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Sunyaev-Zeldovich Effect in Galaxy Clusters

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Abstract. Free electrons within the hot diffuse plasma (ICM) of clusters of galaxies scatter the photons of the Cosmic Microwave Background (CMB), an effect predicted by Zeldovich and Sunyaev (SZ) in 1969. Clusters thus appears as cold (hot) spots in the low (high) radio frequency observations of the CMB. The magnitude of the SZ effect is independent of the cluster redshift. Therefore, surveys of SZ clusters are a powerful tool to measure the cosmological parameters and constrain the model of the formation of the large-scale structure. Moreover, high angular resolution observations of the SZ effect can provide information on the ICM thermal properties.

Key words. cosmology: miscellaneous – galaxies: clusters: general – large-scale structure of the Universe – methods: numerical

1. Basics

The inverse Compton scatter of the CMB photons by the free electrons in the hot ICM plasma changes the specific intensity I_ν of the CMB by the amount $\Delta I_\nu^t \propto \int n(r)T(r)dl \propto \tau kT/m_e c^2$, where $n(r)$ is the free electron number density in the cluster, $T(r)$ the electron temperature, T an appropriate average of $T(r)$, $\tau \propto \int n(r)dl$ the ICM optical depth, m_e the electron mass, c the light speed, and the integrals are taken along the line of sight. In the CMB rest frame, both the ICM thermal energy and the cluster peculiar velocity β, in units of c, contribute to the kinetic energy of the ICM electrons. Therefore, besides the SZ thermal component ΔI_ν^t just shown, we have a kinetic component $\Delta I_\nu^k \propto \int n(r)\beta(r)dl \propto \tau\beta$, where $\beta(r)$ is the ICM velocity field, and β is an appropriate average of $\beta(r)$. Observations provide $\Delta I_\nu = \Delta I_\nu^t + \Delta I_\nu^k$.

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Massive clusters typically have ICM optical depths $\tau \sim 10^{-2}$ and ICM temperatures $kT/m_e c^2 \sim 10^{-2}$, which yield $\Delta I_\nu^t/I_\nu \sim 10^{-4}$. These tiny variations require an accurate control of the radio observation systematics; their correction, present in early measurements, has only recently made reasonably accurate SZ detections feasible (Carlstrom et al. 2002).

The kinematic component of the SZ effect is a factor of ten smaller than the thermal component, because typical cluster peculiar velocities are $\beta \sim 10^{-3}$. Moreover the CMB temperature variation associated to the kinematic component is independent of frequency and the systematics of its detection are more subtle (Forni & Aghanim 2004).

2. Cluster Surveys

SZ clusters are the ideal target for cluster surveys, because the SZ effect intensity ΔI_ν is independent of the cluster distance: clusters

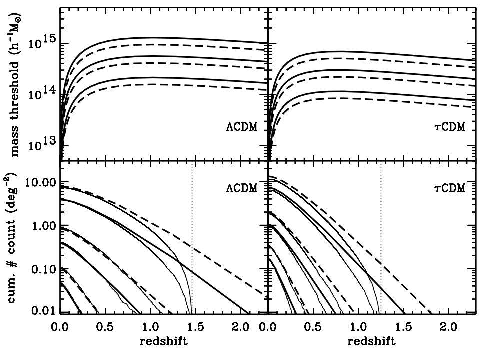

Fig. 1. Upper panels: mass threshold corresponding to $S_\nu^{\min} = 200, 50, 10$ mJy (top to bottom) for $\nu =$ 143 GHz (solid) and $\nu = 353$ GHz (dashed lines). Lower panels: redshift cumulative cluster number counts corresponding to $S_\nu^{\min} = 10, 50, 200$ mJy (top to bottom). Bold lines are the expected distribution; thin lines are the distribution measured in N-body simulations. Dotted lines indicate the redshift limit of the simulations. Left and right columns are for two different cosmological models. From Diaferio et al. (2003).

can be detected at any redshift, as early as at their formation time. It follows that a flux-limited SZ survey is basically a mass-limited survey: the minimum mass of clusters is $M_{\rm th} \propto D_A^{6/5}(z)H^{-2/5}(z)S_{\min}^{3/2}$ (Diaferio et al. 2003), where $S_{\min}$ is the survey flux limit, D_A the angular diameter distance and $H(z)$ the Hubble constant, and the redshift dependences of D_A and H almost cancel out at $z \gtrsim 0.2 - 0.3$ (upper panels of Figure 1). Therefore, comparing models of structure formation with these observations requires fewer assumptions than comparing models with optical or X-ray cluster samples, because theoreticians predict mass functions more easily than luminosity or temperature functions.

The redshift distribution of SZ clusters is sensitive to the Universe density Ω_0, the cosmological constant Ω_Λ, and the power spectrum normalization σ_8 of the initial density fluctuations (lower panels of Figure 1). The degeneracy between these parameters can be broken by combining the SZ constraints with CMB and SNIa observations. These latter measures cover the $\Omega_0 - \Omega_\Lambda - \sigma_8$ planes differently, because they probe the cosmic distance scale rather than the growth rate of structure.

The difficulty in determining the SZ cluster redshift distribution resides in the fact that we need an optical follow-up to estimate cluster redshifts, as the SZ amplitude is redshift independent. However, the estimation of the redshifts from high-resolution SZ observations alone seems to be possible by exploiting the redshift dependence of the wavelet moment spectrum of the SZ cluster morphology decomposition (Schäfer et al. 2003).

SZ clusters are also a tool for measuring the Hubble constant H_0. H_0 was indeed the first cosmological parameter to be recognized to be measurable by combining SZ and X-ray observations (Cavaliere et al. 1977). In fact, from the SZ intensity $\Delta I_{SZ} \propto nTR$, where R is the cluster size along the line of sight, the X-ray intensity $\Delta I_X \propto n^2\Lambda(T)R$, where $\Lambda(T)$ is the cooling function, and the assumption of spherical symmetry, which yields $R \sim \theta D_A$, where θ is the angular size of the cluster, we obtain, by eliminating n from the two intensities, $D_A \propto \Delta I_{SZ}^2 \Delta I_X^{-1}\Lambda(T)T^{-2}\theta^{-1}$. $D_A(z)$, and thus H_0, can be estimated once we have a measure of T from the X-ray spectrum. A sample of clusters within $z \sim 0.5$ provides $H_0 = 61 \pm 3 \pm 18$ km s^{-1} Mpc^{-1} (Reese 2004).

If both the temperature T and the total cluster mass M are known, the SZ intensity provides a tool, alternative to the X-ray emission, for estimating the baryon fraction f_b. In fact, $n \propto f_b M$, and the integration of ΔI_ν^t over the solid angle covered by the cluster yields $S_{SZ} \propto D_A^{-2}(z)H^{2/3}(z)f_b MT$. LaRoque et al. (2004) use a sample of 39 clusters at $z \lesssim 1$ to measure $f_b = 0.079^{+0.010}_{-0.007}$ in a ΛCDM universe with $H_0 = 70$ km s^{-1} Mpc^{-1}.

3. Structure Formation

The measure of the evolution of the large-scale velocity field is complementary to the measure of the redshift distribution of galaxy clusters, because, in linear theory, the latter depends on the growth factor of structure, whereas the former depends on its time derivative. Entering the non-linear regime of course complicates the situation (Peel 2005): for example, the distribution of the peculiar velocities of dark matter halos depends on the density of their environment (Sheth & Diaferio 2001). This correlation could be exploited to identify superclusters at high redshift (Diaferio et al. 2000), because their members populate the large-value tails of the non-Gaussian distribution of the kinetic SZ intensities (Yoshida et al. 2001).

The estimate of the peculiar velocity of clusters with the kinetic SZ effect is therefore of the outmost interest to constrain models of the formation of cosmic structures. However, the detection of the kinetic SZ component is extremely more challenging than the detection of the SZ thermal component, because, besides its small amplitude ($\Delta I^k_\nu/I_\nu \sim 10^{-5}$), it has the same spectrum as the CMB and it requires both multi-wavelength radio observations and the estimate of the ICM temperature. Uncertainties on peculiar velocities recently estimated with the kinetic SZ effect are typically a few times the velocity itself (Benson et al. 2003) and more accurate estimates of individual cluster velocities seem currently unfeasible. In any case, internal bulk flows of the ICM and systematic differences between the electron temperature and the temperature derived from the X-ray emission set a 200 km s^{-1} lower limit to the peculiar velocity errors (Diaferio et al. 2005). Alternatively to individual velocities, mean bulk flows of $\sim (100h^{-1}\mathrm{Mpc})^3$ volumes and the rms of peculiar velocities on these scales can be used to measure the density of the Universe (Atrio-Barandela et al. 2004).

4. Properties of the ICM

The magnitude of the SZ effect is proportional to the free electron number density n within the ICM. Heating of the ICM from supernovae and AGN's, star formation and radiative cooling can be responsible for varying n at fixed cluster mass.

High resolution cosmological simulations, which include an advanced treatment of gas dynamics, are a valuable tool to assess the relevant processes setting the thermal properties of the ICM. Diaferio et al. (2005) have recently investigated the scaling relations of simulated cluster thermal properties. Figure 2 shows an example of the X-ray emission, thermal and kinetic components of the SZ effect in a simulated cluster. Figure 3 shows three scaling relations between X-ray and SZ properties. Despite the fact that the simulated sample contains clusters systematically less massive than real clusters (the simulation volume is not sufficiently large to contain many massive clusters), the simulation roughly reproduces the observed normalizations, slopes and scatters. Therefore the simulation includes most of the gas physics relevant processes. However, the agreement is not yet quantitatively satisfactory, neither between simulations and observations nor between the observed samples; probably, the latter samples are not yet representative of the global cluster population. A more robust comparison requires more massive simulated clusters and more reliable real samples.

If the cosmological parameters are known from other data, SZ observations can constrain the gas thermal properties. For example, Mei & Bartlett (2004) show that by combining the number count of SZ clusters with ther angular correlation function one can measure the product between f_b and the normalization of the mass-temperature relation within 15%. By including kwnowledge of the cluster redshifts, Moscardini et al. (2002) show that the length scale of the SZ cluster correlation function in redshift space can constrain the evolution of the mass-temperature relation.

5. Conclusion

Detecting the SZ effect in galaxy clusters is relevant to constrain cosmological parameters, models of the formation of cosmic structures and ICM thermal properties. Over the last years a large number of dedicated interferometers (AMI, AMiBA, SZA) and bolometers (APEX, ACT, BOLOCAM, SPT, ACBAR) have been working or planned to measure this effect. Of course, the accuracy of these measures depends on how well observers are able to keep the various systematics under control: at low frequencies emission from the Galaxy, instrumental noise, atmospheric and ground emission; at high frequencies Galactic dust and young galaxies; at all frequencies radio sources

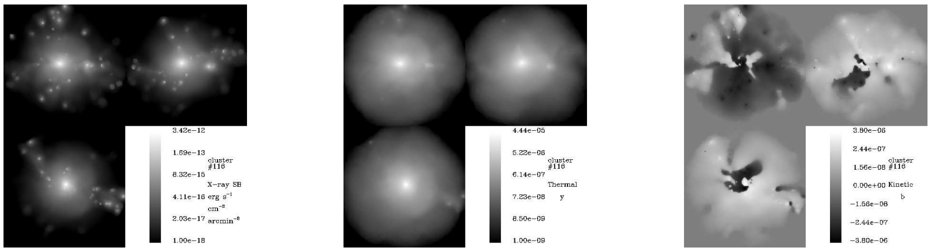

Fig. 2. Maps along three orthogonal directions of the X-ray surface brightness, thermal and kinetic SZ effects (left to right) for a simulated cluster with mass $M(< R_{\rm vir}) = 3.76 \times 10^{14} h^{-1} M_\odot$. Each pixel has size $52h^{-1}$ kpc on a side and the field of view is $6.7h^{-1}$ Mpc on a side (Diaferio et al. 2005).

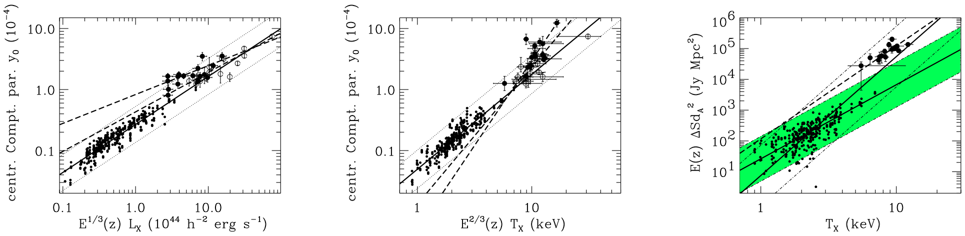

Fig. 3. Central peak of the SZ thermal effect vs. the X-ray bolometric luminosity (left panel) and the X-ray emission weighted temperature (middle panel); right panel: SZ flux decrement at 145 GHz, integrated within r_{2500}, vs. the X-ray emission weighted temperature. The dots are the simulated clusters, the open and solid circles with error bars two observed cluster samples. The solid and dashed lines are the best fits to the simulated and observed clusters respectively. See Diaferio et al. (2005) for further details.

and the CMB itself. The golden mine buried in the SZ effect will no doubt repay the effort.

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