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Tackling the Nature of Faint Blue Galaxies with HST and Keck

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Abstract. We summarize the new forms of information that HST offers to tackle the nature of faint blue galaxies and the importance of complementary spectra from the Keck Telescope. As an example of the potential of this combination, we present data for a sample of 33 field galaxies, the vast majority of which are fainter than $I = 22$. At redshifts $z \sim 1$, such faint galaxies have luminosities similar to that of typical galaxies today. Though small, our sample already suggests that the median redshift for $I > 22$ galaxies is higher than the $z = 0.6$ expected for the "maximal merger model" of Carlberg (1995). The HST images show that galaxies with redshifts $z > 0.7$ have frequent signatures of mergers, interactions, and infall of minor galaxies into larger hosts; possess a wide diversity of morphological types; and consist of stellar populations in several objects that are already so red that their major formation epoch occurred at redshifts $z > 2$.

1. Introduction

1.1. Overview of Faint Blue Galaxy Puzzle

A key astronomical observation is that galaxy counts and colors reveal a large surface density of very faint, blue, field galaxies. Despite intensive observational and theoretical work for nearly two decades, such high counts remain a major cosmological mystery. The classical explanation is that such galaxies are those seen at higher redshifts during earlier epochs of more extensive star formation. Yet, ever deeper redshift surveys by several groups and comparisons to their models did not reveal the expected, high-redshift population. This paradox paved the way for a number of more exotic explanations, including the need for a cosmological constant, rapid merging, disappearing populations, bursting dwarves, or rapid changes with redshift in the shape of the galaxy luminosity function. Others proposed that such exotic models were premature, given our incomplete knowledge of the local luminosity function, selection effects, and uncertainties in the models (references and a recent review of these issues can be found in Koo 1996). Although some convergence has been achieved over the last few years by the different groups, no consensus has been reached. Thus the nature of faint blue galaxies is a puzzle that persists, but has recently been amenable to powerful new studies by HST and Keck.

1.2. Contributions from HST

HST provides several new approaches to studying faint galaxies. Taking advantage of the higher spatial resolution and the relative constancy at high redshifts of apparent sizes for a given linear scale, several groups have classified the morphologies of very faint galaxies. They find that the blue galaxies are dominated by late-type or peculiar morphologies and that such galaxies indeed exceed their model predictions by large factors (see overview by Longair in these proceedings). Moreover, the peculiar morphologies are suggestive of increased interactions and mergers among higher redshift galaxies. Besides providing morphology as an independent check of the input models used to interpret faint counts and colors, HST data also provide size measurements. Such measurements can reveal whether new populations (e.g., very blue, compact galaxies undergoing starbursts) are appearing. Sizes can also yield the surface brightnesses of distant galaxies (assuming redshifts are available) and hence a direct measure of luminosity evolution, assuming intrinsic galaxy sizes have not evolved. Similarly, bulge to disk ratios, color gradients, the shapes of light profiles, and the colors of nuclei are all potential tools to detect the presence of new components (e.g., larger fraction of AGN activity) or the evolution of known galaxy components, but these more sophisticated methods have yet to be exploited fully (see Schade in these proceedings). Even the shapes and orientations are useful, e.g., in gravitational lensing tests that can indirectly probe the redshifts of objects too faint for spectroscopy or in testing for the intrinsic shapes of very faint galaxies. The higher spatial resolution also offers improved measures of the clustering of galaxies on small scales (see Griffiths in these proceedings). Finally, HST accesses the deep ultraviolet, a regime where the relationship of low redshift Lyman α lines to field galaxies or the UV colors of local galaxies can be studied. Such data can then be compared to similar, but more distant, samples.

1.3. Contributions from Keck Telescope

Large, ground-based telescopes, such as the Keck 10-m, provide complementary data to unravel the nature of faint galaxies. Of perhaps greatest importance, Keck provides redshifts to very faint limits. Such redshifts are crucial to determine whether particular galaxies are near or far, intrinsically blue or red, bright or faint, large or small, low or high surface brightness, etc. Even the interpretation of a galaxy's morphology is dependent on its observed rest-frame wavelength and thus its redshift. But Keck spectra provide more than redshifts. With sufficient spectral and spatial resolution and quality, the spectra of faint galaxies can also yield rotation curves and the velocity dispersions of gas and stars (e.g., Forbes *et al.* 1996, Vogt *et al.* 1996). Combined with the size and inclination from HST images, these internal kinematics translate to direct measures of the *total* masses, whether luminous or dark, of distant galaxies. Such masses provide entirely new methods to tackle galaxy evolution and to address such fundamental questions as whether the faint blue galaxies are massive or not, whether they are in their early phases or later stages of star formation, whether they follow local relationships such as the Tully-Fisher, Faber-Jackson, elliptical fundamental plane, etc. The masses of distant galaxies are more closely tied to theoretical simulations than luminosities and colors (which depend on understanding star formation) and thus serve as more direct probes of the merger rate. Finally, Keck spectra of high quality can also yield direct clues to the ages and metal abundances of the stellar populations of distant galaxies. Such information provide independent checks of both cosmology (via time) and galaxy evolution, via the dependence of metal production with star formation.

1.4. DEEP Project

Distant galaxy programs which exploit these new parameters from HST and Keck are very much in their infancy. One such program now underway is called the Deep Extragalactic Evolutionary Probe, or DEEP (Mould 1993, Koo 1995). Here we provide early results of a new DEEP pilot survey that combines redshifts from the Keck Telescope with photometry, colors, and morphologies from refurbished HST images taken by Groth *et al.* (1996). Though this Keck redshift sample has only 33 galaxies (due to the loss of 80% of the run to weather), the magnitudes are so faint (11 with $I < 22$, 13 with $22 < I < 23$, and 9 with $I > 23$) and the redshifts so high (median $z \sim 0.8$), that this survey provides a unique glimpse of the nature of faint, distant field galaxies *of typical luminosities (L^*)* at an epoch beyond half the Hubble age. We highlight several intriguing hints that have already emerged.

2. Observations

Photometry and morphology are extracted from HST images taken by Groth *et al.* (1996). The survey region consists of 28 overlapping WFPC2 fields, each observed in the F606W (V) filter for 2800s and F814W (I) for 4400s. One field, however, was exposed for 7 hours in the same filters. Our spectroscopic survey was centered on this very deep field, but also covered four other flanking fields of shallower depth.

All but two bright galaxies were observed through masks cut with multiple slitlets, which allowed simultaneous exposure of ∼25 or more targets with the Low Resolution Imaging Spectrograph (LRIS, see Oke *et al.* 1995). We adopted a slitwidth of 1.1 arcsecs and achieved a dispersion of 1.28Å per px (3-4px resolution) over a spectral range of 6500Å to 9100Å.

The galaxies chosen for spectroscopy do not constitute a totally random, magnitude-limited sample, but were instead chosen to be *representive* of a variety of morphologies, magnitudes, and colors to a limit of $(V+I)/2 \approx R \sim 24$. Three of the faintest emission-line redshifts were found serendipitously in the slit of the primary target; eight galaxies, all with $I > 22$, had no or uncertain redshifts. Also note that [OII] 3727Å is redshifted beyond our spectral limit of $\sim$ 9100Å for redshifts $z > 1.4$. Thus we were gratified to achieve an overall completeness of 80% (33/41) to a limit of $I > 24$. This is presumably due to the high incidence of strong emission lines among very faint galaxies.

3. Discussion

Figure 1 summarizes our results in a V-I color versus redshift diagram for our entire Keck sample, including 18 galaxies from Forbes *et al.* (1996). The curves provide guides to the intrinsic colors of the galaxies. One striking aspect of our data is the high concentration at redshifts $z \sim 0.8$ and 1.1, which yields a median $z \sim 0.8$ to 1.0, regardless of the redshifts of the eight failures. This median redshift is *not* consistent with $z \sim 0.6$, a value predicted by the "maximal merger models", which otherwise fit existing brighter observations (Carlberg 1995). The higher median, however, matches an extrapolation of the landmark $I = 22$ Canada-France Redshift Survey (Lilly *et al.* 1995) or even some simple luminosity evolution models (e.g., Gronwall and Koo 1995).

Figure 1 shows how well the galaxies fall within the bounds seen in the colors of normal, local galaxies. We find neither unusually blue nor unusually red galaxies. Other implications from the figure are (i) that at high redshifts $z \geq 0.7$, some *field* galaxies do exist with intrinsic colors comparable to that found for local ellipticals; (ii) that the most recent major star-formation event in these red galaxies (assuming no dust) occurred at redshifts $z \geq 2$; (iii) that the current model of Babul and Ferguson (1996) does not quite match the observed color distribution nor the presence of very blue galaxies beyond redshifts $z \sim 1$; and (iv) that intrinsically blue galaxies partake in the strong clustering seen at redshifts $z \sim 0.8$ and 1.0. Furthermore, although HST images show strong and frequent hints of mergers, interactions, other peculiar patterns, and infall of minor galaxies into larger hosts, normal galaxies are also visible. The morphologies of $z \sim 1$ galaxies are thus not confined to late-type, peculiar systems and, conversely, the late-type galaxies seen in deep HST images are not predominantly at low redshifts (i.e., of low-luminosity).

This glimpse of very faint $z \sim 1$ field galaxies strongly suggests that we need to invoke an unknown, possible complex, mixture of physical processes to account for the faint blue galaxies, rather than to rely on a single dominant mechanism, such as mergers or bursting dwarfs.

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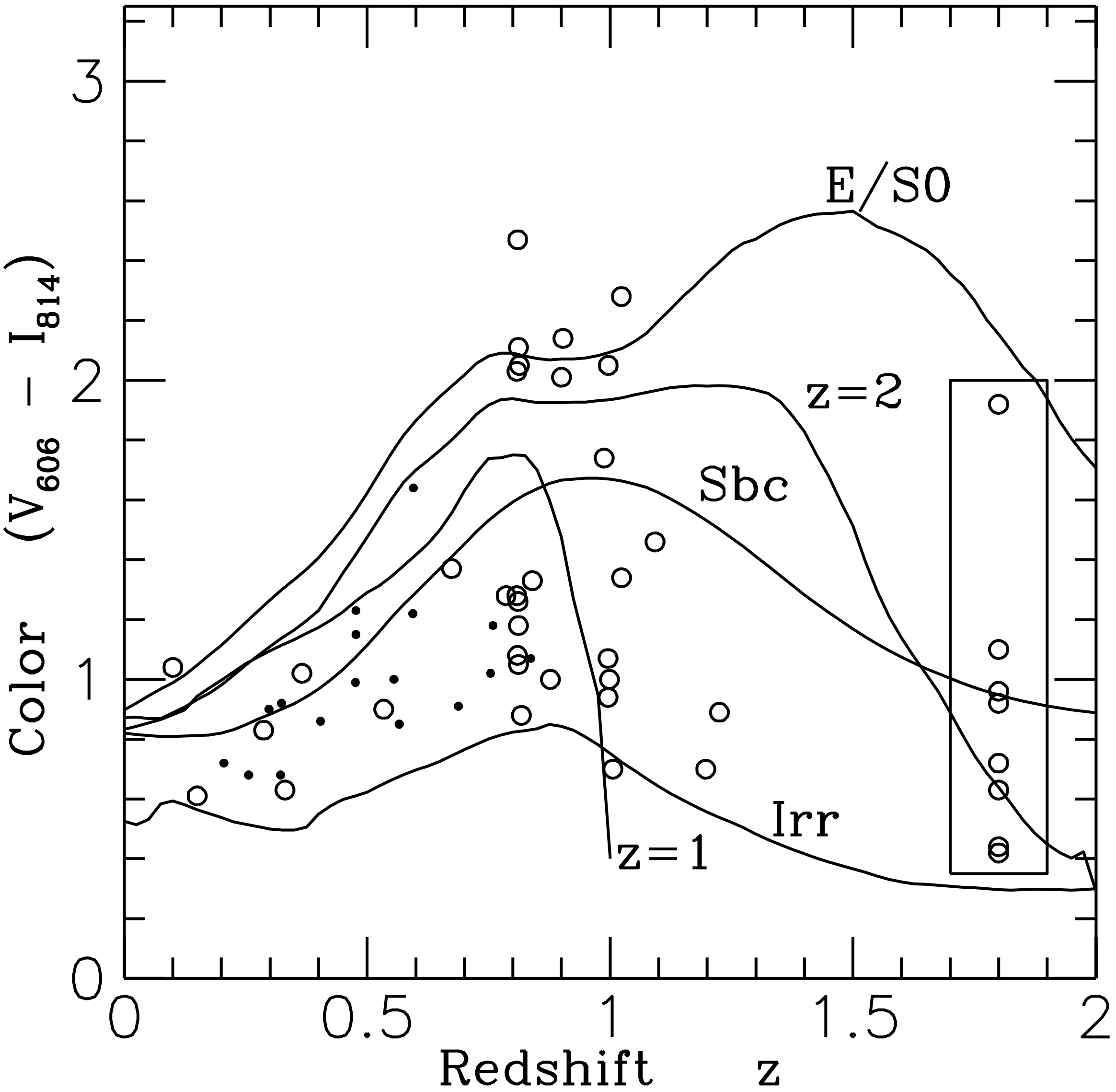

Figure 1. $V - I$ color vs redshift plot of Keck targets from this work (open circles) and Forbes *et al.* 1996 (points). Objects without redshifts are placed in the separate box to the right. Several labeled lines show the expected colors for various spectral energy distributions, including one resulting from an instantaneous burst of star formation at redshift $z = 2$ (using the models of Bruzual and Charlot 1993) that becomes almost as red as a non-evolving local elliptical or S0 (E/S0) by $z < 1$; another resulting from a model burst at $z = 1$ that might be compared to the bursting dwarfs in the model of Babul and Ferguson (1996); another to the colors of a local Sbc galaxy; and the bluest one for N4449, a very actively star-forming Irr galaxy.

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