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SCIENCE FROM A SERENDIPITOUS GALAXY CLUSTER SURVEY WITH *XMM-NEWTON*

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We have modelled the expected properties of an *XMM-Newton* serendipitous cluster survey for three different cosmological models, using the Extended Press–Schechter framework. We estimate that, over the ten year design lifetime of *XMM*, the EPIC camera will image a total of around 800 square degrees in fields suitable for the serendipitous detection of clusters of galaxies. For the presently-favoured low-density model with a cosmological constant we predict that this survey would yield a catalogue of more than 8000 sources, ranging from poor to very rich clusters, with around 750 detections above z=1. A low-density open Universe yields similar numbers, though with a different redshift distribution, while a critical-density Universe gives considerably fewer clusters. The catalogue resulting from an *XMM* serendipitous cluster survey would facilitate a variety of follow-up projects, including the quantification of evolution in the X-ray luminosity-temperature relation, the study of high-redshift galaxies via gravitational lensing and the analysis of foreground contamination in cosmic microwave background maps. Most importantly, the catalogue will allow stringent constraints to be placed on the values of the total amount of matter in the Universe and of a possible cosmological constant.

1 Introduction

Galaxy clusters are the largest gravitationally-bound structures in the Universe today. They are proving to be extremely powerful cosmological probes: their rareness makes their number density extremely sensitive to the underlying cosmological model, while by virtue of their size they are less subject to complicated astrophysical processes than smaller objects such as galaxies. As one example, the number density of clusters in the present Universe currently offers the most reliable constraint on the size of density perturbations on small scales, around 8/h Mpc [1,2]. An exciting prospect is that the evolution of the rich cluster number density with redshift has the potential to be a powerful probe of the total matter density in the Universe [3,4,5,6,7,8].

There is a pressing need for a new galaxy cluster catalogue, of greater size, and in particular going to higher redshift, than existing ones. To ensure robust results, the catalogue should be based on a single selection criterion. Especially to high redshifts, the most useful selection is in the X-ray, due to the high contrast of clusters against the X-ray sky. In this contribution, we summarise the results of Romer et al. (2000), which describes in considerable detail how such a catalogue may be constructed through serendipitous detections of galaxy clusters in archival data from the *XMM-Newton* satellite. By examining the many thousands of pointings which will be made, it will be possible to build a representative sample of randomly, and hence objectively, selected X-ray clusters. The proposed survey will not only be an invaluable resource for cosmological studies, but will also have a variety of other applications.

2 Survey Sensitivity Limits

We estimate that if *XMM* operates for the full ten years of expected lifetime, and makes an average of three pointings per day, then the total area imaged by the EPIC camera will be about 2000 square degrees. Many of these images will not be suitable for serendipitous detections of galaxy clusters. We therefore estimate that the actual areal coverage of the proposed *XMM* cluster survey (hereafter *XCS*) will be around 800 square degrees.

In order to determine how many, and what type of, clusters the *XCS* might detect, we have calculated the survey sensitivity limit as a function of several parameters, including cluster temperature, cluster redshift, exposure time, telescope vignetting, cosmological parameters. The cluster and background count rates were determined using Xspec (version 10.00, Arnaud 1996).

Several simplified assumptions were made when performing the calculations: we concentrated only on the EPIC-pn camera, more sensitive than the EPIC-MOS; a minimum detection threshold of 8σ was used; when calculating the detection significance we only considered the inner 50 per cent of the total cluster flux; the clusters were modelled as spherically-symmetric systems that follow an isothermal profile, with $\beta = 2/3$; we considered that the present-day relations between cluster core radius and luminosity [11] and cluster temperature and luminosity [12], as well as the mean metallicity of the intracluster medium (1/3 solar), do not change as one goes back in time; the hydrogen column density was fixed at $4 * 10^{20}\,\mathrm{cm}^{-2}$. A detailed description of the determination of the expected cluster and background count rates in the EPIC-pn camera is given in Romer et al. (2000).

If the cluster count rate is high enough (and/or the exposure time is long enough), then one can do more than simply detect the cluster flux - one can also estimate the cluster temperature. Cluster temperatures are extremely useful for cosmological parameter estimation because they provide a more direct measure of the cluster mass than luminosities. Therefore, we have also calculated the sensitivity limits that correspond to the minimum requirements for temperature estimation for clusters with different temperatures, redshifts, assuming several values for the exposure times and cosmological parameters.

However, we would like to stress that even if a serendipitous cluster observation yields more than a minimum of 1000 photons, one will have to wait until the redshift of that cluster has been determined before attempting to measure the cluster temperature. This is because there is a degeneracy between temperature and redshift in the spectral fitting. The exception to this rule would be the case of very high signal-to-noise spectra, from which it is possible to measure the position of, and hence redshifts from, emission features such as the 7 keV Fe line.

The number density of high-redshift clusters depends sensitively on cosmology, so the properties of the *XCS* will vary depending on what values those parameters take. We have concentrated on three popular cosmological models: the currently-favoured spatially-flat low-density cosmology with $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$; a critical-density cosmology, with $\Omega_0 = 1.0$; an open cosmology, with $\Omega_0 = 0.3$ ($\Omega_\Lambda = 0.0$). In each case we assume that structure formation proceeds through gravitational instability from a Gaussian distribution of primordial density perturbations. The

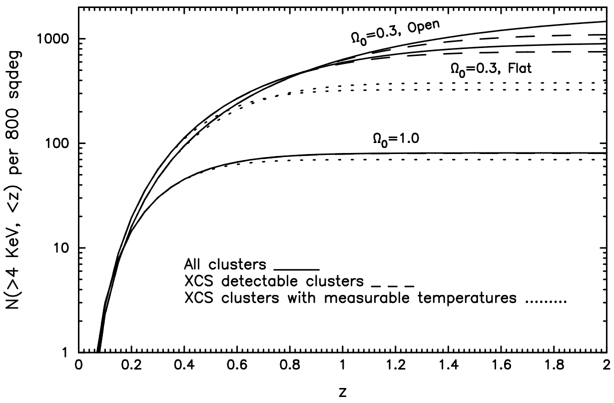

Figure 1: The cumulative redshift distribution N($< z$) of galaxy clusters per 800 square degrees with X-ray temperature in excess of 4 keV. The solid lines show the result one would obtain if there was no limitation on the detectable flux. The dashed and dotted lines show our predictions for the *XCS*, respectively representing the expected number of $> 8\sigma$ detections and the expected number of galaxy clusters bright enough to allow temperature measurements.

current shape of the linear power spectrum of these perturbations is taken to be of the kind expected in cold dark matter dominated models, being the shape parameter fixed at $\Gamma = 0.23$, as suggested by some analysis of galaxy clustering [13].

The number density of clusters was computed using an extended Press-Schechter [14] calculation, which includes a tracking of the merger histories of clusters in order to properly account for their time of formation when predicting their expected temperature from their virial mass (see Viana & Liddle 1996, 1999 for details).

We have only considered galaxy clusters with X-ray temperatures in excess of 2 keV, as the Press-Schechter formalism becomes unreliable for lower mass systems. In Press-Schechter theory, the relative abundance of galaxy clusters of a given mass at two given redshifts depends only on the growth rate of perturbations, which in turn is a function of just Ω_0 and Ω_Λ. The evolution in the cluster number density with redshift is most pronounced for the higher temperature clusters, which, therefore, are the best for distinguishing between different cosmologies, so we will largely focus our discussion on clusters with X-ray temperatures in excess of 4 keV.

In Figure 1 we show as dashed lines the number of clusters with T$>$ 4 keV we expect to have serendipitously detected by the end of the *XMM* 10 years lifetime, up to some redshift z. In Figure 2 we present for the same type of clusters, the number we expect to find above a redshift z. The calculations were made for the three cosmologies previously mentioned. In the same figures, in full it is given the total number of clusters above 4 keV that actually exist, while as dotted lines it is shown the number of clusters, among those detectable, for which one will be able to determine the X-ray temperature from the serendipitous detections.

We note that when deriving the properties of the *XCS* we have assumed that the exposure time distribution of the constituent pointings will follow that of the 760 pointings in the *XMM* GTO program.

3 Science with the Survey

The *XCS* catalogue will have many advantages over present catalogues, and offers vast avenues for exploitation. Here we are only able to touch briefly on a subset of these, to give a feel for the kind of science which will be possible. We divide this loosely in two categories. The first is science which can be obtained from the catalogue itself (for the most part assuming that follow-up has provided cluster redshifts and enabled temperature determination where possible), and

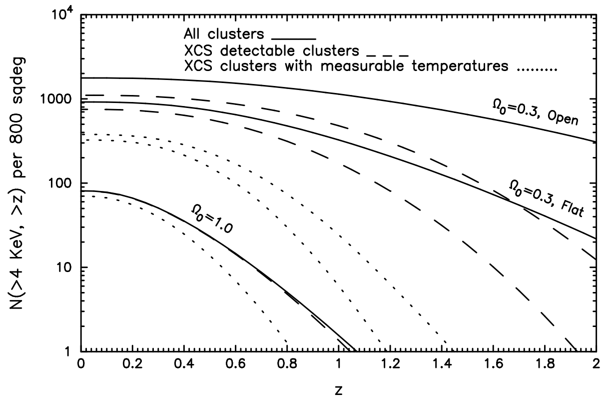

Figure 2: The same as in Figure 1, but for N(> z).

the second is ways in which the catalogue can be used as input to future scientific programmes.

Among the first we find the placing of constraints on cosmological parameters and the determination of the evolution of X-ray related quantities. The cluster temperature and redshift distributions can be used as a direct probe of the cosmological parameters Ω_0 and Ω_Λ. The survey's size, redshift distribution and selection criteria are ideally suited to this task, and it will be able to resolve the current disagreements as to whether or not clusters significantly constrain Ω_0, as well as potentially offering a first constraint on Ω_Λ from cluster number density evolution. Its power to constrain these parameters is clearly demonstrated in the two figures, from which it is apparent that there is an order of magnitude difference between the number of high-temperature (T> 4 keV) clusters in the $\Omega_0 = 1$ case compared to either of the two $\Omega_0 = 0.3$ cases. In order to go beyond measurements of Ω_0 and start to constrain Ω_Λ, one must study the z> 1 population. From the two figures we can see that there is little difference between the cluster number density evolution predictions for the two $\Omega_0 = 0.3$ cosmologies below z=1. But, for z> 1, the number density of galaxy clusters for $\Omega_0 = 0.3$ in open models is more than twice that in flat models. If all the z> 1 clusters detected have measured redshifts and eventually also temperatures then it should be possible to constrain Ω_Λ. Unfortunately, the uncertainties in the estimation of both Ω_0 and Ω_Λ will only be known when the actual data is available. It is important to note that the cosmological constraints derived will be important even in the era of sensitive cosmological microwave background (CMB) anisotropy experiments such as Planck. This is because the cluster measurements can help to break degeneracies in cosmological parameter estimation inherent in CMB analysis.

Another important consequence of the *XCS* will be the great improvement it will lead in our understanding of how related X-ray cluster quantities, such as luminosity, temperature, metallicity, gas mass fraction, core radius, change as we go back in time. For the first time, it will allow the luminosity-temperature relation to be measured in a coherent fashion over a wide redshift range.

The *XCS* will also act as input for other important scientific programmes. One is follow-up using the Sunyaev-Zel'dovich (SZ) effect [15], which is the upscattering of CMB photons from the same cluster gas responsible for the X-ray emission. As the SZ surface brightness is redshift-independent, an experiment with sufficient angular resolution (around an arcminute) can see clusters to extremely high redshift. However, at the moment there is no capability to carry out a large-field survey to identify such clusters directly through SZ selection. The combination of X-ray and SZ observations of clusters is potentially extremely powerful, being used for example in the estimation of the Hubble parameter. For z> 1 clusters, it can in principle even be used to determine the amount of (de-)acceleration of the Universe.

Other areas that may benefit from the *XCS* are gravitational lensing of background galaxies and analysis of CMB foregrounds. The magnification of background galaxies via gravitational lensing through galaxy clusters is well known at optical wavelengths, but, as shown by Smail, Ivison & Blain (1997), it is particularly exciting in the sub-millimetre. Here, the combination of the lensing amplification and the positive K-correction in the sub-millimetre (resulting from the sharp decline in the spectral energy distribution of starbust galaxies longward of about 100 μm) means such galaxies can be readily detected to extremely high redshift ($z > 5$). The follow-up of lensed galaxies around *XCS* clusters with the coming generation of (sub-)millimetre instruments, such as the ALMA, would therefore provide an important insight into the star formation history of the Universe.

The limit to which the MAP and Planck satellites can determine the power spectrum of CMB anisotropies on small scales is likely to be set by the effectiveness of the foreground analysis. One of the major sources of foreground confusion will be the SZ signal from X-ray clusters of galaxies. The *XCS* will not only play a crucial role in the understanding of this signal, by providing a statistically unbiased description of the cluster population out to high redshifts, but also, in the regions covered by the *XCS* it will be possible to mask out the signal from individual clusters from the CMB maps.

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