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Clusters in the Optical

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Abstract.
I present a brief review of studies of galaxy clusters in the optical. Clusters of galaxies were historically detected in the optical, and this selection provided the first large, statistical samples of clusters. I describe how these samples have been instrumental in characterizing the properties of the local cluster population, tracing large scale structure, and constraining cosmology. More sophisticated cluster detection techniques in the optical have now made it possible to detect large numbers of clusters up to $z \sim 1.4$. I describe these advances and discuss how large-area and deep surveys are being used to determine the evolution in the global cluster properties and the properties of cluster galaxy populations.

1. The Historical Selection

1.1. Original Catalogs

Clusters of galaxies were historically detected in the optical pass bands. G.O. Abell and F. Zwicky compiled the first catalogs of galaxy clusters at redshifts of $z \lesssim 0.2$ by searching by eye for surface density enhancements in the Palomar Sky Survey plates (Abell 1958; Zwicky et al. 1961). The Abell and Zwicky catalogs contained over 2700 and 9000 clusters, respectively. Further improvements on the surface density enhancement technique utilized automatic detection in digitized sky plates, for example the Edinburgh-Durham Cluster Catalog (EDCC; Lumsden et al. 1992) and the Automated Plate Measuring Survey (APM; Dalton et al. 1994a). These surveys provided statistical samples of poor to the richest clusters in the nearby universe and have been used to determine the properties of the cluster population. Typical cluster properties include Abell richness (30–300 galaxies), radius (1–2 h^{-1} Mpc), velocity dispersion (400–1400 km s^{-1}), mass within an Abell radius (0.1–3 $\times 10^{15}$ h^{-1} $M_\odot$), blue luminosity (0.6–6 $\times 10^{12}$ h^{-2} $L_\odot$), mass-to-blue light ratio (~ 300 h $M_\odot/L_\odot$), and number density of richness class 1 and above clusters ($\sim 6 \times 10^{-6}$ h^3 Mpc^{-3}).

Rich clusters are also efficient tracers of the large scale structure of the Universe. Consequently, the large-area cluster catalogs provided one of the first means to quantify the clustering of clusters. This clustering was expressed in terms of superclusters (e.g., Bahcall & Soneira 1984) or the cluster-cluster correlation function which stays positive out to ~ 100 h^{-1} Mpc (e.g., Dalton et al. 1994b; Bahcall et al. 2003a).

1.2. Cosmological Constraints

Because clusters are the most massive systems in the universe, their global properties place strong constraints on cosmology – specifically the mass density of the universe, Ω_m, and the normalization of the power spectrum, σ_8. Many different measurements of cluster optical properties can be used to constrain these cosmological parameters, including the mass-to-light ratio on large scales, the cluster mass function, and the cluster-cluster correlation function. As been known for many years, all of these cluster observations suggest that $\Omega_m = 0.1 - 0.4$ (e.g., Bahcall & Cen 1993; Bahcall, Lubin & Dorman 1995; Bahcall et al. 2003a).

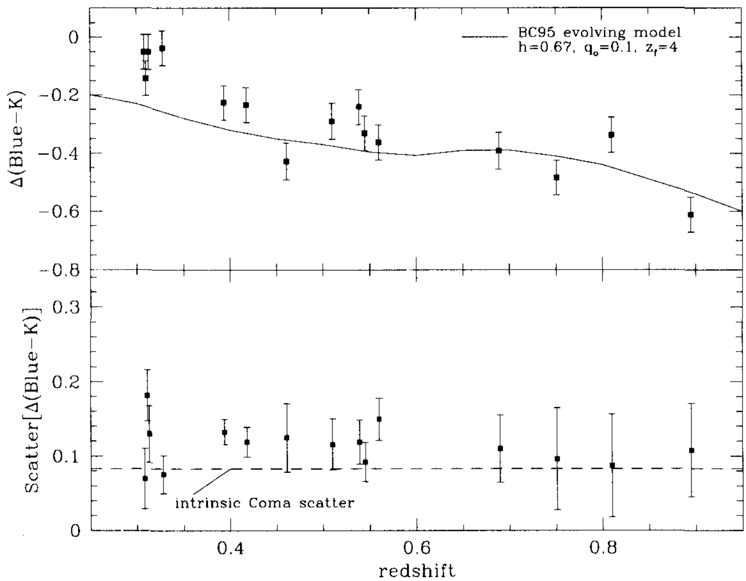

Figure 1. (*Top*) Color of the red sequence (relative to the rest-frame color of the Coma) versus cluster redshift. Solid line indicates the expected color evolution from the 1995 version of the Bruzual & Charlot (1993) evolving model of a single burst of star-formation at $z_f = 4$. (*Bottom*) Color scatter in the red sequence versus cluster redshift. Dashed line indicates intrinsic scatter in the Coma cluster. This figure is taken from Dickinson (1996).

2. Modern Cluster Finding Techniques

Detection of galaxy clusters in the optical has significantly improved with the introduction of large-area imaging surveys which employ sophisticated, automated techniques whose contamination and completion rates can be easily quantified. Improving on the EDCC and APM surveys, adaptive-kernel density mapping and automatic detection of surface brightness fluctuations of cluster overdensities are being used in the Northern Sky Optical Cluster Survey (Gal et al. 2003;

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5800 deg^2; $z < 0.3$) and the Las Campanas Distant Clusters Survey (Gonzalez et al. 2001; 69 deg^2; $0.3 < z < 1$). The Palomar Distant Cluster Survey (Postman et al. 1996; 5 deg^2; $0.2 \leq z \leq 1.2$) was the first survey to employ a matched filter algorithm that used both galaxy position and brightness to detect objectively clusters up to $z \sim 1.2$. This algorithm and its derivatives have been used for cluster detection in the Sloan Digital Sky Survey (Bahcall et al. 2003b; 400 deg^2; $0.05 \leq z \leq 0.3$), the ESO Imaging Survey (Scodeggio et al. 1999; 17 deg^2; $0.2 \leq z \leq 1.2$), and the Deep Range Survey (Postman et al. 2002; 16 deg^2; $0.2 \leq z \leq 1.2$).

Another technique exploits the fact that the early-type galaxy population in clusters forms a distinct locus in the color-magnitude (CM) diagram. This sequence is distinguished by extremely red colors and a tight CM relation. So far, all massive clusters up to redshifts of $z \sim 1.3$ exhibit a reasonably-strong red sequence in the CM diagram (e.g., Stanford, Eisenhardt & Dickinson 1995, 1997; Lubin et al. 1998, 2003; van Dokkum et al. 2000, 2001; Blakeslee et al. 2003). As such, the Red-Sequence Cluster Survey (RCS; Gladders & Yee 2000) utilizes the form and color of this distinct feature to optimize cluster detection over the blue field population. The RCS covers 100 deg^2 and expects to detect over 1000 clusters at redshifts of $0.1 < z < 1.4$.

3. Cluster Evolution

Using the increasing numbers of high-redshift clusters, it is now possible to study the evolution of massive clusters and their galaxy populations.

One of the obvious global properties to measure as a function of time is the number of clusters. In a low-Ω universe, density fluctuations evolve and freeze out at early times, producing little evolution at recent times, i.e. redshifts of $z < 1$. In a flat ($\Omega = 1$) universe, fluctuations start growing only recently, thereby producing strong evolution at recent times. Optical surveys have revealed only a mild decline in the co-moving volume density of rich (Abell richness class 1 and above) clusters out to $z \sim 1$. The existence of massive clusters at these redshifts again favors a low Ω_m Universe (Postman et al. 1996, 2002; Carlberg et al. 1997; Bahcall & Fan 1998).

By charting the change in the color of the red sequence (see §2), it is possible to determine how the stellar populations in early-type galaxies have evolved from $z \sim 1$ to the present day. Figure 1 shows the evolution in the color and color scatter of the red sequence for 15 clusters between $z \sim 0.3$ and $z \sim 0.9$. The broad-band color distribution of the early-type galaxy population shows significant bluing; the observed trend is consistent with passive stellar evolution of a relatively well synchronized initial starburst occurring at $z \gtrsim 2$ (e.g. Stanford, Eisenhardt & Dickinson 1995, 1997), although continuing star-formation in a fraction of the galaxies is not strongly constrained (van Dokkum & Franx 2001).

Even though clusters of galaxies at high redshift still contain a large number of early-type galaxies, the fraction of early-type galaxies is evolving with time. This trend was first observed as the progressive bluing of cluster's galaxy population with redshift (Butcher & Oemler 1984). Butcher & Oemler found that the fraction of blue galaxies in a cluster is an increasing function of redshift (see Figure 2), indicating that clusters at redshifts of $z \sim 0.5$ are significantly bluer than their low–redshift counterparts. At redshifts of $z \sim 0.4$, the fraction of blue galaxies is $\sim 20\%$, compared to $< 5\%$ locally. High-angular-resolution HST images have revealed that most of these blue galaxies are either "normal" spirals or have peculiar morphologies, resulting in late-type fractions which are 3 to 5 times higher than the average current epoch cluster (e.g., Dressler et al. 1994, 1997; Couch et al. 1994).

This trend continues to $z \sim 1.3$ (Lubin et al. 1998, 2002, 2003; van Dokkum et al. 2000, 2001; Blakeslee et al. 2003). Figure 2 shows the evolution of the early-type fraction with cluster redshift. At $z \sim 1$, this fraction is lower by a factor of 1.5 – 2.0, compared to local clusters. Consequently, the fraction of late-type (spiral, irregular, and peculiar) galaxies increases with redshift. This evolution implies that early-type galaxies are forming out of the excess of late-type galaxies over this $\sim$ 7 Gyr time scale. The key question now is what physical process associated with the cluster environment is responsible for the observed evolution.

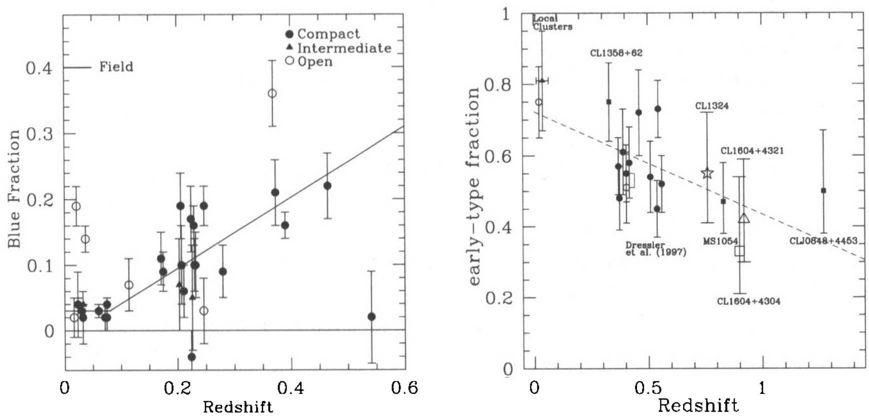

Figure 2. (*Left*) Cluster blue fraction versus redshift. Different symbols represent clusters of different concentrations. This figure is taken from Butcher & Oemler (1984). (*Right*) Early-type fraction versus cluster redshift. Data points are taken from Dressler (1980); Dressler et al. (1997); Andreon 1998, Lubin et al. (1998, 2002, 2003); Fabricant, Franx & van Dokkum (2000); and van Dokkum et al. (2000, 2001). The dashed line indicates best-fit least-squares line. This figure is taken from Lubin et al. (2003).

4. Conclusions

Detecting and examining clusters of galaxies in the optical has provided a wealth of information over the last 40+ years. Optical selection provided the first large, statistical samples of galaxy clusters. These samples have been used to define the local cluster population, study structure on scales up to $\sim$ 100 Mpc, and to constrain the cosmological world model. Sophisticated, automated cluster finding techniques are now extending cluster catalogs up to redshifts of $z \sim 1.4$.

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Optical observations of the ever-increasing numbers of moderate-to-high redshift clusters have been critical in studying in detail how clusters and their galaxy populations have evolved with time.

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