An Analysis of Soft X-Ray Structures at Kiloparsec Distances from the Active Nucleus of Centaurus A Galaxy

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Abstract

Here we reanalyze the archival Chandra data for the central parts of the Centaurus A radio galaxy, aiming for a systematic investigation of the X-ray emission associated with the inner radio lobes in the system, and their immediate surroundings. In particular, we focus on four distinct features characterized by the soft excess with respect to the adjacent fields. Those include the two regions located at kiloparsec distances from the nucleus to the west and east, the extended bow-shock structure to the south, and a fragment of a thin arc north of the center. The selected north, west, and south features coincide with the edges of the radio lobes, while the east structure is seemingly displaced from the radio-emitting plasma. Our X-ray spectral analysis reveals (i) a power-law emission component with photon index $\Gamma \sim 2$ in the north, east, and south regions, and (ii) a dense (number density $\sim$0.3 cm$^{-3}$) and relatively cold (temperature $\sim$ 0.2 keV) gas in the east and west regions. The power-law emission is consistent with the synchrotron continuum generated at the edges of the radio structure, and implies that the efficiency of the electron acceleration at the terminal bow shock does not vary dramatically over the inner lobes’ extension. The presence of gaseous condensations, on the other hand, could possibly be understood in terms of a massive outflow from the central regions of the galaxy.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); X-ray active galactic nuclei (2035); Non-thermal radiation sources (1119); Active galaxies (17); X-ray astronomy (1810); X-ray sources (1822)

1. Introduction

The famous radio galaxy Centaurus A, hosted by NGC 5128, is located at a distance of 3.85 ± 0.35 Mpc (Rejkuba 2004; Ferrarese et al. 2007). NGC 5128 is an elliptical with a prominent dust lane and other morphological features indicating multiple merger events occurred about 200–700 Myr ago (see the reviews by Israel 1998; Morganti 2010, and references therein). It harbors a central black hole with an estimated mass of $(0.5–1.1) \times 10^9 M_\odot$ (Marconi et al. 2006; Neumayer et al. 2007; Cappellari et al. 2009). Cen A is a strong source of multifrequency emission detected on various scales. The large-scale structure of the system has been resolved in the radio domain, from very low frequencies up to millimeter wavelengths, to have an angular size of $8^\circ \times 4^\circ$, equivalent to the projected linear dimensions of 500 kpc $\times$ 250 kpc (Hardcastle et al. 2009; Feain et al. 2011; McKinley et al. 2013). These giant lobes have also been resolved in high-energy $\gamma$-rays by the Large Area Telescope (LAT) on board the Fermi satellite (Abdo et al. 2010a; Sun et al. 2016), and selectively mapped in X-rays with Suzaku (Stawarz et al. 2013).

On smaller scales, in particular at the distance of several–tens of kiloparsecs north of the Cen A nucleus, a diffuse and low-surface brightness radio structure called the “northern middle lobe” is seen (Morganti et al. 1999). Around and within this structure, a complex net of optical filaments of ionized gas, clouds of atomic gas with anomalous velocities, young stars, and large-scale X-ray filaments composed of discrete knots, have been observed, all suggestive of a complex interaction between the evolving large-scale radio jet with the interstellar medium (Morganti et al. 1999; Oosterloo & Morganti 2005; Kraft et al. 2009; Crockett et al. 2012; Neff et al. 2015; Salomé et al. 2016).

Finally, on yet a smaller scale of a few/several arcminutes, the inner structure of the Cen A radio galaxy consists of several components clearly visible in radio and X-rays when imaged with arcsecond resolution, including the bright nucleus, the jet extending to the northeast up to four kiloparsecs from the core, and the counterlobe pronounced to the south (e.g., Hardcastle et al. 2007; Croston et al. 2009). The X-ray emission spectrum of the nucleus in the energy range 3–10 keV is well fitted by a heavily absorbed power-law model plus a neutral and narrow fluorescence iron line (Evans et al. 2004); the jet X-ray emission continuum, contributed by multiple bright knots and a diffuse component, is best described as an unabsorbed steep power law (see Kataoka et al. 2006; Snios et al. 2019). Another X-ray feature within the inner parts of the Cen A system is a ring-like structure extending to several kiloparsecs in the direction perpendicular to the jet, as reported by Karovska et al. (2002).

The Cen A core has been detected in soft and high-energy $\gamma$-rays by all the instruments on board the Compton Gamma Ray Observatory (Steinle et al. 1998, and references therein), as well as by the Fermi-LAT (Abdo et al. 2010b). The radio galaxy has also been detected in the very-high-energy $\gamma$-ray range (>100 GeV) by the H.E.S.S. observatory (Aharonian et al. 2009). The most recent analysis of the broadband $\gamma$-ray continuum of the source reveals a spectral hardening above the photon energies of a few GeV (Sahakyan et al. 2013; H.E.S.S. Collaboration et al. 2018); the extension of the H.E.S.S. source reported recently by H.E.S.S. Collaboration et al. (2020), seems to point to the kiloparsec-scale jet as the most likely origin of this observed “excess” $\gamma$-ray emission (see, e.g., Tanada et al. 2019).

In this paper we reanalyze the archival Chandra data for the central parts of the Cen A radio galaxy, focusing on the spectral analysis for the diffuse features associated with the inner radio lobes, and characterized by the excess soft X-ray emission with respect to the adjacent fields. The data acquisition, analysis,
and modeling are described in Section 2. The results are interpreted and discussed in Section 3 and summarized in Section 4.

2. Chandra Data

We have reviewed all the available Chandra Advanced CCD Imaging Spectrometer (ACIS) data for the innermost region of the Cen A system, and selected the exposures for which the ACIS readout streaks are restricted (as much as possible) to the plane perpendicular to the jet axis, in order to avoid any overlaps with the lobes and their immediate surroundings. The ObsIDs of the selected observations are: 316, 962, 2978, 3965, 8489, and 8490. For these, the analysis was carried out using the software package CIAO 4.10 (Fruscione et al. 2006) and the calibration database CALDB 4.7.9. Before the analysis, the data were reprocessed using the chandra_repro script recommended in the CIAO analysis threads. Next, the data were merged and binned with a factor of 1.0, which corresponds to the original Chandra pixel size of 0".492. The images of the selected observations, merged and smoothed with a 3σ Gaussian, are shown in Figure 1 for the energy ranges 0.4–2.5 keV and 2.7–8.0 keV.

2.1. X-Ray Hardness Analysis

The Chandra map of the Cen A radio galaxy in the energy range 0.4–2.5 keV (Figure 1 left), reveals a pronounced soft X-ray emission from the central kiloparsec region, characterized roughly by an “hourglass” appearance, and coinciding roughly with the innermost segments of the radio lobes; this structure is not prominent in the higher energy range 2.7–8.0 keV (right panel of the figure). The kiloparsec-scale jet to the northeast, and the bow-shock structure to the south marking the outer edge of the counterlobe are also manifesting clearly in the soft X-ray range, although both structures can also be noted on the hard X-ray Chandra map. In addition to those, in the soft image, a fragment of a thin but distinct arc located to the north of the nucleus is clearly visible as well; its position and orientation are both consistent with the extension of the edge of the main radio lobe.

Figure 2 presents the hardness ratio map of the analyzed system, based on the exposure-corrected images, and smoothed with the Gaussian of σ = 5 px. The hardness ratio here is defined as the ratio of the 2.7–8.0 and 0.4–2.5 keV count rates, with the energy gap between the two photon energy ranges chosen to account for the energy resolution of Chandra’s ACIS (which is of the order of 150 eV). For comparison, in the figure we also display the contours of the lobes’ continuum radio emission at 21 cm, taken from the NRAO Very Large Array archive (Condon et al. 1996). As shown in the figure, while the jet, the southern bow shocks, and the northern arc are all still prominent on the hardness map, the soft diffuse X-ray hourglass structure “collapses” to two distinct but symmetric features with relatively sharp and well-defined boundaries, located to the east and west of the core. Moreover while the aforementioned north, west, and south regions do overlap well with the lobes’ edges on the radio map, the east feature appears seemingly displaced from the radio-emitting plasma of the main lobe.

We note that the two peculiar structures to the east and west are inclined at ~35 deg with respect to the jet axis, and are approximately cone-shaped; the core-vertex angular separation for both reads as ~2/4 each, indicating the projected distances of about 2.7 kpc for the conversion scale 19 pc arcsec⁻¹ adopted hereafter.

The exact regions selected for the following spectral analysis are shown in Figure 2. The corresponding background regions were chosen to avoid any overlaps with the radio lobes on one hand, and the dust lane on the other hand (for the east and west features); we emphasize, however, that the choice of the background region in such a crowded field deep within the host galaxy and close to the very bright nucleus, is in general rather difficult, and will always be, to some extent, arbitrary. We have therefore repeated the fitting with the enlarged and modified background regions, obtaining consistent results. We have also attempted an analysis of the spectra of the other segments of the lobes’ edges/surroundings, including mirror reflections of the west and east regions with respect to the jet axis, but due to a combination of a complicated field and low photon statistic, we failed to obtain proper fits for such.

Note that the X-ray emission of the regions overlapping with the south and west features studied in this paper was examined...
before by Croston et al. (2009); the east and north features, however, were never subjected to any spectral modeling in the past. Also, here we do not discuss the kiloparsec-scale jet emission, referring instead to the previous detailed analysis by Kataoka et al. (2006) for the jet diffuse X-ray emission component, and Snios et al. (2019) for the most recent update on the compact jet knots.

2.2. Spectral Modeling

For the spectral analysis of the selected regions, first we extracted the corresponding spectra from each ObsID considered in our study, using the specextract tool from the CIAO software package. Next we combined the spectra for each region using the combine_spectra script. Because of the extended wings of the point-spread function (PSF) of the extremely bright nucleus, which in addition is subjected to a severe pileup in the instrument, we restricted the analysis to the photon energy range up to 3 keV (see in this context also Croston et al. 2009). We note that both the east and west regions are located at similar distances from the core, and so are their background regions, hence any photon leakage from the central PSF should affect the spectral analysis of both regions in a similar/comparable manner; the north and especially the south regions, on the other hand, are expected to be subjected to a much lesser extent by the pollution from the core emission.

After the background extraction, the fitting was performed for the grouped data (with the minimum signal-to-noise ratio = 5 for the west, east and south regions, and a minimum signal-to-noise ratio = 7 for the north region because of a much lower photon statistics) using the Sherpa fitting application (Freeman et al. 2001). The initial values of the model-free parameters were chosen based on the preliminary fitting using the Monte-Carlo method in Sherpa.

The fitted model for all the regions included a thermal component (xsapec) plus a power-law component (xspowerlaw), moderated by the Galactic absorption and the internal absorption (xsphabs). All the model parameters were set free, except for the Galactic equivalent hydrogen column density in the direction of the source, which was frozen at $N_{\text{H,Gal}} = 7.31 \times 10^{20}$ cm$^{-2}$ following Kalberla et al. (2005). For the north and south regions, we applied a simple absorbed power-law model, with no contribution from a thermal component; in fact, for these regions the two-component model (power-law plus apec) did not provide any substantial improvement over the one-component model (consisting of a single power-law emission). The spectra of the east and west regions, on the other hand, could not be fitted at all with a one-component model, consisting of either an absorbed single power-law emission, or an absorbed single-temperature plasma, and hence below we do not discuss those attempts.

The final results obtained with the Levenberg–Marquardt optimization method, using the chi-squared statistic (chisquare) with variance calculated from the data, are presented in Figure 3, and the corresponding best-fit values of the model-free parameters are summarized in Table 1. In Figure 4, we also provide the confidence contour plots of the main model parameters for the two-component model applied to the east and west regions. The results of the spectral fitting for all four analyzed regions can be summarized as follows:

1. In the east region, which is seemingly displaced from the radio-emitting plasma of the main lobe, we clearly see a thermal component with the best-fit temperature of $kT \sim 0.2$ keV, and subsolar abundance $\sim 0.1$, moderated

![Figure 2](https://example.com/figure2.png)
by a hydrogen column density $\sim 0.4 \times 10^{22} \text{ cm}^{-2}$ much in excess of the Galactic value. The power-law component seen in the spectrum is characterized by a very flat (although not well constrained) slope and a low amplitude.

2. In the west region, which does overlap with the edge of the southern radio lobe, we see the same thermal component as in the east region ($kT \sim 0.2 \text{ keV},$ subsolar abundance of $\sim 0.2,$ hydrogen column density $\sim 0.65 \times 10^{22} \text{ cm}^{-2}$). However, in addition we also detected a power-law emission characterized by a relatively steep slope ($\Gamma \approx 1.75 \pm 0.28$) and a high amplitude.

3. In the south region, which is located at larger distances from the core and which corresponds to the southernmost edge of the radio counterlobe, we do not see any particularly pronounced thermal emission component, or a hydrogen column density in excess of the Galactic value. The single absorbed power-law component (though with hardly constrained absorbing column density, consistent with zero) dominating the radiative output of the region, is characterized by a relatively steep slope ($\Gamma \approx 2.14 \pm 0.13$), and a high amplitude.

4. In the case of the north region, which is also located at a larger distance from the core (when compared to the west and east regions), and which overlaps with the edge of the main radio lobe, despite very low photon statistics, an acceptable fit could be obtained assuming a single power-law model, yielding a steep slope of the continuum ($\Gamma \approx 2.02 \pm 0.43$), its relatively small amplitude, and unconstrained absorbing column density consistent with zero. Removal of the internal absorption from the model improves the fit.

As mentioned previously, because of the extremely high flux of the Cen A nucleus, leading to a severe pileup in the detector, we have restricted our spectral analysis to the low-energy range of the ACIS instrument (see in this context Evans et al. 2004; Kraft et al. 2007; Croston et al. 2009). However, the contribution of the core’s PSF seems still to be present within the east region, even below 3 keV. Indeed, as discussed in Mingo et al. (2011) and Hardcastle et al. (2016), the extended wings of high-flux unresolved sources are in general expected to manifest as low-amplitude and flat-spectrum power-law components even at larger distances from the targets, due to a combination of the energy-dependent Chandra’s PSF, and a
significant instrumental pileup affecting predominantly low-energy segments of the targets’ spectra. Hence, we believe that the low-amplitude and flat-spectrum power-law component seen within the east region is due to this effect, i.e., it represents only the very broad PSF wings of the Cen A nucleus. As such, it should be also present in the west region, located at a comparable distance from the core. We have therefore repeated the spectral fitting for the west region adding an additional flat-spectrum power-law component, with the model parameters fixed at values within 1σ of the best-fit power-law component emerging from the spectral analysis of the east region. The remaining model parameters obtained in this way turned out basically the same as the ones reported in Table 1, which is as expected given the much lower amplitude of the flat-spectrum power-law component to be compared with the steep-spectrum one.

On the other hand, the steep-spectrum power-law component with the best-fit photon index Γ ≈ 2.0, which can be seen in the north, west, and the south regions, cannot be simply an instrumental artifact. Our fitting results for the south region are in fact in agreement with the modeling presented in Croston et al. (2009), who argued that the X-ray power-law continuum of that region, with the best-fit photon index of Γ ≈ 2.0 ± 0.04 (model IV therein), is due to the synchrotron emission of very-high-energy electrons energized at the front of the bow shock, induced in the ambient medium by the expanding radio counterlobe.

We also note that the field partly overlapping with our west region was also analyzed by Croston et al. (2009, “Region 3” therein); the best fit obtained by these authors assumed in this case a thermal model, and yielded a relatively high plasma temperature of ≈0.95 keV. The reason for the discrepancy between our fitting results and those presented by Croston et al. for the west feature is the differences in the source and background extraction regions, as well as in the fitting procedure; as a result, in

### Table 1: Spectral Fitting Results

| Region/Model       | Parameter | Value  | 1σ Errors | Units       |
|--------------------|-----------|--------|-----------|-------------|
| East               | $kT$      | 0.23   | 0.01      | keV         |
|                    | norm      | 0.4    | 0.1       | $10^{-4} \times apec$ |
|                    | Abundanc  | 0.09   | 0.03      | --          |
|                    | Γ         | 2.24   | 0.66      | --          |
|                    | ampl      | 2.5    | 1.5       | $10^{-6} \times ph \text{keV}^{-1} \text{cm}^{-2}$ at 1 keV |
|                    | $N_H$     | 0.40   | 0.04      | $10^{22} \text{cm}^{-2}$ |
|                    | Final fit statistic | 125.33 | | |
|                    | Degrees of freedom | 92 | | |
| West               | $kT$      | 0.19   | 0.01      | keV         |
|                    | norm      | 1.9    | 0.7       | $10^{-2} \times apec$ |
|                    | Abundanc  | 0.20   | 0.09      | --          |
|                    | Γ         | 1.75   | 0.28      | --          |
|                    | ampl      | 32.1   | 7.1       | $10^{-6} \times ph \text{keV}^{-1} \text{cm}^{-2}$ at 1 keV |
|                    | $N_H$     | 0.65   | 0.03      | $10^{22} \text{cm}^{-2}$ |
|                    | Final fit statistic | 208.34 | | |
|                    | Degrees of freedom | 128 | | |
| South              | $kT$      | 0.52   | 0.03      | keV         |
|                    | norm      | 0.06   | 0.01      | $10^{-2} \times apec$ |
|                    | Abundanc  | 0      | (unconstr.) | --          |
|                    | Γ         | 1.00   | 0.20      | --          |
|                    | ampl      | 15.2   | 3.3       | $10^{-6} \times ph \text{keV}^{-1} \text{cm}^{-2}$ at 1 keV |
|                    | $N_H$     | 0.16   | 0.03      | $10^{22} \text{cm}^{-2}$ |
|                    | Final fit statistic | 179.68 | | |
|                    | Degrees of freedom | 118 | | |
|                    | xspowerlaw | Γ      | 2.14   | 0.13      | --          |
|                    | ampl      | 46.4   | 4.2      | $10^{-6} \times ph \text{keV}^{-1} \text{cm}^{-2}$ at 1 keV |
|                    | $N_H$     | 0.026  | 0.030    | $10^{22} \text{cm}^{-2}$ |
|                    | Final fit statistic | 104.49 | | |
|                    | Degrees of freedom | 118 | | |
| North              | $kT$      | 0.16   | 0.05      | keV         |
|                    | norm      | $8 \times 10^{-5}$ | (unconstr.) | $10^{-2} \times apec$ |
|                    | Abundanc  | 0.24   | 0.71      | --          |
|                    | Γ         | 2.52   | 0.26      | --          |
|                    | ampl      | 4.5    | 2.0       | $10^{-6} \times ph \text{keV}^{-1} \text{cm}^{-2}$ at 1 keV |
|                    | $N_H$     | 0.21   | 0.065     | $10^{22} \text{cm}^{-2}$ |
|                    | Final fit statistic | 43.69  | | |
|                    | Degrees of freedom | 59  | | |
|                    | xspowerlaw | Γ      | 2.02   | 0.43      | --          |
|                    | ampl      | 3.0    | 0.65      | $10^{-6} \times ph \text{keV}^{-1} \text{cm}^{-2}$ at 1 keV |
|                    | Final fit statistic | 8.82   | | |
|                    | Degrees of freedom | 15  | | |
our spectral modeling instead of a hot plasma we see a prominent power-law component in addition to the relatively cold thermal gas emission. We believe that our estimates are robust, however, because almost exactly the same thermal gas parameters emerge for the east region, where we do not see any physical power-law component (above the low-level emission related to the PSF wings of the bright nucleus).

Two issues should be clarified at this point regarding the thermal component fitting. One is that the emerging low abundance values may not necessarily correspond to a real low metallicity, but instead may only signal an unresolved multi-temperature gas, for which the best-fit temperature of $\sim 0.2$ keV should be considered an average value, while the metallicity is most likely much closer to the solar one (see in this context the discussion in Kraft et al. (2009), regarding the X-ray knots within the northern middle lobe). The other issue is that the residuals of the best-fit models presented in Figure 3 for the east and west regions indicate clearly the presence of linelike emission features in the analyzed spectra. We have therefore repeated the spectral fitting for both regions, adding additional Gaussian components; the results of the modeling are given in the Appendix. In short, by introducing two additional Gaussian spectral components, we do improve the quality of the fitting in terms of the reduced $\chi^2$ values. Moreover, the best-fit line positions, $\sim 1$ keV and $\sim 1.85$ keV, correspond to the well-known neon/iron L-shell and silicon blends, respectively (see, e.g., Peterson & Fabian 2006; Böhringer & Werner 2010). Note that previously Evans et al. (2004) reported on the detection of the neutral silicon Kα line in the nuclear spectrum of Cen A, with the source-extracted region corresponding effectively to $\lesssim 1$ kpc radius (see also the related discussion in Croston et al. 2009).

3. Discussion

One of the two main results emerging from the analysis presented in the previous section is the detection of the power-law emission component with a relatively steep photon index $\Gamma \sim 2$ not only at the southernmost edge of the radio counterlobe, as reported previously by Croston et al. (2009), but also in the north and west regions, which overlap with the side edges of the main radio lobe and the counterlobe, respectively. We follow Croston et al. in interpreting this emission component as representing the synchrotron continuum of very-high-energy electrons energized at the front of the lobes’ termination shock. If that is the case indeed, then the implication of our analysis would be that the efficiency of the electron acceleration at the termination shock front does not vary dramatically over the inner lobes’ extension. The acceleration efficiency in this context stands not only for the

Figure 4. Confidence contours of 1$\sigma$, 2$\sigma$, and 3$\sigma$ for the chi2datavar statistic on the two-thaw-parameter planes, for the west region (upper panels), and the east region (lower panel).
maximum electron Lorentz factors $\gamma \sim 10^3$ enabled by a balance between the acceleration and radiative cooling timescales (see the discussion in Croston et al. 2009), but regards also the potential for the formation of a “shock-type” energy spectrum of ultra-relativistic electrons $\propto E^{-3}$ with $s \sim 2$, assuming the observed synchrotron X-ray photons are produced in the strong cooling regime, i.e., that $s = 2(\Gamma - 1)$.

The other main finding following from the spectral analysis presented in the previous section is the presence of a relatively cold and dense gas within the two regions located at kiloparsec distances to the west and east from the nucleus. The exact emission volumes for these are unknown, and in fact hard to define, but based on the particular regions selected for spectral modeling, we estimate such volumes as $V \approx 0.43$ kpc$^3$ and $\approx 0.23$ kpc$^3$, respectively, assuming the structures are cone-shaped, with the main axes on the plane of the sky. Assuming further that each region is filled uniformly with fully ionized hydrogen, we derive the gas density $n$, total mass $M = mpnV$, and the internal energy $\epsilon_{\text{int}} = \frac{3}{2}pV$ for the corresponding thermal pressure $p = nkT$, based on the normalization parameter in the xspec model, $10^{-11}n^2V/4\pi D^2$ cgs (see Table 1), where $D = 3.85$ Mpc is the distance to the source. For the west region, the derived parameters are $n \approx 0.5$ cm$^{-3}$, $M \approx 5.5 \times 10^7$ M$_\odot$, $p = 1.6 \times 10^{-10}$ dyn cm$^{-2}$, and $\epsilon_{\text{int}} \approx 3 \times 10^{54}$ erg. For the east structures, we obtain $n \approx 0.3$ cm$^{-3}$, $M \approx 1.6 \times 10^8$ M$_\odot$, $p = 1.2 \times 10^{-10}$ dyn cm$^{-2}$, and $\epsilon_{\text{int}} \approx 1 \times 10^{54}$ erg.

Note that by assuming a clumpy distribution of the X-ray emitting gas in the analyzed regions, the derived gas density, and hence also the pressure, would increase. Such an increase would be problematic, however, since even with the filling factor of the order of unity, the thermal gas present in the analyzed regions appears much denser than, and overpressured with respect to, the diffuse ISM at the corresponding distance from the nucleus; for this “unperturbed” ISM, following Kraft et al. (2003) we adopt $n_{\text{ISM}} \sim 0.01$ cm$^{-3}$, $kT_{\text{ISM}} \sim 0.35$ keV, and $p_{\text{ISM}} \sim 10^{-11}$ dy n cm$^{-2}$. At the same time, the thermal gas we see in the east and west regions turns out to be in a pressure balance with the nonthermal plasma present around the edges of the lobes, for which Croston et al. (2009) estimated $p_{\text{bell}} \sim 10^{-10}$ dy n cm$^{-2}$. This could suggest that what we see is simply a result of a shock compression of the ISM by the expanding radio lobes. However, the corresponding high density contrast $n/n_{\text{ISM}} \sim 50$, together with the temperature ratio $T/T_{\text{ISM}} \lesssim 1$, impose a general problem for any interpretation involving adiabatically shocked ISM, in which case one would expect the density jump $\sim 4$ at most, and $T/T_{\text{ISM}} \gg 1$.

An unusual density increase along with a rapid temperature drop down to the preshock value, on the other hand, could possibly be encountered in a radiative shock, i.e., when the gas cooling in the near downstream is sufficiently fast that a relatively narrow radiative relaxation layer is formed. In the specific case of an “isothermal shock” with the upstream plasma bulk velocity $u_-$, the gas temperature in the far downstream settles at $T \sim T_{\text{ISM}}$, and the density contrast reaches

$$n \sim n_{\text{ISM}} \left(\frac{u_-}{c_s}\right)^2 \sim 0.2 \left(\frac{u_-}{10^3 \text{ km s}^{-1}}\right)^2 \text{ cm}^{-3}$$

(1)

consistently with the gas temperature and density derived above for the analyzed east and west regions, as long as $u_- \sim 10^3$ km s$^{-1}$.

However, the problem with this scenario is that the radiative cooling of the ISM gas immediately behind the shock (related to the free–free and line emission), is not sufficiently short. In fact, assuming a strong shock with $u_- \gg c_s$, the compression ratio in the near downstream should be simply $n_{\text{ISM}} \sim 4$ cm$^{-3}$, and the gas temperature

$$kT_c = \frac{3}{16}mpu_-^2 \sim 2 \left(\frac{u_-}{10^3 \text{ km s}^{-1}}\right)^2 \text{ keV}.$$ 

(2)

With $u_- \sim 10^3$ km s$^{-1}$, the thermal cooling timescale is

$$\tau_{\text{cool}} = \frac{5}{2} \frac{n_{\text{ISM}} kT_c}{n^2 \Lambda} \sim 300 \text{ Myr},$$ 

(3)

where $\Lambda$ stands for the radiative cooling function (Peterson & Fabian 2006), and we assumed approximately one-third solar abundance. This would then be orders of magnitude longer than the dynamical timescale involved,

$$\tau_{\text{dyn}} \sim \frac{d}{u_-} \sim 3 \text{ Myr},$$ 

(4)

where $d \sim 2.7$ kpc is the physical distance from the outer edges of the east and west regions to the Cen A nucleus (assuming no significant projection effects).

The emerging relatively low temperature of the thermal gas derived for the analyzed west and east features could not be explained—still in the framework of the shock scenario—by postulating that the electron temperature is lower than expected from the standard shock jump conditions, because of an inefficient heating of thermal-pool electrons at the shock front. There are two reasons for this. First, the decreased efficiency of the electron heating is expected at low Mach number shocks (see the discussion in Stawarz et al. 2014, and references therein). And second, even if the fraction of the kinetic energy of the outflow that is dissipated to heat thermal electrons at the shock front is in our case low, the electron–ion temperature equilibration due to Coulomb collisions would anyway increase the electrons temperatures in the near downstream of the shock, on the particularly short timescale of

$$\tau_{\text{eq}} \sim 0.01 \frac{m_p (kT_e)^{3/2}}{e^n m_\text{e}} \lesssim 0.01 \text{ Myr},$$

(5)

assuming electron temperature $kT_e \sim 0.2$ keV and number density as given in Equation (1).

The alternative explanation for the east and west structures, motivated by their cone-shaped morphologies, as well as the derived temperatures that are comparable to the ISM temperature, could be that those features represent Mach cones, formed after the ejections of dense plasmoids from the nucleus of Cen A, with supersonic velocities. Such ejections should drive the pressure waves, which merge at the Mach cone into a sonic boom propagating further within the ISM at the speed of sound $c_s = \sqrt{5kT_{\text{ISM}}/3m_p} \sim 230$ km s$^{-1}$. In the framework of this scenario, the velocity of the ejection, $u_{\text{ej}}$, could be estimated by measuring on the Chandra maps the half-opening angles of the east and west cones, $\theta$, which give the Mach numbers $M = 1/\sin \theta$. For both analyzed regions we obtain roughly $M \approx 3-5$, i.e., the ejection velocity within the range $u_{\text{ej}} = M c_s \sim 600-1000$ km s$^{-1}$. This leads to the elapsed time, since the ejection event $\tau_{\text{ej}} \sim d/u_{\text{ej}} \sim 3$ Myr. This timescale is of the same order as the timescale for the formation of the inner radio jets and lobes in Cen A (see Croston et al. 2009; Morganti 2010, and references therein), and also as the X-ray cooling timescale of 0.2 keV gas with 0.3 cm$^{-3}$ number density.
(see Equation (3)). Hence, the ejection episode postulated here could indeed be considered as accompanying/coinciding with the onset of the currently ongoing jet activity in the system.

Moreover, the derived ejection velocities are relatively high, but on the other hand consistent with the velocities of nuclear outflows detected in several AGN. In the particular case of Cen A, we note in this context that based on the Suzaku observations of the Cen A nucleus, Tombesi et al. (2014) claimed the detection of the Fe XXV H\ensuremath{\alpha} and Fe XXVI L\ensuremath{\gamma}\ensuremath{\alpha} absorption lines with the equivalent widths of the order of 10 eV, corresponding to the ionized hot absorber with the outflow velocities \( \leq 1500 \text{ km s}^{-1} \). What is more, in the recent Herschel data for the central 500 pc of Cen A, Israel et al. (2017) detected an outflow of cold, neutral, and ionized gas, roughly along the axis of the radio jet, with a mass of several million solar masses, and the projected velocity of 60 km s\(^{-1}\). We do not necessarily identify those currently observed nuclear or circumnuclear outflows with the ejection episode postulated here to explain the east and west features at kiloparsec distances from the core. The point is, rather, that one can indeed expect formation of massive gaseous outflows and plasma ejected systems in the central, with high and very high velocities.

A possible complication to the scenario outlined above, however, is again the very high pressure contrast between the analyzed regions and the ISM. On the other hand, as the required propagation velocity is most likely super-Alfvénic, for the Alfvén speed \( V_A = B_{\text{ISM}}/\sqrt{4\pi n_{\text{ISM}} m_p} < 200 \text{ km s}^{-1} \) with \( n_{\text{ISM}} \approx 0.01 \text{ cm}^{-3} \) and the anticipated \( B_{\text{ISM}} < 10 \mu\text{G} \), one may speculate that the magnetic draping effect, expected as long as the coherence scale of the ISM magnetic field is large enough (see in this context Moss & Shukurov 1996), effectively increases the total ISM pressure ahead of the ejection by the piled-up magnetic field (see Lyutikov 2006), so that the pressure balance is maintained.

### 4. Summary and Final Remarks

In this paper we reanalyze the archival Chandra data for the central parts of the Centaurus A radio galaxy, aiming for a systematic investigation of the X-ray emission associated with the inner radio lobes, and their immediate surroundings. After inspection of the X-ray hardness maps of the system, we focus on four distinct features characterized by the soft excess with respect to the adjacent fields. Those include the two regions located at kiloparsec distances from the nucleus to the west and east, the extended bow-shock structure to the south, and a fragment of a thin arc north from the center. The selected north, west, and south features coincide with the edges of the radio lobes, while the east structure is seemingly displaced from the radio-emitting plasma.

We perform the spectral analysis for the selected regions, assuming a combination of the absorbed power-law and thermal emission components. We found out that for the north and south features, a simple power-law model consistent with no thermal contribution and no intrinsic absorption provided satisfactory fits to the data. The spectra of the east and west regions, on the other hand, could not be fitted at all with a one-component model, consisting of either an absorbed single power-law emission, or an absorbed single-temperature plasma; for those, a two-component model was required.

One of the two main results emerging from our spectral analysis is the detection of the power-law emission component with a relatively steep photon index \( \Gamma \approx 2 \) not only at the southernmost edge of the radio counterlobe, as reported previously by Croston et al. (2009), but also in the north and west regions, which overlap with the side edges of the main radio lobe and the counterlobe, respectively. This emission component can be naturally explained as representing the synchrotron continuum of very-high-energy electrons energized at the front of the lobes’ termination shock. Hence, we conclude that the efficiency of the electron acceleration at the termination shock front, does not vary dramatically over the inner lobes’ extension.

The other main finding following from our spectral analysis is the presence of a relatively cold (temperature \( \approx 0.2 \text{ keV} \)) and dense (number density \( \approx 0.3 \text{ cm}^{-3} \)) gas within the two regions located at kiloparsec distances to the west and east from the nucleus, which appears overpressured (by one order of magnitude) with respect to the surrounding diffuse ISM. We argue that the scenario in which this gas represents the ISM shocked by the expanding radio lobes is not self-consistent because of the required effectively “isothermal compression.” Instead, we propose that the presence of such a cold and dense gas could possibly be related to a massive nuclear outflow from the central regions of the galaxy.

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**Facility:** Chandra (ACIS).

**Software:** CIAO (Fruscione et al. 2006), Sherpa (Freeman et al. 2001).

### Appendix

**Emission Lines in the West and the East Regions**

Residuals are clearly seen in the best-fit models \( \text{xphabs}^* (\text{xsapec+xspowerlaw}) \) presented in Figure 3 for the east and west regions, indicating the presence of line-like emission features. We have investigated this issue by introducing first an additional Gaussian component to the model, \( \text{xphabs}^* (\text{xsapec+xspowerlaw} + \text{xsgaussian}) \), and next allowing for two different Gaussian features, \( \text{xphabs}^* (\text{xsapec+xspowerlaw} + \text{xsgaussian1} + \text{xsgaussian2}) \), each time with the source frame line widths frozen at \( \sigma = 10 \text{ eV} \), and plasma abundances frozen at the best-fit values emerging from the basic \( \text{xphabs}^* (\text{xsapec+xspowerlaw}) \) fits for the two regions (see Table 1). The results of the modeling are presented in Figure 5, and summarized in Table 2. As shown, by introducing two additional Gaussian spectral components, one can indeed improve the quality of the fitting in terms of the reduced \( \chi^2 \) values, with no significant change in the best-fit values of the other model parameters. The best-fit positions of the first line-like feature reads as \( \sim 1 \text{ keV} \), indicating either a hydrogen-like Ne L\ensuremath{\gamma}\ensuremath{\alpha} line, or the iron L-shell blend (the position of which depends however on the plasma temperature; see Böhringer & Werner 2010); the best-fit position of the other line, \( \sim 1.85 \text{ keV} \), allows for the identification with the Si XIII blend (e.g., Peterson & Fabian 2006).
Figure 5. Chandra spectra along with the best-fit models (and residuals) for the east region (left column) and west region (right column). The models displayed consist of a mixture of absorbed thermal and nonthermal components, $\text{xshabs} \times (\text{xspec} + \text{xpowerlaw})$, with the addition of either one or two Gaussian features $\text{xsgaussian}$ (upper and lower rows, respectively).
| Region/Model | Parameter | Value | 1σ Errors | Units |
|-------------|-----------|-------|------------|-------|
| East        | $kT$      | 0.22  | 0.01       | keV   |
|             | norm      | 0.5   | 0.1        | $10^{-2} \times \text{apec}$ |
|             | $\Gamma$  | 0.11  | 0.50       |       |
|             | ampl      | 1.5   | 0.6        | $10^{-6} \times \text{ph} \text{keV}^{-1} \text{cm}^{-2} \text{at 1 keV}$ |
|             | Line position | 1.85 | 0.01 | keV |
|             | Line normalization | 0.93 | 0.02 | $10^{-6} \times \text{ph} \text{cm}^{-2} \text{s}^{-1}$ |
|             | $N_H$     | 0.42  | 0.04       | $10^{22} \text{cm}^{-2}$ |
|             | Final fit statistic | 124.08 | | |
|             | Degrees of freedom | 91 | | |
| West        | $kT$      | 0.19  | 0.01       | keV   |
|             | norm      | 2.2   | 0.5        | $10^{-2} \times \text{apec}$ |
|             | $\Gamma$  | 1.4   | 0.34       |       |
|             | ampl      | 22.1  | 6.5        | $10^{-6} \times \text{ph} \text{keV}^{-1} \text{cm}^{-2} \text{at 1 keV}$ |
|             | Line position | 1.83 | 0.02 | keV |
|             | Line normalization | 1.4  | 0.3  | $10^{-6} \times \text{ph} \text{cm}^{-2} \text{s}^{-1}$ |
|             | $N_H$     | 0.67  | 0.02       | $10^{22} \text{cm}^{-2}$ |
|             | Final fit statistic | 190.5 | | |
|             | Degrees of freedom | 127 | | |
| East        | $kT$      | 0.22  | 0.01       | keV   |
|             | norm      | 0.4   | 0.2        | $10^{-2} \times \text{apec}$ |
|             | $\Gamma$  | 0.25  | 0.74       |       |
|             | ampl      | 2.4   | 1.65       | $10^{-6} \times \text{ph} \text{keV}^{-1} \text{cm}^{-2} \text{at 1 keV}$ |
|             | Line 1 position | 1.0  | ... | keV |
|             | Line 1 normalization | 7.6  | 1.6  | $10^{-6} \times \text{ph} \text{cm}^{-2} \text{s}^{-1}$ |
|             | Line 2 position | 1.83 | 0.03 | keV |
|             | Line 2 normalization | 0.42 | 0.21 | $10^{-6} \times \text{ph} \text{cm}^{-2} \text{s}^{-1}$ |
|             | $N_H$     | 0.42  | 0.03       | $10^{22} \text{cm}^{-2}$ |
|             | Final fit statistic | 99.55 | | |
|             | Degrees of freedom | 89 | | |
| West        | $kT$      | 0.19  | 0.01       | keV   |
|             | norm      | 0.4   | 0.2        | $10^{-2} \times \text{apec}$ |
|             | $\Gamma$  | 1.75  | 0.32       |       |
|             | ampl      | 30.2  | 7.7        | $10^{-6} \times \text{ph} \text{keV}^{-1} \text{cm}^{-2} \text{at 1 keV}$ |
|             | Line 1 position | 1.02 | ... | keV |
|             | Line 1 normalization | 17.1 | 3.4 | $10^{-6} \times \text{ph} \text{cm}^{-2} \text{s}^{-1}$ |
|             | Line 2 position | 1.83 | 0.02 | keV |
|             | Line 2 normalization | 1.2  | 0.3  | $10^{-6} \times \text{ph} \text{cm}^{-2} \text{s}^{-1}$ |
|             | $N_H$     | 0.42  | 0.03       | $10^{22} \text{cm}^{-2}$ |
|             | Final fit statistic | 99.55 | | |
|             | Degrees of freedom | 89 | | |

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