A GLIMPSE OF FIELD GALAXIES AT REDSHIFTS $Z \sim 1$ USING HST AND THE KECK TELESCOPE

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Abstract. Data from the Keck and Hubble Space Telescopes have been combined to explore the nature of very faint $I > 22$ field galaxies. At a redshift $z \sim 1$, such galaxies have luminosities similar to that of typical galaxies today. Though small, our sample of 33 redshifts already suggest that the median redshift for $I > 22$ galaxies is higher than the $z = 0.6$ expected for the "maximum merger model" of Carlberg (1995). At redshifts $z > 0.8$, mergers, interactions, and infall of minor galaxies into larger hosts appear to be common events; a wide diversity of morphological types existed; and some stellar populations were already so red that their major formation epoch occurred at redshifts $z > 2$.

1. Introduction

The nature of very faint, blue field galaxies is still a major cosmological mystery. Although deep refurbished Hubble Space Telescope (HST) images to $I \sim 24$ or fainter show a predominance of late-type or unusual galaxy morphologies in both clusters (see Oemler in these proceedings) and the field (see Driver in these proceedings), their redshifts remain largely unknown. Yet 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. With sufficient resolution and quality, spectra can also serve as probes of internal velocities and hence masses (see Illingworth in these proceedings), ages, and metal abundances of galaxies. Such a program, using the Keck 10m Telescope for the spectroscopy, is now underway as a new initiative called the Deep Extragalactic Evolutionary Probe, or DEEP (Mould 1993, Koo 1995).

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Here we provide early results of a new DEEP survey that combine redshifts from the Keck Telescope with photometry, colors, and morphologies from refurbished HST images taken by Groth *et al.* (1995). 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.* (1995). The survey region consists of 28 overlapping WFPC2 fields with 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 4 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 $(V+I)/2 \sim 24$. 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 $\sim$ 9100Åfor 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. Results and 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.* (1995). 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 9 failures . This result is inconsistent with $z \sim 0.6$ as predicted by the "maximum merger models", which otherwise fit existing brighter observations

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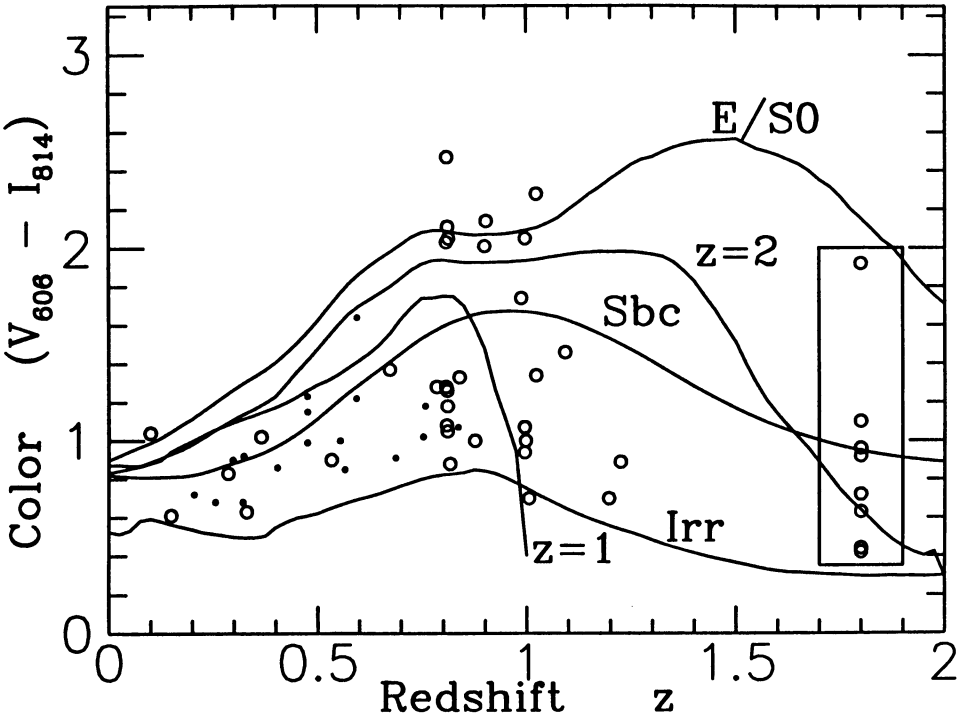

Figure 1. $V - I$ color vs redshift plot of Keck targets from this work (open circles) and Forbes *et al.* 1995 (points). Objects without redshifts are placed in the separate box to the right. Several labeled lines show the expected colors for various spectral energy distributions, including one resulting 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 SO (E/SO) 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 (1995); another to the colors of a local Sbc galaxy; and the bluest one for N4449, a very actively star-forming Irr galaxy.

(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 that (i) *field* galaxies do exist at high redshifts $z \gtrsim 0.7$ which have intrinsic colors comparable to that found for local ellipticals; (ii) that the most recent major star-formation event in these red galaxies presumably occurred at redshifts $z \gtrsim 2$; (iii) that the current model of Babul and Ferguson (1995) 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 necessarily of low redshifts and thus of low-luminosity.

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

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Questions and Answers

E. Kachikian: Did you find Seyfert-type spectra among your objects?
D. Koo: Not yet, but this is not unexpected for our small sample.
M. Dickinson: Just a comment on the red galaxies – for *clusters*, at least, we are seeing very red, ordinary, boring $r^{1/4}$-law profile ellipticals out to $z = 1.2$.
D. Koo: We see these too. I was just pointing to one with an unusual profile and was *not* implying that the finding of an exponential profile was common.
S. Zepf: The unusual morphology of the red object suggests that their colors might be affected by dust. What are the spectral types of these red galaxies?
D. Koo: We have not yet examined the spectral types, but dust is visible in some cases.
U. Hopp: How many single-lined objects do you have at $z \sim 1$? What further arguments did you use to assign a redshift to a single-line spectrum?
D. Koo: Most are single lines of [OII]3727. This identification was usually based on a rising continuum with Balmer absorption to the red, sometimes on the resolution of the doublet, and on the lack of [NII] or [SII] if H_α is a possibility. Some uncertainties definitely remain.