The Sunyaev-Zeldovich effect as a probe of the galaxy formation process

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Abstract. The Sunyaev-Zeldovich (SZ) effect has proven to be an extremely powerful tool to study the physical and evolutionary properties of rich clusters of galaxies. Upcoming SZ experiments, with their much improved sensitivity and angular resolution, will provide unique information also on phases of galaxy evolution characterized by the presence of large amounts of hot proto-galactic gas. We present a preliminary analysis of the SZ signals that can be expected at the collapse of the proto-galaxy when, according to the standard scenario, the gas is heated at its virial temperature, and during episodes of strong energy injections from the active nucleus. The contributions of such signals to excess power on arc-minute scales recently found by CBI and BIMA experiments are briefly discussed.

INTRODUCTION

The currently standard hierarchical clustering paradigm for large scale structure formation in a ΛCDM universe has successfully confronted a broad variety of observations, ranging from the formation of galaxy clusters, to large scale velocity fields, to power spectra of the galaxy distribution and of the microwave background, and more (see, e.g., [56]). However, the theory of formation and evolution of galaxies is not in a very satisfactory state. Serious challenges have emerged in the last years ([54]): the excess of predicted small scale structure; the persistent inability of even the best semi-analytic models ([11, 14, 37, 55]) to account for the surface density of massive galaxies at substantial redshifts detected by (sub)-mm surveys with SCUBA and MAMBO ([5, 52]) and by deep K-band surveys ([10, 26]); the difficulties to account for the distribution of velocity dispersions of low-ionization damped Lyman-α systems at z > 1.5 ([48, 49]); the low predicted specific angular momentum of galactic disks ([16, 44]); the observational evidence contradicting the existence of the central cusp in the dark matter distribution, predicted by numerical simulations ([27, 39, 43]). On larger scales, the observed relationship between X-ray luminosity and gas temperature for groups of galaxies strongly deviates from expectations of the simplest hierarchical clustering models.

Solutions of these problems may require advances in different fields that may
include particle physics (self-interacting dark matter?), deviations from a power law of the power spectrum of primordial density perturbations (as may be suggested by WMAP data, 56), or the astrophysics of galaxy formation and evolution. In any case, a better understanding of the complex physical processes governing the galaxy formation is mandatory.

We discuss here how unique information may be provided by the Sunyaev-Zeldovich (SZ) effect. In fact, the the proto-galactic gas is expected to have a large thermal energy content, leading to a detectable SZ signal, both when the protogalaxy collapses with the gas shock-heated to the virial temperature (50, 61), and in a later phase as the result of strong feedback from a flaring active nucleus (1, 25, 31, 41, 42, 47).

**GALAXY-SCALE SUNYAEV-ZELDOVICH EFFECT**

Let us consider a fully ionized gas with a thermal energy density $\epsilon_{\text{gas}}$, within the virial radius

$$R_{\text{vir}} = \left( \frac{3M_{\text{vir}}}{4\pi\rho_{\text{vir}}} \right)^{1/3} \simeq 1.610^2 h^{-2/3}(1+z_{\text{vir}})^{-1} \left( \frac{M_{\text{vir}}}{10^{12} M_\odot} \right)^{1/3} \text{kpc},$$

(1)

where $h$ is the Hubble constant in units of 100km s$^{-1}$ Mpc$^{-1}$ and $\rho_{\text{vir}} \simeq 200 \rho_u$, $\rho_u = 1.88 \times 10^{-29} h^2 (1+z_{\text{vir}})^3$ g cm$^{-3}$ is the mean density of the universe at the virialization redshift $z_{\text{vir}}$.

The Comptonization parameter $y$, characterizing the amplitude of the Sunyaev-Zeldovich effect due to this gas, can be estimated as (64):

$$y \simeq \frac{1}{4} \frac{\Delta \epsilon}{\epsilon_{\text{CMB}}};$$

(2)

here $\epsilon_{\text{CMB}} = a_{BB} T_{\text{CMB}}^4 \simeq 4.2 \times 10^{-13} (1+z)^4$ erg cm$^{-3}$, $a_{BB}$ being the black-body constant and $T_{\text{CMB}} = T_0 (1+z)$ the temperature of the cosmic microwave background (CMB). The amount $\Delta \epsilon$ of gas thermal energy transferred to the CMB through Thomson scattering is:

$$\Delta \epsilon \simeq \epsilon_{\text{gas}} \frac{2(R_{\text{vir}}/c)}{t_c},$$

(3)

t$_c$ being the gas cooling time by Thomson scattering.

A useful reference value for the thermal energy content of the gas, $E_{\text{gas}}$ is its binding energy ($E_{b,\text{gas}} = M_{\text{gas}} v_{\text{vir}}^2$, $v_{\text{vir}} = 162 h^{1/3} (1+z)^{1/2} (M_{\text{vir}}/10^{12} M_\odot)^{1/3}$ km s$^{-1}$ being the circular velocity of the galaxy at its virial radius, cf. 7, 13). The amplitude of the SZ dip in the Rayleigh-Jeans region can be written as:

$$|\Delta T|_{\text{RJ}} \simeq 2y T_{\text{CMB}} \simeq 1.7 \left( \frac{h}{0.5} \right)^2 \left( \frac{1+z_{\text{vir}}}{3.5} \right)^3 \frac{M_{\text{gas}}}{M_{\text{vir}}} \frac{M_{\text{vir}}}{0.1} \frac{E_{\text{gas}}}{10^{12} M_\odot E_{b,\text{gas}}} \mu\text{K}. \quad (4)$$

Although current estimates of the ratio of the mass in stars to the total mass in massive spheroidal galaxies yield average values of $M_{\text{star}}/M_{\text{vir}} \simeq 0.03$ (33, 35), a
value of $M_{\text{gas}}/M_{\text{vir}} \approx 0.1$, close to the cosmic ratio between baryon and total mass density, is likely to be more appropriate for proto-galaxies before a large fraction of the initial gas mass is swept off by the combined action of supernova explosions and of quasar feedback.

The SZ effect in Eq. (4) shows up on small (typically sub-arcmin) angular scales. Quasar-driven blast-waves could inject into the ISM an amount of energy several times higher than the gas binding energy, thus producing larger, if much rarer, SZ signals.

**SZ EFFECT FROM QUASAR FEEDBACK**

Impressively many lines of evidence converge in indicating that the formation of super-massive black holes powering nuclear activity is intimately linked to the formation of their host galaxies ([17, 62]). These include:

- the discovery that Massive Dark Objects (MDOs), with masses in the range $\sim 10^6$–$3 \times 10^9 M_\odot$ and a mass function matching that of baryons accreted onto black holes during the quasar activity ([51]), are present in essentially all local galaxies with a substantial spheroidal component ([28, 30, 32, 53]);
- the tight correlation between the MDO mass ($M_{\text{BH}}$) and the velocity dispersion ($\sigma$) of stars in the host galaxy ([19, 20, 32, 58]), the mass of the spheroidal component ([15, 36]), and the mass of the dark halo [17]; recently [53] have found that the $M_{\text{BH}}$–$\sigma$ correlation is already present at redshift up to $\sim 3$;
- the correspondence between the luminosity function of active star-forming galaxies at $z \approx 3$, the B-band luminosity function of quasars, and the mass function of dark halos at the same redshift ([24, 38]);
the similarity between the evolutionary histories of the luminosity densities of galaxies and quasars (e.g. [9]).

As a consequence, the evolutionary histories of both active nuclei and spheroidal galaxies (or galactic bulges) can only be understood if we properly allow for their mutual feedback. As discussed by [22, 23]), the mutual feedback between galaxies and quasars during their early evolutionary stages may indeed be the key to overcome some of the crises of the currently standard scenario for galaxy evolution.

One ingredient of the scenario proposed by [23] are powerful quasar driven outflows, carrying a considerable fraction of the quasar bolometric luminosity, \( L_{\text{bol}} \), increasing as \( L_{\text{bol}}^{1/2} \) (for emission close to the Eddington limit). For large enough galaxies (\( M_{\text{vir}} \geq 10^{12} M_\odot \)), the interstellar medium (ISM) is eventually swept out, and, correspondingly, the star-formation is switched off, on shorter timescales for more massive objects. The outflows are expected to be highly supersonic, and therefore liable to induce strong shocks, transiently heating the interstellar gas to temperatures exceeding the virial value.

A black-hole (BH) accreting a mass \( M_{\text{BH}} \) with a mass to radiation conversion efficiency \( \epsilon_{\text{BH}} \) releases an energy \( E_{\text{BH}} = \epsilon_{\text{BH}} M_{\text{BH}} c^2 \). We adopt the standard value for the efficiency \( \epsilon_{\text{BH}} = 0.1 \) and assume that a fraction \( f_h = 0.1 \) of the energy is fed in kinetic form and generates strong shocks turning it into heat. Actually the fraction, \( f_h \), of energy going into heating of the interstellar gas may be a function of the BH mass, or of the bolometric luminosity of the active nucleus (AGN). For example, [23] argue that, based on the model for AGN-driven outflows by [40], for emission at the Eddington limit, the fraction of bolometric luminosity released in kinetic form increases as \( L_{\text{bol}}^{1/2} \). This conclusion is, however, model-dependent and we prefer the simpler assumption of a constant value for \( f_h \), that may be viewed as an effective, luminosity weighted value. As discussed by [8, 47], \( f_h \sim 0.1 \) can account for the pre-heating of the intergalactic medium in groups of galaxies.

Using the recent re-assessment by [58] of the well known correlation between the BH mass and the stellar velocity dispersion

\[
M_{\text{BH}} = 1.410^8 \left( \frac{\sigma}{200 \text{ km/s}} \right)^4 M_\odot .
\]  

(5)

we get

\[
\frac{E_{\text{BH}}}{E_{\text{h, gas}}} \approx 4.7 \left( \frac{h}{0.5} \right)^{-2/3} \epsilon_{\text{BH}} \ f_h \ 1 + z_{\text{vir}} \left( \frac{M_{\text{gas}}/M_{\text{vir}}}{0.1} \right)^{-1} \left( \frac{M_{\text{vir}}}{10^{12} M_\odot} \right)^{-1/3} .
\]  

(6)

The amplitude of the SZ dip in the Rayleigh-Jeans region due to quasar heating of the gas is then estimated as:

\[
\left| \left( \frac{\Delta T}{T} \right)_{\text{RJ}} \right| \approx 1.8 \times 10^{-5} f_h \left( \frac{h}{0.5} \right)^2 \left( \frac{\epsilon_{\text{BH}}}{0.1} \right)^{1/2} \left( \frac{E_{\text{BH}}}{10^{42}} \right)^{1/2} \left( \frac{1 + z}{3.5} \right)^3 .
\]  

(7)
FIGURE 2. Power spectra of galaxy-scale SZ effects at 30 GHz, compared to the CMB power spectrum and to the CBI ([34]; large square) and BIMA ([3]; point with 68% confidence error bars and 95% confidence upper limit) data. The dashed lines correspond to SZ effects due to proto-galactic gas, the solid lines to quasar-driven blast-waves. For each set, the steep straight line refers to Poisson fluctuations, the flatter line to fluctuations due to clustering, the uppermost line to the sum (in quadrature) of the two contributions. The dotted line is the sum (in quadrature) of all contributions. The downward arrows signify that, as mentioned in the text, the contributions of proto-galactic gas (dashed lines) are actually upper limits. We also argue that the CBI results (large square) might be, conservatively, interpreted as upper limits.

Following [47], we adopt an isothermal density profile of the galaxy. The virial radius, encompassing a mean density of $200\rho_u$, is then:

$$R_{\text{vir}} \simeq 120 \left( \frac{h}{0.5} \right)^{-1} \left( \frac{E_{\text{BH}}}{10^{62}} \right)^{1/4} \left( \frac{\epsilon_{\text{BH}}}{0.1} \right)^{-1/4} \left( \frac{1 + z_{\text{vir}}}{3.5} \right)^{-3/2} \text{kpc} ,$$

(8)

corresponding to an angular radius:

$$\theta_{\text{SZ}} \simeq 17'' \left( \frac{E_{\text{BH}}}{10^{62}} \right)^{1/4} \left( \frac{\epsilon_{\text{BH}}}{0.1} \right)^{-1/4} \left( \frac{1 + z_{\text{vir}}}{3.5} \right)^{-3/2} \frac{d_A(2.5)}{d_A(z)} ,$$

(9)

where $d_A(z)$ is the angular diameter distance.

COUNTS AND SMALL-SCALE FLUCTUATIONS

The "flux density", which in the Rayleigh-Jeans region is actually negative, associated to the SZ effect is given by (neglecting relativistic corrections):

$$S_{\text{SZ}}(\nu) = \frac{2(kT_{\text{CMB}})^3}{(hc)^2} g(x)y_\omega ,$$

(10)
where \( \omega = \pi \theta_{SZ}^2 \) and

\[
g(x) = \frac{x^4 e^x}{(e^x - 1)^2} \left( x \frac{e^x + 1}{e^x - 1} - 4 \right),
\]

with \( x = h\nu/kT_{CMB} \).

### Quasar-driven SZ signals

The counts of quasar-driven SZ signals, and the corresponding small scale fluctuations, can be estimated from the evolving B-band luminosity function of quasars, \( \phi(L_B, z) \), relating the total amount of energy released, \( E_{BH} \), to the B-band luminosity, \( L_B \). If the quasar radiates at the Eddington limit \( E_{BH} = k_{bol} L_B t_S \), where \( k_{bol} \) is the bolometric correction and \( t_S \approx 4.5 \times 10^7 \) yr is the quasar lifetime for \( \epsilon_{BH} = 0.1 \).

The lifetime, \( t_{SZ} \), of the transient SZ effect due to the quasar-driven blast-waves is approximately the time for the shock to reach the outer border of the host galaxy. Using the expression (12) for the evolution with time of the radius of a self-similar blast-wave expanding in a medium with an isothermal density profile, \( \rho \propto r^{-2} \), we have:

\[
t_{SZ} \approx 1.5 \times 10^8 \left( \frac{h}{0.5} \right)^{-3/2} \left( \frac{E_{BH}}{10^{62} \text{erg}} \right)^{1/8} \left( \frac{\epsilon_{BH}}{0.1} \right)^{-5/8} \left( \frac{f_h}{0.1} \right)^{-1/2} \left( \frac{1+z}{3.5} \right)^{-9/4} \text{yr.}
\]

The number density of SZ sources per unit interval of SZ “flux” \( S_{SZ} \) can then be estimated as

\[
\phi_{SZ}(S_{SZ}, z) = \phi(L_B, z) \frac{t_{SZ}}{t_{q, opt}} \frac{dL_B}{dS_{SZ}},
\]

where \( L_B(S_{SZ}, z) \) is the blue luminosity of a quasar at redshift \( z \) causing an SZ flux \( S_{SZ} \), and \( t_{q, opt} \) is the duration of the optically bright phase of the quasar evolution.

Figure 1 shows, as an example, the predicted counts at 30 GHz, as a function of \( S_{SZ} \), obtained adopting the exponential model for the evolving luminosity function of quasars derived by [46] for an Einstein-de Sitter universe, an Hubble constant of 50 km/s/Mpc, and an optical spectral index of quasars \( \alpha = 0.5 \) \( (S_{\nu} \propto \nu^\alpha) \). The parameters have been set at \( \epsilon_{BH} = 0.1 \), \( f_h = 0.1 \), \( k_{bol} = 10 \), \( t_{q, opt} = 10^7 \) yr.

### SZ signals from proto-galactic gas at virial temperature

As discussed by [22] quasars can be used as effective signposts for massive spheroidal galaxies in their early evolutionary phases; this allows us to bypass the uncertainties in the normalization of the primordial perturbation spectrum affecting estimates based on the various versions of the Press & Schechter formalism. According to [18], the mass of their dark-matter halo, \( M_{vir} \), is related to the mass
of the central black-hole by:

\[
\frac{M_{\text{BH}}}{10^8 M_\odot} \sim 0.1 \left( \frac{M_{\text{vir}}}{10^{12} M_\odot} \right)^{1.65}.
\]  

(14)

Under the assumption that quasars emit at the Eddington limit, the number density of sources with gas at virial temperature, producing SZ dips of amplitude given by Eq. (4), can be straightforwardly related to the quasar luminosity function \( \phi(L_B, z) \) by an equation analogous to Eq. (13), replacing \( t_{SZ} \) with the gas cooling time, \( t_{\text{cool}} \).

The counts shown in Fig. 1 refer to the same cosmological model and the same lifetime of the quasar optically bright phase as above and to \( M_{\text{gas}}/M_{\text{vir}} = 0.1 \). As for the cooling time, which is rather uncertain, we have made the extreme assumption that \( t_{\text{cool}} = t_{\text{exp}} \). Thus the counts plotted have to be taken as upper limits.

**Small scale fluctuations**

The Poisson fluctuations are straightforwardly computed from the counts; since the latter are very steep, the results are insensitive to the upper flux density cutoff.

To estimate fluctuations due to clustering we adopted the spatial correlation function of quasars estimated by [12] for an Einstein-de Sitter universe \( (\xi(r) = (r/r_0)^{-1.58} \), with \( r_0 = 4.29h^{-1}\text{Mpc} \), constant in comoving coordinates), cut-off at \( r = 3r_0 \).

The power spectra of fluctuations due to both the gas in virial equilibrium and heated by the quasar feedback are compared, in Fig. 2, with the recent measurements of arcminute scale fluctuations at 30 GHz by the CBI ([34]) and BIMA ([13]) experiments. We stress again that our estimated of signal from the gas at the virial temperature is based on an over-simplified treatment. In fact, the thermal history of the protogalactic gas is quite complex: only a fraction of it may be heated to the virial temperature ([2, 4]); cooling may be relatively rapid in the densest regions; on the other hand, significant heating may be provided by supernovae and by the central active nucleus. Also, we expect that ([23]), particularly in the case of the most massive halos virializing at high \( z \), the quasar feedback removes the residual interstellar gas on a timescale ranging to 0.5 to a few Gyrs. Thus, again, the results shown in Fig. 2 are (possibly generous) upper limits.

**DISCUSSION AND CONCLUSIONS**

Evidences of statistically significant detections at 30 GHz of arcminute scale fluctuations in excess of predictions for primordial anisotropies of the cosmic microwave background (CMB) and also in excess of the estimated contamination by extragalactic radio sources have recently been obtained by the CBI ([34]) and BIMA ([13]) experiments.
It may be noted that, although the CBI group applied a quite elaborated treatment of radio-sources, the sensitivity of their 31 GHz point source observations does not really guarantee proper allowance for this foreground. Their strategy comprised pointed 31 GHz observations with a $4\sigma$ detection limit of $S_{31\text{GHz}} = 6\text{mJy}$, of all NVSS sources with $S_{1.4\text{GHz}} \geq 6\text{mJy}$ and a direct survey reaching a flux limit of $S_{\text{lim,31GHz}} = 6\text{mJy}$, over an area of 1.8 square degrees. If the slope of their 31 GHz counts keeps constant down to flux densities several times lower than $S_{\text{lim,31GHz}}$, the Poisson fluctuations due to sources below the detection limit amount to $\approx 30\mu\text{K}$, and may entirely account for the measured signal. Thus, their excess signal (15-30 $\mu\text{K}$ in the multipole range $\ell = 2000$–$4000$) may be more conservatively interpreted as an upper limit.

The BIMA group ([13]) carried out a VLA survey at 4.8 GHz of their fields down to a flux density limit of $\sim 150\mu\text{Jy}$ to identify and remove point sources. In this case, the residual contamination is indeed likely to be small, at the cost of a loss of sensitivity.

If indeed the detected signal cannot be attributed to extragalactic radio sources, its most likely source is the thermal SZ effect ([21]). The SZ within rich clusters of galaxies has been extensively investigated ([6, 28]). The estimated power spectrum was found to be very sensitive to the normalization ($\sigma_8$) of the density perturbation spectrum. A normalization $\sigma_8 \geq 1$, somewhat higher than indicated by other data sets, is apparently required to account for the CBI data. High resolution hydrodynamical simulations of structure formation ([60, 63]) have highlighted the presence of substantial SZ structure on sub-arcmin scales.

We have carried out an analytical investigation of the SZ signals associated to the formation of spheroidal galaxies. We find that they are potentially able to account for the BIMA results. Proto-galactic gas heated at the virial temperature and with a cooling time comparable with the expansion time may provide the dominant contribution; in this case we expect clustering fluctuations of amplitude comparable to Poisson fluctuations, although with a flatter power spectrum.

Potentially detectable SZ signals can also be produced by strong feedback from the central active nucleus. It is, in fact, becoming increasingly clear that the interplay between star-formation and nuclear activity plays a key role in shaping the early evolution of both the host galaxy and the active nucleus. The enormous amounts of energy that the active nuclei (AGNs) release to their environment, not only in radiative but also in kinetic form, can strongly influence the gas both in the host galaxy and in the surrounding intergalactic medium, with conspicuous effects on X-ray emission and on the SZ signal. A flaring AGN can drive an energetic shock, causing a transient, strong rise of the average gas pressure and, consequently, of the amplitude of the SZ effect. These signals are much rarer but can individually reach substantially higher values.

High frequency surveys with sub-arcmin resolution can directly detect individual SZ sources. We expect a surface density of $\approx 1\text{deg}^{-2}$ at $S_{90\text{GHz}} \approx 1\text{mJy}$. Of course, the counts at these relatively bright fluxes are likely dominated by SZ effects in clusters of galaxies, which however should be easily distinguishable because of their much larger angular size and much lower redshift.

We thus conclude that the SZ effect is an effective probe of the thermal state
of the gas, of its evolution and, in particular, of the AGN feedback. The main parameter governing the global effect on the ambient medium of the energy released by AGNs is the ratio, $\Delta E/E$, between the amount of energy deposited in the medium and the binding energy of the receiving gas. $\Delta E/E$ can plausibly be $\geq 1$ for very massive galaxies and small groups, but is $\ll 1$ for rich clusters. Qualitatively different effects are therefore expected in the two cases. If $\Delta E/E \geq 1$ the energy injection heats the gas and partially ejects it out of the potential well. This may lead directly to a correlation between the black-hole mass and the velocity dispersion of stars (or the bulge mass) with slope and normalization in nice agreement with the data. Also, the ensuing increase of the gas temperature and decrease of the X-ray luminosity (because of the decreased gas density) may explain the deviation of the observed $T-L_X$ from predictions of the hierarchical clustering scenario, in the presence of gravitational effects only. Ongoing and forthcoming high resolution surveys in the cm/mm region may directly test this scenario. Clearly theSZ effect is a much more effective probe of the thermal energy content of the plasma than the X-ray emission. The former is in fact an almost perfect calorimeter (R), being directly proportional to the thermal energy. On the contrary, X-ray emission is very sensitive to the details of the density distribution of the emitting gas.

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