SHOCKS AND SONIC BOOMS IN THE INTRACLUSTER MEDIUM:
X-RAY SHELLS AND RADIO GALAXY ACTIVITY

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ABSTRACT
Motivated by hydrodynamic simulations, we discuss the X-ray appearance of radio galaxies embedded in the intracluster medium (ICM) of a galaxy cluster. We distinguish three regimes. In the early life of a powerful source, the entire radio cocoon is expanding supersonically and hence drives a strong shock into the ICM. Eventually, the sides of the cocoon become subsonic and the ICM is disturbed by the sonic booms of the jet’s working surface. In both of these regimes, X-ray observations would find an X-ray shell. In the strong shock regime, this shell will be hot and relatively thin. However, in the weak shock (sonic-boom) regime, the shell will be approximately the same temperature as the undisturbed ICM. If a cooling flow is present, the observed shell may even be cooler than the undisturbed ICM due to the lifting of cooler material into the shell from the inner (cooler) regions of the cluster. In the third and final regime, the cocoon has collapsed and no well-defined X-ray shell will be seen. We discuss ways of estimating the power and age of the source once its regime of behavior has been determined.

Subject headings: galaxies: jets, galaxies: clusters: general, hydrodynamics, shock waves

1. INTRODUCTION

In the powerful Fanaroff-Riley type II radio galaxies (FR-II; Fanaroff & Riley 1974), jets from a central AGN propagate at relativistic speeds before terminating in a series of shocks resulting from interaction with the surrounding material. The spent jet material is then thought to inflate a broad cocoon which encases the jets and is seen as the observed radio lobes. In very powerful or young sources, the cocoon is probably overpressured (Begelman & Cioffi 1989) with respect to the surrounding ambient material (either the interstellar medium [ISM] of the host galaxy, or the intracluster medium [ICM] of the host cluster). The cocoon then undergoes supersonic pressure driven expansion into the ambient medium, sweeping the ambient medium into a shocked shell. A contact discontinuity separates the relativistic cocoon material from the shocked ambient material.

X-ray observations provide one with a direct probe of the interaction of the ISM/ICM with the radio galaxy cocoon. X-ray imaging observations with the high resolution imagers (HRIs) on the ROSAT satellite discovered several systems in which the observable radio lobes are seen to reside in evacuated cavities within the ICM which are bounded by shells of enhanced emission (e.g. Cygnus-A: Carilli et al. 1994; Perseus-A: Bohringer et al. 1992; A 4059: Huang & Sarazin & 1998). In order to further explore the shell/cavity in Cygnus-A, Clarke, Harris & Carilli (1997) performed 3D hydrodynamic simulations of a jet propagating into a cluster-like atmosphere. They found that the X-ray cavities are readily identified with the radio cocoon (whose pressure driven expansion excludes the ICM), and that the X-ray shells can be identified with strong shocks in the ICM. Kaiser & Alexander (1999) showed how analytic self-similar hydrodynamic models can be used to obtain similar results. More recently, Rizza et al. (2000) performed 3-D hydrodynamic simulations in an attempt to model subtle X-ray structure in A 133, A 2626, and A2052.

In a complementary study, Heinz, Reynolds & Begelman (1998; hereafter HRB98) used a simple “bubble” model for the cocoon/shock system (Begelman & Cioffi 1989; Reynolds & Begelman 1997) to predict the X-ray appearance of radio galaxies as a function of their age and power. A central assumption used in the HRB98 model is that the presence of an X-ray shell bounding the sides of a radio cocoon indicates a lateral shock front, which in turn implies that the sides of the cocoon are still expanding at supersonic speeds. This assumption is based upon the hydrodynamical fact that, once the sideways expansion of the cocoon becomes subsonic, the contact discontinuity separating the cocoon and the ICM will become susceptible to the Rayleigh-Taylor instability on timescales shorter than the expansion timescale of the cocoon. One might then expect the cocoon to collapse, with the corresponding disappearance of the X-ray cavities.

In this letter, we follow up the study of HRB98 by using moderate-to-high resolution 2-D hydrodynamic simulations to study the interaction of radio-galaxies with the ICM. We find that powerful radio galaxies in which the entire cocoon is supersonic do indeed produce a well defined shell/cavity structure, although backflows within the shocked ICM shell increase its thickness substantially over that predicted by the bubble model (also see Kaiser & Alexander 1999). However, we also find a shell/cavity structure in sources in which the sides of the cocoon are expanding at subsonic speeds (or even not expanding at all). In this case, the cocoon has not had time to collapse, despite the fact that Rayleigh-Taylor instabilities are gradually destroying it. The X-ray shell corresponds to emission from a weak shock or compression wave (i.e. a sonic boom) which is driven into the ICM by the supersonic motion of the cocoon head. We find that ICM material can be lifted into this emitting shell without passing through a strong shock, which has important implications for the temperature structure of such X-ray shells and entropy injection into the ICM. This study is particularly timely given its relevance to Chandra observations of radio galaxies embedded within galaxy clusters.
Section 2 briefly discusses the configuration and results of our hydrodynamic simulations. In Section 3, we compute emissivity maps and discuss the nature of X-ray shells and cavities. Section 4 describes how one may use X-ray data to estimate the power and age of a given radio galaxy. We summarize our conclusions in Section 5.

2. HYDRODYNAMIC SIMULATIONS

The simulations discussed in this paper were performed using the ZEUS3D code (Stone & Norman 1992a, 1992b; Clarke, Norman & Fielder 1994) to solve the equations of ideal hydrodynamics. Major advantages of this code are its flexibility in the choice of the computational grid, and the fact that it has been extensively tested. In all of the simulations reported in this paper, this code is used in its pure-hydro form (i.e., there are no magnetic fields present) and we assume axisymmetry, thereby reducing the computational domain to two spatial dimensions.

We model back-to-back jets originating from a source residing in the center of a galaxy/cluster atmosphere, i.e., no assumption regarding reflection symmetry in the plane normal to the jets was made. The simulations were performed in spherical polar coordinates \((r, \theta, \phi)\), and the computational domain was the region \(r \in (0.1, 10)\). The ambient galaxy/cluster gas was assumed to be isothermal with a (adiabatic) sound speed of unity \((c_{\text{ICM}} = 1)\) and a density gradient given by a \(\beta\)-model with \(\beta = 0.5\) and core radius \(r_0 = 2\): \[
\rho(r) = \frac{1}{[1 + (r/r_0)^2]^{3/4}}.
\]
The gravitational potential was set so as to keep this ambient material in hydrostatic equilibrium. It is assumed that the gravitational potential is dominated by background dark matter, i.e., the self-gravity of the gas is negligible. This reasonable assumption prevents us from having to solve Poisson’s equation for the self-gravity of the gas, which is negligible as part of the hydrodynamic simulations. The jets themselves are initially conical with a half opening angle of \(15^\circ\), and are in pressure equilibrium with the ambient medium. They are given initial densities of \(\rho_{\text{jet}}\) and Mach numbers (with respect to the sound speed of the injected jet material) of \(M\).

In addition to studying X-ray shells/cavities, these simulations were tailored to study mixing across the contact discontinuity and the evolution of passive sources after the jets have turned off. An array of runs was performed to study the influence of the systems parameters and numerical resolution. A full discussion of all of these hydrodynamic simulations, together with a discussion of ICM/cocoon mixing and the evolution of passive sources, will be presented in Reynolds, Heinz & Begelman (2001; hereafter RHB01). Here, we focus on two of those simulations. Run 1 has \(\rho_{\text{jet}} = 0.01\) and \(M = 10.5\), giving a kinetic luminosity of \(L_1 = 24.8\). Run 2 has the same Mach number but a higher jet density of \(\rho_{\text{jet}} = 0.1\), giving a lower kinetic luminosity of \(L_2 = 7.7\). Both of these runs use a \(600 \times 600\) grid in the \((r, \theta)\)-plane, with non-uniform grid spacing that concentrates resolution towards the cluster center and along the two jet axes.

We can relate quantities within the code to physical quantities by fixing the parameters of the background medium. Suppose we set \(r_0 = 100\) kpc, \(c_{\text{ISM}} = 1000\) km s\(^{-1}\) and a central number density of \(n_0 = 0.01\) cm\(^{-3}\) — values representative of galaxy clusters. Then, one code unit of time corresponds to 50 Myr. The kinetic luminosities of the jets in Run 1 and Run 2 are then \(9.3 \times 10^{45}\) erg s\(^{-1}\) and \(2.9 \times 10^{45}\) erg s\(^{-1}\), respectively.

The detailed hydrodynamics of the jet is very similar to that found by Lind et al. (1989). In particular, the presence of a conical shock in the jet sprays the jet material into a wide fan as it approaches the end of the cocoon, thereby producing a 2-d version of the “dentist-drill” effect (Scheuer 1974) which spreads the jet momentum over a large working surface. The detailed hydrodynamics of the jet and the contact discontinuity will be discussed in RHB01. Here we focus on the implications of this work for X-ray shells and cavities.

3. SHOCKS AND SONIC BOOMS: IMPLICATIONS FOR OBSERVABLE X-RAY SHELLS

Figure 1 shows density maps, temperature maps and simulated Chandra ACIS-S X-ray maps for time \(t = 0.1\) from Run 1, and times \(t = 1.3, 2.4\) from Run 2. The X-ray maps assume a source inclination of \(60^\circ\), and were made by integrating the total X-ray emissivity along lines of sight through the simulated system. The X-ray emissivity was derived using spectra from the MEKAL thermal plasma model (Mewe, Gronenschild & van den Oord 1985; Arnaud & Rothenflug 1985; Mewe, Lemen & van den Oord 1988; Kaastra 1992) in the XSPEC software package folded through the Chandra ACIS-S response curve.

The density maps clearly show the disturbance in the ICM, and the contact discontinuity between the disturbed ICM and the low density cocoon. Kelvin-Helmholtz instabilities are clearly visible along this contact discontinuity. In the early stages of Run 1 (e.g., left panels of Fig. 1), the entire cocoon is expanding supersonically and a well defined shell of shocked ICM exists around the cocoon. As the simulation progresses, the sideways expansion of the cocoon becomes subsonic and eventually halts altogether. However, the supersonic cocoon head still drives a sideways disturbance into the ICM (in the form of a very weak shock, or a sonic boom) which creates a thick shell of slightly compressed ICM surrounding the radio cocoon. After several ICM dynamical timescales, the cocoon will collapse almost entirely, destroying the shell-like appearance of the system. However, there will be a significant portion of the sources lifetime in which one would observe a clear X-ray shell which corresponds to a sonic boom rather than a strong shock.

This distinction between the strong shock and sonic boom is important for the following reason. In the shock scenario, the ICM experiences a significant jump in both density and entropy at it crosses the shock front. Of course, the entropy jump is due to the irreversible thermalization of the bulk kinetic energy of the undisturbed ICM as viewed in the frame of reference of the shock. This leads to a rather thin shell of shocked ICM that is appreciably hotter than the undisturbed ICM. It also injects substantial entropy into the ICM which may build up and produce observational consequences long after the radio galaxy has died.

On the other hand, there is a negligible entropy jump associated with the sonic boom. Since this is more akin to a compression wave (with a 10–20% jump in density across the wavefront), the only heating of the disturbed ICM is due to adiabatic compression. In the case of a radio galaxy expanding into an isothermal cluster atmosphere, this will produce a thick shell of disturbed ICM. Immediately within the compression wave, the material is slightly hotter due to the action of compressional heating. However, regions of the shell are also slightly cooler than the undisturbed ICM due to the action of adiabatic cooling as material is adiabatically lifted into lower pressure parts.
of the atmosphere. These effects tend to cancel, producing an observed X-ray shell that is almost the same temperature as the undisturbed ICM. In the case of a cooling flow (where the temperature decreases with decreasing radius), the shell may be significantly cooler than the undisturbed ICM due to the lifting of cool material into the shell. This result, which is in stark contrast with the strong shock scenario, may be very relevant to recent Chandra observations of Hydra-A (McNamura et al. 2000) and Perseus-A (Fabian et al. 2000).

It is also worth noting that a backflow exists in the disturbed ICM which significantly depletes the amount of ICM material near the head of the cocoon. To illustrate this point, the amount of mass contained in the part of the disturbed ICM shell that lies within the cone $\theta < 15^\circ$ is only half of the ICM mass which was swept up in this cone. This, together with the fact that the shock is rather narrow and very hot, makes the strong shock bounding the head of the cocoon very hard to detect in X-ray maps. Indeed, no observations to date have detected thermal emission from this region.

4. FURTHER DISCUSSION

If we wish to measure physical parameters (e.g., kinetic luminosity and age) of a given radio galaxy, it is important to know whether it is in the strong or weak shock regime. Given X-ray data of sufficient quality, the two regimes can be easily distinguished by the temperature and morphology of the X-ray shell — hot narrow shells indicate strong shocks whereas thick shells with little or no temperature difference (or even a lower temperature) indicate weak shocks.

In the strong shock case, the detailed hydrodynamics of the shocked shell leads to surprisingly large deviations in the thickness of the shell as compared with the simple bubble model. For this reason, the diagnostic diagrams of Heinz et al. (1998) require some modification. New and detailed diagnostic diagrams, based upon applying scaling relations to full hydrodynamic simulations, will be presented in a future publication.

On the other hand, there are some robust diagnostics from the X-ray band that can be used in the weak shock case. Since the lateral expansion velocity of the weak shock is the ICM sound speed, the age of the source is given by

$$t_{\text{RG}} \approx \frac{r_{\text{shell}}}{c_{\text{ICM}}} \quad (2)$$

where $r_{\text{shell}}$ is the lateral size of the observed disturbed shell (which is independent of the inclination angle of the source), and $c_{\text{ICM}}$ is the adiabatic sound speed of the ICM. Once the temperature $T$ of the ICM has been measured, the sound speed is given by $c_{\text{ICM}} = \sqrt{5kT/\mu m_p}$ where $\mu \approx 0.5$ is the mean molecular weight of the gas. Assuming an orientation and source geometry, one can estimate the volume of the X-ray cavities $V$. The average kinetic power of the source is then given by

$$L_{\text{kin}} = \rho \frac{pV}{t_{\text{BG}}} \quad (3)$$

where $\rho$ is the pressure of the displaced ICM which can be estimated from X-ray observations, and $f \gtrsim 2$ is a factor of order unity which includes the enthalpy term and accounts for spatial gradients in the pressure.

5. CONCLUSIONS

Guided by 2-D hydrodynamic simulations, we distinguish three regimes of radio galaxy evolution which have importance for understanding the structure of X-ray cavities and shells. In the early life of a powerful radio galaxy, the entire cocoon is expanding supersonically and a strong shock is driven into the ICM in all directions. One would see a relatively narrow and hot X-ray shell surrounding the radio lobes. However, eventually, the lateral expansion velocity of the contact discontinuity becomes subsonic. There can be a substantial phase of the source’s life in which the cocoon is subsonic but has yet to collapse and is surrounded by a rather thick shell of disturbed ICM which has suffered a weak shock or compression wave. X-ray observations of such a system would reveal a rather thick shell bounding a cavity. The temperature of this shell would be very similar to the temperature of the undisturbed ICM. If a cooling flow is present, this shell would contain cooler material that has been lifted from further down in the cluster potential. Even if the ICM is isothermal, regions of the disturbed shell could be slightly cooler due to the action of adiabatic expansion. We also note that a backflow exists in the disturbed ICM shell which significantly depletes the shocked shell near the head of the jet and renders it difficult to observe. After several ICM dynamical timescales, the cocoon will collapse and the apparent X-ray shell will vanish.

Finally, at very late times, after the radio galaxy activity has ceased, the relic lobes may appear as ‘naked’ cavities within the ICM emission (i.e. X-ray cavities that are not bounded by shells). Such structures have been explored in recent work by Churazov et al. (2000).

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Fig. 1.— Density, temperature and simulated X-ray maps (top, middle and bottom respectively) for times $t = 0.10$ of Run 1 and $t = 1.3, 2.4$ of Run 2 (left, middle, and right respectively). The left panels are $3 \times 2$ code units in extent, the middle panels are $9 \times 6$ code units and the right panels are $18 \times 12$ code units. These three cases represent the three regimes of behaviour that we have noted.
This figure "compilation.gif" is available in "gif" format from:

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