THE SUBPARSEC-SCALE STRUCTURE AND EVOLUTION OF CENTAURUS A

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ABSTRACT

We have studied the closest Fanaroff-Riley type I radio galaxy, Centaurus A, over the period 1991 - 2001 using VLBI, monitoring the subparsec-scale structure and evolution of the jet which originates close to the massive black hole central to the active nucleus. We have measured the apparent motions of components in the jet at approximately 0.12c and observed several episodes of rapid variability internal to these components. We have also detected a subparsec-scale counterjet. Together these observations lead us to conclude that the jet is at least mildly relativistic on subparsec-scales and lies at an angle to our line-of-sight of 50^o – 80^o. In addition, multi-frequency VLBI observations show unambiguous evidence for free-free absorption toward the unresolved nuclear radio source, implying the existence of a subparsec-scale structure containing ionised plasma that surrounds the central engine. Future high dynamic range VLBI observations will allow us measure the apparent speeds of components in the subparsec-scale counterjet and investigate the expected free-free absorption toward the counterjet. Also, future high frequency space VLBI observations will be required to resolve the initial collimation region of the jet, expected on scales of 0.002 pc.

INTRODUCTION

Centaurus A (NGC 5128) is the closest FR-I radio galaxy at a distance of approximately 3.4 Mpc [1]. As such, high angular resolution very long baseline interferometry (VLBI) observations return very high spatial resolution at the source (1 milliarcsecond is equivalent to 0.02 pc at the distance of Centaurus A), allowing detailed investigations of the parsec and subparsec-scale radio emission from the jet of material that originates close to the massive black hole at the heart of the active nucleus of the galaxy. From its origins on the subparsec-scale, the jet in Centaurus A feeds classical FR-I lobes on scales of arcminutes (kiloparsecs) [2-4]. As well as these "inner" lobes, larger and more difuse "outer" lobe structures are also apparent, on angular scales up to approximately 10^o [5]. A bridge of emission connecting the inner and outer lobes has recently been found with the Australia Telescope Compact Array [6] and it has been suggested that part of the outer lobe structure is formed by a buoyant bubble of plasma deposited by an intermittently active jet [7].

On the smallest scales, VLBI observations initially revealed a compact structure suggestive of a jet that was highly aligned with the jet seen on the kiloparsec-scale, together with a self-absorbed nucleus [8,9]. The results presented in this paper are derived from the most recent VLBI observations of Centaurus A, obtained using the Southern Hemisphere Long Baseline Array (LBA) and the Very Long Baseline Array (VLBA), over the period 1991 – 2001. A more detailed description of these observations, the data reductions and analyses, and results can be found in previous publications [10-13].

RESULTS

Temporal Evolution of Centaurus A

Over the course of approximately 10 years we have obtained 21 observations of Centaurus A at a frequency of 8.4 GHz with an angular resolution of typically 2 – 5 milliarcseconds [11,13]. These observations have revealed a source with the following structure: an unresolved nucleus; an extended diffuse jet-like structure orientated at a position angle of approximately 51^o east of north, approximately 50 milliarseconds in length and up to 5 milliarcseconds in width; embedded within this jet are several discrete but resolved components. The discrete components obviously have complex structures and are composed of sub-components. Three components can be consistently identified over the 21 epochs and have been designated C3, C2, and C1, in order of increasing distance from the unresolved nucleus (C1 most distant).

In more sensitive VLBI images a sub-parsec-scale counterjet has been discovered [10] and there is some tentative evidence that components within the counterjet are also moving away from the nucleus at apparent speeds similar (but slower) to C1 and C2 [13]. The jet to counterjet surface brightness ratio is between 4 and 8.

Over the course of the observations, two distinct types of temporal variability have been noted: (1) a gradual linear motion of two of the components (C1 and C2) away from the nucleus, along the jet, with an apparent speed of 0.12c; (2) periods when the components (C1 especially) vary in flux density, on time-scales at least as short as a few months. It is generally thought that the moving components observed with VLBI are due to shock structures in the jet material. This raises the possibility that the shocks may appear to travel slowly while the underlying fluid in the jet moves much more rapidly. From the periods of rapid variability it is possible to make a (model dependant) estimate of the underlying jet fluid speed from the data, yielding >0.5c, much faster than the observed gradual component motions of 0.12c.

If the true speed of the jet is reflected by the apparent motions of the components C1 and C2 (0.12c), the jet to counterjet surface brightness ratio noted above can only be produced if the jet is highly aligned (to within a few degrees) with our line-of-sight. This does not seem likely, given the already large size of the radio source and the morphology of the optical galaxy. Using the implied jet fluid speed from the component variability (>0.5c) in conjunction with the jet to counterjet surface brightness ratio gives a range for the jet angle to the line-of-sight of 50^o to 80^o. This is far more plausible and agrees with other estimates of the jet angle from observations of X-ray emission [14] and infrared emission [15].

The tentative estimates for the apparent speeds of the components in the counterjet [13] are also consistent with the estimated range in jet angle to the line-of-sight. Taking the apparent motions of the approaching and receding components together with the jet to counterjet surface brightness ratio implies that the intrinsic speeds of the components (shock structures) are within the range 0.09c to 0.20c.

Frequency-dependent structure of Centaurus A

Some of the early VLBI observations of Centaurus A found that the nucleus had a highly frequency-dependent appearance, probably due to synchrotron self-absorption of the unresolved nuclear component [8]. In 1992, we obtained two VLBI observations three days apart at 4.8 and 8.4 GHz and produced images that show in detail the frequency-dependant nature of the subparsec-scale structure [11,16]: the nucleus, unresolved at a resolution of 2 milliarcseconds, has a highly inverted spectrum, with spectral index $\alpha \sim 4$ (flux density proportional to ν^α where ν is the observing frequency); the remainder of the subparsec-scale source, the jet and embedded components, has the spectral index of an optically thin plasma, $\alpha \sim -0.6$.

Such an inverted spectrum for the nucleus cannot be produced purely from synchrotron self-absorption (a maximum of $\alpha \sim 2.5$ is theoretically possible) and an additional absorption mechanism is required. A plausible candidate is free-free absorption, which, like synchrotron self-absorption, preferentially absorbs photons at low radio frequencies. To quantify the effects of free-free absorption a series of near-simultaneous, multi-frequency (2.2, 5.0, and 8.4 GHz) VLBA observations were obtained in 1999 May [12]. From the observations, matched-resolution images were made at the three frequencies and registered, allowing a pixel-by-pixel analysis. The simplest free-free absorption model involves an intrinsic powerlaw spectrum, representing the radio emission from Centaurus A, and an absorption term involving the free-free optical depth. The optical depth itself depends upon the path length through the free-free absorbing structure, the temperature of the structure, and the density of the structure – however, for the purposes of the model, the optical depth represents a single free parameter. The powerlaw spectrum contains two further free parameters. So, with three free parameters and observations at three frequencies, this simple model can be constrained.

This free-free absorption model was applied to each pixel of the images and it was found that toward the unresolved nucleus a free-free optical depth of approximately 0.9 was required at a frequency of 2.2 GHz. This implied that the observed spectral index of approximately 3.8 between 2.2 and 5.0 GHz corresponded to an intrinsic spectral index of 2.0, plausible from synchrotron self-absorption alone. No free-free absorption was required toward the jet, and the counterjet emission was too weak to probe that region for free-free absorption.

The estimated free-free optical depth, assuming a temperature of 10,000 K and adopting a path length estimated from the VLBI observations of 0.016 pc gives a density of at least 31,000 cm^{-3} and a mass for the absorber of 0.01 solar masses, assuming a simple spherical geometry.

Data at higher frequency are also available. In this case we can take advantage of the frequency dependence of Centaurus A, pushing to higher frequencies where the nucleus is brighter and the resolution of interferometers also higher. The highest frequency for which VLBI images of Centaurus A have been published is 22 GHz [11]. These images have a spatial resolution of 0.02 pc and show the jet to be well collimated on these scales.

CONCLUSIONS

We have learned a great deal about the sub-parsec-scale structure and evolution of Centaurus A from VLBI observations. The prospects for future advances in our knowledge also look good.

Further high sensitivity and high dynamic range multi-frequency VLBI observations could allow us to do two significant things. First, we should be able to robustly detect the subparsec-scale counterjet at three or more frequencies. This would greatly enhance the free-free absorption analysis. If the free-free absorbing structure is a disk which lies perpendicular to the jet axis then we would expect to see very little absorption toward the approaching jet (supported by the current data), significant absorption toward the nucleus (supported by the current data), and significant absorption toward the counterjet (beyond the limitations of the current observations). If we could probe the free-free emission (if any) toward the counterjet we should be able to tightly constrain the geometry and dimensions of the free-free absorbing structure.

Secondly, by accurately measuring the apparent motions of components in the counterjet it may be possible to further constrain the jet angle to the line-of-sight. This would be important for estimates of the intrinsic speeds of the shocks within the jet and could provide a constraint on models for relativistic jets. Also, the central black hole mass in Centaurus A has been estimated to be between 60 and 500 million solar masses [17]. Some of the uncertainty in this measurement could be removed if an accurate estimate of the jet angle to the line-of-sight could be obtained.

Also relevant to the black hole mass may be the length scale on which the jet is first produced and collimated. High frequency VLBI observations of M87 show a very large jet opening angle on scales of 0.03 pc [18]. The estimated black hole mass for M87 is approximately a factor of ten higher than for Centaurus A, so 0.03 pc corresponds to approximately 100 Schwarzschild radii. The large opening angle on these scales is interpreted as the initial collimation of the jet, occurring between 100 and 1000 Schwarzschild radii from the nucleus [18]. If we assume that this collimation scale is the same for all objects, we would expect the collimation region of the jet in Centaurus A to lie a factor of ten below the highest resolution yet obtained from VLBI imaging. Indeed, from 8.4 and 22 GHz VLBI observations there is no evidence to suggest the type of structures that have been seen in M87 [11]. However, these observations are only sensitive to structure on scales greater than 1000 Schwarzschild radii. Next generation space VLBI missions at 22 GHz and above will be required to provide the factor of ten improvement in resolution needed to resolve the region in Centaurus A where initial collimation of the jet is likely to occur.

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