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QUASAR FEEDBACK ON THE INTRACLUSTER MEDIUM

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ABSTRACT

Galaxy groups are quite underluminous in X-rays compared to clusters, so the intracluster medium (ICM) has to be considerably underdense in the former. We consider this to be due to substantial energy fed back into the ICM when the baryons in the member galaxies condense into stars ending up in supernovae (SNe) or accrete onto central supermassive black holes energizing active galactic nuclei (AGNs). We compute the outflow and the blowout effects driven by the AGNs and the resulting steep luminosity-temperature correlation L_X-T. We compare this with the SN contribution and with the X-ray data; the latter require the AGN energy to be coupled to the surrounding ICM at fractional levels around 5×10^{-2}. We link the L_X-T behavior with the parallel effects of the AGN feedback on the gas in the host galaxy; we find that these yield a correlation steep up to $M_{BH} \propto \sigma^5$ between the galactic velocity dispersions and the central black hole masses.

Subject headings: galaxies: clusters: general — quasars: general — shock waves — X-rays: galaxies: clusters

1. INTRODUCTION

Groups and clusters of galaxies shine in X-rays owing to the thermal bremsstrahlung radiation emitted by the hot intracluster medium (ICM) they contain. But the poorer groups are found to be progressively underluminous, so as to lie substantially below the simple scaling $L_X \propto T_v^2$. For the latter to hold, in the luminosity $L_X \propto n^2 R^3 T^{1/2}$ the ICM number density n would have to be proportional to the gravitationally dominant dark matter (DM) mass density ρ. This constraint adds to the temperature T being close the virial value T_v and the size R scaling as the virial radius $R_v \propto T_v^{1/2} \rho^{-1/2}$.

In fact, the observed L_X-T correlation has a shape more like $L_X \propto T_v^3$ for richness 1 clusters (Kaiser 1991), and in moving toward poor groups it bends further down to $L_X \propto T_v^5$ or steeper (Ponman, Cannon, & Navarro 1999; see also § 3). So in groups the ICM is considerably underdense relative to the cluster values $n \approx 10^{-1} \rho/m_p$.

Correspondingly, the central ICM entropy $S/k = \ln kT/n^{2/3}$ deviates upward from the simple scaling $e^S \propto T_v$, to attain in poor groups the "floor" value $kT/n^{2/3} \approx 140$ keV cm^2 (Lloyd-Davies, Ponman, & Cannon 2000). This requires a density deficit associated with increased or constant T/T_v. Such a non-adiabatic behavior may be traced back to energy losses from, or additions to, the ICM.

Here we focus on the "heating" that arises as the baryons in the member galaxies condense into stars followed by supernovae (SNe) or accrete onto a supermassive black hole (BH) kindling an active galactic nucleus (AGN). Two issues stand in the way: (1) any extra energy from sources has to compete with the huge thermal value $E \approx 10^{61} (kT_v/\mathrm{keV})^{5/2}$ ergs for the ICM in equilibrium, and (2) the extra energy that can be coupled to it is still poorly known. We discuss these issues and derive two observables that bound or probe at group and at galactic scales the amount of energy coupled.

2. FEEDBACK FROM SNe

Obvious first candidates for energy discharges into the ICM are the SN explosions following star formation in the member galaxies of groups and clusters. Prompt, Type II SNe canonically release 10^{51} ergs; these are effectively coupled to the gas when SN remnants propagate cooperatively over galactic scales to drive galactic winds (Ostriker & McKee 1988; Wang et al. 2001; Pettini et al. 2001; Heckman 2002). With a coupling around one-half, the energy input (including winds from hot stars) comes to $\Delta E \lesssim 3 \times 10^{48}$ ergs per solar mass condensed into stars. In a fiducial group with $kT_v \approx 1$ keV, virial mass $M_v \approx 5 \times 10^{13}\, M_\odot$, and stellar mass around $3 \times 10^{12}\, M_\odot$, this would raise by $k\Delta T \approx 0.3$ keV the temperature of the entire ICM. The outcome looks like a modest $\Delta E/E = \Delta T/T_v \approx \frac{1}{3}$.

Actually, SNe make optimal use of their energy in that they produce *hierarchical preheating* of the ICM, while a group and its ICM are built up hierarchically through merging events with a range of partners. About half the final DM mass M_v is contributed to the main progenitor by smaller partners with masses within the window $M_v/3$ to $M_v/20$, corresponding to temperatures from $0.6T_v$ down to $0.15T_v$ (Lacey & Cole 1993; Menci & Cavaliere 2000).

Smaller lumps in the window have shallower gravitational wells and produce more star-related energy on scales closer to the dynamical time t_d; so they are more effective in heating/ejecting their gas share. During each subsequent step of the hierarchy, such gas preheated *externally* will less easily flow into the main progenitor's well. Thus, the effects propagate up the hierarchy, and lower ICM densities are induced in all structures up to poor clusters.

Two main density suppression factors arise in moving from clusters to groups. These are best discussed on referring to ICM in hydrostatic equilibrium within the DM potential well $\Delta\phi$ (Cavaliere & Fusco-Femiano 1976; Jones & Forman 1984). In the corresponding ICM density run $n(r) = n_2 \exp[\beta \Delta\phi(r)]$, the energy injection resets the values of $\beta = T_v/T$ and of n_2.

One factor is related to the outflow and is given by β; the latter is lowered by about 0.6 from rich clusters toward poor groups where stellar preheating provides a contribution to T comparable to T_v. A second factor is the differential containment expressed by the boundary value n_2. If this is set by jump conditions across the accretion shocks at $r \approx R_v$ (see Takizawa

& Mineshige 1998; Gheller, Pantano, & Moscardini 1998), the density is further suppressed from clusters to groups by another factor approaching $\frac{1}{2}$ on average (see Menci & Cavaliere 2000).

These authors model the process on grafting the ICM equilibrium onto the semianalytic treatment (SAM) of star and galaxy formation. This is based on the merging histories of the DM and includes star formation and gas heating/ejection by SNe in terms of simple recipes. The latter imply heating to dominate at scales of bright galaxies and larger; only in small galaxies the gas fractions blown out exceed 10^{-1} (see Madau, Ferrara, & Rees 2001).

With SN feedback, the SAMs provide detailed fits to the stellar observables. But the agreement with the available L_X-T data for poor groups is marginal if both the Navarro, Frenk, & White (1997) potential $\Delta\phi$ and the standard flat Λ cosmology are adopted. This is illustrated in § 3 (see also Borgani et al. 2001).

Note that the SAMs include the amount of cooling suitable for baryon condensation to stars, which helps in lowering the ICM density. A leading role of cooling (combined with suitable feedback) to remove the low-entropy gas has been discussed by Bryan (2000), Muanwong et al. (2002), and Voit et al. (2002). We concentrate on a maximal but realistic feedback process.

3. FEEDBACK FROM AGNs

The natural sources of strong feedback are the AGNs, energized by accretion of cool baryons onto supermassive BHs in galactic cores (see Wu, Fabian, & Nulsen 2000; Bower et al. 2001). The outputs are large, of order $2 \times 10^{62}(M_{\rm BH}/10^9\ M_\odot)$ ergs for an accreted mass $M_{\rm BH}$, with the standard mass-energy conversion efficiency of order 10^{-1}. If a fraction f is coupled to the surrounding medium, the energy actually injected comes to $\Delta E \approx f10^{50}$ ergs per solar mass condensed into stars; we have used 2×10^{-3} for the ratio of the BH mass to that of the current host bulges (Ferrarese & Merritt 2000; Gebhardt et al. 2000; see also Fabian & Iwasawa 1999).

Compared with SNe, AGNs potentially provide a larger energy output in shorter times, close to t_d of the host galaxies. However, f is more uncertain than the analogous quantity for SNe, although it is expected to be lower.

The 10% radio-loud AGNs directly produce large kinetic energies in the form of jets, but up to now the observations indicate limited impact on the gas surrounding a number of active sources (see McNamara et al. 2001; Terashima & Wilson 2001; Young, Wilson, & Mundell 2001). In the 90% radio-quiet AGNs, a smaller coupling $f \approx 10^{-2}$ is expected in view of their flat spectra and of the low photon momenta. Values up to $f \sim 10^{-1}$ are conceivable only in systems where the photons are heavily scattered/absorbed within the gravitational reach of the BH and escape in hard X-rays if at all (Fabian, Wilman, & Crawford 2002).

Whence the interest in probing f from overall effects on the ICM. During the AGN activity, the gas initially contained in a host galaxy or a group will be heated up and partially blown out. We will treat blowout and outflow driven *internally* in poor groups with $kT_v \sim 1$ keV where $\Delta E/E \sim 1$. These effects are maximized in spherical symmetry, not unfit for the radio-quiet AGNs.

Within the structure's dynamical time t_d, we describe the transient regime as a blast wave sweeping through the surrounding gas (see Platania et al. 2002); when $\Delta E/E \lesssim 1$ holds,

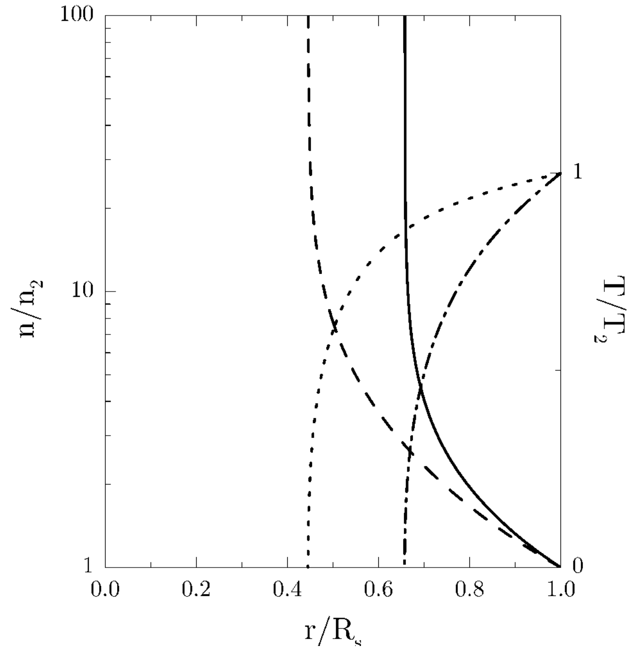

FIG. 1.—Radial distributions of density and temperature (normalized to their postshock values) in a blast wave driven by a flaring AGN. Dot-dashed and dotted lines refer to the temperature behind a strong ($\Delta E/E = 1.8$) or a weak ($\Delta E/E = 0.3$) shock, respectively; solid and dashed lines refer to the density. On approaching the piston ($r = 0.66R_s$ or $r = 0.45R_s$ for the adopted values of $\Delta E/E$), the density diverges weakly while the mass inside r vanishes.

the leading shock at $r = R_s$ is not necessarily strong, and DM gravity is important.

From the relevant hydrodynamical equations, we have derived (and illustrate in Fig. 1) a family of self-similar solutions of the Sedov (1959) type that include the DM gravity and finite initial pressure, a steep initial density gradient, and centrally injected energy $\Delta E(t)$ growing over times of order t_d. The radiative cooling is slow on mass average in our groups.

Our fiducial case will have $\Delta E(t) \propto t$ injected into an initial configuration with $n(r) \propto r^{-2}$, i.e., isothermal ICM in hydrostatic equilibrium ($\beta \approx 1$) in the potential provided by DM density $\rho(r) \propto r^{-2}$; we denote by $E(R_s)$ the modulus of the total initial energy within the shock radius R_s. Then the leading shock moves outward at a constant speed v_s, only moderately supersonic when $\Delta E/E \lesssim 1$.

Self-similarity implies $\Delta E(t)/E(R_s)$ to be independent of time and position, as is especially simple to see in our fiducial case where $E(R_s) \propto R_s \propto t \propto \Delta E(t)$. For two values of $\Delta E/E$, we show in Figure 1 the density and temperature runs. The flow begins at a "piston," the inner contact surface where the density diverges weakly while the gas mass within r and the temperature $T(r)$ vanish.

In fact, the perturbed gas is confined to a shell with inner (piston) radius λR_s and outer (shock) radius R_s. Self-similarity implies the thickness $\Delta R_s/R_s = 1 - \lambda$ of such a shell to depend only on $\Delta E/E$; for strong shocks driven by $\Delta E/E \gg 1$ we find $\lambda \rightarrow 0.84$, while for a weak shock corresponding to $\Delta E/E = 0.3$ we find $\lambda = 0.45$.

These considerations lead us to represent our solutions in terms of the simple "shell approximation," known to provide results reliable to better than 15% (see Cavaliere & Messina 1976; Ostriker & McKee 1988). In this approximation, the energy balance reads

$$\Delta E + E = \frac{1}{2} m v_2^2 + \frac{3}{2} \bar{p} V - \frac{GMm}{R_s} \quad (1)$$

and directly shows the relevance of $\Delta E/E$. Here M is the DM mass within R_s; also, $V = 4\pi R_s^3(1-\lambda^3)/3$ is the volume of the shell; m and $\bar{p}$ are the associated gas mass and mean pressure; finally, $v_2 \propto v_s$ is the postshock velocity given by the Rankine-Hugoniot conditions.

Self-similarity requires all terms in equation (1) to scale like R_s; the coefficients depend only on $\Delta E/E$ and are easily derived following the pattern indicated by the above authors. We find the ratio of the kinetic to the thermal energy (i.e., the first to the second term on the right-hand side of eq. [1]) to range from 5×10^{-2} up to 2 when $\Delta E/E$ increases from 0.3 to values larger than 1. Analogously, one may derive the dependence of v_s on $\Delta E/E$ and an analytic approximation to the mass distribution within the shell.

After the passage of the blast wave, and before a major merging event reshuffles the DM mass substantially, the gas recovers hydrostatic equilibrium and again $n(r) = n_2 \exp(\beta\Delta\phi)$ holds; but now the governing parameters are those given in Table 1. The value of $\beta = T_v/T$ (related to outflow) is reset using the mass-averaged temperature T. The new ICM mass $m - \Delta m$ (left behind by the blowout) is taken to be that still residing at $t = t_d$ between the piston and R_v; thus, the boundary condition n_2 is reset by requiring consistency with the volume integral of $n(r)$.

We then compute $L_X \propto T^{1/2} \int dr\, r^2 n^2(r)$ and plot it as a function of temperature in Figure 2; here we approximate T with T_v, since these differ only modestly, as seen from the values of β in Table 1. Our results are given for two values of the energy coupled; these bracket $\Delta E = 2 \times 10^{60}$ ergs, corresponding, e.g., to $f \approx 5 \times 10^{-2}$ and to $M_{BH} = 10^9\ M_\odot$ for the largest BH (or sum of BHs) formed within t_d in groups with membership around 10, mostly unpertured bright galaxies.

The variable T_v may be related to the quantity $\Delta E/E$ that governs the blast wave on using $E \propto (kT_v)^{5/2}$ (see § 1). Assuming $\Delta E \propto M_{BH}$ (see the beginning of this section), the correspondence is simply given by

$$\frac{\Delta E}{E} = 0.1 \frac{f}{10^{-2}} \frac{M_{BH}}{10^9\ M_\odot} \left(\frac{kT_v}{\text{keV}}\right)^{-5/2}. \quad (2)$$

In Figure 2, we have actually implemented the second approximation $\Delta E \propto M_{BH}[1 + (kT_v/\text{keV})^{6/7}]/2$.

This accounts for the cosmological evolution of the AGNs that occurs at redshifts $z < 2.5$, when groups and clusters with increasing $kT_v \propto M_v^{2/3}(1+z)$ are formed by the standard hierarchical clustering. In the critical universe, the above (normalized) correction stems from: (1) the diminishing fraction of member galaxies activated within the increasing t_d, which scales simply as M_v, i.e., approximately as $(1+z)^{-5}$, and (2) all outputs weakening as $(1+z)^3$ (see Cavaliere & Vittorini 2002). In the standard flat Λ cosmology, the result provides a close upper limit.

In Figure 2, we also recall the contribution from SNe and report the available X-ray data.

TABLE 1

Parameters of the Recovered Equilibrium

$\Delta E/E$	β	$1-\Delta m/m$
0.3 ……	0.94	0.92
1 ………	0.86	0.58
1.8 ……	0.8	0.16

Note.—The approximation $\Delta m/m \approx 0.5(\Delta E/E)$ holds to better than 10% for $\Delta E/E < 1.4$.

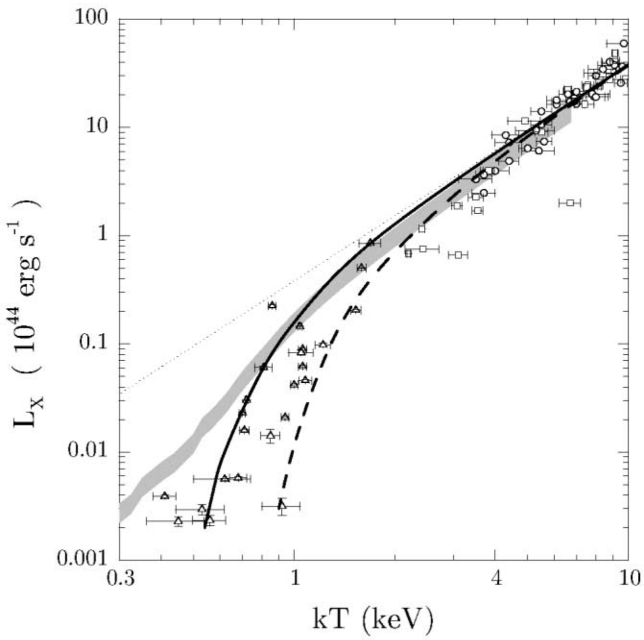

Fig. 2.—L_X-T correlation; bolometric L_X including standard line emissions. *Thin dotted line*: Gravitational scaling $L_X \propto T_v^2$. The shaded 1-sigma strip results from a SAM including the stochastic merging histories of the DM and the SN feedback (see § 2). *Thick lines*: Our results with feedback from AGNs accreting as specified at the end of § 3 and with $f = 3 \times 10^{-2}$ (*solid line*) and $f = 10^{-1}$ (*dashed line*). Data are from Markevitch (1998; *circles*), Arnaud & Evrard (1999; *squares*), and Helsdon & Ponman (2000; *triangles*).

4. DISCUSSION AND CONCLUSIONS

Two key features are apparent in Figure 2 and are spelled out in Table 1. First, into the cluster range the deviations from the gravitational scaling vanish because both $1 - \Delta m/m$ and $\beta = T_v/T$ saturate to 1. Second, moving into the group range, the luminosity is nonlinearly suppressed as $L_X \propto n_2^2 \propto (1 - \Delta m/m)^2$ owing to the increasing contribution from the blowout as $\Delta E/E$ rises toward 1.

The current X-ray data in groups are seen to require values around $f \approx 5 \times 10^{-2}$ in our blast-wave model. With these, the feedback from AGNs dominates over SNe in poor groups, causing stronger suppression of L_X and further bending of the L_X-T relation. Variance of f from 3×10^{-2} to 10^{-1} produces a widening strip but one still consistent with the current data and their scatter. This also covers the effects of moderate nonspherical deviations.

As our L_X-T relation intrinsically steepens toward poor groups, we can check it in the adjoining galactic range, where cooling still does not dominate. In terms of the velocity dispersion $\sigma = (kT_v/0.6m_p)^{1/2}$ from the virial relation, we find a steepening correlation $L_X \propto \sigma^n$; for the upper values of f, the slope ranges from $n \approx 8.5$ to 10 in large galaxies with $\sigma =$

300 km s^{-1}, which accords with the detections and the fit by Mahdavi & Geller (2001).

Our result is due to a blast wave with $\Delta E/E \approx 1.2$ causing $\Delta m/m \approx 0.6$. Down to what scales can we extend the increasing trend of $\Delta E/E$? We argue $\Delta E/E$ *on average* will not exceed 1 by much, nor will $\Delta m/m$ attain 1.

First, we impose the limiting constraint $\Delta E/E \approx 1$ to eq. (2) and find the accreted masses

$$M_{\rm BH} \approx 2 \times 10^9\ M_\odot \left(\frac{f}{10^{-2}}\right)^{-1} \left(\frac{\sigma}{300\ \rm km\ s^{-1}}\right)^5 . \qquad (3)$$

Such values, consistent with those adopted in our computations, for f in the range (3–5) $\times 10^{-2}$ gratifyingly agree with the masses of dark objects detected at the center of many galaxies. Also the trend accords with the similar correlation pointed out by Ferrarese & Merritt (2000) and Gebhardt et al. (2000). Note that on using the second approximation to $M_{\rm BH}$ discussed after equation (2), our correlation is somewhat flatter than $M_{\rm BH} \propto \sigma^5$; it has the slope 4.3 around $\sigma \approx 300$ km s^{-1} and the prefactor $3 \times 10^9\ M_\odot$.

Next, we discuss how our limiting value $\Delta E/E \approx 1$ arises in galaxies from BH accretion regulated by the AGN itself (see also Silk & Rees 1998). On the one hand, sustaining $\Delta E/E$ to about 1 requires sufficient cold gas made available for inflow. The requirement is met by gravitational torques exerted in the host by companion galaxies within small groups (see Cavaliere & Vittorini 2002). During encounter or flyby times of order t_d, such interactions destabilize fractional gas masses of order 10^{-2}, while the values needed to satisfy eq. (3) in the host galaxies are only of order $\sigma^2/f\eta c^2 \approx 2 \times 10^{-3}(\sigma/300\ \rm km\ s^{-1})^2$.

On the other hand, $\Delta E/E$ will be limited if the accretion itself can be affected on the timescale t_d by the AGN feedback; if so, the AGN will fade out. Declining luminosities are included in our self-similar blast-wave family under the form $L \propto t^{5(2-\omega)/\omega}$ if the initial density gradient follows a steeper law $n \propto r^{-\omega}$ with $\omega \geq 2$. Increasing ω up to 2.5 corresponds to $L(t)$ going from constant to a spike; up to $\omega \approx 2.4$, the nonlinear behavior of L_X-T around $\Delta m/m \approx \frac{1}{2}$ is generic.

But when ω approaches 2.5, the timescales effective for $L(t)$ become quite shorter than t_d; the corresponding blast waves cause larger values of $\Delta m/m$ at a given $\Delta E/E$. This behavior is indicative of runaway conditions prevailing in the host galaxy when this happens to grow a large BH in short times. Then most galactic gas is blown away beyond R_v, so the star formation activity is suppressed already at $z \approx 2$ (see also Granato et al. 2001). Such may have been the case for some of the recently discovered extremely red objects (EROs; see Cimatti et al. 2002; Alexander et al. 2002).

To sum up, we find that the AGN feedback sharply *steepens* the L_X-T correlation in the poor group range, and *links* its shape to that of the galactic $M_{\rm BH}$-σ correlation. This is because in moving from clusters to groups the energy ΔE injected by AGNs within t_d grows relative to the unperturbed E, and *overwhelms* SNe. But on entering the galactic range, $\Delta E/E$ approaches unity and constrains the accretion itself. These correlations provide two linked but observationally independent *probes* of the hidden parameter f. On the basis of our blast-wave model, the existing X-ray data concur with the optical ones to indicate values around $f \approx 5 \times 10^{-2}$.

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