THE ASTROPHYSICAL JOURNAL, **266**:L93–L96, 1983 March 15

VLBI OBSERVATIONS OF THE NUCLEUS OF CENTAURUS A

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Received 1982 June 14; accepted 1982 November 24

ABSTRACT

VLBI observations of the nucleus of Centaurus A have been made at 2.3 GHz on baselines with minimum fringe spacings of 0".15 and 0".0027. The nuclear component is found to be elongated with a maximum extent of ~ 0".05 which is equivalent to a size of ~ 1 pc at the 5 Mpc distance of Centaurus A. The position angle of the nucleus is 30° ± 20°, a value that is roughly consistent with the orientations of the inner radio double lobes and the radio, X-ray, and optical jets. The ratio of nuclear jet length to width is $\lesssim$ 20. The nuclear flux density was found to be 6.8 Jy, which is almost 3 times that of a decade ago. No core component was found with an extent $\lesssim$ 0".001 ($\lesssim$ 0.02 pc) with a flux density of $\gtrsim$ 20 mJy. Our data in combination with earlier VLBI and spectral data lead to a model of the Centaurus A nucleus composed of at least two components: (1) an elongated source of ~ 0".05 (~ 1 pc) size which contains most of the 2.3 GHz nuclear flux, and (2) a source of ~ 0".0005 (~ 0.01 pc) size which is nearly completely self-absorbed at 2.3 GHz but strengthens at higher frequencies.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: structure — interferometry — radio sources: galaxies

I. INTRODUCTION

Centaurus A (NGC 5128) is the nearest (~ 5 Mpc) giant radio galaxy. Optically, it is one of the most luminous galaxies known (Graham 1979); however, it has only a relatively small radio luminosity (Kellermann *et al.* 1975) compared with other radio galaxies. The peculiar optical structure of Centaurus A, an E0 galaxy whose main body is crossed by a striking equatorial dust band, was first noted by Herschel (1847).

The known radio structure of Centaurus A has three prominent features. (1) A large double structure is centered on the optical galaxy with a position angle of ~ 0° (Wade 1959; Bolton and Clark 1960). These components extend over ~ 10°, or equivalently ~ 900 kpc. (2) A smaller double structure is also centered on the optical galaxy with a position angle of ~ 50°, which is nearly perpendicular to the optical dust lane (Cooper, Price, and Cole 1965; Christiansen *et al.* 1977). The component separation is ~ 7' (~ 10 kpc), which is comparable in size to the optical galaxy. (3) An extremely small nucleus is positioned in the center of the optical galaxy. Wade *et al.* (1971) determined the size of the radio nucleus to be $\lesssim$ 0".5 (~ 10 pc), and VLBI nuclear structure has been detected at the 5×10^{-4} arcsec (~ 10^{-2} pc) level (Jauncey *et al.* 1983). Infrared, X-ray, and γ-ray emissions have also been detected from the nucleus (Grindlay 1975). Significant variations in the nuclear radio and X-ray flux have been observed (Beall *et al.* 1978). Optical and X-ray jets have been detected within a few arc minutes of the nucleus and are aligned with the nucleus with a principal axis that roughly matches (P.A. ~ 60°) the inner double radio structure (Blanco *et al.* 1975; Dufour and van den Bergh 1978; Schreier *et al.* 1979). Recent VLA maps at 20 and 6 cm (Schreier, Burns, and Feigelson 1981) also show an inner radio jet extending inward to within a few arc seconds of the nucleus, with a strong correlation between radio and X-ray hot spots.

Since Centaurus A is the nearest active galaxy, its physical processes can be studied in greater linear detail than other similar galaxies. Previous VLBI investigations have attempted to uncover the radio fine structure of the nucleus but have been hampered by the southerly declination of Centaurus A (−43°) and the sparsity of VLBI capability in the southern hemisphere, leading to only scattered single-point (u, v) coverage. In this *Letter*, we report on VLBI observations of the nucleus of Centaurus A from three southern hemisphere observatory sites, thus providing more extensive (u, v) coverage than previously available.

II. OBSERVATIONS AND DATA REDUCTION

The VLBI observations of Centaurus A were performed at 2.3 GHz on 1980 April 22–27. Participating observatories were located at Tidbinbilla and Parkes in Australia and Hartebeesthoek in South Africa. Observations at Tidbinbilla were made at either the 64 m antenna (DSS 43) or the 34 m antenna (DSS 42), both of which achieved ~ 20 K system temperatures with traveling wave maser amplifiers. The 64 m antenna at Parkes was outfitted with a parametric amplifier to obtain a system temperature of ~ 110 K. At Hartebeesthoek, the 26 m antenna utilized a maser receiver yielding a system temperature of ~ 35 K. All observations were made with right circular polarization. A hydrogen maser frequency standard was used at Tidbinbilla, and rubidium standards were used at the other two sites.

The short baseline (Tidbinbilla to Parkes) provided a baseline length of 275 km (2.1×10^6 λ) with fringe spacings ranging from 0″15 to 0″35. The long baseline (Australia to South Africa) provided a baseline length of 9700 km (74×10^6 λ) with a nearly constant fringe spacing of ~ 0″003. Two complete (u, v) tracks (Fig. 1) were obtained for both the short and long baselines. In general, 10 minute VLBI observations were made at average intervals of 45 minutes. Although no useful flux density measurements of the nucleus were made at the time of the main observing session, the 2.3 GHz nuclear flux density was determined to be 6.8 Jy in 1981 April by a separate VLBI measurement on a 25 km baseline at Goldstone, California (~ 0″5 resolution).

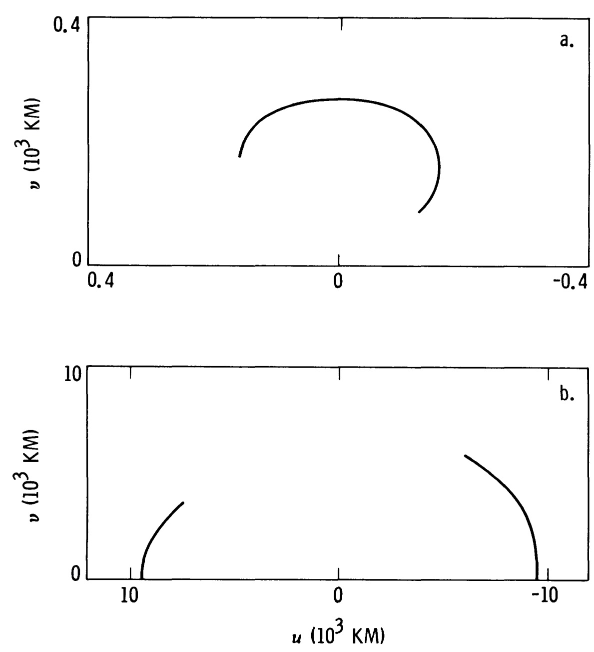

FIG. 1.—The (u, v)-plane coverage is shown for: (a) Tidbinbilla/Parkes; (b) Tidbinbilla/Hartebeesthoek.

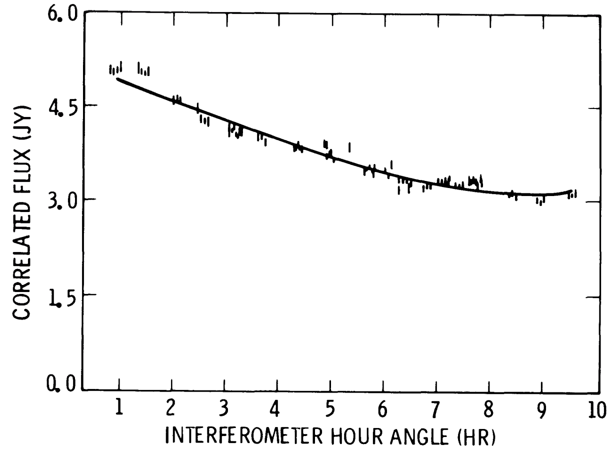

FIG. 2.—Correlated flux density on Parkes/Tidbinbilla baseline as a function of interferometer hour angle. Solid line indicates the best fit elliptical Gaussian model.

A 1.8 MHz bandwidth was digitally sampled with the Mark II VLBI recording system (Clark 1973). Correlation coefficients were obtained from the VLBI data by use of the Caltech/JPL Mark II correlator and postprocessing programs. Correlated flux densities were calculated by multiplying each correlation coefficient by a constant b ($b = 2.6 \pm 0.2$, Niell 1980), by the geometric mean of the antenna sensitivities (Jy/K), and by the geometric mean of the system temperatures. The 5 σ VLBI detection limits were about 20–40 mJy for each 10 minute observation on both the long and short baselines. Correspondingly, the random uncertainty in each measured correlated flux density was about 4–8 mJy. However, uncertainties in values of correlated flux density were dominated by calibration errors at the 10% level.

III. RESULTS

Figure 2 shows the measured correlated flux density as a function of interferometer hour angle on the Tidbinbilla-Parkes baseline. These data were fitted by an elliptical Gaussian model (see solid line in Fig. 2), the most complex model justified by the data. The best fit elliptical Gaussian model has a major axis (FWHM) of 0″05 ± 0″01 (~ 1.2 pc). The minor axis has a maximum value of 0″03 ± 0″01 (~ 0.8 pc) but could be much smaller. The position angle along which the nucleus is elongated is 30° ± 20°. In the fitting process, the total flux density of the elliptical nuclear component was assumed to be within 1 Jy of the value measured 1 year after the VLBI observations (not an unreasonable assumption since the source appears to be ~ 3 light-years in extent). The uncertainties in the parameter values are derived by searching for the extreme values of the parameters which provide a model that is consistent with the data within the estimated data errors.

On the Australia–South Africa baseline, the nucleus was completely resolved, indicating there is no 2.3 GHz nuclear source $\lesssim 0''.001$ ($\lesssim 0.02$ pc) with a flux density $\gtrsim 20$ mJy.

IV. DISCUSSION

Nuclear jets of 1 pc in length seem to be common in radio galaxies where the radio emission is largely from regions a few arc seconds to several degrees in size, symmetrically located about the associated optical object, with a weak compact nuclear radio source associated with the optical object (e.g., Cohen and Readhead 1979; Linfield 1981). Centaurus A falls in this category as does another nearby radio galaxy, Virgo A, which has been shown to possess a 1 pc nuclear jet at 2.3 GHz (Cotton, Shapiro, and Wittels 1981).

The major axis of the measured elliptical shape of the Centaurus A nuclear component is aligned within the estimated errors with the radio, optical, and X-ray jets and the inner double radio structure, which are all aligned at nearly the same position angle. Hence, the elongated VLBI nucleus is probably the interior reaches of the jet that formed these more extended structures. The size of the nuclear jet is a factor of $\sim 10^4$ smaller than the maximum extent of the aligned structure. The outer radio lobes of Centaurus A are not aligned with the interior structure, which suggests that the position angle of the nuclear jet changes with time or that the jet path bends with increasing distance from the nucleus.

The radio, optical, and X-ray jets outside the nucleus are one-sided pointing to the northeast, but our data do not allow us to determine if the nuclear jet is one-sided or two-sided. The double-sided nature of the inner radio lobes does provide evidence that material has been ejected from the nucleus in both a northeast and southwest direction, although perhaps not simultaneously. The observation of only a one-sided jet does not necessarily imply that the opposing jet is not simultaneously present, since the brightness of a jet may be strongly influenced by relativistic effects if the jet is aligned with the observer, or by an asymmetric galactic environment (Cohen and Readhead 1979).

We note that our measured value of nuclear flux at 2.3 GHz is almost 3 times larger than the 2.7 GHz value of 2.4 Jy measured a decade earlier by Wade *et al.* (1971). This indicates that the core has been active in the recent past.

The failure to detect the nuclear jet on the Australia to South Africa baseline allows limits to be placed on the nuclear jet's width, since the projected baseline was at one point approximately orthogonal to the nuclear jet direction. The jet width probably exceeds 2 milli-arcsec ($\gtrsim 0.05$ pc), making the ratio of jet length to width $\lesssim 20$ and the jet opening angle $\gtrsim 3°$.

As noted by Backer (1978), VLBI observations of the Centaurus A nucleus might measure an angular size larger than the intrinsic angular size as a result of interstellar scattering within Centaurus A itself. However, to be affected by this at the milli-arcsecond level at 2.3 GHz, the scattering would have to be somewhat worse than looking toward our own galactic center. The scattered size of the galactic center source at 2.3 GHz (Backer 1978) corresponds to an apparent size of $\sim 0''.0004$ at the distance of Centaurus A.

No attempt has yet been made to create VLBI images of the nucleus at higher frequencies, but limited VLBI studies at 8 GHz have determined that nuclear structure exists at the ~ 0.1 pc level (Kellermann *et al.* 1975) with at least one component ~ 0.01 pc in extent (Jauncey *et al.* 1983). Since this 0.01 pc nuclear structure at 8 GHz had an estimated flux density of ~ 0.5 Jy, this component must be highly self-absorbed at 2.3 GHz or have significantly decreased in strength to explain our nondetection of structure at the 0.02 pc level. If self-absorption alone is the reason for our nondetection, the spectral index of this component between 2.3 and 8 GHz must be $\geqslant 2.5$ ($S \equiv kf^{\alpha}$). The hypothesis that the 8 GHz structure is highly self-absorbed at 2.3 GHz is consistent with the 3–100 GHz spectral information (Kellermann 1974) which indicates the presence of a very small (~ 0.01 pc), highly self-absorbed source.

Hence, we propose a model for the nucleus of Centaurus A which has at least two components: (1) a 1 pc long jet which dominates the flux at 2.3 GHz, and (2) a component with a size of ~ 0.01 pc which is detected at 8 GHz but is highly self-absorbed and contributes negligible flux at 2.3 GHz. Evidence also exists for structure at the 0.1 pc level. We note that Grindlay (1975) proposed a two-component model of the nucleus based on radio through gamma-ray spectral data alone, but the proposed component diameters were $0''.0004$ and $0''.0009$.

Southern hemisphere VLBI investigations of greater complexity are necessary if we are to understand completely the nuclear radio structure of Centaurus A and, hence, gain insight into the physical processes in active galactic cores at small linear size scales. From the example of Centaurus A, we see that activity in a region as small as 0.01 pc probably has strong influence on the origin, evolution, and energetics of galactic structural components up to a factor of 10^8 larger.

We gratefully acknowledge the assistance of Lyle Skjerve of JPL and the staffs of the Tidbinbilla, Parkes, and Hartebeesthoek telescopes. This research was supported in part by NASA contract NAS 7-100.

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