The Color-Magnitude Relation of Early-Type Galaxies: A Tool for Cluster Finding and Redshift Determination

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Abstract. The color-magnitude relation (CMR) of early-type galaxies in clusters provides a powerful tool for finding clusters and determining photometric redshifts for clusters using two-filter imaging data. We demonstrate the high accuracy of photometric redshifts attainable using the CMR by applying the technique to a sample of 45 Abell clusters with known redshifts. Furthermore, by using the red sequence of galaxies from the CMR, we have developed an extremely efficient technique for detecting clusters and groups of galaxies. We demonstrate this using both observed photometric catalogs with redshifts (from the CNOC2 Survey) and simulations.

1. Introduction

Early-type galaxies form the dominant population in the core of all galaxy clusters with few or no exceptions—from low redshift to $z > 1$, from poor to rich clusters. The uniformity of the properties of early-type galaxies provide important tools, such as the fundamental plane and the color-magnitude relation (CMR), in the study of galaxy clusters and their evolution.

The CMR for early-type galaxies (E/S0's) was first noted by Baum (1959) in that the colors for elliptical galaxies become bluer as they become less luminous. Furthermore, E/S0 galaxies are also the reddest normal galaxies at any single given redshift. Hence, the E/S0's form a sequence on the color-magnitude plane which is sometimes called the “red sequence”, as illustrated for the cluster Abell 2256 using data from López-Cruz & Yee (1999a, also see López-Cruz 1997) in Figure 1. The existence of the CMR is in general attributed to a metallicity effect due to the varying ability of spheroids of different masses to retain metals in the presence of supernovae driven winds (e.g., see Kodama & Arimoto 1997 and references therein). The dispersion, color, and slope of the red sequence in clusters have been used to study the evolution of cluster galaxies up to a redshift as high as $\sim$ 1 (e.g., Bower et al. 1992; Aragón-Salamanca et al. 1993; Stanford et al. 1998; and Gladders et al. 1998).
In this paper, we demonstrate the efficiency of using the color-magnitude relation of clusters as a powerful tool for estimating the redshift of clusters photometrically and detecting clusters from two-filter imaging data.

2. The CMR as a Redshift Estimator

The red sequence of early-type galaxies in clusters provides a powerful means for estimating the cluster redshift using only two filters. The efficacy of using the red sequence to determine redshift arises from two factors. First, early-type galaxy spectra, because of the large 4000 Å break, provide the largest signal for photometric redshift determination. By predetermining the spectral type of the galaxies, (i.e., picking the reddest galaxies available by virtue of the prominence of the red sequence), only a single color (from two filters, assuming that they straddle the 4000 Å break) is needed to provide the redshift signature. Second, the red sequence is composed of many such galaxies; hence, if the whole sequence is used instead of a single galaxy, the measurement uncertainty would diminish significantly.

To test the efficiency and accuracy of this method, we use two-color CCD photometry from a sample of 45 Abell clusters from the Low-Redshift Cluster Optical Survey (LOCOS) of López-Cruz & Yee (1999a). The clusters have a redshift range between 0.025 to 0.18. The LOCOS data set consists of BRI photometry obtained using the 2K×2K T2KA CCD on the KPNO 0.9m over a field size of 23′×23′ to a depth of typically $M_R = -17.5$ ($H_0 = 50$ km/s/Mpc). The details of the analysis of the CMR of the clusters are presented in López-Cruz & Yee (1999b) and Gladders et al. (1998). Briefly, the CMR for each cluster is fitted with a linear function on the $B - R$ vs $R$ color-magnitude plane, using a robust regression method with outlier rejection. The resultant slopes of the fits indicate that the CMR is consistent with being universal in the redshift range of the sample, reflecting the high $z$ formation epoch of the red galaxies in the clusters (see also Gladders et al. 1998). We note that in order to apply the color of the red sequence to obtain a photometric redshift, we must assume that the red galaxies in different clusters at the same $z$ are coeval – a condition that is approximately met if the cores of clusters are formed at high $z$. 
2.  From the fit of the CMR, the $B - R$ color of a red sequence at any $R$ can be determined. We have chosen a fiducial, though arbitrary, magnitude of $R = 17$ for the purpose of obtaining an empirical calibration between $z$ and the $B - R$ color. We note that an apparent magnitude is chosen since in determining a photometric redshift, no prior knowledge of the redshift can be assumed. The correlation between $z$ and the $B - R$ color of the red sequence at $R = 17$ is shown in Figure 2. A second degree polynomial fit to the data produces a residual in $z$ of 0.008, or a $\Delta z/z \sim 0.1$. Comparing to the residual of $\sim 0.04$ to 0.07 ($\Delta z/z \sim 0.1$ to 0.2) of typical empirical photometric redshift techniques using four colors (see e.g., Brunner et al. 1997, Yee 1999, and papers in these proceedings), the empirical calibration of the cluster redshifts using a single CMR color is remarkably tight and robust.

3. The CMR as a Tool for Detecting Galaxy Clusters

The ubiquitousness of the early-type galaxy red sequence can be used as a powerful tool for detecting high spatial density regions such as galaxy clusters and groups. Selecting galaxies in color slices in the color-magnitude diagram would preferentially increase the density enhancement of any grouping of early-type galaxies which are normally found in clusters or groups. This technique can be used not only as a very efficient cluster finding algorithm, but also as a means of separating projected clusters and groups.

3.1. Separating Projected Clusters

Cluster catalogs created by primarily locating surface density enhancements of galaxies, such as the Abell and APM catalogs, suffer from projection effects. Estimates of such projection effects in the Abell catalog range from 10 to 20% (e.g., Olivier et al. 1990). Figure 1 demonstrates the ability of using the color-magnitude diagram of a cluster field to detect background clusters in an efficient manner. A second red sequence above the red sequence of A690 can be clearly seen. The galaxies in this second red sequence, which corresponds to a redshift of $\sim 0.25$, are found to be clustered to the NW of the main A690 cluster (at $z = 0.079$), and coincident with a secondary X-ray peak.
In the LOCOS data set, we identified 6 clusters out of the 45 as having a significant background cluster (López-Cruz & Yee 1999b), giving a contamination rate of ~10 to 15% for the Abell clusters. A similar rate (2/9) is also obtained for the control fields. We note that such contaminations are also present in the X-ray maps, although at a smaller rate of 1/2 to 1/3 of the optical images.

3.2. A Red Sequence Cluster Survey

A major problem in existing galaxy cluster catalogs from optical surveys (e.g., Abell 1958, Postman et al. 1996) is that they are susceptible to projection effects. An additional difficulty for any survey that attempts to find high-redshift clusters is the accumulated column density of galaxies in the foreground of a cluster, which decreases the surface density enhancement of galaxies in the cluster. The red sequence of early-type galaxies in clusters and groups, however, provides a crucial signature which allows us to identify such high-density regions.

We are in the process of carrying out a large optical imaging survey for galaxy clusters to redshifts \( z \gtrsim 1 \), using the red sequence as a primary marker (Gladders & Yee 1999). The survey, conducted at the CFHT 3.6m and the CTIO 4m using large mosaic CCD imagers, will obtain images over 10 deg\(^2\) in area in the \( z' \) (\( \sim 9200\) Å) and \( R \) bands sufficiently deep to detect galaxy clusters to \( z \sim 1 \).

4. The main scientific goals are to obtain the mass spectrum of clusters of galaxies as a function of redshift in order to constrain the cosmological parameter pair: \( (\Omega_m, \sigma_8) \), and to study the evolution of clusters over a large redshift range with a sample of clusters covering a wide range of properties.

The cluster detection algorithm uses combined information on the color-magnitude plane and the x-y position plane. Galaxies are chosen based on slices in the \( z' - R \) vs \( z' \) plane which mimic the CMR of early-type galaxies at various redshifts. Model CMRs as a function of redshift can be obtained from synthesis models from, e.g., Kodama (1997). Surface enhancements of galaxy density in the x-y plane in these slices are then cataloged as cluster candidates. For images with good seeing, morphological information in the form of a concentration parameter can also be used to further isolate early-type galaxies. In short, clusters are identified in the 5-dimensional space of RA, Dec, color, magnitude, and morphology.

The use of the red sequence minimizes projection effects from fore- and background clusters and groups, as the color allows a crude separation in redshift space. Furthermore, by isolating one color slice at a time (and with added morphological selection when available), the excess signal from the cluster is greatly enhanced. The detected red sequence can then be used to estimate a photometric redshift for the candidate, using either CMR models or an empirically calibrated relation. With a photometrically measured redshift, global properties such as the luminosity function, richness, and blue fraction for the cluster can be estimated statistically from the photometric data.

3.2.1. Testing the Red Sequence Algorithm with CNOC2 Data

We have tested the cluster detection algorithm using both real and simulated data. The CNOC2 survey (Yee et al. 1998) provides the largest redshift/multi-color photometry database currently available for intermediate redshifts. Using 3/4 of the data (about 1.2 deg\(^2\)), we construct a catalog of groups/clusters using \( I \) and \( g \) photometry and the method outlined above. For each of the identified
groups, a photometric redshift is determined by comparing with CMR models from Kodama (1997). The groups are then verified using the redshift catalogs. Every identified group is found to have a corresponding group in redshift space. The average richness of these groups is sub-Abell richness class 0, with a mean velocity dispersion of about 350 km/s. Figure 3 shows the comparison of the photometric redshifts as derived from the red sequence with the spectroscopic redshifts of the groups. The agreement is excellent over the redshift range of 0.1 to 0.7 with a mean ∆z of only 0.028, comparable to or better than the best photometric redshift results using 4 colors (e.g., Brunner et al. 1997). This demonstrates that the red sequence method is able to detect very poor clusters and groups and to estimate their redshifts with remarkably high accuracy using CMR models.

3.2.2. Testing the Red Sequence Algorithm with Simulated Data
To test the efficiency, robustness, and systematic effects of the red sequence method, we have also constructed detailed models of the observed sky projection of field galaxies. The simulations of the background field galaxy distribution reproduce known galaxy count distributions (to AB magnitude ∼ 29), galaxy luminosity functions, galaxy redshift distributions, color distribution, density morphology relation, and angular covariance function. Clusters of different properties, such as blue fraction, richness, ellipticity, and core radius etc., at different redshifts are then placed in the simulated field. The cluster finding and photometric redshift procedures are then applied to the simulated data. Figure 4 shows the results of one set of simulations in which the blue fraction is varied for a sample of Abell richness 1 clusters. The simulated galaxy photometry catalogs have the same depth as the cluster survey with a 5σ detection limit of $z' = 23.6$ and $R = 24.8$. It is found that the detection probability essentially stays constant at near 100% for clusters with blue fractions less than 0.8 up to $z \sim 1.2$; and the detection probability remains significant at ∼50% at $z \sim 1.4$. At $z > 1.4$, the $z'$ band passes blueward through the 4000Å break, essentially erasing the advantages of using the red sequence method. Poorer clusters, of about Abell richness class 0, can be detected at near 100% detection probability up to $z \sim 0.9$. Other tests indicate that properties such as the ellipticity and core radius of the clusters have little or no effect on the detectability.
4. Summary

The CMR is a powerful tool for detecting galaxy clusters and estimating their redshifts. We have demonstrated that at low-redshift where one can obtain an empirically calibrated relation between the color of the red sequence and redshift, cluster redshifts can be estimated to a high accuracy (∼ 0.01) using just two filters. The red sequence is also an extremely efficient method for identifying clusters over a large richness and redshift range. We have begun a 100 deg² survey using modern mosaic CCD imagers on 4m class telescopes, from which we expect to find upward of 100 rich clusters at z ∼ 1.

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