Projection Effects in the Abell Catalogue

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Abstract. We investigate the influence that projection effects have on the completeness of the the Abell cluster catalogue in the context of an $\Omega_0 = 1$ CDM Universe. We construct a galaxy catalogue and identify clusters using an algorithm that mimics Abell's method. Over 30% of Richness Class $\geq 1$ clusters have been selected despite not meeting the required intrinsic (3D) richness criterion. Velocity dispersions are shown to have been systematically overestimated.

1. Introduction

The abundance and masses of clusters of galaxies are a very sensitive probe of both the spectrum of initial fluctuations and of the cosmological parameter $\Omega_0$. The clusters in most catalogues available at present have been detected as an overdensity of galaxies on photographic plates. However, the 2D nature of this selection procedure leads to contamination by both foreground and background galaxies. The incompleteness this causes is likely to have serious consequences for measures such as the cluster-cluster correlation function and the distribution of cluster velocity dispersions.

The most widely used optically selected (2D) cluster catalogues are those compiled by Abell (1958) and ACO (Abell et al. 1989). Recent machine based surveys (Dalton et al. 1992; Lumsden et al. 1992) have yielded catalogues of only small regions of the sky (10-20%, compared with the all-sky ACO catalogue) but should suffer less from projection effects. At present though, most studies that use clusters are still based on the Abell and ACO catalogues; for example, the recently completed ESO Key Programme on Rich Clusters of Galaxies (Katgert et al. 1996). This study has shown that many Abell clusters have more than a single system along the line of sight. By taking over 50 redshifts for a large number of clusters, they have established that such projection effects are fairly common. Judging from the data presented by Katgert et al. (1996), it appears as though a significant fraction (perhaps as high as 30%) of Richness class $\geq 1$ clusters may be seriously affected by projection effects.

It is obvious that a careful investigation of the completeness of optical cluster catalogues is warranted. We report here on the first results of such a study, using artificial galaxy catalogues. Similar techniques were used by Frenk et al. (1990) and White (1991,1992). A more comprehensive account can be found in two forthcoming papers (van Haarlem, Frenk & White 1996; van Haarlem & Frenk 1996).
2. Construction of a Galaxy and Cluster Catalogue

The results discussed in this paper are based on a set of 8 Standard CDM N-body simulations described more fully by Eke et al. (1995) and performed with an adaptive P$^3$M code using $128^3$ particles in an $L_{\text{box}} = 256h^{-1}$Mpc comoving periodic box. At the output time used for the galaxy catalogue $\sigma_8$, the rms amplitude of mass fluctuations in a sphere with radius $8h^{-1}$Mpc, had a value of 0.63. Only a single epoch was used, in order to concentrate on the differences caused by the selection of clusters in 2D and not by the inherent uncertainties in the galaxy formation process.

2.1. Constructing Galaxy Catalogues

There is no satisfactory method that allows us to construct a large catalogue of galaxies while treating the dissipative processes of star and galaxy formation and their evolution in a representative way. However, such a catalogue is clearly required, if we are to select clusters in a manner similar to the way they are found on photographic plates. We have chosen to use the peak-background split technique to make a selection of the total number of particles available, and identify them with individual galaxies. The idea behind this process is that galaxies will form at the sites where the initial density field exceeds a threshold on a scale that we associate with that of an individual galaxy. Because our simulations cover a large volume, the initial resolution is only $4h^{-1}$Mpc, which is somewhat greater than the scale $r_s$ of a galaxy (on average the mass contained within a top-hat with a radius $r_s = 0.54h^{-1}$Mpc is of the order of $10^{12}M_\odot$). The peak-background split technique uses the machinery developed by Bardeen et al. (1986) to predict the number density of peaks on a scale $r_s$ in a Gaussian Random Field which we can only resolve on a scale $r_b > r_s$. Further details can be found in White et al. (1987) and in van Haarlem et al. (1996). We first smooth the initial density field, using a sharp $k$-space filter to remove all power below $r_b$ which eliminates artificial correlations between the smooth field and the peaks we are looking to find. Using a value of $r_b=8.75h^{-1}$Mpc, we calculate the conditional probability that the initial density field exceeds a local threshold for galaxy formation, given its actual value found in the smoothed field. The procedure is applied to all the points in the density field, sampled at the initial locations of the particles on the grid. A final (volume limited) catalogue is compiled by taking a random sample from the particles, while considering the probability computed above. The total number of galaxies is determined independently by requiring that the luminosity density of our model catalogue is consistent with recent determinations of luminosity function parameters (e.g. Loveday et al. 1992; Marzke et al. 1994). The value of $\rho_L = 0.0176L_\star h^3\text{Mpc}^{-3}$ also reproduces the observed abundance of Abell clusters ($\sim 8 \times 10^{-6}h^3\text{Mpc}^{-3}$; Bahcall & Soneira 1983) when we use the method described below to identify the clusters. Where necessary, we have assumed that the galaxies follow a Schechter luminosity function

$$\phi(L)dL = N_* L^{-\alpha} \exp(-L)/\Gamma(2-\alpha)dL, \tag{1}$$

where $L$ is expressed in units of $L_\star$, and $\Gamma$ is the Gamma function. Apart from matching the observed number of Abell clusters, the two point correlation function of the galaxies in our catalogue also agrees well with the observed $\xi_{gg}$. 
2.2. Cluster Selection

Each volume limited catalogue was projected onto a plane along the three coordinate axes, thus producing three different 2D galaxy catalogues from each simulation. A friends-of-friends group finding algorithm with a linking length 30% of the mean intergalaxy separation was then applied to the 2D catalogue. The list of groups it produces forms the starting point of the search for clusters using a procedure that mimics Abell’s selection criteria closely.

Abell defined a rich cluster as an enhancement of galaxies on the Palomar Sky Survey plates. To qualify as a cluster, the number of galaxies within the Abell radius \( r_a = 1.5h^{-1}\text{Mpc} \) from the proposed cluster centre had to exceed \( n_a \), after subtracting the background count. These galaxies were constrained to the magnitude interval between \( m_3 \) and \( m_3 + 2 \), where \( m_3 \) is the apparent magnitude of the third brightest galaxy. For the lowest richness class that is often assumed to be reasonably complete, \( n_a \) has to exceed the background count by at least 50 galaxies (Abell richness class \( R = 1 \)). The relation between \( n_a \) and the luminosity density of each catalogue follows from the assumed functional form of the luminosity function and this richness criterion. As is shown in more detail in van Haarlem et al. (1996) this assumption leads to the following relation

\[
n_a = \frac{N_*}{\Gamma(2-\alpha)} \int_{0.1585L_3}^{L_3} L^{-\alpha} \exp(-L) dL.
\]

Here, \( N_*L_* \) represents the total luminosity projected within \( r_a \) and \( L_3 \) is the median luminosity of the third brightest galaxy. The 50 galaxies that are needed for an \( R = 1 \) cluster correspond to \( 60L_* \), which is achieved when the total catalogue contains \( N_{gal} = \rho L n_a V/N_* \) galaxies. For the present set of simulations \( N_{gal} \sim 3.4 \times 10^5 \). Since the number of galaxies that are found in clusters is only a small fraction of the total number in each volume we may assume that on average the fore- and background contribution is directly proportional to the volume projected onto the cluster, i.e. a cylinder with a radius \( r_a \) and length \( L_{box} \). Within an Abell radius we therefore expect, on average, a contamination of 27 galaxies, in addition to the 50 that belong to the cluster. Each of the groups identified using the friends-of-friends method in the 2D galaxy catalogue was checked. The poorer of a pair of overlapping clusters (projected separation \(< 2r_a \)) was removed. On average 139 clusters were found in each catalogue \(( \sim 8 \times 10^{-6}h^3\text{Mpc}^{-3}) \).

One final preliminary is the translation of the 60\( L_* \) that represents an \( R = 1 \) cluster in a 2D catalogue, to an intrinsic (3D) luminosity. This value can be obtained by deprojection of a 2D profile, and comparing the integrated mass within a cylinder (2D) and sphere (3D). For a power-law density profile \( \rho(r) \propto r^{-\gamma} \), with \( \gamma \sim 2.2 \) as found by Lilje & Efstathiou (1988), the ratio turns out to be 0.72. We will therefore consider clumps of galaxies that have a luminosity greater than 43\( L_* \) as 3D Abell clusters.
3. Completeness of the Cluster Catalogue

In order to assess the success of the cluster selection technique in identifying real clusters while rejecting projection effects, we have computed the luminosity associated with all clumps of particles in the original N-body output. Once again we used a friends-of-friends algorithm, but now with a small linking length (10% of the mean interparticle separation) in order to pick up small groups. In Figure 1 we show the results for one of our projected catalogues. Along the horizontal axis we have plotted the number of galaxies counted within a projected Abell radius (the background count has not been subtracted, hence an $R = 1$ cluster corresponds to $n \geq 77$). The total luminosity within a sphere with radius $r_a$ centred on the three most luminous groups found along the line of sight to each cluster is plotted along the vertical axis. The main cluster is shown as a filled square, the second and third most luminous group as a cross and circle respectively. The dashed line shows the $43L_*$ that we derived above. Averaged over all 24 catalogues, a significant fraction (34$\pm$6%) of all clusters do not have a single clump along the line of sight which has a luminosity in excess of $43L_*$. We also found that 32$\pm$5% of the total number of groups that are brighter than $43L_*$ were not associated with $R \geq 1$ clusters. This last effect is due to a low background count, which has effectively led to an overestimate of the fore- and background contribution. The overall conclusion we come to is that approximately a third of all $R \geq 1$ clusters must be replaced by clusters that have not been picked out by the selection procedure. Although lowering the threshold, or calculating a local background value would presumably lead to a higher detection rate, it would also increase the number of phantom clusters.
4. Velocity Dispersions

Through the virial theorem, the velocity dispersions of clusters provide a means of deriving the mass distribution of clusters, which is known to be a powerful discriminant between different cosmological scenarios (White, Efstathiou & Frenk 1993; Bahcall & Cen 1993). A useful way of looking at the velocity dispersions is by plotting their cumulative distribution function $n(> \sigma_{v,los})$, the number density of line of sight velocity dispersions. Projection effects will have a tendency to increase the high $\sigma_v$ tail of the distribution, because small clumps in the vicinity of the cluster are difficult (if not impossible) to remove. In Figure 2 we show the effect of 3 different methods of calculating $\sigma_v$. Firstly, we compute $\sigma_v$ in an analogous manner to the way most observational samples have been treated. Using the redshifts of all the galaxies within a cylinder with radius $r_a$ centred on the cluster, we identify the peak of the histogram. All galaxies more than 4000 km/s from this peak are removed, and an iterative 3$\sigma$-clipping technique is applied to the remaining data. The resulting $n(> \sigma_{v,los})$ is shown as the filled squares in Figure 2. It is quite noticeable that there appears to be a significant tail in the distribution, extending to at least 2000 km/s. By using a smaller aperture, the cross-section for possible projection effects is sharply reduced. One also notices the effect on $\sigma_v$. We have applied the same algorithm described above to all the galaxies within $r_a/3 = 0.5 h^{-1}$Mpc, and find a marked reduction in the number of high velocity dispersion clusters (open squares). Finally, the triangles in Figure 2 use the iterative scheme developed by den Hartog & Katgert (1995). Within an aperture of $1.0 h^{-1}$Mpc, they apply a radially varying criterion for the elimination of interlopers. At each projected radius, they determine the extreme values of the radial component of both the infall and circular velocity, and reject all galaxies that exceed these extremes. In each case they use conservative limits in order not to reject too many galaxies. This leads to a further decrease in the amplitude of the high-$\sigma_v$ tail (triangles in Figure 2). However, none of these techniques is capable of approaching the intrinsic (3D) velocity dispersions, obtained directly from the dark matter particles within a sphere with radius $r_a$. The distribution of $\sigma_v$ of all dark matter clumps is shown as the solid line. This curve also reveals that our richness selected catalogue is very incomplete below $\sigma_v \sim 1000$ km/s. If these factors are taken into account, then a comparison of velocity dispersions determined from clusters taken directly from N-body simulations and compared with observations must lead to serious errors. Bahcall & Cen’s (1993) rejection of the $\Omega_0 = 1$ CDM model on the basis of the cluster mass function therefore seems somewhat premature.

5. Conclusions

We have shown that, in the context of an $\Omega_0 = 1$ CDM Universe, contamination is a serious problem that leads to around one-third of clusters being misclassified as an $R \geq 1$ Abell cluster, while a similar fraction is not recognised. Projection effects also influence the velocity dispersions that one can estimate from observations. Even the most elaborate techniques of removing interlopers, are not able to recover the true 3D velocity dispersion distribution of dark matter clumps.
Figure 2. The cumulative distribution of cluster velocity dispersions based on all synthetic cluster catalogues. See text for details.

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