The Stony Brook Photometric Redshifts of Faint Galaxies in the Hubble Deep Fields

Kenneth M. Lanzetta¹, Hsiao-Wen Chen¹, Alberto Fernández-Soto², Sebastian Pascarelle¹, Rick Puetter³, Noriaki Yahata¹, and Amos Yahil¹

Abstract.

We report on some aspects of the current status of our efforts to establish properties of faint galaxies by applying our photometric redshift technique to faint galaxies in the HDF and HDF-S WFPC2 and NICMOS fields.

1. Introduction

Over the past several years, we have applied our photometric redshift technique to faint galaxies in the Hubble Deep Field (HDF) and Hubble Deep Field South (HDF-S) WFPC2 and NICMOS fields. Our objective is to establish properties of galaxies that are too faint to be spectroscopically identified by the largest ground-based telescopes. Our experiences indicate that photometric redshift measurements are at least as robust and reliable as spectroscopic redshift measurements (and probably more so). The photometric redshift technique thus provides a means of obtaining redshift identifications of large samples of faint galaxies. Here we report on some aspects of the current status of our efforts.

2. Observations and Analysis

Our current observations and analysis differ from our previous observations and analysis in three ways: First, we have included all publicly available ground- and space-based imaging observations of the HDF, HDF-S WFPC2, and HDF-S NICMOS fields. Details of the observations are summarized in Table 1. Second, we have developed and applied a new quasi-optimal photometry technique based on fitting models of the spatial profiles of the objects (which are obtained using a non-negative least squares image reconstruction method) to the ground- and space-based images according to the spatial profile fitting technique described previously by Fernández-Soto, Lanzetta, & Yahil (1999). For faint objects, the

¹Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, NY 11794-3800, U.S.A.

²Department of Astrophysics and Optics, School of Physics, University of New South Wales, Kensington–Sydney, NSW 2052, AUSTRALIA

³Center for Astrophysics and Space Sciences, University of California at San Diego, La Jolla, CA 92093-0424, U.S.A.
signal-to-noise ratios obtained by our new photometry technique are larger than the signal-to-noise ratios obtained by aperture photometry techniques by typically a factor of two. Third, we have measured photometric redshifts using a sequence of six spectrophotometric templates, including the four templates of our previous analysis (of E/S0, Sbc, Scd, and Irr galaxies) and two new templates (of star-forming galaxies). Inclusion of the two new templates eliminates the tendency of our previous analysis to systematically underestimate the redshifts of galaxies of redshift $2 < z < 3$ (by a redshift offset of roughly 0.3), in agreement with results found previously by Benítez et al. (1999).

| Field | Filters                                      |
|-------|---------------------------------------------|
| HDF   | F300W, F450W, F606W, F814W, F110W, F160W, J, H, K |
| HDF-S WFPC2 | F300W, F450W, F606W, F814W, U, B, V, R, I, J, H, K |
| HDF-S NICMOS | F110W, F160W, F222M, STIS, U, B, V, R, I |

The accuracy and reliability of the photometric redshift technique is illustrated in Figure 1, which shows the comparison of 108 photometric and reliable spectroscopic redshifts in HDF and HDF-S. (Note that a non-negligible fraction of published spectroscopic redshift measurements of galaxies in HDF and HDF-S have been shown to be in error and so must be excluded from consideration.) With the sequence of six spectrophotometric templates, the photometric redshifts are accurate to within an RMS relative uncertainty of $\Delta z/(1 + z) \lesssim 10\%$ at all redshifts $z < 6$ that have as yet been examined.

Figure 1. Comparison of 108 photometric and reliable spectroscopic measurements of galaxies in HDF and HDF-S. The RMS dispersion between the photometric and reliable spectroscopic measurements is $\approx 0.1$ at $z < 2$, $\approx 0.3$ at $2 < z < 4$, and $\approx 0.15$ at $z > 4$. 

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3. Stony Brook Faint Galaxy Redshift Survey

Our analysis of the HDF and HDF-S WFPC2 and NICMOS fields constitutes a survey of galaxies to the faintest energy flux density and surface brightness limits currently accessible. Properties of the survey are as follows:

First, we have determined nine- or 12-band photometric redshifts of galaxies in three fields. Second, we have selected galaxies at both optical and infrared wavelengths, in two or more of the F814W, F160W, $H$, and $K$ bands (depending on field). Third, we have characterized the survey area versus depth relations, as functions of both energy flux density and surface brightness. Fourth, we have established properties of the extremely faint galaxy population using a maximum-likelihood parameter estimation technique and a bootstrap resampling parameter uncertainty estimation technique. The parameter uncertainties explicitly account for the effects of photometric error, sampling error, and cosmic dispersion with respect to the spectrophotometric templates. The Stony Brook faint galaxy redshift survey includes nearly 3000 faint galaxies, of which 671 galaxies are of redshift $z > 2$.

4. Some High (and Not So High) Redshift Galaxies

Examples of some high and not so high redshift galaxies are shown in Figure 2, which shows the observed and modeled spectral energy distributions and redshift likelihood functions of galaxies A through C, which we previously identified as candidate extremely high redshift galaxies on the basis of ground-based near-infrared measurements (Lanzetta, Yahil, & Fernández-Soto 1998). Our current analysis indicates that galaxy A is probably an early-type galaxy of redshift $z = 2.34 \pm 0.36$ and that galaxies B and C are probably star-forming galaxies of redshift $z > 13$. (An extremely high redshift interpretation of galaxy A is apparently ruled out by faint but significant energy flux density in the F606W and F814W filters. A low-redshift, highly obscured and reddened interpretation of galaxies B and C is apparently ruled out by the large flux decrement between the $K$ and F160W images.)

5. The Galaxy Luminosity Function at $z > 2$

We have modeled the rest-frame 1500 Å luminosity function of galaxies of redshift $z > 2$ by adopting an evolving Schechter luminosity function

$$
\Phi(L, z) = \Phi_\star / L_\star(z)[L/L_\star(z)]^{-\alpha} \exp[-L/L_\star(z)]
$$

with

$$
L_\star(z) = L_\star(z = 3) \left(\frac{1 + z}{4}\right)^\beta.
$$

The best-fit parameters for a simultaneous fit to the HDF and HDF-S WFPC2 and NICMOS fields (where we have related selection in different bands by adopting the spectral energy distribution of a star-forming galaxy) are $\Phi_\star = 0.004 \pm 0.001 \ h^3 \ \mathrm{Mpc}^{-3}$, $L_\star = 2.7 \pm 0.3 \times 10^{28} \ h^{-2} \ \mathrm{erg} \ \mathrm{s}^{-1} \ \mathrm{Hz}^{-1}$, $\alpha = 1.49 \pm 0.03$, and $\beta = -1.2 \pm 0.3$. The best-fit model is compared with the observations in
Figure 2. Observed and modeled spectral energy distributions (left panels) and redshift likelihood functions (right panels) of galaxies A through C.

Figure 3, which shows the cumulative galaxy surface density versus redshift and magnitude for galaxies selected in the F814W and F160W bands.

6. Effects of Cosmological Surface Brightness Dimming

Results of the previous section indicate that the galaxy luminosity function is only mildly evolving at redshifts $z > 2$, i.e. as $(1 + z)^\beta$ with $\beta \approx -1$. But due to $(1 + z)^3$ cosmological surface brightness dimming, the measured luminosity of extended objects will decrease with increasing redshift, even if the luminosities of the objects remain constant. For this reason, we consider it almost meaningless to interpret the galaxy luminosity function (or its moments) over a redshift interval spanning $z = 2$ through $z = 10$, at least without explicitly taking account of surface brightness effects.

To make explicit the effects of cosmological surface brightness dimming on observations of high-redshift galaxies, we have constructed the “star formation rate intensity distribution function” $h(x)$. Specifically, we consider all pixels contained within galaxies on an individual pixel-by-pixel basis. Given the redshift of a pixel (which is set by the photometric redshift of the host galaxy), an empirical $k$ correction (which is set by the model spectral energy distribution of the host galaxy) and a cosmological model determine the rest-frame 1500 Å luminosity of the pixel, and an angular plate scale and a cosmological model determine the proper area of the pixel. Adopting a Salpeter initial mass func-
Figure 3. Cumulative galaxy surface density versus redshift and magnitude (i.e. surface density of galaxies of redshift greater than a given redshift) for galaxies selected in the F814W (left panel) and F160W (right panel) bands. Smooth curves are best-fit model, and jagged curves are observations. Different curves show different magnitude thresholds, ranging from $AB = 24$ (bottom curves) through $AB = 28$ (top curves).

...tion to convert the rest-frame 1500 Å luminosity to the star formation rate and dividing the star formation rate by the proper area yields the “star formation rate intensity” $x$ of the pixel. Summing the proper areas of all pixels within given star formation rate intensity and redshift intervals, dividing by the star formation rate intensity interval, and dividing by the comoving volume then yields the “star formation rate intensity distribution function,” which we designate as $h(x)$. The star formation rate intensity distribution function $h(x)$ is exactly analogous to the QSO absorption line systems column density distribution function $f(N)$ (as a function of neutral hydrogen column density $N$). In terms of the star formation rate intensity distribution function, the unobscured cosmic star formation rate density $\dot{\rho}_s$ (or equivalently the rest-frame ultraviolet luminosity density) is given by

$$\dot{\rho}_s = \int_0^\infty x h(x) dx. \quad (3)$$

Results are shown in Figure 4, which plots the star formation rate intensity distribution function $h(x)$ versus star formation rate intensity $x$ determined from galaxies identified in the HDF and HDF-S NICMOS field. Several results are apparent on the basis of Figure 4: First, the star formation rate intensity threshold of the survey is an extremely strong function of redshift, ranging from $x_{\text{min}} \approx 5 \times 10^{-4} M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ at $z \approx 0.5$ to $x_{\text{min}} \approx 1 M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ at $z \approx 6$. Second, at redshifts $z \lesssim 1.5$ [at which $h(x)$ is measured over a wide range in $x$], the distribution is characterized by a relatively shallow slope at $\log x \lesssim -1.5 M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ and by a relatively steep slope at $\log x \gtrsim -1.5 M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$. These slopes are such that the bulk of the cosmic star formation rate density occurs at $\log x \approx 1.5 M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$, which is measured only at redshifts $z \lesssim 2$. We conclude that the cosmic star formation rate density (or equivalently the rest-frame ultraviolet luminosity density) has not yet been measured at redshifts $z \gtrsim 2$. Third, the comoving volume density of the highest star formation rate intensity regions increases monotonically with increasing redshift. We conclude
that the comoving volume density of the most intense star formation regions increases monotonically with increasing redshift (see also Pascarelle, Lanzetta, & Fernández-Soto 1998).

Figure 4. Logarithm of star formation rate intensity distribution function $h(x)$ versus logarithm of star formation rate intensity $x$, determined from galaxies identified in the HDF and HDF-S NICMOS field. Different panels show different redshift intervals, ranging from $z = 0$ through 10. Points show observations, with vertical error bars indicating $1\sigma$ uncertainties and horizontal error bars indicating bin sizes. Smooth curves show a fiducial model (based on a bulge spatial profile) adjusted to roughly match the observations at $z = 0 - 0.5$.

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