THE ASTROPHYSICAL JOURNAL, 285:L35–L38, 1984 October 1

THE JET AND FILAMENTS IN CYGNUS A

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Received 1984 April 2; accepted 1984 June 29

ABSTRACT

Multiconfiguration VLA observations of Cygnus A at 1.4 and 5 GHz have been used to produce detailed maps of exceptional dynamic range. A radio jet extends from the core into the northwest lobe. The broad radio lobes reveal an unexpected wealth of filamentary structure. Two new hot spots are identified. The pressure of the cluster gas in which Cyg A is embedded appears to be insufficient to confine either the jet or the filaments. From the necessarily high mechanical luminosity of the jet and the high energy densities of the hot spots, we conclude that the jet is probably relativistic. The surface brightness of the jet is high in absolute terms, but the total radiated power of the jet is only 10^{-3} of that of the whole source.

Subject headings: galaxies: jets — interferometry — radio sources: galaxies

I. INTRODUCTION

The large angular size and high flux density of the radio galaxy Cygnus A (3C 405) have made it one of the most extensively observed extragalactic radio sources. With a 1.4 GHz monochromatic power of 6×10^{34} ergs s^{-1} Hz^{-1} (we use a Hubble constant of 75 km s^{-1} Mpc^{-1} throughout, giving a scale of 1 kpc per arc second), it is one of the most luminous radio galaxies known, comparable with the radio-loud quasars. Cygnus A is optically identified with a cD galaxy (Spinrad and Stauffer 1982) of redshift 0.0562 (Simkin 1977) and lies within a luminous X-ray cluster (Fabbiano *et al.* 1979). At radio wavelengths, Cygnus A has a double structure with total projected extent of ~ 120 kpc. Small regions of high intensity (hot spots) are located at the extrema, and diffuse lobes stretch back toward the optical galaxy. These structural characteristics are typical of high-luminosity radio sources (i.e., those with 1.4 GHz spectral powers exceeding $\sim 10^{32}$ ergs s^{-1} Hz^{-1}); indeed, Cygnus A is widely regarded as the prototype of such sources.

Cygnus A provides one of the sternest tests for theories of radio galaxy structure and evolution due to the extreme values of its minimum total energy (10^{60} ergs), radio luminosity (10^{45} ergs s^{-1}), and energy density (up to 10^{-8} ergs cm^{-3}). The discovery of the hot spots (Hargrave and Ryle 1974), located ~ 60 kpc from the nucleus, led to models in which energy is continuously and efficiently channeled from the nucleus to the hot spots by way of highly collimated supersonic jets (Blandford and Rees 1974; Scheuer 1974). Shock deacceleration of these jets can cause efficient particle acceleration by the first-order Fermi process (Bell 1978; Blandford and Ostriker 1978); the hot spots are identified with these shocks. The lobes are the regions behind the advancing hot spots where "waste" particles are deposited. This model predicts the existence of jets in (essentially) all extended radio galaxies and quasars, and considerable effort has been put into detection of these jets at radio frequencies. The results of these observational efforts have strongly supported the model: over 125 radio galaxies and quasars have been found to contain jets (Bridle and Perley 1984). However, the expected jet in Cygnus A has proven difficult to detect—until now, only a milli-arcsec extension of the core has been found (Kellermann *et al.* 1975; Linfield 1981).

II. OBSERVATIONS AND RESULTS

High dynamic range mapping of complex radio sources requires very dense sampling of the synthesized aperture plane. To satisfy this requirement, data were taken in the A, B, and two mixed configurations of the VLA at both 4885 MHz and 1446 MHz. After standard calibration, the data were removed to the AIPS processing system. The self-calibration program of Schwab (1980) was used to enhance the dynamic range, while deconvolution of the maps was performed with the Clark implementation of CLEAN (Högbom 1974; Clark 1980) and also with maximum entropy analysis (Wernecke and D'Addario 1976; Cornwell and Evans 1984). Careful comparison of the resulting images from the different techniques shows no important differences. We will give a full description of these techniques elsewhere. The resulting dynamic ranges (peak brightness to rms noise in a nearby region) are $\sim 3000{:}1$ and $\sim 10{,}000{:}1$ at 6 and 20 cm, respectively. We report here

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

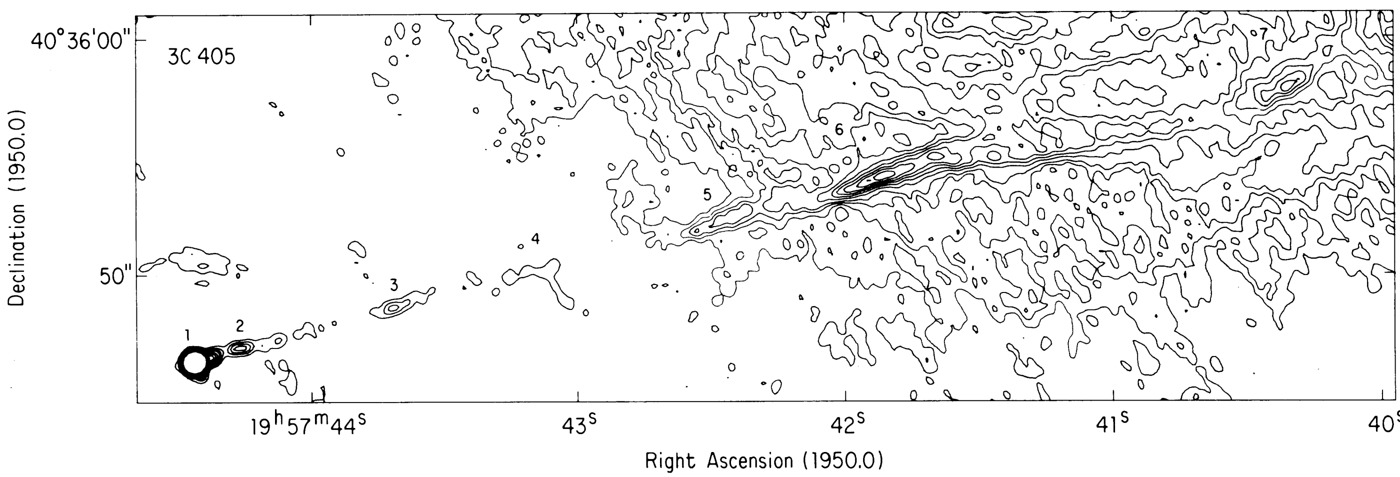

FIG. 3.—A contour plot of the jet of Cygnus A at 6 cm wavelength with 0″.4 resolution. This map is the result of convolving a maximum entropy map with a 0″.4 Gaussian restoring beam. The contour levels are at 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and 1.1% of the peak intensity of 3.26 Jy per beam.

only the total intensity results; the polarization data will be presented in a future, more comprehensive paper.

Figure 1 (Plate L1) shows a sequence of three gray-scale representations of a 5 GHz, 0″.4 resolution map with progressively deeper "exposures." Figure 2 (Plate L2) shows two gray-scale images of a 1.4 GHz map with 1″.25 resolution. These figures clearly show the presence of the jet as well as an unexpected wealth of fine detail in the lobes. We are certain of the reality of these faint, complex structures both because they bear no resemblance to the artifacts commonly produced in extended structures by undersampling or deconvolution and, more importantly, because they appear on maps made at both frequencies with similar resolution.

Figure 3 displays a contour plot of the jet, showing that the jet can be traced more or less continuously from the nucleus to well inside the northwest lobe. The brightness enhancements of the jet (labeled 1–7), indicate that the jet is lumpy with brightness contrasts exceeding 4:1. The jet is partially resolved and displays at least two regions of expansion. In these regions (up to knot 2 and after knot 4) the expansion angles are $\sim 5°$, while between knots 2 and 4 the jet is of constant width. The jet surface brightness generally declines with distance from the core until the jet enters the lobe, at which point the jet widens, brightens, and bends through an angle of $\sim 8°$. After another bend, the jet enters the high-brightness region of the lobe and disappears.

There are some indications of what may be a counterjet in the southeast lobe (see Fig. 1*c*), but a definitive detection must await yet more data. Since the jet is only about 4 times the minimum brightness which we believe to be reliable, the jet/counterjet brightness ratio must be greater than or equal to 4.

Although the jet is weak in comparison to the lobes, contributing only 0.1% of the total source flux density, it is very bright in absolute terms, averaging 90 mJy arcsec^{-2} at 6 cm, considerably brighter than any other well-resolved radio jet.

With a linear resolution of 0.4 kpc, the seemingly smooth radio lobes of earlier maps can be seen to contain complex filamentary structures. These filaments appear to lack any general order in the brighter regions of the lobes but exhibit a more orderly structure, roughly aligned with the source axis, in the inner, fainter parts of the lobes. (We use "inner" and "outer" to denote regions of a feature which are found toward and away from the nucleus.) Most of the filaments are only slightly resolved with a typical width of less than 500 pc and a 6 cm brightness of from 500 mJy arcsec^{-2} to less than 100 mJy arcsec^{-2}. In the inner regions of the lobes, some of the filaments are as long as 20 kpc.

A striking elliptical ringlike feature located in the SE lobe is clearly evident in Figure 2. The dimensions of this ring are 16 kpc by 8 kpc, with the major axis aligned perpendicular to the source axis. The typical thickness and 20 cm surface brightness are ~ 2 kpc and ~ 100 mJy arcsec^{-2}. The ring cannot be traced all the way around, as the outer part is embedded in a region of greatly enhanced diffuse emission. Other arcs of similar dimension appear in this region but are less prominent.

The NW lobe also appears to have ringlike structures, but they are not as distinct as the prominent one in the SE lobe. Approximately 8″ to the east of the A hot spot (using the nomenclature of Hargrave and Ryle 1974) is a thick loop, perhaps akin to that recently reported in 3C 310 (van Breugel and Fomalont 1984). In the vicinity of the A and B hot spots, several thin arcs can also be seen. These have a similar appearance to some of the features seen in Hercules A (Dreher and Feigelson 1984) but are lacking in the organization which characterizes the rings of that source.

The outer, leading edges of the lobes are very sharp, being unresolved ($< 0''.2$) in many places, while the inner edges are diffuse. Sharp boundaries to the emission can also be seen at several locations on the sides of the lobes and may indicate that these regions are rapidly expanding transverse to the source axis.

Two new hot spots are clearly evident. One, which we label "E," is located 5″ west of "D" and appears to have been first detected by Bentley *et al.* (1975), and later by Scott (1982), and by Alexander, Brown, and Scott (1984). The other knot is

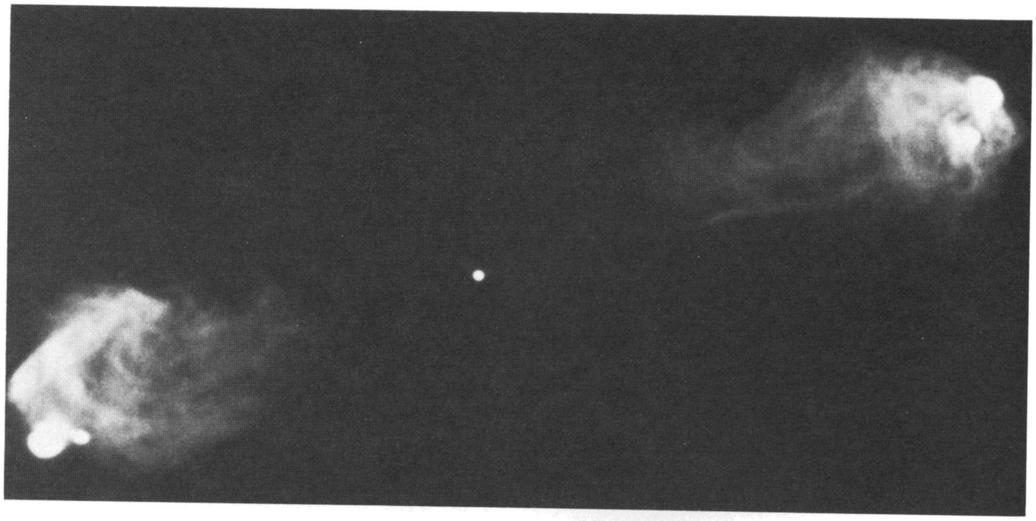

FIG. 1*a*

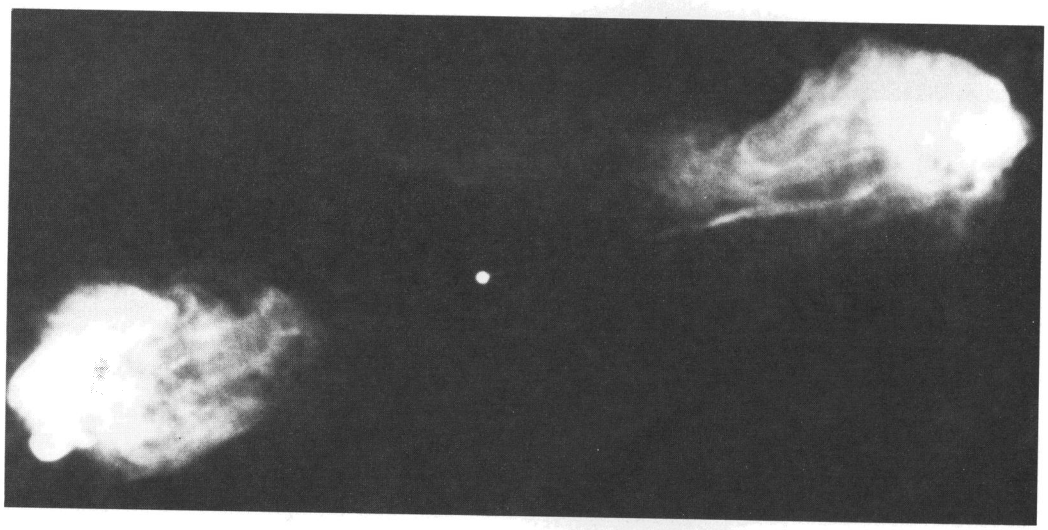

FIG. 1*b*

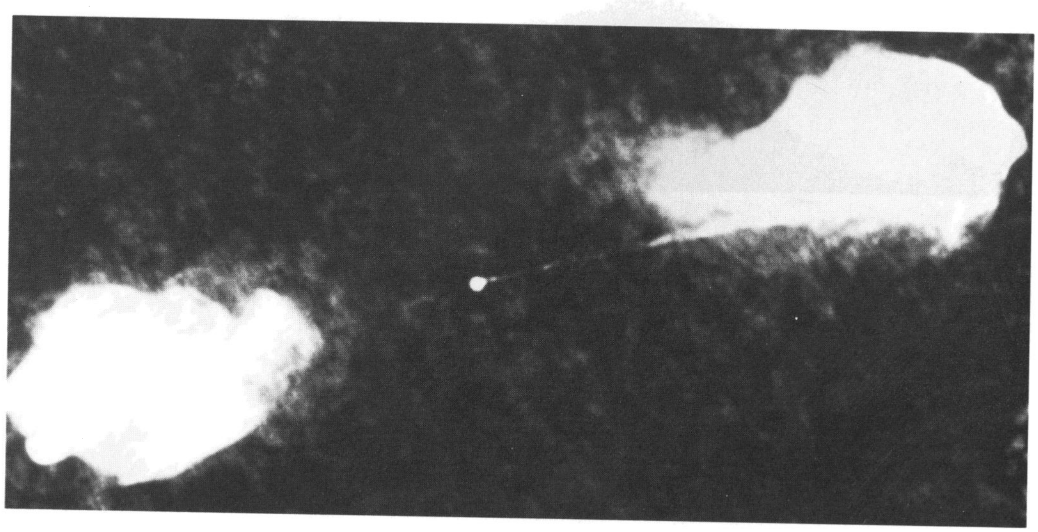

FIG. 1*c*

FIG. 1.—Photographic representation of Cygnus A at 6 cm wavelength with 0″.4 resolution. The exposures are varied such that saturation occurs at 250, 60, and 15 mJy per beam in Figs. 1*a*, 1*b*, and 1*c*, respectively. The east-west extent of the radio emission is 127″.

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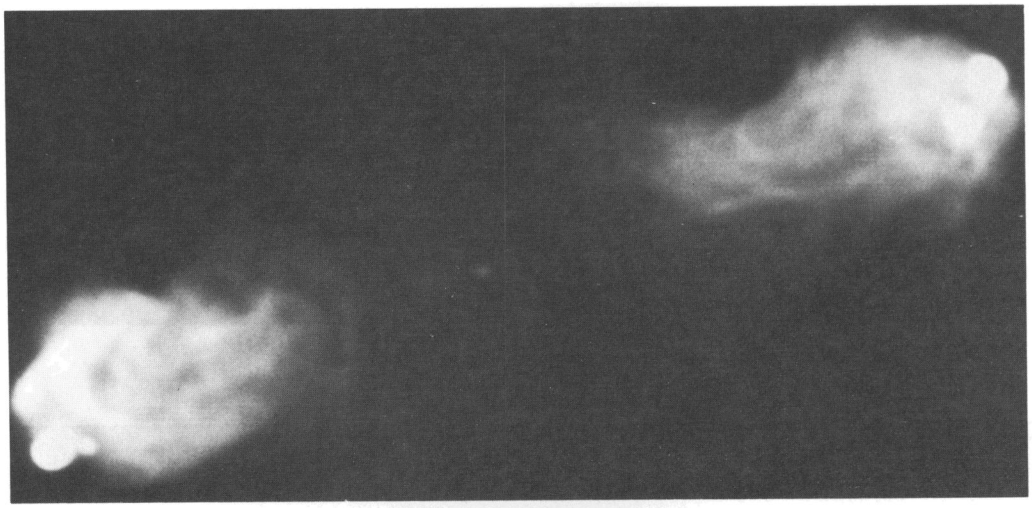

FIG. 2a

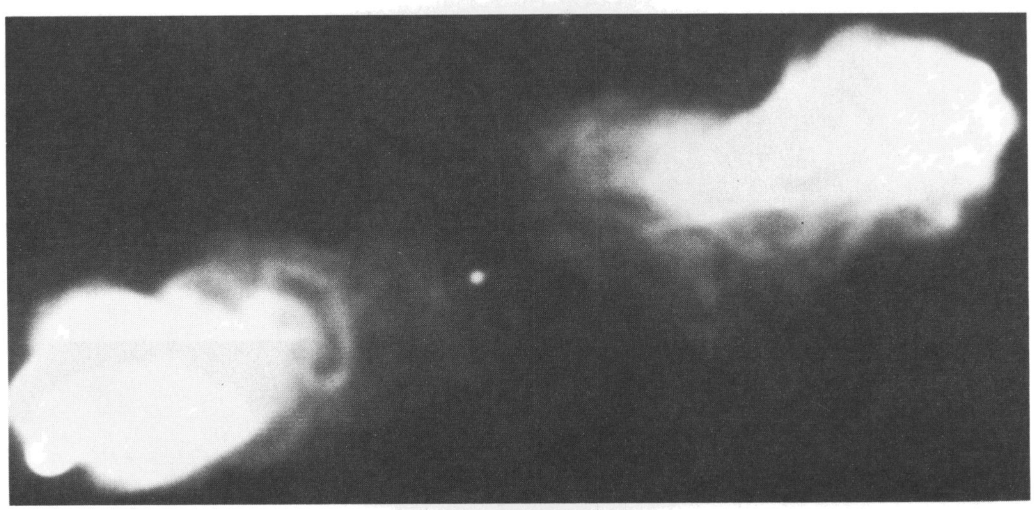

FIG. 2b

FIG. 2.—Photographic representation of Cygnus A at 20 cm wavelength with 1″25 resolution. The exposures are varied such that saturation occurs at 4 and 1 Jy per beam in Figs. 2a and 2b, respectively.

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~ 5″ southeast of B. It is only slightly resolved and has no detectable emission on the 20 cm maps. The resultant spectral index of ~ 0 makes its identification with Cygnus A unlikely.

III. DISCUSSION

a) The Filaments

If the filament geometry is ropelike, the filament depths will be similar to their observed widths. This results in an equipartition field of about ~ 130 microgauss. On the basis of the apparent depolarization of the lobes, Hargrave and Ryle (1974) suggested the thermal gas density there is $\sim 3 \times 10^{-3}$ cm^{-3}. If this value applies to the filaments, they will expand at their internal sound speed and dissipate in $\leq 10^5$ years unless some confining mechanism is present. This cannot be provided by the relativistic pressure of the interfilament medium, since its emissivity and hence, pressure, is far less than that of the filaments (unless it is far from equipartition). Another estimate of the interfilament pressure can be made from the properties of the X-ray emission, presuming that the lobes are in pressure equilibrium with the cluster gas. Although the detailed X-ray data on the cluster have not been analyzed, the high X-ray luminosity (2×10^{44} ergs s^{-1} in the 2–6 keV band; Fabbiano *et al.* 1979), angular extent ($\geq 2'$), and presence of an exceptionally large central galaxy argue that the morphology will be of the evolved XD type (Jones and Forman 1984). For typical clusters of this type, hydrostatic-isothermal models give central densities and core radii of $\sim 5 \times 10^{-3}$ cm^{-3} and 0.25 Mpc. Using a gas temperature of 7×10^7 (Longair and Willmore 1974), the thermal gas pressure is 5×10^{-11} dyn cm^2, an order of magnitude less than the filament pressure. The same parameters will give an X-ray luminosity of 2×10^{44} ergs s^{-1}. From this, it appears that unless the cluster temperature and/or density are unusually high, or another confinement mechanism operates, the filaments cannot be static.

It may be, however, that the filaments are transient features which do not require confinement. In this case, it can be imagined that they are shocks, perhaps caused by the supersonic motion of the jet or hot spot. The filamentary structure would then be the loci where our line of sight is nearly in the plane of the curved surface of a sheet. The shock velocity can be estimated by balancing its internal pressure against the dynamic pressure of the interfilament medium, giving $0.01c$, similar to the lobe expansion velocity (Winter *et al.* 1980).

It has been customary in dealing with the energetics of extended extragalactic radio sources to assume a filling factor of unity when applying equipartition formulae. While the complex nature of the filaments limits accuracy, we estimate that the filling factor in the lobes of Cygnus A is between 0.03 and 0.3. This factor will roughly halve the minimum energy required for the lobes.

Detailed examination of the lobe structure suggests that there is a smooth underlying distribution of synchrotron emission in addition to the filaments. The minimum (6 cm) brightness found in the inner, fainter regions of the lobes is ~ 50 to 100 mJy arcsec^{-2} which, combined with path lengths of ~ 20 kpc, yields minimum pressures (Burns, Owen, and Rudnick 1979) less than or comparable to the X-ray cluster pressure. In the outer regions of the lobes, however, the minimum brightnesses are higher, ~ 200–300 mJy arcsec^{-2}; since the ambient pressure presumably declines with radius, pressure balance between the interfilament medium and external gas may not exist in these regions. A detailed comparison must await analysis of the X-ray data.

b) The Jet

As shown by Bridle and Perley (1984), the ratio of jet kinetic energy flux to thrust in a high Mach number jet is $v\gamma/(\gamma + 1)$. Estimates of these quantities thus give (model-dependent) estimates of the jet velocity. Hargrave and Ryle (1974) have argued that the jet luminosity is $\sim 3 \times 10^{45}$ ergs s^{-1}; a second estimate of $(6 \times 10^{44}/\varepsilon)$ ergs s^{-1} is obtained from the total radio luminosity, where ε is a conversion efficiency factor. The jet thrust can be computed from the minimum pressure and area of the "D" hot spot, giving $\sim 6 \times 10^{34}$ dyn. The resulting ratio of ~ c indicates that the jet may be relativistic. A slow jet ($v \ll c$) can only be obtained by greatly increasing the efficiency ε and/or increasing the pressure of the hot spot well beyond the value given by equipartition. Although the estimates of jet kinetic energy and thrust are subject to considerable error, we believe it unlikely that the jet γ is less than ~ 1.6. This velocity leads to a comoving jet density $< 2 \times 10^{-29}$ g cm^{-3} and a mass flux of $< 0.03\ M_\odot$ yr^{-1}. On the basis of the spectral steepening of the lobe emission, Winter *et al.* (1980) estimated the age of Cygnus A to be 6×10^6 yr. With this value, and the observed lobe volume, the lobe density should be $\sim 10^{-6}$ cm^{-3}, more than three orders of magnitude less than the value derived by Hargrave and Ryle (1974) from interpreting the low 6 cm polarization as being due to Faraday depolarization. If the lobes are indeed depolarized by internal thermal gas, this gas is unlikely to have originated from the jet and is probably cluster gas which somehow entered the lobe. Data necessary to clarify this important point are now being processed.

With this velocity, relativistic brightening effects become significant. For $v/c = 0.8$, two opposed jets of equal intrinsic brightness would exhibit an apparent brightness ratio of ≥ 4 if their inclination from the plane of the sky were as little as 30°. Hargrave and Ryle (1974), Simkin (1977), and van den Bergh (1976) have argued that the main axis of the radio structure does lie within ~ 30° of the sky. Thus, the observed jet/counterjet brightness asymmetry can easily be obtained. However, the observed brightness ratio on milli-arcsec scales of > 15:1 (Linfield 1982) implies a *minimum* jet inclination of ~ 30° from the plane of the sky along with a jet velocity of ~ c. Considerable deceleration (perhaps combined with mass entrainment) may be required between parsec and kiloparsec scales. We note that Doppler beaming with jet inclination angles approximately in the plane of the sky cannot account for the brightness variations seen in the vicinity of the bends in the jet.

The equipartition magnetic field strength in the jet varies from somewhat greater than 200 microgauss in knot A to ~ 90 microgauss in the faintest detected portions. The corresponding minimum pressures vary from $\sim 25 \times 10^{-10}$ to 4×10^{-10} dyn cm^{-2}. As argued in § III*a*, the external thermal gas pressure is unlikely to exeed $\sim 5 \times 10^{-11}$ dyn cm^{-2}.

Thus, as in the case of the powerful jet in 4C 32.69 (Potash and Wardle 1980; Wardle and Potash 1982; Dreher 1982) and the much less powerful jet in M87 (Biretta, Owen, and Hardee 1983), the bright knots in Cygnus A jet cannot be confined by any known external pressure. This discrepancy might be taken as evidence that the Cyg A jet is free; however, the distinct stages of expansion and the bends in the jet both argue for a confined jet. Furthermore, it is probably erroneous to argue that the jet is unconfined based on observations of hot condensations which may well represent unconfined shocks. Detection of the jet between the knots, and proper analysis of the X-ray data, are required to further enlighten this problem.

We conclude by noting that these observations may cause considerable rethinking of the physics of extended radio sources, a role which Cygnus A has played since its discovery. We fully expect that more surprises will arise from analysis of our continuing observations of this source.

This work was supported in part by the National Science Foundation through grant AST 82-14964 at the University of Oklahoma and AST 82-10996 at MIT. We thank Ed Fomalont, Tim Cornwell, and Alan Bridle for valuable comments on an earlier version, and Eric Feigelson for useful discussions on X-ray cluster emission.

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