

Inhomogeneous Comptonization of CMB by Cosmological Blastwaves

P. Platania¹, M. Bersanelli², C. Burigana³, E. Lazzaro⁴

¹*Dipartimento di Fisica Universita' degli Studi, Via Celoria 16 20133, Milan, Italy*

²*IFCTR - CNR - Via Bassini 15, 20133 Milan, Italy*

³*TESRE - CNR - Bologna, Italy*

⁴*IFP - CNR - Via R. Cozzi 53, 20125 Milan, Italy*

1-Motivation

The anisotropy of Cosmic Microwave Background (CMB) radiation is a very powerful tool to study the Early Universe: inhomogeneities on angular scales $\vartheta > 2^\circ \Omega^{1/2}$ (where Ω is the total density of the Universe in units of critical density) reflect the primordial angular distribution because they were not causally connected at the epoch of last scattering, while inhomogeneities at $\vartheta < 2^\circ \Omega^{1/2}$ provide a good test of the influence of causal processes on the CMB. New precise measurements, such as the BOOMERANG and MAXIMA-1 recent results, on the CMB anisotropies down to $\vartheta \sim 15'$ - $10'$ of angular scale provide strong constraints on models for the Early Universe [1,2]. The future space mission Planck Surveyor [3], dedicated to imaging the CMB anisotropies, will look down to a few arcminutes angular scale where the amplitude of the anisotropies is sensitive also to models of structure formation. In fact secondary anisotropies from the reionization process could give a significant contribution to temperature inhomogeneities ($\Delta T/T$) at those angular scales.

The nature of reionization is still a great uncertainty; nevertheless, there is evidence from cosmological observational results that the intergalactic medium (IGM) is highly ionized at redshift $z \sim 4$ [4], probably due to some kind of energy injection from astrophysical sources after the recombination of the primeval plasma at $z \sim 1100$. In fact distant quasars (QSOs) spectra do not show the continuum of absorption expected for neutral hydrogen (Gunn-Peterson test) [5]. The nature of the sources causing the IGM reionization is still not exactly known but the most popular candidates are forming galaxies, massive stars and high- z quasars [6]; possible mechanisms for heating the IGM are photoionization [7 and references therein], and shocks by hot blastwaves [8 and references therein].

In this work we focus our attention on the latter scenario involving outflows from highly energetic QSO's that blow bubbles of hot gas expanding in the surrounding environment. We are particularly interested in the interaction via Compton scattering between the electrons in the expanding bubble and the Cosmic Microwave Background (CMB) photons; the effect is known as thermal Sunyaev-Zel'dovich [9] effect (hereafter S-Z) and produces distortion on the CMB radiation spectrum and inhomogeneities on its spatial distribution across the sky. We choose two very different environments in which the blastwaves expand the IGM or the much more dense gas of the host galaxy. In the first case we focus our attention on the possible relevance of a global S-Z effect from a freely expanding "hollow" blastwaves population (Section 2), in the second on the S-Z effect of a distribution of dense blastwaves of small angular width (Section 3) and want to verify if effects associated with them are potentially observable by Planck Surveyor.

¹ The redshift is defined by $z = \lambda_{\text{obs}}/\lambda_{\text{rest}} - 1$, where λ_{obs} is the observed wavelength of an atomic line of a distant galaxy and λ_{rest} is the proper wavelength of the same line. The redshift z is used as a measure of time and $z=0$ means the present time.

2- Model of Cosmological Blastwave “Fog” and its effect on the CMB

Many authors have extensively studied the problem of energy injection from explosions in the IGM [10]. We follow the exhaustive theoretical study of [11] focusing on the case of cosmological adiabatic blastwaves (with $\rho^{1-\gamma}T = \text{const}$ and $\gamma = 5/3$) for which the authors found a self-similar solution for the evolution's equations. In [8] the relevant quantities from [11] are expressed with simple analytical formulae, in terms of cosmological parameters, explosion initial energy and redshift. For a bubbles with spherical shock wave structure produced by an explosive event at $z = z_1$, with an initial energy E_0 , the shock radius as function of z , is given by:

$$R(z) = 7.5[(1 + \Omega_0 z_1) / \Omega_0^2 (1 + z_1)^2]^{3/2} E_0^{3/2} h_{50}^{-4} / 5 \Omega_{\text{IGM}}^{-1/5} [1 - ((1 + \Omega_0 z) / (1 + \Omega_0 z_1))^{1/2}]^{2/5} (1 + z)^{-1}$$

in Mpc (1 pc = 3.088×10^{18} cm), where $\Omega_0 = \rho_0 / \rho_c$ is the mass density in units of critical density $\rho_c = 3 \cdot H_0^2 / 8\pi G$ with the Hubble constant H_0 giving the present Universe expansion rate; E_0 is the initial energy in units of 10^{61} erg; h_{50} is the Hubble constant in units of $H_0 / 50$ (km/sec Mpc); $\Omega_{\text{IGM}} = \rho_{\text{IGM}} / \rho_c$ is the density of the IGM in units of critical density. The velocity of the spherical shock front as function of z is in km/s:

$$v_s(z) = 75[\Omega_0^2 (1 + z_1)^2 / (1 + \Omega_0 z_1)]^{0.3} E_0^{3/2} / 5 h_{50}^{1/5} \Omega_{\text{IGM}}^{-1/5} [1 - ((1 + \Omega_0 z) / (1 + \Omega_0 z_1))^{1/2}]^{-0.6} (1 + z) / (1 + z_1)$$

and the related shock temperature $T_s(z) = 1.38 \cdot 10^5 [v_s(z) \cdot 10^{-2}]^2$ K. We calculate the mean electron temperature inside the blastwave $\bar{T}_e(z) = 9T_s(z) / ((9 - 2\gamma_p))$ and the mean electron numerical density $\bar{n}_e(z) = (7/8) \cdot c_p \cdot N_{\text{IGM}} \cdot [3/(3 - \gamma_p)] \cdot (1 + z)^3$ where N_{IGM} is the baryonic number density of the IGM, and c_p indicates the compression rate of the shock front (for an MHD shock model, the Rankine-Hugoniot relations give a typical value of $c_p = 4$ for a strong shock). The evolution of each bubble, after the initial QSO explosion, proceeds independently from that of the mother object; this allows us to evaluate the number of bubbles at each time simply from the QSOs luminosity function (LF). We use the well known LF from [12] and assume that only a fraction $f_{\text{exp}} \sim 10\%$ of QSOs have enough energy to drive outflows and form bubbles. The IGM becomes thus a patchy radiation scattering medium; for which we can use a general form of the Kompaneets equation, a Fokker-Planck equation for the photon distribution function. For that purpose we calculate suitable ensemble averages for the temperature and the numerical density

We evaluate the local Comptonization distortion choosing the range of initial energies between $10^{58} \leq E_0 \leq 10^{63}$ erg. The global effect on the CMB can be evaluated by a simple model including the "filling factor" $f(z, z_1, E_0)$ for the blastwaves depending on the two parameters z_1, E_0 model for the single bubble. The evolution of each bubble, after the initial QSO explosion, proceeds independently from that of the mother object, unlike the photoionization mechanism that is directly linked with the object life. This allows us to evaluate the number of bubbles at each time simply from the QSOs luminosity function (LF); we use the well known LF from Boyle 1993 and assume that only a fraction $f_{\text{exp}} \sim 10\%$ of QSOs have enough energy to drive outflows and form bubbles (Voit 1994). The IGM becomes thus a patchy radiation scattering medium; the inhomogeneities of a "cloudy" IGM can be treated with a general form of the Kompaneets equation, a Fokker-Planck equation for the photon distribution function. For that purpose we calculate suitable ensemble averages for the temperature and the numerical density

$$\langle T_e(z, z_1) \rangle = \frac{9}{9 - 2\gamma_p} \frac{\int f(E_1, z, z_1) dE_1 T_{es}(E_1, z, z_1)}{\int f(E_1, z, z_1) dE_1} \quad \text{and} \quad \langle n_e(z, z_1) \rangle = \frac{3}{3 - \gamma_p} n_{es}$$

where $f(z, z_1, E) \equiv f_{\text{exp}} V(E, z, z_1) \Phi(E, z_1)$ is the ‘‘filling factor’’ constructed from the LF $\Phi(E, z_1)$ and the volume of the spherical blast-wave. Hot electrons inside the blastwave Compton scatter the CMB photons and produce a distortion of the radiation spectrum expressed in term of the Comptonization parameter $u(z)$ [9,13]

$$u(z) = \int_{1+z}^{1+z_1} (\phi(z') - \phi_i(z')) \frac{\kappa_B T_r}{m_e c^2} n_e \sigma_T c t_{\text{exp}} \frac{d(1+z')}{(1+z')}$$

where $\phi(z) = T_e/T_r$, $T_r = T_0(1+z)$ being the radiation temperature at redshift z and T_0 the present radiation temperature, $\phi_i(z) = T_i(1+z)/T_r$, κ_B is the Boltzmann constant, m_e the electron's rest mass, σ_T the Thomson cross section, and t_{exp} is the expansion time.

Changing T_e and n_e with the corresponding averages we obtain the temperature fluctuation $\Delta T/T$ of the ensemble of bubbles as function of z

$$\frac{\Delta T}{T} \approx -2u(z, z_1) = -\frac{6}{3 - \gamma_p} \int_{1+z}^{1+z_1} \left(\frac{\langle T_e(z', z_1) \rangle_{\text{tot}}}{T_0(1+z')} - \frac{T_i(1+z_1)}{T_0(1+z')} \right) \frac{\kappa_B T_0(1+z')}{m_e c^2} n_{es} \sigma_T c t_{\text{exp}} \frac{d(1+z')}{(1+z')}. \quad \text{We}$$

show in Figs. (1) the decrease of the ensemble temperature from the explosion to our time and in Figs (2-4) the evolution of the Comptonization factor for different energies and densities. The results shown in Figs (1-4) support the conjecture that in the second order distortion to the CMB spectrum could be observable.

3- Effect on CMB of Blast waves in protogalaxies

The most plausible environment for the first phases of a QSO life is the dense gas of a protogalaxy [14,15]; in the mentioned references, despite the rather similar astrophysical context, the authors assume different density values for the environment. In [14] the gas mass density is supposed to have a r^{-2} dependence: $\rho = \sigma^2/2\pi G r^2$, where σ is the dispersion velocity, typically 300 km/sec. The shock velocity is constrained by the fact that the shell has to escape the protogalaxy, thus $v_s > \sigma$. Considering a typical blastwave starting from $z \sim 5$ with an explosion energy $E \sim 10^{62}$ erg, $v_s = 330$ Km/sec corresponding to $T_s \sim 1.45 \cdot 10^6$ °K and $R_s \sim 1$ Mpc. Using the density $n_e \approx 10^{-4}$ we find a Comptonization factor for a single bubble $u(0) \sim 10^{-5}$. In the second scenario [15] the electron density is modeled as a constant value $n \sim 10^{-2} \text{ cm}^{-3}$ growing to $4n_e$ at the shock front. Again a typical radius is $R_s \sim 1$ Mpc and $v_s \cong 3 \cdot 10^3$ km/sec, one order of magnitude higher than the previous one. In this case the shock temperature is higher $T_s \sim 10^8$ °K, leading to a Comptonization factor $u(0) \sim 10^{-5}$.

We independently derive an estimate of the effect in a non-uniform medium from the general treatment of [11]; with the same formalism as in section 2 we find very simple expressions or radius (in Mpc) and shock velocity (in km/sec):

$$R_s = 2.5 E_0^{1/3} h_{50}^{-2/3} \left[(1 + \Omega_0 z_1) / \Omega_0^2 (1 + z_1) \right]^{1/3} \left[1 - (1 + \Omega_0 z)^{1/2} / (1 + \Omega_0 z_1)^{1/2} \right]^{2/3} (1 + z)^{-2/3}$$

$$v_s = 45 E_0^{1/3} h_{50}^{1/3} \left[\Omega_0^2 (1 + z_1)^2 / (1 + \Omega_0 z_1) \right]^{1/3} \left[1 - (1 + \Omega_0 z)^{1/2} / (1 + \Omega_0 z_1)^{1/2} \right]^{-1/3} (1 + z)^{1/3}$$

where the numerical constants have been evaluated using the power law formula for the ambient density [14]. The constraint $v_s > \sigma$ leads to very high explosion energy ($E = 10^{63}$ ergs) (here $\Omega = 0$, $h_{50} = 0$) and $R_s \cong 6$ Mpc ($\vartheta < 1'$). Given the density $n_e(0) \cong 4 \cdot 10^{-6}$ the Comptonization factor is $u(0) \sim 1.5 \cdot 10^{-5}$, corresponding to a distortion $\Delta T/T \sim -3 \cdot 10^{-5}$. Considering higher redshift bubbles, the requirement on the explosion energy relaxes lowering to 10^{62} at $z = 2$, for example. Given these orders of magnitude, the

described effect could be detectable by a high resolution and sensitivity of Planck Surveyor; future measurements will allow to test the considered models.

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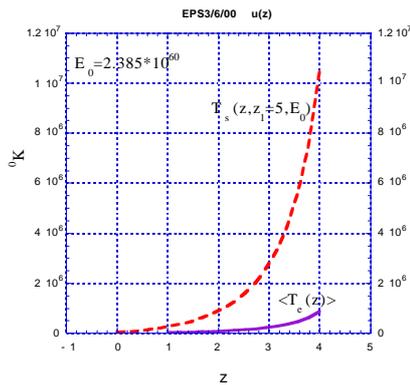


Fig.1

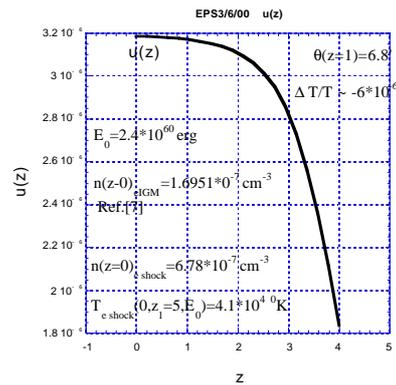


Fig.2

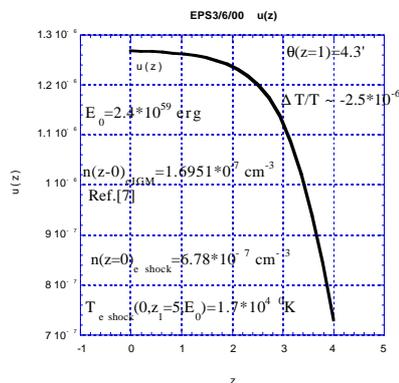


Fig.3

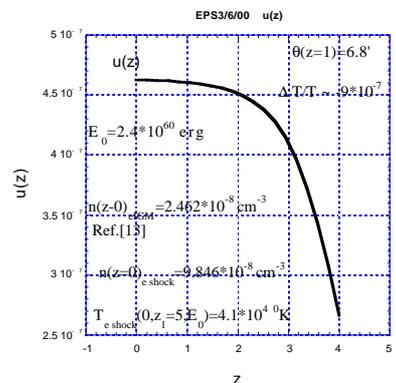


Fig.4