Sunyaev–Zel’dovich effect from quasar-driven blast waves

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ABSTRACT
Quasar-driven winds are currently the best candidates for accounting for the pre-heating of the intergalactic medium in clusters. Such winds, occurring during early phases of the evolution of spheroidal galaxies, shock-heat the interstellar gas, thus inducing a detectable Sunyaev–Zel’dovich effect. We estimate the amplitude and the angular scale of such an effect as well as its counts as a function of the Comptonization parameter $y$. The contamination arising from radio emission by the quasar itself is also discussed. The corresponding mean Compton distortion of the cosmic microwave background spectrum is found to be well below the COBE/FIRAS upper limit.

Key words: galaxies: formation – quasars: general – cosmic microwave background.

1 INTRODUCTION
It is natural to expect that extremely powerful sources, such as quasars, strongly affect the surrounding medium. The recent evidence of a tight relationship between black hole mass and velocity dispersion of the host galactic bulges (Ferrarese & Merritt 2000; Gebhardt et al. 2000a,b; McLure & Dunlop 2001; Merritt & Ferrarese 2001a,b) have significantly strengthened the case for a close connection between the evolutionary pathways of spheroidal galaxies and of quasars. Super-massive black holes have been found to be ubiquitous at the centres of local spheroidal galaxies (Kormendy & Richstone 1995; Magorrian et al. 1998; van der Marel 1999). The observed correlation between the mass of the black hole and that of the galaxy spheroidal component hints at a substantial feedback of the nuclear activity to the surrounding medium (Silk & Rees 1998; Monaco, Salucci & Danese 2000; Granato et al. 2001): energetic quasar-driven winds can sweep up the interstellar gas and halt both star formation and the growth of the central black hole.

If a significant fraction of the huge amount of energy released by quasars goes into ionization and heating of the neighbouring gas, Compton cooling may produce a detectable Sunyaev–Zel’dovich (SZ, 1972) effect. The idea of strong shock heating of the medium originated by energetic outflows from early quasars, originally developed by Ikeuchi (1981), was recently revived by Natarajan, Sigurdsson & Silk (1998), Natarajan & Sigurdsson (1999) and Aghanim, Balland & Silk (2000). Evidence of strong quasar-driven winds can be seen in broad absorption lines (BAL) quasars, comprising 10–15 per cent of optically selected quasars (Hamann & Ferland 1999 and reference therein). The dynamic interaction of such energetic outflows with the surrounding protogalactic gas can heat it to a high temperature. The release of an amount of mechanical energy from active galactic nuclei several times larger than that produced by supernovae in the surrounding galaxies may be necessary to account for the pre-heating of the intergalactic medium in clusters (Kravtsov & Yepes 2000; Wu, Fabian & Nulsen 2000; Balogh et al. 2001; Bower et al. 2001). Natarajan & Sigurdsson (1999) suggested that the SZ effect associated with very energetic, quasar-driven winds may account for the reported isolated cosmic microwave background (CMB) temperature decrements in directions where no clusters of galaxies are detected, but quasar pairs are present (Jones et al. 1997; Richards et al. 1997). Detection of this effect would obviously be informative concerning the physics of quasar/galaxy evolution.

In this paper we present a new investigation of the problem, taking explicitly into account the relevant energetics as well as the observed relationships between black hole and host galaxy properties. Our approach, focusing on energetics, is less liable to uncertainties ensuing from poor knowledge of the details of the gas heating process. In Section 2 we introduce the basic ingredients entering our calculations and estimate the amplitude and the angular scale of the SZ effect. In Section 3 we present tentative estimates of its number counts. The results are discussed in Section 4.

2 SZ EFFECT FROM QUASARS
The main factors determining the amplitude of the quasar-driven SZ effect, usually measured in terms of the Comptonization parameter

$$y = \frac{\int_{-R}^{R} \frac{kT_e(r)}{m_e c^2} \sigma_T n_e(r) dr}{\int_{-R}^{R} n_e(r) dr},$$

(1)

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The fractional amount of energy, \( \Delta \epsilon / \epsilon_{\text{CMB}} \), transferred to the CMB by Compton cooling of the plasma is related to \( y \) by (Zel’dovich & Sunyaev 1969)

\[
y \simeq \frac{1}{4} \frac{\Delta \epsilon}{\epsilon_{\text{CMB}}},
\]

(2)

where \( \epsilon_{\text{CMB}} = a T_{\text{CMB}}^4 \simeq 4.2 \times 10^{-3}(1 + z)^4 \text{erg cm}^{-3} \).

In the redshift range where quasars are observed (\( z \lesssim 6.3, \) Fan et al. 2001b) and for realistic values of the density of the medium, energetic cosmological blast waves remain adiabatic to relatively low \( z \), i.e. the cooling time is longer than the expansion time-scale, \( t_{\text{exp}} \) (Voit 1996; see also the discussion below). Thus, if a fraction \( f_b \) of the total energy released by the quasar, \( E_{\text{tot}} \), goes into heating of the gas, the amount of energy per unit volume transferred to the CMB through Comptonization in a time \( t < t_c \) is

\[
\Delta \epsilon \simeq \frac{f_b E_{\text{tot}}}{V} t_c^{-1},
\]

(3)

where \( V \) is the volume occupied by the hot gas and \( t_c = 3 mh_{\odot} / 4\pi a T_{\text{CMB}}^4 \simeq 7.3 \times 10^9(1 + z)^{-2} \text{s} \) is the Compton cooling time-scale. We adopt, for simplicity, an Einstein–de Sitter cosmology, so the expansion time-scale is \( t_{\text{exp}} = a(t)/a(t_0) = (1/H_0)(1+z)^{-3/2} \), where \( a(t) \) is the cosmic scalefactor and \( 1/H_0 \simeq 6.17 \times 10^5 h_{50}^{-1} \text{s} \), with \( h_{50} = H_0/50 \text{km s}^{-1} \text{Mpc}^{-1} \).

2.1 Evolution of the shock within the quasar host galaxy

Close relationships between the mass of the central black hole, \( M_{\text{bh}} \), and the properties of host elliptical galaxies or of galaxy bulges have been reported. Kormendy & Richstone (1995), Magorrian et al. (1998) and McLure & Dunlop (2001) found that \( M_{\text{bh}} \) is proportional to the luminosity of the spheroidal galaxy component. A tighter correlation between \( M_{\text{bh}} \) and the line-of-sight velocity dispersion, \( \sigma \), was discovered by Gebhardt et al. (2000a) and Ferrarese & Merritt (2000), although the two groups find somewhat different slopes. We adopt the relationship obtained by Gebhardt et al. (2000a,b), based on a larger sample:

\[
M_{\text{bh}} = 1.2 \times 10^8 \left( \frac{\sigma}{200 \text{km s}^{-1}} \right)^{15/4} M_{\odot}.
\]

(4)

The total amount of energy released by the quasar is \( E_{\text{tot}} = \epsilon_b M_{\text{bh}} c^2 \), where \( \epsilon_b \simeq 0.1 \) is the mass-to-energy conversion efficiency of the black hole.

We model the host galaxy as an isothermal sphere with density profile

\[
\rho(r) = \rho_0 r^{-2},
\]

(5)

with

\[
\rho_0 = \frac{\sigma^2}{2\pi G}
\]

(6)

and an outer cut-off radius \( R_s \) defined by the condition that the mean density within \( R_s \) is \( \rho = 200 \) times higher than the mean density of the Universe at the redshift \( z_t \) when the galaxy formed [numerical simulations (Cole & Lacey 1996) show that this radius approximately separates the virialized and infall regions; see also Navarro, Frenk & White (1997)].

\[
R_s = \frac{2\sigma}{H_0^2(1+z_t)^{3/2}} \simeq 130 h_{50}^{-1} \left( \frac{E_{\text{tot}}}{10^{52} \epsilon_b} \right)^{4/15} \left( \frac{\delta}{200} \right)^{-1/2} \times \left( \frac{3.5}{1+z} \right)^{3/2} \text{kpc},
\]

(7)

Several lines of evidence indicate that massive ellipticals were already in place by \( z \simeq 2.5 \) (Renzini & Ciatti 1999; Daddi, Ciatti & Renzini 2000; Ferguson, Dickinson & Williams 2000; Cohen 2001), although the issue is still somewhat controversial. For \( z_t \simeq 2.5 \) equation (7) yields values for \( R_s \) consistent with current estimates for massive galaxies (see, e.g., Peebles 1993). We assume that the distribution of baryons reflects that of dark matter.

It is interesting to note, in passing, that this model, together with the Gebhardt et al. (2000a,b) relationship (equation 4) implies \( M_{\text{bh}} \propto M_{\text{DM}}^{1.25} \), where \( M_{\text{DM}} \) is the total mass of the galaxy, dominated by the dark matter halo. McLure & Dunlop (2001) find a best-fitting relationship between the black hole mass and the \( R \)-band luminosity of the host galaxy bulge \( M_{\text{bh}} \propto L_R^{1.25} \). Adopting, as they do, the relationship \( M_{\text{bulge}} \propto L_R^{1.31} \), determined by Jorgensen, Franx & Kjærgaard (1996), we have \( M_{\text{bh}} \propto M_{\text{bulge}} \). If we adopt the Magorrian et al. (1998) dependence, \( M_{\text{bulge}} \propto L_R^{1.18} \), which according to Laor (2001) may be more appropriate, we find \( M_{\text{bh}} \propto M_{\text{bulge}}^{1.15} \). In both cases the observationally derived relationship between \( M_{\text{bh}} \) and \( M_{\text{bulge}} \) is very close to that yielded by the present model if \( M_{\text{bulge}} \propto M_{\text{DM}} \).

The radius \( R_s \) of a self-similar blast wave carrying energy \( E_s = f_b E_{\text{tot}} \), expanding in a medium for which the density varies as \( r^{-2} \), increases with time as (Ostriker & McKee 1988)

\[
R_s = \left( \frac{\xi E_s}{3 \rho_0} \right)^{1/3} t^{2/3},
\]

(8)

where \( \xi \approx 1.5 \).

Using equations (7) and (8) it is easily checked that, for realistic values of the parameters, the time, \( t_{\text{ff}} \), required for the shock front to reach the outer radius of the galaxy

\[
t_{\text{ff}} \simeq 8.9 \times 10^6 h_{50}^{-3/2} \left( \frac{E_{\text{tot}}}{10^{52}} \right)^{1/6} \left( \frac{\epsilon_b}{0.1} \right)^{-2/3} \left( \frac{f_b}{0.1} \right)^{-1/2} \times \left( \frac{\delta}{200} \right)^{-3/4} (1 + z)^{-9/4} \text{s}
\]

(9)

is always shorter than the expansion time-scale \( t_{\text{exp}} \). Therefore, the shocks propagate outside of the host galaxy, and can heat up the general intracluster medium (ICM). However, owing to the much lower electron density in the ICM, compared with the mean density within the galaxy, most of the SZ signal comes from within \( R_s \) (see also da Silva et al. 2001).

The main radiative cooling process for the redshifts of interest here (\( z \leq 6 \)) is free–free, for which the cooling time-scale is

\[
t_{\text{ff}} = \frac{3 n_e k T_e}{u_{\text{ff}}},
\]

(10)

where \( u_{\text{ff}} = 1.4 \times 10^{-27} T_{\text{k}}^{1/2} n_e^2 \text{erg s}^{-1} \) is the cooling rate of a plasma with electron number density \( n_e \) and temperature \( T_e \). The present mean ratio between baryon (mostly in stars) and dark matter mass in massive spheroidal galaxies is estimated to be \( M_b/M_{\text{DM}} \simeq 0.03 \) (McKay et al. 2001; Marconi & Hudson 2002).

An upper limit to the cooling rate (and, correspondingly, a lower limit to \( t_{\text{ff}} \)) is obtained by assuming that essentially all such baryons were in the interstellar gas, so that

\[
n_v(r) = 3 \times 10^{-2} \frac{\sigma^2}{2\pi G m_p r^2}
\]

(11)

where \( m_p \) is the proton mass, we find (setting \( g = 1 \)) that \( t_{\text{ff}} < t_{\text{ff}} \) (equation 9) for
Energies of the shock

The fraction of power released by the quasars that goes into heating of the gas is highly uncertain. Natarajan & Sigurdsson (1999) assume this fraction to amount to about half of the bolometric luminosity. Analyses of the X-ray properties of the intracluster medium assume this fraction to amount to about half of the bolometric luminosity of the gas is highly uncertain. Natarajan & Sigurdsson (1999) estimate that an energy of $\epsilon B \sigma T / 4 \pi r^2 V$ (see equation 8). Therefore in the following we neglect the radiative losses.

2.2 Energetics of the shock

The fraction of power released by the quasars that goes into heating of the gas is highly uncertain. Natarajan & Sigurdsson (1999) estimate that an energy of $\epsilon B \sigma T / 4 \pi r^2 V$ (see equation 8). Therefore in the following we neglect the radiative losses.

2.3 Amplitude and angular scale of the SZ effect

As argued in Subsection 2.1, most of the SZ signal is expected to come from within the galaxy, so that in equation (3) we will set $V = V_{z} = (4\pi/3) R_{s}^{3}$ and $t = t_{q}$. On the other hand, only a minor fraction $f_{b}$ of the energy carried by the blast wave goes into heating of the gas within the galaxy (most of it is dissipated in the ICM). Inserting the above results in equation (2), using for $f_{b}$ the expression of equation (13), and taking into account that, in the Rayleigh–Jeans region $\Delta T / T_{10^4} = -2y$, we end up with

$$f_{b} \simeq 4.7 \times 10^{-2} \frac{\epsilon_{S}}{0.08} \left( \epsilon_{R} / 0.1 \right)^{-4/5} \left( E_{\text{int}} / 10^{62} \right)^{-1/5} h_{50}^{3/2} \times \left( \frac{\delta}{200} \right)^{-1/2} \left( 1 + \frac{z}{3.5} \right)^{-3/2}$$

indicating that the mechanical power is a minor fraction of the bolometric luminosity.

3 COUNTS OF SZ SIGNALS FROM QUASARS

The epoch-dependent ‘luminosity function’ of SZ signals, $\phi_{\text{SZ}}(y, z)$, can be roughly estimated from the luminosity function of quasars, given the quasar lifetime $t_{q}$. We have adopted one of the analytical evolutionary models for the B-band luminosity function, $\phi_{B}(L_{b}, z) \log L_{B} dz$, proposed by Pei (1995): the two-power-law model with $h_{50} = 1$, $q_{0} = 0.5$, and optical spectral index $\alpha_{0} = 0.5$ $[f(\nu) \propto \nu^{-\alpha_{0}}]$. This model works well up to $z \simeq 4.5$, but appears to underpredict the surface density of higher-redshift quasars by a large factor, which, however, are so rare (Fan et al. 2001) that their contributions to the counts of the SZ signal is small.

The $B$-band luminosity is related to the total energy released by $E_{\text{int}} = k_{B} L_{B} t_{q}$, where $k_{B}$ is the bolometric correction for which we adopt the value $k_{B} = 6$ [the median value for the sample of Elvis et al. (1994), corrected to account for the different definition of $L_{B}$ used by Pei (1995)]. If $t_{q}$ is independent of both luminosity and redshift, and considering only the SZ effect within the host galaxy, we have

$$\phi_{\text{SZ}}(y, z) = \frac{15}{4} \phi_{B}(L_{b}, z) t_{q}$$

where $\phi_{B}(y, z)$ is the ‘luminosity function’ of the SZ signal per unit log $y$ and $z$ intervals, and the factor of 15/4 comes from $d \log L_{B} / d \log y = d \log E_{\text{int}} / d \log y$ (equation 14). The quasar lifetime is still very uncertain. Recent estimates (Salucci et al. 1999; Monaco et al. 2000; Martini & Weinberg 2001) suggest $t_{q}$ to be in the range $8 \times 10^{9} - 10^{10}$ yr, with values $\pm 10^{9}$ yr being favoured (Haehnelt, Natarajan & Rees 1998; Pentericci et al. 2002; Ciotti, Haiman & Strikkovsky 2001).

Inserting equation (13) in the expression for $t_{q}$ (equation 9) we have

$$t_{q} \simeq 7.7 \times 10^{15} h_{50}^{3/4} \left( E_{\text{int}} / 10^{62} \right)^{4/15} \left( \epsilon_{R} / 0.1 \right)^{-4/15} \left( \epsilon_{S} / 2.8 \right)^{-1/2} \times \left( \frac{f_{b}}{0.03} \right)^{-1/2} \left( \frac{\delta}{200} \right)^{-1/2} \left( 1 + \frac{z}{3.5} \right)^{-3/2}$$

Although the amplitude of the SZ effect is distance independent, the observed signal is affected by distance-dependent beam

$$d_{A}(z) = \frac{2c}{H_{0}} \left( 1 + z \right)^{1/2} \frac{\left( 1 + \frac{z}{3.5} \right)^{3/2}}{\left( 1 + \frac{z}{3.5} \right)^{3/2}} + \frac{\left( 1 + \frac{z}{3.5} \right)^{3/2}}{\left( 1 + \frac{z}{3.5} \right)^{3/2}}$$

From equation (7) we have

$$\theta_{\text{SZ}} \simeq 17 \text{arcsec} \left( E_{\text{int}} / 10^{62} \right)^{4/15} \left( \epsilon_{R} / 0.1 \right)^{-4/15} \left( 1 + \frac{z}{3.5} \right)^{-3/2} \frac{d_{A}(2.5)}{d_{A}(z)} \left( 1 + \frac{z}{3.5} \right)^{3/2}$$

where $d_{A}(2.5) = 1595 h_{50}^{-1} \text{Mpc}$. The amplitude and the angular diameter of the effect, $\theta_{\text{SZ}} \simeq 34$ arcsec, for the reference values of the parameters, are not far from the results reported by Richards et al. (1997): $|\delta T / T| \sim 10^{-4}$ over an area of $30 \times 65$ arcsec$^{2}$ and by Jones et al. (1997): $|\delta T / T| \sim 1.4 \times 10^{-4}$ in a beam of $100 \times 175$ arcsec$^{2}$. Since powerful high-$z$ quasars are highly clustered (Croom et al. 2001), the larger than expected observed angular scale might be interpreted as being caused by the combination of blast waves from neighbouring quasars. It should be stressed, however, that in neither case is the explanation in terms of quasar-driven blast waves clearly supported by observations. A more conservative explanation is that the observed signals come from the SZ effect in previously unknown clusters.
dilation or resolution effects, so that the SZ signal observed with an instrumental solid angle \( \omega_{\text{beam}} \)

\[ y_{\text{obs}} \simeq y F(\omega_{\text{beam}}/\omega_{\text{SZ}}), \]  

(19)

where \( \omega_{\text{SZ}} = \pi \theta_{\text{SZ}}^2 \) and

\[ F(\omega_{\text{beam}}/\omega_{\text{SZ}}) \simeq \begin{cases} \omega_{\text{beam}}/\omega_{\text{SZ}} & \text{if } \omega_{\text{beam}} < \omega_{\text{SZ}} \\ \omega_{\text{SZ}}/\omega_{\text{beam}} & \text{if } \omega_{\text{beam}} > \omega_{\text{SZ}}. \end{cases} \]  

(20)

For given \( z, F \propto E_{\text{tot}}^{8/15} \propto y^{1/2} \), with the sign of the exponent depending on the ratio \( \omega_{\text{beam}}/\omega_{\text{SZ}} \) (see equation 20), so that \( y_{\text{obs}} \propto y^{1/2} \).

The differential counts per steradian of \( y \) values of quasars between the quasar blue luminosity and the present model. Clearly, the assumption of dispersionless relation. It comes from the combined effect of the steep slope of the bright end of the counts is model dependent. It comes from the combined effect of the steep slope of the high-luminosity portion of the quasar luminosity function and of the mild dependence of \( y \) on \( E_{\text{int}} \) (see equation 14), implied by the present model. Clearly, the assumption of dispersionless relationships between the quasar blue luminosity and \( E_{\text{int}} \), and between \( E_{\text{int}} \) and \( y \) is an oversimplification. Dispersions will result in a flattening of the bright end of the counts.

The surface density of SZ signals is strongly dependent on the amount of thermal energy injected into the interstellar gas of the host galaxy, which, according to the present model, is proportional to \( y^{1/2} \). For \( t_q \) in the range \( 10^7 \text{–} 10^8 \) yr, we expect some \( 10^5 \) SZ signals \( \Delta n_{\text{SZ}} \) with \( y > 2 \times 10^4 \) to be detected with an imaging survey with \( \lesssim 30 \) arcsec resolution (FWHM). For higher values of \( y \), the expected surface density is strongly dependent on the quasar lifetime \( t_q \). The survey should be carried out at \( 10 < v < 150 \) GHz to avoid blurring of the SZ signal by local radio or dust emission. The signal is strongly diluted in most current surveys aimed at mapping CMB anisotropies with angular resolution \( \gtrsim 5 \text{–} 10 \) arcmin. Even high-sensitivity, all-sky surveys such as those to be carried out by ESA’s Planck mission, cannot detect such signals efficiently. Much better prospects for detecting SZ effects from quasar-driven blast waves are offered by ground-based bolometric arrays and interferometers with arcmin or subarcmin resolution, such as the Arcmin MicroKelvin Imager (Kneissl et al. 2001) and AMiBA (Lo et al. 2001).

Since, in the present framework, quasars are signposts of massive galaxies at high redshifts and are therefore strongly biased tracers of the matter distribution, we expect them (and the associated SZ signals) to be highly clustered.

### 4 DISCUSSION

#### 4.1 Effect of local radio emission

It is entirely plausible, and perhaps required by evidence of a substantial pre-heating of the intracluster gas, that quasars inject in the surrounding medium an amount of energy sufficient to produce a detectable SZ effect. The corresponding angular scale is expected to be relatively small (subarcmin), so that the blurring effect by the emission from the quasar itself or from the host galaxy may be important.

To estimate to what extent the radio emission associated with the quasar might blur the SZ signal, we refer to the median ratio of monochromatic luminosities at 5 GHz and at \( v \beta \approx 6.82 \times 10^{14} \) Hz (corresponding to \( \lambda_{\text{q}} = 0.44 \mu\text{m} \), for the radio-loud and radio-quiet quasars in table 2 of Elvis et al. (1994)). We find \( \log(t_{5\text{GHz}}/t_{\text{qu}})_{\text{median}} = -0.47 \) for radio-quiet quasars and \( =2.2 \) for radio-loud ones.

Taking into account that the contribution to the antenna temperature at the frequency \( v \) within a solid angle \( \omega_{\text{SZ}} = \pi \theta_{\text{SZ}}^2 \), of a source of 5-GHz flux \( S_{5\text{GHz}} \) and spectral index \( \alpha \simeq 0.7 (S_{5\text{GHz}} \propto \nu^{-\alpha}) \) is

\[ \Delta T_A = \frac{S_{5\text{GHz}}(v/5 \text{GHz})^{-\alpha}c^2}{2k_\text{B}v^2\omega_{\text{SZ}}}. \]  

(22)

we have, for radio-quiet quasars, in the Rayleigh–Jeans region

\[ \frac{\Delta T_A}{T_A} \simeq 1.1 \times 10^{-3} \left( \frac{E_{\text{tot}}}{10^6} \right)^{7/15} \left( \frac{E_{\text{q}}}{0.1} \right)^{8/15} \left( \frac{k_{50}^2 10^9 \text{yr}}{t_q} \right) \times \left( \frac{5 \text{GHz}}{v} \right)^{2+\alpha} \left( \frac{1+z}{3.5} \right)^{-\alpha}. \]  

(23)

In the case of radio-loud quasars the coefficient would be about 500 times higher and therefore the radio emission would easily overwhelm the SZ signal, except, perhaps, at high frequencies (\( \gtrsim 100 \) GHz). However, only a minor fraction (\( \lesssim 10 \) per cent) of quasars are radio loud. However, even in the case of radio-quiet quasars the radio emission may, at least partially, fill up the SZ dip at \( v < 10 \) GHz, particularly if the quasar is surrounded by an intense starburst, which is also radio bright, as is frequently the case at high \( z \) (Omont et al. 2001). The contamination by radio emission...
sinks down rapidly with increasing frequency, but at $\nu \gtrsim 150$ GHz, dust emission powered by star formation in the host galaxy, may take over, owing to its spectrum rising steeply with increasing frequency.

On the other hand, the quasar lifetime and the duration of intense starbursts are generally shorter than the time $t_b$ for the blast wave to reach the boundary of the host galaxy. Therefore, the SZ signals may be observed when the quasars that originated them are dead.

4.2 Global Comptonization distortion

The mean distortion of the CMB spectrum owing to Comptonization by the electrons heated by the blast waves, measured by the mean value $\langle y \rangle$ of the parameter $y$ integrated along the line of sight, is one-quarter of the fractional amount of energy injected in the CMB per unit volume:

$$\langle y \rangle = \frac{f_{\text{h,eff}}}{4} \int_0^\infty \frac{d \log L_B}{L_B} \frac{k_B L_B}{\epsilon_{\text{CMB}}(z)} \frac{\tau_{\text{exp}}}{t_c} dz,$$

(24)

where $f_{\text{h,eff}}$ is the effective fraction of the total energy released by the quasars carried by blast waves. From the above discussion it follows that pre-heating of the ICM requires $f_{\text{h,eff}} \lesssim 0.1$. Using the double-power-law quasar luminosity function from Pei (1995), we find

$$\langle y \rangle \simeq 2.4 \times 10^{-6} \frac{f_{\text{h,eff}}}{0.1}. \quad (25)$$

Using the exponential luminosity function from Pei (1995), the value of $\langle y \rangle$ increases by 20 per cent. On the other hand, it may be noted that equation (24) includes the contribution (which turns out to be quite substantial) of low-$z$ quasars to the integral (the contribution from the redshift range $0-2$ is comparable to that from $2 < z < 4$); however, in the present framework, the most energetic blast waves should be associated with early phases of the quasar/galaxy evolution. Thus the expected global Comptonization distortion of the CMB spectrum induced by quasar-driven blast waves is well below the COBE/FIRAS limit $\langle y \rangle < 1.5 \times 10^{-5}$ (Fixsen et al. 1996). This limit could be (marginally) exceeded only in the unrealistic case that the total energy emitted by all quasars over the entire life of the Universe went into heating of the surrounding gas. This would also entail an excessive (by almost one order of magnitude) pre-heating of the ICM.

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