are observed in star-forming galaxies like the LMC [79] and in intense starburst galaxies [80,81]. These clusters have half-light radii of less than $5\,\mathrm{pc}$, masses of 10^4 to $10^7\,\mathrm{M}_\odot$, 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 [82]. However, it's not entirely clear that cluster luminosity is a good indicator of mass since some range of cluster ages is usually present.

Evidence is accumulating that the globular cluster systems of field ellipticals are partly due to cluster formation in merger-induced starbursts:

- Ongoing and recent mergers (eg., NGC 4038/9, NGC 7252, NGC 3921) have populations of blue luminous clusters with ages of less than 1 Gyr [81,83,84].
- Older remnants (eg., NGC 3610) have redder and fainter clusters with ages of a few Gyr [85].
- Predicted specific frequencies[1] in merger remnants increase to $S_{\mathrm{N}} \simeq 2$ or 3 over $\sim 10\,\mathrm{Gyr}$ as the stellar populations fade [83,84].
- Globulars in elliptical galaxies have bimodal color (metalicity) distributions.

[1] The specific frequency S_{N} is defined as the number of globular clusters divided by the galaxy luminosity in units of $M_{\mathrm{V}} = -15$.

These findings imply that metal-rich star clusters form during mergers and are gradually assimilated into existing globular cluster populations [86]. However, the large populations of metal-*poor* globulars found in cluster ellipticals are *not* consistent with mergers of field spirals [87]; predicted specific frequencies of metal-poor clusters are $S_{\rm N}^{\rm P} \simeq 1$, while in fact $S_{\rm N}^{\rm P} \simeq 4$. This problem is even worse for cluster systems in cD galaxies, which have $S_{\rm N}^{\rm P} \simeq 10$; obviously, no amount of merging between metal-rich systems will produce metal-poor clusters!

The question of high-$S_{\rm N}$ 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 globulars 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 $S_{\rm N}^{\rm P} \simeq 4$. However, mergers of Milky Way halos (or dwarf elliptical galaxies [88]) still fall short of the high $S_{\rm N}^{\rm P}$ values of cD galaxies. Another way to end up with fewer stars is to eject most of the gas after the initial epoch of cluster formation; the problem here is that the ejection efficiency must be *higher* in cD galaxies, which have the deeper potential wells and should be better at retaining gas [89].

Alternately, the production of globular clusters may have been more efficient in high-redshift starbursts. Even at low-z, about 20% of the UV emitted by starbursts comes from knots identified with young clusters [80]; if all these clusters survive, the specific frequency for a pure starburst population is $S_{\rm N} \simeq 60$. Moreover, these clusters are concentrated where the surface densities are highest; it's likely that net yields of star clusters increase rapidly with increasing surface density.

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 starbursts, while predominantly metal-rich systems (eg., NGC 5846) formed in more recent starbursts. Metallicity distributions for cluster systems support this idea; giant elliptical galaxies have a range of distributions with multiple peaks between [Fe/H] $\simeq -1.2$ and 0.2 [90]. Such variety seems hard to explain in a picture where internal events determine the timing of cluster formation (eg., [87]); on the other hand, it's easy to imagine that different distributions result from the different merging histories of individual galaxies.

CONCLUSIONS

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:

1. Starbursts and AGN are signposts of high-redshift mergers; the high incidence of such objects at $z \simeq 2$ to 4 reflect frequent merging of juvenile galaxies.

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

3. Cluster ellipticals merged before $z \simeq 2$; their immediate progenitors were few and only moderately gassy.

4. The metal-rich globular cluster systems of these ellipticals are relics of their final mergers.

Finally, direct observations of high-redshift events are complemented by archeological investigation of nearby systems. Both approaches are needed to discover what happened at redshifts $z = 2$ to 5.

I thank Alex Stephens and Hector Velázquez for communicating results in advance of publication. I also thank Jun Makino and the University of Tokyo for hospitality while I prepared this article. This research made use of NASA's Astrophysics Data System Abstract Service. Travel to the conference was covered by air miles accumulated while following the Grateful Dead.

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