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The Sunyaev-Zeldovich Effect Imaging and Interferometry: BIMA-CBI-OVRO State of the Art and Future Prospects

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Abstract. This talk presents a summary of the most recent results from microwave and millimeter-wave surveys of the Sunyaev-Zeldovich Effect (SZE) in massive clusters of galaxies. The SZE is caused by Compton scattering of low-energy CMB photons off high-temperature ionized gas in cluster atmospheres, and is a direct measurement of the baryon content of the intracluster medium. New results from the Chicago-BIMA SZE survey of Carlstrom et al., the Penn-OVRO SZE program of Mason et al., and the Caltech-CBI SZE project of Padin et al. are discussed, along with prospects for future imaging and interferometric studies of clusters to pin down the astrophysical properties of cluster baryons and dark matter as well as possible constraints on cosmological parameters.

1. Introduction

The Sunyaev-Zeldovich Effect (SZE) is the inverse Compton scattering of photons from the 2.73 K Cosmic Microwave Background (CMB) off of the nearly relativistic electrons in the hot phase of the intra-cluster medium of massive galaxy clusters. Photons are conserved during the up-scattering in energy that results, and thus the SZE exhibits itself as a *decrement* in spectral intensity longward of the CMB blackbody peak at a wavelength of $\lambda \sim 1$ mm and an *increment* shortward of said peak. The results described here will all be from observations made at wavelengths longer than 1 mm, and thus the SZE will show up as a negative "hole" in the sky brightness in the direction toward the cluster.

Progress in the measurement of the SZE at astrophysically interesting sensitivity levels has been hampered by the difficulty of the measurement itself. The level of the SZE for a massive cluster is around -200 to $-400\,\mu$K in brightness temperature, less for the run-of-the-mill clusters and groups of galaxies. At wavelengths from 1 – 2 cm the Earth's atmosphere contributes an overall signal of 6 – 15 K (for $\tau = 0.02 - 0.05$) with spatial variations on the order of 1 mK on arcminute scales. In single-dish observations, much of the gross sensitivity provided by the low-noise receivers is lost due to the expense of beam-switching, scanning, and careful calibrations — this is not a task for the timid! However, in recent years, the use of interferometric techniques has supplanted single dish observations for SZE studies.

The SZE is proportional to the Compton optical depth through the cluster and thus the line integral of the electron pressure $n_e T_e$. For a typical isothermal profile $n_e \propto r^{-2}$ the SZE angular profile falls as θ^{-1} and thus spans a range of angular scales (out to several core radii) which adds to the imaging difficulties. The nearest massive cluster Coma ($z = 0.023$) has a projected core radius of $10'$, while clusters at redshifts $z \sim 0.3$ have core radii of an arcminute or less. Interferometers in particular can have significant dilution as this shallow profile transforms to an exponential fall-off of the signal with baseline.

In addition to scattering the CMB radiation, the electrons of the hot ICM will themselves scatter off the ion nuclei, producing thermal bremsstrahlung radiation. For typical cluster temperatures (energies) of $kT_e = 2$–10 keV, this emission comes out at X-ray wavelengths. Because the emission is proportional to the square of the density $S_X \propto n_e^2 T_e^{1/2}$, comparison to the SZE signal will provide a measure of the path-length through the cluster, and hence behaves as a distance indicator when compared with its angular diameter. This property has been exploited for some time now (eg. Birkinshaw, Hughes & Arnaud 1991) as a method for determining the Hubble constant independent of the standard distance ladder. Much of the current effort in this field is directed toward refining this test, as will be described below. Much of the utility of the SZE as an astrophysical probe of the nearby Universe comes from its complementarity with the X-ray properties of the clusters, while the great promise of SZE surveys are to observe clusters out to great cosmological distances where they are too faint to be seen in optical or X-ray images.

In addition to probing the conditions in the intracluster medium itself, the SZE allows tests of cosmology to be performed. In particular, as the SZE is redshift independent in magnitude (for a given cluster temperature and baryon content), it can be used at distances beyond those for which X-ray emission can be measured using the current and planned observatories. The cosmological parameters probed by observations of the SZE are:

- the comoving distance $r(z)$ to the cluster through comparison of the SZE to X-ray emission. This yields a distance-ladder independent measurement of the Hubble Constant H_0, and for clusters at redshifts $z > 0.5$ possible determination of the overall cosmology (eg. q_0, Ω)

- the surface density in baryons in the ICM can be determined from the SZE (from n_e assuming T_e) and deprojected and integrated to estimate the baryonic mass within some radius of the cluster to compare with gravitational mass estimates. This "baryon fraction" estimate can be combined with Big-Bang Nucleosynthesis (BBN) values for Ω_B to infer Ω_m for matter.

- counts of clusters with redshift $N(z)$ are a powerful constraint on the overall cosmology (Ω_m,Ω_Λ,Ω_{tot})

- the morphology and ellipticities of clusters as a function of redshift are also potentially useful tests of cosmology. SZE images of clusters might constrain models of cluster merging and evolution as well as the cosmological parameters (Ω_m,Ω_Λ,Ω_{tot})

- if measurements of the SZE spectrum are made above and below the CMB peak at $\lambda = 1$ mm, the peculiar velocities of the clusters can in principle be determined (see Holzapfel et al. 1997). The magnitude of the peculiar velocities is sensitive to the cosmological model.

In this contribution, several recent observational programs aimed at SZE cosmology are described. Due to the limitations in these measurements, only the first two of the above parameter determinations have been attempted with this data. However, an number of future experiments are being proposed to fully exploit the promise of this method.

At this Symposium, a number of different observations have led to what might be called "a new standard model" — that of a flat Universe ($\Omega_{tot} = 1$) with a non-zero cosmological constant or missing energy term ($\Omega_\Lambda = 0.7$) and a low matter density which is ($\Omega_m = 0.3$) dominated by cold dark matter (CDM). We will denote this model as ΛCDM. Note that of the matter component, only around 10% is in baryons, in line with the canonical BBN value of $\Omega_B\, h^2 = 0.019 \pm 0.002$ (Burles & Tytler 1998). In this contribution, we adopt the convention that the Hubble parameter h is defined as $\mathrm{H}_0 = 100\, h\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$. As an alternative model, we may also quote results for a flat matter-dominated cosmology with $\Omega_{tot} = \Omega_m = 1$ ($\Omega_\Lambda = 0$) that we will designate as CDM.

It has been a worry in this field that the internal "gastrophysics" of the clusters themselves might introduce biases in the cosmological results derived from the SZE. In particular, it has long been recognized that the intrinsic nonsphericity of the clusters introduces uncertainty in the comparison of angular diameter and Compton path-length (optical depth) through the cluster, perhaps as much as 30% if the clusters sampled have ellipticities this high. Furthermore, near the flux limit of an X-ray survey, one might expect a bias toward clusters with high path-lengths along the line-of-sight, and thus brighter in the X-ray — this will lead to a systematic underestimate of the Hubble constant in consequence. Other (probably less worrisome) contaminants are multi-phase effect (cooling flows) which can bias the X-ray emission, and substructure which will also bias the X-ray determinations of the mean density. One of the prime goals in the design of the surveys described below is the elimination or mitigation of these potential biases. See the contribution by Birkinshaw for more details on the theory of the SZE and issues such as these for cosmology.

2. The Old School – The OVRO SZE Survey

Tools of the trade: **Single Dish Observations**

- OVRO 5.5-meter telescope
- $7'.35$ FWHM, beam switched $22'.16$
- 32 GHz center, 5.7 GHz bandwidth
- Nearby Clusters – $z < 0.1$ X-ray flux & luminosity limited sample

From 1993 to 1999, the 5.5-meter radiotelescope at the Caltech Owens Valley Radio Observatory (OVRO) was used to carry out a survey of X-ray luminous nearby clusters of galaxies. The Coma cluster (A1656) was observed by Herbig et al. (1995), followed by the clusters A478, A2142, and A2256 (Myers et al.

1997). In Myers et al. 1997, an X-ray flux limited sample of 11 clusters ($z < 0.1$) was defined from which the reported clusters were drawn, and using the SZE and existing X-ray data for these five clusters values for the following cosmological parameters were derived: $\mathrm{H}_0 = 54 \pm 14$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_0\, h \lesssim 0.21 \pm 0.05$. Much of the error budget in these results was due to the relatively poor models of the cluster ICM derived from the older X-ray data.

New observations were carried out of additional clusters by Mason (1999). The calibration of the flux density and temperature scale at $\lambda = 1$ cm was refined by Mason et al. 1999. In addition, detailed analysis of *ROSAT* data in the public archive yielded improved models of the ICM in these clusters (Mason & Myers 2000). These improvements reduced calibration uncertainties to 3% in the radio data, and 8% in the X-ray data! The results of this reanalysis, plus the new data on A399, will be presented in Mason et al. (2000). The main result is that the best-fit value for the Hubble constant rises to $\mathrm{H}_0 = 75 \pm 7$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (ΛCDM), with most of the change due to improvements in the X-ray temperature measurements from *ASCA*. A summary of these results is given in Table 1. Alas, in addition to the statistical errors of $\pm 7 \mathrm{km\,s^{-1}\,Mpc^{-1}}$ quoted for the sample results in the table, there is a systematic uncertainty of $\pm 16 \mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Note that several other distance-scale key projects discussed at this meeting also are producing values for the Hubble parameter around $h = 0.75$. This may be a passing fad, though it was noted by several speakers that if true then we could well have averaged 50 and 100 a long time ago and been done with it!

When taken together with the X-ray emission models of the cluster, plus the canonical BBN baryon density, the new data give an estimated total matter density parameter of $\Omega_m = 0.30 \pm 0.06$, which is consistent with the "new standard model" with a flat Universe plus cosmological constant (ΛCDM) being promoted elsewhere in this Symposium. One of the future goals of high-redshift SZE surveys is to measure the departure from a CDM decelerating universe as is now being done by the supernova cosmology programs.

Table 1. OVRO SZE Survey – from Mason et al. (2000)

CLUSTER	H_0 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$	REF
A399	98^{+32}_{-27}	Mason et al. 2000
A478	61^{+15}_{-14}	Myers et al. 1997
A1656	61^{+24}_{-20}	Herbig et al. 1995
A2142	80^{+19}_{-17}	Myers et al. 1997
A2256	68^{+21}_{-18}	Myers et al. 1997
SAMPLE	73 ± 7	$(\Omega_\Lambda = 0.0,\ \Omega_m = 1.0)$
SAMPLE	75 ± 7	$(\Omega_\Lambda = 0.7,\ \Omega_m = 0.3)$

The goals of this X-ray SZE survey are to control orientation biases by observing a complete sample based upon total X-ray flux. By targeting nearby $z < 1$ clusters, which are all well-known and more importantly, well observed at X-ray wavelengths, uncertainties introduced by the modelling of the ICM should in principle be minimized. Even after the *ROSAT* reanalysis carried out in Mason & Myers (2000), the statistical error is still dominated by the X-ray model uncertainties. In particular, the X-ray temperature profile of the clusters are poorly constrained. The improved sensitivity at high temperatures provided by *XMM* and *Chandra* should greatly reduce these uncertainties. That should leave the primary CMB anisotropy ($\sim 50\,\mu$K on these scales, not included in the above error budget, but see Mason et al. 2000) as the limiting factor for these measurements!

However, we can still do better. The single dish observations at centimeter wavelengths are limited to clusters without background (or foreground) radio source contamination as the signal from point sources cannot be easily separated from the smooth SZE decrement. In 1999, the 5.5-meter telescope at OVRO was decomissioned from the SZE survey in anticipation of Cosmic Background Interferometer (see below).

3. The New School – BIMA / OVRO and the CBI

Tools of the trade: **Millimeter-Wave Interferometers**

- OVRO MMA 6 × 10.4-m antennas, baselines 14 – 240 m, 252″ FWHM
- BIMA MMA 9 × 6.1-m antennas, baselines 7.5 m – 1 km, 396″ FWHM
- 26–36 GHz
- Distant Clusters – $z > 0.1$ X-ray selected clusters

Although intended for difficult observations at millimeter wavelengths, the interferometer arrays of the OVRO and the Berkeley-Illinois-Maryland Association (BIMA) have provided superb platforms for the carrying out of SZE (and CMB anisotropy) imaging of clusters at intermediate and high redshifts at centimeter wavelengths. In the band from 26–36 GHz, these two instruments have sensitivity on angular scales relevant to clusters at $z > 0.1$. To this end, custom-built centimeter-wave receivers were constructed and installed by John Carlstrom and his group (Carlstrom, Joy, & Grego 1996). Pioneering measurements made starting in 1994 at OVRO, and from 1996 at BIMA.

Unfortunately, for these more distant clusters, the limitations of the X-ray data are even more severe than for the nearby clusters in the OVRO single-dish survey. This will be greatly aided by sensitive new measurements from *XMM* and *Chandra*, which will also hopefully yield a larger complete X-ray selected sample (the current sample is based on the *ROSAT* EMSS). The most compelling determinations of the Hubble constant from the BIMA / OVRO observations were reported for MS0451.6-0305 and CL0016+16 by Reese et al. (2000), with best-fit values of $H_0 = 63\,^{+12}_{-9} \pm 21$ km s^{-1} Mpc^{-1} (ΛCDM). Results from observations of A1995 were published by Patel et al. (2000), yielding $H_0 = 52\,^{+11}_{-12} \pm 18$ km s^{-1} Mpc^{-1} (ΛCDM). Grego et al. (2000a) present data for A370, though no value for the Hubble constant is reported.

These values for the Hubble constant are consistent, within the quoted uncertainties, with the OVRO 5.5-m single dish results given above. There is marginal evidence for these more distant clusters coming in with slightly lower values of H_0, though it is truly too early to tell whether this is a significant difference. Even more so than for the single dish nearby cluster sample of Mason et al., the error budget in the measurements of the Hubble constant from these more distant clusters is dominated by uncertainties in the X-ray model and calibration. As their sample is filled out and *XMM* and *Chandra* X-ray data become available, the BIMA / OVRO SZE program will provide a unique window into cluster evolution in the distant Universe and the dependence of the comoving distance with redshift, thus moving beyond the Hubble constant and complementing the SNeIa efforts in constraints on the cosmological constant and the possibility of an accelerating Universe.

SZE and X-ray data from a sample of 18 clusters was jointly analyzed by Grego et al. (2000b), yielding a gas fraction $f_g\,h = 0.081^{+0.009}_{-0.011}$ (ΛCDM). Assuming this represents the Universal average baryon density with the BBN value for Ω_B, an upper limit of $\Omega_m < 0.4$ (68% confidence) is placed, with a best-fit value of $\Omega_m \approx 0.26$ ($h = 0.7$). The analysis presented by these authors used the two-dimensional SZE profile as determined from model-fitting to the OVRO and BIMA data, along with 3-dimensional gas density profiles deduced by deprojecting the X-ray data with gravitational masses determined through the assumption of hydrostatic equilibrium (also: isothermal and spherically symmetric clusters). The highest redshift clusters in the sample were at $z \sim 0.8$ — these most distant clusters showed the same gas fraction as the lower redshift clusters in the sample. Note that these values are consistent with those presented previously by Myers et al. (1997) for the OVRO SZE survey and by Mohr et al. (1998) for X-ray data. See Grego et al. (2000b) for details.

Tools of the trade: **The Cosmic Background Imager**

- 13 × 90-cm antennas
- $45'$ FWHM at 30 GHz
- 1-m to 5-m baselines, $4\overset{'}{.}7$ synth beam
- 26–36 GHz in 10 × 1 GHz channels
- polarization 12×L and 1×R
- Nearby Clusters – $z < 0.1$ X-ray flux & luminosity limited sample

The Cosmic Background Imager is a 13-element interferometer dedicated to imaging anisotropies in the CMB on angular scales from $4'$ to $45'$ in the 1-cm band. The CBI was built by the Caltech group led by Steve Padin and Tony Readhead, and has been operating at the future ALMA site in the Atacama desert region of northern Chile (altitude 16500 ft!) since January 2000. In addition to measuring the angular power spectrum of primary CMB anisotropies, the CBI is also capable of imaging SZE decrements in nearby clusters. In particular, the CBI is currently surveying the expanded sample of 31 nearby clusters defined in Mason & Myers (2000). With the high sensitivity of the CBI instrument, the capability to both spectrally and spatially separate out foreground and background emission as well as the ability to construct 2D images of the SZE, the CBI is the natural successor to the 5.5-m telescope in carrying out the nearby cluster survey, and will greatly improve the microwave data on these clusters. The CBI is described in the contribution by Pearson to this Symposium.

The CBI-based SZE program will be highly complementary with the BIMA and OVRO surveys of Carlstrom et al., and together will join the vanguard of the new suite of microwave interferometers designed specifically for the determination of cosmological parameters. Not surprisingly, there are even more ambitious projects in the pipeline as we enter the "Decade of Precision Cosmology".

4. Beyond the New School!

There are a number of upgrades and new instruments planned for the coming decade, building upon the promise shown by the programs detailed above and elsewhere in this Symposium. In particular, the groups highlighted in this contribution have ambitious proposals for the next generation of SZE instrumentation. In addition to expanding and refining the targeted cluster surveys outlined above, the future programs will also aim at detecting the "ambient" SZE from the superposition of less massive clusters and the foam of large scale structure at high redshift. These structures will be nearly invisible at optical and X-ray wavelengths due to cosmological dimming, and the distance independence of the SZE make it the ideal probe of clustering out into the "dark ages" of the Universe beyond $z > 6$! An early prediction of the power of the SZE for high-redshift cosmology was given in Bond & Myers (1996), as shown in Figure 1. A more recent and more detailed demonstration of the practicality of faint SZE survey can be found in Holder et al. (1999).

Figure 1 shows CMB maps for the SZE from clusters and groups at 30 GHz for a CBI or JCA-style experiment. Some simulation details: A pure CDM model with $\Omega = 1, \Omega_B = 0.05, \mathrm{h} = 0.5$ and an initially scale invariant spectrum, normalized to $\sigma_8 = 0.7$ was chosen. This is contrasted with (d) the large primary anisotropies expected in this model and (c) the relatively small Thomson-scattering anisotropies induced as a result of the peculiar velocity of the clusters and groups. The normalization $\sigma_8 = 0.7$ was chosen so that the X-ray temperature distribution of clusters comes out approximately correctly, although the COBE normalization is higher, $\sigma_8 \approx 1$. The large scale bulk flow normalization also gives $\sigma_8 \approx 1$. The peak-patch method (Bond & Myers 1996) was used to construct the group and cluster catalog used in (a)-(c), and the gas profiles in the clusters were chosen to be spherical, with density $\propto (1 + (r/r_{core})^2)^{-1}$ (a $\beta = 2/3$ profile), with the core radius a fixed fraction of the cluster radius (0.1) up to a maximum allowed value of 300 kpc. The temperature distribution was taken to be isothermal, taken to be proportional to the internal energy of the clusters, with a constant $C_T \approx 1 - 1.2$ translating between the two. For (a), $C_{SZ} = (\Omega_{Beff}/(2\Omega_B))C_T$ also depends upon an effective baryon abundance Ω_{Beff} which takes into account separation of gas from the dark matter and so may be higher than the primordial Ω_B. For (b), $C_X = (\Omega_{Beff}/(2\Omega_B))^2 C_T^{1/2}$. The minimum contour level for the ROSAT map is a level similar to the ROSAT 5σ sensitivity for long exposure pointed observations. For (c), the peculiar ve-

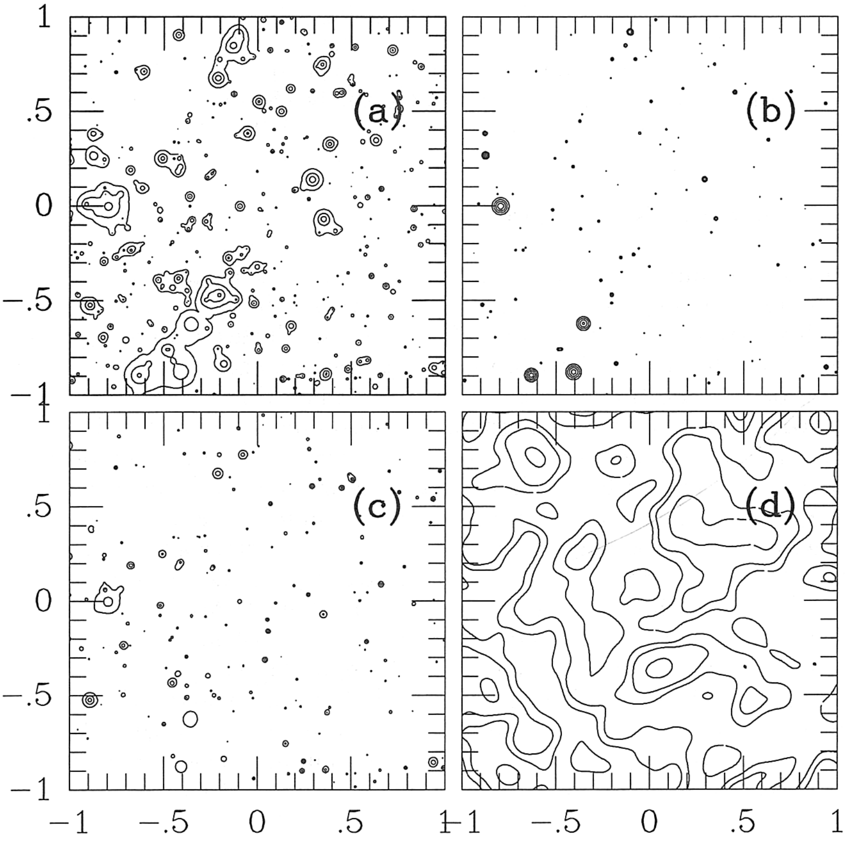

Figure 1. A theorist's conception of the microwave sky. Typical 2° × 2° $\Delta T/T$ and X-ray maps with 500^2 pixels for a $\Omega_B = 0.05$ scale-invariant CDM model with $\sigma_8 = 0.7$: (a) the SZ effect for 30 GHz, with contours $-5 \times 10^{-6} C_{SZ} \times 2^{n-1}$; (b) the associated ROSAT map (0.1−2.4 keV), with contours $10^{-14} C_X \times 2^{n-1}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$; (c) the Thomson scattering anisotropy induced by the bulk motion of the clusters, with contours now $\pm 1.25 \times 10^{-6} C_V \times 2^{n-1}$; (d) primary anisotropies, with contour levels at $\pm 10^{-5} \times 2^{n-1}$. Negative contours are dotted. The C_{SZ}, C_X and $C_V \approx C_{SZ}$ are order-unity correction factors. Courtesy J. R. Bond & S. T. Myers.

locities of the clusters are those computed for the peak-patches. The correction factor is $C_V = (\Omega_{Beff}/0.1)$. The sources are both positive and negative. The lack of extension is due to the small values: lowering the contour by a factor of 4 shows source extensions similar to that of Figure 1(a), but with many more small scale sources being important. No correction factor is necessary for the primary anisotropies of (d), which are everywhere large: the SZ effect is only competitive in the cores of clusters. The pixel size is 14″. The hills and valleys of the primary anisotropies are therefore natural, and would allow us to probe the physics of how the photon decoupling region at redshift $\sim$ 1000 damped the primary signal. The maps have the following minima, maxima, mean offsets, and *rms*, in units of 10^{-6}: (a) $(-47, 0, -2.0, 3.0)C_{SZ}$; (b) $(0, 12, 0, -0.05, 0.23) \times 10^{-14} C_X$; (c) $(-7.57, 6.03, -0.04, 0.36)C_V$; (d) $(-53, 48, -0.06, 18)$. The upshot of this simulation is that indeed the SZE probes deeper into the universe than the cosmologically dimmed X-ray emission. What remains to be demonstrated is how to separate the weak SZE signals from the stronger primary CMB, likely through a combination of spatial and spectral filtering.

The future instruments planned by the Cosmic Background Imager (Readhead et al.), UChicago / BIMA / OVRO (Carlstrom et al.), and NRAO (various) groups include:

- **CBI upgrade:** The Cosmic Background Imager is planning to install a suite of new 90 GHz receivers sometime after the 2001 observing season. This will scale the current capabilities down in angular scale by a factor of three, allowing an SZE survey of intermediate redshift clusters and providing overlap with the BIMA / OVRO sample while extending it to the Southern sky.

- **BIMA / OVRO plans:** An outrigger array of 10×2.5-m antennas (JCA) has been proposed by Carlstrom et al. to be constructed at the site of the soon to be combined BIMA–OVRO arrays (CARMA). This is planned to operate with 8×1 GHz channels placed in the band from 26–36 GHz and is targeted at surveying a large area of sky for distant clusters using the SZE itself (Holder et al. 1999). It is predicted that clusters with masses above $1.25 \times 10^{14}\, h^{-1}\, M_{\odot}$ can be detected *at any redshift*, and total rates of $\sim$ 25 clusters per square degree (cosmology dependent) are estimated.

- **ALMA plans:** In addition to being the flagship millimeter array of the new millennium, the Atacama Large Millimeter Array (ALMA) will be a superb platform for SZE astrophysics and cosmology. Consisting of at least $64x12$-m antennas, with the possibility of a supporting compact array of $\sim$ 10×7-m antennas, and including the capability of observing in the 30 GHz and 90 GHz bands, ALMA will bring to the Southern sky the capabilities of the current BIMA / OVRO array. Although not as efficient as the planned dedicated SZE experiments, ALMA will allow higher resolution images to be made of targeted clusters, constraining substructure issues and aiding in foreground/background source removal. ALMA is a joint NSF/ESO project (with likely Japanese involvement) scheduled for construction in the mid-decade 2000 at the Atacama site (16500 ft. altitude) in Chile.

In addition to these planned projects, there are a number of others in the works, some of which were presented at this Symposium. In particular, the Taiwan group has plans for an interferometer array for SZE (AMiBA). There are a number of bolometer-based single dish programs underway to carry out CMB polarization, as well as balloon borne telescopes. Finally, the upcoming MAP and Planck space missions will pave the way with all-sky images of the microwave background, and Planck in particular will have sensitivity to the SZE. Indeed, we should have an embarrassment of cosmic riches in the coming decade.

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