A REVIEW OF HIGH-REDSHIFT MERGER OBSERVATIONS

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Abstract. Evolution in the merger rate as a function of redshift is *in principle* the key observable testing hierarchical models for the formation and evolution of galaxies. However, *in practice*, direct measurement of this quantity has proven difficult. In this opening review I outline the current best estimates for the merger rate as a function of cosmic epoch, focusing mostly upon recent advances made possible by deep ground-based redshift surveys and morphological studies undertaken with *HST*. I argue that a marriage of these techniques, in an attempt to determine the space density of mergers amongst the abundant morphologically peculiar population at high redshifts, is probably the most promising currently-available avenue for determining the prevalence of mergers at high redshifts. However, resolved kinematical studies, which seem set to become available in the next few years, are probably the best hope for a definitive determination of the space density of mergers at high redshifts.

1. Observational Techniques:

Three observational techniques have been used to probe changes in the merger rate as a function of cosmic epoch. These are (a) studies of angular and physical correlation functions, (b) pair counts, and (c) morphological studies. The advantages (+) and disadvantages (−) of each of these approaches for studying high-redshift mergers can be crudely summarized as follows.

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1.1. CORRELATION FUNCTIONS

- \+ A close connection to large-scale structure work via the clustering statistics $w(\theta)$ and $\xi(r)$. Since mergers can be identified as the end-products of large-scale clustering, changes in the correlation function at small radius provide a conceptual link between the large-scale and small-scale regimes being probed with the same statistics.
- \+ Biases in measuring correlation functions are fairly well-understood.

- – Measurement of correlation functions is best suited to large samples.
- – These statistics are hard to measure at small radii, particularly when galactic components (such as giant HII regions) become difficult to distinguish from merging companions. This is often the case when probing distant galaxies in the rest-frame ultraviolet, *eg.* in the Hubble Deep Field, where knots of star-formation cannot easily be distinguished from companions (Colley et al. 1996).
- – *Not really measuring merger rate (see below).*

1.2. PAIR COUNTS APPROACH

- \+ Simple statistics to measure (described in detail in the next section).
- \+ Conceptually the pair-counts approach is an integration over the two-point correlation function, with better signal-to-noise properties at small radii, so the biases are also fairly well-understood.

- – Like correlation functions, the statistic becomes ambiguous when merging companions become indistinguishable from galactic components.
- – *Not really measuring merger rate (see below).*

The most important criticism common to both the correlation function and pair counts approaches is that neither provides a direct measure of the merger rate. The fundamental difficulty is *the uncertain physical timescale over which merging occurs*, given physical proximity between galaxies. Both statistics probe the fuel "reservoir" available for close gravitational interaction, but what we really seek is an understanding of the rate at which the merger "engine" operates in converting these galaxies into the by-products of mergers. To understand this, one must observe the mergers in progress. So the third approach must necessarily be a morphological one:

1.3. MORPHOLOGICAL APPROACH

- \+ Direct observation of *mergers in progress.*

- – Poorly-understood biases (*eg.* morphological K-corrections).

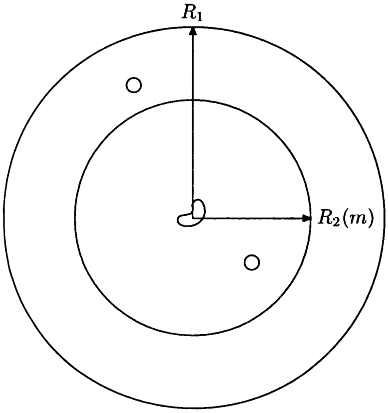

Figure 1. Cartoon showing the search criteria for the "mixed" redshift-photometric analysis of pair-density evolution undertaken by Yee & Ellingson (1995). The search radius R_1 is fixed by the physical scale being probed, while radius R_2 varies with the companion magnitude.

Because of space limitations, and because they are well-reviewed elsewhere, this review ignores studies of the correlation function (eg. Neuschaefer et al. 1997), and touches only rather superficially on recent studies on pair-counts in §2, in order to focus mostly on summarizing very recent progress made on morphological studies at high-redshift with *HST* in §3.

2. Evolution in Density of Pairs

Because existing redshift surveys are not yet deep enough to allow a direct analysis of pair-density evolution to be undertaken, pair count studies can be broadly grouped into two categories: (1) pure photometric analyses with no redshift information, and (2) photometric searches around galaxies with known redshifts. A flavor for the methodology adopted in the latter "mixed" category of redshift-photometric surveys is sketched out in Fig. 1, which illustrates the technique adopted by Yee & Ellingson (1995). Searches are conducted within an aperture projected onto the sky, defined by a projected *physical* radius of $R_1 = 20h^{-1}$ kpc of a galaxy of known redshift. But because low-redshift galaxies will have a large search radius that is likely to be littered with faint unrelated background galaxies, additional restrictions must be placed on the search radius based on the apparent magnitude of the putative companion galaxy. Each companion must lie within a radius $R_2(m) = D_{\rm nm}(m)/3$ where $D_{\rm nm}(m)$ is the expected nearest neighbor distance for galaxies brighter than companion magnitude m ($D_{\rm nm}(m) = \frac{1}{2\sigma(m)^{1/2}}$ (Rose 1977), where $\sigma(m)$ is the surface density of galaxies brighter than m.) A correction can then be made for the expected mean number of unrelated galaxies in the search area, assuming Poisson statistics: $\overline{N} = P_{\rm o}\left[1 + 2\ln\frac{R_1}{R_2(m_l)}\right]$

Results from all published surveys of pair-density evolution (from both classes of survey) are summarized below, in the form of power-law evolution in the density of pairs $(1+z)^n$:

2.1. PURE PHOTOMETRIC ANALYSES

1. Zepf & Koo (1989) ⇒ $(1+z)^{4.0\pm2.0}$
2. Burkey et al. (1994) ⇒ $(1+z)^{3.5\pm0.5}$
3. Carlberg, Pritchet, & Infante (1994) ⇒ $(1+z)^{3.5\pm1.0}$
4. Woods, Fahlman, & Richer (1995) ⇒ No evolution!

2.2. SEARCHES AROUND GALAXIES WITH KNOWN REDSHIFTS

1. Yee & Ellingson (1995) ⇒ $(1+z)^{4.0\pm1.5}$
2. Patton et al. (1997) ⇒ $(1+z)^{2.8\pm0.9}$

The recent work by Patton et al. is based on the largest redshift sample to date: 545 field galaxies with a mean redshift of $z = 0.3$. Clearly these published surveys do not yet probe very far out in redshift space, but it is curious that with the exception of the pure photometric study by Woods and collaborators, all pair-count work to date (but not all correlation function work, eg. Neuschaefer et al. 1997) is roughly consistent with the $(1+z)^{2.7\pm0.5}$ increase in co-moving luminosity density from the Canada-France Redshift survey (Lilly et al. 1996). It is perhaps worth re-stating that the pair fraction increase is *not* the same thing as the merger rate increase: conversion between these is sensitive to assumptions made with regard to merger timescales. No particular consensus exists amongst the various authors regarding the appropriate conversion between pair density and merger rate. For example, given pair evolution with the form $(1+z)^n$, the merger rate is variously assumed to take the form $(1+z)^{n-1}$ by Burkey et al., $(1+z)^{n+1}$ by Carlberg et al., and $(1+z)^n$ by Yee & Ellingson. It is interesting that from the distribution of the projected distances of companions as a function of redshift, Patton et al. conclude that mergers are likely to occur over timescales of 150 Myr – 400 Myr.

3. High-Redshift Morphology

Convincing observations of high-redshift galaxy morphology have only become possible recently, with WF/PC2 observations on *HST*, and the resulting flood of imaging data has resulted in a great increase in our understanding of the field galaxy population at high redshifts. Selected highlights (with apologies to many colleagues whose work cannot be included here due to space limitations) from recent *HST*-based imaging work, relevant to high-redshift mergers, are summarized below. I then go on to describe what seem to me a number of "key issues" with regard to understanding the connection between these imaging observations and high-redshift merger scenarios.

3.1. *HST* FIELD SURVEYS WITH MORPHOLOGICAL INFORMATION

Early work from the Medium Deep Survey (MDS) reported an excess of faint peculiar systems (Griffiths et al. 1994), but the excess become much more convincing with the extension of this work to include number counts as a function of magnitude (Glazebrook et al. 1995; Driver et al. 1995; Abraham et al. 1996). Worries with regard to bulk misclassification of peculiar galaxies have been eased by the incorporation of objective machine-based classifications, which are now routinely being used to supplement (and in some cases replace) visual morphological classifications from a number of different surveys (Abraham et al. 1996; Odewahan et al. 1996; Naim et al. 1997; Brinchmann et al. 1997). The incorporation of redshift information, probing the regime out to roughly $z < 1$, has generally confirmed the photometric work, and in turn pushed much further in terms of our understanding of the contributions of the morphological classes to the star-formation history of the Universe (Cowie, Hu, & Songaila 1995; Schade et al. 1996; Pascarelle et al. 1996; Brinchmann et al. 1997). Imaging follow-up observations of Lyman-limit systems have in turn yielded views of systems at $z > 2$ (Giavalisco et al. 1996). Because of their unprecedented depth, and intensive spectroscopic and photometric redshift follow-ups (Cohen et al. 1996; Lanzetta et al. 1996; Mobasher et al. 1996; Lowenthal et al. 1997; Phillips et al. 1997; Sawicki et al. 1997), Hubble Deep Field observation of faint galaxy morphology are the likely to yield the greatest insights into evolving distribution of morphological types at high redshifts for some time to come (Abraham et al. 1996; van den Bergh et al. 1996; Bouwens et al. 1997; Guzman et al. 1997). Eagerly anticipated are the results from high-resolution infrared observations in the HDF with NICMOS, and forthcoming observations of the HDF South. Deeper observations (and, perhaps more importantly, greater sky coverage) will perhaps have to await completion of the *HST* Advanced Camera, and hopefully *NGST*.

While recent work (Fig. 2) has left little doubt that much of the high-redshift Universe is morphologically peculiar (about 1/3 of all galaxies by $I_{300\mathrm{W}} \sim 24$ mag), the nature of these systems is currently unknown. In the context of the present meeting, the bottom-line question seems to be: what fraction of morphologically peculiar galaxies are mergers in progress? Unfortunately this question cannot be answered at the present time. Part of the problem is simply one of subjective and confusing taxonomy used to describe the morphologies of faint galaxies. For example, are "Morphologically Peculiar" (Griffiths et al. 1994), "Chainlike" (Cowie, Hu, & Songaila

1995), "Blue Nucleated" (Schade et al. 1996), "Irregular/Peculiar/Merger" (Glazebrook et al. 1995; Abraham et al. 1996a,b; Brinchmann et al 1997), and "Tadpole" (van den Bergh et al. 1996) galaxies similar objects simply denoted by different names, or a true reflection in the diversity of the morphologies of galaxies in the distant Universe? At a more mundane level, is bandshifting of the rest-frame of observation (the so-called "morphological K-correction") playing an important role, by fooling us into mistaking systems with normal UV morphology for new classes of galaxy? I have argued (Abraham et al. 1996a,b) that problems with both taxonomy and morphological K-corrections can be circumvented by abandoning conventional galaxy classification schemes in favor of objective classifications, based on measurement of simple structural parameters (such central concentration and asymmetry), and by calibrating such measurements against simulations of the appearance of galaxies at a range of redshifts. The best example of this approach is recent work by Brinchmann et al. (1997). In this work, *HST* imaging and ground-based spectroscopic data for ~ 300 galaxies with good completeness to $I < 22$ mag are used demonstrate that the peculiar galaxy excess is already in place at redshifts where morphological K-corrections have a minimal effect. Simple and objective approaches to quantifying galaxy morphology seems to me the safest course until the observational biases are better understood, but of course one pays a price by "smoothing over" much of the interesting diversity (denoted with correspondingly charming nomenclature) seen in galaxy forms on deep images.

What fraction of this diverse set of peculiar galaxies are actually mergers in progress? The problems inherent in answering this question are illustrated in Color plate 2 (p. xx), which shows candidate Lyman limit systems in the Hubble Deep Field with $I_{814} < 25$ mag. Obviously most are morphologically peculiar, but how many readers can honestly claim that these resemble the appearance of local merging systems? The difficulties inherent in identifying mergers amongst the distant morphologically peculiar population are made clear by simulations recently published by Hibbard and Vacca (1997), who use *HST* WF/PC camera ultraviolet data to predict the appearance of the high-redshift counterparts to local merging starburst systems. Because the usual signatures of mergers (tidal tails, distorted disks) are no longer visible at high redshifts, merging starbursts seem to provide at least qualitatively reasonable counterparts to many faint peculiar galaxies (Fig. 3). While very suggestive, such simulations need to be interpreted with some caution, because they do not explicitly account for evolutionary effects which are known to be important at high redshifts. For example, in the simulations shown in Fig. 3 the smooth components of the galaxy are invisible largely because their stellar populations are evolved in the local reference images and are subject to strong K-corrections. However at

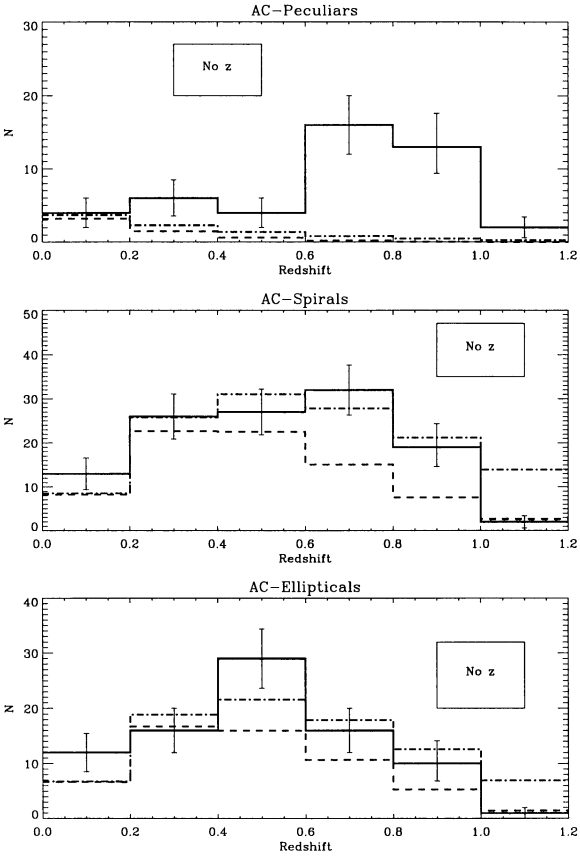

Figure 2. Morphologically segregated redshift distributions (taken from Brinchmann et al. 1997) for irregular/peculiar/merging galaxies (top), spirals (middle), and ellipticals (bottom). The sample consists of ~ 300 galaxies from the CFRS (Lilly et al. 1995) and LDSS (Ellis et al. 1996) redshift surveys. Classifications have been based upon measurements of central concentration and asymmetry on deep *HST* WF/PC2 I_{814}-band images, calibrated by simulations for the effects of bandshifting of the rest-frame of observation. (Although over the redshift range probed such effects are small.) Dashed and dot-dashed lines are the predictions of no-evolution, and mild evolution models. Note the marked excess in the number of irregular/peculiar/merging systems at high redshifts.

$z \sim 2$ *all* stellar populations are relatively young. More detailed simulations incorporating explicitly the effects of evolution would be valuable.

Clearly the best way forward will be to incorporate dynamical information to determine directly which peculiar galaxies show distinct kinematical sub-components. Unfortunately these observations are not currently feasible, although they may soon become possible with adaptive optics and the new generation of 8m-class telescopes. In the meantime, a promising ap-

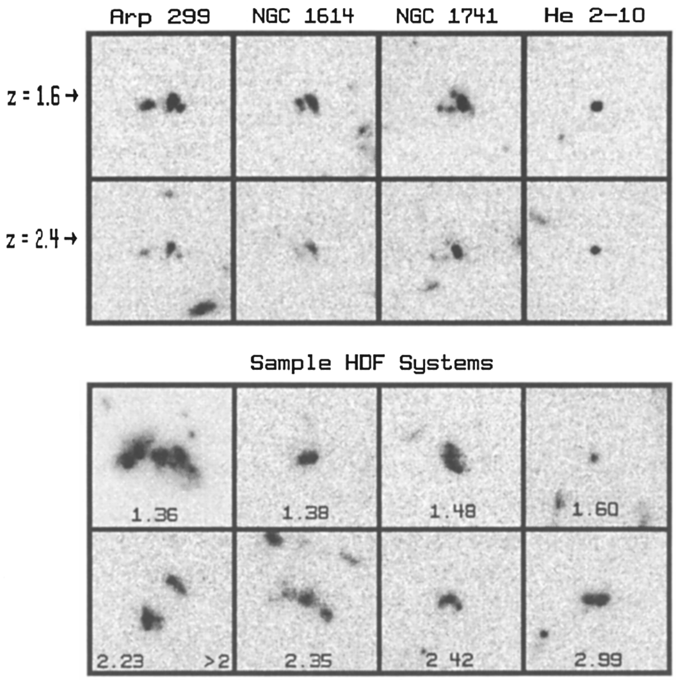

Figure 3. (Top montage:) Simulations (based on ultraviolet *HST* WF/PC observations) taken from Hibbard & Vacca (1997), showing the predicted appearance of local well-known merging starburst galaxies as seen at high-redshifts in the Hubble Deep Field. (Bottom montage:) Morphologically similar galaxies in the Hubble Deep Field.

proach to quantifying the fraction of mergers amongst the distant peculiar galaxy population may be to measure statistics which are relatively insensitive to image distortions resulting from bandshifting and surface-brightness biases, but which track probable merger activity. One such statistic is the "Lee Ratio", a measure of image bimodality. This statistic been applied to images of galaxies in the CFRS survey (Fig. 4) and to HDF galaxies, with the result that around $\sim$ 40% of faint peculiar systems are significantly bimodal, with an $\sim (1+z)^3$ increase in the merger rate (Le Févre et al., in preparation).

Another promising approach to quantifying the fraction of high-redshift mergers is to better understand the nature of the star-formation activity in distant peculiar galaxies, in order to test if their star-formation histories are consistent with merging. One overlooked method for accomplishing this is modeling of the *internal* pixel-by-pixel colors of these galaxies. This approach splits the galaxy up into components under the assumption that morphology can be used to identify stellar populations. In prin-

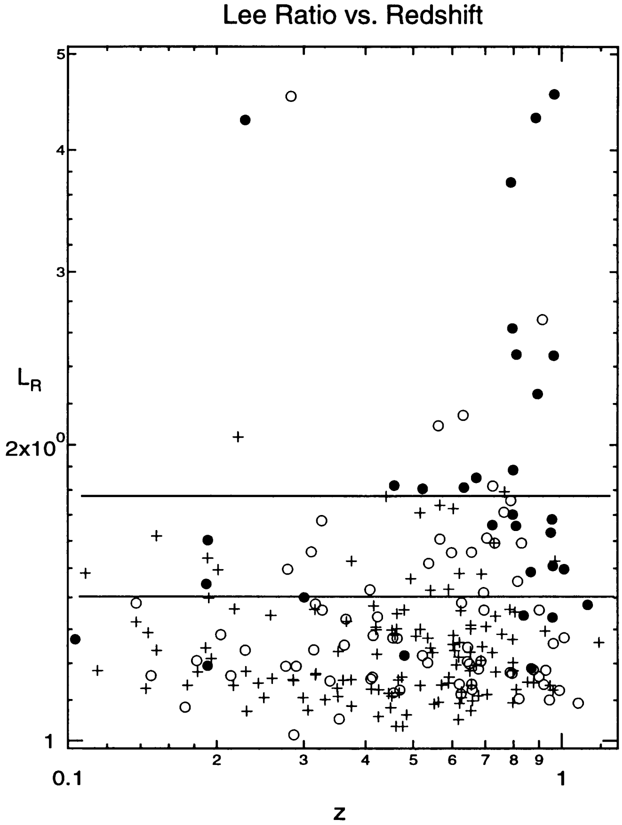

Figure 4. Lee ratio L_R bimodality index for *HST* WF/PC2 images of galaxies in the Canada-France Redshift survey, taken from Le Fèvre et al. (in preparation). Plot symbols correspond to visual classifications of the galaxies as "major mergers" (solid circles), "minor mergers" (open circles), and undisturbed galaxies (crosses). There is a marked increase in the number of merger candidates at $z > 0.5$. Note also the fairly good agreement between classification as a major merger and high Lee ratio.

ciple, this breaks much of the degeneracy inherent in population synthesis modeling which treat galaxies as point sources, and puts constraints not only on merger activity, but also on the dust content, relative ages of disk and bulge, and general star-formation history. As an example, Color plate 3 (p. xxi) shows two "chain galaxies" in the Hubble Deep Field. The resolved color analysis indicates that these systems are showing well-organized star-formation activity – a strong constraint on possible merging scenarios. The "knots" in these galaxies are unlikely to be individual galaxies; star-formation seems to be triggered linearly along the body of the galaxy, starting from a initial "seed" starburst, with individual knots that are about as luminous as "super star clusters" that are the putative progenitors of globular clusters. If such systems are mergers in progress then a mechanism for igniting the chain reaction via mergers must be invoked. Work is currently in progress (Abraham et al. 1998) to apply these ideas to all peculiar galaxies in the HDF in order to determine which galaxies are the strongest merger candidates. Until kinematical studies become available with resolution sufficient to detect merging subsystems at high redshifts, color-based studies may be the best way to detect distinct physical subcomponents in morphologically peculiar galaxies.

4. Conclusion

The most recent pair-count analyses seem to suggest that the fraction of physical pairs grows as $\sim (1+z)^3$. However, the conversion between pair fraction and merger rate is uncertain, and the pair count work so far published is limited to fairly low redshifts ($\langle z \rangle \sim 0.3$). At higher redshifts morphological work with *HST* indicates that by $I = 24$ mag something over 30% of all galaxies are morphologically peculiar. Simulations and follow-up spectroscopic work suggest this excess in morphologically peculiar systems is a physical effect, and not merely the result of "morphological K-corrections". The fraction of mergers amongst these morphologically peculiar galaxies is unknown, because obviously merging local systems, such as nearby major starburst galaxies, no longer appear like conventional mergers at high redshifts. A preliminary analysis of image bimodality (a robust parameter that in principle flags major mergers even at high redshift) amongst $I < 22$ mag peculiar systems with $z < 1$ suggests that around 40% the morphologically peculiar galaxies are strongly bimodal, and thus probably merging. This is consistent with a merger rate increasing like $\sim (1+z)^3$. Internal color analyses of morphologically peculiar systems is an interesting next step in probing high-redshift mergers, leading ultimately to kinematical investigations in the next few years.

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