Structure and evolution of the compact radio source in NGC 1275

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ABSTRACT Investigations of the fine-scale structure in the compact nucleus of the radio source 3C 84 in NGC 1275 (New General Catalogue number) are reported. Structural monitoring observations beginning as early as 1976, and continuing to the present, revealed subluminal motions in a jet-like relatively diffuse region extending away from a flat-spectrum core. A counterjet feature was discovered in 1993, and very recent nearly simultaneous studies have detected the same feature at five frequencies ranging from 5 to 43 GHz. The counterjet exhibits a strong low-frequency cutoff, giving this region of the source an inverted spectrum. The observations are consistent with a physical model in which the cutoff arises from free–free absorption in a volume that surrounds the core but obscures only the counterjet feature. If such a model is confirmed, very-long-baseline radio interferometry observations can then be used to probe the accretion region, outside the radio jet, on parsec scales.

The compact nucleus of the radio source 3C 84 in NGC 1275 (New General Catalogue number) was the most complex of those originally studied by very-long-baseline (radio) interferometry (VLBI) techniques. Initial attempts to determine its structure (1) were unsuccessful. Interest in this source, the closest (z = 0.018) of the bright compact radio nuclei, remained high because of its potential to reveal structural details unattainable in weaker or more distant sources.

This paper combines a review of some of the early observations that form the basis for studies of structural evolution in 3C 84 with a presentation of preliminary results from the most recent observations. These new images, the first made of this source with the Very Long Baseline Array (VLBA), reach unprecedented dynamic ranges even in preliminary form, and have revealed a number of new features.

Early VLBI Observations

Improved modeling techniques—still rudimentary by modern imaging standards—allowed Pauliny-Toth et al. (2) to obtain the first structural information on 3C 84, revealing three main emission regions aligned in the same position angle, near −9°, in which the much larger-scale structure was elongated. The northernmost region was found to be significantly more compact, a central feature was (at the time) dominant in brightness, while a more diffuse southern component exhibited a slow expansion transverse to the axis of alignment of the three emission peaks.

The earliest hybrid maps of 3C 84, produced by Romney et al. (3) from observations in 1979–81 at 10.7 GHz, revealed motion of the brightness peak in the southern component, at an apparent velocity of 0.58c [0.34 milliarcsec/year; \( H_0 = 50 \) km/s per megaparsec (Mpc; 1 parsec = 3.09 \times 10^{16} \text{ m})]. This is the speed of light relative to the central and northern peaks, the first motion at detectable but subluminal velocity seen in an extragalactic object. Also apparent were an increase in brightness of the northern region and a new orientation of its strongest component in position angle 45°, with a sharp bend toward the otherwise ubiquitous −9° angle. At the same time, the central feature had declined in brightness.

Subsequent 10.7-GHz observations (4) yielded a revised subluminal velocity of 0.4c (0.24 milliarcsec/year). With the best dynamic range in those observations reaching only 50:1, nevertheless fairly high for that time, no counterjet was detected despite an explicit search in the appropriate region of the image. In the context of the relativistic-beaming model commonly invoked for sources exhibiting apparent superluminal motions, these two observations required either an orientation extremely close (within a few tenths of a degree) to the line of sight for the typical jet Lorentz factor of about 7 postulated in superluminal sources, or a mildly relativistic jet (\( \gamma \approx 2 \)) at a more likely angle of about 5° to the line of sight.

Observations at other frequencies (5, 6) confirmed this general picture: the identification of the northern component as the “core,” with a relatively flat spectrum and more rapid variability than other regions; subluminal motion of components in the more extended regions to the south at velocities ranging up to 0.63c (7); and an orientation of the most compact structure in the core in position angles near 45°, with an abrupt bend toward −9°. Venturi et al. (8) include a fairly comprehensive review of these observations.

Recent VLBA Observations

Background. 3C 84 was observed at 8.4 GHz in mid-1993, as commissioning of the VLBA correlator was nearing completion. Only eight of the VLBA stations were used, and no effort was taken to establish proper calibration. Nevertheless, Walker, Romney, and Benson (9) achieved a dynamic range of 4000:1, high by VLBI standards. An unanticipated discovery appeared in the image: a weak diffuse feature extended toward the north from the compact component identified as the core on the basis of morphological similarity to previous images. Despite caution about such a startling new result emerging in the first end-to-end use of a new instrument (indeed, this feature was cropped out of the image included in the formal correlator “First Science” announcement), imaging tests demonstrated that this apparent counterjet was not an artifact of the calibration or imaging processes. The ratio of the core brightness to the peak intensity of the counterjet is about 60:1, just beyond the 50:1 limit established 15 years earlier at a nearby frequency. This paper also considers the relativistic kinematics for

Abbreviations: VLBI, very-long-baseline (radio) interferometry; VLBA, very-long-baseline radio array.
various cases of the jet pattern speed and angle to the line of sight, concluding that the apparent motions in the jet, and the length ratio of the jet to counterjet, are consistent with a simple relativistic-beaming model with mildly relativistic velocities and modest angles to the line of sight.

The counterjet feature was discovered simultaneously in observations made more than 2 years earlier at 22 GHz by Vermeulen, Readhead, and Backer (10). Comparison of the two images suggested that the counterjet feature had an inverted spectrum, unless extremely rapid variations in intensity, otherwise not seen in 3C 84, had occurred. These authors also discuss a model, considered further below, in which the inverted spectrum arises through free–free absorption occurring in a toroidal region surrounding the core, in a plane of symmetry perpendicular to the axis of the jets.

**The Observations.** A series of new observations of 3C 84 were undertaken, to establish the spectral dependence of the various components by obtaining simultaneous multifrequency images and to continue monitoring of structural evolution. A total of four apparitions of 3C 84 were observed by the VLBA, at a total of six frequencies, in the last 2 weeks of January 1995. All were correlated within 3–4 weeks after the observations, and only became available for analysis about a month before this colloquium. The results presented here are thus quite preliminary.

One particular area in which they are preliminary is in the overall brightness scale. While we now believe we know the appropriate amplitude scaling (“b factor”) to use in calibration of VLBA measurements, the scaling of older results, using various versions of the correlator and AIPS software, has not been completely resolved. This currently frustrates any attempt to generate a spectral index map, and we have resorted to presenting contour plots using a uniform set of brightness levels.

We present here the images at 5, 8, 15, 22, and 43 GHz. These images span nearly a decade in frequency and represent the first nearly simultaneous spectral study of fine-scale structure in this source. To best present the structural variations over this large range of frequency, but without completely obscuring some features in the higher-frequency images, we have smoothed groups of images to a common beam size appropriate to the lowest frequency in each group.

In Fig. 1, images at all frequencies are smoothed to a 1.2 × 1.6 milliarcsec beam, in position angle 0°, approximately that for the lowest-frequency 5-GHz data set. Fig. 2 includes images at 15, 22, and 43 GHz, smoothed to a 1.04-milliarcsec circular beam appropriate to the 15-GHz data set. Fig. 3 is the 43-GHz image of the core component, restored using its own 0.16 × 0.21 milliarcsec beam, in position angle −7°. In Figs. 1 and 2, the multiple images are plotted on a common angular scale, with the north–south alignment based on the location of the brightness peak in the central core.

**Spectrum and Nature of the Counterjet.** The general structure of the compact source is seen to be basically the same at all frequencies below 43 GHz. The counterjet feature is plainly apparent, although weak, even in the 5-GHz image (Fig. 1a), where it contains about 20 milli-Janskys (mJy; 1 Jy = 10⁻²⁶ W per m² per Hz) of integrated flux. At 8 GHz, the feature is stronger and extends much closer to the core. A similar pattern occurs at 15 GHz (Fig. 1c), where the counterjet is yet stronger, and both its peak and its outer contours are closer to the core than at 8 GHz.

The peak brightness of the counterjet in the full-resolution 15-GHz image (Fig. 2a) reaches about 2% that of the core, just at the noise level of the 1979 10.7-GHz image, the best of that early series, in which no counterjet was detected.

Comparison of the 15-GHz and 22-GHz images (Fig. 2a and b) shows the counterjet to be even brighter and to extend closer to the core with a further increase in frequency. A bridge of emission between these two components is visible at 22 GHz.

![Fig. 1. Images of 3C 84 at 5 GHz (a), 8 GHz (b), and 15 GHz (c). All three images share a common angular scale and are smoothed to the same 1.2 × 1.6 milliarcsec beam, in position angle 0°, approximately that for the 5-GHz data set. The lowest positive (solid) contours are 1, 4, and 15 mJy per beam, respectively; other contours are at the following multiples of these levels: −2, −1, 1, 2, 2.8, 4.0, 5.7, 8.0, .... Brightness peaks in the images are 1.9, 3.8, and 7.0 Jy per beam, respectively. The crosses in b and c are explained in the text.](image1)

![Fig. 2. Images of 3C 84 at 15 GHz (a), 22 GHz (b), and 43 GHz (c). All three images share a common angular scale and are smoothed to the same 1.0-milliarcsec circular beam, approximately that for the 15-GHz data set. The lowest positive (solid) contours are 15, 5, and 15 mJy per beam, respectively; other contours are at the following multiples of these levels: −2, −1, 1, 2, 2.8, 4.0, 5.7, 8.0, .... Brightness peaks in the images are 5.1, 5.3, and 2.0 Jy per beam, respectively. The cross in a is explained in the text.](image2)
Additional observational evidence that extends this pattern to lower frequencies is the absence of any counterjet feature in the 1.7-GHz image published by Biretta, Bartel, and Deng (11), although this observation is several years older than those reported in this paper.

All these comparisons show the counterjet feature to exhibit a strong low-frequency cutoff and probably an inverted spectrum over the entire decade range of frequencies. A spatial gradient leaves the cutoff stronger toward the core. These effects are all consistent with the model, proposed by Vermeulen, Readhead, and Backer (10), that the cutoff arises from free-free absorption in an accretion disc that lies in front of the counterjet feature but is behind the main jet. Further theoretical work by Levinson, Laor, and Vermeulen (12) indicates that this model is plausible in the case of a toroidal geometry for the absorbing matter but that a spherical distribution is excluded by a combination of radio, optical, ultraviolet, and x-ray data. These authors also predict that any variations in the optical depth of the free-free absorption should be accompanied by simultaneous variations in the [O III] line flux, which cools the absorbing gas.

If such a model can be confirmed by further analysis of the observations reported herein, by new observations, or through the predicted linkage of variations in the radio absorption and optical cooling lines, it will allow VLBI observations to provide insight into the accretion region near the active nucleus, outside the high-brightness jet. Further observations should yield both the magnitude and the radial dependence of the absorption and, thus, impose strong constraints on the physical conditions on parsec scales.

The Extremely Fine-Scale Structure of the Core. The full-resolution 43-GHz image (Fig. 3) reveals structure within the core not seen previously. The core is resolved into an extremely close pair of bright knots, separated by 0.5 milliarcsec (0.26 pc) in a position angle close to the −9° which appears in 3C 84 on angular scales from tenths of milliarcseconds to arcminutes. At the southern knot, there is an abrupt bend toward a position angle of about 45°. This orientation is apparent as well in the 15- and 22-GHz images (Fig. 2a and b) and is seen in older observations going back to the 1979 image (3) at 10.7 GHz. After extending about 1.2 milliarcsec (0.63 pc) in this orientation, and becoming more diffuse, the structure appears to return to the −9° position angle.

We cannot fully reconcile this structure with that reported by Krichbaum et al. (13), where the 45° orientation is also seen, but the northern bright knot is absent. It is possible that we are observing a new component. This would be consistent with the time scale on which major structural changes seem to occur at 43 GHz. More frequent observations are necessary to identify the components unambiguously and to trace their motions.

Motion in the Main Jet. The crosses in Figs. 1b and c and 2a—the 8- and 15-GHz images—mark the position, at the epoch of those images, of a putative component that continues the motion at 0.34 milliarcsec/year (0.58 c) observed in the 1979 and 1981 observations (3) at the nearby frequency of 10.7 GHz. Those observations could not determine the position angle of motion accurately; here it has been set, arbitrarily, to match the −9° orientation present in this source over a wide range of angular scales. The positional coincidence after 15 years—an extrapolation by a factor of 7.5 from the interval over which the velocity was measured—suggests that the motion has continued approximately as predicted. Nevertheless, in view of the varied motions that have been reported in observations at somewhat higher spatial resolution [for example, by Venturi et al. (8)], it is not clear that the brightness peak in this region has undergone a uniform translation throughout this period. Both the 15-GHz and 22-GHz images (Fig. 2a and b) are designed to continue earlier studies of jet motions (the 10.7-GHz series had to be shifted to 15 GHz since the former frequency was not implemented on the VLBA), and we anticipate obtaining more definitive results with continued regular observations.

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