XMM, Clusters and Cosmology

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ABSTRACT

XMM combines a large field of view with good spectral and spatial resolution and is several times more sensitive than ROSAT, ASCA or AXAF. Thus XMM is the perfect instrument for cluster studies at high and low redshift. XMM will have a major impact on our understanding of cosmology. We discuss here how XMM observations of clusters can be used to put constraints on the value of two fundamental cosmological parameters; H_0 and Ω_0.

1. Using XMM observations of clusters to constrain Ω_0

In a high Ω_0 universe, the density of the most massive clusters will be vanishingly small at high redshift. This density rises rapidly as Ω_0 decreases, meaning that the discovery of only one or two massive clusters at a redshift of $z{\sim}1$ has the potential to rule out $\Omega_0{=}1$ to high significance [2]. This sensitivity has meant that measurements of cluster abundances[1] have become a popular means by which to constrain Ω_0. However, one has to be extremely cautious when making cluster abundance measurements, since any observational bias which mimics an under (or over) abundance of massive clusters will lead to an over (or under) estimate of Ω_0. The two main observational issues that need to be addressed when attempting to measure Ω_0 from cluster abundances are; (*i*) the completeness of the cluster catalog under study and (*ii*) the accuracy of the cluster mass estimates. We describe the positive impact that XMM will have in both areas below.

1.1. Improving cluster mass estimates

It has been shown that there is a tight relationship between cluster mass and X-ray temperature (T_x) in a virialized system [11]. Existing T_x data, derived from ASCA and GINGA observations [15], provide only weak constraints on Ω_0 [30], but we can expect these constraints to tighten dramatically after the launch of AXAF & XMM. These satellites will provide T_x values more accurately, and more efficiently, than ever before. As an illustration, let us compare the expected countrates[2] for the most luminous cluster in the EMSS (MS0015.9, $z{=}0.54$) in the AXAF

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[1] By "abundances" we mean the number density of clusters as a function of mass and redshift.

[2] These countrates were derived using HEASARC W3PIMMS webpage and assuming an 8keV Raymond-Smith spectrum and the total [0.3-3.5 keV] flux quoted in [13].

ACIS-I camera (0.15 s^{-1}), the XMM EPIC pn-camera (0.57 s^{-1}) and an ASCA SIS camera (0.05 s^{-1}). With $\simeq$2000 photons, or a 3.5 ks XMM observation, one can measure T_x for this cluster to a reasonable accuracy ($\delta T_x/T_x<0.2$) [15]. XMM will also be able to provide temperature profiles for high z clusters; in only $\simeq$ 14 ks one could measure a T_x value in 4 independent radial apertures for MS0015.9 with XMM. (With ASCA, temperature profiles have only been feasible for high flux, low redshift, clusters [20].) Temperature profiles are important since they allow one to correct T_x for the influence of shock fronts at subcluster boundaries and of cooling flows in the cluster core.

1.2. An XMM Serendipitous Cluster Survey

In addition to the EMSS, which was produced from Einstein-IPC data, there are now several samples of X-ray selected, high redshift, clusters based on ROSAT PSPC data [*e.g.* 5,26,31]. These ROSAT surveys cover smaller areas[3] ($17-200\,\square^\circ$) than the EMSS ($40-730\,\square^\circ$), which is a distinct disadvantage, since it is areal coverage, not flux limit, that determines the number of high z, high mass, clusters in a given survey. For example, in only a 1 ks XMM observation one could detect a massive cluster at z=1 to a signal-to-noise greater than 10. (Here we define a "massive cluster" to be one with a luminosity greater than $L_\star$, where $L_\star\simeq$3e44 erg/s [10].) But, since these clusters are so rare beyond z=0.3, one would need to make $\simeq$420, non-overlapping, XMM pointings to guarantee a single detection. (This estimate was based on the number of $0.3<z<1$, $L_x>L_\star$ clusters in the EMSS [13].)

Apart from a possible "XMM Slew Survey", which would have an effective exposure time of less than 100 seconds (Jones & Lumb, this proceedings), there are no plans to use either XMM or AXAF as survey instruments. Any new cluster catalogs would, therefore, have to be based on serendipitous detections. Given the growing number of ROSAT derived cluster catalogs, and the huge areal coverage of the EMSS, would yet another serendipitous cluster survey be worthwhile? We suggest that is it not only worthwhile, but imperative. This is because all surveys to date have been based on less than ideal X-ray data, meaning one cannot fully define their selection functions, and hence completeness, using simulations. For example, (*i*) several of the EMSS clusters were detected at only the 5σ level [22] and (*ii*) ROSAT-PSPC cluster surveys which rely on source extent have problems with blended emission (blends make up $\sim$ 50% of the cluster candidates in the Bright SHARC sample [26]. The only way to remove observational biases like these is to create a new cluster sample based on higher quality X-ray data.

If the XMM-EPIC camera remains in service during the whole lifetime of the satellite, then one could use it to build up an X-ray cluster survey with the same areal coverage as the EMSS. Under the conservative assumption of only 3 pointings per day, then XMM would be able to cover a total area of 2200 $\square^\circ$ in 10 years. (The XMM field of view is $0.2\,\square^\circ$ compared to $1.6\,\square^\circ$

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[3] ROSAT-PSPC surveys based on pointing data will never cover more than $\sim 200\,\square^\circ$ because the PSPC instrument was retired after only 4 years in service.

for the Einstein-IPC.) Not all of the available area will be of use to a cluster survey, however, since some will fall in the galactic plane and some will be in the field of diffuse X-ray sources, such as low z clusters and supernova remnants. Using the ROSAT archive as a guide, one can expect that only $\simeq$1/3 of the XMM pointings will be suitable for a serendipitous cluster survey, but this would still yield $\gtrsim 700\,\square^\circ$ over the lifetime of the satellite[4]. Such a survey will be aided both by the planned pipeline processing at the XMM Survey Science Center and by the spatial resolution of the EPIC cameras: The XMM spatial resolution is better, even at the edges of the FOV, than the on-axis resolution of the ROSAT-PSPC. This means that far fewer blended point sources will be falsely flagged as cluster candidates, which in turn eases optical follow-up. In addition, a new XMM cluster sample will require much less X-ray follow-up than the EMSS or the ROSAT-PSPC samples. This is because the majority of XMM exposures are expected to be at least ten times longer than the 1 ks required for a 10σ detection of a z=1, $L_\star$ cluster. Therefore, most serendipitous cluster observations will yield sufficient counts to allow cluster profiles and global T_x values to be measured directly.

2. Using XMM observations of clusters to constrain H_0

As a cosmic microwave background (CMB) photon travels from the surface of last scattering ($z \simeq 1000$) to an observer, it may pass through a cluster of galaxies and interact with the electrons in the intracluster medium (ICM) via inverse Compton scattering [28]. This results in a distortion of the CMB spectrum at the milliKelvin level. This distortion, known as the Sunyaev-Zeldovich (S-Z) effect, is significantly brighter than the intrinsic (μK) fluctuations in the CMB.

The S-Z effect has two components; a thermal effect due to the random motion of the electrons in the ICM and a kinetic effect due to the peculiar velocity of the cluster. It has long been realised that the thermal S-Z effect, when combined with X-ray surface brightness profiles and X-ray temperature data, can be used to provide a measurement of Hubble's Constant (H_0). This method is attractive because it does not rely on the cosmic distance ladder and can be applied to high redshift (the S-Z signal is redshift independent as long as the cluster is resolved). The H_0 derivation relies on the fact that both the X-ray luminosity and the S-Z signal are functions of the electron temperature and number density, T_e and n_e;

$$SZ \propto \int n_e T_e \, \mathrm{d}l \quad L_x \propto \int n_e^2 \sqrt{T}_e \, \mathrm{d}l,$$

where and l is the metric, line of sight, distance through the cluster. (One obtains H_0, via the angular distance relation, by solving for l from L_x and S-Z measurements.) Measurements of S-Z signals are now becoming routine and are yielding estimates of H_0 in the range 30–70 km s^{-1} Mpc^{-1} (*e.g.* 17,16,18,6,21,27,29,3).

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[4] It will not be practical to carry out a serendipitous cluster survey with AXAF because its FOV for imaging is even smaller ($0.08\,\square^\circ$) than that of XMM. In addition, unlike XMM, AXAF is not able to produce imaging data when the diffraction gratings are in place.

To date, most groups have concentrated on centimeter observations of high-redshift ($z > 0.2$) clusters. However, there are several drawbacks to these types of studies: First, X-ray temperatures and surface brightness profiles become increasingly harder to obtain as redshift increases. Second, by $z = 0.5$, the uncertainties in the cosmological parameters Ω_0 and Λ_0 introduce a 10%-20% error in the value of H_0 [17]. Third, at centimeter wavelengths, confusion from unrelated radio sources is a major concern.

In principle, millimeter observations of low redshift clusters would suffer from none of these problems. However, in practise, such observations have not been very successful because low z clusters are very extended ($> 2°$) in S-Z. The few detections of $z < 0.2$ clusters reported to date come from single dish observations[5] [21]. In the past, single dish telescopes have had small beam throws ($\sim 30'$), so it has been impossible to measure the full strength of the S-Z effect from low redshift clusters, because signal from the cluster wings is always included in the background subtraction.

2.1. The Viper Sunyaev-Zeldovich Survey

The new two-meter CMU Viper telescope[6] has been operational at the South Pole since February 1998. Viper has an exceptionally large beam throw (4 degrees) meaning it is ideally suited to the study of low redshift clusters. Viper minimizes the effects of ground emission and atmospheric variations through a combination of design (fast raster scanning & baffling) and location (weather conditions at the Pole are extremely stable and dry). For its first year of operation, Viper has been fitted with a single 45GHz (8GHz bandpass) HEMT receiver. This will be replaced in 2000 with a bolometer array which operates simultaneously at 90, 150, 218 & 350 GHz. The bolometer will probe the regime where the thermal S-Z effect switches from a decrement to an increment. This capability will facilitate measurements of the kinematic S-Z effect and also solidify thermal S-Z measurements by highlighting contaminating sources.

One of the key programs for this new telescope is the Viper Sunyaev-Zeldovich Survey (VSZS)[7]. The goal of the VSZS is to make the most robust estimate yet of H_0 from S-Z measurements. We will achieve this by carefully controlling the systematic uncertainties associated with the method. The VSZS will provide an accurate value for H_0 and act as a feasibility study for higher redshift S-Z studies.

We have chosen fourteen clusters as primary targets for the VSZS. These clusters should be representative of the cluster population as a whole since they were selected from the XBACS

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[5] Interferometers cannot be used because they "resolve out" signals on large angular scales.

[6] http://cmbr.phys.cmu.edu/viper/

[7] The VSZS collaboration currently comprises of the following CMU astronomers; Romer, Nichol, Peterson, Griffin.

survey [10] and form an X-ray luminosity limited ($L_x > 3.5 \times 10^{44} \mathrm{erg\,s^{-1}}$ [0.1-2.4 keV]) sample. With such a large, statistically complete, sample we will be able to "average out" H_0 errors introduced by cluster alignment and peculiar velocity effects [See 17 & 25 for a full description of these, and other, effects]. All clusters have declinations less than δ=-30°, to be visible from the South Pole, and redshifts less than z=0.1.

Crucial to the derivation of H_0 from these S-Z maps is access to accurate X-ray surface brightness and temperature maps for each cluster. One introduces a large error in H_0, of up to $\sim$ 50%, if one uses an assumed (rather than measured) value for T_e. An additional $\sim$ 20% error is introduced if one does not model the surface brightness distribution correctly. XMM will play an important role in the VSZS, since it can simultaneously provide detailed X-ray surface brightness and temperature maps. The large FOV of XMM means that it will include $>$ 85% of the flux from a $z > 0.05$ cluster. By studying high luminosity clusters at such low redshifts, the XMM EPIC-pn countrates will be very large. For example, a 10ks observation of A3667 will provide 270,000 counts which will yield more than 100 independent temperature values!

3. Summary

After the launch of XMM, it will be possible to remove several observational biases that have dogged previous attempts to measure Ω_0 from cluster abundances. Progress will come via the derivation of accurate virial temperatures for a large number of clusters and via the development of a new, large area, cluster survey. XMM will also make a significant impact on attempts to measure the value of H_0 from Sunyaev-Zeldovich images of clusters. XMM will provide X-ray images of low redshift clusters with unprecedented metric resolution, allowing one to de-project the density and temperature profile of the X-ray gas very accurately.

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