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Probing AGN Feedback on the ICM with the Sunyaev-Zel'dovich Effect

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Abstract

We show that AGNs feed back enough energy as to deplete the density of the hot gas pervading galaxies and groups, and *depress* not only the equilibrium X-ray emission but also the Sunyaev-Zel'dovich effect. But we also predict transient, *enhanced* SZ signals to be produced during the AGN activity especially at high z. We show that the same feedback imprints the *steep* correlation observed between the masses of relic black holes and the host galaxy velocity dispersions.

1.1 Introduction

The SZ effect (Sunyaev-Zel'dovich 1980) at μwave or sub-mm wavelengths, and the brems emission in X-rays constitute two direct probes of the amount and thermal content of the diffuse baryons pervading galaxies and their groups and clusters.

The intracluster medium (ICM) temperatures T are found to be close to the virial values T_v. In rich clusters the ICM masses amount to $m \approx 0.15M$ relative to the dark matter's (DM). In moving toward groups at constant m/M ratio, the X-ray luminosities L_X and the Comptonization parameter y should follow the "gravitational" scaling laws $L_g \propto T_v^2(1+z)^{-3/2}$ and $y_g \propto T_v^{3/2}\,(1+z)^{3/2}$ (Kaiser 1986; Cole & Kaiser 1988).

However, the poor groups are found to be clearly underluminous, with $L_X \ll L_g$ indicating the ICM to be considerably depleted when $kT_v \lesssim 1$ keV. This requires either extensive cooling (Voit & Bryan 2001), or energy injections by SNe or AGNs causing dynamical blowout, thermal outflow, and external preheating that hinders the gas infall into the DM potential wells.

To within the wide scatter of the X-ray data for groups (Mulchaey 2004), the observed $L_X - T$ correlation may be explained with any of the above processes. So the independent probe provided by SZ observations is welcome or even needed. To now, SZ signals have been measured in rich clusters at levels $y \approx 10^{-4}$, corresponding in μwaves to CMB temperature decrements $\Delta T_{CMB} \approx -5.4\,y \approx -0.5$ mK (see Birkinshaw 1999; Zhang & Wu 2000: Reese et al. 2002).

In groups at equilibrium, where the continuum L_X is depressed well below L_g, we predict a related *deficit* of y on using the model-independent link $y/y_g = (L_X/L_g)^{1/2}\,(T/T_v)^{3/4}$, see Cavaliere & Menci (2001). But if such depressions are caused by substantial energy additions ΔE from AGNs to the equilibrium gravitational energy E, we also expect *enhanced* SZ signals during the source activity.

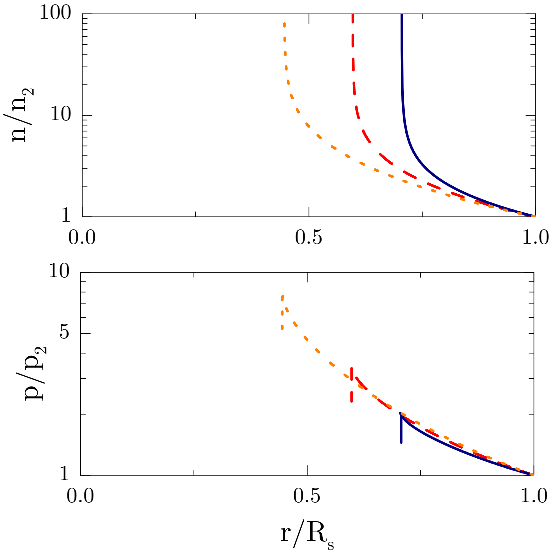

Fig. 1.1. Radial distributions of density and pressure in the AGN-driven blast. The flow is confined to a shell bounded by the leading shock at R_s and the inner "piston" at R_p. Normalizations refer to the post-shock related to the pre-shock values by $n_2/n_1 = 4\mathcal{M}^2/(\mathcal{M}^2+3)$ and $p_2/p_1 = (5\mathcal{M}^2-1)/4$. *Dotted* lines: a weak shock with $\Delta E/E = 0.3$; *dashed* lines: an intermediate shock with $\Delta E/E = 1$; *solid* lines: a strong shock with $\Delta E/E = 3$. Relatedly, $R_p \approx 0.45\,R_s$, $0.6\,R_s$, $0.7\,R_s$.

1.2 Feedback from AGNs

Large energies $\Delta E \approx 10\,f\,(M_\bullet/10^9\,M_\odot)\,(m/0.15\,M)^{-1}\,(kT_v/\mathrm{keV})^{-3/2}$ keV/particle are potentially provided by AGNs as a mass $M_\bullet$ is accreted with conversion efficiency 10^{-1} on a supermassive black hole over the host dynamical time t_d. But the fraction f actually coupled to the surrounding baryons is poorly known, and may range from less than 10^{-2} up to some 10^{-1}. The extra ΔE has to compete with the (total) value $E \approx (kT_v/\mathrm{keV})$ keV/particle of the diffuse baryons in equilibrium.

The extra input from the AGN will drive through the surrounding gas a blastwave (Platania et al. 2002), moderately or strongly supersonic depending on the key parameter $\Delta E/E = 0.1\,(f/10^{-2})\,(M_\bullet/10^9\,M_\odot)\,(m/0.15\,M)^{-1}\,(kT_v/\mathrm{keV})^{-5/2}$ compared to 1. The transient is described by Cavaliere, Lapi & Menci (2002) with a self-similar hydrodynamical flow that includes DM gravity, finite initial pressure and a density gradient $n(r) \propto r^{-2}$, driven by a source luminosity $L = \mathrm{const}$ over t_d. Fig. 1.1 represents the density and pressure profiles in the blast for relevant values of $\Delta E/E$.

After the passage of the blast the gas recovers hydrostatic equilibrium. The residual mass $1-\Delta m/m$ left behind is that still residing at $t \approx t_d$ within the virial radius, overtaken by the shock; the final temperature T will be the mass average in the shell. Relevant quantities are reported in Table 1; for $\Delta E/E < 1$ good fits are provided for the ejected ICM mass by $\Delta m/m \approx \Delta E/2E$, and for the temperature raise by $\Delta T/T_v \approx \Delta E/10E$.

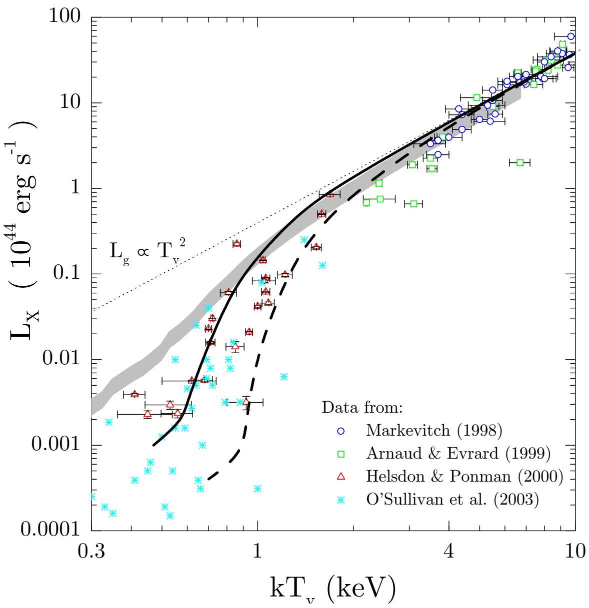

Fig. 1.2. The $L_X - T$ correlation. *Shaded* strip: results from a semianalitic model including the stochastic merging histories of the DM, star formation and the SN feedback, see Cavaliere & Menci (2001). *Lines*: results from Cavaliere, Lapi & Menci (2002) for AGN feedback with $f = 3 \times 10^{-2}$ (*solid*) and $f = 10^{-1}$ (*dashed*).

Table 1.1. *Relevant quantities for AGN-driven blasts*

	$n \propto r^{-2}, L = \mathrm{const}$				$n \propto r^{-2.4}, L \propto t^{-5/6}$	
$\Delta E/E$	$\mathcal{M}$	$\langle p \rangle / p_1$	$1 - \Delta m/m$	T_v/T	$\mathcal{M}$	$\langle p \rangle / p_1$
0.3	1.2	3.6	0.92	0.94	2.1	17.8
1	1.5	4.6	0.58	0.86	3.0	21.7
3	1.9	6.3	~ 0	0.72	4.7	26.2

In isothermal conditions, the new density distribution reads $n(r) \propto (1 - \Delta m/m) r^{-2T_v/T}$. The X-ray luminosity follows from $L_X \propto T^{1/2} \int d^3r\, n^2(r)$, and the central SZ effect from $y \propto T \int dr\, n(r)$. The resulting correlations are plotted in Fig. 1.2 and 1.3, respectively, and are compared with the corresponding results from SN feedback.

From clusters to groups, $\Delta E/E \propto T_v^{-5/2}$ increases, and the AGN feedback progressively depresses the equilibrium X-ray luminosities and SZ effects relative to L_g and y_g. But on approaching galaxy scales the depression peters out (see Fig. 1.2) since $\Delta E/E$ must saturate to a few; in fact, it also governs the overall equilibrium of the gas in the potential well (Silk & Rees 1998).

However, the energy injection by AGNs is enough to also produce *enhanced* SZ effects during the transient regime. We find (Lapi, Cavaliere & De Zotti 2004, submitted)

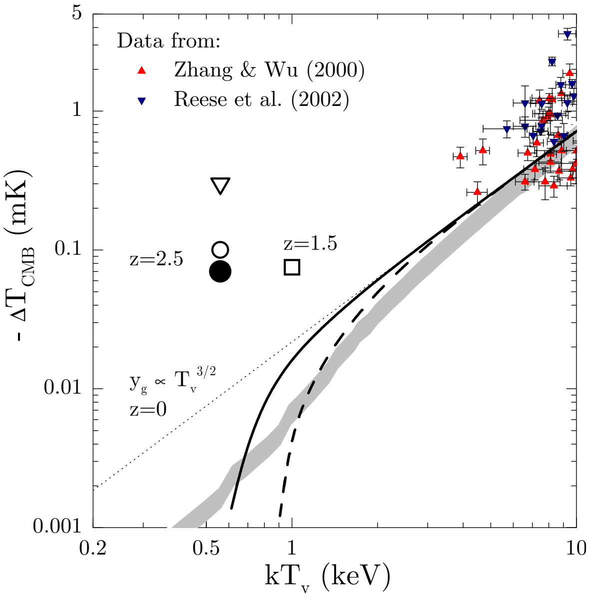

Fig. 1.3. SZ signals predicted in equilibrium and during the transient. Shaded *strip* and *lines* as in previous figure. The *circles* represent the transient SZ signals driven by an AGN with $f \approx 5\times10^{-2}$ in a gas rich, massive galaxy with $\sigma = 300$ km s^{-1} at $z = 2.5$. The *filled* circle is for $\Delta E/E = 1$ or $M_\bullet = 6\times10^8 M_\odot$; the *empty* one is for $\Delta E/E = 3$ or $M_\bullet = 3\times10^9 M_\odot$, just compatible with the observed scatter of the $M_\bullet - \sigma$ correlation. The circle areas illustrate the statistics: 1% and 10% relative to bright galaxies for the filled and the empty circle, respectively, estimated from the optical quasar luminosity function observed by Boyle et al. (2000). The *triangle* is again for $M_\bullet \approx 3\times10^9 M_\odot$ but for a nearly impulsive energy liberation, and constitutes a realistic upper limit. The *square* refers to a 1 keV group at $z = 1.5$.

$$\bar{y}/\bar{y}_g = \langle p\rangle/p_1 \times [1-(R_p/R)^3]/3 \tag{1.1}$$

for the parameter $\bar{y}$ averaged over the shell at $R_s \approx R$ in terms of the mean pressure $\langle p\rangle$ given in Table 1. Our results are plotted in Fig. 1.3.

Relatedly, the galaxian limiting condition $\Delta E = E$ once recast in terms of the DM velocity dispersion $\sigma \approx (kT_v/0.6\,m_p)^{1/2}$ reads

$$M_\bullet = 3\times10^9 M_\odot\,(f/10^{-2})^{-1}\,(\sigma/300\,\mathrm{km\,s^{-1}})^5\ . \tag{1.2}$$

For the same value $f \approx 5\times10^{-2}$ indicated by the X-ray data, this relation remarkably agrees in slope and normalization with the observations of relic black holes in the bulges of many galaxies by Ferrarese & Merritt (2000); Gebhardt et al. (2000); and Tremaine et al. (2002).

But if a galaxy happens to grow a large black hole in times shorter than t_d, the AGN will inject an energy $\Delta E \gtrsim E$ impulsively; we expect this to hinder further accretion and cause the AGN to fade or quench. We describe such conditions on extending our basic self-similar blast as shown in Table 1.1. We find strongly enhanced SZ signals during the subsequent transient (triangle in Fig. 1.3), but also eventual ejection of a substantial gas fraction $\Delta m/m \to 1$. 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 et al. 2002).

1.3 Conclusions

From Figs. 1.2 and 1.3 we see that in going from clusters (where all non-gravitational effects are small) toward groups and galaxies, the mainly external preheating provided by SNe is overwhelmed by the internal actions of the AGN feedback.

Specifically, as the relative energy input $\Delta E/E$ increases toward low T_v fuller gas ejections $\Delta m/m \approx \Delta E/2E$ occur, mainly by dynamical blowout. While $L_X \propto (1-\Delta m/m)^2 T^{1/2}$ is strongly depressed already at 1 keV, in the Comptonization parameter $y \propto (1-\Delta m/m)T$ the density depletion is balanced at first by the temperature raise $\Delta T/T_v \approx \Delta E/10E$; eventually, the former dominates and causes the equilibrium SZ *deficits* shown in Fig. 1.3.

But on approaching the galactic range no further depressions occur, because the AGN feedback is self-limited and $\Delta E/E$ saturates to about 1. Such a limit yields by the same token the steep $M_\bullet - \sigma$ correlation observed and the strongly *enhanced* SZ signals in and around early galaxies that we also show in Fig. 1.3. These arise during the blast transit as the gas is just redistributed in an expanding shell, while the temperature is raised.

Searching for such enhanced SZ signals on scales $\lesssim 0.5'$ (galaxies) or $1'$ (poor groups) is challenging at present, but will soon be feasible in μwaves with single-dish radiotelescopes being equipped with the new multibeam technology, or with the coming generation of interferometers. On the basis of Fig. 1.3, these SZ enhancements may contribute equally or more than clusters to the excess power detected by Mason et al. (2003) at high multipoles.

Resolved detections will catch the AGN feedback in the act. Considering the statistics in Fig. 1.3, they will highlight a dominant contribution of the AGN feedback in galaxies and groups, so resolving the debate over the origin of the bulk of the ICM thermal content.

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