CEN A AND ITS INTERACTION WITH THE X-RAY EMITTING INTERSTELLAR MEDIUM

D. M. Worrall
Dept. of Physics, University of Bristol
Tyndall Avenue, Bristol BS8 1TL, U.K.
D.WORRALL@BRIS.AC.UK
R. P. Kraft, M. Birkinshaw, M. J. Hardcastle, W. R. Forman, C. Jones, S. S. Murray
RKRAFT@CFA.HARVARD.EDU, MARK.BIRKINSHAW@BRIS.AC.UK, M.HARDCASTLE@BRIS.AC.UK,
WFORMAN@CFA.HARVARD.EDU, CJONES@CFA.HARVARD.EDU, SSM@CFA.HARVARD.EDU

Abstract

As the closest radio galaxy, Centaurus A is a powerful laboratory for the X-ray study of radio-emitting structures and their interactions with the hot interstellar medium (ISM). This paper details our interpretation of the remarkable X-ray enhancement which caps the inner southwest radio lobe, at a radius of about 6 kpc from the galaxy center. The shell of X-ray-emitting gas is hotter than the ambient ISM, and overpressured by a factor of 100. We argue that it is heated compressed material behind the supersonically-advancing bow shock of the radio lobe, the first example of the phenomenon to be clearly detected. The results demonstrate that Cen A is actively re-heating nearby X-ray-emitting gas. The shell's kinetic energy is ~ 5 times its thermal energy, and exceeds the thermal energy of the ISM within 15 kpc of the center of the galaxy. As the shell dissipates it will have a major effect on Cen A's ISM, providing distributed heating.

1 Introduction

There is much current interest in the possibility that radio sources heat the interstellar and intracluster medium. Such heating would help to explain the weakness or absence of lines from gas cooling below 1 keV in the densest central regions of galaxies and clusters (e.g., Peterson et al., 2001). A good place for heating would be behind the bow shock of a supersonically expanding radio structure. In this paper we outline the simple theory and its application to Cen A, the first source to show clear and direct X-ray evidence of supersonic expansion and heating.

2 Theory

The standard model for the expansion of a powerful radio source powered by a jet which is supersonic with respect to the X-ray-emitting interstellar medium (ISM) is illustrated in Fig. 1. The jet terminates at the beam head (in a feature identified as the radio hotspot) where the jet fluid passes through a strong shock to inflate a cocoon of radio-emitting plasma. The energy and momentum flux in the flow is normally expected to be sufficient to drive a bow shock into the ambient medium ahead of the jet termination shock. In the rest frame of the bow shock, ambient gas is heated as it crosses the shock to fill a region surrounding the lobe of radio-emitting plasma.

The sound speed in gas of temperature T is given by

$$c_{\rm s} = \sqrt{\frac{\gamma k T}{\mu m_{\rm H}}} \qquad (1)$$

where γ is the ratio of specific heats, which for a monatomic non-relativistic gas is 5/3, k is the Boltzmann constant, $m_{\rm H}$ is the mass of the hydrogen atom, and $\mu m_{\rm H}$ is the mass per particle, which is 0.6 $m_{\rm H}$ for a gas with normal cosmic abundances. Under these conditions, $c_{\rm s} \approx 516\ (kT/{\rm keV})^{1/2}$ km s^{-1} $\approx 0.54(kT/{\rm keV})^{1/2}$ kpc Myr^{-1}.

The Mach number of the speed of advance, $v_{\rm adv}$, of the bow shock into the ambient medium is $\mathcal{M} = v_{\rm adv}/c_{\rm s}$, which in convenient units can be expressed as

$$\mathcal{M} \approx 580(v_{\rm adv}/c)(kT/{\rm keV})^{-1/2} \qquad (2)$$

where c is the speed of light. In a simple application

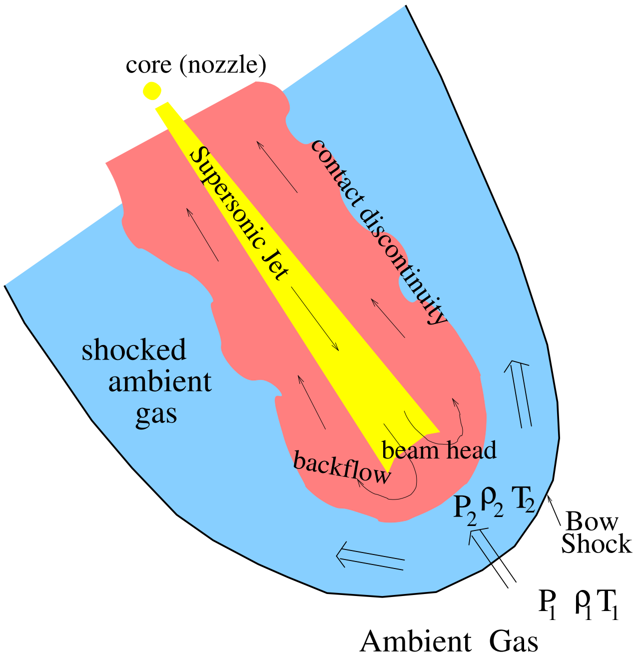

Figure 1: In the standard model for powerful radio sources, a supersonic jet (yellow) terminates at the beam head, producing a radio hotspot. Provided the shocked radio-emitting fluid forming the radio lobe (pink) has enough internal energy or momentum density to drive a leading bow shock, ambient X-ray-emitting gas will be heated as it crosses the shock to fill the blue region.

of the Rankine-Hugoniot conditions for a strong shock (e.g., Spitzer, 1978), the pressure, density, and temperature, respectively, in the unshocked (subscript 1) and shocked (subscript 2) regions at the head of the bow shock are related by

$$P_2/P_1 = (5\mathcal{M}^2 - 1)/4 \qquad (3)$$

$$\rho_2/\rho_1 = 4\mathcal{M}^2/(\mathcal{M}^2 + 3) \qquad (4)$$

$$T_2/T_1 = (5\mathcal{M}^2 - 1)(\mathcal{M}^2 + 3)/16\mathcal{M}^2 \qquad (5)$$

for a monatomic gas.

If the density in an X-ray-emitting gas is described by the proton number density, $\eta_{\rm p}$, then the thermal pressure is given by

$$P = \eta_{\rm p} kT/X\mu \qquad (6)$$

where X is the abundance of hydrogen by mass, which is 0.74 for normal cosmic abundances (e.g., Birkinshaw & Worrall, 1993).

For hot X-ray emitting gas where the cooling in line radiation is unimportant, the X-ray emissivity, $\mathcal{E}$, between energies E_1 and E_2 depends on temperature and proton density approximately as

$$\mathcal{E} \propto \eta_{\rm p}^2 T^{0.5}(e^{-E_1/kT} - e^{-E_2/kT}) \qquad (7)$$

where the weak energy dependence of the Gaunt factor is ignored. At temperatures below ~ 1 keV, line radiation cannot be ignored, and the plasma models incorporated into X-ray-spectral-fitting programs such as XSPEC can be used to find the dependence of the emissivity on energy. We find that in the energy band 0.8–2 keV, where *Chandra* and *XMM-Newton* are most sensitive, for an $\mathcal{M} = 4$ shock, the X-ray emissivity contrast between shocked and unshocked gas is a factor of 3 higher if the ambient gas is at 0.29 keV (as found for Cen A, Table 1) than if the external medium has a typical cluster temperature of 4 keV.

Complications apply in reality, and in practice these are difficult to treat even with data from observatories as powerful as *Chandra* and *XMM-Newton*. Firstly, there is observational evidence that in supernova remnants with shocks of comparable Mach number to that found for Cen A the post-shock electrons are cooler than the ions (e.g., Hwang et al., 2002; Rakowski, Ghavamian & Hughes, 2003). This is not taken into into account in our modeling. Secondly, the simple Rankine-Hugoniot equations that we quote and apply do not take into account the fact that the bow shock around a lobe is oblique away from its head, with a consequent change in the jump conditions and the emissivity contrast (e.g., Williams, 1991). However, if Cen A's shell represents a spherical expansion rather than a lobe structure, then the shock should be normal everywhere and the equations above will hold.

3 Historical perspective

It is possible to interpret *ROSAT*-detected X-ray cavities coincident with the inner parts of the radio lobes of Cygnus A as due to an emissivity contrast between bow-shock heated gas outside the lobes (heated to temperatures above the *ROSAT* energy band) and the more easily detected ambient cluster medium (Carilli, Perley & Harris, 1994). However, the parameters of the shock are not effectively constrained by the *ROSAT* X-ray data. Similarly, *Chandra* observations of Cygnus A find gas at the sides of the lobes to have $kT \sim 6$ keV, slightly hotter than the value of 5 keV from ambient medium at the same cluster radius, possibly indicating cooling after bow-shock heating, but again the data do not usefully constrain model parameters (Smith et al., 2002). Other reports of lifting of gas (leading to eventual heating) by radio lobes or hot bubbles are not thought to involve supersonic expansion (e.g., Churazov et al., 2001; Quilis, Bower & Balogh, 2001), although it has been suggested recently that filaments of hot gas in the atmosphere of M87 are slowing from supersonic speeds after ejection from the galaxy center (Forman et al., 2004; Kraft et al., 2005).

The first and best example of a shell of heated gas which can reasonably be attributed to supersonic expansion is in Cen A. High-quality *Chandra* and *XMM-Newton* data (Kraft et al., 2003, 2005) provide the temperature and density constraints needed to test the model and measure the supersonic advance speed of the bow shock responsible for the heating.

4 Cen A

Cen A is our nearest radio galaxy, at a distance of 3.4 Mpc (Israel, 1998) so that $1''$ corresponds to $\sim$ 17 pc, and is an example of a low-power radio galaxy. In such sources the radio jet is normally expected to have slowed considerably through entrainment of ambient material (Bicknell, 1994), at which point the model described by Fig. 1 no longer holds. The full extent of Cen A's radio emission covers several degrees on the sky (Junkes et al., 1993). Within this lies a sub-galaxy-sized double-lobed inner structure (Burns, Feigelson & Schreier, 1983) with a predominantly one-sided jet to the northeast and a weak counter-jet to the southwest (Hardcastle et al., 2003), embedded in a radio lobe with pressure 1.4×10^{-12} Pa or more, greater than the pressure in the ambient ISM ($\sim 1.8\times10^{-13}$ Pa; Table 1), and so which should be surrounded by a shock. Around this southwest lobe there is a shell of X-ray emitting gas which appears to have the geometry of the shocked ambient gas in Fig. 1 (Kraft et al., 2003, 2005). Although the capped lobe is around the weak counter-jet, so it is not evident that the lobe is being thrust forward supersonically with respect to the external interstellar medium (ISM) by the momentum flux of an active jet, the current high internal pressure in the radio lobe ensures its strong expansion.

5 Application of the model to Cen A

The temperature, proton density and pressure of the ambient ISM and the X-ray shell, taken from Kraft et al. (2003) are given in Table 1. The ambient medium is measured to have $\eta_{\rm p} \sim 1.7\times10^3$ m^{-3} and kT = 0.29 keV, whereas the shell is ten times hotter, at kT = 2.9 keV, and twelve times denser, with $\eta_{\rm p} \sim 2\times10^4$ m^{-3}. From equations (4) and (5) above, we see that temperature and density measurements for both the ambient medium and the shocked gas directly test shock heating, since only two of the four parameters are required to measure the Mach number, and the other two test the model.

The most straightforward application of the equations finds an inconsistency, since the densities and temperatures are not self-consistent. The shell's density and temperature are wrong for gas directly in contact with the bow shock. However, we can find a Mach number consistent with shocking the gas to a temperature and density such that the combined thermal and ram pressure is in pressure equilibrium with the thermal pressure of the detected shell: $\mathcal{M}$ = 8.5, $v_{\rm adv} \approx$ 2400 km s^{-1}. The post-shock temperature is $kT_2 \sim$ 6.8 keV. The 6.8 keV gas flows back from the shock, into the X-ray-detected shell at 2.9 keV. The characteristics of this undetected hotter gas are given in Table 1. In this table we also quote estimates of the relative X-ray emissivity (per unit volume) of gas in the different structures over the 0.4–2 keV energy band, where the *Chandra* response peaks and is relatively flat. The gas directly behind the bow shock has a predicted emissivity that is an order of magnitude fainter than that in the shell, accounting for its absence in our measurements.

6 Conclusions

- A hot shell of X-ray-emitting gas caps the southwest radio lobe of Cen A.

- Shock jump conditions for an advance speed of $\sim 0.008c$ ($\mathcal{M}$ = 8.5) are satisfied if the shell is in pressure balance with unseen gas at $kT \sim$ 6.8 keV behind the bow shock. The emissivity of the 6.8 keV gas is too low to separate its X-rays from those of the ten-times-brighter gas of the shell.

- The radiative timescale for material in the shell ($\sim$ 2×10^9 yrs, using equation 5.23 of Sarazin (1986)) is large compared with the lobe expansion time

Table 1: Physical parameters of the gas in various regions of Cen A

Structure	kT (keV)	η_p Proton density (m^{-3})	Pressure (Pa)†	0.4–2 keV relative emissivity, $\mathcal{E}$
ISM (measured)	0.29	1700	1.8×10^{-13}‡ (thermal)	1
Behind bow shock (inferred)	6.8	6530	2.1×10^{-11} (thermal+ram ∗)	13
Shell (measured)	2.9	20,000	2.1×10^{-11} (thermal)	127

† 1 Pascal = 10 dyn cm^{-2}

‡ incorrectly reported in Table 5 of Kraft et al. (2003)

∗ $\rho_1 v_{\rm adv}^2/4$

By comparison, the minimum-energy pressure in the radio lobe is $\sim 1.4\times10^{-12}$ Pa.

($< 2.4\times10^6$ years), so the material in the shell behaves as an adiabatic gas (e.g., Alexander, 2002).

- The cooling has improved the shell–ISM contrast by an order of magnitude, an important factor in the detection and modeling of the shell.

- The lobe is (or was) powered by energy deposition from a jet, and is overpressured relative to the ambient ISM. Monitoring the intensity and searching for proper motions in the knots of the weak counter-jet on this side of the source would provide important diagnostics for establishing the current state of the jet within the southwest lobe.

- To order of magnitude, the mass in the hot shell is consistent with material swept up from the ISM. There must have been sufficient time since any earlier epoch of lobe expansion in the region for the ISM to be replenished.

- The shell is overpressured compared with the minimum-energy pressure in the radio lobe (in magnetic field and radiating electrons) by a factor of ~ 10. There is no particular reason to think that a dynamical object, seen in a snapshot, should be in a state of minimum energy. However, if we do assume minimum energy in the lobe, and that the shell has reached equilibrium [but note that the sound-crossing time in the shell (thickness ~ 0.3 kpc, $c \sim 9\times10^{-7}$ kpc yr^{-1}) is about 15 per cent of the maximum time we estimate it has taken the lobe to reach its current size], the shell's overpressure relative to the radio lobe could be balanced by the ram pressure from internal motions in the lobe for a moderate relativistic proton loading.

- The shell's kinetic energy is ~ 5 times its thermal energy, and exceeds the thermal energy of the ISM within 15 kpc of the center of the galaxy. As the shell dissipates, most of the kinetic energy should ultimately be converted into heat and this will have a major effect on Cen A's ISM, providing distributed heating.

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