*Aust. J. Phys.*, 1994, **47**, 619–24

# Centaurus A,
# The Core of the Problem*

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*Abstract*

The bright, peculiar elliptical galaxy Centaurus A (NGC 5128, PKS 1322−427) was one of the first extragalactic radio sources to be optically identified (Bolton *et al.* 1949). At a distance of 4 Mpc, Centaurus A is the closest active radio galaxy and affords the highest linear imaging resolution (1 mas $\approx 0\cdot 02$ pc) and hence the best prospects for studying an active nucleus close to the central radio source. We present the results of multi-epoch, 8·4-GHz, very long baseline interferometry (VLBI), imaging observations of the nucleus made over the past three years. The nucleus possesses a core–jet structure where the inner portion of the jet shows apparent linear motion with a velocity substantially less than the speed of light.

## 1. Introduction

The first optical identification of the three discrete radio sources Centaurus A, Virgo A and Taurus A, by Bolton, Stanley and Slee (1949), was a major step forward in elucidating the properties of the radio source populations. It is difficult to overestimate the importance of these original identifications, as all three objects remain at the centre of current research in astronomy. In particular the dust-lane galaxy Centaurus A has been imaged over virtually the entire energy spectrum, from decametre wavelengths ($\sim$10–46 eV, Shain 1958) to PeV ($\sim 10^{15}$ eV) cosmic ray energies (Clay *et al.* 1994).

To obtain the necessary high angular resolution to measure radio positions of sufficient precision and so to make reliable optical identifications, Bolton *et al.* set up aerials, in Australia and in New Zealand, on high cliffs overlooking

* Refereed paper based on a contribution to the John G. Bolton Memorial Symposium held at the Parkes Observatory, 9–10 December 1993.

0004-9506/94/050619$05.00

the sea, to time the rising and setting of the sources (see Orchiston, this issue p. 000). Since that time, investigators of the compact nuclear core of Centaurus A have built their interferometers to stretch across Australia and on to China, Japan, South Africa and the United States. Future interferometers will probably extend not only across the Earth but also into space.

At a distance of 4 Mpc (Harris *et al.* 1984) Centaurus A is a complex radio source covering an area of about $5°\times10°$ on the sky (Cooper *et al.* 1965). The radio source has been imaged with arcminute resolution at Parkes, and is a highly polarised FR I double-lobed source with structure extending up to 350 kpc from the nucleus at a position angle of 0° (Junkes *et al.* 1993). On kpc scales, a double-lobed source lies at a position angle of 51°, roughly perpendicular to the dust lane which bisects the elliptical galaxy. A flat-spectrum nucleus has been found between these two lobes (Christiansen *et al.* 1977) with a one-sided radio jet emerging from it in a north-easterly direction (Burns *et al.* 1983). The core and the jet have been detected at X-ray and infrared wavelengths (Burns *et al.* 1983; Joy *et al.* 1991).

We have been studying the nucleus with VLBI at 2·3 GHz on 0·2 to 2·0 pc scales and find a one-sided jet at the same 51° position angle and direction as the larger scale jet (Meier *et al.* 1989, 1993). Changes in total flux density were found but no significant changes in structure were detected over an eight-year period from 1980 to 1988 (Meier *et al.* 1989). We changed our observing strategy in 1990 to concentrate on higher resolution VLBI imaging observations at 8·4 GHz, given that the nucleus possesses a strong and variable inverted-spectrum radio core (Kellermann 1974; Botti and Abraham 1994).

## 2. The 8·4-GHz VLBI Observations

Our 8·4-GHz SHEVE (Southern Hemisphere VLBI Experiment) imaging observations used the Australia Telescope National Facility telescopes at Culgoora (22 m) near Narrabri, Mopra (22 m) near Coonabarabran, and Parkes (64 m), New South Wales, together with the 26-m antenna of the University of Tasmania's Mt Pleasant Observatory near Hobart, the 34 and 70 m antennas of the NASA Deep Space Network at Tidbinbilla, near Canberra, the 15-m antenna of the European Space Agency at Gnangara near Perth and the 26-m telescope of the Hartebeesthoek Radio Astronomy Observatory in South Africa. All observations were made in right-hand circular polarisation with a 1·8-MHz recorded bandwidth using the MkII recording system (Clark 1973), and correlated on the California Institute of Technology/Jet Propulsion Laboratory processor in Pasadena, California. A more complete description of the SHEVE array and data analysis procedures was given by Preston *et al.* (1989, 1993). Fig. 1 shows the typical $u$–$v$ coverage for Centaurus A using the eastern Australian antennas at Culgoora, Mopra, Parkes, Tidbinbilla and Hobart.

The eastern Australian SHEVE array at 8·4 GHz synthesises a $3\times7$ mas beam, and successful imaging observations of Centaurus A were undertaken at 1991·17, 1991·90 and 1992·24; the resulting three images are shown in Fig. 2.

## 3. Structure and Evolution of the Nuclear Source

Each of the images in Fig. 2 shows a strong core at the base of the elongated jet. The actual position angle on the sky of the jet is 51°, the same as that

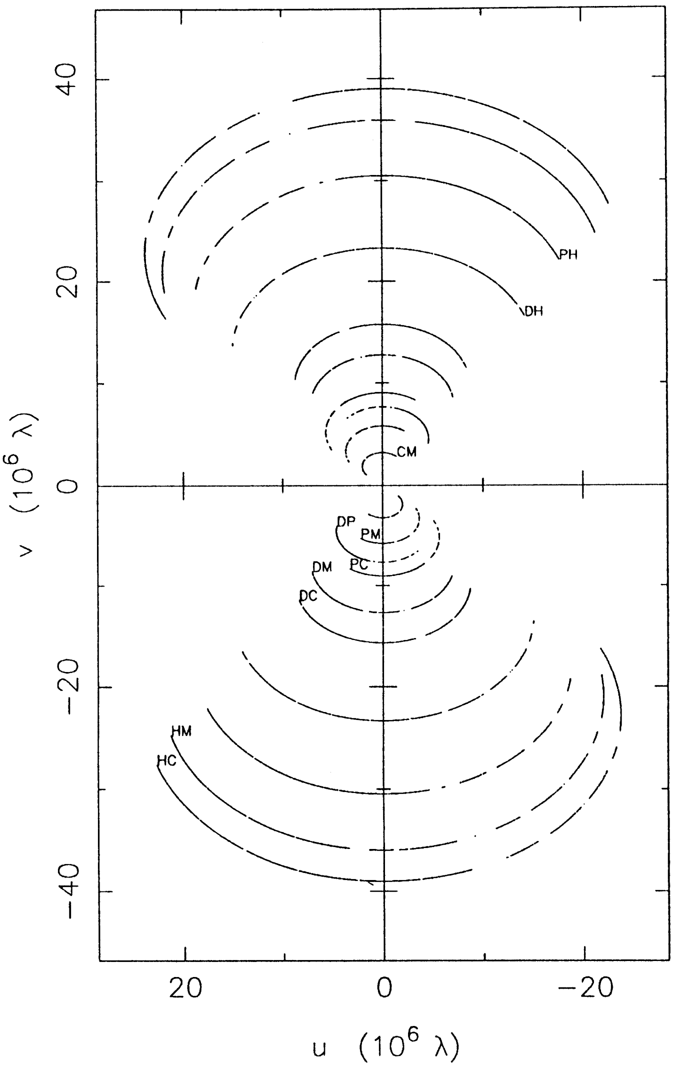


**Fig. 1.** The u–v coverage for Centaurus A using the eastern Australian antennas at Culgoora, Mopra, Parkes, Tidbinbilla and Hobart.

found at $2\cdot3$ GHz in the 1982 observations (Meier *et al.* 1989). There is also a second component that appears to be stationary about 15 mas from the core. This component is clearly present in all three images but is significantly weaker in the $1991\cdot90$ image. In addition, the core appears to have expanded slightly along the jet direction over the $1\cdot07$ years spanning the three images, and has decreased in peak flux density from $3\cdot6$ to $2\cdot5$ Jy beam$^{-1}$.

The apparent shortness of the jet in the $1991\cdot17$ image is not real, as it results from a lack of short baselines and poorer *u–v* coverage which affects only the largest scale structure in the $1991\cdot17$ image.

To quantify the structural changes, we have modelled the observations at each epoch with basic elliptical Gaussian components, a smooth jet (C4) on which are

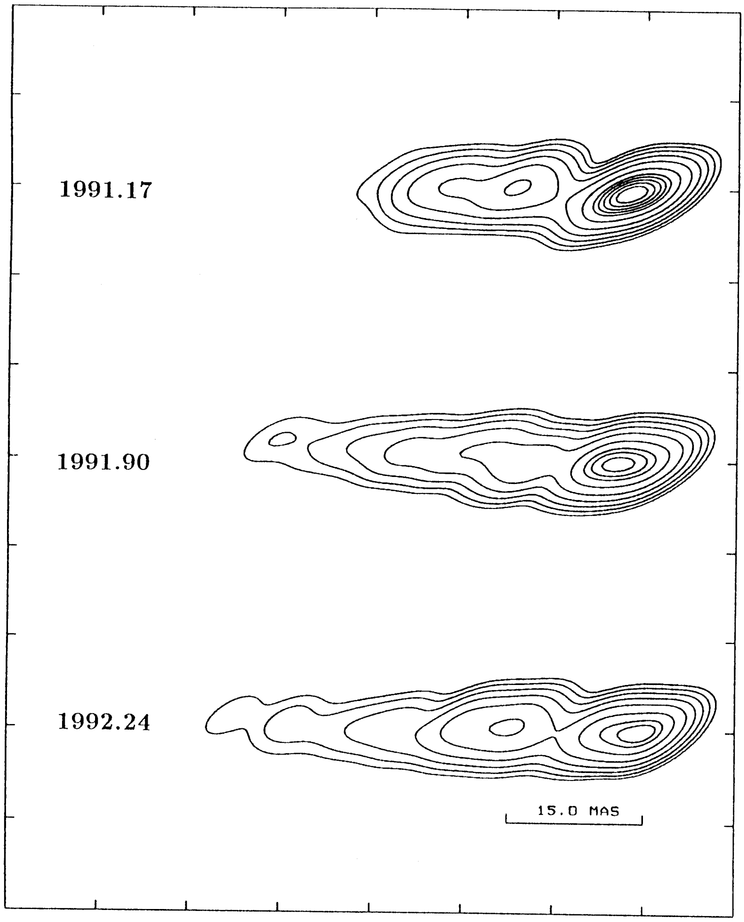


**Fig. 2.** Images of Centaurus A at three epochs, 1991·17, 1991·90 and 1992·24. All images were produced using DIFMAP in the CALTECH VLBI package and are arranged to place the earliest at the top of the figure. The three images have been rotated anticlockwise by 39°. Contours are 1, 2, 4, 8, 16, 32, 50, 60, 70, 80 and 90% of the peak flux density of 3·6 Jy beam$^{-1}$. The beam has major and minor axes of 7 and 3 mas at a position angle of 121°.

superimposed, near one end, a bright core (C1) plus an extended component (C3) ~15 mas away, and a further component close to the core (C2). Our modelled results indicate that component C2 has moved away from the core along the jet and has changed its position by 1·3 mas over the 1·07 years of these observations.

It is important to establish limits on the allowable change in position of component C2. To do this, we stepped the position of C2 out from the core and re-fitted the data at each new position of C2, allowing the other modelled parameters to vary. By visually examining the fitted visibility curves, and from the agreement factors (as described in Jauncey *et al.* 1989), we found that displacements outside the range 1·3+1·35/−1·20 mas provided unacceptable fits to the data. The displacement of 1·3+1·35/−1·20 mas over the 1·07 years translates to a separation velocity of 0·08+0·09/−0·07*c*.

In addition to the structural changes in C2, its flux density has also changed significantly, while the flux density of the core component itself, C1, has changed little. Component C1 in the models changes from 2·3 to 2·2 to 2·4 Jy at the three epochs, while C2 has flux densities of 2·9, 2·7 and 1·8 Jy respectively. It seems that the core flux density stays relatively stable while the flux density of the slowly moving component, C2, has steadily decreased over the course of the observations. The drop in the combined fitted flux densities of C1 and C2 agrees well with the drop in the measured peak flux density.

Component C3, which is $\sim$15 mas from the core, appears stationary within the errors given by the models. However, it has changed considerably in flux density and extent, explaining its discrete appearance in 1991·17, the smooth appearance in 1991·90 and the discrete appearance again in 1992·24. The details of this picture of slow structural change are valid only if the components at any one epoch can be uniquely identified with those at another epoch. Hence we cannot entirely rule out the possibility that both the flux density and structural changes are occurring on timescales substantially shorter than four months, particularly as there is some evidence for intra-day variability in the total nuclear flux density (Botti and Abraham 1994).

The simplest interpretation consistent with our results is that of a relatively stable nuclear core with a rapidly evolving component moving slowly away from the core at $0 \cdot 08c$. In addition, there appears to be a stationary extended component 15 mas, or 0·3 pc, away, which also evolves rapidly in flux density and may represent a stationary shock-front in the path of the jet.

## 4. The Future

We will continue our regular monitoring of the core flux density and our VLBI imaging of the nucleus of Centaurus A at 2·3, 4·8 and 8·4 GHz. The VLBI imaging observations now include both the SHEVE array and the NRAO's very long baseline array (VLBA) as the north–south coverage; for southern sources, long tracks of the SHEVE array complement the east–west coverage of the VLBA. In addition, more frequent single-baseline, 8·4-GHz Tidbinbilla–Hobart observations are being scheduled to determine the shortest timescale for structural variations.

## Acknowledgments

Many people have contributed to the success of the SHEVE VLBI program. We thank the Directors of the Observatories and Facilities for their continued support, and the support staff of the JPL/CALTECH block II correlator facility, the European Space Agency, the NASA Deep Space Network, British Aerospace, Australia, and Telstra for generously making their facilities available for VLBI. Part of this research was carried out at the Jet Propulsion Laboratory of the California Institute of Technology, under contract to NASA. SJT is supported by an Australian Postgraduate Research Award.

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Manuscript received 6 May, accepted 1 July 1994