SUNYAEV-ZEL'DOVICH EFFECT REVIEW

F.-X. DÉSERT
Laboratoire d'Astrophysique de l'Observatoire de Grenoble
BP53 414 rue de la piscine, Domaine Universitaire de Saint Martin d'Heres
38041 Grenoble Cedex 9 France

I review the present observational status of the observations of the SZ effect due to the Compton scattering of the 3K background on the hot electrons of clusters of galaxies. I raise the relevant issues from theoretical and X-ray aspects of the question that challenge the present experiments. Future instruments like powerful radio interferometers and bolometric cameras should give us access to the statistics of clusters as well as their internal morphology within the next ten years. They will provide an approach complementary to space experiments (XMM, Chandra, Planck) for some fundamental cosmological and large scale structure issues.

1 General Presentation

The presence of a hot teneous and fully ionised gas ($T_e = 10^8\,\mathrm{K}$, $n_e = 10^3\,\mathrm{m}^{-3}$) in the intracluster medium was revealed with the first X-ray measurements toward clusters of galaxies. This gas which fell in the deep gravitational well of clusters of galaxies and thus heated up to very high temperature can only cool down via the free-free emission process. Only in the very center of clusters is the density of the electrons and nuclei enough for the cooling timescale to be less than the age of the Universe. Another cooling process exists via inverse Compton scattering on the (cold) cosmic microwave background.

This secondary cooling is called the Sunyaev-Zel'dovich (hereafter SZ) effect[1]. This effect preserves the number of CMB photons. If it were a pure scattering effect without energy change the CMB would not be globally affected. But there is a net energy gain by the CMB photons in the direction of clusters. The CMB is thus spectrally distorted. The adimensional Comptonisation parameter y measures the SZ distortion:

$$y = \frac{kT_e}{m_e c^2} \sigma_T N_e \,, \tag{1}$$

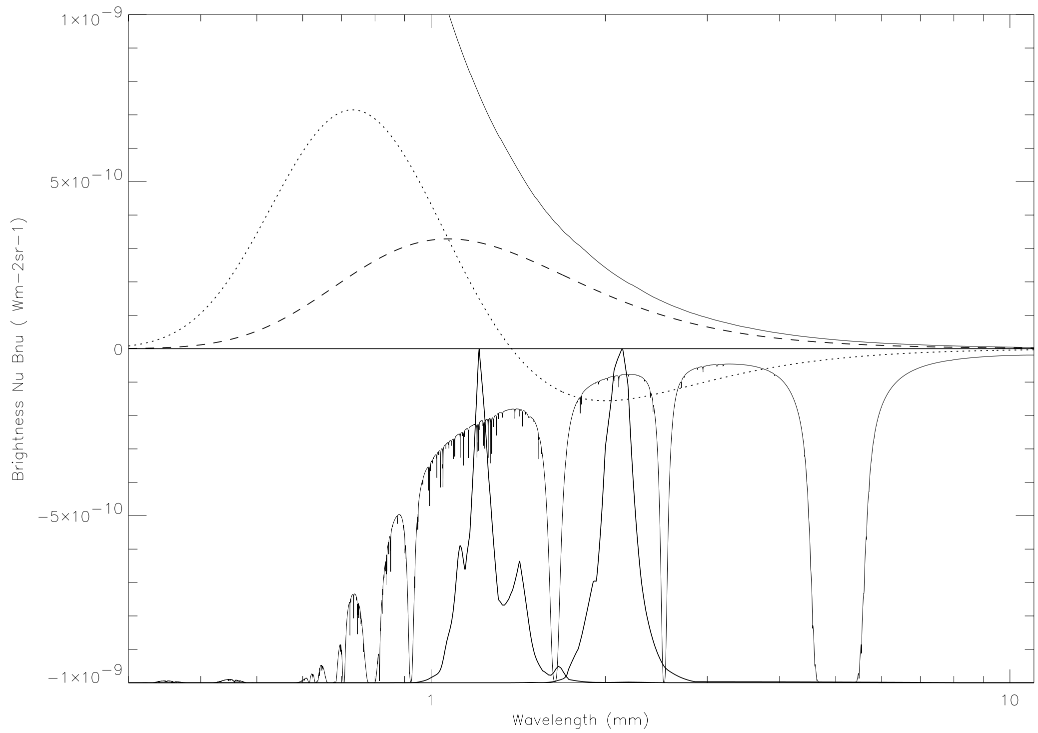

Figure 1: Differential CMB brightness change as a function of wavelength, towards a cluster with $y = 10^{-4}$ (dotted curve) and $b = -10^{-4}$ (dashed curve). The lower panel gives the atmospheric transmission (between 0 and 1) for 3 mm of precipitable water and the two Diabolo instrument bandpasses. The upper solid curve gives the colour of the atmospheric noise.

where T_e, m_e, $N_e = \int n_e dl$, and n_e are resp. the electronic temperature, mass, column density and density. The integral is taken along the line of sight through the cluster. σ_T is the Thomson cross-section. The second (and usually much weaker) SZ effect called kinetic effect is due to the peculiar cluster velocity v_c and is measured by:

$$b = \frac{v_r}{c} \sigma_T N_e \tag{2}$$

Figure 1 shows the universal distortion spectrum produced by the thermal (dots) and kinetic (dashes) SZ effects.

The SZ effect is thus a radio, millimetre and submillimetre phenomenon. The thermal SZ effect has a very specific spectral signature (always negative for $\lambda \leq 1.4\,\mathrm{mm}$) whereas the kinetic SZ effect is undistinguishable from the spectrum of the CMB primordial anisotropies. Both SZ effects are brightness effects which are spectrally independent of redshift in the observer's frame, contrary to X-ray emission which shows the usual $(1+z)^{-4}$ brightness dimming. A well-resolved cluster will show the same SZ effect whether it is at low or high redshift.

The energy density (which is the focus of this conference) of the CMB is enhanced towards clusters by the following amount:

$$E = 4y\sigma_S T^4_{CMB} \tag{3}$$

The opacity $\tau = \sigma_T N_e$ and comptonisation parameter y are of the order of a few 10^{-2} and 10^{-4} resp. in the richest clusters which therefore make the SZ effect a relatively small and linear distortion.

It has recently been acknowledged that one cannot neglect relativistic corrections to the (non-relativistic) universal spectral template, shown in Fig. 1, and independent on redshift. A complete review of the SZ effect is clearly beyond this presentation. An exhaustive recent review was made by Birkinshaw[2].

2 Observational status

2.1 Astrophysical and Cosmological objectives

Witness the 3K remoteness

With several clusters firmly detected at a redshift up to about 0.5, the 3 K background cannot have an origin in the local Universe. There are not so many direct probes of the presence of the CMB at high redshift.

Measure the hot cluster gas distribution

The SZ effect directly measures the hot electron pressure along the line of sight. If one assumes a constant gas temperature, an electronic density following a King profile (with r the radius from the cluster center, and a the core radius) is often assumed:

$$n_e = n_{e0}(1 + (r/a)^2)^{-3\beta/2}, \tag{4}$$

and will produce a SZ angular distribution

$$y_{SZ} = y_0(1 + (\theta/\theta_a)^2)^{-3\beta/2+1/2}. \tag{5}$$

The measurements are therefore linearly linked to the density of baryonic matter.

Total mass of gas

The quantity that is directly measured in a given experiment is really the brightness integrated over the instrument beam, something that can be loosely defined as $Y = \int_{beam} y d\Omega$. The big virtue of SZ measurements is to give an easy access which is weakly dependent on redshift to the total gas mass of the cluster in the beam:

$$M_g \simeq 2 \times 10^{13} M_\odot \left(\frac{T_g}{10\,\mathrm{keV}}\right)^{-1} \frac{Y}{10^{-5}\mathrm{arcmin}^2} f(z), \tag{6}$$

where the redshift function f depends on the cosmological parameters (through the angular-diameter redshift dependence). The following table (computed for a critical standard model without cosmological constant) shows a subtle dependence of the measured SZ effect with redshift.

z	$f \times 10^3$
0.1	2
0.3	9
1.0	20

Total gravitational mass

Through the hydrostatic equation and from the gas pressure profile, one can deduce the total cluster mass M_T. Although this has been done with X-ray measurements, the SZ effect could in principle be used for a rather direct measurement of the total mass. It would be valuable, when precise measurements become available, to reassess the baryonic crisis: $M_g/M_T \neq \Omega_b/\Omega_0$.

Peculiar radial velocity

The kinetic SZ effect is a 10 times weaker effect that the thermal effect. Accurate measurements of it in many cluster could in principle probe the large scale velocity field in the distant Universe. The CMB primary anistropies are in that case a 'pollution' to these measurements which could be attempted by the Planck mission (Aghanim[11]). Ground-based attempts have so far provided upper limits (Holzapfel et al.[8])

H_0 **,** q_0 **measurement**

The measurements of $\int T_e n_e dl$ with the SZ effect and $\int n_e^2 dl$ and T_e with X-ray space observations yield an estimate of the true physical depth of the cluster. Assuming the cluster is spherical, this quantity can be compared with the angular size of the cluster and its redshift to give H_0. The weak dependence of that result on q_0 has been analysed, but the prospect of a serious measurement of it is marred by cluster evolution (see below). Measurements of the Hubble constant is clearly within reach, once systematic effects are well understood over a statistically significant sample of observed (local) clusters. The complementarity of the SZ effect with XMM-Newton and Chandra is obvious in that respect. This is one of the most important cosmological targets for SZ measurements. The second one is:

SZ Cluster number counts

Having SZ surveys over large area could provide a rather unbiased measurement of the cluster number counts. Optical and X-ray surveys have been known to be biased by chance alignments and resolution & surface brightness limits respectively. The weak dependence on redshift of the SZ effect (Eq. 6) makes a (costly) survey quite attractive for two reasons:

1. to determine the exact number density of local clusters (say of redshift less than 0.3) and the mass distribution function
2. to measure the evolution of this density and search for high redshift clusters.

Structured Matter Energy injection into the CMB

The average comptonisation parameter on any line of sight is about $y \sim 10^{-6}$. From Eq. 3, the energy injection into the Universe by large scale non-linear structure formation is of the order of at most 10^{-5} of the energy in the CMB itself.

Search for distant clusters : $z > 1$

The search of SZ effect without the a-priori of X-ray maps have so far led to the as yet unconfirmed detection of two radio extended brightness decrements (Richards et al.[12], Saunders et al.[13]). The secure detection of just few clusters at redshift above 1 would severely endanger models of the Universe with a critical matter density parameter (Bartlett et al.[14]).

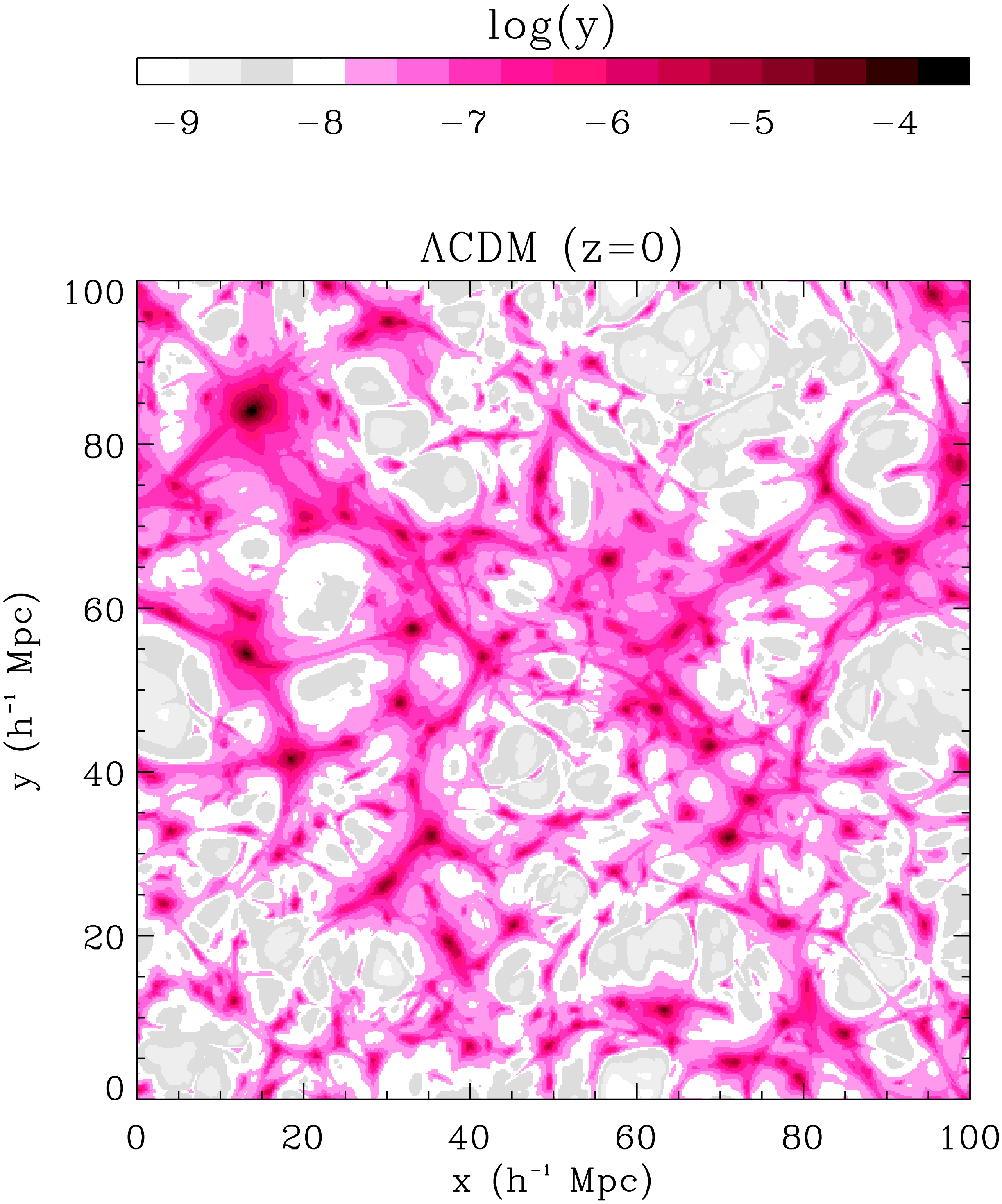

Figure 2: A SZ map produced by a simulated cube of Universe (Refregier et al.[10]). Only the darkest spots corresponding to cluster cores can be measured now. Notice the SZ spider web like network that crosses the sky.

Single dish radio telescopes

Pionneered by Birkinshaw and collaborators, this was the first standard technique to successfully measure the SZ effect. It was and remains the best adapted technique for local clusters with a very large extent (e.g. Coma: Herbig et al.[15])

Radio interferometers

The most sensitive detections have been provided by radio interferometers which are less affected by sidelobe effects and can remove point sources by using the long baseline measurements. Moreover they benefit from large integration times (several months per year). The Ryle telescope (Saunders and Jones, this conference) in England and the OVRO-BIMA interferometer fitted (perverted) with radio receivers (Carlstrom et al.[10]) have obtained very sensitive maps of now tens of clusters with arcminute resolution at 15 and 30 GHz frequencies.

Bolometer photometers

The SuZie experiment provided the first detection of the SZ effect in the millimeter domain at the CSO 10m telescope (Wilbanks et al.[9], Holzapfel et al.[8]). It is made of 6 bolometers at a wavelength of 2 mm. By using a drift scan technique whereby fixing the telescope in local coordinates, the cluster drifts through the detectors with the Earth's diurnal motion, hence avoiding sidelobe effects and microphonic noise. The cluster A 2163 (the second X-ray brightest known cluster) was later detected at 1mm using the SuZie experiment with different filters and in the submillimeter domain by the balloon borne photometer PRONAOS-SPM (Lamarre et al.[7]) showing for the first time the change of sign of the SZ effect (see Fig. 1). Although in the (sub)millimeter domain, the point sources should not contaminate the SZ measurements so much, interstellar dust thermal emission must be dealt with to correct the measurements. Another limitation comes from sky noise: the water vapour is inhomogeneous in the atmosphere. Its emission in the telescope is variable in time and angle and frequency (see Fig. 1). The Diabolo experiment (Benoit et al.[4]) uses a dichroic beam splitter with six 0.1 K bolometers in order to simultaneously measure and hence subtract the water vapour emission at 1.2 mm (where the SZ effect is almost vanishing) from the SZ measurement at 2.1 mm. At the IRAM 30 m telescope, it provided the highest angular resolution of the SZ effect on several clusters with 30 arcsecond beam in 1995 (Désert et al.[6]) and 22 arcsecond beam since 1997 (Pointecouteau et al.[5] and this conference).

3 The next SZ ten years

The sensitivity of present ground-based detectors is quite close to photon noise limits, typically an effective value $y(1\sigma) \sim 10^{-4}\mathrm{hour}^{-\frac{1}{2}}$ for a single bolometer. This is also typical for interferometers. All 3 kinds of observing techniques are also currently limited by the range of angular scales that can be measured, whereas the angular distribution of clusters of galaxies is widespread, from core radii to Abell radii, along with substructure scales. We can see that the main goals of SZ observations in the next years are:

1. Improve the statistics on H_0 measurements
2. Number counts of SZ clusters and high redshift cluster search
3. Detailed analysis of individual clusters

For point 1 and 2, interferometers are clearly very promising. Dedicated radio telescope arrays which are currently being built with modest size telescopes aim at covering a large range of angular scales (in particular the shortest baselines). By covering a large frequency bandwidth and by using smaller telescopes (!), improvements in detectivity could be better by as much as a factor of 1000 in the next 3 years (e.g. the AMI project: Jones, this conference). For point 3, bolometer arrays (with hundred to thousands of pixels) should bring a clear multiplex advantage over existing technology[16]. They will give unprecedented high angular resolution maps in the near future (20 arcseconds), that will be useful to study the detailed angular distribution of clusters (whether at low or high redshift) to unravel the cosmogony of large scale structures. In that respect, the structure of high redsihft clusters (e.g. Ebeling et al.[18]) which is far from smooth is interesting for cluster formation scenarios but may prove a show stopper for q_0 and other second order effect measurements.

Future space missions will provide a different perspective. Planck will give an unbiased catalog of at least several thousands of SZ sources. MAP, although not sensitive to individual clusters, may still see some signal by correlation with large scale structures as seen in the optical (Refregier et al.[17]).

The interpretation of SZ data is depending on the quality of other data, and vice-versa. The arrival of Chandra and XMM-Newton is a strong incentive for improving SZ measurements. Comparison with visible and near-infrared data obtained by large telescopes (substructures and weak lensing) is also very valuable.

We have clearly moved from detection experiments towards a powerful tool for the study of clusters. A global approach, using SZ observations but also other wavelengths, is a must for the understanding of clusters of galaxies.

Acknowledgments

We wish to thank the organisers for such a pleasant and lively forum of discussions of which the SZ effect was one of the foci. We thank A. Refregier for allowing us to show the large scale SZ simulated map.

References

1. Sunyaev, R. A., & Zel'dovich, Ya. B., *Comm. Ap. Sp. Phys.* **4**, 173 (1972)
2. M. Birkinshaw, *Phys. Rept.* **310**, 97 (1999)
3. A. Benoit, et al., *Astron. Astrophys. Supp. Ser.* **141**, 523 (2000)
4. Pointecouteau, E., Giard, M., Benoit, A. et al., *Astrophys. J. Lett.* **519**, L115 (1999)
5. Désert et al. *New Astron.* **3**, 655 (1998)
6. Lamarre, J.-M., et al. *Astrophys. J. Lett.* **507**, L5 (1998)
7. Holzapfel, W. L., Ade, P. A. R., Church, S. E., et al., *Astrophys. J.* **481**, 35 (1997)
8. Wilbanks, T. M., Ade, P. A. R., Fischer, M. L., et al., *Astrophys. J. Lett.* **427**, L75 (1994)
9. Carlstrom, J. E., Joy, M., Grego, L, *Astrophys. J. Lett.* **456**, L75 (1996)
10. Refregier, A., Komatsu, E., Spergel, D. N., & Pen, Ue-Li, *Phys. Rev.* D **in press**, (2000)
11. Aghanim, N., et al. , *Astron. Astrophys.* **325**, 9 (1997)
12. Richards E.A. et al., *Astron. J.* **113**, 1475 (1997)
13. Jones M. et al. *Astrophys. J. Lett.* **479**, L1 (1997)
14. Bartlett, J. et al. *Astron. Astrophys.* **336**, 425 (1998)
15. Herbig, T., Lawrence, C. R., Readhead, A. C. S., Gulkis, S., *Astrophys. J. Lett.* **449**, L5 (1995)
16. Désert, F.-X., Benoit, A., *IRAM Newsletter* **38**, (1999) `http://iram.fr/ARN/jan99/jan99.html`, astro-ph/9901414
17. Refregier, A., Spergel, D. N., Herbig, T., *Astrophys. J.* **531**, 31 (2000)

18. Ebeling, H., Jones, L. R., Perlman, E. et al., *Astrophys. J.* **534**, 133 (2000)