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Probing Quasar Feedback through Enhanced Sunyaev-Zel'dovich Signals

Andrea Lapi and Alfonso Cavaliere

Dip. Fisica, Univ. 'Tor Vergata', Via Ricerca Scientifica, 1 - 00133 Roma, Italy

Abstract. We show that powerful quasars feed enough energy back to the diffuse ambient baryons as to cause transient, enhanced Sunyaev-Zel'dovich effects, especially in early galaxies and groups. We compute amplitudes and statistics of the related signals in μwave and submm bands, and discuss their detectability with present and future instruments.

Key words. Galaxies, groups and clusters – X rays – Quasars – Blastwaves – Sunyaev-Zel'dovich effect.

1. Introduction

Clusters of galaxies are the largest bound structures in the Universe. They comprise some $10^2 \div 10^3$ galaxies within sizes R of a few Mpcs; however, the baryonic mass condensed in stars is only a small fraction of a cluster's total content. The latter is mainly constituted by non-baryonic dark matter (DM), whose masses may match or even exceed $M \sim 10^{15}$ $M_\odot$. These set gravitational potential wells of depths $\sigma^2 \propto G\,M/R$, marked by 1-D velocity dispersions $\sigma \sim 10^3$ km s^{-1}.

Large amounts up to $m \approx M_{DM}/5$ of diffuse baryons pervade such potential wells in hydrostatic equilibrium with the DM gravity, at specific energies $kT \sim 5$ keV close to the virial values $kT_v \equiv \mu m_p\,\sigma^2$. Such hot baryons emit copious X-ray powers $L_X \propto n^2\,R^3\,\sqrt{T} \sim 10^{45\pm1}$ ergs s^{-1} mainly by thermal bremsstrahlung, from which gas densities $n \sim 10^{-3}$ cm^{-3} are inferred. So these diffuse baryons with $kT/e^2\,n^{1/3} > 10^{11}$ constitute a very good ion-electron plasma, the intracluster plasma or ICP.

The ICP can be also probed through the Sunyaev-Zel'dovich ((Sunyaev , 1980), SZ) effect. This arises when the hot ICP electrons Compton upscatter some of the CMB photons crossing the structure; then the pure black body spectrum is tilted toward higher energies. In the μwave band the tilt mimics a diminution of the CMB temperature $\Delta T_{\mu w} \approx -5.5\,y$ K proportional to the Comptonization parameter $y \propto n\,T\,R \propto p\,R$, the electron pressure p integrated along the line of sight. Since $y \propto E/R^2$ holds, the SZ effect acts like a *calorimeter* probing the ICP total thermal energy $E \propto p\,R^3$. To now, SZ signals have been measured in many rich clusters at levels $y \approx 10^{-4}$ or $\Delta T_{\mu w} \approx -0.5$ mK (see (Zhang , 2000; Reese , 2002; Birkinshaw , 2004)), consistent with the ICP densities and temperatures derived in X rays.

In moving to poor clusters and groups, it is found that these emit in X rays far less than expected if the intragroup plasma (IGP) had been

Send offprint requests to: A. Lapi
Correspondence to: lapi@roma2.infn.it

'gravitationally' heated to $T \approx T_v$ as it fell supersonically into the DM potential wells. In that case the baryon to DM ratio would stayed put at the cluster value $m/M \approx 1/5$ (Kaiser , 1986); hence the luminosity would follow the law $L_X \propto T^2$, or even would approach the higher scaling $L_X \propto T$ at $kT < 2$ keV where a pinch of highly excited metals produces important line emission. Instead, not only the observed average correlation $L_X \propto T^{3\div4}$ is considerably steeper, but it is also scattered downward especially in poor groups and galaxies (Mushotzky , 2004), see Fig. 1 (*left*).

Thus the IGP is surprisingly (underluminous and so) *underdense* in relatively smaller, cooler and conceivably earlier structures. How this may come about constitutes a widely debated issue.

2. Cooling or heating?

Interesting hints comes from considering the ICP/IGP specific entropy s (or rather the *adiabat* $K \equiv kT\, n^{-2/3} \propto e^{2s/3k}$, (Bower , 1997)). This is linked to L_X by the simple, local relation $K \propto L_X^{-1/3}\, T^{5/3}$, where $T^{5/3}$ goes over to $T^{4/3}$ for important line emission.

As a function of T the adiabat behaves as $K \propto T^{2/3}$, and so deviates substantially upwards relative to the simple *gravitational* scaling $K \propto T$. Such an entropy excess proves that non-gravitational processes occurred during a structure's cosmic history.

Concerning these, one view centers on extreme radiative losses (see (Voit , 2001)), which may operate by removing much low-entropy gas and by condensing it into stars. However, it has been argued that the extensive cooling needed to raise the ICP/IGP entropy and depress L_X as observed would produce too many, unseen stars (e.g., (Muanwong , 2002)).

An alternative line of explanation (Valageas , 1999; Wu , 2000; Nath , 2002; Cavaliere , 2002) focuses on energy *injections* affecting the ICP/IGP equilibrium. The inputs are provided when the baryons in member galaxies condense to form massive stars (possibly in starbursts) then exploding as supernovae, and/or when they accrete onto central supermassive black holes energizing active galactic nuclei (AGNs). Such feedback actions deplete the ICP/IGP density from the inside causing dynamical blowout and thermal outflow; meanwhile, they preheat the gas exterior to the newly forming structures, hindering its flow into the DM potential wells (see Fig. 1).

Although it is clear that both cooling and heating must play a role in determining amount and thermal state of the ICP/IGP, it is not easy to identify the leading process amidst the wide scatter of the X-ray data (especially for groups, see (Mushotzky , 2004)). So the independent probe provided by the SZ effect is welcome or even needed. However, SZ measurements in groups are challenging at present, and still missing.

In groups at equilibrium, where the adiabat $K \propto T^{2/3}$ is enhanced well above the scaling $K \propto T$, we predict (Cavaliere , 2001) a related *deficit* of y

$$y \propto K^{-3/2}\, T^3 \propto T^2 \qquad (1)$$

relative to the baseline value $y \propto T^{3/2}$ that would hold for constant m/M ratio (Cole , 1988). But if such depressions are caused by substantial energies ΔE added by AGNs to the large-scale gravitational energy E, we also expect transient, *enhanced* SZ signals during and soon after the source activity (see also (Aghanim , 2000)). These would constitute specific *signatures* of strong feedback caught in the act, because extended cooling which depletes n without increasing T hardly could enhance $y \propto n\, T$.

3. Enhanced SZ signals from quasars

We start from expressing the equilibrium $y_{eq} \propto E/R^2$ in terms of the unperturbed gas thermal energy $E \propto p_{eq}\, R^3$. A small group or an early massive galaxy with their virial temperatures $kT_v \approx 1$ or 0.5 keV would produce SZ signals $\Delta T_{\mu w}/0.5\,\mathrm{mK} \approx -5$ or $-3\times10^{-2}\,(1+z)^{3/2}$. Larger energies $\Delta E \gtrsim E$ added to the IGP are expected to enhance the SZ signals yielding $y/y_{eq} \sim 1 + \Delta E/E$.

Such may be the case with powerful quasars that potentially produce large outputs $\Delta E \approx 2\times10^{62}\, f\ \ (M_\bullet/10^9\, M_\odot)\,(1+z)^{-3/2}$

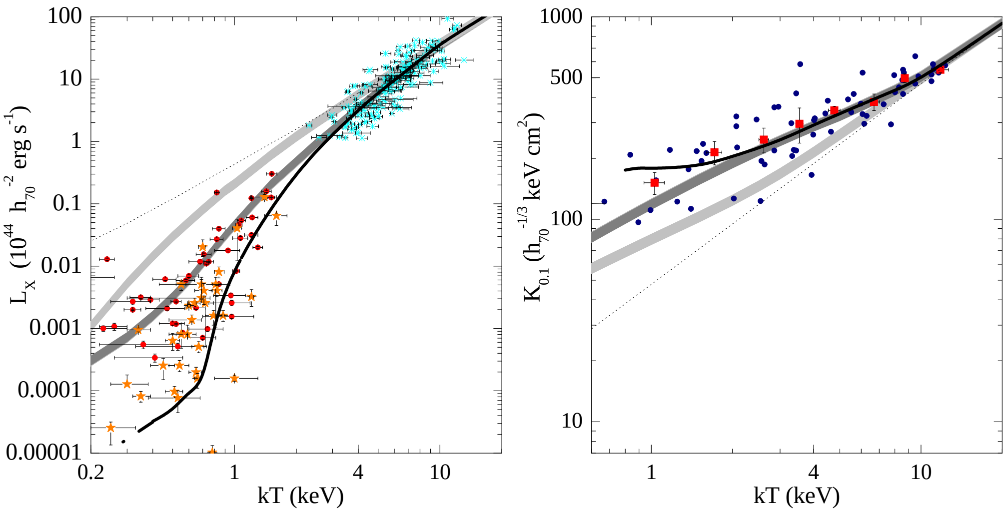

Fig. 1. Left panel: Integrated X-ray luminosity L_X (including line-emission) vs. X-ray temperature T. Data for clusters (*crosses*) are from (Horner , 2001), for groups (*circles*) from (Osmond , 2004), and for early-type galaxies (*stars*) from (O'Sullivan , 2003). *Dotted line*: pure gravitational heating; *light shaded strip*: preheating by SNe ($k\Delta T = 1/4$ keV per particle); *heavy shaded strip*: preheating by SNe + AGNs (a total $k\Delta T = 3/4$ keV per particle); *solid line*: internal impact from quasars. The coupling level of the quasar output to the ambient medium is set at $f = 5 \times 10^{-2}$. **Right panel**: Central entropy K (at $r \approx 10^{-1} R$) vs. X-ray temperature T. Data are from (Ponman , 2003): *circles* mark individual systems and *squares* refer to binned data. *Strips* and *lines* as above. See (Lapi , 2004) for detailed derivation of all these results.

as a mass $M_\bullet$ is accreted over the host dynamical time $t_d \sim 10^8$ yr on a central supermassive black hole with conversion efficiency 10^{-1}. But the coupling level f of this energy to the ambient baryons is poorly known; including inefficiencies due to low momentum transfer and non-spherical geometry it may range from 10^{-2} up to 10^{-1}. In fact, values $f \approx v_w/2\,c \approx 5{\times}10^{-2}$ are suggested by wind speeds up to $v_w \approx 0.4\,c$ incresingly observed in many broad and narrow line quasars (Chartas , 2003; Pounds , 25). These values of f are shown in Fig. 1 to be also consistent with the X-ray observations.

The extra ΔE has to compete with the (total) value $E \approx 2 \times 10^{61}\,(kT_v/\mathrm{keV})^{5/2}\,(1+z)^{-3/2}$ keV of the plasma in equilibrium. The relevant ratio

$$\frac{\Delta E}{E} = \frac{1}{2}\,\frac{f}{5\times10^{-2}}\,\frac{M_\bullet}{10^9\,M_\odot}\left(\frac{kT_v}{\mathrm{keV}}\right)^{-5/2} \qquad (2)$$

is small in clusters but increases toward groups, approaching unity in poor groups to attain a few in large galaxies. Then over distances of order 10^2 pc the quasar wind acts as an efficient piston to drive through the IGP a blastwave terminating into a leading shock (see Fig. 2 *left*, also (Yamada , 2001; Platania , 2002; Granato , 2004)).

Note, however, that these blasts are never very strong because toward galaxies $\Delta E/E$ is not to exceed a few, lest the gas contained within kpcs is removed and the accretion it feeds is cut down (Silk , 1998). The pivotal value $\Delta E/E \approx 1$ yields

$$\frac{M_\bullet}{10^8\,M_\odot} = 6\left(\frac{f}{5\%}\right)^{-1}\left(\frac{\sigma}{300\,\mathrm{km\,s^{-1}}}\right)^{5} \qquad (3)$$

Since in turn σ is found to correlate after $\sigma \propto \sigma_\star^{4/5}$ with the dispersion of the galactic bulge $\sigma_\star$ (Ferrarese , 2002), then for the same value $f \approx 5 \times 10^{-2}$ indicated by the X-ray data the above relation pleasingly agrees with the relic black hole masses observed in many galactic bulges (Tremaine , 2002).

To describe these quasar-driven blasts, we take from (Lapi , 2003) self-similar solutions for the hydrodynamic flow perturbing an equilibrium plasma density $n(r) \propto r^{-\omega}$ ($2 \leq \omega < 2.5$), under the push of the energy $\Delta E(t) \propto t^{2\,(5-2\,\omega)/\omega}$ added over t_d. The case $\omega = 2$ will constitute our fiducial choice, but models with $\omega > 2$ will also be useful to describe the quasar fading out due to its own feedback on the accreting gas. These solutions include the restraints set to gas dynamics by a finite initial pressure $p(r) \propto r^{2\,(1-\omega)}$ and by DM gravity; thus they provide *realistic* predictions for the moderate blasts driven by values of $\Delta E/E$ constrained after Eq. (3). The parameter $\Delta E/E$ determines the Mach number $\mathcal{M}$ of the leading shock, as shown in Table 1.

Fig. 2 (*left*) provides a schematic illustration of the perturbed flow; this is confined into a shell bounded by the leading shock at R_s, and by a trailing 'piston', the contact discontinuity located at $R_p = \lambda R_s < R_s$ where the action of the source is transferred to the plasma. Here the density diverges weakly but the mass vanishes (so the overall cooling is negligible), while the temperature goes to zero so as to make the pressure finite. The mean pressure $\langle p \rangle$ within the shell of the swept-up plasma exceeds the initial, equilibrium value p_{eq} owing to the thermal energy deposited by the blast; Table 1 presents the ratio $\langle p \rangle / p_{eq}$ as a function of the blast strength $\Delta E/E$, a relation to be used next.

In computing how y is *enhanced* during the blast transit, we focus on $\bar{y} \propto (2/R^2) \int ds\, s\, y(s)$ averaged over the structure area, as this will subtend small angles $\lesssim 1'$ for an early group or galaxy (see the relevant geometry in Fig. 2 *left*). We find

$$\frac{\bar{y}}{\bar{y}_{eq}} = \frac{\langle p \rangle}{p_{eq}} \frac{1-\lambda^3}{3} \tag{4}$$

for the parameter $\bar{y}$ averaged over the shell at $R_s \approx R$ (a condition that optimizes the observability) in terms of the mean pressure $\langle p \rangle$ given in Table 1.

Table 1. Relevant quantities for quasar-driven blasts

	$\omega = 2$		$\omega = 2.4$	
$\Delta E/E$	$\mathcal{M}$	$\langle p \rangle / p_{eq}$	$\mathcal{M}$	$\langle p \rangle / p_{eq}$
0.3.....	1.2	3.6	2.1	17.8
1........	1.5	4.6	3.0	21.7
3........	1.9	6.3	4.7	26.2

Our results are represented in Fig. 2 (*right*) vs. the depth kT_v of the host potential well. The square illustrates the *minimal* enhancement we expect from an early group at $z = 1.5$ with $kT_v = 1$ keV, $f = 5 \times 10^{-2}$ and $M_\bullet = 10^9\, M_\odot$, so with $\Delta E = 0.5\, E$. With radii $R \approx 250$ kpc, the angular sizes $\approx 1'$ are close to their minimum in the Concordance Cosmology.

The circles represent our results for a massive ($\sigma = 300$ km s^{-1}, $R \approx 100$ kpc) galaxy at $z = 2.5$. The open circle refers to $\Delta E = E$ or $M_\bullet = 6 \times 10^8\, M_\odot$; the filled one to $\Delta E = 3\, E$ or $M_\bullet = 2 \times 10^9\, M_\odot$, just compatible with the observed scatter in the $M_\bullet - \sigma$ correlation. The related angular sizes are around $0'.5$; with resolution fixed at $\approx 1'$, the signals will be diluted by a factor $\approx 1/4$ and scaled down to $\Delta T_{\mu w} \approx -20\,\mu$K.

The inset represents the corresponding statistics. This is evaluated on inserting the related blue luminosities $L = \Delta E/10\, f\, t_d \approx 5 \times 10^{45}$ and 1.5×10^{46} ergs s^{-1} (with a bolometric correction 10) in the quasar luminosity function observed by (Croom , 2004), and discussed by (Cavaliere , 2000). In terms of the cumulative fraction of bright galaxies hosting a quasar brighter than L, this reads

$$N(L)\, L \approx 2 \times 10^{-2}\, (1+z)^{3/2} \left(\frac{L_b}{L}\right)^{2.2} \tag{5}$$

beyond the break at $L_b = 5 \times 10^{45}\, [(1+z)/3.5]^3$ ergs s^{-1}. The same luminosity function interpreted in terms of interactions of the host galaxy with its group companions yields a few signals per 10 poor groups, with the strength represented by the square in Fig. 2 (*right*).

If a galaxy happens to grow a large black hole in times shorter than t_d, the AGN will inject an energy $\Delta E > E$ impulsively; we expect this to hinder further accretion and cause

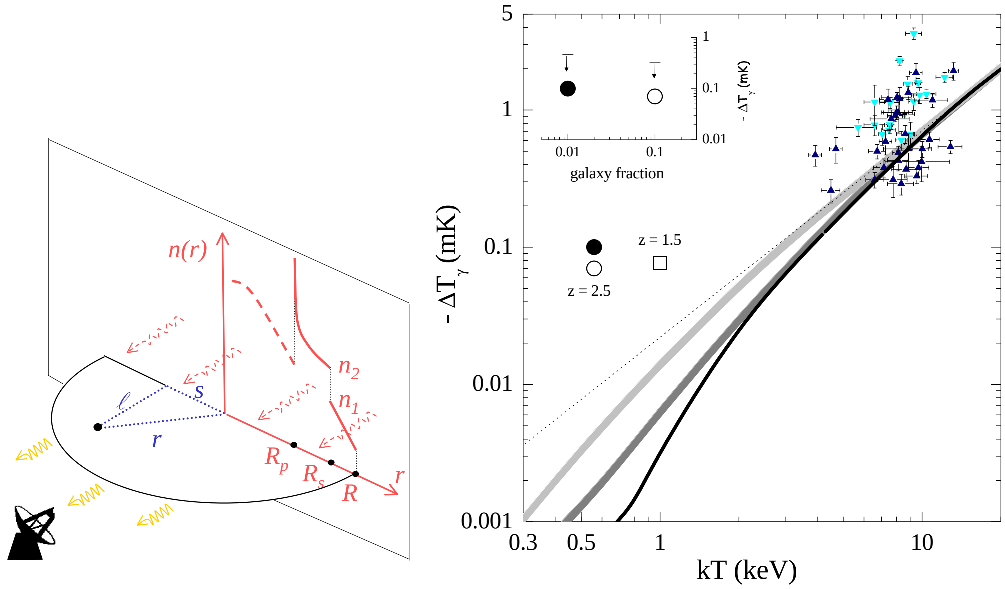

Fig. 2. Left panel: Geometry relevant to our computations of SZ signals. For a point in the structure r is the radial coordinate, s is its projection on the plane of the sky, and ℓ is the coordinate along the line of sight. On the vertical axis we also outline the initial density run, and the flow perturbed by the quasar-driven blastwave. **Right panel**: Predicted SZ signals as a function of T_v in galaxies, groups and clusters. Data from (Zhang , 2000; Reese , 2002). *Strips* and *lines* as in Fig. 1. *Square*: area-averaged, undiluted signal from a group at $z = 1.5$, driven by quasar activity with $M_\bullet = 10^9\, M_\odot$ and $f = 5\times10^{-2}$. *Circles*: same from a massive galaxy at $z = 2.5$, for $\Delta E = E$ (*open*) or $3\,E$ (*filled*); the inset specifies the statistics, and the bounds (*bars*) for impulsive energy injection.

the quasar to fade or quench. We describe such conditions using our models with $\omega > 2$. So we find strongly enhanced SZ signals during the subsequent transient (see Table 1 and *bars* in the inset of Fig. 2 *right*), but also eventual ejection of a substantial gas fraction. So star formation is likely to be terminated early, at $z \sim 2$; such may have been the case in some of the recently discovered EROs (see (Cimatti , 2002)).

4. Discussion and conclusion

Searching for the enhanced SZ signals discussed above requires either resolutions of order $0'.5$ (galaxies) and $1'$ (poor groups), or must live with some signal dilution. Detecting such signals is challenging at present, but will soon be feasible through single-dish radiotelescopes equipped with the recent multibeam technology, or through the upcoming generation of interferometers. In particular, the Atacama Large Millimeter Array (ALMA) with its 64 antennas of 12-m size will be able to do imaging between 10 mm and 350 μm, at arcsec resolution (`www.alma.nrao.edu`). The SZ enhancements we predict may contribute more than clusters to the excess power detected at high multipoles with BIMA (Dawson , 2002).

Resolved detections will catch single episodes of quasar feedback *in the act*. Many such events ought to correlate with pointlike AGN emissions, while causing little extended X-ray enhancement, at variance with major merging events (Ricker , 2001). Such features will highlight a dominant AGN contribution in setting the amount and energy balance of the cosmic baryons that pervade the virialized structures.

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