Photometric Redshifts: A New Tool for Studying High-Redshift Clusters

L.M. Lubin & R.J. Brunner

Palomar Observatory, 105-24, California Institute of Technology, Pasadena, CA 91125

Abstract.

We present the first results of our application of photometric redshifts to the study of galaxy populations in high-redshift clusters. For this survey, we are examining a sample of galaxy clusters at $z > 0.6$ which have already been well-studied in the optical and infrared wavelengths (Oke, Postman & Lubin 1998). Our main goal is to use photometric redshifts to delineate accurately between field and cluster galaxies. Once we isolate the cluster galaxies, we can directly study the properties of the galaxy population in each high-redshift cluster. Specifically, we are studying the cluster morphological fractions, the morphology-density relation, and the large scale structure distribution. Although we have encountered some operational problems with our photometric redshift technique, early results suggest that this procedure will become a significant tool in studying high-redshift clusters.

1. Introduction

The techniques involved in calculating photometric redshifts have become increasingly more sophisticated and precise. Accuracies of $\sigma_z = 0.05$ can be routinely achieved (Brunner et al. 1999 and references therein). Therefore, it is now possible to use photometric redshifts to answer specific scientific questions. In light of this, we have begun a program to use accurate photometric redshifts to study the galaxy populations in high-redshift clusters of galaxies. For this study, we have examined galaxy clusters at $z > 0.6$ which are the subject of an extensive spectroscopic, photometric and morphological survey by Oke, Postman & Lubin (1998). Oke et al. (1998) have compiled an unprecedented amount of observational data for each cluster, including deep $BVRIK$ photometry, over 150 high-quality Keck spectra, and high-spatial-resolution WFPC2 imagery from HST.

Using the existing $BVRIK$ imaging and redshift data, we have refined an empirical technique to measure photometric redshifts for all galaxies down to $R = 24$ in each cluster field (see Brunner et al. 1999). From our calibration sample, we are able to determine both a redshift which is accurate to $\Delta \sigma \leq 0.05$ (Figure 1), as well as an estimated redshift error for each galaxy in our catalog. This approach works well for almost all types of galaxies over our redshift range of interest. Specifically, we are able to measure photometric redshifts for normal
blue, star-forming galaxies and red, elliptical-like galaxies which are expected to comprise the vast majority of cluster members. With these photometric redshifts, we can accurately delineate between field and cluster galaxies, by utilizing the statistical nature of photometric redshift estimation (Brunner 1997). In practice, this reduces to selecting all galaxies which have a probability higher than a predetermined threshold of lying within a redshift shell centered on the cluster. The redshift probability distribution function (PDF) for each galaxy is calculated assuming a Gaussian PDF with mean and sigma given by the photometric redshift and redshift error estimates. Both the probability threshold and the width of the redshift shell are free parameters which we estimate using a maximum likelihood technique. Consequently, we can study directly the galaxy populations of the high-redshift clusters. In these proceedings, we present the first results of our work, as well as a discussion of the operational difficulties that we have currently encountered.

2. The Scientific Goals and The Need for Photometric Redshifts

For this study, our principal scientific goals are (1) to study the distribution of galaxy morphologies in high-redshift clusters; (2) to measure the morphology-density relation at high redshift; and (3) to map large scale structure at high redshift. Traditionally, all of these studies have been performed using a statistical analysis where the contamination rate of the foreground and background galaxies had to be estimated and subtracted from the cluster field. This technique was necessary because of the limited number of spectroscopically confirmed cluster members. Unfortunately, considerable uncertainty (and the resultant systematic effects) can be introduced if the properties of the background population have not been estimated correctly. Some issues which adversely affect this procedure
are: (1) the background contamination can be very large at high redshift (as high as 85%; see Oke et al. 1998); (2) the morphological mix of the background population is normally derived from the pre-classified field counts of the HDF and MDS (van den Bergh et al. 1996; Abraham et al. 1996). Visual typing can be very subjective; therefore, using classifications by other classifiers can introduce an additional uncertainty (Naim et al. 1995a,b); and (3) there is a strong variation in galaxy color in high-redshift clusters (including a dominant population of red galaxies and an increased fraction of blue galaxies). Consequently, we do not want to discount inadvertently any part of the total cluster population. With photometric redshifts, we can directly examine the cluster population by choosing only those galaxies which have a high probability of belonging to the cluster.

3. The Preliminary Results

In Figure 2, we present the F814W WFPC2 image of CL1324+3011 at $z = 0.76$. This cluster is clearly defined by the central concentration of bright, elliptical-like galaxies. Based on the spectroscopic survey of Oke et al. (1998), there are 18 galaxies which are confirmed cluster members (Postman, Lubin & Oke 1999). These galaxies are circled in Figure 2. Based on our photometric redshifts, we have identified all those galaxies in the HST field-of-view which are likely cluster members. These galaxies are indicated by diamonds. From this figure, we can see that using photometric redshifts we have done a reasonable job with our initial attempt at identifying all those spectroscopically confirmed cluster members. In addition, we have identified over a factor of 2 more cluster members than the spectroscopy alone. However, there are some confirmed cluster members which were not identified by the photo $z$ method. Typically, these galaxies have low luminosities and are compact. Many but not all have been visually classified as early-type galaxies, which we naively expect based on our current requirement for accurate multi-band photometry.

In Figure 3, we present the distribution of galaxy morphologies in two high-redshift clusters, CL0023+0423 at $z = 0.83$ and CL1604+4304 at $z = 0.90$. For each cluster, we show two morphological distributions – one determined from the traditional statistical approach (Lubin et al. 1998; 1999) and one determined from photometric redshifts alone. We see in the case of CL0023+0423 that the two distributions agree well. This system is dominated by blue, late-type (spiral and irregular/peculiar) galaxies. For the case of CL1604+4304, the two distributions differ significantly. While the statistical analysis indicates that this cluster is strongly dominated by early-type (elliptical and S0) galaxies, the photo $z$ analysis indicates a significantly larger population of late-type galaxies. This discrepancy may result from the fact that we are systematically missing some fainter early-type galaxies with the photo $z$ method (see above); however, it may also indicate that the statistical approach is flawed and that we have overestimated the fraction of late-type galaxies in the background population. At this point, we are still in the process of determining the true distribution of morphologies in these clusters.
Figure 2. The HST image of CL1324+3011 taken with the WPFC2 in the F814W filter. The cluster center is clearly defined by the concentration of bright, elliptical-like galaxies. The spectroscopically confirmed cluster members are indicated by circles, while those galaxies believed to be cluster members based on their photometric redshifts are indicated by diamonds. Using our initial photometric redshift estimates, we have done a reasonable job at identifying all of the spectroscopically confirmed cluster members.
The shaded histograms represent the morphological distributions calculated using the statistical method, while the solid-line histogram represent those distributions calculated using the photo z method.

4. The Future

Based on our work, we believe that photometric redshifts are an ideal way to study the galaxy populations in high-redshift clusters. This method eliminates the need for extensive spectroscopic surveys and the uncertainty of estimating the background contamination. We have, however, encountered some operational problems. These problems include, firstly, large errors in the photometric redshifts when the photometry is poor. Such errors limit our ability to gauge whether a galaxy is a cluster member or not. Secondly, the lack of depth in the bluest bands preferentially discriminates against early-type galaxies and can, therefore, skew the cluster galaxy distribution. Thirdly, our photo z method, as it now stands, cannot accurately estimate the redshift of “unusual” galaxies, such as E+A galaxies which have a spectrum characterized by strong Balmer absorption features and are common in the cluster environment (e.g. Dressler & Gunn 1983). Consequently, these galaxies are currently excluded from the analysis. We anticipate that we will be able to overcome these problems with further refinement of the photometric redshift technique and a specifically designed photometric survey which contains the appropriate wavelength coverage and depth. Therefore, we expect that, in the near future, we will be able to utilize fully the capabilities of this technique for cluster research.
References

Abraham, R.G., Tanvir, N.R., Santiago, B.X., Glazebrook, K., Ellis, R.S. & van den Bergh, S. 1996b, MNRAS, 279, L47
Brunner, R.J, PhD. Thesis, The Johns Hopkins University, 1997.
Brunner, R., Connolly, A.J., & Szalay, A.S. 1999, ApJ, 516, 563
Dressler, A. & Gunn, J.E. 1983, ApJ, 270, 7
Lubin, L.M., Postman, M., Oke, J.B., Ratnatunga, K.U., Gunn, J.E., Hoessel, J.G. & Schneider, D.P. 1998, AJ, 116, 584
Lubin, L.M., Postman, M., Oke, J.B., Brunner, R.J., Gunn, J.E., Hoessel, J.G. & Schneider, D.P. 1999, AJ, in press
Naim, A., Lahav, O., Buta, R.J., Corwin, H.G., De Vaucouleurs, G., Dressler, A., Huchra, J.P., van den Bergh, S., Raychaudhury, S., Sodre, L. & Storrie-Lombardi, M.C. 1995a, MNRAS, 274, 1107
Naim, A., Lahav, O., Sodre, L. & Storrie-Lombardi, M.C. 1995b, MNRAS, 275, 567
Oke, J.B., Postman, M., & Lubin, L.M. 1998, AJ, 116, 584
Postman, M., Lubin, L.M., & Oke, J.B. 1999, AJ, in press
van den Bergh, S., Abraham, R.G., Ellis, R.S., Tanvir, N.R., Santiago, B.X. & Glazebrook, K. 1996, AJ, 112, 359