SEARCHING FOR AGN-DRIVEN SHOCKS IN GALAXY CLUSTERS

A. Cavaliere¹ and A. Lapi¹,²

Received 2006 March 27; accepted 2006 June 28; published 2006 July 31

ABSTRACT

Shocks and blast waves are conceivably driven into the intracluster medium filling galaxy groups and clusters by powerful outbursts of active galactic nuclei or quasars in the member galaxies; the first footprints of shock fronts have been tentatively traced out with X-ray imaging. We show how overpressures in the blasts behind the shock can prove the case and also provide specific marks of the nuclear activity: its strength, its current stage, and the nature of its prevailing output. We propose to detect these marks with the aimed pressure probe constituted by the resolved Sunyaev-Zel’dovich effect. We compute and discuss the outcomes to be expected in nearby and distant sources at different stages of their activity.

Subject headings: cosmic microwave background — galaxies: clusters: general — quasars: general — shock waves

1. INTRODUCTION

Density jumps have been recently pinpointed by X-ray imaging of the hot intracluster medium (ICM) that pervades galaxy groups and clusters with average densities around n ~ 10⁻³ cm⁻³ and temperatures T in the keV range. These jumps have been interpreted in terms of shock fronts propagating into the ICM out to radial distances r ~ 0.2 Mpc, with Mach numbers around M ~ 1.5, and involving energies up to ΔE ~ 3 x 10⁶⁸ ergs (Mazzotta et al. 2004; McNamara et al. 2005; Forman et al. 2005; Nulsen et al. 2005a, 2005b).

Shocks over large scales with such intermediate strengths were specifically expected by Cavaliere et al. (2002) as marks of the energy being fed back into the ICM by active galactic nuclei (AGNs) when they flare up in member galaxies of a group or cluster. Such events occur when a central supermassive black hole (BH) accretes an additional mass M₂ ~ 10⁻⁹ M☉, with standard efficiency η ~ 10⁻¹ for mass-energy conversion, this yields over times Δt ~ 10⁸ yr energies of order 2 x 10⁶⁸ (M₂/10⁹ M☉) ergs.

If these outputs couple at levels f ~ a few percent to the surrounding ICM, they constitute, in principle, considerable additions ΔE ~ 10⁶⁸ (f/5%) (M₂/10⁹ M☉) ergs to its binding energy. In fact, the latter comes to E ~ GMm/Ar ~ 3 x 10⁶⁸ ergs in the central 0.2 Mpc of a cluster, which encompasses a dark matter (DM) mass M ~ 5 x 10¹⁵ M☉ and an ICM mass fraction m/M ~ 0.15. With such appreciable ratios ΔE/E, we expect in the ICM a large-scale blast wave formed by a leading shock that starts from the host galaxy and moves into the surrounding ICM out to several 10⁻³ Mpc.

In fact, the shock Mach numbers are provided in the simple form M ~ (1 + ΔE/E)₁/₂ by the hydrodynamics of the ICM (see Lapi et al. 2005), a good electron-proton plasma that in thermal equilibrium (see § 4) constitutes a single “monatomic” fluid with pressure P ~ 2 n kT. For BH masses bounded by M₂ ~ 5 x 10⁹ M☉ (Ferrarese 2002; Tremaud et al. 2002), relative energy inputs ΔE/E ~ 1 obtain and yield just M ~ 1.5; they also yield standard Rankine-Hugoniot jumps of the postshock pressure P ≈ 2 n kT, 1.7 consistent with the X-ray analyses. What other marks will establish such shocks and blasts?

One is constituted by the temperature. This rises sharply across a shock but then falls down into the blast, helped by cooling. In any case, resolved spectroscopic measurements of the electron T require many X-ray photons, more than currently available from distant clusters or groups.

Pressure provides another, independent mark; the electron pressure is directly sensed with the SZ effect (Sunyaev & Zel’dovich 1972). The pressure at the shock has to jump up from the unperturbed level P₁ by a factor P₂/P₁ = (5M₂ - 1)/4, which distinguishes a shock from a cold front; moreover, P must retain sufficiently high levels throughout the blast to propel forward the ICM it sweeps up.

We will see that the radial pressure run P(r) actually rises from the leading shock to an inner “cavity,” as long as the blast is driven on by a central AGN. Power must be transmitted from it to the surrounding ICM blast by means of an intervening medium. This may be constituted either by relativistic particles filling up a radio volume energized by jets (Scheuer 1974; Heinz et al. 1998), or by another and hotter plasma heated up by the impact of radiation-driven superwinds (see Lamers & Cassinelli 1999). Thus, SZ pressure probing will have direct implications for the kind and the time cycles of the AGN outputs—in particular, for the radio-loud components.

2. COMPUTING OVERPRESSURES IN BLAST WAVES

In predicting pressure distributions, a divide is set by the source timescale Δt compared to the blast crossing time R_s/R_s ~ 2 x 10⁸ M⁻¹(R_s/0.2 Mpc) yr; here R_s is the shock radial position, and R_s = M c_s its velocity in terms of the sound speed c_s = (5P/3nm)₁/₂.

The impact on the ICM of a short-lived AGN source can be modeled as an instantaneous central explosion launching the classic self-similar blasts of Sedov (1959) and Parker (1963); these propagate freely at high if decreasing Mach numbers M (which make P and gravity irrelevant) into an initial density run n(r). When the latter is provided in the form n(r) ~ r⁻² by the standard atmosphere in isothermal equilibrium, the pressure P in the blast declines toward the center. Steeper density runs yield an even stronger decline, while flatter ones still imply P ~ P_2.

But in some sources the observations recalled in § 1 show proximity of the shocks to the edge of the radio volumes. This indicates blasts being currently driven by the relativistic particles associated with the radio source and calls for considering AGN outputs sustained during the propagation. A similar in-
dication is provided by the evidence at redshifts \( z \approx 0.3 \) of superwinds driven by shining quasars (see Stockton et al. 2006). The moderate values observed for \( M \) require including the effects of gravity and finite initial pressure \( P_i \).

These conditions are aptly modeled with the self-similar blasts derived by Lapi et al. (2005). A significant test bed is again provided by the isothermal distribution of both the DM and the unperturbed ICM in the gravitational field of the former; their cumulative masses out to \( r \) scale as \( m(< r) \propto M(< r) \propto r \), and the ICM pressure as \( P_i(r) \propto n_i(r) \propto r^{-2} \).

The overall parameters of the perturbing blast may be derived from the simple “shell approximation,” long known to be effective and precise (see Cavaliere & Messina 1976; Ostriker & McKee 1988). This treats the blast as a shell containing the mass \( m(< R_s) \) swept up to the radius \( r = R_s \) and propelled outward by the volume-averaged pressure \( \langle P \rangle \) against, we add, the upstream pressure \( P_i \) and the DM gravity \( GM(< R_s)/R_s^2 \).

This leads to the momentum equation

\[
\frac{d}{dt} [m(< R_s) v_z] = 4 \pi R_s^2 \langle P \rangle - \frac{G M(< R_s)}{R_s^2} m(< R_s) \tag{1}
\]

in terms of the postshock velocity \( v_z = 3(M^2 - 1) \dot{R}/4M^2 \).

Here the pressure terms scale following \( P_R^2 = \text{const} \), as does the gravitational term. Self-similar solutions require also the left-hand side to remain constant as the blast moves out; since \( m(< R_s) v_z \propto R_s \dot{R} - R_s c_s^2 \dot{R} \) holds (with \( c_s = \text{const} \)), the consistent solution must satisfy \( \dot{R} \propto c_s \). Thus the shock moves outward following \( R_s = M c_s t \).

On the other hand, the gravitational energy in the DM potential well scales as \( GM(< R_s)/R_s \propto R_s \), and so do all energies including the binding \( E \); this implies that for the energy injection \( \Delta E(t) \propto t \) holds; that is, the power \( L(t) = \text{const} \) is sustained over a crossing time. Then the blast runs unattenuated with \( \Delta E(t)/E[< R_s(t)] \) and \( M \approx (1 + \Delta E/E)^{1/2} \) independent of time and position.

The actual existence of the self-similar solutions is proven from the full hydro equations. By self-similarity these reduce to a set of three ordinary differential equations in the normalized variable \( r/R_s \), which can be integrated inward of the shock, where Rankine-Hugoniot boundary conditions hold; see Lapi et al. (2005). Here we focus on the shape of \( P(r/R_s) \), which is plotted in detail in Figure 1 (left).

The point to stress is that \( P(r/R_s) \) rises from the shock to the blast inner boundary, namely, to the “piston.” This is the contact discontinuity separating the ICM from the inner medium in the cavity; some of the swept-up gas piles up there, causing the density to diverge mildly whereas the temperature \( T(r) \) vanishes. In the blast the two combine to yield a rising \( P(r/R_s) \); at the piston this attains a value \( P_f \) exceeding \( P_s \) by factors of \( 3-4 \) (see Fig. 1), and larger at lower \( M \).

The rising trend is best understood in the shell approximation on computing the coefficients of equation (1), given the scalings above; simple algebra and some labor yield

\[
\frac{\langle P \rangle}{P_s} = 4 \frac{5M^2 + 7}{5M^2 - 1} \left[ \frac{5}{4} (M^2 - 1) + 3 \right] = \frac{5M^2 + 7}{5M^2 - 1}. \tag{2}
\]

The first additive term in the middle expression embodies the contribution to \( \langle P \rangle \) from the shell momentum; the second, those from the initial pressure (contributing \( \dot{v} \) plus gravitation \( \dot{v}^2 \)).

The final expression shows that \( \langle P \rangle/P_s \), and hence the monotonic \( P(r)/P_s \) go to unity for \( M \gg 1 \), the result known from Sedov blasts launched into a density gradient with negligible gravity and initial pressure. On the other hand, \( \langle P \rangle \) and \( P(r)/P_s \) increase as \( M \rightarrow 1 \); this concurs with the lowering jump \( P_f/P_s \) to yield an overall value \( P_f \) that decreases slowly, as shown by Figure 1.

In sum, a driving source tends to excavate in the ICM a cavity with very low inner X-ray emission; this is bounded by
the blast (from a rim at the piston to the leading shock) in a cocoon-like topology; radio source asymmetries introduce minor changes (see Heinz et al. 1998). Enhanced values \( P_p / P_s \) relate mainly to gravity, important to the ICM as long as all velocities do not strongly exceed \( c_s \) or the DM velocity dispersion; so at lower \( \mathcal{M} \) a relatively stronger push is required to propel the cocoon on.

From the energy standpoint, high values of \( P_p \) may be viewed as necessary for soaking up—in the form of work \( 4\pi R_i^2 P_s \) done at the piston—the power fraction transferred from the source via the inner medium filling the cavity. The fraction is \( \alpha \approx \frac{1}{3} \) when the medium is constituted by relativistic particles (see Cavaliere & Messina 1976), and \( \alpha = 1 \) in the case of a thermalized superwind.

3. MEASURING OVERPRESSURES WITH THE SZ EFFECT

The enhanced pressures in the blast can be directly probed with the SZ effect. This arises when photons of the cosmic microwave background (CMB) crossing a cluster are Compton upscattered by the hot ICM electrons; then the blackbody spectrum of the CMB is tilted slightly toward higher energies.

The resulting intensity change \( \Delta I \) of the CMB radiation at a normalized frequency \( x = h\nu/kT_{\text{CMB}} \) is given in the thermal, nonrelativistic case (Rephaeli 1995) by

\[
\Delta I = 2 \frac{(kT_{\text{CMB}})^{3/2}}{(hc)^2} g(x) y.
\]

The effect strength is set by the Comptonization parameter

\[
y(w) = 2 \frac{\sigma_T}{m_e c} \int_0^{l_{\text{max}}} dl \, p(r),
\]

just proportional to the electron pressure \( p = n kT \) integrated along the line of sight (LOS) at a projected distance \( w \) from the cluster center; \( l_{\text{max}} = (R_i^2 + w^2)^{1/2} \) applies if the ICM boundary is set at the virial radius \( R \). The spectral shape is encoded in the factor \( g(x) \). This has a crossover point at \( \nu \approx 220 \text{ GHz} \); it is positive for larger \( \nu \) with a peak at \( \nu \approx 370 \text{ GHz} \), and negative for lower \( \nu \) with a minimum at \( \nu \approx 130 \text{ GHz} \). The approximation \( g(x) \approx -2x^2 \) applies at the Rayleigh-Jeans end of the CMB spectrum.

As \( \Delta I \propto y \propto P \) holds, we expect that in an AGN-driven blast the SZ signal is enhanced from shock to piston, relative to the equilibrium value \( I_{\text{eq}} \) on the LOS grazing the shock. In Figure 1 (lower panels) we show the outcome of our computations based on equation (3) and on \( P(r/R) \) given in the top panel.

We describe our results beginning with \( \nu < 220 \text{ GHz} \). The rise of \( \Delta I / I_{\text{eq}} \) starts up at the shock position \( w = R_s \) with a high derivative arising from the contribution of the pressure jump \( P_s / P_r \) to the LOS integral. The subsequent rise toward the piston reflects the further pressure increase into the blast.

Inward of the piston, \( \Delta I / I_{\text{eq}} \) rises still further when the inner medium is constituted by a very hot thermal plasma with constant pressure \( P_r \) (dashed lines); this is the case with a thermalized superwind, where \( c_s \) is high owing to the high pressure \( P_r \gg P_s \) and the low density \( n < n_i \).

Conversely, \( \Delta I / I_{\text{eq}} \) declines for \( w < R_s \) (solid lines) when the cavity within \( R_s \) is filled with relativistic electrons (with \( c_s \approx c / \sqrt{3} \)). In fact, these provide the pressure \( P_r \approx 8P_s \) but contribute little to the overall SZ signal on two grounds. First, relativistic pressures \( P_{\text{rel}} = P_r \) imply low electron densities, even with minimal Lorentz factors of a few (see Pfrommer et al. 2005; Colafrancesco 2005). Second, relativistic electrons are generally inefficient contributors at a given \( \nu \) since the tilt they cause in the CMB spectrum is stretched toward high frequencies.

For comparison, we also show the thermal SZ effect produced by free Sedov-Taylor blast waves launched by a strong but short explosion (dotted lines). Here the pressure declines below \( P_s \) after the shock jump, so \( \Delta I / I_{\text{eq}} \) rises modestly inward of \( w = R_s \), and soon decreases.

In fact, the paired panels of Figure 1 show the shapes of \( \Delta I / I_{\text{eq}} \) expected with SZ instruments having two angular resolutions; in the middle panel we show our results smoothed with a Gaussian window of 1” (about 2 kpc at \( z \approx 0.1 \)), and in the bottom panel with 10” (about 20 kpc). The latter resolution is currently achieved, while the former will be attained in the near future (see § 4).

For frequencies above 220 GHz, similar shapes obtain for \( w \leq R_s \), except that the nonthermal contribution is generally lower than plotted in Figure 1. The thermal/nonthermal ratio is maximized at \( \nu \approx 370 \text{ GHz} \), to decline only at much larger \( \nu \). At \( \nu \approx 220 \text{ GHz} \) only the nonthermal component survives; here the spatial shape of the SZ signal differs significantly on two accounts. First, the rise begins at the piston position \( w = R_s \) with a sharp transition of up to \( \gamma \) for \( \rho > \) up to \( P \); second, saturation occurs at low levels.

Finally, we discuss why the initial isothermal atmosphere, where \( n \propto r^{-w} \) applies with \( \omega = 2 \), provides reliable evaluations of the SZ signals from driven blasts. Flatter runs with \( \omega < 2 \) occur in a cluster at \( r \leq 100 \text{ kpc} \); here the gravity is weaker but the mass \( m_l(r) \) swept up by the blast increases faster, and in the shell approximation equation (2) yields for \( P / P_r \) a value \( \gamma \) of the isothermal case. Steeper atmospheres corresponding to \( 2 < \omega < 2.5 \) apply for \( r \geq 500 \text{ kpc} \); these also yield self-similar blasts propagating at constant \( \mathcal{M} \) when acted on by a fading AGN with integrated energy \( \Delta E \propto r^{2.5-2\omega} \).

The outcomes include larger pressure jumps but also flatter runs of \( P(r) \) at equal values of \( \Delta E / E \) (see Lapi et al. 2005); overall, somewhat higher levels of \( P_r \) obtain.

4. DISCUSSION AND CONCLUSIONS

SZ signals are widely measured in clusters at levels \( y \approx 10^{-4} \) (see Reese et al. 2002 and Birkinshaw 2004). Lapi et al. (2003) discuss subarcminute resolutions to detect the integrated effects of AGN outbursts on the ICM of clusters and groups. Here we have focused on SZ signals resolved at levels of 10” or better, to probe the structure and the dynamics of the shocks and blasts so produced.

The SZ probe is best used in scanning the ICM around density jumps selected in X-rays. In fact, the bremsstrahlung surface brightness proportional to \( n^2 \) is well suited for pinpointing density jumps and providing positions and Mach numbers of candidate shocks. But measuring \( T \) from X-ray spectroscopy must contend with the paucity of photons and the narrow postshock range where \( T \) exceeds the unperturbed value.

So in conditions of low surface brightness (outskirts or distant structures) the SZ effect will lend a strong hand by unveiling the other key observable, namely, the overpressures behind the shocks; this is due to three circumstances. First, pressures are sensed directly through the parameter \( y \propto P \). Second, \( y \) is independent of \( z \) for sources wider than the instrumental beamwidth. Third, we expect (see Fig. 1) thermal pressures to rise throughout a blast continuously driven over a
crossing time; from shock to piston at radii 40%–30% smaller, \( P(r) \) rises up to values \( P \approx (8–9)p_\gamma \), considerably larger than the shock jump \( P_\gamma/P \approx 2.6–4.8 \) for \( M \approx 1.5–2 \); this is due to the dynamical stress in running blasts.

This rising behavior of \( P(r) \) is just opposite to the run down from shock to center expected for free blasts launched by short-lived AGN activity. We compare in Figure 1 the results we expect; they constitute an aim particularly interesting for shocks of intermediate \( M \) pinpointed in close proximity to a radio volume or around a currently shining AGN. Clear study cases will be provided by clusters or groups in quiet conditions, with no sign of outer merger-induced dynamics.

What is needed for SZ probing at \( z \approx 0.1 \) is a resolution around 10\(^{\prime}\) in the upper microwave band, already approached with the Nobeyama radio telescope (Kitayama et al. 2004).\(^3\)

Upcoming instruments such as CARMA\(^4\) will do better; at resolutions of a few arcseconds, blasts in clusters at \( z \approx 0.5 \) may be probed at levels comparable to the middle panel of Figure 1. ALMA,\(^5\) with its planned resolutions around 1\(^{\prime}\) and sensitivities down to 1 \( \mu \)K, will do better yet both in the microwave and submillimeter bands. Following the noise analysis by Pfrommer et al. (2005) and Kocsis et al. (2005), a 5 \( \sigma \) detection with ALMA of the thermal SZ signal we focus on will require scanning a limited area in the vicinity of an X-ray-preselected position for a few hours per cluster.

We add that once kiloparsec scales are resolved, 2-fluid effects will be interesting as may arise from disequilibrium between the electrons and ions (see Ettori & Fabian 1998; Fabian et al. 2006). They may cause a gradual rise of the electron pressure in front of the shock, to converge behind it with the declining ion pressure toward the equilibrium values considered above.

Here we stress three issues. First, how common are shocks in clusters? The frequent occurrence of quenched cooling flows argues for widespread shocks driven by central AGNs injecting energies \( E_c \) in excess of the radiative cooling losses (see Birzan et al. 2004; Nulsen et al. 2005a, 2005b).

Second, in what prevailing mode does an AGN release the driving energy \( E_c \), in mechanical form and radio jets or in radiation-driven superwinds? To a first approximation the mode little affects the total energy injected, based on the simple rule \( E_c \sim \alpha q \eta M_\bullet \Delta t \sim \) const that we extract from Churazov et al. (2005); that is, mechanical energy and jets gain on grounds of coupling efficiency (\( \alpha \eta \approx \frac{1}{2} \) vs. a few percent) what they lose to radiation on grounds of \( q \). Conversely, the shock energetics alone will not distinguish the mode.

Third, what other probe may help? The specific SZ probing we propose can trace the distinguishing features of the injection: its timescale (past or ongoing) and its prevailing content (relativistic particles or photons). The SZ effect resolved at levels of 10\(^{\prime}\) or better will directly detect the mark of a blast launched or driven by a powerful AGN, namely, the hydro overpressure jumping up at the shock and sustained throughout the blast. But when the radio source drive persists over the transit time the pressure actually rises in the blast and the SZ signal is enhanced; it is boosted up by plasma in the cavity if the drive is helped by AGN superwinds.

These outcomes are independent of model details; rather, they depend on a few overall parameters: the relative injection energy \( E_c \) evaluated from \( M \); the active time of the AGN compared with the blast crossing time; and the injection mode, whether dominantly in mechanical or radiative energy. We conclude that SZ measurements concurring with the X-ray imaging can effectively probe the injection mode, the dynamics of the blasts, and the history of the driving AGN sources.

We thank our referee for helpful comments. Work supported by ASI, INAF, and MIUR.

REFERENCES

Birkinshaw, M. 2004, in Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, ed. J. S. Mulchaey, A. Dressler, & A. Oemler (Cambridge: Cambridge Univ. Press), 161

Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800

Cavaliere, A., Lapi, A., & Menci, N. 2002, ApJ, 581, L1

Cavaliere, A., & Messina, A. 1976, ApJ, 209, 424

Churazov, E., Sazonov, S., Sunyaev, R., Forman, W., Jones, C., & Böhringer, H. 2005, MNRAS, 363, L91

Colafrancesco, S. 2005, A&A, 435, L9

Ettori, S., & Fabian, A. C. 1998, MNRAS, 293, L33

Fabian, A. C., et al. 2006, MNRAS, 366, 417

Ferrarese, L. 2002, ApJ, 578, 90

Forman, W., et al. 2005, ApJ, 635, 894

Heinz, S., Reynolds, C. S., & Begelman, M. C. 1998, ApJ, 501, 126

Kitayama, T., et al. 2004, PASJ, 56, 17

Kocsis, B., Haiman, Z., & Frei, Z. 2005, ApJ, 623, 632

Lamers, H. J. G. L. M., & Cassinelli, J. P. 1999, Introduction to Stellar Winds (Cambridge: Cambridge Univ. Press), chap. 12

Lapi, A., Cavaliere, A., & De Zotti, G. 2003, ApJ, 597, L93

Lapi, A., Cavaliere, A., & Menci, N. 2005, ApJ, 619, 60

Mazzotta, P., Brunetti, G., Giacintucci, S.,Venturi, T., & Bardelli, S. 2004, J. Korean Astron. Soc., 37, 381

McNamara, B. R., Nulsen, P. E. J., Wise, M. W., Rafferty, D. A., Carilli, C., Sarazin, C. L., & Blanton, E. L. 2005, Nature, 433, 45

Nulsen, P. E. J., Hambrick, D. C., McNamara, B. R., Rafferty, D., Birzan, L., Wise, M. W., & David, L. P. 2005a, ApJ, 625, L9

Nulsen, P. E. J., McNamara, B. R., Wise, M. W., & David, L. P. 2005b, ApJ, 628, 629

Ostriker, J. P., & McKee, C. 1988, Rev. Mod. Phys., 60, 1

Parker, E. N. 1963, Interplanetary Dynamical Processes (New York: Wiley)

Pfrommer, C., Enßlin, T. A., & Sarazin, C. L. 2005, A&A, 430, 799

Reese, E. D., et al. 2002, ApJ, 581, 53

Rephaeli, Y. 1995, ARA&A, 33, 541

Scheuer, P. A. G. 1974, MNRAS, 166, 513

Sedov, L. I. 1959, Similarity and Dimensional Methods in Mechanics (New York: Academic Press)

Stockton, A., Fu, H., Henry, J. P., & Canalizo, G. 2006, ApJ, 638, 635

Sunyaev, R. A., & Zel’dovich, Ya. B. 1972, Comments Astrophys. Space Phys., 4, 173

Tremaine, S., et al. 2002, ApJ, 574, 740