

Sunyaev-Zel'dovich constraints from black hole-seeded proto-galaxies

N. Aghanim¹, C. Balland¹, and J. Silk²

¹ Université Paris Sud, IAS-CNRS, Bâtiment 121, 91405 Orsay Cedex, France

² University of Oxford, Department of Astrophysics, NAPL, Keble Road, Oxford OX13RH, UK

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Abstract. Recent studies of galactic nuclei suggest that most galaxies are seeded by super-massive black holes which power the central nucleus. In this picture, the proto-galactic object is likely to have undergone a very active phase during which the surrounding medium was shocked and heated up to very high temperatures. We predict the cosmological effects of this scenario in terms of the thermal and kinetic Sunyaev-Zel'dovich distortions induced on galactic scales by a population of proto-galaxies. These predictions are compared to the observational limit on the mean Compton distortion set by the COBE-FIRAS instrument. This enables us to derive tight constraints on the fraction of proto-galaxies seeded by super-massive black holes as well as on the black hole-to-spheroid mass ratio. Finally, we estimate the contribution of such a population to the angular power spectrum of the Cosmic Microwave Background temperature anisotropies on very small angular scales ($l \simeq 10^4 - 10^5$).

Key words: Galaxy: formation – cosmology: cosmic microwave background

1. Introduction

Most theories of hierarchical structure formation are based on the study of the evolution of density perturbations under their own gravity. A density fluctuation, which represents an over- (or under-) density with respect to the mean matter distribution, contains both baryonic and dark matter (DM). The baryonic component sinks into the gravitational potential of the DM halo. It collapses and cools, resulting in star formation. In these scenarios, after the gravitational collapse of the DM halo, stars are assumed to be the first objects to form. A structure will thus end up as an emitting object after virialisation has occurred.

An alternative picture involves the formation of a super-massive black hole (BH) that powers the central regions of galaxies (Lynden-Bell 1969). Numerous studies have been performed that relate the quasar luminosity function to galaxy formation scenarios by assuming that the formation of quasars (i.e., BH) in the potential well of the DM halos constitutes one of the phases in the galaxy formation process (Efstathiou & Rees 1988; Haehnelt & Rees 1993;

Nusser & Silk 1993; Haiman & Loeb 1997). Recent observations even suggest that a super-massive BH may be present in the centres of all galaxies with spheroidal components (Kormendy & Richstone 1995).

Several authors have looked at several consequences of the presence of massive BHs on galaxy formation and evolution (Haiman & Loeb 1997; Natarajan et al. 1998; Silk & Rees 1998). In this paper, we investigate the cosmological implications of such an alternative scenario for the Cosmic Microwave Background (CMB) anisotropies and spectral distortions. More specifically, we study the effects of the outflows, driven by the BH activity, on the gas within the seeded proto-galaxy. In fact, the outflow expands and shock-heats the ambient medium (proto-galactic gas), and then interacts with the inter-galactic medium (IGM). Three regimes of interest may be considered: 1) the high density region of the proto-galaxy, 2) the low density IGM and 3) the thin compressed layer (four times denser than the IGM) induced by the front shock. The second and third regimes give results very similar to those computed in Aghanim et al. (1996). We thus focus on the first regime, i.e. the localised effects of the BH-driven shock on the gas within the seeded proto-galaxy. This shock-heated gas will Compton scatter the CMB photons and induce spectral distortions and temperature anisotropies through the so-called Sunyaev-Zel'dovich (SZ) effect (Sunyaev & Zel'dovich 1980). The thermal SZ effect depresses the CMB brightness in the Rayleigh-Jeans region and increases it above a frequency of about 219 GHz. Its amplitude represents the integral along the line of sight of the electron pressure. It is proportional to the electron density n_e and is characterised by the Compton parameter y defined by:

$$y = 2 \int_0^R \frac{kT}{m_e c^2} \sigma_T n_e(l) dl, \quad (1)$$

where T is the temperature of the gas, R the physical size of the structure, m_e the electron mass, k the Boltzmann constant, c the speed of light and σ_T the Thomson cross section. An additional secondary anisotropy arises due to the first-order Doppler effect of the CMB photons when they scatter on a structure moving with respect to the Hubble flow, with radial peculiar velocity v_r . This interaction is called the SZ kinetic effect. It generates an

anisotropy, with no specific spectral signature, whose amplitude is given by:

$$\frac{\delta T}{T} = \frac{v_r}{c} \times \left(2 \int_0^R \sigma_T n_e(l) dl \right). \quad (2)$$

Previous work on galaxy formation has evaluated the global distortion of a population of galaxies in the virialised regime. The global Compton parameter was found to be much smaller than the constraints set by the FIRAS instrument (Far InfraRed Absolute Spectro-photometer) on board COBE (COsmic Background Explorer) (Fixsen et al. 1996) on the global SZ distortion of the universe. By contrast, our model focuses on a regime in which proto-galaxies undergo a BH formation phase that induces larger distortions. The paper is organised as follows: in Sect. 2, we model the shock in an individual structure and give its physical characteristics (size and temperature). In Sect. 3, we compute the predicted number density of primordial galaxies, using the Press & Schechter (1974) mass function. In Sect. 4, we generalise the description of the shock to the whole population of proto-galaxies and we simulate maps of the induced secondary anisotropies. We estimate this contribution to the CMB anisotropies. We also compare our predicted global y parameter to the COBE-FIRAS value and derive constraints on the model. Conclusions are given in the last section.

2. Modelling the shock

In the galaxy formation canonical scenario, a galaxy forms in the gravitational potential well of a DM halo of mass M_{halo} . Following Silk & Rees (1998), we consider that each forming galaxy, which is fully described by the mass M_{halo} , hosts a super-massive BH. The fraction of seeded proto-galaxies is thus 100%. For the sake of simplicity, we assume that all proto-galaxies are spheroids. A more refined and accurate description would take into account morphological segregation (Balland et al. 1998). However, these effects do not introduce significant differences. We assume that the BH radiates during its lifetime t_{BH} a fraction $\epsilon_E = 0.1 - 0.2$ (Natarajan & Sigurdsson 1999) of its Eddington luminosity ($L_{BH} = \epsilon_E L_{edd}$). The latter is fixed by the BH mass, M_{BH} :

$$L_{edd} = \frac{4\pi M_{BH} m_p G c}{\sigma_T}, \quad (3)$$

where m_p is the proton mass and G the gravitational constant. The mass of the BH should be directly related to the mass of the proto-galaxy it seeds, and thus to the fraction of baryonic matter locked up in the spheroid in which the central BH collapses. We assume a simple relation of proportionality ($M_{BH} = \epsilon_{BH} M_{sph}$) between the mass of the BH and the mass of the spheroid M_{sph} . Haehnelt & Rees (1993) give $\epsilon_{BH} \simeq 10^{-3}$ and they assume that ϵ_{BH} declines with mass. However, observations of galactic nuclei (Kormendy et al. 1997; Magorrian et al. 1998) indicate that ϵ_{BH} is relatively constant. Here, we take the value $\epsilon_{BH} = 2.10^{-3}$ as advocated by Magorrian et al. (1998) and Silk & Rees (1998). We

assume that the medium is instantaneously ionised, which is very likely due to the intense radiation emitted by the central BH (Voit 1996). We therefore study the propagation of a strong shock driven by a mechanical energy which represents some fraction of the BH luminosity. The first analytic solutions of spherically symmetric explosions were given by Taylor (1950) and Sedov (1959) and applied to several astrophysical problems such as stellar winds and supernovae explosions (Ikeuchi et al. 1983; Bertschinger 1986; Koo & McKee 1992a,b; Voit 1996). Following Voit (1996), we study the expansion of the shock and its effects on the gas within the seeded proto-galaxy. We characterise the shock in an expanding universe by a set of physical properties (its radius, velocity and temperature). Adapting Voit's solutions to our study, the shock at a redshift $z < z_*$, where z_* is the redshift at which the BH switches on, has a radius R_s which reads as:

$$R_s \simeq \left(\frac{\pi G E_0}{H_0^4 \delta \Omega_0^3} \right)^{1/5} \frac{(1 + \Omega_0 z_*)^{1/5}}{(1 + z_*)^{2/5}} \times \left[1 - \left(\frac{1 + \Omega_0 z}{1 + \Omega_0 z_*} \right)^{1/2} \right]^{2/5} (1 + z)^{-1}. \quad (4)$$

It propagates at a velocity

$$v_s = \frac{2}{5} \left[\frac{\pi E_0 H_0 G}{3 \delta \Omega_b} \frac{\Omega_0^2 (1 + z_*)^3}{(1 + \Omega_0 z_*)^3} \right]^{1/5} \times \left[1 - \left(\frac{1 + \Omega_0 z}{1 + \Omega_0 z_*} \right)^{1/2} \right]^{-3/5} \left(\frac{1 + z}{1 + z_*} \right). \quad (5)$$

In the two previous equations, $E_0 = \epsilon L_{BH} t_{BH}$ represents the mechanical energy which drives the shock. Very little is known about the fraction ϵ which can be on the order of 0.5 or even higher (Natarajan & Sigurdsson 1999). For the lifetime of the BH in the bright phase, we choose the recent value derived by Haiman & Loeb (1997): $t_{BH} = 10^6$ years (our results, however, are not very sensitive to the exact value of t_{BH}). δ is the mean over-density of the proto-galaxy (assumed to be spherical), H_0 is the Hubble constant, Ω_0 is the density parameter and Ω_b is the baryon density in the universe. Zero subscripts denote present day values. In the following and throughout the paper, we use $h = H_0 / (100 \text{ km/Mpc/s}) = 0.5$ and $\Omega_b = 0.06$ (Walker et al. 1991) and give the results as a function of Ω_0 , for $\Omega_0 = 1$ and $\Omega_0 = 0.3$.

Following Natarajan & Sigurdsson (1999), we assume that the BH radiates 10% of its Eddington luminosity, i.e. $\epsilon_E = 0.1$ and that half of the corresponding energy is mechanical. Furthermore, we consider that galaxies form at sufficiently high redshifts (> 5) so that only hydrogen and helium are present in substantial amounts. We compute both the size and velocity of the shock and find that the host proto-galaxy is always embedded in the shocked region.

2.1. Cooling mechanisms

The temperature of the shocked medium can be directly derived from the equipartition of energy:

$$T \simeq v_s^2 \mu m_p / k. \quad (6)$$

Here, $\mu = 0.6$ is the mean molecular weight of a plasma with primordial abundances. The galactic matter can be shock-heated up to very high temperatures. For the most massive galaxies, we find that the matter is heated up to a few 10^8 K, a value comparable to the temperature of the intracluster medium in galaxy clusters. For these temperatures and redshifts (> 5), the main cooling process at play is bremsstrahlung. Therefore, the shocked gas loses heat with a cooling rate given by a temperature-dependent cooling function $\Lambda(T)$. We have compared three different cooling functions (Bertschinger 1986; Koo & McKee 1992a; Voit 1996) given in the literature for temperatures between a few 10^5 and 10^8 K. We find that the condition required for efficient cooling is always satisfied in our redshift range. This means that the cooling time, given by $t_{cool} = 5kT/n_H\Lambda(T)$ with n_H the hydrogen number density, is always smaller than the age of universe. Cooling is thus very efficient in our picture. The comparison between the three cooling functions shows that they all give essentially the same final temperature after cooling. We follow Bertschinger (1986) and we find that the shocked matter cools down to $T \simeq 10^5$ K at $z \simeq 5$.

3. Number counts of primordial galaxies

In order to quantify the global effect of the formation of primordial galaxies on the CMB, we apply our formalism to a synthetic population of galaxies with masses $10^9 M_\odot \leq M \leq 10^{12} M_\odot$.

We first assume that the galaxy number density traces, within a linear bias, the abundance of collapsed DM halos, as predicted by the Press–Schechter (PS) mass function (Press & Schechter 1974). We use an initial power-law spectrum with an effective spectral index $n = -2$ on galaxy scales. We express the amplitude of primordial matter fluctuations in terms of the rms variance in spheres of $8h^{-1}$ Mpc, $\sigma_8 = 0.6$ (as cluster-normalised, e.g. Viana & Liddle (1996)), which corresponds to a bias factor $b \simeq 1.67$. For $\Omega_0 = 1$, the set of parameters corresponds to the “standard” biased cold DM model, which does fit neither small- and large-scale velocities (Vittorio et al. 1986) nor COBE normalisation. However, we take it as a study case for the computations, our second model is the low density cosmological model with $\Omega_0 0.3$. In our picture (no stars are formed yet), the spheroid is gaseous. Its mass is related to the mass of the DM halo via $M_{sph} = \frac{1}{3} M_{halo}$. The mass and luminosity of the central BH and thus the predicted SZ distortions are therefore inferred from M_{sph} ($M_{BH} = \epsilon_{BH} M_{sph}$, and $\epsilon_{BH} = 2 \cdot 10^{-3}$; cf Sect. 2).

To compute the kinetic SZ term of a population of proto-galaxies, we need an estimate of their peculiar velocities with respect to the reference frame. As suggested by numerical simulations (Bahcall et al. 1994; Moscardini et al. 1996), we assume that velocities follow a Gaussian distribution. The peculiar velocity of each proto-galaxy is drawn from a Gaussian which is

completely defined by its rms value σ_v . In the range of redshifts we have adopted, the structures are in the linear regime, so that $\sigma_v(z) = \sigma_0 f(z)$, where the redshift dependence of the velocities is given by $f(z)$ (Peebles 1980, 1993) as a function of the cosmological parameters. In this equation, σ_0 is the present-day rms peculiar velocity. It is related to the mass variance on mass scale M , $\sigma(M) = (1.19\Omega_0)^{(n+3)/6} \sigma_8 M^{-(n+3)/6}$ (Mathiesen & Evrard 1998), where n is the index of the power spectrum. The rms velocity can thus be computed for each mass scale.

4. Results and discussion

The shock-heated gas within proto-galaxies interacts with the CMB photons through the SZ effect (thermal and kinetic). These interactions generate secondary temperature anisotropies and spectral distortions. We simulate maps of the secondary anisotropies generated by a population of seeded proto-galaxies formed between redshift 5 and 10. The maps have a resolution of about 0.2 arcseconds to resolve the galaxies and contain 600×600 pixels. The number of sources of mass M at redshift z is derived from the PS mass function. Their positions are drawn at random in the map. The y and $\delta T/T$ profiles for, respectively, the thermal and the kinetic effects are directly derived from the integration of the gas profile $n_e(R)$ along the line of sight (Eqs. 1 and 2) assuming spherical symmetry.

Similarly to the case of galaxy clusters, we assume that in the early stages of formation the gas settles into a hydrostatic equilibrium within the DM potential. A universal density profile is motivated by Navarro et al. (1996). However, the gas profile may be softer than that of the DM, and moreover the existence of a central cusp is “unobserved” (Krautsov et al. 1998). We thus conservatively adopt the following parametrised profile for the gas distribution:

$$n_e(R) = n_0 \left[1 + \left(\frac{R}{R_c} \right)^2 \right]^{-\alpha}, \quad (7)$$

where n_0 is the central density. α is left as a free parameter describing the steepness of the profile, whereas R_c is identified with a core radius as in galaxy clusters. On cluster scales, R_c is typically 10 to 30 times smaller than the cluster virial radius R_{vir} . In our model, we introduce the parameter $p = R_{vir}/R_c$ which we vary, similarly to clusters, between 10 and 30. The central density n_0 can be derived from the gas mass of the proto-galaxy using the following equation:

$$M_{sph} \left(\frac{\Omega_b}{\Omega_0} \right) = m_p \mu \int_0^{R_{vir}} n_e(R) 4\pi R^2 dR, \quad (8)$$

where the virial radius of the structure is given by:

$$R_{vir} = \frac{(GM)^{1/3}}{(3\pi H_0)^{2/3}} \frac{1}{1 + z_{coll}}, \quad (9)$$

for a critical universe. It is fixed solely by the mass and the collapse redshift z_{coll} .

We will give the results for a flat model with no cosmological constant ($\Omega_0 = 1$) and an open model ($\Omega_0 = 0.3$). Varying the

cosmological parameters will vary the number of proto-galaxies along the line of sight as well as their peculiar velocities. It will also modify their physical properties, i.e. the size and velocity of the shock and thus the gas temperature. The two cosmological models represent the upper and lower bounds between which all other cosmological models involving a non-zero cosmological constant fall.

4.1. Compton distortion

The CMB photons, scattering off the electrons of the ionised hot gas, induce a spectral distortion whose amplitude is given by Eq. 1. The FIRAS experiment has measured the mean Compton parameter resulting from all the interactions undergone by the photons. The result is $\bar{y}_{FIRAS} = 1.5 \cdot 10^{-5}$ (Fixsen et al. 1996). This stringent observational limit incorporates the (negligible) contribution of the rather cold intergalactic medium and that of all other extragalactic signals. Among these signals, there is the contribution of the hot ionised gas in galaxy clusters. The global distortion induced by intra-cluster gas has been computed (De Luca et al. 1995; Barbosa et al. 1996), and found to be of the order of a few 10^{-6} . In addition to galaxy clusters, one has to take into account the contribution of the proto-galaxy population in terms of the overall Compton distortion, \bar{y}_{PG} , induced by the scattering of CMB photons on the shock-heated gas.

Based on simulated maps, we predict \bar{y}_{PG} and we compare it to the limit set by COBE-FIRAS. Among all the parameters of the model, there are four major quantities that substantially affect the predictions of the mean Compton parameter. Two of them, α and p , are related to the gas distribution (Eq. 7). The two others are the fraction, f , of BH-seeded proto-galaxies and the BH-to-spheroid mass ratio ϵ_{BH} . We compare our predicted overall distortion to the COBE-FIRAS limit and look for the combinations of parameters for which our predictions fit the observations. This allows us to constrain the assumptions of our model.

For $\alpha = 1/2$, $f = 100\%$, $\epsilon_{BH} = 2 \cdot 10^{-3}$ and both cosmological models, we find $\bar{y}_{PG} \simeq 10^{-4}$ which exceeds the observational value. In order for our prediction to be reconciled with the COBE-FIRAS limit, f must be only a few percent. This constraint on f strongly violates the actual observations (Magorrian et al. 1998; Richstone et al. 1998). $\alpha = 1/2$ is thus excluded by the limit on the global distortion whatever value we choose for $p = R_{vir}/R_c$.

For $\alpha = 1$ (i.e. an isothermal profile), an $\Omega_0 = 1$ model, $f = 100\%$ and $\epsilon_{BH} = 2 \cdot 10^{-3}$, we find $\bar{y}_{PG} > \bar{y}_{FIRAS}$ whatever we adopt for p . The fraction f must be smaller than 75% for the prediction to be compatible with the observational limit. Again, this fraction is significantly smaller than the 95% advocated by Magorrian et al. (1998). Such a constraint could rule out the isothermal profile. However, up to now, ϵ_{BH} was assumed to be constant and equal to $2 \cdot 10^{-3}$. If we now use the lower limit of Magorrian et al. (1998), that is $\epsilon_{BH} = 10^{-3}$, together with $f = 95\%$ or higher there is only a marginal agreement for $p \sim 30$ between the predicted and measured distortions. In the open model case ($\Omega_0 = 0.3$), we find approximately the same

results. For \bar{y}_{PG} to be compatible with \bar{y}_{FIRAS} , if $p = 10$, the fraction of BH seeded proto-galaxies should be smaller than 80% if $\epsilon_{BH} = 2 \cdot 10^{-3}$ or $f < 95\%$ if $\epsilon_{BH} = 10^{-3}$. The predictions for $p = 30$ agree with observations in all the cases.

For $\alpha = 3/2$ (i.e. the gas profile approximates a King profile) and for both cosmological models, we find \bar{y}_{PG} of about 10^{-6} to a few 10^{-6} , a prediction compatible with \bar{y}_{FIRAS} . This result remains valid for all values of p between 10 and 30 including the highest boundaries of f and ϵ_{BH} , respectively, 100% and $2 \cdot 10^{-3}$.

4.2. Predicting the angular power spectrum

We choose the set of parameters associated with the isothermal profile which agrees with the COBE-FIRAS limit: $\alpha = 1$, $p = 30$, $f = 95\%$ and $\epsilon_{BH} = 2 \cdot 10^{-3}$. Within this context, we predict the upper limit on the contribution to secondary temperature anisotropies induced by the SZ, thermal and kinetic effects, of the proto-galactic gas. We express this contribution in terms of an angular power spectrum plotted in Fig. 1 together with the main other well-known secondary anisotropies.

At very small scales ($l \sim$ a few 10^5) corresponding to galactic scales, the kinetic SZ contribution of the shock-heated gas (Fig. 1, thick solid line for $\Omega_0 = 1$ and thick dashed line for $\Omega_0 = 0.3$) is very large. It is interesting to note the good agreement between our results and those obtained by Peebles & Juszkiewicz (1998) for the scattering of the CMB photons by the cloudy proto-galactic plasma. The power spectrum of the kinetic SZ anisotropies for the $\Omega_0 = 0.3$ model is significantly larger than the $\Omega_0 = 1$ model. This is mainly due to the higher number of sources per unit comoving volume in open models. In all other flat cosmological models involving a non-zero cosmological constant, the power spectrum will lie between the two curves. The expected power spectrum due to the thermal SZ effect is not plotted in this figure. It is more than one order of magnitude smaller than the kinetic effect contribution. This is due to the efficiency of bremsstrahlung cooling which lowers the temperature down to a few 10^5 K.

We compare the contribution of the proto-galaxies due to their SZ kinetic effect to the major sources of secondary temperature anisotropies. In each case, we choose the most extreme cases for the comparison with our upper limit prediction. The power spectra displayed in Fig. 1 are taken from the literature. The dotted line represents the upper limit of the contribution of the inhomogeneous reionisation as computed by Aghanim et al. (1996) for a quasar lifetime of 10^7 yrs. The dot-dashed line represents the Rees-Sciama effect (Rees & Sciama 1968) taken from Seljak (1996) ($\sigma_8 = 1$, $\Omega_0 h = 0.25$). The dashed line represents the galaxy cluster contribution due to kinetic SZ effect from Aghanim et al. (1998) with a cut-off mass of $10^{14} M_\odot$. The triple-dot-dashed line represents the Vishniac-Ostriker effect (Ostriker & Vishniac 1986; Vishniac 1987) computed by Hu & White (1996) with a total reionisation occurring at $z_i = 10$. Finally, the solid thin line represents the power spectrum of the primary CMB anisotropies in a standard cold DM model computed using the CMBFAST code

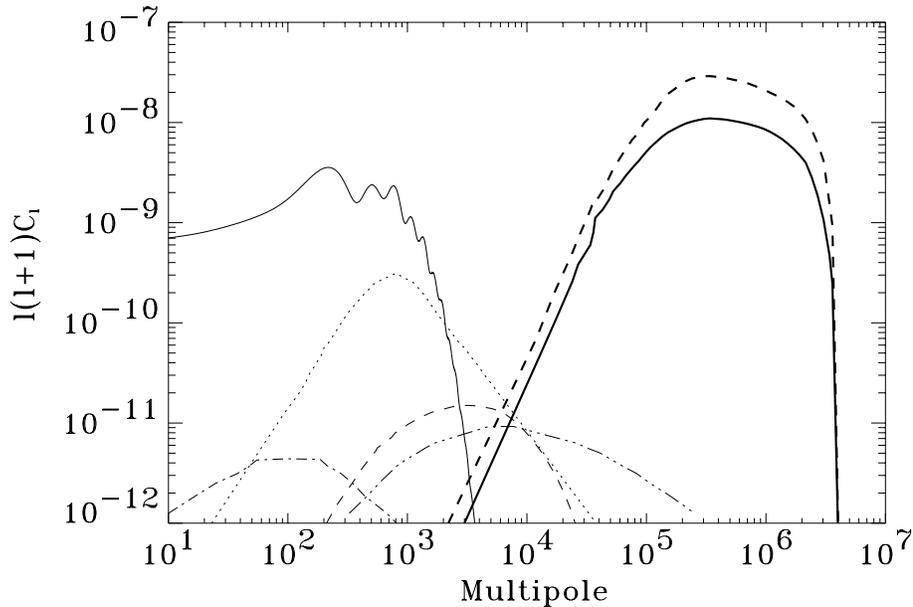


Fig. 1. Power spectrum of the temperature anisotropies. The solid thin line represents the CMB primary anisotropies. The solid thick line represents the SZ kinetic effect of the proto-galaxies for $\Omega_0 = 1$. The thick dashed line is obtained for $\Omega_0 = 0.3$. The triple-dotted-dashed line represents the Vishniac-Ostriker effect. The dashed and dotted-dashed lines represent respectively the galaxy cluster contribution due to the kinetic SZ effect and the Rees-Sciama effect.

(Seljak & Zaldarriaga 1996). The primary CMB anisotropies dominate at all scales larger than the damping around 5 arcminutes. At intermediate scales, several effects take place among which the inhomogeneous reionisation, the Ostriker-Vishniac and the SZ effect. In Fig. 1, we do not plot the power spectra of the thermal SZ effect of galaxy clusters. It is about one order of magnitude larger than the kinetic SZ effect. At very small scales, the anisotropies are totally dominated by the proto-galactic contribution.

5. Conclusions

Previous studies on galaxy formation have evaluated the global distortion of a population of galaxies in the virialised regime. In these studies, the global Compton parameter was found to be very small, and smaller than the COBE-FIRAS value. In contrast, our model focuses on a regime in which proto-galaxies undergo a BH formation phase. During this phase, the proto-galactic matter is shock-heated up to a few 10^8 K and cools down to 10^5 K. CMB photons undergo inverse Compton scattering on the heated gas. In addition, galaxy peculiar motions induce temperature anisotropies through the SZ kinetic effect. We have estimated the global Compton parameter due to a population of proto-galaxies and the expected power spectrum of the induced secondary anisotropies. We find that there are four main parameters that control our model: the fraction f of BH-seeded proto-galaxies, the fraction ϵ_{BH} of the spheroid mass in the BH, the steepness of the density profile α and the gas core radius $p = R_{vir}/R_c$. The comparison between our predictions and the COBE-FIRAS observation constrains these parameters. Given the observed fraction of seeded galaxies, $f = 95\%$, our results put rather strong constraints on the density profile and on ϵ_{BH} . Indeed, our predictions agree with the observations whatever p if the density profile is an approximation to a King profile. On the contrary, if the density profile is isothermal, then

the core radius must be at least 30 times smaller than the virial radius and the BH-to-spheroid mass ratio has to be small, of the order of 10^{-3} . The computations in the two extreme cosmological models show that the global Compton parameter due to proto-galaxies is not very sensitive to Ω_0 .

We compare the power spectra of the different contributions to the temperature anisotropies. Our results show that the SZ effect of the very early shock-heated proto-galaxies could constitute the major source of CMB distortions on very small scales (arcsecond and sub-arcsecond scales). The anisotropies are likely to be detected and measured by future long baseline interferometers such as ALMA. The shock heating is likely to contribute to the re-heating of the proto-galactic gas, which plays a role in galaxy formation theory. Blanchard et al. (1992) used preheating to modify the galaxy luminosity function, suppressing and finally delaying dwarf galaxy formation. We do not take into account this effect in our model, therefore, our results should be taken as an upper limit to the proto-galaxy contribution in terms of secondary anisotropies.

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