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EINSTEIN OBSERVATIONS OF THE X-RAY STRUCTURE OF CENTAURUS A: EVIDENCE FOR THE RADIO-LOBE ENERGY SOURCE

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ABSTRACT

The X-ray source at the center of the radio galaxy Centaurus A has been resolved into the following components with the imaging detectors on board the *Einstein* X-ray Observatory: (1) a point source coincident with the infrared nucleus; (2) diffuse X-ray emission coinciding with the inner radio lobes; (3) a 4′ extended region of emission about the nucleus; and (4) an X-ray jet between the nucleus and the NE inner radio lobe. The 2×10^{39} ergs s^{-1} detected from the radio lobes probably arises from inverse Compton scattering of the microwave background. The average magnetic field in the SW lobe is determined to be ≥ 4 microgauss. The extended region may be due to emission by a cloud of hot gas, cosmic-ray scattering, or stellar sources. The jet provides strong evidence for the continuous resupply of energy to the lobes from the nucleus. A consistent model is presented for the X-ray jet, an optical jet, and the inner radio lobe.

Subject headings: galaxies: nuclei — radio sources: galaxies — X-rays: sources

I. INTRODUCTION

The structure of Centaurus A (NGC 5128) has been well studied at optical, radio, and, in less detail, X- and γ-ray wavelengths. The observed X-ray low-energy cutoff of greater than 3 keV implied that the X-rays were emitted at the nucleus of the galaxy (Tucker *et al.* 1973); the variability of the hard X-rays (e.g., Winkler and White 1975; Lawrence, Pye, and Elvis 1977) required a compact source. Thus the observed X-ray emission was consistent with a point source at the nucleus of the galaxy. An extended component to the hard X-ray emission has been reported from *SAS 3* data (Delvaille, Epstein, and Schnopper 1977). However, *HEAO 1* scanning modulation collimator data contradict this and are consistent with a point source above 2 keV, with a 99% confidence upper limit of 10^{41} ergs s^{-1} for the emission from an extended source (Doxsey *et al.* 1978). Further contributions of the X-ray observations to the theoretical interpretation of the source have been limited to comparisons of flux and variability at various wavelengths (see Grindlay 1975; Mushotzky *et al.* 1978; Beall *et al.* 1978).

We have now observed the central region of Cen A with the *Einstein* X-ray Observatory, using both the high-resolution imager (HRI) and the imaging proportional counter (IPC) as well as the monitor proportional counter (MPC). A description of the observatory can be found in Giacconi *et al.* (1979). The MPC (similar to *Uhuru* in area, spectral response, and field of view) shows an equivalent counting rate of 3.6×10^{-10} ergs cm^{-2} s^{-1}, 2–10 keV (15 UFU), and a power-law number spectrum with slope $n = 1.7$ and cutoff $E_a = 3.8$, consistent with published spectra (see Mushotzky *et al.* 1978). The imaging detectors show four distinct spatial components to the X-ray emission: a compact source at the nucleus, excess emission coincident with the inner radio lobes, an extended component with about 2′ radius centered on the nucleus, and a jetlike feature located 1′ to the NE of the nucleus. The compact nuclear source corresponds to the previously known variable hard X-ray source, and the possibility of inverse Compton X-ray emission in the inner radio lobes has long been recognized. The NE component, an X-ray jet or new inner lobe, represents a new phenomenon. We suggest that this feature provides evidence for a continuous supply of energy from the nucleus to the inner radio lobe.

II. OBSERVATIONS

The HRI was used to observe Cen A for a total of 13,200 s on 1979 January 15. The 25′ field containing some 36,400 photons was centered 10′ north of the nucleus as a result of an operational error, leading to a several arcsec degradation of the nominal 4″ resolution due to coma. An obvious strong source is centered 0″.7 from the infrared nucleus (Kunkel and Bradt 1971). The statistical uncertainty is 0″.5, and systematic aspect error is estimated to be less than 2″. In addition, the image shows a jetlike feature to the NE of the nucleus. An iso-intensity contour map of the field (Fig. 1) reveals the feature to be clumpy, with its principal component centered 59″ ± 2″ from the nucleus at a position angle 58° east of north. Other fainter components are seen 1′.5 from the nucleus in the same direction.

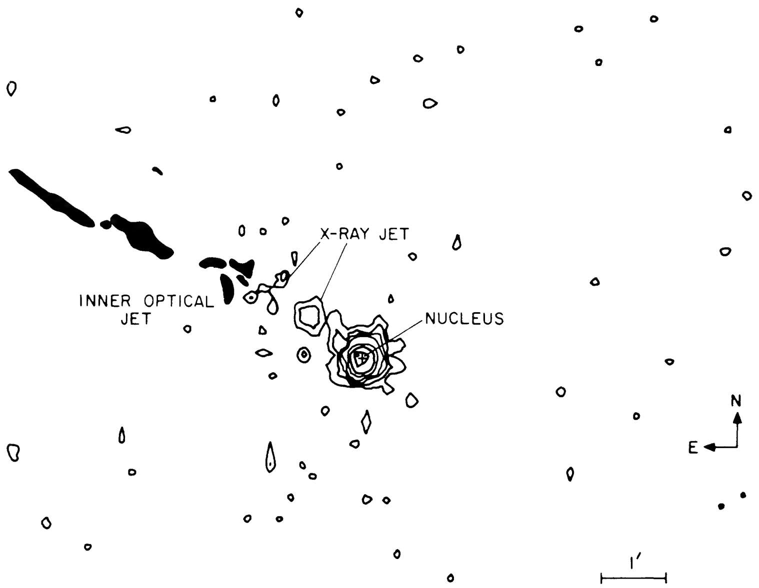

FIG. 1.—Iso-intensity contour map of the HRI image around the nucleus. The X-ray jet to the NE is clearly seen. The dark shapes to the NE show the positions of diffuse features in the optical jet discovered by Dufour and van den Bergh (1978).

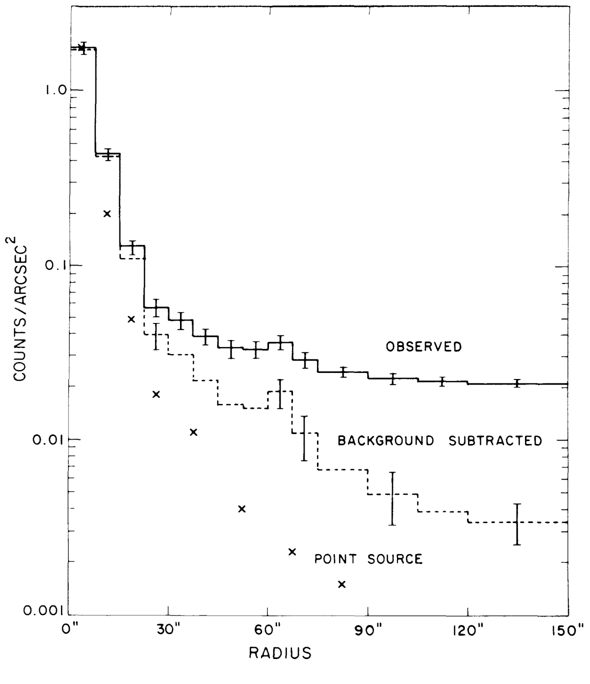

FIG. 2.—Radial distribution of surface brightness (HRI counts arcsec^{-2}), with and without subtraction of background. The X's show the radial distribution of a 3 keV calibration point source seen at the same distance off-axis as Cen A.

The radial surface-brightness distribution of the observed and background-subtracted HRI data is shown in Figure 2. There is emission in excess of the known point-source response, also shown, extended at least 2′ from the nucleus. The small bump at 1′ is the NE jet. We estimate the luminosity of the extended source by subtracting the predicted point-source contribution from the total flux; the calibration point response function (for an image 10′ off-axis) is normalized by folding the observed MPC flux through the telescope and HRI response functions. Assuming in this fashion that the point source dominates the hard, cutoff emission observed by the MPC, we predict a total flux in the HRI from the point source to be 0.04 ± 0.01 counts s^{-1}, within a 150″ radius. Subtracting this from the total (background-subtracted) flux, we find an excess of 0.04 ± 0.01 counts s^{-1} within a 150″ radius due to the extended component. The quoted errors are due to estimated uncertainty in the point-source spectrum and instrument response. Although this excess is sensitive to the local background level, which varies by about 5% over the field, we find a positive detection of the extended component at the 3.5 σ level even for the highest observed background level. Furthermore, if the extended source contributes to the MPC flux, we have overestimated the point-source contribution to the HRI; our extended source contribution is then a lower limit. The new northeast feature represents an excess flux of 0.0029 ± 0.0005 counts s^{-1}, about 10% of the extended emission or 4% of the total 0.3-3 keV emission.

The IPC data were accumulated on 1979 February 4 with an exposure of 13,100 s. The emission is dominated by the central point source with a counting rate of 1.9 counts s^{-1}. The 1′.5 resolution of the IPC is not adequate to distinguish the point, extended, and X-ray jet components seen in the HRI. However, the image appears elongated to the NE and SW and correlated with the inner radio lobes (Fig. 3 [Plate L10]). Figure 4 shows the azimuthal distribution of surface brightness in an annulus between 3′ and 5′ from the nucleus. Excess emission is seen in the directions corresponding

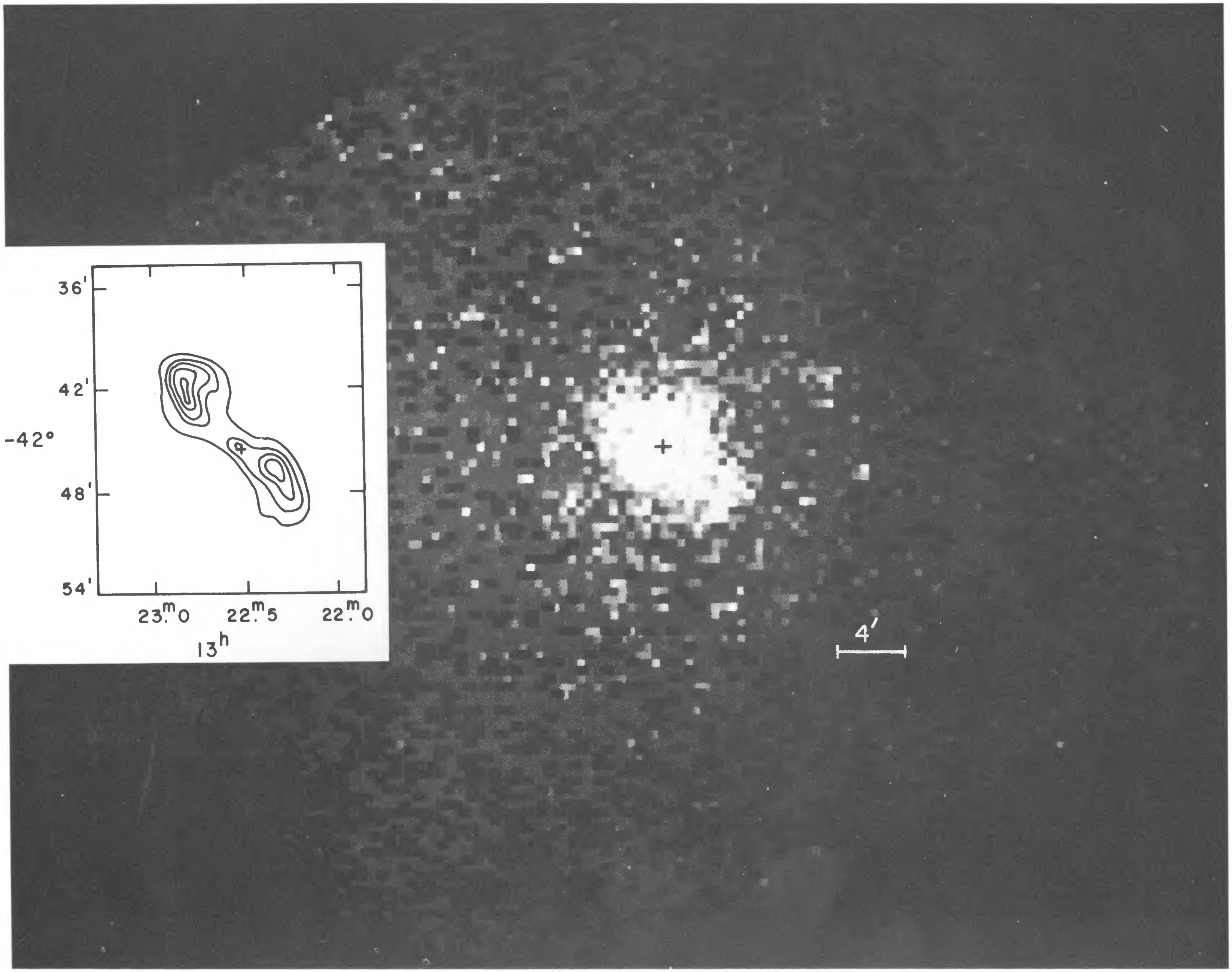

FIG. 3.—Imaging proportional counter (IPC) image of the central region of Cen A, showing the excess counts 3′–5′ SW of the nucleus. Radio contours of the inner radio lobes at 1.4 GHz from Christensen *et al.* (1976) are shown to the same scale as the X-ray image (inset).

SCHREIER *et al.* (*see* page L40)

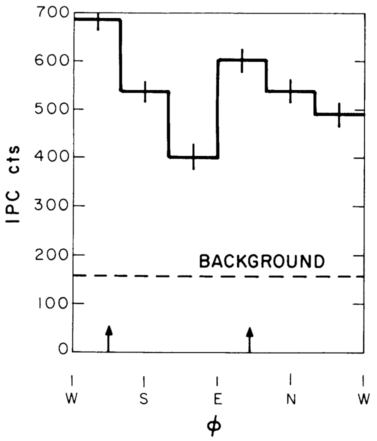

FIG. 4.—Azimuthal distribution of IPC counts in an annulus 3′–5′ from the nucleus. The arrows show the positions of the inner radio lobes.

to the inner lobes, as indicated by the arrows. A total of 0.00565 ± 0.00017 counts s^{-1} $arcmin^{-1}$ (source and background) is seen at those positions; the average for the entire annulus is 0.00464 ± 0.00007 counts s^{-1} $arcmin^{-1}$. This corresponds to a detection of the inner lobes at the 5.6 σ level. The excess emission associated with the lobes is approximately 0.026 counts s^{-1}, with the SW lobe being about twice as strong as the NE lobe. The extent of the SW X-ray lobe is at least 1′. The X-ray emission is centered 4′ from the nucleus, coincident with the 408 MHz radio centroid (Cameron 1969), but displaced $1'.5$ from the 1.4 GHz radio centroid (cf. Fig. 3).

Preliminary analysis of the IPC pulse-height analyzer (PHA) data was performed both for the central source out to 3′ and for the excess emission associated with the lobes. The data from the central source are consistent with the highly cut-off hard X-ray source and the MPC spectrum. The PHA data from the region of the inner lobes, using the remainder of the data in that annulus as background, are best fitted by a power-law number index $n = 1.0$, when a cutoff due to $N_H = 1.2 \times 10^{21}$ cm^{-2} of galactic absorption is imposed (Daltabuit and Meyer 1972). The statistical significance is not high and the data are consistent with the same number index ($n = 1.7$) as the point source.

III. DISCUSSION

a) The Nuclear Component

The central compact component is clearly identifiable with the hard, cut-off variable X-ray source. The HRI counting rate and the IPC spectrum are consistent with the detector responses to a source with the flux and spectrum seen with the MPC. If we use $n = 1.66$ and $E_a = 3.7$ keV (see Mushotzky *et al.* 1978), the observed flux corresponds to a luminosity of 1.0×10^{43} ergs s^{-1} in the 0.1–100 keV band. The intrinsic luminosity of the point source would be 1.7×10^{43} ergs s^{-1} in this band, with approximately 6×10^{42} ergs s^{-1} being absorbed near the nucleus. The intrinsic luminosity in a nominal HRI band of 0.3–3 keV is 2.8×10^{42} ergs s^{-1}; we supply this for comparison with the features discussed below, where we do not know the spectra and do not have independent higher energy measurements of the flux.

These luminosities, and all those following, apply if NGC 5128 is at a distance of 5 Mpc. This has been the most commonly assumed distance, dating from the work of Burbidge and Burbidge (1959), although certain assumptions in that work (such as $H_0 = 75$ km s^{-1} Mpc^{-1} and a galaxy luminosity function limit of $M_v = -22.5$) may no longer hold. However, recent work on dwarf irregular galaxies of the Centaurus group suggest a distance of 4–6 Mpc (Webster *et al.* 1979). In addition, considerations of H II region sizes, in conjunction with a review of other recent work, led Dufour *et al.* (1979) to suggest a distance of 6 ± 2 Mpc. We therefore use the classical value of 5 Mpc, and allow an uncertainty of a factor of 2 in luminosity.

b) The Inner Radio Lobes

The X-ray luminosity of the stronger SW lobe is 2×10^{39} ergs s^{-1} (0.3–3 keV), assuming a power law with $n = 1.7$ and galactic absorption. If we assume the observed X-ray emission is produced by inverse Compton scattering of the radio electrons off the microwave background, we can calculate the mean magnetic field of the lobe via the standard formalism (e.g., Tucker 1975). Using a radio spectrum $S_\nu = 1.9 \times 10^4 \nu_{\mathrm{MHz}}^{-0.73}$, which holds for $85 \leq \nu_{\mathrm{MHz}} \leq 1415$ (Christensen *et al.* 1976), and a microwave temperature $T = 2.7$ K, we derive a magnetic field strength $B = 4$ microgauss. This is 10–20 times lower than the estimated equipartition field strength. The field may be as low as 3 microgauss if the radio spectrum flattens at frequencies $\lesssim 20$ MHz (see Shain 1958). The field may be considerably stronger than our estimate if other mechanisms (e.g., inverse Compton scattering off starlight photons, or thermal bremsstrahlung from a hot plasma) contribute to the X-ray emission.

c) The Extended Component

Assuming a power-law spectrum with $n = 1.7$ and no intrinsic absorption, we calculate a luminosity of 2×10^{40} ergs s^{-1} (0.3–3 keV) for the extended component detected in the HRI image. This is 1% of the intrinsic point-source luminosity (most of which is not seen in this band due to strong absorption). Several interpretations of the extended component can be considered. (i) Electron scattering of the intrinsic point-source X-ray flux by a surrounding cloud (see Fabian 1977) appears unlikely. It would require a geometry where most of the cloud is illuminated directly by the point source; the high absorption we observe would then perhaps be due to an accretion disk aligned with the dust lane and obscuring our line of sight. However, the size of the observed emission region (~6 kpc) exceeds that of the dust lane and requires that the cloud be at X-ray emitting temperatures if pressure-supported. A cloud of the necessary density (~1 particle cm^{-3}) to provide the observed flux by scattering

1979ApJ...234L..39S

would emit more X-rays by bremsstrahlung than are observed. (ii) Thermal emission from $\sim 6 \times 10^8 M_\odot$ of hot gas in the potential well of the Cen A galaxy is a possibility by the preceding argument. (iii) The luminosity could be due to the integrated emission of discrete X-ray sources. The size of the region divided by the number of resolution elements gives a lower limit of about 300 for the number of discrete sources; the average source luminosity would be less than 10^{38} ergs s^{-1}. (iv) Another possible mechanism involves diffusion of the intrinsic cosmic-ray electrons out of the central source. These could then undergo inverse Compton scattering with starlight or the nuclear infrared emission. This might be consistent with the bridge of radio emission between the inner radio lobes (Berlin *et al.* 1975).

Further observations to better define the extent and spectrum of the extended component are intended to help interpret this emission.

d) The Inner Jet

The new feature observed 1′ to the NE of the nucleus of Centaurus A is most remarkable in the context of the radio and optical structure of the source. It is aligned with, but just within, the optical jet found by Dufour and van den Bergh (1978), shown superposed on the HRI contour map in Figure 1. This in turn is reasonably well aligned with the inner radio lobe and extends out to the Hα emitting filaments found by Blanco *et al.* (1975). The main component appears about 0.4 kpc (15″) in size; it has a greater X-ray surface brightness that the radio lobes, which are too diffuse to be apparent in the HRI image. The alignment argues against infalling or rotationally supported material. We believe that the feature provides evidence for the existence of a jet of matter from the nucleus, consistent with the need to power the inner radio lobes (see Blandford and Rees 1978).

Although one can consider various detailed models for the jet, the presence of X-ray emission near to the nucleus and optical emission farther out is suggestive of a thermal model. Using this as a working hypothesis, we assume that the power in such a jet must be at least equal to that required to replenish the inner lobe, $P \geq 5 \times 10^{40}$ ergs s^{-1}. Equating the power with the kinetic energy flux of a matter stream, we calculate a mass transfer rate

$$\dot{M} = 10^{26} v_8^{-2} P_{41.7}\, \epsilon_{0.1}^{-1}\ \mathrm{g\ s^{-1}}\,,$$

where $v_8 = v/10^8$ cm s^{-1}, $P_{41.7} = P/5 \times 10^{41}$ ergs s^{-1}, and an efficiency $\epsilon_{0.1} = \epsilon/0.1$ has been assumed for the conversion of kinetic energy in the jet into relativistic particles at the radio lobe. Continuity arguments can be used to calculate the particle density in a conical jet at a distance r (kpc) from the source:

$$n = \frac{\dot{M}}{m_{\mathrm{H}} v \pi (r\theta/2)^2} = 1.3 P_{41.7} v_8^{-3} r^{-2} \theta^{-2}_{0.25}\, \epsilon_{0.1}^{-1}\ \mathrm{cm^{-3}}\,,$$

where $\theta_{0.25}$ is the opening angle in units of 0.25 rad, the estimated angle subtended by the X-ray jet at the nucleus (15″ at a distance of 60″). Assuming that the X-rays are due to thermal bremsstrahlung, the luminosity of the jet between radii of 1 and 2 kpc (the approximate jet extent) is

$$L_x \approx 10^{-27} \int_{r=1}^{r=2} n^2 \pi r^2 \theta^2 T^{1/2} dr$$

$$= 4 \times 10^{39} T_7^{1/2} P^2_{41.7} v_8^{-6} \theta^{-2}_{0.25}\, \epsilon_{0.1}^{-2}\ \mathrm{ergs\ s^{-1}}\,.$$

If we assume a temperature of 10^7 K, and galactic absorption, we convert the observed flux of 0.0029 counts s^{-1} (0.3–3 keV) to a luminosity of $\sim 3 \times 10^{39}$ ergs s^{-1} (0.3–3 keV), in good agreement with the above expression. Line emission may be important if $T_7 \sim 1$.

The strongest dependence of the luminosity expression is on the flow velocity. Velocities of about 10^8 cm s^{-1} have been inferred from the structure and dynamics of the jet in 3C 31 (Blandford and Icke 1978) and from depolarization measurements of 3C 449 (Perley, Willis, and Scott 1979). We can also estimate the flow velocity from the opening angle

$$v = c\theta^{-1}\,,$$

$$v_8 = 1.2 T_7^{1/2} \theta^{-1}_{0.25}\,,$$

where c is the sound speed in the gas. These direct and indirect estimates suggest that $v_8 \approx 1$, lending support to this origin for the X-ray emission in the jet.

The cooling time for matter in the jet, due to bremsstrahlung radiation, is

$$t_c = \frac{2 \times 10^{11} T^{1/2}}{n}$$

$$= 4 \times 10^7 T_7^{1/2} P^{-1}_{41.7} v_8^3 r^2 \theta^2_{0.25}\, \epsilon_{0.1}\ \mathrm{yr}\,.$$

Additional cooling due to line emission and/or inhomogeneities in the stream may decrease the cooling time by an order of magnitude, leading to cooling-time estimates as low as 10^6 years. This should be compared with the flow time of matter from the nucleus to the jet $t_f = r/v = 10^6 r_{\mathrm{kpc}} v_8^{-1}$ yr. Thus the possibility of thermal instability exists, suggesting that the inner optical jet is due to emission from matter in the stream which has cooled and is moving ballistically outward ($\sim 10^6 M_\odot/10^6$ years). This interpretation is consistent with optical observations (Dufour and van den Bergh 1978; Graham 1979; Osmer 1978). The stream would have to avoid cooling too soon (radii less than 1 kpc), which might imply greater velocities in the stream closer to the nucleus. It should be noted that most of the energy in the above model for the jet resides in a dense subrelativistic plasma. A mechanism for reacceleration of electrons is required to provide for synchrotron emission in the lobe. The above cooling time scales indicate that little X-ray emission is produced within the lobes by bremsstrahlung. A higher and possibly variable stream velocity may lead to shocks and X-ray emission as suggested for the M87 jet (Rees 1978; Blandford and Königl 1979), but our observations are consistent with much of the energy being fed into the northern inner radio lobe via a dense subrelativistic plasma. The lack of an observed jet to the south may be due to a factor ~2 higher velocity, or to an intrinsic variability in the jet production mechanism.

IV. CONCLUSIONS

The images of the central region of Centaurus A have resolved the X-ray structure into four components: the hard, cut-off point source; extended emission coincident with the inner radio lobes; a several kpc region of emission surrounding the nucleus; and a jetlike structure located between the nucleus and an inner radio lobe. The clear alignment of the NE X-ray, optical, and radio features argues in favor of continuous or repetitive ejection of material from the nucleus. In addition, the self-consistent calculation in which hot gas emits X-rays and then cools to emit visible light provides a physically plausible model. A better understanding of the features of this nearby giant radio galaxy will be important for the interpretation of emission from more distant radio galaxies and active galactic nuclei.

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Note added in proof.—It should be noted that the positions of the optical features listed in Table 2 of Dufour and van den Bergh (1978) differ from those in their Figure 3 by a factor of ~2. We have used those in the table. There would be no significant effect on our conclusions if we used the figure directly.

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