Cosmology with SZ and X-ray cluster surveys

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Abstract. Hydrodynamical simulations are used in combination with the Press-Schechter expression to simulate Sunyaev-Zel’dovich (SZ) galaxy cluster sky maps. These are used to gauge the ability of future SZ observations to provide information about the cosmological parameters $H_0$, $\Omega_M$, and the gas fraction $f_g$ in clusters. This work concentrates on prospects for AMI, the Arcminute MicroKelvin Imager, a new type of compact interferometric array currently proposed in Cambridge. The expectations are contrasted with those for X-ray missions, such as XMM, and the benefits of combining SZ and X-ray data are highlighted.

1 AMI and SZ cluster skys

The Sunyaev-Zel’dovich (1972, SZ) effect, unlike optical and X-ray cluster surveys, is not affected by redshift because it measures the integrated line of sight intracluster gas pressure via its Compton scattering of cosmic microwave background (CMB) photons. During the last 10 years, interferometric techniques have been developed, which are providing firm detections of known clusters (eg. Jones et al. 1993, Carlstrom, Joy and Grego 1996). The technology and expertise is now available to survey the sky to discover clusters.

The construction of a CMB telescope for the observation of the CMB on angular scales of one to several arcminutes and with a sensitivity of a few micro-Kelvin, comparable to the Planck Surveyor, has been proposed in Cambridge. The Arcminute MicroKelvin Imager (AMI) will consist of a small compact array of 4 meter dish antennas combined with the existing Ryle telescope antennas in an extended array, with a new receiving system and novel correlator. This design achieves optimal sensitivity to the cluster SZ effect and a separation with other components such as the primary CMB and radio sources. Although the instrument is dedicated to the study of clusters, it will generally probe the structure of the CMB on sub-Planck and super-ALMA scales. Therefore it is also sensitive to other phenomena such as, inhomogeneous ionisation, density - velocity correlations (Vishniac and Ostriker effect), filaments and topological defects, if they exist, which are all of immense interest as well. In the following however we demonstrate the ability of AMI to discover clusters.

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1 Contribution to “Large Scale Structure in the X-ray Universe” Workshop, Santorini, Greece, September 1999, eds. M. Plionis and I. Georgantopoulos (Editions Frontieres)
To produce simulated SZ cluster sky maps, the Press-Schechter expression (1974) is used to create a list of cluster masses and redshifts having an abundance consistent with the local cluster temperature function (Eke et al. 1996). These clusters are placed at random angular positions within a $5^\circ \times 5^\circ$ sky map with 40 arcsec pixels. To model the cluster SZ signal, template maps have been created from the hydrodynamical simulations of Eke, Navarro and Frenk (1998), and these are pasted, suitably scaled, onto the cluster positions. This procedure is performed for two cases, a low present density ($\Omega = 0.3$) and a high density ($\Omega = 1$) universe, both with a Hubble constant of 70 km s$^{-1}$ Mpc$^{-1}$. The gas fraction is fixed at 10% in both cases rather than to the primordial nucleosynthesis value, which would have introduced an $\Omega$ dependence, enhancing the differences. Our value for the gas fraction is at the low end of the value estimated from X-ray clusters (Ettori and Fabian 1999) and Mohr, Mathiesen and Evrard (1999) find it to be 0.1-0.25 at the 95% CL), and the model SZ number counts would increase with a less conservative choice. We also produced corresponding X-ray maps in 0.5-2 and 2-10 keV bands, and have checked that they are complete to an X-ray flux limit of $1 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ [0.5-2 keV].

2 An SZ survey and X-ray / optical follow-up

The sensitivity of future instruments, we use AMI specific numbers, is high enough to allow a survey of the sky for SZ clusters. To make our simulation of the observation process computationally feasible we simplified the observation by running a compensated beam with carefully chosen shape and amplitude over the cluster map. This procedure had been gauged with detailed simulations of the interferometer response including the specific noise properties of a field observation and through the recovery process. The resulting number counts are shown in figure 1. There is a turn-over at the confusion limit for a 4.5 arcmin beam. Also shown in figure 1 are sensitivity lines each corresponding to a fixed observation time and displayed as the inverse of the survey area against the flux limit. The ratio between the number counts and the sensitivity lines is the number of clusters detected in the respective time. The maximum detection number lies at a limiting observed flux of about 100 $\mu$Jy or a corresponding survey area of 5 deg$^2$ and about 10 clusters for the high density case and tens of clusters for low density are expected for a 6 months observation. Since the optimum is shallow it will also be possible to adopt different surveying strategies at a low cost of inefficiency. This will probe the slope of the number counts which is a function of $\Omega$. The parameters of the simulations, which have the largest effects on the number counts are listed with present uncertainties in table 1. Their effect is considerable, but substantial improvements can be expected in the future, in particular from the new X-ray missions.

Due to the $(1+z)^4$ dimming of bolometric X-ray flux compared to the Compton scattering process the X-ray and SZ flux limited cluster samples have very different
redshift distributions, even for an X-ray limit of $5 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ [0.5-2 keV] in the case of the currently favoured low density model. With scaling laws we find that the ratio between SZ to X-ray flux scales with $(1 + z)^{5/2}$ and with only a weak dependence on $\Omega$ and the cluster temperature. When observing the same field in microwaves and X-rays this "photometric" redshift effect will immediately allow a crude measure of the redshift distribution (see figure 2). A limit on the redshift will be obtained for the SZ clusters undetected in X-rays. A major uncertainty in determining $\Omega$ from this distribution comes from $f_\sigma$. However when optical redshifts are obtained we find that for the flux limit reached with AMI the median redshift of only 20 clusters will allow to distinguish between the two cases with more than 99 % confidence. Going back to the X-ray and SZ data with an estimate of $\Omega$, the gas physics for example $f_g(z)$ can be studied.

Figure 1: SZ number counts and AMI sensitivity
Table 1: Model parameters affecting SZ number counts

| parameter | change in percent | fractional change in $N(>Y)$ |
|-----------|-------------------|-------------------------------|
| $h$       | 20 %              | 1.3                           |
| $f_g$     | 30 %              | 1.5                           |
| $\sigma_8$ | 7 % (1σ)          | 1.5                           |
|           | 14 % (2σ)         | 3.2                           |

Compare this to $N(\Omega = 0.3)/N(\Omega = 1) \approx 3.5$

3 Conclusions

Instruments to survey the sky for SZ clusters can be build. The expected number of clusters is greater than 10 for a half year observation and depends strongly on the matter density. The SZ data in combination with X-ray and optical data can be used to constrain $\Omega, f_g, \sigma_8$, and from distance measurements, $H_0$ and most likely $\Omega_\Lambda$, if enough suitable clusters are present at high redshift. SZ cluster surveys will be particularly useful as pathfinders for future X-ray missions such
as Constellation-X and XEUS, which will have small fields of view. With the cluster SZ effect a sample of massive clusters at high redshift can be provided as targets for a detailed study of the plasma physics in X-rays, interesting for the understanding of cluster formation and cosmology.

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