A PARSEC-SCALE ACCELERATING RADIO JET IN THE GIANT RADIO GALAXY NGC 315

W. D. COTTON
National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-2475

L. FERETTI AND G. GIOVANNINI
Istituto di Radioastronomia del CNR, Via P. Gobetti 101, I-40129 Bologna, Italy

L. LARA
Instituto de Astrofísica de Andalucía, CSIC, Apdo. 3004, 18080 Granada, Spain

AND

T. VENTURI
Istituto di Radioastronomia del CNR, Via P. Gobetti 101, I-40129 Bologna, Italy

ABSTRACT

Observations of the core of the giant radio galaxy NGC 315 made with VLBI interferometers are discussed in the context of a relativistic jet. The sidedness asymmetry suggests Doppler favoritism from a relativistic jet. The presence of moving features in the jet, as well as jet counterjet brightness ratios, hint at an accelerating, relativistic jet. An increasing jet velocity is also supported by a comparison of the jet’s observed properties with the predictions of an adiabatic expansion model. On the parsec scale, the jet is unpolarized at a wavelength of 6 cm to a very high degree, in clear distinction to the high polarization seen on the kiloparsec scale.

Subject headings: galaxies: individual (NGC 315) — galaxies: jets — galaxies: structure — radio continuum: galaxies

1. INTRODUCTION

There is growing evidence that the jets observed in the inner regions of powerful extragalactic radio sources have highly relativistic flows (see, e.g., Urry & Padovani 1995). The relativistic effects of such jets will cause their apparent properties to be strongly dependent on the viewing angle. The lines of argument for relativistic motion include side-to-side asymmetries in brightness and polarization, prominence of the core, less X-ray emission than expected from a very high brightness radio core, and apparent superluminal motions in the radio jets. The case for highly relativistic motions in low-luminosity sources is less clear. At present, evidence is growing that parsec-scale jets are relativistic also in low-power sources (see Lara et al. 1997), but a detailed study of more sources is necessary to understand the jet dynamics. In recent years, we have been engaged in a program of studying a complete sample of low-power radio sources in order to address this question; this is the ninth paper of this series.

The radio source associated with the galaxy NGC 315 has been well studied since its initial discovery (Davis 1967) and is classified as a low-luminosity Fanaroff-Riley type I (FR I) radio galaxy. This galaxy is a 12th magnitude dusty elliptical (Ebneter & Balick 1985) at $z = 0.0167$ with Hα + [N II] emission lines (Marcha et al. 1996). The large-scale (50′) structure of this radio source (0055+30) has been observed using Arecibo, Westerbork, and the VLA (Fanti et al. 1976; Bridle et al. 1976; Willis et al. 1981; Jägers 1987). On this large scale, the radio source has a long, straight, highly polarized jet (Fomalont et al. 1980; Jägers 1987) with a sharp bend near the end. The counterjet is much weaker and has an S-shaped symmetric bend at its end. The source contains a prominent, peaked spectrum core coincident with the nucleus of the galaxy. This core has been observed using VLBI arrays by Linfield (1981), Preuss (1983), and recently by Venturi et al. (1993) at 18, 6, and 3.6 cm. On the basis of high core prominence, low level of nuclear X-ray emission, as well as the jet sidedness, Venturi et al. (1993; but see also Lara et al. 1997) concluded that the jet was highly relativistic but could not detect the expected motions in the jet in comparison with the images of Linfield (1981) and Preuss (1983). The flux density of the core was monitored from 1974 to 1980 by Ekers, Fanti, & Miley (1983), but no variations were detected.

At the distance of this source, 1 mas corresponds to 0.47 pc. We present new observations of NGC 315 using the Very Long Baseline Array (VLBA) radio telescope. Many of these data include measurements of the linear polarization.

2. OBSERVATIONS AND DATA REDUCTION

In this section the details of the observations and the reduction techniques are given. The resultant images are presented in the following section.

The galaxy NGC 315 was observed at wavelengths of 6 and 3.6 cm (5 and 8.4 GHz) using the VLBA on 1994 November 14 (total intensity only) and at 6 cm on 1995 October 28 (dual polarization), 1996 May 10 (dual polarization), and 1996 October 7 (dual polarization). These observations are summarized in Table 1. In the November 1994 observations we switched wavelength every half-hour between 6 and 3.6 cm, obtaining a good UV coverage at both wavelengths. In the 1995 October observations, the VLA failed to give fringes to the VLBA, although internal VLA observations showed no problems. The loss of the VLA seriously reduced the sensitivity that is needed for...
linear polarization observations, and the observations were repeated in 1996 May. During these reobservations, the complete failure of VLBA–St. Croix and serious tape recorder problems at VLBA–Pie Town and VLBA–Mauna Kea reduced the resolution of the data, and the observations were rescheduled for 1996 October. This latter session was successful and produced the polarization measurements presented here.

The VLBA data were all correlated on the VLBA correlator in Socorro (New Mexico) and all processing used the NRAO AIPS package. Amplitude calibration was initially done using the standard method employing measured system temperatures and an assumed sensitivity calibration. The VLBA calibration for the VLA was determined from the NGC 315 data. In the 1995 and 1996 observations, the amplitude calibration was refined using the measured flux densities of the compact calibrator sources (0235 + 164 in 1995, BL Lacertae in 1996).

Phase calibration of the 1995 and 1996 data employed the pulsed phase calibration system to remove variations in the difference of the phases of the right- and left-handed polarized signals. All data were globally fringe fitted (Schwab & Cotton 1983) and then self-calibrated.

The VLA was used in parallel with the 1995 and 1996 VLBA observations to determine the flux density and polarization of the VLBA calibrators. Because NGC 315 is too extended to be used as a phasing calibrator for the VLA, the nearby source 0042 + 233 was used to periodically phase the VLA antennas. In the 1996 October session, 3C 48 was used to calibrate the flux density and polarization angle, and 3C 84 was used to determine the instrumental polarization for the VLA.

The polarization calibration and imaging followed the general method of Cotton (1993). The polarization calibrator for the 1995 observations was 0235 + 164 and for the 1996 observations, BL Lac. The 1996 October data was of much higher quality than the previous measurements, so the polarization results presented here are from that session.

Observations of BL Lac were used to derive the cross polarized delay and phase corrections to the VLBA data. The polarization angle corrections were derived independently in each 8 MHz band using the sum of the $Q$ and $U$ CLEAN components from a deconvolution. This procedure makes the plausible assumption that all of the source measured by the VLA was also measured by the VLBA. Instrumental polarization corrections for the VLBA were initially determined from measurements of 3C 84, which was assumed to be unpolarized. After it was determined that NGC 315 had no detectable polarization with this calibration, corrections to the VLBA instrumental polarization calibration were determined from the NGC 315 data assuming the source to be unpolarized in the region to which these data were sensitive.

3. RESULTS

3.1. Monitoring of the Arcsecond Core Flux Density

Flux density monitoring of NGC 315 at a wavelength of 6 cm by Ekers et al. (1983) from 1974 to 1980 with the Westerbork synthesis radio telescope showed no evidence for variations. They found a core flux density of 633 mJy with rms = 27 mJy. More recent VLA observations show a flare between 1990 and 1995. Flux density measurements at 6 cm are given in Table 2. Many of these measurements are given in this paper for the first time as reported in Table 2. They result from long integrations on the VLA that have been extensively cross-calibrated; relative errors are likely lower than the quoted precision. More details on the new VLA data will be given in a future paper, in preparation, on the large-scale structure of NGC 315. The flux density flare is confirmed also by two observations at 3.6 cm that give a core flux density of 588 mJy in 1990.92 (Venturi et al. 1993) and of 746 mJy in 1994 June (present paper).

3.2. Total Intensity

Calibrated and edited visibility data were used to produce total intensity maps. We used the AIPS package following the standard procedure: a first map was made using the AIPS task IMAGR and several iteration of phase self-calibration followed by a final phase and gain self-calibration were made. In order to exploit the high dynamic range in the 1996 October data, baseline-dependent

| Date          | Flux Density (mJy) | Reference |
|---------------|-------------------|-----------|
| 1978.48      | 620.0             | 1         |
| 1989.28      | 585.9             | 2         |
| 1995.83      | 735.2             | 3         |
| 1996.36      | 694.8             | 3         |
| 1996.77      | 686.2             | 3         |
| 1996.84      | 668.1             | 3         |
| 1997.53      | 688.7             | 3         |

Note.—The quoted flux densities for the 1989–1997 measurements have a relative accuracy of better than 0.1 mJy.

References.—(1) Bridle et al. 1979; (2) Venturi et al. 1993; (3) this paper.
complex gain factors were determined from the NGC 315 data by dividing by the Fourier transform of the best self-calibrated model and averaging over the entire time of the observations. Since the NGC 315 jet is very homogeneous, special care was taken to avoid CLEAN artifacts by using a very low gain factor (0.03) in all the deconvolutions.

3.2.1. Total Intensity Images

In Figure 1 we present the NGC 315 maps at 6 cm at the four different epochs; details of the images are given in the figure caption. All the images have been rotated by $-41.5^\circ$ and convolved to the same angular resolution. The radio source morphology, a strong core emission and a straight jet, are in good agreement in all four different images. The noise level in the first three images is similar, although the lack of three telescopes (see § 2) in the May 1996 image produced some residual artifacts and a more irregular zero level in this epoch. Due to the good quality of the data and the very accurate calibration, the October 1996 image has a noise level a factor of 10 lower than the others and a very low level of artifacts.

A comparison of the images in Figure 1 suggests evidence for expansion in the jet. To investigate further the possibility of motions in the jet, enhanced resolution images were obtained from the 6 cm images by restoring the CLEAN components from deconvolution with a Gaussian function of the size used for the 3.6 cm image. This was not done for the 1996 May observations because of the lack of long baselines. These high-resolution images are presented in Figure 2 similar to those in Figure 1. To check whether the CLEAN deconvolution could have created artifacts in the superresolved maps, we compared the 1994 November
superresolved map at 6 cm with the same epoch 3.6 cm map (Figs. 3a and 3b). The strong similarities between the two images of NGC 315 give some confidence in the validity of our procedure.

3.2.2. Spectral Index Image

We used the same epoch observations (1994 November) at 6 and 3.6 cm to produce a spectral index image of the NGC 315 jet at the resolution of 2.5 × 1.5 mas. The two images were produced using as similar as possible UV coverage, with the same gridding and convolved with the same beam.

The calibration procedure used on this data does not result in accurate relative registration of the 6 and 3.6 cm images. As the location of the peak of the “core” may be frequency dependent, a weaker but more isolated feature “C” from the images shown in Figure 3 was used to align the images. With this registration, the peaks of the core at the two wavelengths are not coincident but slightly shifted (0.3 mas) with the 3.6 cm peak “upstream” of the 6 cm peak. In the following analysis, the center of activity is assumed to be at the location of the 3.6 cm peak.

The trend of the spectral index along the ridge of maximum brightness is shown in Figure 4. The core region appears strongly self-absorbed and has an inverted spectrum. The spectral index of the jet away from the core is consistent with a relatively constant value of approximately 0.5.

There are several effects that will corrupt the spectral index image. The relatively poorer UV coverage at 3.6 cm wavelength will result in poorer surface brightness sensitivity that will result in incorrectly steep estimates of the spectral index. The rapidly declining surface brightness of the jet will cause any image registration errors to result in systematic variations in the derived spectral index. What can be reliably determined from Figure 4 is that the core region is optically thick and the jet spectral index steepens to optically thin values.

3.3. Polarization

Images of NGC 315 in linearly polarized light do not reveal any polarized emission clearly due to the source, in spite of the low noise level of 0.066 mJy beam⁻¹ in the

![Fig. 3.](image)

![Fig. 4.](image)
Stokes $Q$ and $U$ images. Off-source apparent artifacts due to imperfect instrumental polarization calibration do not exceed 0.22% of the peak total intensity in the image.

One possible cause of the lack of polarization would be a very high rotation measure in the source in which variations across the bandpass decorrelate the signal. A rotation measure of 82,000 rad m$^{-2}$ will cause a 50% decorrelation across our full 32 MHz bandpass. To test for the possibility of very high rotation measure in this source, a polarized intensity image was generated for each of the 64 0.5 MHz channels in the data, and these polarization images were averaged. This scalar averaging of the polarization results in a very slow increase in signal-to-noise ratio with increasing number of channels (the final sensitivity is only a few times that of a single 0.5 MHz channel), but this process is much less sensitive to large rotation measures. The half-decorrelation rotation measure is 5,200,000 rad m$^{-2}$ for the scalar-averaged polarization image. No polarized emission was detected in the scalar-averaged image; this effectively eliminates the possibility of depolarization due to a constant, but very large, Faraday rotation. Table 3 gives upper limits to the source polarization at a number of locations along the jet using both the scalar- and vector-averaged polarization images. The upper limit quoted is the polarized amplitude at the corresponding image location. High-resolution VLA images (to be published elsewhere) indicate 26% polarization at a distance of 700 mas from the core.

### Table 3

Upper Limits to Polarization

| Distance (mas) | $I$ (mJy) | $P_{\text{scalar}}$ (mJy) | $P_{\text{vector}}$ (mJy) | $\%_{\text{scalar}}$ | $\%_{\text{vector}}$ |
|---------------|-----------|---------------------------|--------------------------|---------------------|---------------------|
| 0.0 ......... | 381.5     | 0.99                      | 0.18                     | 0.26                | 0.05                |
| 5.5 ......... | 33.1      | 1.0                       | 0.10                     | 3.02                | 0.30                |
| 10.25 .......| 9.4       | 1.1                       | 0.29                     | 11.7                | 3.09                |

Note: Distance is from the peak of the core. $I$ is the total intensity, $P_{\text{scalar}}$ is the scalar averaged polarized intensity, $P_{\text{vector}}$ is the vector-averaged polarized intensity, $\%_{\text{scalar}}$ is the scalar-averaged percent polarization, $\%_{\text{vector}}$ is the vector-averaged percent polarization.

than our resolution of about 1 pc (projected). A constant, large Faraday rotation is effectively ruled out by the lack of detected polarization averaged over many 0.5 MHz bands. One possibility for an external depolarizing screen is the narrow-line region (NLR). According to Urry & Padovani (1995) the NLR extends up to ~32 pc, corresponding to ~70 mas for NGC 315. As described above, the jet is probably inclined to the line of sight by approximately 35º, so the line of sight to the inner portion of the jet almost certainly intersects the NLR. Much farther from the core, at 700 mas, VLA observations show that the jet is highly polarized (26%); on this scale the jet is certainly outside of the NLR. Moreover, we have to take in account that the inner 5–6 mas are dominated by the core region with an inverted spectrum (see Fig. 4) where the intrinsic polarization is much lower than in the synchrotron transparent regions. High surface brightness sensitivity polarization observations at higher frequencies are needed to determine the extent over which the jet is unpolarized. Unfortunately, polarization VLBI observations of other FR I sources are not yet available for a comparison.

### 4.2. Nuclear Activity

The radio emission from the core of NGC 315 was relatively constant during the 1970s, when it was monitored by Ekers et al. 1983. Since the late 1980s the core has been more active, with an event apparently peaking in the early 1990s, although during these years the available flux density measurements are too sporadic to properly define the light curve.

There is some fluctuation of the brightness of the unresolved “core” component, but most of the additional emission does not appear to be associated with a distinct component. Although the measurements of the core variability are too sparse to allow a correlation with the evolution of the parsec scale structure, they are a clear indication of the activity in this radio galaxy.

### 4.3. Proper Motion

Comparing the images available for NGC 315 (Fig. 1) at different epochs allows the detection of apparent motion. The 1996 May image was not included due to the problems discussed above. The main difficulty in this analysis is that the jet is very homogeneous, and the evidence of substructure is not very strong.

The distance from the core of the various features as a function of the epoch is given in Table 4 and shown in Figure 5. The inner four features in the first two epochs and the inner five in the last epoch are from the superresolved image (Fig. 2), while point E is from the normal resolution images (Fig. 1). The final feature, F, is the location of a sharp

### Table 4

Jet Feature Position and Apparent Velocity

| Epoch        | A0  | A   | B   | C   | D   | E   | F   |
|--------------|-----|-----|-----|-----|-----|-----|-----|
| 1994 Nov     | 2.7 | 4.1 | 5.4 | 7.1 | 7.6 | 8.5 |
| 1995 Oct     | 3.7 | 5.2 | 6.4 | 7.9 | 8.5 | 10.1|
| 1996 Oct     | 2.9 | 4.1 | 5.8 | 7.5 | 9.1 | 10.3|
| $\beta_{\text{app}}$ |      | 1.13 $h_{50}^{-1}$ | 1.37 $h_{50}^{-1}$ | 1.70 $h_{50}^{-1}$ | 1.62 $h_{50}^{-1}$ | 2.18 $h_{50}^{-1}$ | 2.51 $h_{50}^{-1}$ |

Note: Distance is from the peak of the 3.6 cm core in mas. A0, A, B, C, and D are from superresolved images; E and F are from normal resolution images. The apparent velocity ($\beta_{\text{app}}$) in $c$ units is between 1994 November and 1996 October; $h_{50}$ is $H_{0}/50$. 
drop in the intensity of the jet. Feature F is not a knot in the usual sense but a well-defined position in the jet where there is a marked decline in emission, perhaps associated with a new region of activity propagating along the jet. We are aware of the fact that the association of features at the different epochs shown by the lines in Figure 5 is not the only one possible. However, it is the one which results in the best set of alignments. In this interpretation of Figure 5, feature A0 is newly emerged from the core.

The measurements shown in Figure 5 are insufficiently precise to show acceleration or deceleration of a given feature, but the general steepening of the lines down the jet indicates an acceleration of the jet. The average velocity of each feature in the jet is used to derive the $v_{\text{app}}$ given in Table 4.

4.4. Jet/Counterjet Ratio

The high-quality image of NGC 315 from 1996 October gives indication of a faint counterjet. The faint and short structure visible in the normal resolution (Fig. 1) and superresolved (Fig. 2) images is even more evident when natural weighting is used (Fig. 6). A test of the reality of this feature was to perform several iterations of self-calibration disallowing CLEAN components in this region. The apparent counterjet persisted throughout this procedure and appears to be required by the data. Including this region results in a map with very low noise level, as well as a decrease in the level of off-source artifacts. Low-resolution images at the other epochs are consistent with a counterjet, although the noise is too high to confirm its presence.

If the jets are intrinsically symmetric, the jet magnetic field has a random orientation and the asymmetries are entirely due to Doppler beaming, it is possible to determine the component of the jet velocity in our direction using the relation

$$R = \frac{[1 + \beta \cos \theta/(1 - \beta \cos \theta)]^{2 + x}}{\beta^2},$$

where $R$ is the jet/counterjet brightness ratio, $\beta$ is the ratio of the jet velocity to the speed of light, and $\theta$ is the jet angle to the line of sight. (see Giovannini et al. 1994 for a more detailed discussion). We note that NGC 315 shows increasingly symmetric, straight jets on the kpc scale, which supports the Doppler favoritism interpretation of the parsec-scale asymmetries.

A simple interpretation of the jet brightness asymmetries depends on the jet being constant in time, otherwise the time delay between the approaching and receding jets must included. The “features” in the jet whose motions were derived in a previous section are relatively minor fluctuations on the underlying jet so they may be ignored for this analysis.

As discussed above, the recent flux density outburst in NGC 315 appears to have resulted in a general brightening in the inner jet, and a time-invariant brightness ratio analysis must ignore the inner 4 mas of the jet. The results of Ekers et al. (1983) suggest that there was an extensive quiescent period prior to the recent outburst.

The image from 1996 October can be used to derive jet/counterjet ratios along the inner portion of the jet. The inner 4 mas of the jet were avoided due the very bright core component and the recent outburst discussed above. The spectral index was assumed to have a constant value of 0.5. The measured brightness values are given in Table 5 with the derived values of $\beta \cos \theta$. If the angle to the line of sight $\theta$ is constant, the values shown in Table 5 imply a higher jet velocity, i.e., an acceleration, with increasing distance from the core.

The derived values of $\beta \cos \theta$ given in Table 5 assumed a constant spectral index, whereas Figure 4 suggests a steepening of the spectrum along the jet. A steepening of the spectral index from 0.5 to 1.5 along the portion of the jet summarized in Table 5 could account for the measured variations in jet/counterjet ratio from a constant velocity jet. As discussed above, the values of $\alpha$ shown in Figure 4...
are subject to substantial error due to imaging difficulties. The optically thick, inner portion of the jet has been excluded from this analysis. A jet spectral index of 1.5 this close to the core would require implausibly rapid energy loss to the radiating electrons; it seems unlikely that the actual spectral steepening could be sufficiently large to produce the increasing brightness ratios observed.

Another possible cause of the jet/counterjet asymmetry could be free-free absorption in an accretion disk around the nucleus as is observed in NGC 1275 (Walker et al. 1998). However, the asymmetries from free-free absorption should decrease with distance from the nucleus as the optical depth through the obscuration decreased. Since the observed jet/counterjet ratio increases away from the core, it appears that free-free absorption is not a major contributor to the brightness asymmetries.

4.5. Jet Velocity

The discussion above indicates that both the derived motion of features in the jet and the analysis of the jet/jet ratio suggest that the jet is accelerating. From the sidedness ratio (Table 5) we can derive the bulk jet velocity assuming a reasonable orientation of NGC 315 with respect to the line of sight. Giovannini et al. (1994), have considered the jet orientation in NGC 315 using a number of observational properties such as X-ray emission, core dominance, and the very large linear size of this source as well as the jet/jet brightness ratio and concluded that \( \theta \) is in the range \( 30^\circ - 41^\circ \). We adopt a value for \( \theta \) of \( 35^\circ \). The derived values of the velocity are plotted in Figure 7.

The apparent motion in units of the velocity of light for a relativistically moving feature is given by the relationship:

\[
\beta_{\text{app}} = \beta \sin \theta (1 - \beta \cos \theta)^{-1}.
\]

Solving for \( \beta \) gives

\[
\beta = \beta_{\text{app}} \times (\beta_{\text{app}} \cos \theta + \sin \theta)^{-1}.
\]

Accurate determination of \( \beta \) depends on knowing the jet’s angle to the line of sight as well as the value of \( H_0 \). Using a value of \( 35^\circ \) for the jet orientation, we note that the bulk and pattern jet velocity are very similar if we assume an Hubble constant \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) (see Fig. 7). This is consistent with the result of Ghisellini et al. (1993) and the general agreement in the literature between the bulk and pattern velocity for superluminal sources (see also Giovannini et al. 1998). In Table 6 we report the derived velocity from the visible proper motion and the brightness ratio assuming \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( \theta = 35^\circ \) at different positions in the jet. The positions are deprojected linear distances in parsecs from the core assuming \( \theta = 35^\circ \).

These two, admittedly weak, derivations of the jet velocity give very nearly the same values of jet velocity and the

### Table 5

| Core distance (mas) | Jet Brightness (mJy beam\(^{-1}\)) | Counterjet Brightness (mJy beam\(^{-1}\)) | \( \beta \cos \theta \) |
|---------------------|-----------------------------------|------------------------------------------|------------------------|
| 4.0 .................. | 75                                | 1.80                                     | 0.63                   |
| 6.0 .................. | 40                                | 0.65                                     | 0.68                   |
| 7.5 .................. | 19                                | 0.15                                     | 0.76                   |
| 9.0 .................. | 13                                | 0.10                                     | 0.76                   |
| 10 ..................  | 13                                | <0.06                                    | >0.79                  |

### Table 6

| Core Distance (pc) | \( \beta_{\text{app}} \) | \( \beta_{\text{knots}} \) |
|-------------------|--------------------------|---------------------------|
| 3.3 ............... | 0.77                     | 0.75                      |
| 3.4 .................. | 0.75                     | 0.81                      |
| 4.8 .................. | 0.83                     | 0.86                      |
| 4.9 .................. | 0.92                     | 0.92                      |
| 6.2 .................. | 0.92                     | 0.95                      |
| 7.5 .................. | >0.96                    | 0.92                      |
| 8.2 .................. | 0.92                     | 0.95                      |

Note—Distance is from the peak of the 3.6 cm core in parsecs deprojected for an angle of \( 35^\circ \) and using \( H_0 = 50 \). The term \( \beta \) is the jet velocity in \( c \) units derived using the brightness asymmetry (second column) or the visible proper motion (third column).
et al. (1997), who obtained the following relationships:

$$I_\nu \propto \frac{(\Gamma_j v_j)^{-2(\frac{2x+3}{3})} r_j^{1-\frac{10x+9}{3}}}{D^{2+z}},$$

and

$$I_\nu \propto \frac{(\Gamma_j v_j)^{-5x+6/3} r_j^{1-7x+6/3}}{D^{2+z}},$$

where $I_\nu$ is the jet surface brightness, $x$ is the spectral index, $r_j$, $v_j$, and $\Gamma_j$ are the jet radius, velocity, and Lorentz factor, and $D$ is the Doppler factor: $D = [\Gamma_j(1 - \beta \cos \theta)]^{-1}$.

The jet transverse FWHM and peak brightness at increasing distance from the core were obtained by fitting a Gaussian function to the transverse profiles of images at resolutions of 2.5 (see Fig. 6) and 1.8 mas. The parameters were then deconvolved from the CLEAN beam, according to the formula given by Killeen, Bicknell, & Ekers (1986), to get intrinsic quantities. The plot of these parameters is given in Figure 8. The trend of the FWHM (left panel) shows a smooth increase with distance, with slope $\sim 0.035$, corresponding to a constant opening angle of $\sim 2^\circ$. The best-fit line does not contain the origin of the axes but gives at the core position (distance = 0) an FWHM of $\sim 0.2$ mas. In agreement with Venturi et al. (1993), we believe that this is the intrinsic angular size of the radio core.

The values of the peak brightness decrease with the FWHM, according to an FWHM$^{-5.31}$ law (Fig. 8, right panel). In an adiabatic jet with constant velocity and $x = 0.5$, the trend implied by the above formulas is $I_\nu \propto$ FWHM$^{-4.67}$ and $I_\nu \propto$ FWHM$^{-3.17}$ for the parallel and transverse magnetic field, respectively. The surface brightness observed in the jet decreases faster than can be explained by adiabatic expansion; increasing Doppler dimming of an accelerating, relativistic jet is one possible explanation.

Using the relationships given above, we have modeled the jet brightness and jet FWHM as a function of the distance from the core. To avoid the variations in the measured quantities due to local fluctuations or the presence of blobs, we used the parameters obtained from the best fits (see Fig. 8). We assumed a jet spectral index $\sim 0.5$, a jet orientation to the line of sight of $35^\circ$, and a jet initial velocity (at 1 mas from the core) of $0.7c$. We considered the extreme possibilities of a purely parallel and purely perpendicular magnetic field, since this information is not available from the observations. The derived values of $\beta$ are shown in Figure 7. The jet velocity increases along the jet up to the distance of 30 mas. The trend of the velocity is not crucially dependent on the orientation of the magnetic field. Also, the use of a lower/higher initial velocity does not change the overall trend but only scales it to lower/higher values.
The jet velocity derived from the adiabatic model is in reasonable agreement with the other two estimates shown in Figure 7 up to a distance of about 10 mas from the core, indicating an acceleration of the jet. After this point, the velocity derived from the adiabatic models are lower than those from the other methods. If this difference is meaningful, then it could indicate a reacceleration of the relativistic particles in the jet in violation of the assumption of an adiabatic jet. The consistency of the adiabatic jet model with the derived proper motion and brightness ratio velocities for the inner portion of the jet further supports the accelerating jet interpretation of the data.

4.7. Where Is the Observed Emission From?

There is growing evidence that FR I jets on the kiloparsec scale have highly relativistic spines surrounded by lower velocity sheaths (Laing 1996). The kiloparsec-scale structure of NGC 315 is consistent with such a model, and high-quality images have been obtained for detailed modeling.

The situation on the parsec scale is less clear. A very highly relativistic spine would be invisible to us if the orientation of the jet is indeed 35° from our line of sight, and only the slowest moving portions of a spine/sheath jet would be visible. The high degree of depolarization of this source suggests a rich environment for the jet providing material for entrainment and acceleration by a highly relativistic spine.

The data presented here suggest an accelerating jet but do not address the question of whether this is merely an acceleration of the outer layers of a mostly invisible, highly relativistic jet or whether the jet has not yet accelerated to a highly relativistic state. If we are seeing only the outer layers, the jet should appear to be hollow and, observed with sufficient resolution, is easily distinguished from a strongly center brightened filled jet. Unfortunately, the surface brightness of the fully transversely resolved portions of the jet is below the threshold of the images presented here, so this test cannot be performed. Given the difficulties of accelerating a powerful jet many parsecs from the central engine and lacking evidence to the contrary, it seems most probable that the emission in the images in this paper come from the outer layers of a highly relativistic jet.

5. CONCLUSIONS

We have presented here a detailed study of the nuclear properties of NGC 315. We can conclude the following:

1. The nuclear source shows occasional increases in the continuum radio emission, indicating very active periods. Unfortunately, the lack of a continuous monitoring does not allow a comparison between the nuclear activity and variation in the parsec-scale morphology.

2. The 6 cm radio structure in the parsec-scale jet of NGC 315 is quite smooth, with some evidence of moving features and a faint counterjet. When interpreted in terms of a relativistic jet model, apparent motion of the features in the jet, as well as the jet/counterjet brightness ratio, indicate an acceleration of the jet in its inner 3–10 pc. A comparison of the jet’s observed properties with the predictions of a simple adiabatic expansion model further supports the interpretation of an increasing jet velocity. The present data is insufficient to determine whether the observed emission is from the entire jet or the slowest portions of an otherwise invisible, highly relativistic jet.

3. The extremely low upper limits on the polarization of the jet indicate either a very disorganized magnetic field in the inner parsecs of the jet or Faraday depolarization either in the jet or in front of it. A strong candidate for the depolarizing mechanism is Faraday depolarization in the NLR, future observations at higher frequency with higher angular resolution will clarify this point.

The authors would like to thank Alan Bridle, Roberto Fanti, Jose-Luis Gomez, and Daniele Dallacasa for several helpful discussions. We would also like to thank the staffs of the observatories who participated in these observations and the Socorro correlator staff. L. F. and G. G. acknowledge partial financial support by the Italian Ministry for University and Research under grant Cofin 98-02-32.

REFERENCES

Baum, S. A., et al. 1997, ApJ, 483, 178
Bicknell, G. V. 1984, ApJ, 286, 68
Biretta, J. A., Zhou, F., & Owen, F. N. 1995, ApJ, 447, 582
Bridle, A. H., Davis, M. M., Fomalont, E. B., Willis, A. G., & Strom, R. G. 1979, ApJ, 228, 19
Bridle, A. H., Davis, M. M., Melyo, D. A., Fomalont, E. B., Strom, R. G., & Willis, A. G. 1976, Nature, 262, 179
Cotton, W. D. 1993, AJ, 106, 1241
Davis, M. M. 1967, Bull. Astron. Inst. Netherlands, 19, 201
Dhawan, V., Kellerman, K., & Romney, J. P. 1998, ApJ, submitted
Ebnete, K., & Balick, B. 1985, AJ, 90, 181
Ekers, R. D., Fanti, R., & Miley, G. K. 1983, A&A, 120, 297
Fanti, R., Lari, C., Parma, P., Bridle, A. H., Ekers, R. D., & Fomalont, E. B. 1982, A&A, 110, 169
Fanti, R., Lari, C., Spencer, R. E., & Warwick, R. S. 1976, MNRS, 174, 5P
Fomalont, E. B., Bridle, A. H., Willis, A. G., & Perley, R. A. 1980, ApJ, 237, 418
Ghisellini, G., Padovani, P., Celotti, A., & Maraschi, L. 1993, ApJ, 407, 65
Giovannini, G., Cotton, W. D., Feretti, L., Lara, L., & Venturi, T. 1998, ApJ, 493, 632
Giovannini, G., Feretti, L., Venturi, T., Lara, L., Marcaide, J., Rioja, M., Spangler, S. R., & Wehrle, A. E. 1994, ApJ, 435, 116
Killeen, N. E. B., Bicknell, G. V., & Ekers, R. D. 1986, ApJ, 302, 306
Kirchbaum, T. P., Alef, W., Witzel, A., Zensus, J. A., Booth, R. S., Greve, A., & Rogers, A. E. 1998, A&A, 329, 873
Jägers, W. J. 1987, A&AS, 71, 75
Junor, W., & Biretta, J. A. 1995, AJ, 109, 500
Laing, R. A. 1996, in ASP Conf. Ser. 100, Energy Transport in Radio Galaxies and Quasars, ed. P. E. Hardee, A. H. Bridle, & J. A. Zensus (San Francisco: ASP), 241
Lara, L., Cotton, W. D., Feretti, L., Giovannini, G., Venturi, T., & Marcaide, M. 1997, ApJ, 474, 179
Linfield, R. 1981, ApJ, 244, 436
Marcha, M. J., Browne, I. W. A., Impye, C. D., & Smith, P. S. 1996, MnRS, 281, 425
Perley, R. A., Bridle, A. H., & Willis, A. G. 1984, ApJS, 54, 291
Preuss, E. 1983, in Astrophysical Jets, ed. A. Ferrari & A. G. Pacholczyk (Dordrecht: Reidel), I
Schwab, F. R., & Cotton, W. D. 1983, AJ, 88, 688
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Venturi, T., Giovannini, G., Feretti, L., Comoretto, G., & Wehrle, A. E. 1993, ApJ, 408, 81
Walker, R. C., Kellermann, K. I., Dhawan, V., Romney, J. D., Benson, J. M., Vermeulen, R. C., & Alef, W. 1998, in ASP Conf. Ser. 114, Radio Emission from Galactic and Extragalactic Compact Sources, ed. J. A. Zensus, G. B. Taylor, J. M. Wrobel (IAU Colloq. 164) (San Francisco: ASP), 133
Willis, A. G., Strom, R. G., Bridle, A. H., & Fomalont, E. B. 1981, A&A, 95, 250