Sunyaev-Zel’dovich Effect as a Cosmological Probe

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Abstract.

We review recent results of Sunyaev-Zel’dovich effect (SZE) observations toward galaxy clusters. Using cm-wave receivers mounted on the OVRO and BIMA mm-wave arrays we have obtained high signal to noise images of the effect for more than 20 clusters. We present current estimates of the Hubble constant and cosmological parameters and discuss the potential of conducting statistical studies with large SZE cluster samples.

1. Introduction

Over the last few years there has been a tremendous increase in the study of galaxy clusters as cosmological probes, initially through the use of X-ray emission observations, and in recent years, through the use of Sunyaev-Zel’dovich effect (SZE). Briefly, the SZE is a distortion of the cosmic microwave background (CMB) radiation by inverse-Compton scattering of thermal electrons within the hot intercluster medium (Sunyaev & Zel’dovich 1980, see Birkinshaw 1998 for a recent review). The change in the CMB brightness temperature observed is:

\[
\frac{\Delta T}{T_{\text{CMB}}} = \left[ \frac{x(e^x + 1)}{e^x - 1} - 4 \right] \int \left( \frac{k_B T_e}{m_e c^2} \right) n_e \sigma_T dl, \tag{1}
\]

where \(x = h\nu/k_B T_{\text{CMB}}\), and \(n_e, T_e\) and \(\sigma_T\) are the electron density, electron temperature and the cross section for Thomson scattering. The integral is performed along the line of sight through the cluster.

The other important observable of the hot intercluster gas is the thermal Bremsstrahlung X-ray emission, whose surface brightness \(S_X\) can be written as:

\[
S_X = \frac{1}{4\pi(1 + z)^3} \int n_e^2 \Lambda_e dl, \tag{2}
\]

where \(z\) is the redshift and \(\Lambda_e(\Delta E, T_e)\) is the X-ray spectral emissivity of the cluster gas due to thermal Bremsstrahlung within a certain energy band \(\Delta E\). By combining the intensity of

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the SZE and the X-ray emission observations, and knowing the cluster gas temperature $T_e$, the angular diameter distance to the cluster can be derived due to the different dependence of the X-ray emission and SZE on the electron density, $n_e$. Combining such distance measurements with redshift allows a determination of the Hubble constant, $H_0$, as a function of certain cosmological parameters (e.g., Hughes & Birkinshaw 1998a). If distance measurements for a sample of clusters exist, then the angular diameter distance with redshift relation can be used to put constraints on the cosmological models, similar to current supernovae constraints at high redshift.

2. Interferometric Observations of the SZ Effect

We have imaged the SZE by outfitting the OVRO and BIMA mm-wave arrays with low-noise cm-wave receivers. One of the key advantages of our system is the ability to use interferometric techniques to produce 2-dimensional images of the SZE with sensitivity to large angular scales (up to 2.5'). The system as installed at OVRO and the first images obtained are discussed in Carlstrom et al. (1996). In Cooray et al. (1998a), we presented the observed cluster sample at OVRO and BIMA during the summers of 1995 to 1997 and detections of radio sources in galaxy clusters at 28.5 GHz. One of the main problems of SZE observations at cm-wavelengths is the presence of bright radio sources towards galaxy clusters, and catalogs of such sources at are important for future SZE and CMB anisotropy observations.

In Figure 1 we present images of the galaxy cluster A2218. The third panel shows our SZ image. The cluster was observed for 60 hours, producing this map with a rms noise of 15 $\mu$K. Currently, we have imaged the SZE with high signal-to-noise (> 20) in ~ 20 clusters from $z \sim 0.14$ to 0.83. Over 80% of this sample is scheduled to be observed with AXAF during the GTO phase. When combined, the SZE and the AXAF X-ray emission data will allow the determination of the Hubble constant, and constraints on the cosmological parameters based on the angular diameter distance relation with redshift, at a level comparable to the present SNIa constraints on cosmological parameters.
3. Cosmological Parameter Constraints

3.1. $H_0$

Table 1

| Cluster     | Redshift | $D_A$ (Mpc) | $H_0$ (km s$^{-1}$ Mpc$^{-1}$) | Reference                  |
|-------------|----------|-------------|-------------------------------|----------------------------|
| A2256       | 0.0581   | $231^{+82}_{-54}$ | $68^{+21}_{-18}$            | Myers et al. 1997          |
| A478        | 0.0881   | $747^{+539}_{-264}$ | $30^{+17}_{-13}$            | Myers et al. 1997          |
| A2142       | 0.0899   | $512^{+797}_{-265}$ | $46^{+41}_{-28}$            | Myers et al. 1997          |
| A1413       | 0.143    | $743^{+348}_{-222}$ | $44^{+20}_{-15}$            | Saunders 1996              |
| A2218       | 0.171    | $678^{+432}_{-190}$ | $59 \pm 23$                 | Birkinshaw & Hughes 1994   |
| A2218       | 0.171    | $1176^{+823}_{-376}$ | $34^{+18}_{-16}$            | Jones 1995                 |
| A2218       | 0.171    | $1050 \pm 230$     | $38 \pm 15$                 | Patel et al. 1998          |
| A665        | 0.182    | $911^{+235}_{-486}$ | $46 \pm 16$                 | Hughes & Birkinshaw 1998b  |
| A665        | 0.182    | $939^{+260}_{-495}$ | $48^{+19}_{-16}$            | Cooray et al. 1998b        |
| A2163       | 0.201    | $778^{+173}_{-313}$ | $58^{+30}_{-22}$            | Holzapfel et al. 1997      |
| Cl0016+16   | 0.5455   | $1713^{+803}_{-562}$ | $47^{+23}_{-15}$            | Hughes & Birkinshaw 1998a  |

$H_0$ is calculated assuming $\Omega_m = 0.2$ and $\Omega_\Lambda = 0.8$.

Table 1 lists published Hubble constant measurements that have been obtained by combining SZE and X-ray emission observations (see Hughes 1997 for further details). In recent years, several studies have questioned the reliability of $H_0$ measurements based on SZ/X-ray route. This is primarily due to various systematic effects involved with this method, which include the nonisothermality of the electron temperature for cluster gas, gas clumping, asphericity of the cluster gas distribution, and radio source contamination and gravitational lensing effects (see Birkinshaw 1998). It is likely that deep AXAF observations will produce reliable cluster electron temperature profiles and constrain the amount of gas clumping. Systematic changes in $H_0$ due to aspherical gas distribution can be treated in a statistical manner for a large sample of clusters.

3.2. Gas Fraction and $\Omega_m$

The SZE is a measurement of the integrated gas (baryonic) mass along the line of slight through the cluster. The total (including non-baryonic) mass of a cluster can be derived based on three methods: gas temperature, gravitational (strong & weak) lensing, and velocity dispersion measurements. The baryonic mass fraction, when compared to the primordial nucleosynthesis determined value for $\Omega_b$ allows constraints on $\Omega_m$ assuming the cluster baryonic fraction is the same as $\Omega_b/\Omega_m$ (based on hierarchical clustering models, where clusters represent the composition of the universe). The present limits on $\Omega_m$ are: $\Omega_m h < 0.3$ (Grego et al. 1998, Myers et al. 1997), based on SZE measurements, and $\Omega_m h^{2/3} < 0.28$ (Evrard, this proceedings), based on X-ray measurements.
3.3. $D_A$ and $q_0, \Omega_m, \Omega_A$

The angular diameter distance relation with redshift is dependent on the cosmological parameters. Thus, if distance measurements exist out to high redshift, one can use the angular diameter distance with redshift to constrain the cosmological parameters. Present SZ/X-ray $D_A$ measurements (in Table 1) do not allow reliable constraints on the $\Omega_m - \Omega_A$ plane; the data in Table 1 are consistent with $q_0 > -0.73$ (90% formal confidence).

4. Scaling Relations as Cosmological Tools

One of the well known facts about the SZE is that it is independent of redshift, allowing a probe of the distant universe. Given that large area SZE surveys and PLANCK will detect a large number of high redshift clusters, it is necessary that techniques independent of X-ray observations be considered. The temperature change due to the SZE is expected to relate to the X-ray luminosity, and the expected relation takes the form of $\Delta T_{SZ} \propto L_{bol}^\alpha$ with $\alpha = 0.6$ to 0.7 depending on the exact form of the $L_{bol} - T_e$ relation. The present SZ data, suggest

$$\Delta T_{SZ} = -(0.46 \pm 0.12) \left( \frac{L_{bol}}{10^{45}} \right)^{0.60\pm0.18} \text{mK},$$

where the uncertainty is the $1-\sigma$ statistical error. The use of such relations, say in a Press-Schechter formalism, can be helpful to constrain the cosmological parameters based on the SZE observations, with the relations normalized based on the X-ray data of the local universe. Another important scaling relation would be between the SZE and the cluster electron temperature. Since the SZE measures the cluster gas mass and cluster temperature measures the total mass, this relation will probe the gas mass fraction in galaxy clusters. The redshift evolution of $\Delta T_{SZ} - T_{e0}$ relation can be used to derive cosmological parameters, similar to what is done in Cooray (1998) for X-ray/lensing data (see also Danos & Pen 1998).

References

[1] Birkinshaw, M. 1998, submitted to Physics Reports.
[2] Birkinshaw, M. & Hughes, J. P. 1994, ApJ, 420, 33.
[3] Carlstrom, J., Joy, M., and Grego, L. 1996, ApJ, 456, L75.
[4] Cooray, A. R. 1998, A&A, 333, L71.
[5] Cooray, A. R., et al. 1988a, AJ, 115, 1388.
[6] Cooray, A. R., et al. 1988b, in preparation.
[7] Danos, R., Pen, U.-L. 1998, submitted to ApJL [astro-ph/9803058].
[8] Grego, L., et al. 1998, in preparation.
[9] Holzapfel, W. L., et al. 1997, ApJ, 480, 449.
[10] Hughes, J. P. 1997, [astro-ph/9711135].
[11] Hughes, J. P. & Birkinshaw, M. 1998a, ApJ, in print.
[12] Hughes, J. P. & Birkinshaw, M. 1998b, in preparation.
[13] Jones, M. 1995, Astro. Lett. Comm., 6, 347.
[14] Kneib, J.-P., 1996, ApJ, 471, 643.
[15] Myers, S. T., et al. 1997, ApJ, 485, 1.
[16] Patel, S., et al. 1998, in preparation.
[17] Saunders, R. 1996, [astro-ph/9611213]
[18] Sunyaev, R. A. and Zel’dovich, Ya. B. 1980, ARAA, 18, 537.