SZ surveys with the Arcminute MicroKelvin Imager

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Abstract. The Arcminute MicroKelvin Imager (AMI) is an instrument currently under construction in Cambridge designed to produce a survey of galaxy clusters via the Sunyaev-Zel’dovich effect. It consists of two interferometric arrays, both operating at 12–18 GHz; one of ten 3.7-m antennas to provide good temperature sensitivity to arcminute-scale structures, and one of eight 13-m antennas (the present Ryle Telescope) to provide flux sensitivity for removing contaminating radio sources. The telescope is due to be observing by 2003, and will produce a public survey of galaxy clusters, as well as being available to guest observers.

1. Introduction

It is now widely recognised that an important next step in cosmology is to conduct a survey of galaxy clusters via the SZ effect. Galaxy clusters are the largest gravitationally bound objects in the universe, and by pointing out the peaks of the initial density field, they provide a sensitive indicator of the growth of structure and the parameters that control it (e.g. Bartlett & Silk 1994). They are also large enough to provide a fair sample of the material constituents of the universe. In order to fully exploit the potential of clusters for learning about the universe, however, it is necessary to be able to select them according to uniform intrinsic properties over a large range in redshift. The promise of SZ surveys is that they can in principle select clusters over a very large redshift range with well-understood and physically meaningful selection criteria (Barbosa et al 1996, Holder et al 2000, Kneissl et al 2001).

The problem is that until now the observations required have been exceedingly difficult. The SZ effect is faint, and existing telescopes have only had sufficient sensitivity and sky coverage to study the most massive clusters, whose existence was previously known from optical or X-ray surveys. A new generation of instruments is now in prospect that will provide a qualitative step in sensitivity and sky coverage to finally fulfil the promise of the SZ technique. Here we will describe one such instrument currently under construction, the Arcminute MicroKelvin Imager, AMI.

2. Interferometers for SZ observation

Although the first detections of the SZ effect were made using single-dish radiometers (e.g. Birkinshaw 1984), the majority of the detections made so far
have been using interferometers (e.g., Jones et al. 1993, Carlstrom, Joy, & Grego 1997). Interferometers offer several significant advantages over total power measurements: they are not susceptible to scan-synchronous systematics; they can use the rotation of the earth to modulate the sky signal in a way that is distinguishable from other signals such as crosstalk or groundspill; they are insensitive to most atmospheric emission; and they can simultaneously measure, and separate, the SZ effect and point source contamination. (Some of these advantages are also available to large focal-plane arrays, which form another promising avenue for future SZ instruments; see e.g., Golwala, this volume).

To observe the SZ effect efficiently, however, the interferometer must have baselines which are well matched to the angular scale of the cluster. Each pair of antennas in an interferometer responds only to a narrow range of Fourier components of the sky brightness, centred at $\lambda/D$ where $D$ is the antenna separation, and of width $\sim \lambda/d$ where $d$ is the antenna size. (More exactly, the shape of the response function in the Fourier plane is the autocorrelation of the illumination function of the antennas.) Most clusters at moderate to high redshift have angular sizes of a few arcminutes, and hence most of their power in the Fourier plane is on scales of a few hundred to a thousand wavelengths (see Figure 1). The interferometers that have provided most of the SZ detections to date, the Ryle Telescope in Cambridge and the OVRO and BIMA arrays in California, have minimum baselines of at least 500 wavelengths (limited by the size of the antennas), and thus resolve out most of the flux density of the cluster. For efficient SZ surveys, telescopes with smaller antennas and hence shorter minimum baselines are required. This also has the beneficial effect of increasing the instantaneous field of view of the telescope, further enhancing the survey speed.

3. SZ observations with the Ryle Telescope

The Ryle Telescope (RT) is an east-west synthesis interferometer with eight 13-m antennas, of which four are fixed at 1.2 km spacings and four are mobile on a railway track. Originally constructed to make high resolution images of radio galaxies (Ryle 1972), it has been adapted for high brightness sensitivity observations at 2 cm wavelength using the five antennas that can be close packed, and made the first interferometric detection of the SZ effect (Jones et al. 1993). Figure 2 shows some of the SZ detections that have been made subsequently. We have recently used five of these, in conjunction with X-ray data, to produce an estimate of the Hubble constant in which a major systematic uncertainty of the SZ/X-ray distance method, orientation bias, can be carefully addressed (Jones et al. 2001).

All but two of these SZ detections have been of objects selected initially by optical or X-ray surveys, the completeness of which are limited, using current techniques, to relatively low redshift, $z \lesssim 0.3$. The other two were attempts to find high-redshift clusters by means of `signposts' of clustered high-redshift objects. PC1643+4631 is a pair of QSOs at $z = 3.8$ with an apparent associated CMB decrement (Jones et al. 1997). However, this observation has not been confirmed by independent measurements (Holzapfel et al. 2000) and must be considered tentative. TOC J0233+3021, however, is a confirmed cluster of galaxies at $z \sim 1$. The signpost in this case was a cluster of faint radio sources
in the NVSS catalogue with no optical counterparts in POSS; an RT observation revealed a significant CMB decrement (labelled TexOx L20 in Figure 2), and subsequent deep optical and near infra-red imaging shows clustered galaxies with colours consistent with the redshift estimate (Cotter et al 2001). The SZ data alone show the cluster mass to be \( \sim 5 \times 10^{14} \text{M}_{\odot} \).

Such observations are useful in establishing the existence of massive high-redshift systems; however, to do more quantitative science with clusters requires a proper survey. For this the RT is simply not adequate. It has a bandwidth of 350 MHz and system temperature of 60 K (considered impressive when it was designed in 1985!), giving a sensitivity of 72 mJy s\(^{-1/2}\) on 4 arcmin scales in a 6 arcmin field. With these parameters, a useful survey—say 1 square degree detecting clusters to \( y = 10^{-5} \)—would take the RT \( \sim 80 \) years.

4. Design parameters of AMI

The design requirements for an SZ survey instrument are: maximum sensitivity, hence low system temperature and high bandwidth; shortest baselines of \( \sim 200 \lambda \) (confusion from primary CMB anisotropies becomes a problem at shorter
Figure 2. A selection of SZ images made with the Ryle Telescope, of clusters ranging from $z = 0.14$ to $z \sim 1$. Because of the east-west arrangement of the RT antennas, the point spread function is elongated in the declination direction by $\csc(\text{declination})$. The clusters with outlined names are those used for a determination of $H_0$ from a complete X-ray selected sample by Jones et al (2001).
Figure 3. Contributions to system temperature as a function of frequency; the atmospheric emission temperature from a sea level site such as Cambridge and a high dry site such as Mauna Kea are shown, along with the typical noise temperature of a HEMT amplifier; the total system noise is the sum of the amplifier and sky noise (plus other contributions from losses, spillover, the CMB etc). The other line (and scale on right) shows the flux/temperature conversion for an unresolved source in a 1 arcmin beam.

baselines); and ability to cope with foregrounds. The first question is the choice of observing frequency—this controls all subsequent aspects of the design.

Figure 3 shows the contributions to the system temperature of a telescope due to the atmosphere, at wet and dry sites, and from typical HEMT receivers. Adding these two contributions together, it can be seen that there is a clear advantage of operating at low frequency, even from a relatively poor site. However, this is offset by the other feature shown on the plot, the temperature contribution of a source of given flux density, which falls as approximately $\nu^{-2}$. Since extragalactic point sources are the main contaminant for SZ observations, this is an important consideration. Several strategies are possible. One
method, adopted by AMI/BA, (see Lo, this volume), is to operate at high frequency, \( \nu \sim 100 \text{ GHz} \), where source contamination is minimised, and to offset the increased system temperature by going to a high, dry site and maximising the number of antennas and the bandwidth. An alternative is to exploit the low system temperature available at low frequency, but to provide sufficient flux sensitivity at higher resolution to detect and then remove the point sources. This is the approach we adopt with AMI, since we have the large antennas of the Ryle Telescope available to do source subtraction. Operating at 15 GHz from Cambridge it is possible to achieve total system temperatures below 25 K, with the cost and logistical advantages of working only a few km from our home institution. A similar approach is adopted by the SZA (Holder et al 2000), using a new array of small antennas in conjunction with the existing OVRO interferometer, at 30 GHz.

With the wavelength fixed at \( \lambda \approx 2 \text{ cm} \), the remaining design parameters are fairly constrained. The available bandwidth is the \( K_a \) waveguide band of 12–18 GHz; the minimum required baseline of \( \sim 200\lambda \) fixes the antenna size at \( \sim 4 \text{ m} \). We use 3.7-m diameter antennas, for which single-piece spun reflectors are available at low cost. The number of these antennas is fixed by the flux sensitivity available for source subtraction from the Ryle Telescope and the 15 GHz source counts (Taylor et al 2001) to about ten, ie a collecting area equal to about one RT antenna. In order to maximize the collecting area available for source subtraction, we plan to move the three distant fixed RT antennas to new fixed positions close to the compact array. This also has the advantage of creating a 2-dimensional array, with much improved beam shape at low declinations.

4.1. The correlator

To maximize sensitivity it is important to use as large a bandwidth as possible. Previous high-bandwidth continuum correlators have used IF bandwidths of \( \sim 1 \text{ GHz} \), with either a single channel (eg the VSA), or covering the entire RF band by splitting the RF band into many IF channels (eg the CBI/DASI correlator, Padin et al). In order to maximize the AMI bandwidth while minimizing the cost of both the correlator and the IF system, we have been developing a correlator to cover the entire available 6 GHz bandwidth in a single IF channel. This design combines the recent cheap availability of the required active components (amplifiers, switches, detectors, voltage-variable attenuators) at frequencies above 10 GHz with the relative ease of design of passive components (splitters, phase-shift networks) at low fractional bandwidth. The correlator thus uses an IF band of 6–12 GHz, with frequency resolution provided by an 8-channel multiple-lag design. An entire multi-channel correlator for one baseline is integrated on to a single substrate. The correlation scheme used is the phase-switched add-and-square type introduced by Ryle (1952), also used in both CAT (Robson et al 1994) and the VSA, which uses single detector diodes as the multiplying elements. For more details, see Holler, this volume.

5. Sensitivity

AMI thus consists of two arrays, one of eight 13-m antennas and one of ten 3.7-m antennas, using the same 12–18 GHz receivers and 6–12 GHz correlator. The
small array provides most of the sensitivity to the SZ effect and the large array most of the sensitivity to point sources, although there is some overlap. The flux sensitivities are $2 \text{ mJy s}^{-1/2}$ and $20 \text{ mJy s}^{-1/2}$ for the large and small arrays, in 6 and 20 arcmin fields of view respectively. The temperature sensitivity depends on the exact array configuration used; a representative number would be about 15 $\mu$K in a week, in a 1.5 arcminute beam and 20 arcmin field of view.

More detailed calculations on the expected sensitivity to clusters and number of clusters detected are given by Kneissl et al. (2001). Figure 5 shows two simulated survey maps of about 1 square degree, under different assumed cosmologies, showing clearly different detected source counts.

6. Conclusions

The next generation of SZ instruments, including AMI as well as AMiBA and the SZA, will provide samples of galaxy clusters with well-defined and largely distance-independent selection criteria. These will be invaluable in a large range of cosmological investigations. AMI itself is now largely funded and under construction; first results are expected by mid-2003. In recognition of the large amount of follow-up work in other wavebands that will result from the AMI surveys, we are proposing to make these surveys public as soon as possible after the data are taken. Also, a significant fraction of observing time on AMI will be open to guest observers – details will be published when the telescope is nearer completion.

7. Acknowledgements

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Figure 5. Simulated 6-month surveys with AMI in high- (left) and low- (right) $\Omega$ models, under pessimistic assumptions (low $f_b$, low $\sigma_8$) about the overall number of detectable clusters. See Kneissl et al (2001) for more details.

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