THE HIGH REDSHIFT POPULATION OF FIELD GALAXIES

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Abstract. In principle, observations of the high redshift population of field galaxies should provide powerful probes of interactions and mergers. As initial examples of such explorations, we highlight recent results from the DEEP program that take advantage of Keck and *HST*, including median redshifts for samples fainter than $I \sim 22$, morphologies and colors to $z \sim 1$, and especially the nature of $z \sim 3$ galaxies in the Hubble Deep Field. Although tantalizing, the results will need much larger samples to be confirmed and better quantified.

1. Introduction

High redshift observations of field galaxies have the potential to offer diverse and independent evidence for the rate and importance of interactions and mergers in the evolutionary history of galaxies. A sampling of indirect methods include:

∗ *morphological* evidence: such as in the frequency of close galaxy pairs or satellites

∗ *photometric* evidence: such as a decrease in the past of the volume density of bright elliptical galaxies with $r^{1/4}$ radial light profiles that are commonly assumed to arise from mergers of disks

∗ *global number count* evidence: such as an overall increase of the volume density of galaxies with lookback time, presumably due to the presence of more pre-merger components in the past

∗ *color* diagnostics: such as the colors of distant bulges, which some astronomers predict would be very red if they were formed prior to disks, while others claim bulge formation was coeval with disk formation and thus should have roughly similar colors at all redshifts

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∗ *fundamental plane* deviations: e.g., this might be observed in the case of an unusually low rotation amplitude in the optical Tully-Fisher diagram for two galaxies colliding roughly head-on in the plane of the sky, resulting in an elongated system that mimics an highly inclined disk system

∗ *theoretical* expectations versus observations: e.g. substantial merging would result in lower median redshifts versus brightness or a different change of the bulge to disk ratio with lookback time

On the other hand, direct evidence for mergers and interactions can also be gathered. Compelling cases for such events would include images of galaxies that show tidal tails or multiple nuclei or spectral evidence for distorted or complex velocity structures. As discussed by Abraham (see proceedings), techniques are being developed which provide quantitative measures of such in-situ evidence for interactions and mergers.

2. Highlights from DEEP

As examples of the potential impact of such high redshift observations, we present some early results that are part of a much more comprehensive Keck survey of very faint galaxies, known as DEEP [1].

2.1. MEDIAN REDSHIFTS

One relatively robust test for whether mergers play a major role in galaxy formation is to compare the predicted median redshift for continually fainter samples of galaxies. Carlberg (1996), for example, estimated that a standard Cold Dark Model (SCDM) model with a substantial rate of mergers would yield a median redshift that remained constant between $20 < I < 28$ with a value near the $z \sim 0.6$ median actually measured by the $I \sim 22$ Canada France Redshift Survey (CFRS: Lilly et al. 1995a). This prediction is, however, found to be inconsistent with our Keck observation of a median $z \sim 0.81$ to 1.00 (95% confidence level), based on a small, but very faint ($22 < I < 24$), sample of 33 field galaxies (Koo et al. 1996). A larger pool of such faint galaxy redshifts observed in the HDF and other fields continue to support this measurement of a high median redshift. Although the "maximal merger rate" model of Carlberg (1996) is no longer compatible with the latest Keck redshifts, mergers may still play a significant, but less prominent, role. Promising matches to the $22 < I < 24$ data can be found, e.g., among more recent and improved merger models that predict median redshift values closer to $z \sim 0.67$ for SCDM and $z \sim 0.91$ for a low $\Omega \sim 0.3$ universe (Baugh et al. 1997).

[1]Information about the Deep Extragalactic Evolutionary Probe project is available on the WWW at URL **http://www.ucolick.org/~deep/home.html**

2.2. MORPHOLOGIES AND COLORS OF $z \sim 1$ GALAXIES

Although the CFRS provides a large pool of very bright galaxies at redshifts $z \sim 1$, the DEEP survey reaches galaxies fainter than $I \sim 22.5$, and thus with luminosities more comparable to typical (L^*) galaxies today. Several tantalizing hints support the view that a large fraction of such galaxies are participating in further agglomerations and in continued star formation due to interactions, major mergers, and infalling satellites by redshifts $z \sim 1$ (Koo et al. 1996). The samples are, however, still small and need to be expanded before firmer conclusions can be drawn.

As examples, we find:

* four of the six very red, high-redshift, early-type *field* galaxies show apparent tidal/merger "tails" or close projected neighbors (Koo et al. 1996). We speculate that we are watching the infall of dwarf galaxies, some quite gas rich, assuming the observed blue colors are due to active star formation. If so, perhaps ellipticals form early and yet can be built up with many more minor mergers over a much longer time period. This process would counter the expected dimming with time of a single-burst stellar population and thus be one possible explanation for the apparent lack of luminosity or density evolution among red galaxies seen in the CFRS (Lilly et al. 1995b) or the Mg II absorber sample (Steidel, Dickinson, & Persson 1994).

* several cases for massive-disk systems (Vogt et al. 1996, 1997) at redshifts $z \sim 1$. Some appear well-formed with thin disks and old bulges while others appear to be less well-organized and perhaps in the earlier phases of disk formation. One well-formed system also shows hints of very blue, very faint satellites that might well settle into it (Koo et al. 1996). This form of evolution has already been proposed for the Milky Way (Majewski 1993).

* Koo et al. (1995), Guzmán et al. (1996, 1997), and Phillips et al. (1997) discuss various kinematic surveys which demonstrate that some compact galaxies at intermediate redshifts are likely to have very low masses. The existence of such systems provide some evidence for the possible presence of pre-merger components or star-bursting dwarfs at high z, but our finding of more massive systems with high star formation rates at higher redshifts appears consistent with the "down-sizing" suggestion of Cowie et al. (1996), which at face-value seems counter-intuitive in a universe in which more massive systems are built up by mergers later in time.

2.3. NATURE OF $z \sim 3$ GALAXIES

An exciting recent advance in observational cosmology has been the pioneering work of Steidel et al. (1996b) in spectroscopically confirming with Keck a relatively large population of high redshift $z \sim 3$ field galaxies. Such

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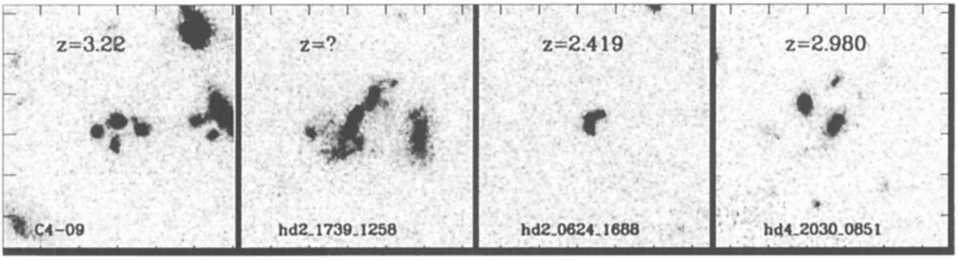

Figure 1. A selection of high-redshift candidate galaxies – three of them confirmed – from the HDF (Steidel et al. 1996a; Lowenthal et al. 1997). Each image is 6 arcsec on a side and the objects are typically $I = 25$. Note the complex morphologies, including linear structures and multiple, spatially separated knots.

galaxies provide direct views of the very early histories of galaxies and certainly place powerful constraints on the role of interactions and mergers in galaxy formation and evolution.

Their candidate selection uses multicolor broadband photometry to look for a "drop-out" of flux due to the redshifted Lyman break in the stellar continuum. This technique was suggested at least three decades ago as a way to look for primeval galaxies by Partridge and Peebles (1967) and followed by numerous surveys since the 1970's (see e.g., review by Koo 1985; Majewski 1989; Cowie 1989; Guhathakurta, Tyson, and Majewski 1990; Lilly, Cowie, and Gardner 1991; Steidel and Hamilton 1992). But none of these earlier efforts had the advantage of a 10-m Keck telescope to confirm any candidates.

To complement the early, important discovery of five such high redshift galaxies by Steidel et al. (1996a) in the HDF, Lowenthal et al. (1997) pushed about one magnitude fainter, used B as well as U band drop-outs to select candidates (see Fig. 2), and secured higher spectral resolution and S/N data to attempt improved kinematic and thus mass measures.

Lowenthal et al. (1997) confirmed 11 more galaxies with high redshifts. Combined with the five from Steidel et al. (1996a), we find an *observed* comoving volume density that is comparable to that of L^* galaxies today, and thus already roughly 3-4 times higher than those from the brighter limits of Steidel et al (1996b). Adjusting for the unobserved or spectroscopically unconfirmed high-redshift candidates in the HDF would yield densities almost 3 times larger. Instead of mainly simple, compact systems for these high redshift galaxies (Giavalisco, Steidel, & Macchetto 1996), we find within our HDF sample of candidates a broad diversity of morphologies, ranging from small, single knots; two more more knots; elongated systems; to more complex, asymmetric morphologies (see Fig. 1).

The nature of these high redshift galaxies is still a mystery. Remain-

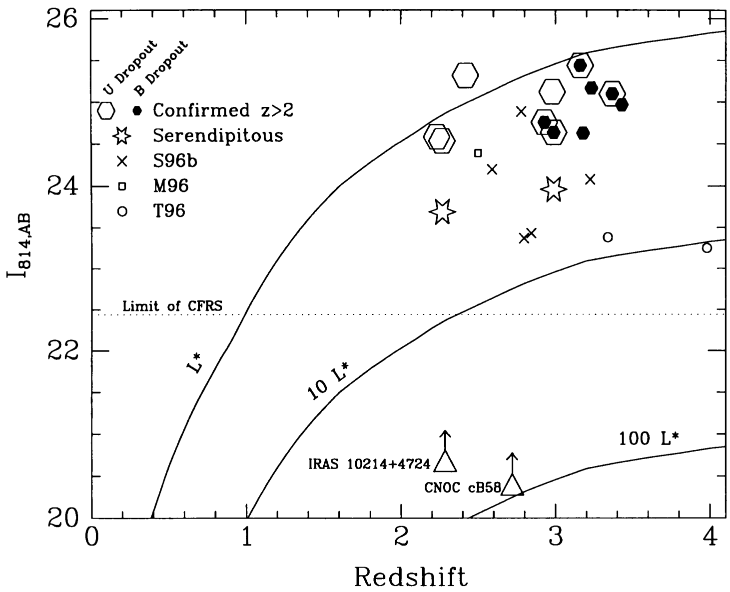

Figure 2. $I_{814\,AB}$ vs. redshift for the confirmed sample of Lowenthal et al. (1997). Also shown for comparison are the three lines corresponding to unevolved L*, 10 L*, and 100 L* blue star-forming galaxies; the five confirmed high-redshift objects in the HDF observed by Steidel et al. (1996b; × symbol); and high-z objects observed in other works as described by Lowenthal et al. (1997). Note that the B-dropouts do add galaxies not found via U-dropouts and have high redshifts, as expected.

ing evidence in support of their being the cores of massive ellipticals and spheroids as suggested by Steidel et al (1996b) are their recent findings of large-scale structure among these galaxies (Steidel et al. 1997), one candidate (C4-09) yielding a mass of roughly 2×10^{11} $M_\odot$ (Lowenthal et al. 1997), and strong theoretical support (e.g., Baugh et al. 1997). On the other hand, the original argument for large velocity widths based on the high equivalent widths of saturated interstellar absorption lines (Steidel et al. 1996a) has been countered by Conti et al. (1996); the smooth, compact morphologies being comparable in size to today's spheroids is no longer as compelling given our finding of large diversity; and arguments based on prior estimates of lower volume densities being consistent with massive galaxies today is now superseded by our fainter, *UB* drop-out survey of higher completeness.

Thus we suggest an alternative view (Lowenthal et al. 1997) that at least some, if not most, of these high redshift galaxies are either the progenitors of local dwarfs, such as spheroidals, with masses closer to 10^{10} $M_\odot$ or the components that will later merge to form more massive galaxies. In support of this view are: the low velocity width of $\sigma \sim 70$ km-s^{-1} measured for one galaxy in the near-IR (Pettini et al. 1997); the similarly low velocity widths of all six Lyα emission lines in our sample; the very high volume densities that would be inconsistent with each high redshift galaxy being an independent massive system today; the discovery of possible lower-redshift counterparts to the high-redshift galaxies among the very luminous, compact systems at intermediate redshift, some of which have very small masses and other characteristics consistent with being the progenitors of some spheroidals today (Koo et al. 1995; Guzman et al. 1996; Phillips et al. 1997); and the low star-formation rates of our fainter, high redshift galaxies that yield masses of only 10^{10} $M_\odot$ after several Gyr and assuming negligible dust extinction to convert UV luminosities to star formation rates.

Clearly a larger sample of reliable mass and star-formation measurements continues to be an important key to resolve the question of whether these systems are the cores of massive ellipticals and spheroids, the progenitors of dwarfs today, or the building blocks of larger galaxies.

3. Acknowledgements

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