Photometric Redshifts: A Perspective from an Old-Timer\textsuperscript{1} on Its Past, Present, and Potential

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Abstract.
I review the early history of photometric redshifts; specify a working definition that encompasses a broader range of approaches than commonly adopted; discuss the pros and cons of template fitting versus empirically-based techniques; and summarize some past applications. Despite its relatively long history, the technique of photometric redshifts remains far from being a mature tool. Areas needing development include the use of spatial structure, the incorporation of large redshift samples with multicolor photometry for empirical calibrations of redshift errors, and improved analysis tools that directly include redshift probability distributions rather than singular values. Photometric redshifts has not only undergone a recent revival – it is also rapidly becoming a crucial tool of mainstream observational cosmology.

1. Brief Early History

Photometric redshifts is a term that has received recent, wide-spread visibility and interest, though the use of multicolor photometry to estimate the redshifts of galaxies has a history that is relatively long. As of March 1999, my search of the ADS abstracts for the term “photometric redshifts” yielded only 9 papers ending in 1994, with the first in 1982, i.e. averaging less than one paper per year. A sudden jump then occurs in 1995 with 6 papers, followed by 1996 with 7, 1997 with 9, and then another major jump to 35 papers in 1998. The broad participation and range of topics of this workshop validate this surge in activity.

Among these papers, the earliest reference to the term “photometric redshifts” is found in the abstract of Puschell et. al. (1982). Their attempt to estimate redshifts of faint radio galaxies via broadband photometry was pioneering (even by today’s standards) in three respects: 1) the use of near-infrared bands ($JHK$) along with optical bands ($RI$), 2) the adoption of $\chi^2$ fits to spectral energy distributions (SED), and 3) the use of different sets of SED templates, ranging from non-evolving local ellipticals, theoretical SEDs from Bruzual, to observed SEDs from known radio galaxies.

The first use of the term in the title was by Loh and Spillar (1986): Photometric Redshifts of Galaxies. This work was pioneering in its use of CCDs to

\textsuperscript{1}Feedback from R. J. Weymann on receiving this title: “Give me a break!!!”
reach quite faint limits of $I \sim 21.5$, along with the use of 6 medium-band filters and again $\chi^2$ template fitting, but only to three observed local SED templates to represent all galaxy types at all redshifts.

The use of multicolors to estimate redshifts actually predates the above papers and the true literature on the subject is significantly more extensive, but due to the ambiguity of the term “photometric redshifts” as detailed in the next section, many workers in this arena chose not to use this term. Probably the first use of multicolor photometry for redshift estimation was by Baum (1962). He obtained photoelectric photometry through 9 medium-wide filters of galaxies in cluster 3C395, assumed that the SEDs were that of ellipticals, and obtained an estimate of redshift $z \sim 0.44$, quite close to the eventual spectroscopic value of 0.46.

Nearly two decades passed before multicolor photometry was used to estimate redshifts. Butchins (1981, 1983) used UK Schmidt plate $BVR$ photometry that reached $B \sim 22$. Because of the overlap in $BVR$ colors of low-redshift ($z \lesssim 0.1$) early-type galaxies with higher redshift ($z \sim 0.4$) later-type galaxies, Butchins applied probability constraints on luminosities that are qualitatively similar to what has more recently been termed “Bayesian”. I was able to reach fainter limits ($B \sim 24$) by using KPNO 4-m plates and had both superior redshift accuracy $\delta z \lesssim 0.05$ and far less degeneracy by exploiting a set of filters (roughly $UBRI$) with much longer wavelength coverage (Koo 1981, 1985, 1986). Since Baum is not here and Butchins is no longer in astronomy, I qualify as the old-timer in the field at this workshop.

Another important set of papers that does not use the term “photometric redshifts”, and yet constrains redshifts from broadband photometry, relies on the so-called “Lyman-break technique” (see contribution by Steidel). The basic idea is to discern very high redshift galaxies via a significant drop in the bluest band for galaxies with otherwise very blue colors in two or more redder bands. This situation occurs when the Lyman break enters, e.g., the $U$ band, at redshifts $z \sim 3$. Since the apparent drop in the $U$ band flux (or especially in redder bands at higher redshifts) is also affected by the intergalactic Lyman-alpha forest depression, a more accurate term should be “Lyman-drop technique”. Early examples of its use include papers by Partridge (1974), Koo (1986), Cowie (1988), Majewski (1988, 1989), Guhathakurta et. al. (1990), and Steidel & Hamilton (1993).

2. Working Definition of Photometric Redshifts

I suggest the following: photometric redshifts are those derived from only images or photometry with spectral resolution $\lambda/\Delta \lambda \lesssim 20$. My choice of 20 is intended to exclude redshifts derived from slit and slitless spectra, narrow band images, ramped-filter images, Fabry-Perot images, Fourier transform spectrometers, etc.

This definition still leaves a wide range of approaches to obtain redshifts, examples of which include:

1. Spatial Correlations: Galaxies are assumed to have, statistically, the redshifts of their neighbors in apparent close pairs, groups, and especially the
cores of rich clusters. Photometric redshifts is an unconventional term to apply in these cases and should thus probably be avoided.

2. Magnitudes: Although using just magnitudes alone to estimate redshifts might be expected to work only for standard candles, such as the brightest cluster galaxies in $R$ or strong-flux radio galaxies in $K$, the convolution of accessible volumes with the shape of the luminosity function of galaxies results in a fairly tight correlation between magnitudes and redshift, even for more common field galaxies (see the redshift-magnitude plot Fig. 4 of Koo & Kron 1992). For any of the following techniques, the addition of magnitudes can thus be expected to provide additional constraints on the redshift probability distribution (see, e.g., Connolly et al. 1995). Just as in the previous approach, the use of the term “photometric redshifts” would be quite unconventional, but technically accurate.

3. One Color: In situations where the SED is known or unique, one color may be sufficient to estimate a redshift. Practical applications include redshift estimates for the reddest galaxies in clusters or field and also very high redshift searches, especially when at least one of the two bands is in the near-infrared. A single-color is probably the minimal information to qualify the use of the term “photometric redshift” as understood by most astronomers today.

4. Two or More Colors: The use of three or more filters is necessary to break the degeneracy between intrinsic color and redshift. This approach is probably the most commonly accepted one when referring to photometric redshifts that employ optical bands, and works surprisingly well even with only three bands (Straitzys & Sviderskiene 1983). This is because most galaxies (at least locally) occupy only a small fraction of the possible multicolor volume (see Fig. 2a); galaxy spectra are often composites of old and young stellar populations which result in bowl-shaped or U-shaped SED (see Fig. 1 and note the more bowl-shaped value of the $z = 0$ locus compared to that of its constituent stars); the pivot point of this curvature lies near the 4000Å break and is roughly independent of the galaxy’s average color and bowl-shaped spectra, when redshifted, result in moving the iso-$z$ loci in a direction perpendicular to these loci (see Fig. 1). Obviously one needs longer wavelength bands to sample the pivot point near 4000Å as one wishes to discern higher redshifts (see Fig. 1). Nature has been kind: if galaxy spectra had instead blackbody shapes of different temperatures or power-laws in shape, we would not be able to separate redshifts using multicolors.

5. Surface Brightness: If the intrinsic surface brightness is roughly constant or slowly varying with time, as might be expected for large spirals that undergo largely constant star formation rate histories, the $(1 + z)^4$ surface brightness dimming can be exploited to yield redshifts.

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1This coincidence of the 4000Å break being where galaxy SEDs have a pivot point results in the common misconception that photometric redshifts work because of the 4000Å break itself.
6. One Color with Light Profiles: In principle, the light profile might yield the type of galaxy (e.g., $r^{1/4}$ profiles might imply a luminous spheroidal or bulge to disk ratios might suggest a probable galaxy type), which in turn might be assumed to have a unique SED so that a single color is sufficient for estimating a redshift (Sarajedini et. al. 1999).

7. One Color with Image Structure: This is a generalization of the last two approaches. Anderson et. al. (1996) has already been exploring the correlations of galaxies among color, surface brightness, and image concentration. This combination appears to be useful to improve the efficiency of gathering photometric redshifts by not requiring deep $U$ photometry, which is very costly in telescope time.

8. etc.

Whether the term “photometric redshifts” should include such a diversity of approaches is debatable, but what should be obvious is that astronomers have yet to exploit the wealth of additional photometric/structural information in refining redshift estimates from image data alone.

3. Methodology

3.1. Template versus Empirical Fitting

The most popular method for estimating redshifts from a set of photometric measurements is the $\chi^2$ (or maximum likelihood) template-fitting method adopted by Puschell et. al (1982), largely because the method is simple, does not rely on having any spectroscopic redshifts, and needs only a few templates (empirical or theoretical) to yield results. With the availability of multicolor CCD photometry, almost anyone can get into the photometric redshift business today. The Achilles heel of the technique is of course the template set. Empirical SEDs are relatively few, almost exclusively confined to local galaxies whose SEDs may not reflect those of more distant galaxies, and which are not necessarily representative in luminosity, dust, inclination, morphology, etc. to the targets of interest. While theoretical SEDs avoid some of these problems, they may not be correct and do not yield information on the probability distribution for the estimated redshifts, since this information relies on having the probability distribution of the SEDs.

To show the level of uncertainty between empirical and theoretical SEDs, see Fig. 1. We note that the empirical spectra (which have traditionally been based on only a handful of measured integrated spectra) differ significantly (0.05 or more in $z$) from the theoretical at all redshifts.

In contrast, the empirical fitting method (e.g., Connolly et. al. 1995, Wang et. al. 1998) uses a large enough pool of spectroscopic redshifts to calibrate the relationship of colors and magnitudes to redshifts. By construction, this method should provide accurate redshifts, but more importantly, it should also yield realistic estimates of the redshift errors. To achieve this in practice, however, requires a sufficiently complete set of known redshifts to the depth of the desired photometry.
Figure 1. These multicolor plots show loci of constant redshift from \( z = 0.0 \) to 1.0 in intervals of 0.1. The roughly vertical lines are based on theoretical SEDs, while the roughly horizontal dashed lines show the trajectory taken by empirical spectra of several types of galaxies, with symbols spaced 0.1 in redshift. The left-hand figure is one where the normal two-color plot \((U-B)\) vs \((B-R)\) is converted to one measuring the average color \((U^+ - F^+\) equivalent to \(U - R\)) on the vertical axis and the curvature of the spectrum \((-U^+ + 2J^+ - F^+\) equivalent to \(-U + 2B - R\)) on the horizontal axis, where humped and bowl shapes are indicated. The right-hand plot adds the \(N^+\) band \((\sim I)\), which extends the wavelength range and thus improves both the color discrimination on the vertical axis and the curvature or shape discrimination on the horizontal. The reader is referred to the caption of Fig. 1 in Koo (1985) for more details.
3.2. Redshift Errors

Except for the mean and rms error when compared to spectroscopic redshifts, photometric redshift errors remain poorly characterized. In particular, the position, shape, and asymmetry of the redshift error distribution should be derived; the sources of the errors and especially whether they are due to random measurement errors, intrinsic dispersions in the SEDs of galaxies, or unknown systematics should be tracked down; and, ideally, the dependence of the errors on a variety of other parameters (color, luminosity, morphology, structure, redshift, environment, etc.) should also be measured. More importantly, these redshift uncertainties should be incorporated explicitly into the analysis, not by using the derived maximum likelihood or minimum $\chi^2$ value of the photometric redshift for each galaxy, but rather the full probability distribution. This idea has already been incorporated for the C-method of deriving the luminosity function from photometric redshifts (SubbaRao et al. 1996), but this approach should be adopted more universally by others in most statistical analyses.

Of special concern in the area of redshift errors is the likelihood both that the SED’s of distant galaxies are different on average from those today and that the intrinsic dispersion in the SEDs are greater. If true, we would expect larger random and systematic errors for galaxies at higher redshifts. Figures 2 and 3 are telling and sobering. More specifically, Figure 2b shows that morphologically peculiar galaxies exhibit a greater spread of values perpendicular to the line in the $UBV$ two-color plots than that of more normal galaxies shown in Figure 2a (Larson and Tinsley 1978). Interactions and mergers appear to be a primary cause of these peculiarities, so if indeed such galaxies are more common in the past, we should expect greater photometric redshift errors at higher redshifts that result from the greater spread in intrinsic SEDs alone. Larson and Tinsley (1978) explain the wider spread as the result of a greater diversity in the star formation histories of galaxies, namely brief starbursts interrupting an otherwise more quiet or more smoothly varying star formation history. Figure 3 shows the possible tracks of galaxies with varying amounts of such bursts in the $UBV$ two-color diagram; note in particular the regions perpendicular to the wide, solid line on top of which most local, morphologically-normal galaxies lie. Such deviations result in systematic errors in photometric redshifts.

3.3. Redshift Calibration Samples

Clearly what is desired for significant progress in our use and understanding of photometric redshifts is a large pool of spectroscopic redshifts that span the full range of redshifts, depth, photometric bands, etc. In 1985, we had about 100 spectroscopic redshifts ($z \lesssim 0.6$) to $R \sim 21$ from 4-5m class telescopes to study photometric redshifts in four bands $UBRI$ (Koo 1985), while roughly the same number has been measured with the Keck 10-m to study the Hubble Deep Field to fainter limits $R \gtrsim 23.5$ and a wider range in redshifts ($z \sim 0.1 - 5.6$). Our current lack of good calibration is, however, changing dramatically. At the lowest redshifts of $z \lesssim 0.2$, the Sloan Digital Sky Survey will yield nearly $10^6$ spectra for a photometric sample that includes 5 filters. At intermediate redshifts between $z \sim 0.2$ to 0.7, CNOC2 will have 6000 spectroscopic redshifts for calibrating their 5 band system (Lin et al. 1999). Keck will be providing over 1000 redshifts for $z \sim 0.7$ to over 1 and $\sim 2.5$ to 4 for passbands that include
some $K$, while handfuls of redshifts are coming in for the desert at $z \sim 1.3$ to over 2 and the highest redshifts $z \gtrsim 5$. With these samples to calibrate the photometric redshift system and especially its errors, photometric redshifts will finally rest on a much more secure foundation.

4. Applications

The scientific potential of using photometric redshifts has been recognized for a long time, especially during an earlier era when redshifts for large samples of galaxies fainter than $B \sim 21$ were difficult or impractical, while multicolor photometry easily sampled the distant universe. The following list is meant to be illustrative, rather than representative or exhaustive, of pioneering projects that were based on older multicolor photographic photometry or small-format CCDs. The topics of other papers from this workshop provide a more current view of how photometric redshifts are being applied in a new era of HST images, large mosaic CCD cameras, and 8-10m telescopes. The use of photometric redshifts has not only undergone a recent revival, but it is also rapidly becoming a crucial tool of many programs in mainstream observational cosmology.

- Searches for primeval galaxies at redshifts $z \gtrsim 3$ via the $U$ band detecting the Lyman break (Cowie 1988, Cowie & Lilly 1989; Guhathakurta et. al. 1990; Koo 1986; Majewski 1988, 1989; Steidel & Hamilton 1993) or even via data further to the red to probe higher redshifts (Partridge 1974).
Figure 3.  $UBV$ two-color plot showing the expected locations and trajectories of galaxies with different star-formation histories (from Fig. 18 of Tinsley 1980, to which the reader is referred for further details). The thick solid line is where galaxies are predicted to lie if they represent a range of smoothly decreasing rates of star formation; as seen in Fig. 2, most local galaxies overlap this locus. The light dotted line is the track for constant star formation over the indicated time (Gyr). The remaining tracks show brief starbursts with different strengths (as % of mass of a 10 Gyr old underlying stellar population) and after indicated periods (Gyr).
• Searches for high redshift QSO’s (see review by Warren & Hewett 1990) or distant radio galaxies (Puschell et. al. 1982; van der Laan 1983).

• Studies of the evolution of field galaxies (Butchins 1983; Cowie et. al. 1988, 1990; Guiderdoni 1987; Koo 1986; Lilly et. al. 1991) or their luminosity function (SubbaRao et. al. 1996)

• Discrimination of cluster members and superclusters at moderate redshifts (Connolly et. al. 1996; Koo 1981, 1986, Koo et. al. 1988)

• Estimate of the geometry of the universe via the volume test (Loh and Spillar 1986)

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