Detecting galaxy clusters at $0.1 < z < 2.0$

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**Abstract.** We present a new cluster-finding algorithm based on a combination of the Voronoi Tessellation and Friends-Of-Friends methods. The algorithm utilises probability distribution functions derived from a photometric redshift analysis and is tested on simulated cluster-catalogues. We use a 9 band photometric catalogue over 0.5 square degrees in the Subaru XMM-Newton Deep Field. The photometry is comprised of UKIDSS Ultra Deep Survey infrared $J$ and $K$ data combined with 3.6 µm and 4.5 µm Spitzer bands and optical $BVriz'$ imaging from the Subaru Telescope. The cluster catalogue contains 13 clusters at redshifts $0.61 \leq z \leq 1.39$ with luminosities $10L^* \lesssim L_\text{tot} \lesssim 50L^*$.

1. Introduction

Clusters of galaxies in the Universe play an important role in our understanding of how dark-matter haloes collapse and large-scale structure evolves. Their number density can place constraints on the mass density of the Universe and the amplitude of the mass fluctuations. Furthermore they can act as astrophysical laboratories for understanding the formation and evolution of galaxies and their environments. Unfortunately, there are only few clusters known at $z > 1$ and the majority of these are from X-ray surveys (e.g. using XMM-Newton; Stanford et al. 2006). Optical searches have been stymied by the fact that the 4000 Å break falls outside the I-filter pass band ($z > 1$) given the predominance of early-type, red galaxies in clusters. However, with the advent of large near-infrared cameras like the Wide Field Infrared Camera (WFCAM) on the United Kingdom Infrared Telescope (UKIRT), it is now possible to select clusters in the near-infrared over large areas. The UKIRT Infrared Deep Sky Survey (UKIDSS, Lawrence et al. 2006) is a suite of deep and wide surveys using WFCAM and provides the ideal opportunity to search for high-redshift clusters in the near infrared. The survey has a high efficiency as WFCAM provides over an order of magnitude increase in survey speed over previous near-infrared imagers.

There are numerous methods for detecting clusters in optical/infrared imaging surveys. The problem is easier with spectroscopic redshifts but large infrared spectroscopic surveys are presently impractical over large areas. However, approximate redshifts can be calculated via photometric redshift estimation. Despite the popularity of the photometric redshift technique remarkably little attention is paid to using photometric redshifts to isolate clusters. Further, little work has been done to compare the various cluster detection method that exist (for a review see Gal 2005).
2. A new cluster finding algorithm

We have developed a new cluster-detection algorithm [see van Breukelen et al. (in prep.) for details] to deal with two common problems of photometric selection methods: (i) projection effects of fore- and background galaxies arising from large redshift errors ($\sigma_z \sim 0.1$); (ii) determining the reality of detected clusters arising from cluster selection biases. We solve these issues in two ways. First, as the photometric redshift probability functions ($z$-PDFs) are often significantly non-Gaussian, and can show double peaks, our cluster-detection algorithm samples the full $z$-PDF instead of a single best redshift-estimate with an associated error. Second, selection biases can be reduced by cross-correlating the output of two substantially different cluster-detection methods. We therefore use both the Voronoi Tessellation (VT) and Friends-Of-Friends (FOF) technique to select the clusters in our survey.

In brief, our algorithm is divided into six steps: (1) We determine the $z$-PDFs for all galaxies; (2) we create MC realisations of the three-dimensional galaxy distribution, based on the galaxy $z$-PDFs; (3) we divide each MC-realisation into redshift slices of $\Delta z = 0.05$ over the range $0.1 \leq z \leq 2.0$; (4) the cluster candidates are isolated in each slice of all MC-realisations using the VT and FOF methods; (5) the probability of cluster candidates for both methods, from the number of MC-realisations, are mapped; (6) the output is cross-correlated for the VT and FOF methods to produce the final cluster-catalogue.

2.1. Detection methods

The VT technique works by dividing a field of galaxies into Voronoi Cells, each containing one object: the nucleus. All points that are closer to this nucleus than any other are enclosed by the Voronoi Cell. One of the main advantages of this method is that it is relatively unbiased: it does not require a particular source geometry (e.g. Ramella 2001). The parameter of interest is the area of the VT cells, the reciprocal of which translates to a density. Overdense regions in the plane are found by fitting a function to the density distribution of all VT cells in the field (see Ebeling & Wiedenmann 1993); cluster candidates are the groups of cells of a significantly higher density than the mean background density. By contrast, the FOF algorithm groups galaxies with a smaller separation than a projected linking distance $D_{\text{link}}$ (‘friends’). A FOF algorithm utilizing photometric redshifts was proposed by Botzler et al. (2004). A crucial difference between our algorithm and previous work is the way we place the galaxies in the redshift slices. We sample the full $z$-PDF to create Monte-Carlo (MC)-realisations of the three-dimensional galaxy distribution. We do not need to assign errors to individual galaxy redshifts. An object with a large redshift error will be distributed throughout many different slices in the MC-realisations, and therefore not yield a significant contribution to the cluster candidates it is potentially found in. Thus there is no need to remove objects with large errors from the catalogue and no additional bias is introduced against faint objects with noisier photometry. A second modification to existing algorithms is the way we link up cluster candidates throughout the redshift slices. Instead of comparing individual galaxies in the clusters and linking up the clusters with
corresponding members (see e.g. Botzler et al. 2004), we use probability maps of all redshift slices to locate likely cluster regions.

2.2. Probability maps and cross-correlation

We combine the cluster candidates in the redshift slices for all MC-realisations to create a cluster probability for both methods for each redshift slice. Figure 1 shows an example of a probability map: the VT cluster candidates in this slice at $z = 1.0$ are contoured and coloured, with black through to red indicating low to high probability. This map is created by overplotting the extent of all cluster detections; the regions of the field that are found to be in a cluster in many MC-realisations are high-probability cluster locations. Since the error on the photometric redshifts of the galaxies is usually larger than the width of the redshift slices, each cluster candidate is typically found in several adjoining slices. We join the cluster candidates that occur in the same location in several slices by locating the peaks in the probability maps and inspecting the area within their contours in the adjoining redshift slices for cluster candidates. All the cluster candidates found in the same region in adjoining redshift slices are linked up into one final cluster; the final cluster redshift is determined by taking the mean of the redshift slices, weighted by the number of corresponding MC-realisations. We cross-correlate the cluster candidates output by the VT and FOF methods and take all cluster candidates that are reliably detected in both.

2.3. Simulations

To test the behaviour of our algorithm we run a set of simulations on mock cluster catalogues ranging in total luminosity from $10 L^*$ to $300 L^*$ and redshift $0.1 < z < 2.0$, superimposed on a galaxy distribution randomly placed in the field within the same redshift range. Realistic galaxy luminosities and number densities are determined by the $K$-band luminosity function of Cole et al. (2001) for the field-distribution and Lin et al. (2004) for the clusters, with the simplifying assumption of passive evolution with formation redshift $z_{\text{form}} = 10$. The galaxies are spatially distributed within a cluster according to an NFW profile (Navarro, Frenk & White, 1997) with a cut-off radius of 1 Mpc.
3. Results: application to the UKIDSS-UDS cluster catalogue

We have applied our cluster-detection algorithm to real data (van Breukelen et al. 2006). We used: near-infrared $J$ and $K$ data from the UKIDSS Ultra Deep Survey Early Data Release (UDS EDR, Foucaud et al. 2006); 3.6µm and 4.5µm bands from the Spitzer Wide-area InfraRed Extragalactic survey (Lonsdale et al. 2005); and optical $BVriz$ Subaru data over the Subaru XMM-Newton Deep Field (SXDF, Furusawa et al. in prep.). We restricted ourselves to a rectangular area of 0.5 square degrees, exhibiting a survey-depth of $K_{AB,lim} = J_{AB,lim} = 22.5$ (UDS EDR 5σ magnitude limits). We included objects with a detection in $i'$, $J$ and $K$ in the galaxy catalogue and to exclude stars and quasars we imposed a criterion of SExtractor stellarity index < 0.8 in $i'$ and $K$. We then calculated photometric redshifts for this sample using a modified version of hyperz (Bolzonella et al., 2000) which resulted in a catalogue of 19300 objects in the range 0.1 ≤ $z$ ≤ 2.0.

Application of our cluster-detection algorithm to the redshift catalogue yielded 13 clusters at 0.61 ≤ $z$ ≤ 1.39 (van Breukelen et al. 2006). To derive the clusters’ luminosity, we compared the results to the output of the simulations. We determined the number of galaxies, $N_{gal,FOF}$, with $K < 22.5$ (corresponding to the completeness limit) in the same way as for our simulated clusters; this allowed us to derive an approximate total luminosity to the cluster by interpolating between the lines of constant total luminosity in the $N_{gal} - z$ plane found in our simulations. We found our clusters span the range of $10L^* \lesssim L_{tot} \lesssim 50L^*$; assuming $(M/M_\odot)/(L/L_\odot) = 75h$ (Rines et al. 2001) this yields $0.5 \times 10^{14} M_\odot \lesssim M_{cluster} \lesssim 3 \times 10^{14} M_\odot$.

Spectroscopic observations of these clusters are essential to confirm their reality, particularly for the $z > 1$ clusters which are cosmologically more valuable. A new generation of highly multiplexed near-infrared spectrometers on 8-metre class telescopes will provide the ideal opportunity for such follow-up.

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