THE ASTROPHYSICAL JOURNAL, 262:61–65, 1982 November 1

RADIO JETS IN NGC 4151

K. J. JOHNSTON
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C.
M. ELVIS
High Energy Astrophysics Division, Harvard-Smithsonian Center for Astrophysics
AND
D. KJER AND B. S. P. SHEN
Department of Astronomy and Astrophysics, University of Pennsylvania
Received 1981 July 23; accepted 1982 May 4

ABSTRACT

The radio radiation associated with the nucleus of the Seyfert galaxy NGC 4151 has been found to lie on a line of extent over 10″ (950 pc) along a position angle of 72°–84°. This nonthermal emission measured at λ6 and λ20 cm consists of at least six components and is similar to jets observed in other compact extragalactic radio sources. The optical line emission region appears to be coincident with the radio emission.

Subject headings: galaxies: individual — galaxies: Seyfert — radio sources: galaxies

I. INTRODUCTION

The bright Seyfert galaxy NGC 4151 has been studied extensively with arc second spatial resolution in the optical. Optical line emission associated with the nucleus of the galaxy has been shown to extend as far as 40″ from the center of the galaxy (Fricke and Reinhardt 1974; Ulrich 1973; Osterbrock and Koski 1976; Simkin 1975). Adopting $H_0 = 50$ km s^{-1} Mpc^{-1} and a systemic radial velocity for NGC 4151 of 980 km s^{-1} (Anderson and Kraft 1969) gives a distance of 20 Mpc and a scale of 1″ corresponding to 95 pc. The extended optical line emission (7600 pc) is roughly aligned along a position angle of ~50° (Fricke and Reinhardt 1974; Ulrich 1973). The polarized optical emission displays a position angle of 88° in the continuum emission from the broad-line emission region (BLR) and 46° in the narrow-line emission region (NLR) (Schmidt and Miller 1980).

The radiation mechanisms in Seyfert nuclei most closely resemble those of quasars. There is a great deal of interest in determining whether the radio emission in this source emanates from a different volume than the optical emission lines. The Very Large Array (VLA) of the National Radio Astronomy Observatory[1] (NRAO) allows one to obtain radio maps of NGC 4151 with a spatial resolution comparable to that of optical observations. A map made at λ6 cm by Ulvestad, Wilson, and Sramek (1981) shows the radio emission to be centered on the nucleus of NGC 4151 and elongated by ~4″ along a position angle of 84°, indicating that the radio radiation may consist of three or more components. In order to investigate the relationship between the radio and optical emission, we have mapped this source at λ20 and λ6 cm using the partially completed VLA.

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

II. OBSERVATIONS AND RESULTS

The observations were performed using the partially completed VLA of the NRAO on 1980 March 30. At this time, 21, 22, and 20 antennas were used at 1485 (λ20 cm), 4885 (λ6 cm), and 15,035 MHz (λ2 cm). The IF bandwidth was 50 MHz. The antenna spacings from the array center varied from 0.08 to 17.2 km. The spacings yielded synthesized beams of 1″.8 × 1″.6, P.A. −48° at 1485 MHz, and 0″.6 × 0″.5, P.A. −50° at 4885 MHz for no tapering applied to the correlated visibility data in the u, v plane. The observations of NGC 4151 were interleaved with observations of 1323+321 which was used as a calibration source. NGC 4151 was observed for a period of 12 hours centered on 12 hr LST. A 10 minute observation of NGC 4151 at λ20 or λ6 cm was followed by a 4 minute observation of 1323+321 at the appropriate wavelength. After cycling twice through the λ20 and λ6 cm measurements, a λ2 measurement was made of the 10 minute duration of NGC 4151 followed by a 5 minute observation of 1323+321. The flux density scale was established by assuming 1328+306 to have a flux density of 14.51, 7.41, and 3.48 Jy at λ20, λ6 and λ2 cm respectively (Baars *et al.* 1977). A single observation of 5 minutes duration of 1328+306 was made at all three wavelengths to establish the flux density ratio of 1328+307 with 1323+321 and NGC 4151.

The data were edited and calibrated in the normal manner using the 1323+321 observations to calibrate the correlated amplitude and phase data of NGC 4151. The standard programs available at the VLA were used. The calibrated amplitudes and phases were transformed

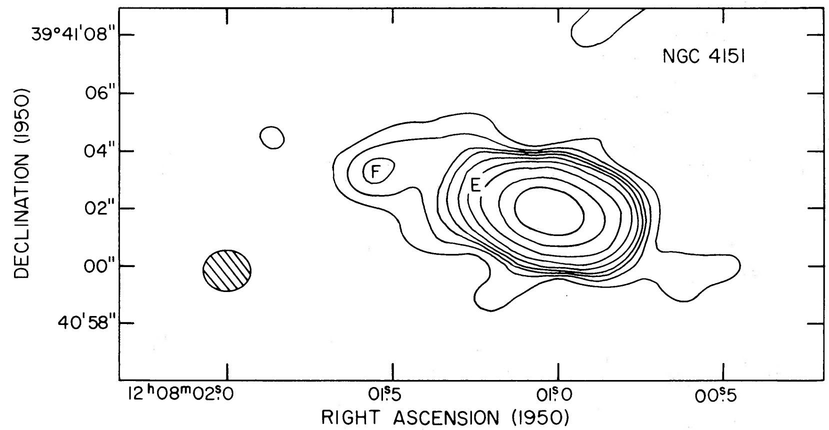

FIG. 1.—Low-resolution, self-calibrated cleaned λ6 cm contour map of NGC 4151. A Gaussian taper of 100 K λ has been applied to the u, v data. The restoring beam of 1".7 × 1".6, P.A. 89° is shown as a shaded ellipse. The contour intervals are 0.5%, 1.5%, 2%, 3%, 5%, 10%, 25%, and 50% of the peak flux density of 72 mJy per restored beam. Note the eastern elongation in structure denoted as component F. The R.A. and decl. scales are for epoch 1950.

to produce maps. The maps were cleaned using the CLEAN algorithm (Högbom 1974). The cleaned components were then used in a self-calibration algorithm (Schwab 1980) to increase the dynamic range of the λ6 cm maps an order of magnitude. The restored, self-calibrated maps at λ6 cm are displayed in Figures 1 (100 K λ Gaussian taper) and 2 (no taper on the u, v data). The 50% contour of the restoring beam is denoted by the crosshatched ellipse. Inspection of Figure 2 shows NGC 4151 to consist of at least five components (A–E) aligned along a position angle of 72° ± 4° for sources east of A and from −96° (B) to −102° (D) for sources west of A. The location of these components is listed in Table 1. The 100 K λ taper, λ6 cm map adds an additional component (F) also listed in Table 1. This component appears to be along a position angle of 87° ± 4°. Figure 3 displays a cleaned 20 cm map with Gaussian taper of 50 K λ applied to the

TABLE 1

RADIO COMPONENTS OF NGC 4151

	Position Offset[a] (arc sec)		Flux Density (mJy)	
Component	$\Delta\alpha$	$\Delta\delta$	λ20 cm	λ6 cm
A	0.0	0.0	250 (A–D)	43
B	−0.9	−0.3		30
C	1.0	0.3		9
D	−1.7	−0.4		8
E	2.8	0.8	>6.6	...
F	6.3	1.3	>3.3	...
Total			330	120

[a] Offsets in position are from $\alpha_{1950} = 12^h08^m01^s.052 \pm 0^s.010$, $\delta_{1950} = +39°41'02''.00 \pm 0''.10$.

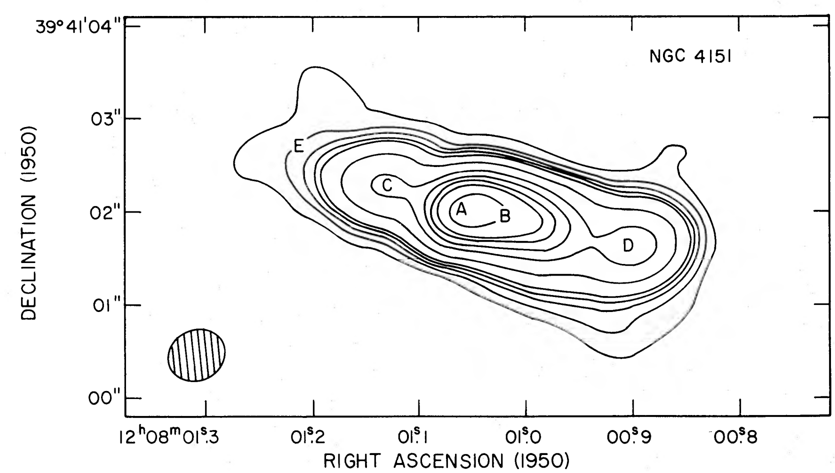

FIG. 2.—Self-calibrated cleaned λ6 cm contour map of NGC 4151. The restoring beam of 0".64 × 0".53, P.A. −64° is shown by the crosshatched ellipse. The contour intervals are 1%, 2%, 3%, 4%, 5%, 10%, 20%, 30%, 40%, 50%, and 75% of the flux density of 41 mJy per restored beam. Individual components are denoted by A through E and are listed in Table 1. The R.A. and decl. scales are epoch 1950.

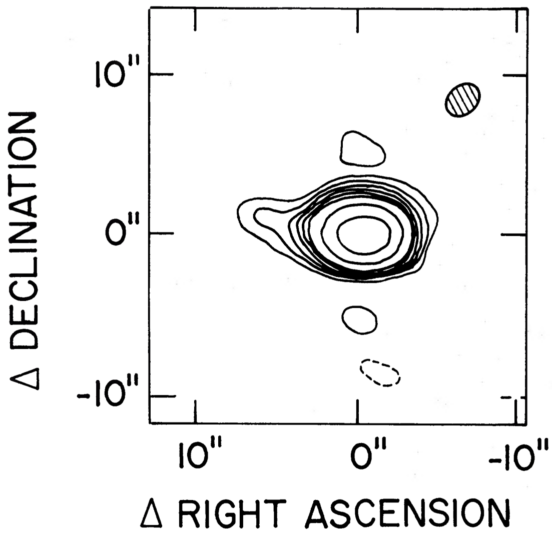

FIG. 3.—A λ20 cm contour map of NGC 4151 produced with Gaussian taper of 10 km applied to the visibility data before transforming. The central position of the map is component A (Table 1). The contour levels are −1%, 1%, 2%, 3%, 4%, 5%, 20%, and 50% of the peak flux density of 210 mJy per beam area. The beam is denoted by the shaded ellipse.

u, v data. Again, the distant western component F lies along a position angle of 80° from component A. The relative positions of components A and B are taken from the λ2 cm observations. The position of the central component (A) listed in Table 1 is based upon an assumed position of 1323+321 of α(1950) = $13^h23^m57\overset{s}{.}914$, δ(1950) = 32°09′43″.0. The central component A appears to be centered on the optical position of NGC 4151, which is α(1950) = $12^h08^m1\overset{s}{.}055$, δ(1950) = +39°41′1″.82 (Clements 1981) to within an error of ±0″.2. The linear alignment of the components appears to be constricted toward the west, while they appear to be distributed farther from the center and are more diffuse toward the east. The total flux densities contained in the 20 and 6 cm maps are 330 and 120 mJy, respectively, giving a spectral index, α, of −0.8 ($S \sim \nu^{+\alpha}$). The total flux density of the maps was obtained from the sum of the clean components and is therefore a lower limit to the flux density at these two wavelengths. The accuracy of the relative positions in Table 1 is ±0″.2 at λ6 cm. The flux densities listed in Table 1 are accurate to ±10%, with the exception of the λ6 cm fluxes of the A and B components which are heavily confused due to lack of adequate resolution at λ6 cm. No linearly polarized radiation of flux density greater than 0.4 mJy was detected at λ6 cm.

An inference that NGC 4151 consisted of at least three components at λ6 cm was made by Ulvestad, Wilson, and Sramek (1981). The observations presented in Figures 1–3 show the radio radiation from this source to extend over at least ~10″ (950 pc), along a position angle of 72°–84°. The position angle toward the east as measured by the λ6 and λ20 cm components appears to vary from 72° to 80° as distance increases from the central source eastward, marginally indicating that the radio emission rotates in position angle with distance from the central source. The emission west of A appears to vary in position angle from −96° (84°) to −102° (78°). The emission appears to be quite confined along a position angle of 72°–84° as the contours of Figure 2 show.

X-ray observations with the *Einstein Observatory* HRI (Giacconi *et al.* 1979) were made on 1980 May 20–21 with an exposure of 9128 s. The centroid of the X-ray emission was found to be α(1950) = $12^h08^m01\overset{s}{.}09$, δ(1950) = +39°41′02″.3. The systematic aspect uncertainty on this position is estimated to be less than 2″. In the HRI band 0.5–3.5 keV, a total of 460 counts was measured, which is equivalent to a luminosity of 5×10^{42} ergs s^{-1} (assuming 1 count $s^{-1} = 2 \times 10^{-11}$ ergs cm^{-2} s^{-1}). There is some marginal evidence for extended X-ray emission in the southwest quadrant toward component F in the radio map. However, a 3 σ limit of 1.2×10^{41} ergs s^{-1} or 25% of the total energy can be put on the X-ray emission of the F component. There is no X-ray emission exceeding 2×10^{40} ergs s^{-1} from a point source (>2″ FWHM) found between a radius of 6″ and 3′ from the central X-ray emission.

III. DISCUSSION

The radio emission associated with radio galaxies is usually divided into four morphological parts: the core, jet, hot spots, and diffuse emission (Miley 1980; Fomalont 1981). The core is a small-diameter component, ≤100 pc, which is coincident with the optical nucleus of the galaxy. In NGC 4151, this may correspond to component A, which is coincident with the optical nucleus. Typically, the spectral index ($S \sim \nu^{+\alpha}$) of the radio radiation from the core is 0 or inverted if the core is self-absorbed. The 2 cm observations of component A put a lower limit on the radio flux density of 8 mJy, making the radio spectral index of component A greater than 0. The measured size of this component is ≤0″.6 (57 pc). This is the region which must power the radio emission if it is to be typical of radio sources associated with elliptical galaxies.

Support for this interpretation is given by the optical polarization data of Schmidt and Miller (1980). The continuum polarization which is variable prefers a position angle of 88°. They interpret this continuum emission as a blend of Balmer continuum and line emission from the BLR and suggest the presence of an optical synchrotron source in the nucleus of NGC 4151 to account for the variations in both brightness and polarization.

NGC 4151 consists of a Seyfert type 1 nucleus which has a high-density BLR close to a nonthermal source of radiation surrounded by a larger volume of lower density material which emits the forbidden lines. Ulvestad, Wilson, and Sramek (1981) estimate that thermal emission from the BLR and NLR in NGC 4151 can contribute 3.1 MJy at λ6 cm or less than 3% of the total observed flux density. Thus the λ6 cm emission is nonthermal.

Radio jets which appear more often in low-luminosity sources may be loosely defined as linear features which originate from one or opposite sides of the radio core, often extending hundreds of kiloparsecs, terminating in a hot spot in the radio lobes. Components B through E are radio jets, while component F may be a hot spot in a diffuse radio lobe. The spectral index of radio jets is about -0.6. These features dominate the $\lambda 20$ and $\lambda 6$ cm emission which has a total spectral index of -0.8. The brighter features of radio jets are sometimes associated with linearly polarized optical emission (Miley *et al.* 1981). We do not observe linear polarization greater than 5% in the $\lambda 6$ cm radio emission of NGC 4151. However, in general, the position angle of the linearly polarized emission of the inner part of the jet is perpendicular to the jet axis and rotates 90° farther out along the jet. The location of this rotation of position angle varies directly with source luminosity, such that, for the most luminous sources, the position angle remains perpendicular to the jet axis. Weaker jets have the position angle of the polarized emission parallel to the jet axis (Fomalont 1981).

In NGC 4151 the radio emission appears to be aligned with the optical narrow emission line clouds which are distributed over $\sim 80''$ along a dominant position angle of $\sim 50°$ (Ulrich 1973; Fricke and Reinhardt 1974). The optical clouds are more confined to the southwest than to the northeast, as is the radio structure. These points suggest a close association between the optical emission-line and the radio structure.

If the optical emission-line gas is entrained in the radio jet, then we can use the velocity information derived from the lines to investigate the radio emission. The emission lines to the northeast are redshifted with respect to the nucleus and those to the southwest are blueshifted. If we use the velocities associated with the scale of a few arcseconds (Ulrich 1973), then the scale is similar to that of the radio jet. The position angle on this scale is rather poorly defined. Ulrich's cloud III is centered $\sim 2''$ northeast of the nucleus and has a redshift with respect to the nucleus of 180 km s^{-1}. If the radio plasma were ejected from the nucleus at 180 km s^{-1}, it would take 5×10^3 years to travel a distance of 95 pc. Taking the spectral index of the radio emission to be -0.8, this emission will have a synchrotron lifetime of $\sim 10^6$ years, and thus the radio emission can easily be accounted for without reacceleration as originating in a jet ejected from the nucleus. Again, from equipartition arguments, the magnetic fields are estimated to be 10^{-4} gauss.

The limits to linear polarized radio emission at $\lambda 6$ cm are $<1\%$ for component A, $<2\%$ for component B, and $<5\%$ for components C and D. Assuming that the radiation is due to a relativistic jet, this emission should be highly polarized ($<20\%$). This radiation may be depolarized by the warm gas in the forbidden-line region (FLR). The size of the radio components is ~ 100 pc, so that the density of the warm gas needed to depolarize the radiation must be greater than 10^{+4} cm^{-3}, assuming a filling factor of 1%. This equals the density obtained for the FLR from optical spectral measurements (Boksenberg *et al.* 1975).

The extended optical emission is dominantly along a position angle of 50° with a slight bulge along a position angle of 90°. If the plasma is ejected by a precessing beam (Hjellming and Johnston 1981), then this beam has rotated $\sim 30°$ during a period of 2×10^5 years if the optical emission measured by Fricke and Reinhardt (1974) is traveling at a velocity of 180 km s^{-1}. The radio synchrotron emission may have decayed via adiabatic expansion.

Previously, extended radio emission has been found in the Seyfert galaxies NGC 1068, NGC 5548 (Wilson and Willis 1980), MK 3 (Wilson *et al.* 1980), Mrk 6, Mrk 78, and probably NGC 4151 (Ulvestad, Wilson, and Sramek 1981). The radio emission is confined to the nuclear regions of the galaxies and exhibits double, triple, or diffuse structure, usually with the peak radio emission coincident with the optical continuum emission. This structural morphology is consistent with the ejection of radio-emitting plasma from the galactic nucleus aligned with the optical line emission regions (Ulvestad *et al.*). With higher resolution observations ($<0\farcs5$), perhaps all Seyfert galaxies will display radio structure similar to that found in elliptical galaxies and quasars. This radio structure is on a smaller scale in Seyfert galaxies because the rate of energy supply from the galactic nucleus is at least two orders of magnitude lower than that available in giant elliptical galaxies or quasars.

Another interpretation for the linearly polarized optical emission in NGC 4151 is that it is caused by electron scattering (Thompson *et al.* 1980). We do not consider this possibility because it cannot easily account for the alignment of the radio emission and polarized optical continuum radiation.

Finally, there is the possibility that the radio radiation is simply caused by the nuclear disk of NGC 4151. Inspection of Figure 2 shows the radio radiation to be confined along a range of position angles from 72°–84°, and to be roughly 100 pc in width and 1000 pc in length. However, the orientation of the NGC 4151 in space does not appear to support this hypothesis. The inclination of the plane of the galaxy NGC 4151 to that of the sky is 21°, while the position angle of its major axis is 26°, and the ratio of the minor axis to the major axis is 0.93. We are looking nearly face-on to NGC 4151.

IV. CONCLUSION

The radio emission at $\lambda 20$ to $\lambda 6$ cm has been shown to extend $10''$ (950 pc) along a position angle of 72°–84°. This emission which is nonthermal in origin is interpreted as synchrotron radiation associated with plasma ejected from the nucleus of NGC 4151. These radio jets appear to be coincident with the optical line emission region in NGC 4151 and are aligned with the position angle of the linearly polarized optical continuum emission.

We would like to thank James Ulvestad and Andrew Wilson for discussions of the results of this paper. This work was supported at the University of Pennsylvania by NASA grant NAS 8-33336 and at the Center for Astrophysics by NASA grant NAS 8-30751.

REFERENCES

Anderson, K. S., and Kraft, R. P. 1969, *Ap. J.*, **158**, 859.
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., and Witzel, A. 1977, *Astr. Ap.*, **61**, 99.
Boksenberg, A., Shortridge, K., Allen, D. A., Fosbury, R. A. E., Penston, M. V., and Savage, A. 1975, *M.N.R.A.S.*, **173**, 381.
Clements, E. D. 1981, *M.N.R.A.S.*, **197**, 829.
Fomalont, E. B. 1981, in *IAU Symposium 94, Origin of Cosmic Rays*, ed. G. Setti, G. Spada, and A. W. Wolfendale (Dordrecht:Reidel), p. 111.
Fomalont, E. B., Bridle, A. H., Willis, A. G., and Perley, R. A. 1982, *Ap. J.*, submitted.
Fricke, K. J., and Reinhardt, M. 1974, *Astr. Ap.*, **37**, 349.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Hjellming, R. M., and Johnston, K. J. 1981, *Ap. J. (Letters)*, **246**, L141.
Högbom, J. A. 1974, *Astr. Ap. Suppl.*, **15**, 417.
Miley, G. 1980, *Ann. Rev. Astr. Ap.*, **18**, 165.
Miley, G. K., Heckman, T. M., Butcher, H. R., and van Breugel, W. J. M. 1981, *Ap. J. (Letters)*, **247**, L5.
Osterbrock, D. E., and Koski, A. T. 1976, *M.N.R.A.S.*, **176**, 61P.
Schmidt, G. D., and Miller, J. S. 1980, *Ap. J.*, **240**, 759.
Schwab, F. R. 1980, *Proceedings of the 1980 International Optical Computing Conference*, ed. W. T. Rhoodes, **231**, 18.
Simkin, S. M. 1975, *Ap. J.*, **200**, 567.
Thompson, I., Landstreet, J. D., Stockman, H. S., Angel, J. R. P., and Beaver, E. A. 1980, *M.N.R.A.S.*, **192**, 53.
Ulrich, M. H. 1973, *Ap. J.*, **181**, 51.
Ulvestad, J. S., Wilson, A. S., and Sramek, R. A. 1981, *Ap. J.*, **247**, 419.
Wilson, A. S., Pooley, G. G., Willis, A. G., and Clements, E. D. 1980, *Ap. J. (Letters)*, **237**, L61.
Wilson, A. S., and Willis, A. G. 1980, *Ap. J.*, **240**, 429.

M. Elvis: High Energy Astrophysics Division, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

K. J. Johnston: Code 4130, Naval Research Laboratory, Washington, D.C. 20375

D. Kjer: Department of Astronomy and Astrophysics, University of Pennsylvania, Philadelphia, PA 19104

B. S. P. Shen: Department of Astronomy and Astrophysics, University of Pennsylvania, Philadelphia, PA 19104