X-ray Arc Structures in Chandra Images of NGC5128 (Centaurus A)

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ABSTRACT

We describe results from our initial study of the diffuse X-ray emission structures in NGC 5128 (Cen A) using the Chandra X-ray Observatory observations. The high-angular resolution Chandra images reveal multi-scale X-ray structures with unprecedented detail and clarity. The large scale structures suggest complex symmetry, including a component possibly associated with the inner radio lobes, and a separate component with an orthogonal symmetry that may be associated with the galaxy as a whole. We detect arc-like soft X-ray structures, extending to \( \sim 8 \) kpc in the direction perpendicular to the jet. These arcs appear to be tracing an ellipse, or a ring seen in projection, and are enclosed between the dust and HI emitting gas in the central region of the galaxy, and the optical and HI shell fragments at a distance of about 8-10 kpc. The diffuse X-ray and the optical emission in the arcs could originate in a region of interaction (possibly a shock) between the infalling material from the outer regions of the galaxy, and the cool dust and HI emitting material in the center, or an equatorial outflow resulting from an outburst of nuclear activity \( \sim 10^7 \) years ago.


1. Introduction

NGC5128 (Centaurus A, Cen A) is a giant elliptical early-type galaxy containing the nearest (at 3.5 Mpc; \( 1' \sim 1 \) kpc) radio-bright AGN. A subparsec scale nuclear region at the center of the galaxy is believed to be associated with a supermassive black hole (\( M_{\text{BH}} = 2 \times 10^8 M_\odot \); Marconi et al. 2001). This low luminosity radio galaxy, a prototype of a major class of active galaxies (Fanaroff-Riley Class I), has been observed by virtually every possible astronomical technique from ground and space (vis review by Israel 1998). Multi-wavelength observations of Cen A accumulated over many decades reveal its extremely complex structure. A radio jet with huge radio lobes extends across the galaxy to several hundreds of kpc from the nucleus (Clarke et al. 1992). Dark bands stretching across the middle of the galaxy, seen in optical and near-IR images of Cen A, are probably due to absorption by dust and other cool material. A system of faint concentric shell fragments and filaments are also detected in the deep optical images of Cen A (Malin et al. 1983). Radio maps obtained in the 21 cm HI line show emission originating from cool material in two distinct
regions of the galaxy: in the central region of the galaxy, along the dust lane, and from several shells 10-16" away from the center; Both the dust lane and the optical and radio shell fragments are thought to be remnants of a merger with a smaller spiral galaxy (Schiminovich et al. 1994).

Cen A was first imaged in X-rays with *Einstein* (Feigelson et al. 1981), leading to the detection of complex X-ray emission from a bright nucleus, an extended jet, and a diffuse emission. The large scale diffuse emission structures suggested a complex geometry, including a component possibly associated with the jet. Later observations with *ROSAT* (Dobereiner et al. 1996; Turner et al. 1997) led to the detection of emission from the southern inner jet radio lobe, and a population of point sources. Cen A was observed on several occasions with *Chandra*, resulting in studies of the X-ray emission from the jet (Kraft et al. 2000, 2002a); the point source population (Kraft et al. 2001); and sub-arcsecond resolution imaging of the nuclear region (Karovska et al. 2001). In this paper we report the results of the analysis of the large-scale diffuse X-ray emission and the resulting detection of arcminute-scale arc-like X-ray structures.

2. Chandra Observations

*Chandra* produces sharper images than any other X-ray telescope to date (FWHM~0.3" on axis). This high-spatial resolution results from the innovative design of this observatory in particular the high-resolution mirror assembly (Van Speybroeck et al. 1997), but also including the guidance systems, and the focal plane detectors. In addition to the photon positions, *Chandra* observations provide information about their number, energy and time of arrival. A detailed description of the Chandra observatory and its capabilities can be found in Weisskopf et al. (2002). The results presented in this paper are based on archival observations made with both imaging detectors; the Advanced CCD Imaging Spectrometer (ACIS-I), and the High-Resolution Camera (HRC-I).

The HRC-I observation (ObsID 463) was carried out on 1999 September 10 for 17 ksec as part of the Orbital Activation and Calibration phase. The Cen A nucleus was centered on the aim-point of the detector. The HRC-I offers the best resolution images, having a pixel size of 0.13" on the sky, smaller then the mirror PSF. The total field of view is 33'x33'. The characteristics of the detector and an initial analysis and results from this observation are discussed by Kraft et al. (2000). The ACIS-I observation (ObsID 316) was carried out on 1999 December 5 with 35.9 ks exposure. ACIS-I contains an array of four frontside illuminated CCDs with a total field of view of 16'x16'. Each pixel on the ACIS-I instrument corresponds to 0.492" on the sky. The Cen A nucleus was centered on the ACIS-I I3 CCD. To analyze the data we used standard CIAO tools.  

We explored the spatial extent of the X-ray sources in the Cen A images by applying an

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1CIAO is the Chandra Interactive Analysis of Observation’s data analyses system package (http://cxc.harvard.edu/ciao)
adaptive smoothing algorithm (csmooth) \(^2\) to the previously binned images. Csmooth is a powerful tool for smoothing images containing complex structures at various spatial scales, since it preserves small-scale spatial signatures and the associated counts. The smoothing scale is determined by convolving the input image with a gaussian kernel of an increasing size (smoothing scale). For each smoothing scale, a significance is computed at each pixel location by comparing the total counts under the kernel to the expected background in the same area. The user sets the desired significance threshold value. The pixels for which the significance exceeds this threshold are smoothed at the current scale. They are then excluded from subsequent smoothing using larger scales.

3. Results and Analysis

We detected structures in the smoothed HRC-I image at scales ranging from few arcseconds to several arcminutes. Figure 1 shows the 16′x16′ field of view from the adaptively smoothed HRC-I image of Cen A. The outer region of the field of view was excluded because of the edge artifacts created by the smoothing process. The smoothed image shows diffuse X-ray emission from Cen A having several distinct components: a small-scale component within a radius of a few arcseconds from the nucleus, a second complex component from a region within about 3′-4′ radius from the nucleus, and a large-scale component which includes weak X-ray diffuse emission extending to ~10′ from the nucleus.

The small-scale component may be associated with the innermost portion of the jet or the nuclear disk (Karovska et al. 2001). The 3′-4′radius component shows complex structures that roughly follow the ridges of the dust lane. The depression in the X-ray emission in the dust-lane regions is probably due to absorption by the dust stretching across the middle of the galaxy (Feigelson et al. 1981). The large scale component includes X-ray emission from regions along the radio jet (discussed in Kraft et al. 2001) as well as a weak diffuse emission component, first noted and studied by Feigelson at al (1981), showing a complex symmetry along two axes: parallel and perpendicular to the jet.

In Figure 2 we show a comparison of the spatial distribution of the X-ray emission (the central 16′x16′ region from the smoothed HRC-I image) with the emission seen at radio wavelengths: the VLA 21cm radio continuum map \(^3\) of the inner lobes of the jet (Condon et al. 1996), and 21 cm HI line emission map \(^4\). This figure demonstrates the complex interaction between the various components of this active galaxy. A comparison of the NE radio and X-ray jets shows near (but not exact) co-alignment of the general geometry up to about 4′ from the nucleus (Kraft et al. 2002). Further away the radio jet develops into a plume and the diffuse X-ray emission seems to be

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\(^2\) csmooth was adapted from the assmooth routine (Harald Ebeling 2000, private communication)

\(^3\) NASA/IPAC Extragalactic Database; http://nedwww.ipac.caltech.edu

\(^4\) J. van Gorkom 2002, private communication
distributed in the outer boundaries of the radio continuum emission, following the curvature of the inner lobe (Fig.2). The component of the diffuse X-ray emission associated with the jet extends to the NE to at least 12′ from the nucleus, almost as far as the HI emission shell. The diffuse X-ray emission associated with the SW lobe of the radio jet is more complicated, and extends up to about 10′ from the nucleus, reaching to the SW HI emission shell. A detailed analysis of the diffuse emission associated with the jet will be discussed elsewhere (Karovska et al., 2002).

In the following we concentrate on a distinct component of the diffuse X-ray emission with a symmetry orthogonal to the jet. The global extent of this emission is similar to the diffuse emission observed with Einstein and ROSAT (e.g. Feigelson et al. 1981; Fabbiano et al. 1992; Dobereiner et al. 1996), but the higher spatial resolution of Chandra, and the adaptive smoothing of the images, make the detailed morphology of the extended diffuse emission more apparent. The most striking part of this large-scale emission are a pair of diffuse arc-like structures (Figure 1 A,B) extending to \( \sim 8 \)′ to the NW, and \( \sim 7 \)′ to the SE (\( \sim 8 \) kpc and \( \sim 7 \) kpc respectively). They appear symmetric about an axis perpendicular to the direction of the jet.

The NW X-ray arc (A) appears to fill a region enclosed between the inner HI emission (central 4′ region), and the NW optical and HI shells at a distance of about 8-10′ from the center (Fig.2; see also Fig 1b in Schiminovich et al. 1994). A similar, somewhat fainter X-ray arc is seen to the SE (B). This arc is similarly located between the inner HI emission and the outer optical shells in the SE (Fig 1b in Schiminovich et al. 1994). The thickness of these arcs is about 2′ (\( \sim 2 \) kpc at the distance of Cen A). The arc-like structures trace an ellipse with a semi-major axis of about 8′, and a semi-minor of about 3′-4′. The geometry is consistent with a ring or torus-like structure seen in a projection (inclination of 60-70° from the plane of the sky), with an axis of symmetry along the direction of the inner jet. As shown in Figure 2, the inner HI emitting region appears to “break through” the X-ray ring roughly in the E-W direction. The apparent gaps in the X-ray ring, and the lower diffuse soft X-ray emission at the inner boundaries of the arcs, may be due to photoelectric absorption by cool HI emitting material in the central regions of the galaxy.

We searched for optical emission that could be associated with the X-ray arcs in the Digitized Sky Survey (DSS)\(^5\) images. In order to increase the visibility of the faint and low contrast features, we applied edge enhancement methods including unsharp masking to deep blue and red DSS images. In the enhanced images we detected several previously unseen shell fragments and arc-like regions (Karovska et al., 2002), in addition to the known system of shells (Malin 1983; Gopal-Krishna and Saripalli, 1984). In particular, we also detected an arc-like region in the blue DSS images which seems to trace the outer boundaries of the NW X-ray arc (dashed line in Figure 2). The optical arc is located between the NW X-ray arc and the NW HI shell (Figure 2). As with the X-ray arcs, this region could be tracing an ellipse with a semi-major axis of 8′, and a semi-minor axis of 4′. The Western segment of this region has been previously detected by Malin et al. (1993) as shell number 8 (see Fig 1b in Schiminovich et al. 1994). Recent UBVRI imaging of this region suggests

\(^5\)http://archive.stsci.edu/dss
a young stellar origin of the emission, possibly associated with a tidal stream (Peng et al. 2001).

The NW arc (A in Figure 1) was detected in the soft band (0.5-2 keV) ACIS-I image as well. To analyze the spectrum, we extracted data from a region centered on the arc. Background was extracted from an emission-free rectangular region to the North of the arc located on the same CCD-chip. The NW arc contains \(~ 2500\) net counts (after removing the point sources) which is about 2.5 times the number of soft (0.5-2 keV) counts in the background. The corresponding number of counts in the region bordering the arc to the South is about two times lower, and the signal to noise in the extracted spectrum is not sufficient for detailed spectral analysis. We grouped the arc-region and the background spectra to contain a minimum of 20 (source + local background) counts per bin, and performed spectral fitting assuming that the emission originates from a thermalized gas.

We first fitted the data with a model consisting of optically thin thermal emission (the model \textit{xsmekal} in Ciao’s Sherpa) absorbed by neutral gas, and allowed the temperature and normalization of the thermal plasma to vary while keeping both the metallicity of the gas and the column density of the absorber frozen to the solar value and to $N_H = 9.6 \times 10^{20}\, \text{cm}^{-2}$, respectively. The assumed $N_H$ is a sum of the intrinsic column density measured from the HI map ($1 \times 10^{20}\, \text{cm}^{-2}$; see Figure 1b Schiminovich et al.) at the South border of the NW arc, and the Galactic column density ($8.6 \times 10^{20}\, \text{cm}^{-2}$; Dickey and Lockman, 1990). This produced a statistically acceptable fit ($\chi^2_{\text{red}}(\text{dof}) = 1.05(80)$), with a temperature of $kT = 0.64 \pm 0.04\, \text{keV}$, and a normalization of $1.27 \times 10^{-4}$ (in units of $(10^{-14}/(4\pi D^2) \times \int_V (n_e n_H) dV$, where $D$ is the source distance, in cm, $n_e$ and $n_H$ are the electron and proton densities respectively, and $V$ is the volume of the emission region). Figure 3 shows the data along with the best fitting thermal model (upper panel), and the residuals in $\sigma$ (lower panel). We estimate the number density in the gas of $n_e = 5.7 \times 10^{-3}\, \text{cm}^{-3}$, and a luminosity of the emitting gas of $4.7 \times 10^{38}\, \text{erg s}^{-1}$. In these calculation we assumed, $n_e \simeq n_H = \text{constant}$, a distance of $D \sim 3.5\, \text{Mpc}$, and an emitting volume of $V \sim 20\, \text{kpc}^3$ (from the size of the source extraction region, and assuming that the region is $\sim 2\, \text{kpc}$ deep). Assuming that the NW arc is about 1/6 of a ring seen in a projection, we estimate a total luminosity in the ring of $\sim 2.8 \times 10^{39}\, \text{erg s}^{-1}$. We then calculate the internal energy of the gas in the ring of $\sim 1.1 \times 10^{55}\, \text{ergs}$, assuming that the mean energy per particle in the gas is $(1/2) kT$.

We also fitted the data allowing the intrinsic equivalent hydrogen column density free to vary. As a result we obtained a somewhat statistically improved fit with a temperature of $kT = 0.40 \pm 0.01$, $\text{norm} = 5.5 \times 10^{-4}$, and $N_H = 3.9 \pm 0.2 \times 10^{21}\, \text{cm}^{-2}$. The best fit parameters are quite different from those obtained in the case with frozen $N_H$. Using these parameters we calculate a slightly higher density of $n_e = 1 \times 10^{-2}\, \text{cm}^{-3}$, and an almost unchanged internal energy of the gas in the ring of $\sim 1.2 \times 10^{55}\, \text{ergs}$. We note that our assumptions may well be too simple: the gas might well have non-constant density, and the absorbing material could be hot. Furthermore, fits with an equilibrium thermal model may not be correct, for example if the emission is a result of the shock. More detailed spectral analysis using more realistic assumptions will be presented elsewhere (Karovska et al., 2002).
4. Discussion

We have detected multi-scale structures in the Chandra images of the diffuse X-ray emission from Cen A with spatial scales ranging from few hundred pc to several kpc. The large-scale diffuse X-ray structures include a set of arcs which are symmetric about an axis perpendicular to the direction of the jet. The NW arc appears to be associated with the nearby optical and HI shells. Its outer boundary is surrounded by an arc of blue stellar emission, possibly a tidally disrupted stream (Peng et al. 2001). These arc-like regions may be fragments of a ring, or a ~2 kpc thick torus, seen in a projection with an outer radius of ~8 kpc lying in a plane perpendicular to the radio jet. The inner boundary of the putative torus borders with dust and HI emission from cool material in the central region of the galaxy. The apparent gaps in the torus could be due to absorption of the soft X-ray by the cool gas and dust lying in front of the X-ray emitting gas.

The diffuse X-ray emission in the large-scale X-ray ring may be associated with the kpc-scale rolling torus structure in the central region of Cen A, suggested by Barker (1999) based on the kinematics studies of the material in the dust lane. The soft X-ray emission may be originating in a region of interaction (possibly a shock) between the infalling gas from a remnant of the spiral galaxy, a tidal-tail, with the material orbiting in the middle of the elliptical galaxy (including cool dust and HI emitting material). However, the apparent symmetry of the ring is hard to reconcile with the tidal origin. Moreover the alignment of the ring perpendicular to the radio jet suggests an origin related to the nucleus. Hence, another possibility is that the emission is a result of an interaction between a powerful equatorial outflow (or wind) from the nuclear region of Cen A, and the system of stellar shells or the galactic ISM. One could speculate that a giant eruption, resulting for example from transient nuclear activity, could have produced a galaxy-sized shock wave propagating in the plane perpendicular to the direction of the jet.

In a nuclear outburst scenario, we derive a mean velocity of the ejecta of ~ 600 km/s, by assuming that the X-ray energy in the torus is equal to the kinetic energy of the ejecta. In the case of uniform expansion, using a value of 8 kpc for the outer radius of the torus, we estimate that the outburst could have occurred ~10^7 years ago. This is consistent with the suggested young age of the stars in the optical arc (Peng et al. 2001), and with the estimated age of the current burst of star formation in the disk (~ 10^7 years; vis Israel, 1998). Based on the estimated energy in the ring, and the X-ray and bolometric luminosities of the nucleus (L_x \sim 10^{42} \text{ erg s}^{-1}, and L_{bol} \sim 10^{43} \text{ erg s}^{-1}, respectively; Israel, 1998; Elvis et al. 1994), the quasar would take \sim 3 \times 10^4 years to radiate the energy in the ring, a short time compared to the time elapsed since the outburst.

We note that X-ray arc-like structures have been detected in other mergers, including Fornax A (Mackie and Fabbiano 1998), and recently the elliptical galaxy NGC 4636 (Jones et al. 2002) who also relate them to outbursts of nuclear activity (Ciotti and Ostriker 1997). To determine the nature and the origin of the emission from the arcs in Cen A and in other similar galaxies, further multiwavelength observations are needed including higher signal to noise X-ray spectra, and detailed studies of the kinematics.
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Figure 1. Adaptively smoothed HRC-I image of the 16′x16′ region centered on the nucleus of Cen A. The pixel size is 4.2″ (32 times HRC-I pixel size of 0.13175″). North is up and East is to the left. The smoothed image shows simultaneously the high-angular resolution bright structures at scales as small as few arcseconds and extended faint structures as large as several arcminutes.
Figure 2. Cen A HRC-I X-ray image (dark blue) with superimposed the VLA 21 cm line HI gas emission (Schiminovich et al. 1994) (green contours). A white dashed line is a schematical outline of the optical arc-like shell we detected in the enhanced blue DSS images. North is up and East is to the left.
Figure 3. ACIS spectrum of the NW arc along with the best fitting thermal model (upper panel), and the residuals in $\sigma$ (lower panel).