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MISALIGNMENT IN THE RADIO JETS OF NGC 6251

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ABSTRACT

The compact nuclear source in NGC 6251 has been observed with VLBI techniques at 2.8 and 13 cm. The source is asymmetric with a bright optically thick core and an optically thin jet. The jet has a small but significant difference in position angle from the outer jet.

Subject headings: galaxies: nuclei — interferometry — radio sources: general

I. INTRODUCTION

In an earlier paper (Readhead, Cohen, and Blandford 1978, hereafter RCB) we reported VLBI observations of NGC 6251 at $\lambda = 2.8$ cm. These showed that the nuclear source consisted of a core and a jet approximately aligned with the outer jet and with the outer components (Waggett, Warner, and Baldwin 1977, hereafter WWB). We now report new observations at two wavelengths, 13 and 2.8 cm, which confirm the earlier model. We also confirm the position angle of the nuclear jet, 301°.0 ± 0°.8, which we now believe to be significantly different from that of the outer jet, 296°.5 ± 0°.5 (WWB). The sense of the difference is such that the jet bends toward the minor axis of the galaxy, at 289° ± 1° (Young *et al.* 1979), somewhere between 1 and 3 kpc.

II. OBSERVATIONS

We observed NGC 6251 at 10651 MHz on 1978 May 30 and 31 using left circular polarization with four telescopes: the 40 m telescope at the Owens Valley Radio Observatory in California, the 43 m telescope at the National Radio Astronomy Observatory in West Virginia,[1] the 37 m telescope at Haystack Observatory, Massachusetts, and the 100 m telescope at the Max Planck Institut für Radioastronomie at Efflesburg, Germany. We used the standard Mk II VLBI recording system and performed the cross-correlations on the CIT/JPL processor in Pasadena. At the time of observations the weather was bad, and the amplitude calibration may contain substantial errors. Nevertheless, the hybrid mapping procedure (Readhead and Wilkinson 1978) converged rapidly. The result is shown in Figure 1. The details of the +5% contour are not reliable, but we believe that the general disposition of flux density is correct.

We observed NGC 6251 at 2291 MHz on 1978 May 7 and 14 using left circular polarization with three telescopes: the 40 m telescope at OVRO, and the 64 m telescopes at the Goldstone and Madrid stations of the Deep Space Network. (The OVRO telescope was used on May 7 only.) The signal-to-noise ratio was very good and the data were of excellent quality; repetition between data sets taken a week apart was excellent (see Fig. 2). There were not enough data to make a hybrid map but we did make a two-component Gaussian model, whose contours are shown in Figure 1. The amplitude data fix the position angle of the model but leave it ambiguous to a 180° rotation. However, the mean closure phase for the hour centered on 13.5 GST is +7° ± 1°, and this fixes the orientation in the sense shown in Figure 1. The width of the long component (0.3 milli-arcsec) is the parameter which is least well determined in the fitting process.

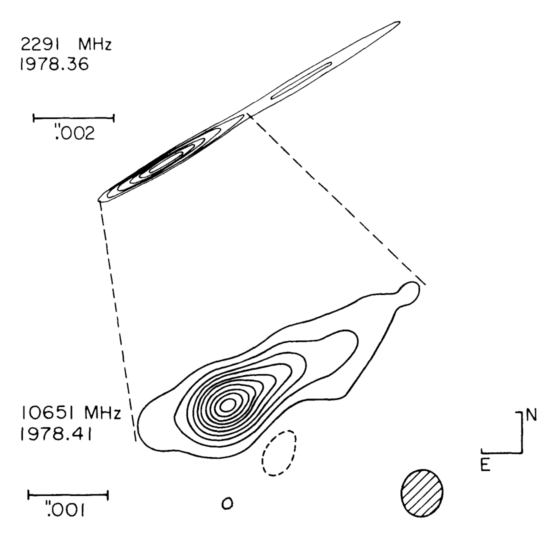

FIG. 1.—Nuclear source in NGC 6251. *Bottom*, hybrid map at $\lambda = 2.8$ cm. Contours −5% (*dashed*), +5, 15, 25, ... 95% of peak. Peak brightness temperature = 1.1×10^{10} °K. *Top*, model at $\lambda = 13.1$ cm. Contours 5, 10, 20, 40, 60, 80% of peak. Note different angular scales.

[1] NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

The 2.8 cm map in Figure 1 is in good agreement with our earlier model (RCB), which was based on data from the three U.S. baselines only. We have more than twice the angular resolution in the new observations, but did not detect any new fine-scale structure. The smoothing beam is 0.5 × 0.6 milli-arcsec and is shown in the lower corner of Figure 1. With this beam the map is unresolved in P.A. 31°, perpendicular to the jet. The original visibility data, although difficult to calibrate, did show baseline-to-baseline differences in this position angle, so the source is somewhat resolved; the width in P.A. 31° is about 0.3 milli-arcsec. This value is only crudely known. It could be refined by repeating these observations in better weather and getting more accurate calibration data, or by using a shorter wavelength to get more angular resolution. The baseline (California to Germany) is 8,200 km long and appreciably longer baselines cannot be attained without using satellites.

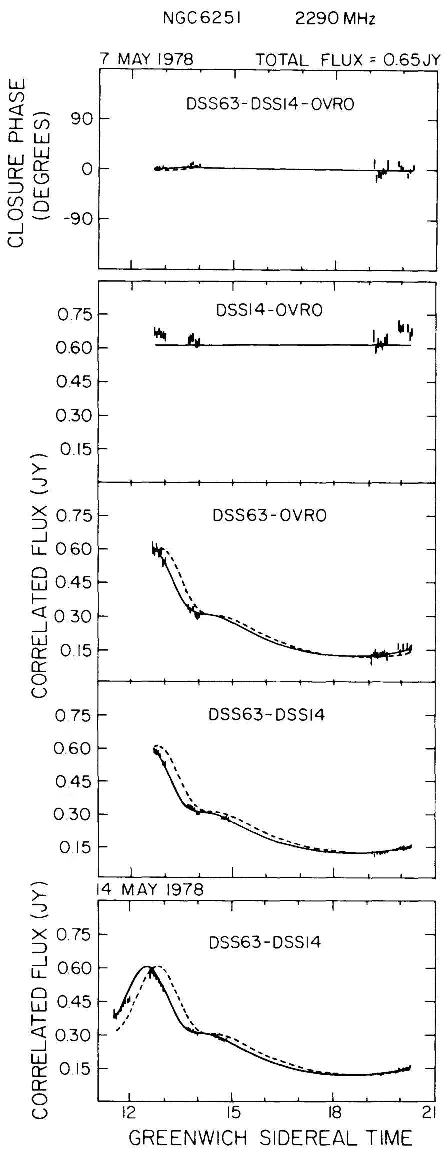

FIG. 2.—Visibility data at 13.1 cm. The solid lines show the fit of the model in Fig. 1 and dashed lines show a rotation of 4°5. Closure phase errors are calculated from the noise statistics, but error bars for the amplitudes also include a 5% allowance for systematic errors in scaling the baselines. DSS 14 = Goldstone station of the Deep Space Network; DDS 63 = Madrid.

III. DISCUSSION

a) *Position Angle*

The best estimate of the position angle of the jet is obtained directly from the visibility curves, shown in Figure 2 for the 13.1 cm data. The peak of the visibility amplitude, near GST = $12^h.5$ gives the position angle of the jet. The solid lines are the visibility for the model in Figure 1, and the dashed lines correspond to a rotation of 4°5, to make the nuclear jet parallel with the outer jet (see below). From this diagram, we conclude that P.A. = 301°3 ± 1°0. Figure 3 shows the 2.8 cm data between Bonn and Haystack. Again the line shows the fit of the map to the data, and the dashed line shows the rotation of 4°5. Our estimate for the position angle at 2.8 cm is 300°7 ± 1°5. The earlier observations at 2.8 cm gave P.A. = 301° ± 2° (amplitude data in RCB). The weighted mean of all these measurements is P.A. = 301°0 ± 0°8. In Table 1 we show the position angle of the inner and outer jets and of the minor axis of the galaxy. The P.A. difference between the jets is 4°5 ± 0°9. It is not possible to fit any of our four sets of data with a model aligned with the outer jet (see Figs. 2 and 3), so the difference is real. There is a similar (but larger) misalignment between the inner and outer components of 3C 273 and 3C 345 (Readhead *et al.* 1978) but these do not have

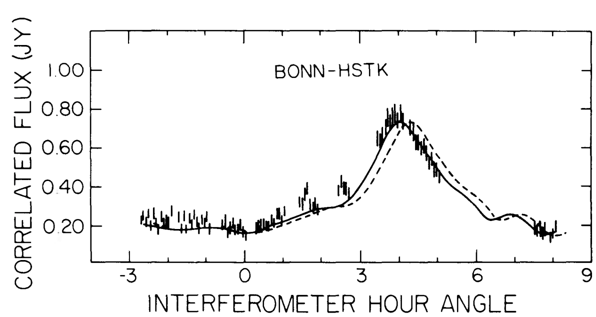

FIG. 3.—Visibility data at 2.8 cm, MPI to Haystack. The solid line shows the fit of the map in Fig. 1, and the dashed lines show a rotation of 4°5.

TABLE 1

POSITION ANGLES IN NGC 6251

	P.A. (deg)	Reference
Inner jet..........	301.0±0.8	This *Letter*
Outer jet..........	296.5±0.5	WWB
Minor axis.........	289.0±1.0	Young *et al.* 1979

large outer lobes and may well be pointing almost at us. Their intrinsic curvature might be only a few degrees, which is amplified to the observed 40° by the small angle to the line of sight (Readhead *et al.* 1978).

The opening angle of the outer jet of NGC 6251 is only about 3° (RCB) so the difference in P.A.'s is not due to a precessional motion; in that case the opening angle would be at least 9°. At 2695 MHz the outer jet is straight down to the resolution limit, 3".7 (WWB). Thus the bending must take place within about 3 kpc; i.e., in the central regions of the galaxy. Table 1 shows that the jet bends toward the minor axis, which suggests that it is bent by interaction with the interstellar medium; e.g., by a pressure gradient (Begelman, Rees, and Blandford 1979).

b) Spectrum

The registration of the diagrams in Figure 1 is unknown, but the 2.8 cm source has the same length as the bright eastern bulge at 13 cm, and we assume that these components are superposed. If this were not the case the spectral index would be unreasonable on one side or the other (Readhead *et al.* 1979). The observations show about 0.9 Jy in the nuclear components at 2.8 cm, and about 0.65 Jy at 13 cm. The combined spectral index is thus about $\alpha = +0.26$. The jet is much longer at 13 than at 2.8 cm; so the index is steep (negative) toward the end of the jet and inverted (positive) at the core. This behavior is identical to that seen in other compact core-jet sources such as 3C 273 (Readhead *et al.* 1979), where at centimetric wavelengths, α is positive at the core and changes to negative in the jet. We interpreted the jet in 3C 273 as a region of low optical depth, with α reflecting the electron injection spectrum, and the core as a region of high optical depth, with $\alpha > 0$ due to synchrotron self-absorption. It is likely that this is also the case in NGC 6251. The optically thick core is about 1 pc long at 2.8 cm, and about 2 pc long at 13 cm.

c) Asymmetry

The nuclear source is strongly asymmetric, with the counterjet, if it exists, having surface brightness a factor 10 or more below the main jet. This morphology exists also for the outer jet at $\lambda = 11$ and 50 cm (WWB, Willis, Wilson, and Strom 1978), where the ratio between the brightness of the visible jet to that of any counter jet is 20 or more. This contrasts strongly with the outer lobes, which have comparable peak brightnesses. NGC 315 is similar; it has a partly visible counter jet but the jet structure is less symmetric than the outer lobes (Willis, Wilson, and Strom 1978).

A common explanation for the jets is that they mark a beam, possibly of relativistic fluid, which carries energy and momentum to the outer lobes. If this is true, then two beams must have existed in the past, in order to have built up the two outer lobes; but lifetime arguments suggest that the beams cannot be off for long periods of time (Hargrave and Ryle 1974). Thus the observed asymmetry seems peculiar. We now comment on three possible explanations for the asymmetry, within the context of the beam theory: (*a*) both beams exist but radiation from the receding one is weakened by a Doppler shift; (*b*) jets are intermittent with a life-time substantially less than that of the outer lobes; and (*c*) the brightness of a jet may be strongly influenced by the galactic environment.

To explain the asymmetry as a Doppler shift we assume, with Blandford and Königl (1979), that the beams contain many moving knots so that the ratio of brightnesses is $R = [(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]^{(2-\alpha)}$, where θ is the angle between the beam and the line of sight, β the velocity of the emitting material, and α the spectral index ($S \sim \nu^{\alpha}$). To avoid a low probability, we set $\theta = 60°$. If α has the common value -0.7, then for $R \geq 10$ we need $\beta \geq 0.8$, which implies a very large energy flow. If $R \geq 50$ (the 50 cm value) then the Doppler explanation has less probability; e.g., $\theta = 60°$ is impossible, and for $\beta = 0.8$, $\theta \leq 40°$. Readhead *et al.* (1978) and Scheuer and Readhead (1979) used the Doppler shift to explain the asymmetry in "core" sources like 3C 273. In this scheme relativistic motions explain both the asymmetry and the superluminal effects (motion and rapid flux variability), and the resulting low probability explains why there are few core sources and many radio-quiet quasars. It is doubtful, however, that NGC 6251 fits into this more extreme case because the superluminal effects have not been seen and because, with θ near 0°, the true overall size would make this much the largest radio source (Valtonen 1979).

The idea that jets are intermittent has been suggested by Willis *et al.* (1978) and others. We may imagine that jets (and the beams which make them) vary widely, on a time scale longer than 10^4 years, and have only a low probability of being strong enough to be seen. Thus few jets are known among all the hundreds of double sources, and if the two sides are substantially independent then the joint probability of seeing both at one time is very small. The beams are on much or all the time, but only occasionally does one flare up enough to make a prominent jet.

It is generally believed that the emission from jets is incoherent synchrotron radiation, but the detailed mechanism which makes the isotropic radiation is not understood. Thus the radio flux from a jet may depend strongly on the interaction between the beam and the surrounding medium, and beams of comparable energy and momentum flux may have substantially different brightnesses, i.e., the beams can have different efficiencies (Turland 1975).

d) Central Mass

Our observations are in good agreement with the earlier ones reported in RCB, and support the physical model developed there. That model had a supersonic free beam with high central pressure. It is difficult to confine this beam by pressure, and we suggested that a large central mass might do it. Young *et al.* (1979) have now obtained evidence for such a mass, by studies of the optical profile of the galaxy. M87 and NGC 6251 both contain a large central mass and both have a jet. It is likely that similar physical processes govern the dynamics of these two objects.

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