RADIO AND X-RAY STRUCTURE OF CENTAURUS A

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Abstract. Recent studies of the nearby radio galaxy Centaurus A with the Very Large Array and the Einstein X-Ray Observatory reveal complex radio and X-ray structures. A prominent one-sided jet comprised of resolved knots located 0.2-6 kpc from the nucleus is seen in both radio and X-rays. The X-ray emission is probably synchrotron, requiring *in situ* reacceleration up to $\Gamma \simeq 10^7$. Inverse Compton emission is not a likely explanation though a thermal model in which the nucleus ejects dense $10^5 M_\odot$ clouds cannot be excluded. An elongated X-ray region is also found near the "middle" radio lobe and optical HII regions $\sim$ 30 kpc NE of the nucleus. Conditions around the active nucleus, the absence of X-rays from the inner radio lobes, and X-ray evidence for a hot interstellar medium are briefly discussed.

1. INTRODUCTION

Centaurus A = NGC5128 first came to the attention of modern astronomers when Sir John Herschel (1853) described it as "an elliptically-formed nebula...cut asunder...by a broad obscure band" and associated it with three similar nebulae (Andromeda, the Sombrero, and NGC4565). The following century witnessed little progress in understanding this unusual object: it was catalogued as the 10^m star CPD-42°6250 (Kapetyn and Gill 1897) and was even considered to be a planetary nebula (Evans 1949). Cen A grew in importance as astronomical studies expanded into non-optical frequencies. It was one of the first radio, X-ray, and γ-ray sources to be identified with an external galaxy, and is now known to be the closest example of an "active galaxy" characterized by a luminous non-thermal nucleus and ejected radio lobes. Its extreme proximity (about 5 Mpc) provides a welcome opportunity to investigate intrinsically faint and small structures associated with such nuclear activity.

I will summarize here results from recent high-resolution observations of Cen A performed with the NRAO Very Large Array (VLA) and the Einstein X-Ray Observatory. The X-ray findings presented in preliminary form by Schreier *et al*. (1979), are discussed in detail by Feigelson

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(1980) and Feigelson et al. (1981). The radio observations are described by Schreier, Burns, and Feigelson (1981) and Burns, Feigelson, and Schreier (in preparation). The following sections deal with several identifiable radio and X-ray structures of the galaxy: the nucleus, NE jet, inner radio lobes, "middle" NE lobe, and interstellar medium. I omit discussion of the X-ray component associated with the dust lane or disk, as we believe it to be of stellar origin. It should also be noted that a recent X-ray map of 15° x 15° around Cen A by Marshall and Clark (1981) demonstrates that, despite an earlier report to the contrary (Cooke et al. 1978), inverse Compton X-ray emission from the outer radio lobes has not been detected to date. The average magnetic field in the outer lobes must thus exceed 1.6 μG.

2. THE NUCLEUS

X-ray emission from the nucleus of Cen A has been extensively studied over the past decade. The principal contribution of Einstein observations is investigation of the gaseous environment immediately around the nucleus. There is considerable evidence that it is enshrouded in a cloud of gas and dust: the column density along the line of sight, deduced from the X-ray spectrum, is very high ($N_H = 1 \times 10^{23}$ cm^{-2}); an optical HII region coincident with the nucleus has been found (Gardner and Whiteoak 1976); and there is excess IR and millimeter emission from its vicinity that may be of thermal origin (see Mushotzky et al. 1978). Seven percent of the X-ray emission is expected to be electron scattered by this surrounding material (Fabian 1977). We have searched unsuccessfully for scattered or emitted soft X-radiation with the Einstein High Resolution Imager (HRI). The nuclear source itself has a radius <0.3" (1σ) or 8 pc, and less than a few percent of its flux ($<1 \times 10^{39}$ erg/s in the 0.5-4.5 keV band) is scattered between 2" and 8" from the nucleus.

The VLA maps show that the inner knots of the jet lie only 10"-20" from the nucleus. Their flux density exceeds that of the nucleus at frequencies below about 1 GHz. The jet thus accounts for the confusing radiation ∿7" in size reported by Wade et al. (1971) and the core-halo structure of the nucleus inferred by Slee and Sheridan (1975), and must have caused overestimation of the nuclear flux density in a number of earlier observations. A downward version of earlier low frequency data casts doubt on the existence of the two synchrotron components invoked by Grindlay (1975) to explain the nuclear X- and γ-ray flux by self-synchrotron Compton emission.

3. THE JET

The 1979 discovery of a jet of X-ray emission protruding from the nucleus (Schreier et al. 1979) was particularly surprising as a radio jet was not yet then known to exist. The first model for the X-ray jet assumed a thermal origin. Now that radio emission with structure very similar to that seen in X-rays has been found, nonthermal (in

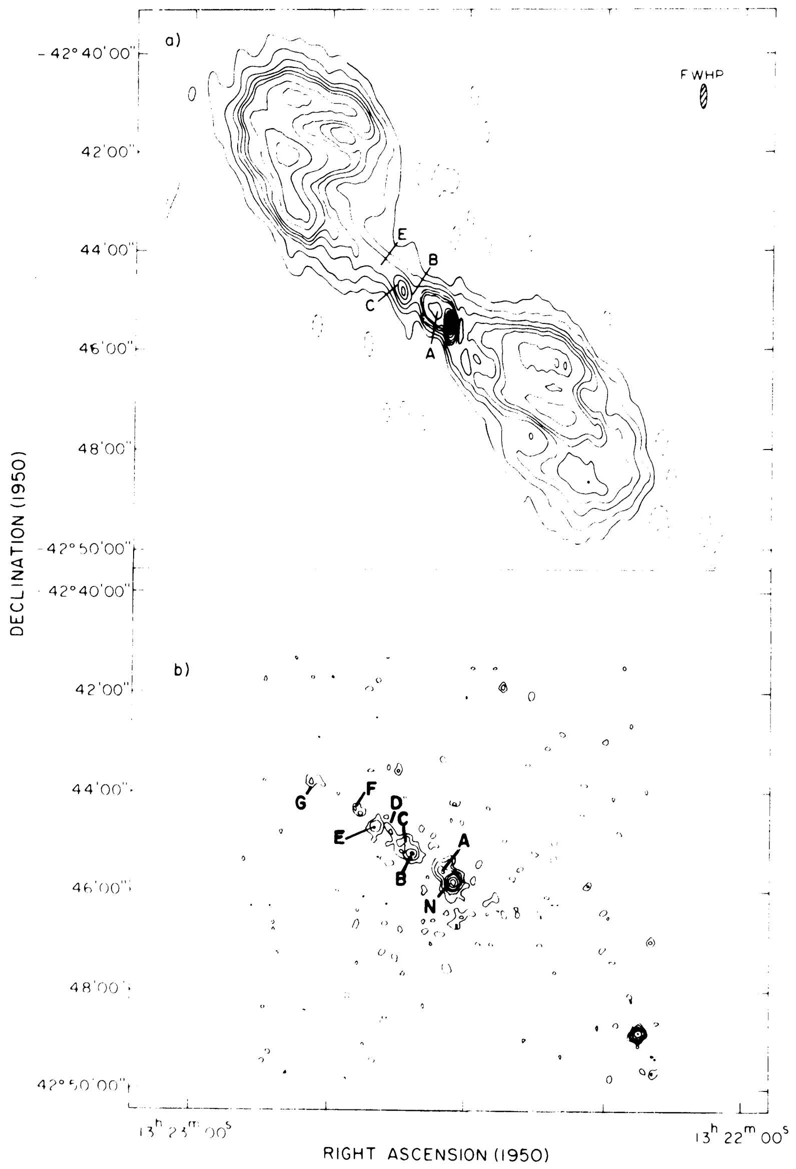

Figure 1. Upper panel: 20-cm radio map of the nucleus, jet, and inner lobes of Cen A. Observations made with the VLA C configuration, beam FWHM = 31" x 10" (Schreier, Burns, and Feigelson 1981). Positions of several X-ray knots are marked.

Lower panel: X-ray map of the same region showing the nucleus, string of jet knots, and (at lower right) foreground dMe star. Observations made with the Einstein Observatory HRI, beam FWHM = 3" (Feigelson et al. 1981).

particular, synchrotron) models seem more likely though the thermal model has not yet been disproved.

Figure 1 (lower panel) shows a contour map of the HRI X-ray image of the nuclear region. The X-ray jet consists of several spatially resolved emission regions (called "knots" here) distributed in a straight line along P.A. 53° between 8" and 4' from the nucleus. There is additional evidence for excess emission between 2" and 8". The bright unresolved X-ray source 4.7' from the nucleus opposite the jet coincides with a 13^m dM2e star and is not a counter-jet. The locations, sizes, and flux densities of the X-ray knots are given in Table 1. Their 0.5-4.5 keV luminosities are 0.5 - 2 x 10^{39} erg/s, comparable to the X-ray luminosity of our galaxy or M31. Each knot is resolved both along and perpendicular to the jet axis with diameters of 0.2'-0.3' (300-450 pc). Knot A is displaced 3" north of the principal jet axis, and has a bright elongated core about 6" long. Knot B, on the other hand, has a round center-filled appearance with FWHM = 12".

The C configuration VLA 20 cm map (Figure 1, upper panel) shows the brighter Knots A and B at levels of 2.3 Jy and 1.1 Jy respectively. The outer knots are not clearly evident, though they may be hidden in the ascending lobe emission. The radio spectral index of the knots appears to be similar to that of the lobe (∿ 0.7), though this is at present poorly determined. Figure 2 shows a preliminary map of the inner knots obtained with the VLA in the A configuration. Knot A is now resolved into 4 small, misaligned subknots while Knot B is large and without structure. The radio and X-ray morphologies are thus quite similar though some differences in detail may be present. Interpretation of Knot A is confused by possible absorption of X-rays (but not radio) in the dust lane.

TABLE 1

X-Ray and Radio Properties of Nucleus, Jet, and Inner Lobe

Feature	Distance, PA from Nucleus	Size	S_{2keV} (μJy)	S_{20cm} (Jy)	α^{2keV}_{20cm}
Nucleus	--	< .3"(1σ)	83 (var)	3.37	0.54
Jet Knot A	17", 38°	18" x 15"	0.1	2.26	0.86
Jet Knot B	57 , 55	20 x 18	0.1	1.11	0.83
Jet Knot C	75 , 53	12 x 12	0.05	∿0.75	
Jet Knot D	93 , 52	22 x 4	0.03		
Jet Knot E	113 , 54	12 x 12	0.05	∿0.53	
Jet Knot F	140 , 54	12 x 8	0.03		
Jet Knot G	208 , 55	12 x 8	0.03		
Inner Lobe	3'-6'	--	<0.06(3σ)	∿120	>1.09

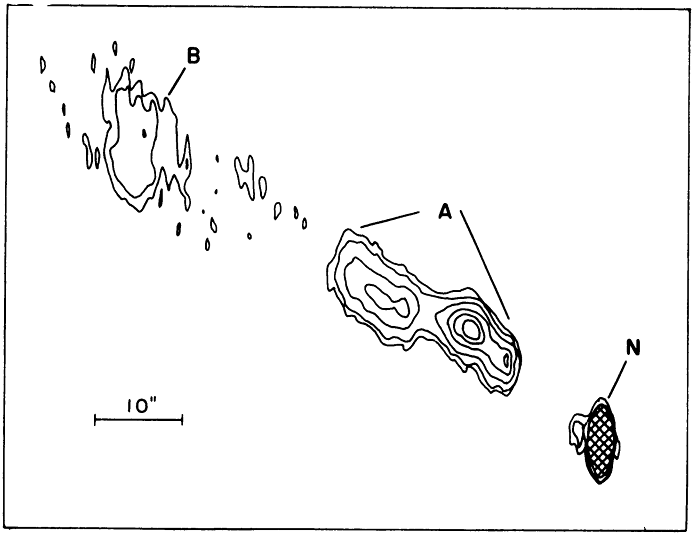

Figure 2. High resolution radio map made at 20 cm with the VLA A configuration showing the nucleus, Knot A, and Knot B. From Burns, Feigelson, and Schreier (in preparation).

The Cen A jet is of considerable interest purely by virtue of its radio properties. It appears to be narrowly collimated within 1 kpc of the nucleus, after which it expands laterally with an opening angle of about 22°. The bend within Knot A occurs on very small (0.1 kpc) spatial scales. But the paramount issue is to explain its X-ray emission. X-rays have now been detected in three radio jets (Feigelson 1980): Cen A, M87, and 3C273. There are three possible ways to produce the X-ray emission: thermal bremsstrahlung, inverse Compton, or synchrotron (Feigelson et al. 1981). In a thermal model, each knot of the Cen A jet is a $2 \times 10^5\ M_\odot$ cloud with a temperature of several $\times\ 10^7$K and density $0.2\ cm^{-3}$. The entire jet can be modeled by the ejection of such a cloud by the nucleus every 10^5 yr at a velocity between 2, and 10,000 km/s. The kinetic power of this "heavy" jet is 10^{43}-10^{44} erg/s, comparable to or exceeding the energy currently radiated by the nucleus. Within these constraints, the thermal model for the X-ray jet is possible. Faraday depolarization measurements, which will be forthcoming, may or may not indicate the presence of the required thermal densities. But such calculations depend on knowledge of the true magnetic field strength, and are thus always uncertain. The principal qualitative argument against the thermal model is that it does not explain the presence of the observed radio knots.

Inverse Compton explanations for the jet X-ray emission are not satisfactory without invoking exceptional conditions. Scattering of microwave background photons to the X-ray band implies a magnetic field of 0.2 μG for Knot B, far below the equipartition field of 30-40 μG. Inverse Compton scattering of starlight photons demands that the jet

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knots contain $\sim 10^{58}$ ergs in $\Gamma = 25$ electrons. This is 10^2 times the minimum energy of the inner lobe that is presumably the depository of all the energy in the jet.

Perhaps the most attractive model is that the X-ray jet, like the radio jet, is direct synchrotron emission. This accounts for the spatial coincidence and similar morphology of the X-ray and radio knots, and makes the Cen A jet closely analogous to the M87 jets where X-ray synchrotron emission is the only viable model (Schreier et al. 1981a). Both the Cen A and M87 jets have flat ($\alpha_r \sim 0.6$) radio spectra, and have a measured (M87) or inferred (Cen A) spectral break around the optical band to give $\alpha_r^x \sim 0.9$. Since X-ray emitting electrons would have radiative lifetimes of only 100 years, substantially shorter than the 1,000 - 20,000 LY travel time from the nucleus, reacceleration of particles within the knots would be necessary. Efficient acceleration up to the required $\Gamma = 10^7$ is not easily explained by Kelvin-Helmholtz induced turbulence or shocks, though resistance instabilities in a current-carrying jet may be feasible (Ferrari and Trussoni 1981). Direct confirmation for the synchrotron model would come from the detection of optical (or IR or UV), continuum knots coincident with the radio/X-ray knots.

4. THE INNER LOBES

The most striking finding regarding the inner lobes 3-5' NE and SW of the nucleus is that they are not seen in X-rays though they are 100 times more luminous than the jet in the radio. Whatever acceleration or thermal processes active in the jet knots are not present in the lobes. The first IPC images of Cen A showed excess X-ray emission 3'-5' NE and SW of the nucleus, which was interpreted by Schreier et al. (1979) to be inverse Compton emission from the inner radio lobes. Additional data revealed that the NE excess was due to jet and the SW excess to a foreground dMe star unfortunately located at the edge of the radio lobe. The current upper limit on inverse Compton emission requires $B > 3\ \mu G$, consistent with an equipartition field strength of $B = 34\ \mu G$ derived from radio data. Furthermore, the synchrotron spectrum of the lobes must have $\alpha_r^x > 1.1$, and each lobe must contain $<3 \times 10^6\ M_\odot$ in hot gas. It is interesting to note that amount of X-ray emission relative to radio emission decreases monotonically from $\alpha_r^x = 0.5$ in the nucleus to $\alpha_r^x = 0.9$ in the jet to $\alpha_r^x > 1.1$ in the lobe (see Table 1).

5. THE "MIDDLE" NE LOBE

Cen A is sometimes called a "double-double" radio source with an inner (4' NE/SW of the nucleus) and outer (3° N/S) pair of lobes. Additional radio structure is also present, however, including an enhancement at 25', P.A. 40° that we choose to call the "middle" NE lobe. Using beams of 7' FWHM, Cooper et al. (1965) report a flux density of 13 Jy at 1.4 GHz, $\alpha_r = 0.6$, and a half-power radius of 15' (23 kpc).

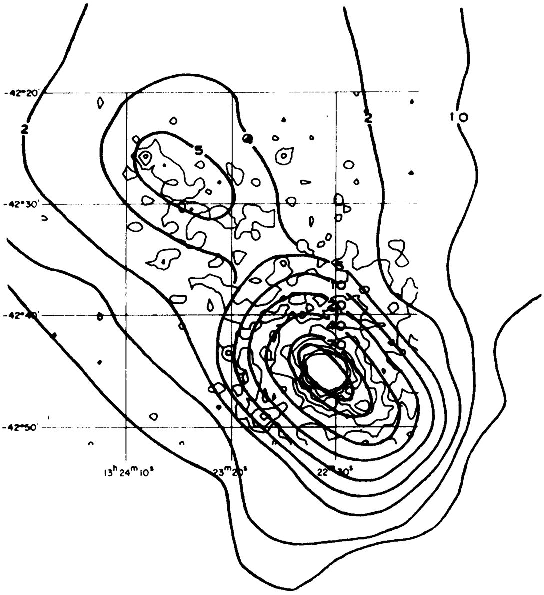

Figure 3. Superposition of Einstein IPC X-ray map (thin contours, from Feigelson et al. 1981) and 2.65 GHz radio map (thick contours, from Cooper et al. 1965) showing association between a faint X-ray feature and the middle radio lobe.

Its only notable property in the radio is the absence of a similar lobe to the SW. A line of X-ray emission about 5' long and 2' wide is detected 8σ above background in the Einstein Imaging Proportional Counter (IPC) coincident with the radio lobe (Figure 3). The feature has $L_X \simeq 1 \times 10^{39}$ erg/s and has an unusually soft X-ray spectrum, with almost all of the photons below 1.5 keV. Using standard assumptions, the observed emission is 30 times more luminous than expected from inverse Compton scattering of the microwave background. It could be direct X-ray synchrotron, as suggested for the X-ray jet above, with $\alpha_r^x = 1.1$. Both non-thermal explanations imply that the radio morphology is similar to that seen in X-rays. Radio maps with resolution $\lesssim 1'$ could determine if this is true.

The middle radio lobe is also accompanied by an unusual optical "jet" that makes a thermal model for X-ray emission more attractive than non-thermal models. A diffuse swath of HII regions, early-type stars, and shocked, turbulent gas (Graham and Price 1981) lies near the X-ray and radio structures. One can imagine that the ejected cloud of particles and magnetic field compressed and heated an ambient interstellar medium, giving rise to enhanced soft X-ray emission. The X-ray images provide independent evidence for a hot interstellar gas residing in the galaxy (see next section). The cooling time of the $\sim 10^6 M_\odot$ of 5×10^6K gas inferred from the X-ray data is short ($\lesssim 10^7$ yr), so it would soon condense into cold gas and young stars. Several radio galaxies have optical emission line regions near radio structures, though only Cen A is known to have associated X-ray emission as well.

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6. A HOT INTERSTELLAR MEDIUM?

Both the HRI and IPC images of Cen A give indications of a faint diffuse X-ray component extending several arc minutes about the nucleus. In the HRI, the background level around the nucleus is higher than elsewhere in the field, though this may be partly or entirely due to instrumental background variations. In the IPC, a real diffuse region of X-rays is seen 5'-10' N-NW of the nucleus. We are unable, however, to determine whether emission is also present in other directions due to the presence of the jet and several unrelated X-ray sources. If this diffuse component is really present, it has $L_x = 1\text{-}3 \times 10^{40}$ erg/s and could be produced either by the integrated emission of dM stars in NGC5128 or by a hot interstellar medium. In the latter case about 2×10^8 $M_\odot$ of gas at 1×10^7K would be present, exerting a hydrostatic pressure comparable to the equipartition pressure of the radio jet knots and the inner lobes. The Cen A jet thus might be confined by an external pressure.

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