A CHANDRA STUDY OF THE LOBE/INTERSTELLAR MEDIUM INTERACTIONS AROUND THE INNER RADIO LOBES OF CENTAUROS A: CONSTRAINTS ON THE TEMPERATURE STRUCTURE AND TRANSPORT PROCESSES

R. P. Kraft and P. E. J. Nulsen
Harvard-Smithsonian Center for Astrophysics, MS-67, Cambridge, MA 02138

M. Birkinshaw and D. M. Worrall
Department of Physics, University of Bristol, Bristol BS8 1TL, UK

R. F. Penna
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; and Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627

W. R. Forman
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

M. J. Hardcastle
School of Physics, Astronomy, and Mathematics, University of Hertfordshire, Hatfield AL10 9AB, UK

C. Jones
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

AND

S. S. Murray
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

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ABSTRACT

We present results from deeper Chandra observations of the southwest radio lobe of Centaurus A, first described by Kraft and coworkers. We find that the sharp X-ray surface brightness discontinuity extends around ~75% of the periphery of the radio lobe and detect significant temperature jumps in the brightest regions of this discontinuity nearest to the nucleus. This demonstrates that this discontinuity is indeed a strong shock that is the result of an overpressure that has built up in the entire lobe over time. In addition, we demonstrate that if the mean free path for ions to transfer energy and momentum to the electrons behind the shock is as large as the Spitzer value, the electron and proton temperatures will not have equilibrated along the southwest boundary of the radio lobe where the shock is strongest. Thus, the proton temperature of the shocked gas could be considerably larger than the observed electron temperature, and the total energy of the outburst correspondingly larger as well. We investigate this using a simple one-dimensional shock model for a two-fluid (proton/electron) plasma. We find that for the thermodynamic parameters of the Cen A shock the electron temperature rises rapidly from ~0.29 keV (the temperature of the ambient ISM) to ~3.5 keV, at which point heating from the protons is balanced by adiabatic losses. The proton and electron temperatures do not equilibrate in a timescale less than the age of the lobe. We note that the measured electron temperature of similar features in other nearby powerful radio galaxies in poor environments may considerably underestimate the strength and velocity of the shock.

Subject headings: galaxies: individual (Centaurus A) — galaxies: ISM — galaxies: jets — hydrodynamics — X-rays: galaxies

1. INTRODUCTION

Radio galaxies are believed to evolve through three phases. Initially, the lobes surrounding the jets are greatly overpressured relative to the ambient medium and the inflation of lobes is highly supersonic. The early, highly supersonic phase of lobe inflation is short lived in most sources and has been conclusively identified in only a small number of radio galaxies and clusters of galaxies, including Centaurus A (Kraft et al. 2003) and NGC 3801 (Croston et al. 2007). As the inflation continues and the bubbles become larger, the pressure in the lobes drops and approaches equilibrium with the ambient gas. In these systems, such as Hydra A (Nulsen et al. 2005) and M87 (Forman et al. 2005), the weak shock surrounding the lobe is often observable as a surface brightness discontinuity in the X-ray emission. Ultimately, the bubble loses energy (via adiabatic expansion and perhaps thermal conduction) as it rises buoyantly in the atmosphere and becomes effectively unobservable, although these late-stage bubbles (radio relics) may become reenergized by mergers (Reynolds et al. 2002; Ensslin 2002).

The proximity of Centaurus A (d ~ 3.4 Mpc, 5 times closer than the Virgo Cluster; see Israel 1998) makes it an ideal astrophysical laboratory. Features can be observed with a sensitivity and linear resolution unattainable in any other active galaxy, allowing detailed study of the hydrodynamics and energetics of lobe inflation. In our previous paper on the X-ray emission from the southwest radio lobe of Centaurus A, we reported the discovery of a hot (~3.5 keV) shell of X-ray emission surrounding the lobe. We interpreted this shell as the result of the highly supersonic expansion/inflation (M ~ 8) of the lobe into the ambient interstellar...
as reported by Kraft et al. (2003). We find marginal evidence for most of the periphery of the lobe, not just the southwest corner between the southwest radio lobe and the ISM extends around important new results. First, the surface brightness discontinuity or Magellanic supernova remnants (SNRs). We report two imaging of the later observations are better suited to study the lobe. As a result, we can study the details of the transport processes in the lobe shock on scales previously observable only in Galactic medium (ISM). The dynamics of this process is of great interest because they can yield information on the transport physics of the intracluster medium (ICM) of clusters of galaxies and early-type galaxies, as well as on the roles that viscosity and thermal conduction play in the release of energy into cool cluster cores.

In this paper we present results from an analysis of four pointed observations of Centaurus A, focusing on the morphology and temperature structure of the X-ray shell around the southwest radio lobe. The combined observation time of the data presented in this paper is 150 ks, more than double that used in the analysis of Kraft et al. (2003), and the detector roll angle and pointing of the later observations are better suited to study the lobe. As a result, we can study the details of the transport processes in the lobe shock on scales previously observable only in Galactic or Magellanic supernova remnants (SNRs). We report two important new results. First, the surface brightness discontinuity between the southwest radio lobe and the ISM extends around most of the periphery of the lobe, not just the southwest corner as reported by Kraft et al. (2003). We find marginal evidence for a temperature gradient in the shocked gas across the X-ray–bright enhancement at the southwestern boundary of the radio lobe. Second, we demonstrate that if the thermal equilibration time of the electrons and ions in the gas is as slow as the Spitzer rate, the electrons will not have thermalized. This suggests that the electron temperature inferred from the X-ray spectra considerably underestimate the strength of the shock, as has been reported for several Galactic and Magellanic SNRs. In addition, we detect sharp surface brightness discontinuities around the northeast radio lobe but lack sufficient source counts to accurately determine its gas density and temperature. The features have temperatures above 1 keV and thus, with their morphologies and locations, are suggestive of shocks.

This paper is organized as follows. Section 2 contains a summary of the observational details. We present the results of the data analysis in § 3, and we discuss the implications in § 4. Section 5 contains a brief summary and conclusions, as well as possible future observations. We assume a distance of 3.4 Mpc to Cen A (Israel 1998) for consistency with our previous work. At this distance, 1″ = 17 pc. All uncertainties are at 90% confidence unless otherwise stated, and all coordinates are J2000.0. All elemental abundances in this paper are relative to the solar abundances tabulated by Anders & Grevesse (1989).

2. DATA ANALYSIS AND METHODS

Centaurus A has been observed 4 times with Chandra ACIS, twice with ACIS-I for ~35 ks each in AO-1, and twice with ACIS-S for ~50 ks each in AO-3 and AO-4 at the same roll angle. Results on the southwest lobe from the first two ACIS-I observations have been published in Kraft et al. (2003). The additional observations more than double the effective exposure. Results from the additional observations on the jet have already been published (Hardcastle et al. 2003; Kataoka et al. 2006). We filtered all data for periods of high background and removed events occurring at node boundaries. The total good times of the ACIS-S and ACIS-I observations are ~94 and ~68 ks, respectively. The four data sets were co-aligned relative to each other to better than 0.1″ by centroiding the positions of 30 bright X-ray binaries within 5′ of the nucleus. The absolute position was then fixed by aligning the radio and X-ray centroid of the nucleus. A comparison of the positions of X-ray binaries and globular clusters demonstrates that the absolute sky coordinates are accurate to better than 0.5″ (Woodley et al. 2007). All four data sets are used for spectral analysis, but only the two ACIS-S observations are used for images and surface brightness profiles presented in this paper. The advantage in signal-to-noise ratio that might be gained from combining the ACIS-S and ACIS-I observations is more than offset by the complexities of interpreting the imaging analysis of data taken at different instrument rolls. Cen A lies at relatively low Galactic latitude (b = 19.4°) and behind the North Polar Spur. The ACIS blank sky backgrounds, created from multiple observations at high galactic latitude, are inappropriate for these observations. Local background is used for all spectral analysis.

3. RESULTS

An adaptively smoothed, exposure-corrected, background-subtracted X-ray image created from the two Chandra ACIS-S observations in the 0.5–2.0 keV band, with 13 cm radio contours overlaid, is shown in Figure 1. It was not possible to remove all the detector artifacts from this image, and the dark bands running northwest/southeast just beyond the northeast lobe and through the middle of the southwest lobe are chip gaps. A raw X-ray image in the same energy band is shown in Figure 2. An X-ray

![Figure 1](image1.png)

**Fig. 1.**—Adaptively smoothed, exposure-corrected, background-subtracted Chandra ACIS-S image of Centaurus A in the 0.5–2.0 keV band. Radio contours (13 cm 30″ × 20″ beam FWHM) are overlaid.

![Figure 2](image2.png)

**Fig. 2.**—Raw X-ray image of the southwest radio lobe of Centaurus A in the 0.5–2.0 keV band. Radio contours (13 cm 30″ × 20″ beam) are overlaid. The white arrows denote the surface brightness discontinuity, which delineates the outer edge of the shock-heated shell of gas.


enforcement surrounds most of the lobe, as denoted by the white arrows in Figure 2, and is visible in both images. In our previous paper, we found that the temperature of this hot shell at the periphery of the southwest lobe is \( \sim 3.5 \) keV. Since the temperature of the ISM is \( \sim 0.3 \) keV (Kraft et al. 2003), the inflation of the lobe is driving a strong shock into the ISM, at least toward the southwest.

3.1. Southwest Radio Lobe

The new, deeper Chandra observations of Centaurus A show details of the structure of this high Mach number shock that were not visible in the shorter ACIS-I observations. First, it is clear from Figure 2 that the surface brightness discontinuity between the ISM and shocked gas is visible around \( \sim 1/4 \) of the periphery of the lobe. This suggests that the lobe is inflating more or less spherically (i.e., energy dominated) and is not simply being driven by jet ram pressure radially away from the nucleus (i.e., momentum dominated). This is consistent with the fact that the minimum pressure of the radio lobe greatly exceeds the pressure of the ISM (Kraft et al. 2003). The shock is strongest (in the sense that the electron temperature of the postshock gas is highest, \( \sim 3.5 \) keV) at the southwestern edge of the lobe, where the ambient gas density is lowest.

The effect of the shock propagating in a region of denser gas can clearly be seen in the vicinity of the northern periphery of the lobe in Figures 2 and 3. Sharp discontinuities in the X-ray surface brightness are labeled S1 and S2. The sharpness of these features strongly suggests that they are due to shocks being driven into the ISM by the lobe expansion. S1 is roughly twice as bright as S2, but the ISM behind S1 is also brighter than that behind S2. Thus, the X-ray surface brightness of the shocked gas is highest where the ambient density of the ISM is highest. In addition, [O iii] emission lines have been detected in this region (J. Bland-Hawthorn 2006, private communication), suggesting that the lobe is shock heating the multiphase ISM of the merging spiral galaxy. The details of this will be presented in a future publication.

We extracted spectra from five regions: two rectangular regions corresponding to S1 and S2, two regions southeast of S1 and S2 (labeled PS1 and PS2), and one region in front of (i.e., in the sense of propagation of the shock, north-northwest of) S1 and S2 (labeled US1 in Table 1). The southwest lobe is commonly believed to lie behind the plane of the sky containing the nucleus (Israel 1998; Tingay et al. 1998), so that any line of sight through regions PS1 and PS2 passes through unshocked ISM, a thin shell of shock heated gas, and the radio lobe (not visible in the X-ray band). We interpret regions PS1 and PS2 as dominated by unshocked ISM that lies along the line of sight between us and the lobe. The lobe is probably expanding spherically, and the shocked gases S1 and S2 are just breaking out of the dense gas of PS1/2 as the lobe inflates to the north. Any line of sight through regions PS1 or PS2 likely passes through two thin layers of the shock-heated shell, but the path lengths through the shell are much shorter than through the ISM, so the best-fit gas temperature is representative of the ISM. The hot, shock-heated shell is not visible over the ISM through these lines of sight. Emission from the shocked gas is much more prominent in S1 and S2, however, because our line of sight through them is nearly tangent to the shock front, maximizing its path length.

We fitted single-temperature, absorbed APEC models to the spectrum of each region. Background was determined from a distant region. Visual examination of archival Hubble Space Telescope Advanced Camera for Surveys data indicates that there is absorption by cold gas in these regions, so we allowed the value of the column density to vary freely, although the minimum was fixed at the Galactic value (Dickey & Lockman 1990). The elemental abundance, \( Z \), was held fixed at the solar value. The abundance is poorly constrained if allowed to vary freely as it can be traded off against the normalization since the emission is line dominated. We feel that fixing the abundance at the solar value is a reasonable approximation since the lobe is likely to be expanding into gas of the merging spiral galaxy. Since the emission is line dominated, the proton density, \( n_p \), of these features scales as \( \sim Z^{-1/2} \). The results of the fits for all five regions are summarized in Table 1. The spectral fits show a clear jump in temperature at S1 and S2, compared to US1, PS1, or PS2, conclusively demonstrating that these surface brightness discontinuities are due to gas that has been heated and compressed as a result of crossing a shock front.

For spectral analysis on larger scales, we divided the southwest radio lobe into the five regions shown in Figure 4. The bright enhancement at the southwest boundary of the lobe, region 1, has been subdivided further into three regions, referred to as 1a, 1b, and 1c, for spectral analysis. Figure 5 contains a plot of the surface brightness profile of the southwest lobe in a 60° sector centered on the lobe. The regions 1a, 1b, and 1c are shown. We fitted the spectrum of each region using a single-temperature APEC model with Galactic (\( N_{\text{HI}} = 8 \times 10^{20} \) cm\(^{-2} \)) absorption and fixed the elemental abundance, \( Z \), at 0.5 times the solar value. Again, the elemental abundance is poorly constrained if allowed to vary freely. Unlike the interior region, however, the derived proton densities

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**Table 1**

| Region | Temperature (keV) | \( N_{\text{HI}} \) (10\(^{21} \) cm\(^{-2} \)) | \( \chi^2 \) |
|--------|------------------|---------------------------------|--------|
| S1     | 0.62 ± 0.04      | 4.5 ± 0.6                       | 1.5    |
| PS1    | 0.23 ± 0.04      | 7.0 ± 1.2                       | 1.8    |
| S2     | 0.78 ± 0.06      | <2.0                            | 0.84   |
| PS2    | 0.28 ± 0.08      | 6.9 ± 0.2                       | 1.3    |
| US1    | 0.24 ± 0.06      | 3.9 ± 0.2                       | 1.3    |

Notes.—The value of \( N_{\text{HI}} \) includes the contribution from Galactic material \((8 \times 10^{20} \) cm\(^{-2} \)). Uncertainties are 90% for one parameter of interest. See text for full description of regions.
are only a weak function of the elemental abundance as the emission is continuum dominated. We chose a lower value for the abundance here as the lobe is expanding into gas of the elliptical galaxy that is unlikely to have been enriched/contaminated by the merging spiral galaxy. The best-fit temperatures and 90% uncertainties for our spectral fits are contained in Table 2. Local background was determined near the lobe. We restricted the energy band of the fit to 0.5 and 3.0 keV in order to minimize contamination from the wings of the point-spread function of the bright nucleus (which dominates the background above 3 keV over most of the field of view), although our results are statistically unchanged if the fit bands are extended to 5 keV.

Along the periphery of the lobe, the single-temperature fits for regions 3–5 are poor, with significant residuals seen between 0.6 and 1.0 keV, the Fe L shell complex of emission lines. We fit these data with two-temperature APEC models (with Galactic absorption), and while the fits are improved, the error bars are so large that no definitive conclusions can be drawn. This suggests that the emission-line temperature may be somewhat less than the continuum electron temperature (i.e., that the electrons have not thermalized with the ions and have not reached collisional ionization equilibrium). We also fitted these data with a nonequilibrium ionization model ("nei" in XSPEC 12.0) with the elemental abundances fixed at 0.5 times solar. The fits were not greatly improved and still formally unacceptable. We conclude that the spectra of regions 3–5 are not well described by single-temperature models, but multitemperature and nonequilibrium ionization models provide little improvement. This suggests a temperature and ionization structure that is too complex to be resolved using the existing data.

### 3.2. Northeast Radio Lobe

We also detect sharp surface brightness discontinuities associated with the northeast radio lobe. Two arcs of X-ray emission, labeled N1 and N2 in Figure 6, are located along the periphery (N1) and the interior in projection (N2) of the lobe. The morphology

**Fig. 4.** Raw X-ray image of the southwest radio lobe of Centaurus A in the 0.5–2.0 keV band showing regions used for spectral fitting and background subtraction. Region 1 was also divided into three radial subregions (1a, 1b, and 1c) as discussed in the text. The best-fit values of the fitted parameters and uncertainties are contained in Table 2. The white lines denote the approximate position of the surface brightness wedge shown in Fig. 5.

**Fig. 5.** Surface brightness profile from the center of the southwest lobe in a 60° sector toward the X-ray enhancement along the southwest boundary in the 0.5–2.0 keV band. The region between the two red dashed lines is the approximate thickness of the shock (i.e., the distance between the shock and contact discontinuity defined by the edge of the radio lobe, ~28°). The regions 1a, 1b, and 1c used for spectral analysis are also identified. Error bars on the data points are 1σ uncertainties due to counting statistics. The best-fit temperatures and 90% uncertainties for each of the regions are summarized on the right (see Table 2).

**Fig. 6.** Raw X-ray image (ACIS-S, 0.5–2.0 keV bandpass) of Centaurus A with 13 cm radio contours (beam 30.4° × 20.3° FWHM) overlaid. Two X-ray enhancements described in the text are labeled N1 and N2.
and location of N1 suggest a shock that would imply that the northeast lobe is expanding supersonically into the ISM, similar to the southwest lobe. The minimum pressure of the northeast lobe greatly exceeds any plausible pressure of the ambient ISM. This conclusion is less clear for N2 as it overlies the lobe in projection. The spectra of both regions are poorly fitted by single-temperature APEC models, although there is considerable flux above 1 keV in both, implying gas temperatures >1 keV.

It is surprising that the radio morphologies and minimum pressures of the northeast and southwest lobes are so similar, but their effect on the ambient ISM is so different. Infrared synchrotron emission has been detected from the northeast lobe (Brookes et al. 2006; Hardcastle et al. 2006), so the jet is still actively accelerating particles to relativistic velocities in this lobe. Several compact X-ray and radio knots in the southwest lobe strongly suggest collimated flow in this direction as well, even if there are no structures that we can definitively term a jet (Hardcastle et al. 2003). The one significant difference between the lobes is that the northeast lobe appears to be connected to the northern middle lobe (NML) through the large-scale jet (Morganti et al. 1999). How in detail the inner jet, northeast lobe, large-scale jet, and NML are related is unclear, but it is almost certainly connected to why we do not see a bright, strong shock around the northeast lobe. In particular, the energy and momentum of both the jet and the counterjet must be comparable (otherwise, the jet would push the ambient ISM interaction as we argue below.

4. INTERPRETATION

4.1. Temperature Structure

4.1.1. Northern Periphery of Southwest Lobe

The sharp surface brightness discontinuity and the temperature jump at regions S1 and S2 and in the southwest demonstrate that the lobe is expanding supersonically in the plane of the sky and hence is likely to be expanding supersonically in all directions. The velocity of the shocks between S1/S2 and the undisturbed ISM can be estimated from the ratio of the preshock to postshock temperatures. It is not clear if regions PS1/PS2 or US1 should be used to determine the thermodynamic parameters of the unshocked gas. The complex morphology of the X-ray surface brightness, combined with spatial variability in the unshocked gas temperature and absorption uncertainties in the three-dimensional distribution of the gas, makes determination of the density profile virtually impossible. However, the gas temperatures of PS1, PS2, and US1 are identical, so we can make some quantitative statements about the energetics and dynamics of the shocks without full knowledge of the density profile.

The ratio of postshock to preshock gas temperatures, $T_R$, as a function of Mach number is (for a purely hydrodynamic shock and $\gamma = 5/3$)

$$T_R = \frac{T_2}{T_1} = \frac{(5M_i^2 - 1)(M_i^2 + 3)}{(16M_i^2)}$$

where $T_2$ and $T_1$ are the post- and preshock gas temperatures, respectively, and $M_i$ is the Mach number of the flow in the preshocked gas. These temperature ratios are 2.7 ± 0.5 and 2.8 ± 0.7 for regions S1 and S2, respectively, at 90% confidence assuming the preshock gas temperatures of PS1 and PS2, respectively. The Mach numbers are then 2.4 ± 0.3 and 2.5 ± 0.5. The uncertainties on the Mach numbers are large because the fractional uncertainties on the preshock gas temperature are large. The velocities of the shocks S1/S2 and the undisturbed ISM are ~600 ± 75 and 680 ± 140 km s^{-1}, respectively. Assuming that the pressure of the lobe is uniform (a good assumption as the sound speed of the lobe plasma is likely orders of magnitude larger than the thermal gas), the ratio of the preshock density of S1 to that of S2 is 1.3 ± 0.3 based on their relative surface brightnesses. We point out that the lower shock temperature of PS1 and PS2 relative to the regions more distant from the nucleus (1–5) is also qualitatively consistent with a picture where the nearly isobaric lobe is expanding more slowly into the denser regions of gas near the nucleus.

4.1.2. Southwest Periphery of Southwest Lobe

As discussed in Kraft et al. (2003), we model the emission as a shell of uniform density rotated to our line of sight. In Figure 5 we have labeled the approximate positions of the contact discontinuity between the shocked gas and radio lobe (the red dashed line on the left), the shock-heated shell (the region between the two dashed red lines), and the transition region (the actual thickness of the shock; see below for detailed discussion [labeled 1a]). We estimate the thickness of the shell and the transition region to be ~28" (476 pc) and ~9" (153 pc), respectively. The distance from the shock to the contact discontinuity is therefore ~37" (630 pc). The width of the transition region is estimated at the distance over which the surface brightness of the shell goes from the background level to its peak value. This is an upper limit on the actual thickness of the transition region as we have neglected projection effects. The ratio of the gas temperature in region 1b to that in region 1c is 0.72 ± 0.20 (90% confidence). Thus, the temperature of the gas closest to the shock is cooler (at marginal significance) than the gas behind the shock closer to the lobe. We have neglected the effects of projection, but projection would tend to wash out any temperature differences, so our estimate of the temperature ratio is really an upper limit. The temperature of the material in the transition region (region 1a) is poorly constrained but is >2.5 keV at 90% confidence. Thus, the transition region is not significantly cooler than region 1b or 1c. A detailed map of the temperature structure of this shock-heated shell would permit us to make a strong statement about the limits of the applicability of a purely hydrodynamical model to the lobe/ISM interaction as we argue below.

4.2. Transport Processes and Electron-Ion Equilibration in the Shock around the Southwest Radio Lobe

4.2.1. Theoretical Considerations

It is almost always assumed that the physics governing radio lobe/ICM interactions is purely hydrodynamic; that is, the electron-ion plasma can be considered as a single, classical fluid. This may not be a good approximation for the high Mach number shock around the southwest radio lobe of Cen A because of its proximity, temperature, and density. The mean free path, $\lambda_m$, for collisional energy exchange between the ions (protons) is

$$\lambda_m = 230 \text{ pc} \left(\frac{T_i}{10^7 \text{ K}}\right)^2 \left(\frac{n_p}{10^{-3} \text{ cm}^{-3}}\right)^{-1},$$

where $T_i$ and $n_p$ are the ion temperature and density, respectively (Spitzer 1962). For simplicity we assume that the plasma is pure hydrogen. The great bulk of the gas kinetic energy is carried into
the shock by the ions. In a strong, collision-dominated shock the kinetic energy is thermalized among the ions over a distance comparable to $\lambda_{\text{ii}}$. Collisional energy exchange between the ions and electrons is a factor of $\sim (m_e/m_i)^{1/2} \approx 43$ slower, so that the region over which the electron temperature differs significantly from the ion temperature is roughly 40 times larger than the thickness of the ion shock. At the observed temperature of $\sim 3.5$–4.0 keV, the ion shock around the southwest radio lobe of Cen A should be spatially resolvable. A plot of the predicted thickness of the transition region as a function of postshock temperature is shown in Figure 7 for the measured gas density ($n_p = 2.2 \times 10^{-2}$ cm$^{-3}$) of the shell. The temperature of the gas in the southwest region of the shell (region 1 of Table 2) is $3.9 \pm 0.7$ keV (for $Z = 0.5$, 90% confidence). The region of allowed parameter space for ion-ion (solid line) and ion-electron collisions (dashed line) is denoted by the vertical dashed lines in Figure 7. Thus, the thickness of the ion shock around the lobe would be several arcseconds at the distance of Cen A. The distance scale for ion-electron equilibration is also shown in Figure 7. Around the southwest lobe in Cen A, this would be more than 1 kpc, which is larger than the thickness of the shell.

Observations of young Galactic and Magellanic SNRs demonstrate that the ion shocks are collisionless (Rakowski 2005); therefore, the ion shock in Cen A is likely to be orders of magnitude smaller than estimated from ion-ion collisions. Plasma effects and magnetic fields, even if not dynamically important, can reduce the mean free path for energy and momentum transfer between ions to a value many orders of magnitude smaller than the Spitzer estimate. The ion shock of Galactic SNRs ($\sim 1000$ times closer than Cen A) with gas temperatures similar to the shock-heated shell in Cen A has never been spatially resolved. It would therefore be surprising if we could observe this region in Cen A.

However, the efficiency with which the protons transfer energy to the electrons in SNR shocks (and in low-density, high Mach number plasma shocks in general) is largely unknown. There may be some collisionless heating of the electrons in the ion shock, but it is believed that this heating will not be efficient and that the electron temperature will be significantly below the ion temperature at the boundary of the ion shock (i.e., where the protons reach their final, postshock temperature; Bagenal et al. 1987; Cargill & Papadopoulos 1988; Schwartz et al. 1988). The plasma (i.e., wave-particle interaction) and MHD processes that reduce $\lambda_{\text{ii}}$ in the ion shock of SNR shocks do not appear to greatly reduce $\lambda_{\text{ie}}$. In fact, large differences between the electron and ion temperatures have been measured in several young SNRs, including SN 1006 (Vink et al. 2003), Tycho, the Cygnus Loop (Raymond et al. 2003), and the LMC remnant Dem L71 (Rakowski et al. 2003). Comparison of X-ray measurements of electron temperatures, $T_e$, with $\text{He}_{\alpha}/\beta$ line ratio estimates of the ion temperature, $T_i$, indicates that there is a strong correlation between the shock velocity and the ratio of $T_e$ to $T_i$ (Rakowski 2005). Stronger shocks in young SNRs tend to have lower ratios of $T_e/T_i$. For Cen A, the ratio of the temperature of the gas in the shell ($\sim 3.5$ keV) to the ISM (0.3 keV) is $\sim 12$. This temperature ratio implies a shock velocity (for a purely hydrodynamical shock) of $\sim 1500$ km s$^{-1}$ ($M \sim 6.2$). For SNRs with a similar shock velocity such as Tycho, $T_e/T_i \sim 0.2$. Therefore, if the transport processes relevant to the expansion of the southwest radio lobe of Cen A are similar to those in young SNRs, it is likely that the proton temperature is considerably higher than the electron temperature, and the electron temperature (i.e., the temperature that we measure with the X-ray spectrum) considerably underestimates the strength of the shock.

Therefore, the electrons and ions are unlikely to have reached thermal equilibrium and there should be an observable radial temperature gradient in the shell. In addition, since we measure the electron (and ionization) temperature with the X-ray spectrum, it is likely that we have underestimated the ion temperature and shock velocity, so the shock may be even stronger than we estimate based on the electron temperature. A time-dependent consideration of Coulomb collisions in plasmas suggests that the ratio, $q$, of the electron temperature, $T_e$, to the final (equilibrium) temperature, $T_f$, after time $t$ is given by

$$\frac{dq}{dt} = Kq^{-3/2} (1 - q),$$

where $K = 2.75 \times 10^{-4} n(T_f/10^7 \text{ K})^{-3/2}$ yr$^{-1}$ and $n$ is the total (i.e., $n_e + n_i$) particle density (Spitzer 1962). Thus, the electron temperature would rise to roughly half the ion temperature in a few times the Spitzer ion-ion collision length (tens of arcseconds in our case) and then more slowly approach equilibrium over a distance of $43\lambda_{\text{oi}}$.

4.2.2. Simulations

To evaluate this phenomenon quantitatively, we created a one-dimensional spherical shock model in a two-fluid (electron/proton) plasma driven by energy injected from the center. Several simplifying assumptions have been made. First, we assume that energy is transferred between the particles only by Coulomb collisions and that the rate of energy transfer is given by the Spitzer value. Second, we assume that there is no separation between the electrons and ions (i.e., $n_e = n_i$). The latter approximation is extremely good as the maximum length scale of separation is on the order of the Debye length, which is hundreds of meters for the parameters of the Cen A shock. Third, we introduce an artificial proton viscosity (the Richtmyer-Morton artificial viscosity) to ensure that we capture the features of the shock at the resolution of the simulation. Finally, we neglect the effects of thermal conduction. More detailed studies of two-fluid shocks demonstrate that thermal conduction from the downstream electrons can heat the preshock electrons, thus creating a shock precursor (Casanova et al. 1991). The presence of such a precursor has not been seen in Galactic SNRs and is unobservable in our data. We emphasize that we are interested in studying the thermal relaxation between the ions and electrons, not thermal conduction.
Under these conditions, motion of the two fluids is described by a single continuity equation

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

where \( \rho \) is the total density and \( \mathbf{v} \) is the common velocity of the two fluids. The Lagrangian time derivative has its usual meaning, \( d/dt = \partial / \partial t + \mathbf{v} \cdot \nabla \). The single momentum equation is

$$\frac{d\rho}{dt} \frac{d\mathbf{v}}{dt} = -\nabla p + \nabla \cdot \mathbf{T} + \rho \mathbf{g},$$

where \( \rho \) is the total gas pressure, \( \mathbf{T} \) is the viscous stress tensor, and \( \mathbf{g} \) is the acceleration due to gravity. Only the artificial viscosity contributes to the viscous stresses in the simulation. The energy equation for the protons is

$$\frac{d\rho_p}{dt} \frac{d\mathbf{v}_p}{dt} = \frac{p_p}{\rho_p} \frac{dp_p}{dt} + \nabla \cdot \mathbf{T} + \rho \mathbf{g},$$

and that of the electrons is

$$\frac{d\rho_e}{dt} \frac{d\mathbf{v}_e}{dt} = \frac{p_e}{\rho_e} \frac{dp_e}{dt} + \nabla \cdot \mathbf{T} + \rho \mathbf{g}.$$
atmosphere show a ~10% increase in the gas temperature from the shock to the contact discontinuity. This can be easily demonstrated from Bernoulli’s equation; the nonzero velocity of the gas just behind the shock must be converted to thermal energy of the gas at the contact discontinuity. The Sedov solution for a point release of energy in an atmosphere with a power-law density gradient predicts an even larger gradient. Kaiser & Alexander (1999) describe this process for a range of model atmospheres. Data of sufficient quality should be able to clearly distinguish between these alternatives.

Fourth, there will be less temperature structure around the periphery of the lobe than one would naively expect based on the Rankine-Hugoniot shock conditions. In particular, the shock will be weaker around the sides (i.e., closer to the nucleus) of the lobe periphery of the lobe than one would naively expect based on the alternative. Sufficient quality should be able to clearly distinguish between these alternatives.

We demonstrate that if the energy transfer between electrons and protons behind the shock of the southwest lobe is purely collisional, their temperatures will not have equilibrated. One-dimensional, two-fluid, field-free simulations show that there will be little temperature structure in the gas between the shock and the contact discontinuity as adiabatic losses will roughly balance Coulomb heating of the electrons. These simulations also predict significant differences in the temperature structure as a function of distance from the nucleus (i.e., around the periphery of the lobe) compared with a purely hydrodynamic model; that is, the shock strength will vary quite strongly around the lobe because of the density gradient in the gas. Our two-fluid simulations suggest that the electron temperature in the shocked gas around the lobe will be more uniform than predicted in a single-fluid hydrodynamic model.

A deep (>500 ks) Chandra observation of Cen A is required to further elucidate the underlying shock physics. In particular, a deeper observation would permit an accurate measurement of the shock temperature and pressure around the periphery of the lobe, thus constraining the expansion velocity, external gas pressure, and external density. A deeper observation of the X-ray—bright enhancement at the southwest boundary of the lobe would allow a detailed estimate of the temperature structure in the shock. This could then be compared with two- and three-dimensional two-fluid simulations of the shock to better estimate the energy in the shock and the degree of coupling between the electrons and ions.

5. CONCLUSIONS

The hot thermal shell of shock-heated gas surrounding the southwest radio lobe of Centaurus A is the best example of a spatially resolvable high Mach number shock in an extragalactic system. It is therefore a unique laboratory in which to study the hydrodynamics and plasma physics of the radio lobe/ISM interaction. We find that the surface brightness discontinuity extends around ~75% of the boundary of the southwest radio lobe. The shock likely extends around the entire lobe, but the current observations do not yet have the sensitivity to detect it. We also report the discovery of two filaments of X-ray emission associated with the northeast lobe, although the data quality is not sufficient to conclusively determine if they are shock-heated gas.

We demonstrate that if the energy transfer between electrons and protons behind the shock of the southwest lobe is purely collisional, their temperatures will not have equilibrated. One-dimensional, two-fluid, field-free simulations show that there will be little temperature structure in the gas between the shock and the contact discontinuity as adiabatic losses will roughly balance Coulomb heating of the electrons. These simulations also predict significant differences in the temperature structure as a function of distance from the nucleus (i.e., around the periphery of the lobe) compared with a purely hydrodynamic model; that is, the shock strength will vary quite strongly around the lobe because of the density gradient in the gas. Our two-fluid simulations suggest that the electron temperature in the shocked gas around the lobe will be more uniform than predicted in a single-fluid hydrodynamic model.

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