Photometric Redshifts Of Starburst Galaxies

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Abstract. Although starburst galaxies have relatively flat spectral energy distributions, their strong optical emission lines and near-UV continua make it very feasible to estimate their redshifts photometrically. In this work, I describe a photometric technique that simultaneously (1) identifies galaxies by star formation rate and (2) measures their redshifts with an accuracy of $\sigma_z = 0.05$ for objects at $z < 1$. (An extension of the technique is potentially feasible, with the use of near-infrared colors, to $1.6 < z < 2.5$.) Applying this technique to a deep multicolor field survey reveals a large excess population of strongly star-forming galaxies at $z \geq 0.3$ compared with $z < 0.3$. Followup with spectroscopy and near-infrared photometry confirms their presence, and suggests that some of them may be in the midst of their initial burst of star formation.

1. Introduction

The work presented here stems from a study of the field galaxy population in the comparatively modest redshift range $z < 0.5$. Using the photometric redshift method developed by Liu & Green (1998), Liu et al. (1998) found a substantial excess of relatively luminous ($M_B < -19$) starbursting galaxies at $z \geq 0.3$ compared with $z < 0.3$ in an optical multicolor survey of six deep blank sky fields (Hall et al. 1996). First, I discuss how and why the photometric technique can successfully identify starbursts and estimate their redshifts. I then present the results of spectroscopic and near-infrared followup that verifies the starburst excess, and hints at a surprising result: a significant fraction of these galaxies may be undergoing their first major star formation episode.

2. Photometric Redshifts And Galaxy Spectral Types

All photometric redshift techniques simultaneously give at least some information about a galaxy’s spectral type – that is, its star formation rate per unit luminosity. The method of Liu & Green (1998) seeks to optimize the ability to discriminate between spectral types without sacrificing redshift accuracy. This is achieved by using a “smallest maximum difference” approach comparing broad-band colors, rather than a “least-squares” approach comparing broad-band fluxes. (The distinction is roughly analogous to using a Kolmogorov-Smirnov test rather than a $\chi^2$ test when measuring the quality of a model fit.
to data.) Another feature of this method is that it does not consider a galaxy’s apparent magnitude in the redshift determination; it is thus somewhat more versatile when evaluating, for example, unusual or evolving galaxy populations.

The method uses six broad-band filters (U/B/V/R/I7500/I8600) and five completely empirical galaxy spectral energy distributions (SEDs). Shown in Figure 1, these SEDs represent objects with star formation rates typical of E/S0, Sab, Sbc, Sed and Irr field galaxies. I refer the reader to Liu & Green (1998) for further details; the net result is an accuracy of $\sigma_z \sim 0.05$ in redshift determination, and slightly better than $\pm 1$ in galaxy spectral type.

Intuitively, it may seem that very blue galaxies such as star bursts would present difficulties for photometric redshift determination. After all, they have weak or no 4000 Å breaks – the most important spectral feature for most photometric redshift schemes – and SEDs that are almost flat in $F_\nu$. However, a glance at Figure 1 shows clearly that starburst SEDs have a steeply rising UV continuum bluerward of 3500 Å, a small but significant continuum “hump” around 4200 Å, and very strong optical emission lines. Together, these characteristics make photometric redshifts of starbursts surprisingly feasible. Indeed, the accuracy for starbursts using the smallest maximum difference method is $\sigma_z \sim 0.05$, identical to the galaxy population as a whole.

Another way to look at it is to look in color-color space, as shown in Figure 2. The solid lines show how the $U - B$ and $B - R$ colors of the five galaxy SEDs change as a function of galaxy redshift, while the dotted lines represent the “iso-
Figure 2. Color evolutionary tracks in $U - B$ vs. $B - R$ for the empirically derived template galaxy spectral types. The tracks assume no luminosity evolution with redshift. Each point on the tracks represents a stepwise increase in $z$ of 0.05. The dotted lines show the iso-$z$ contours for $z = 0.1, 0.2, 0.3, 0.4$ and 0.5.
redshift contours” at \( z = 0.1, 0.2, 0.3, 0.4 \) and 0.5 for the galaxy SEDs that have ongoing star formation. For these two colors, \( 0.1 < z < 0.5 \) is the redshift range in which the rest-frame near-UV continuum, the 4200 Å hump, and at least one of the three major rest-frame optical emission line regions ([O II], H\( \beta \)+[O III], and H\( \alpha \)+[N II]) are all covered. As a result, the iso-redshift contours are roughly parallel and cleanly separated from each other. This means that even very blue starburst galaxies can yield reliable photometric redshifts.

Figure 2 reveals two more interesting points. First, the effect of dust extinction is shown by the vector in the lower right; it will move any given galaxy SED roughly parallel to the iso-redshift contours. So a dusty galaxy may mimic a spectral type with a lower star formation rate, but to first order its photometrically determined redshift will not be strongly affected. Second, these \( UBR \) colors alone yield surprisingly accurate photometric redshifts for strongly star-forming galaxies (\( \sigma_z \sim 0.07 \)). Note that the \( I, J \) and \( H \) bands cover in the range \( 1.6 < z < 2.5 \) almost exactly the same rest wavelengths as the \( U, B \) and \( R \) bands cover in the range \( 0.1 < z < 0.5 \) – a happy coincidence! Potentially, IJH colors could be used to obtain photometric redshifts of galaxies, with an expected accuracy of \( \sigma_z \sim 0.20 \) over the range \( 1.6 < z < 2.5 \), a somewhat difficult range in which to measure galaxy redshifts using optical spectra. This would then allow the direct comparison of similarly selected samples of high, medium and low redshift star-forming galaxies.

3. Spectroscopy And Infrared Photometry - Evidence For Galaxy Formation at \( z \sim 0.3 \)?

The Deep Multicolor Survey of Hall et al. (1996), obtained at the Mayall 4-meter telescope at KPNO, was the testbed dataset for the Liu & Green (1998) photometric redshift method. As described in Liu et al. (1998), a surprising excess of starburst galaxies was detected in the range \( 0.3 \leq z \leq 0.5 \).

As impressive as photometric redshifts may be, they are nonetheless only statistically reliable. For any given object, true confirmation of its redshift must still come via spectroscopy. With this in mind, spectra were obtained of 30 of these objects, using the Steward Observatory 2.3-m telescope on Kitt Peak and the Multiple Mirror Telescope on Mt. Hopkins. Every single one of these galaxies was confirmed to be a strongly star-forming galaxy. Their redshifts range from \( 0.23 \leq z \leq 0.56 \), and the rms error of the photometric redshifts is 0.046, exactly consistent with prediction. The rest-frame equivalent widths of the \([O II]\lambda 3727\) emission line range from 27 to 93 Å, with a median of 40 Å; compare this with a typical Sc galaxy, which has a type \( EW[O II] \) of 10-20 Å. A representative sample of the galaxy spectra is presented in Figure 3.

Now the question is: what are these excess starbursting objects? Two possibilities come to mind. They could be galaxies temporarily brightened by global starbursts, perhaps triggered by a merger event; or they could be new galaxies undergoing their first major burst of star formation. In either scenario, such a galaxy would subsequently fade and redden at lower redshifts, disappearing into the throng of “ordinary” field galaxies. The way to distinguish between these two cases is with infrared photometry, followed by differential spectral synthesis to measure the mass of old stars in these objects. The infrared observations are
Figure 3. Spectra of 17 starburst galaxies representative of those photometrically identified by Liu et al. (1998). The galaxies range from $z = 0.23$ (top) to $z = 0.56$ (bottom), and have been deredshifted and plotted in arbitrary units of $F_{\lambda}$. Note the strong [O II]λ3727Å emission line in every galaxy.
in progress, and so far H-band data have been obtained for 21 of these starbursts. (Alice Quillen of Steward Observatory is my collaborator in this endeavor.) Preliminary results suggest that as many as half of them may have at most 20% of their mass in stars older than $10^8$ years. Is this possible evidence of new galaxies forming at $z \sim 0.3$?

Although this may be a tempting conclusion, I dare not draw it until more infrared data are obtained. At present, these figures are reliable only at the 2-3σ level, and any further claims would be purely speculative. At the redshifts of these objects, K-band data will be absolutely necessary to quantify the presence of an old stellar population. I will therefore defer any further discussion of this tantalizing idea until those data are in hand.

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References

Hall, P. B., Osmer, P. S., Green, R. F., Porter, A. C., & Warren, S. J. 1996, ApJS, 104, 185.
Liu, C. T., & Green, R. F. 1998, AJ, 116, 1074.
Liu, C. T., Green, R. F., Hall, P. B., & Osmer, P. S. 1998, AJ, 116, 1082.