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EXTENDED OPTICAL LINE EMISSION FROM 3C 293: RADIO JETS PROPAGATING THROUGH A ROTATING GASEOUS DISK

WIL VAN BREUGEL[1]
Steward Observatory, University of Arizona
TIMOTHY HECKMAN[2]
Astronomy Program, University of Maryland
HARVEY BUTCHER
Kitt Peak National Observatory[3]
AND
GEORGE MILEY[2]
Sterrewacht Leiden, The Netherlands; and Kitt Peak National Observatory[3]
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ABSTRACT

We present optical images and long-slit spectra of extended, line-emitting gas associated with the peculiar radio galaxy 3C 293. These data provide strong evidence that the galaxy contains a rotating gaseous disk in which the powerful, kiloparsec-sized radio core of 3C 293 is immersed. The emission lines from this gas are relatively broad, suggesting that noncircular motions are important. 3C 293 is shown to resemble in many respects the well-studied radio galaxy 3C 305. We propose that in both these radio galaxies, jets propagate through the dense rotating gaseous disks. Interaction of the jets with this medium affects both the emission lines and the radio source. We suggest that the radio and optical emission is associated with shocks, driven by the jets, which propagate through a multiphase interstellar medium. The **Z**-shaped radio morphology may be due to collisions between the jet and dense disk material (clouds): After being slowed down, the jets may be bent through "sweeping" (by the gaseous disk), as proposed by Wilson and Ulvestad. If the average gas density in the inner few kiloparsecs of VV 5-33-12 is similar to that in our own Galaxy, this would require that the jets are light, fast, and efficient in producing radio emission. As opposed to 3C 305, the large-scale radio emission in 3C 293 suggests that in this source the jets are still able to pierce the disk after being deflected, supplying energy to the weaker outer lobes.

Subject headings: galaxies: individual — galaxies: internal motions — galaxies: jets — particle acceleration — radio sources: galaxies

I. INTRODUCTION

The morphologies of both the radio source 3C 293 and its associated galaxy (VV 5-33-12) are unusual (e.g., Argue, Riley, and Pooley 1978). Recent Very Large Array (VLA) observations by Bridle, Fomalont, and Cornwell (1981, hereafter BFC) show that 3C 293 is dominated by a kiloparsec-sized steep-spectrum core which consists of various compact ($\leq 0''.1$) regions, or "knots." The core is linked by a curved bridge of faint radio emission to a bright extended outer hot spot approximately $1'.5$ (~ 70 kpc; a Hubble constant of 75 km s^{-1} Mpc^{-1} is assumed throughout this paper) northwest of the galaxy. A much fainter bridge and hot spot are also present to the southeast, and the overall morphology of the source is slightly **Z**-shaped. The major axis of the radio core is misaligned by about 35° with these bridges and by about 60° with the galaxy minor axis. To explain these misalignments, BFC present models based on jet refraction in a dense and hot gaseous halo (Henriksen, Vallée, and Bridle 1981).

The associated galaxy has a highly flattened, complex morphology crossed by what seems to be a prominent, irregular dust lane (Argue, Riley, and Pooley 1978; Battistini *et al.* 1980). The galaxy has been variously classified as an Sb (Sandage 1966), S0 (Colla *et al.* 1975), and D6 (Burbidge and Crowne 1979) and has optical line emission ([O II] λ3727, Sandage 1966; Hα, Burbidge 1967). In addition, a faint bridge appears to connect VV 5-33-12 to a small galaxy approximately 40″ to the southwest (Wills and Parker 1966; Argue, Riley, and Pooley 1978).

Neutral hydrogen absorption of the core region of 3C 293 was detected by Baan and Haschick (1981). They report several absorption features: a narrow (41 km s^{-1}) absorption line at the systemic velocity ($\sim 13{,}500$ km s^{-1}) of the galaxy and much wider (~ 130 km s^{-1}) blueward- and redward-displaced absorption lines. The total velocity width of ~ 480 km s^{-1} is one of the broadest yet detected. The data are consistent with either a rotating or radially moving absorbing gas.

The combined presence of a bright, steep-spectrum, kiloparsec-sized radio core and optical line emission warranted a further optical investigation of the line-emitting gas. There are several indications of a statistical nature that such kiloparsec-sized radio cores are closely related to "narrow-line"

[1] Work partially completed while at Kitt Peak National Observatory and at Leiden Observatory.
[2] Visiting Astronomer, Kitt Peak National Observatory.
[3] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

emission regions (Heckman *et al.* 1981; Miley 1981). Furthermore, a detailed radio and optical study of the peculiar radio galaxy 3C 305 showed that close *spatial* correlations also exist in that galaxy between the radio-emitting plasma and the optical line-emitting gas (Heckman *et al.* 1982). Similar associations have also been found on a larger scale for 3C 277.3 (Miley *et al.* 1981; van Breugel *et al.* 1984*a*) and other radio galaxies (van Breugel and Heckman 1982).

In this paper (§§ II and III) we present broad-band blue and narrow-band Hα + [N II] $\lambda\lambda$6548, 6583 imaging together with long-slit spectroscopic data on the [O II] λ3727 and [O III] λ5007 lines. These new results show that the galaxy has a rotating gaseous disk which encompasses the radio core. Its relationship to the radio structure of 3C 293 is discussed, and a comparison with the very similar source 3C 305 is made in § IV.

II. OBSERVATIONS AND REDUCTION

a) *Optical Imaging*

Optical images of 3C 293 were obtained 1979 April 22 with the Kitt Peak National Observatory (KPNO) video camera system (Robinson *et al.* 1979) on the 4 m Mayall telescope. To obtain an overall picture of the galaxy with its dust lane, a 13 minute exposure was taken in $\sim 1''$ seeing using a broad-band ($\sim$900 Å full width half-maximum [FWHM]) blue filter. To map the optical line emission a narrow-band ($\sim$55 Å FWHM) exposure was taken centered on the redshifted Hα line, and a corresponding "off-band" image was taken through a filter centered on the continuum at $\sim$6200 Å ($\sim$175 Å FWHM). Using appropriate calibrations these images were corrected for nonuniformities in response across the field and geometrical distortions (see Ford and Butcher 1979). The "off-band" and "on-band" images were then aligned, scaled to correct for differences in filter throughput, and subtracted to yield an "on-off" image. Absolute flux calibration was applied using measurements of the standard star EG 119 (Oke 1974), observed through the same Hα + [N II] filter.

b) *Spectroscopy*

In order to derive the kinematics of the emission-line gas, long-slit ($\sim 2'' \times 166''$) spectra were taken in 1981 June and 1982 April with the High-Gain Video Spectrometer (HGVS) on the 4 m telescope at Kitt Peak. During the 1981 June observations, two orthogonal slit positions were used, and the grating was chosen to cover the redshifted [O II] λ3727 doublet. This line was selected because the HGVS is more sensitive in this spectral region than it is near the Hα + [N II] $\lambda\lambda$6548, 6583 lines (the only other strong emission lines reported to be present in the spectrum of 3C 293). The 1982 April observations were conducted primarily to obtain information on the *stellar* dynamics of 3C 293 (results to be published elsewhere). The spectral region observed included the [O III] λ5007 and Hβ emission lines, and the data relevant to the kinematics of the line-emitting gas will be discussed here. Details concerning the HGVS specifications and the gratings used are given in Table 1. The reduction was carried out in the standard way described by Heckman *et al.* (1981, 1982).

TABLE 1

PARAMETERS OF THE HGVS SPECTRA

Position Angle (°)	Wavelength Coverage (Å)	Wavelength Resolution (Å)	Integration Time (min)
60	3824–4184	2.5	13
150	3824–4184	2.5	13
65	5021–5711	3.9	52

To derive the velocities and line widths from the [O II] doublet, which is blended in our spectra, we have used a Gaussian deconvolution technique, assuming an intensity ratio of the doublet of $\sim$1. This is equivalent to the assumption of a density of $\sim$600 cm^{-3} of the emission-line gas. This assumption is probably reasonable because of the close resemblance of the core properties of 3C 293 to 3C 305, where typical densities of $\sim 10^3$ cm^{-3} were found (Heckman *et al.* 1982). The derived *widths* are relatively insensitive to these assumptions, and we estimate that the total uncertainties are not larger than 25%. The uncertainty in the relative *velocities* due to the blend is at most ± 35 km s^{-1}. The uncertainties in the [O III] λ5007 velocities and line widths are comparable to those for the [O II] doublet.

c) *Radio Imaging*

High-resolution radio maps of the core of 3C 293 have been made with the VLA at 2 cm ($\sim$0ʺ2 resolution; BFC) and at 1.3 cm ($\sim$0ʺ08 resolution; van Breugel *et al.* 1984*b*) and with MERLIN at 18 cm (0ʺ25; BFC). The VLA maps are reproduced in this paper (Figs. 4 and 5) for comparison with the optical data.

III. RESULTS

a) *Imaging*

The broad-band blue and narrow-band Hα + [N II] images of 3C 293 are shown in Figures 1*a* and 1*b* (Plates 2 and 3).

The blue exposure clearly shows the peculiar morphology of the galaxy. It appears as if a nonuniform, warped dust lane obliquely crosses the main body of the galaxy. Near the bright central region, the dust lane is smoothly curved. If we assume that in this region the dust lane encircles the nucleus of the galaxy, we can identify the northwestern part of the galaxy as the near side. The inner radio position angle is almost perpendicular to this central dust lane, as is the case for many other radio galaxies (Kotanyi and Ekers 1979).

The reproduction of the blue image in Figure 1*a* has been optimized to show the central region. A contour representation of the same data (Fig. 2) clearly shows the faint bridge stretching along the major axis toward a small galaxy at the southwest edge of the image (originally pointed out by Wills and Parker 1966).

The Hα + [N II] exposure also shows evidence for obscuration. The overall appearance of the emission-line region is similar to that of the galaxy; i.e., both are highly flattened (minor/major axis ratio ≈ 0.4), and their major axes are approximately aligned to within $\sim 15°$. Such an appearance would be expected if the emission-line region and the galaxy are both disk shaped and viewed at a large inclination angle of $i \approx 65°$. The irregular surface brightness distributions

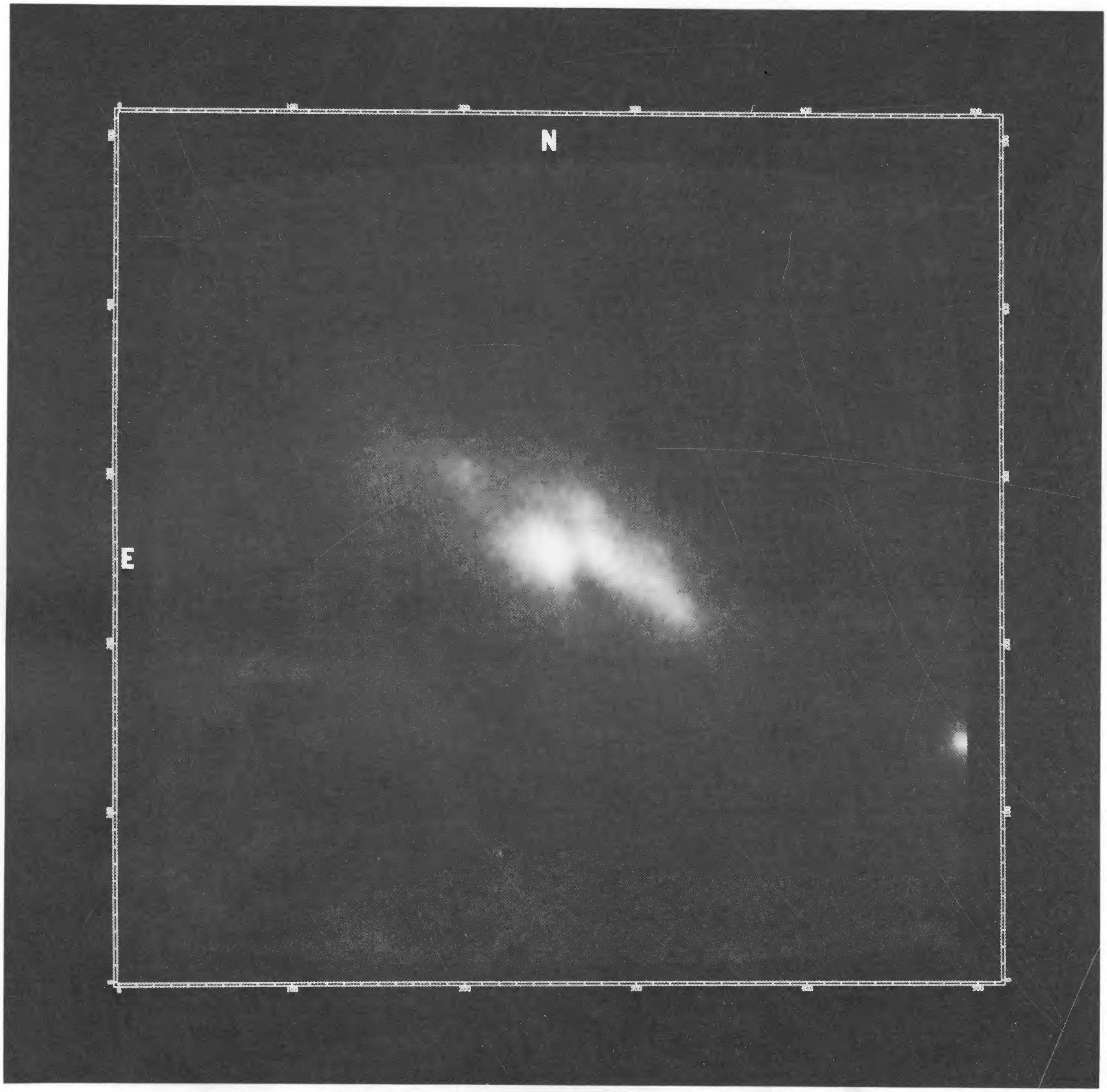

FIG. 1*a*.—Blue image (75″ × 75″) of the galaxy VV 5-33-12 associated with 3C 293. Part of a companion object can be seen just at the southwestern edge of the field. (See also Fig. 2.) The curved boundaries are the result of a distortion correction, which has been applied to the video camera data. North is upward, and east is to the left.

VAN BREUGEL *et al.* (*see* page 83)

1984ApJ...277...82V

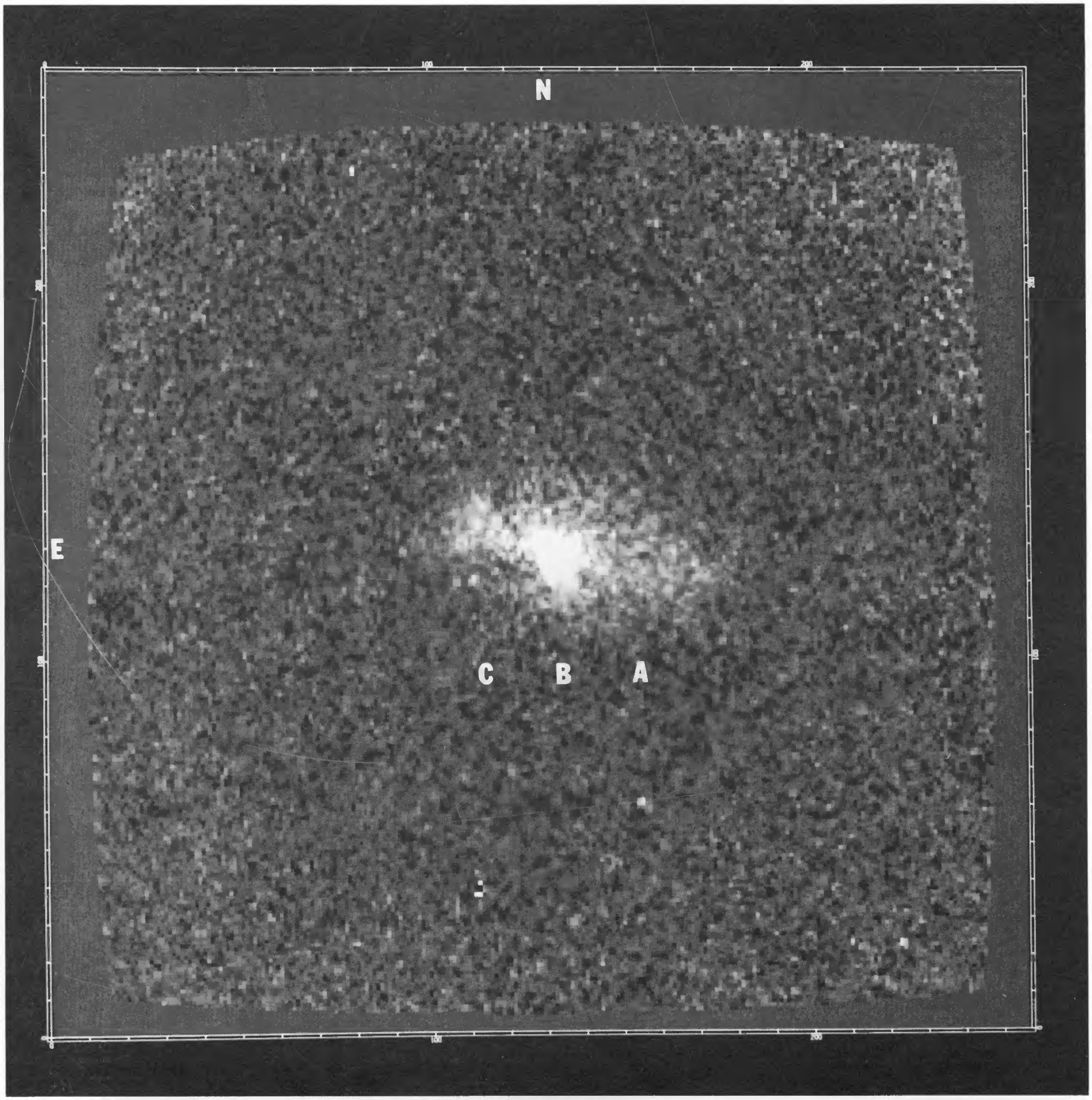

FIG. 1*b*.—Hα + [N II] $\lambda\lambda$6548, 6583 image of the same field as shown in Fig. 1*a*

VAN BREUGEL *et al.* (*see* page 83)

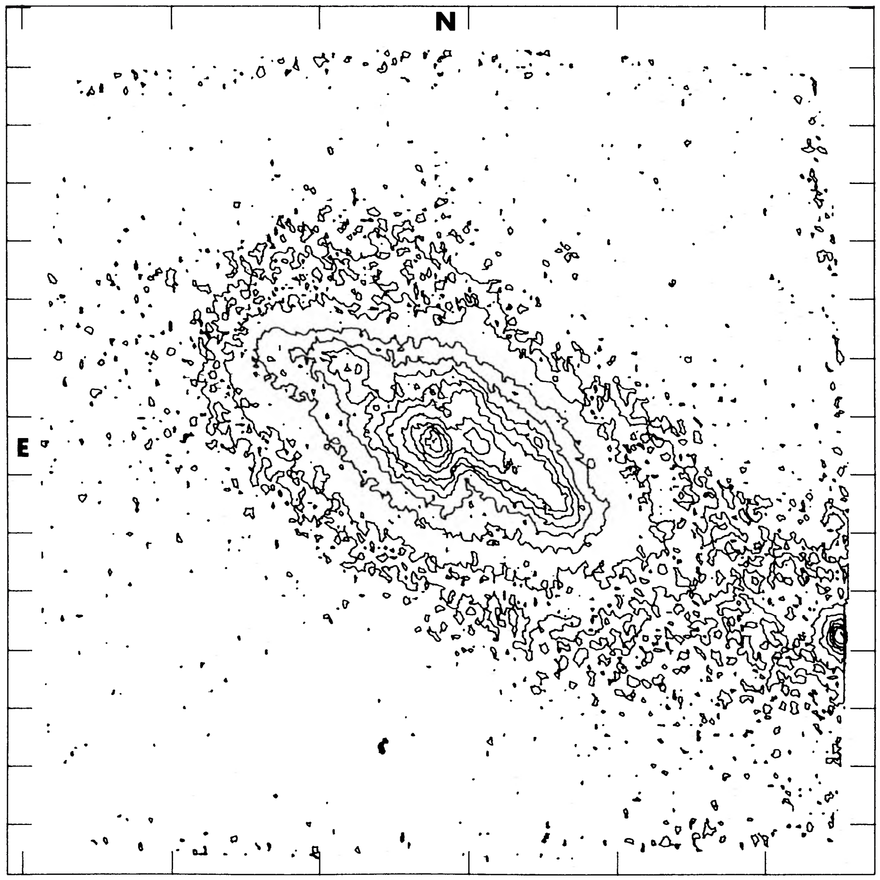

FIG. 2.—A contour representation of the same blue image shown in Fig. 1*a*

of the galaxy and the emission-line region preclude a more detailed analysis of the brightness profiles, which should be exponential in the case of a disk (see, for example, Freeman 1975).

The gaseous component of 3C 293 can be traced over ~16″ × 6″, which is an appreciable fraction of the entire optical extent of the galaxy. It easily encompasses the entire radio core (~2″.5 × 0″.6; BFC). The major axes of the gaseous disk, the galaxy, and the radio core are almost, but not quite, aligned. The position angles of these and other features are summarized in Table 2. Finally, we note that the central, bright Hα + [N II] line emission peaks at approximately the same location as the blue continuum and is probably associated with the nucleus. However, the presence of the

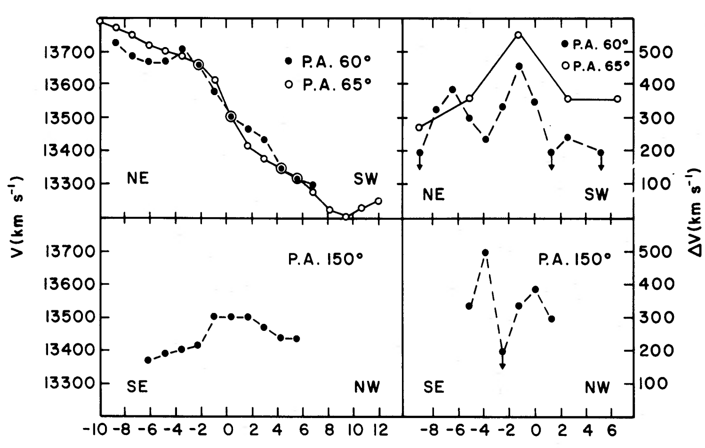

FIG. 3.—The velocity (V) and line widths (ΔV) of the gaseous disk measured at two orthogonal position angles using the [O II] λ3727 doublet (*filled circles*) and [O III] λ5007 (*open circles*). Uncertainties are typically ~35 km s^{-1} in V and less than 15% in ΔV. The galaxy velocity is ~13,500 km s^{-1}.

TABLE 2

Radio and Optical Parameters of 3C 293 and 3C 305

Parameter	3C 293[a]	3C 305[b]
Galaxy (VV 5-33-12)		
Redshift	0.0450	0.0417
Galaxy type	pec (Sb, S0, or D6)	pec (Sa, S0, or E)
M_V	−22.0	−22.6
Size (kpc)	38 × 15	37 × 29
Emission-Line Gas		
Morphology	oval	**Z**-shaped
Maximum extent (kpc)	13	12
Maximum velocity (km s^{-1})	300	260
Typical emission-line widths (km s^{-1}): nucleus	570	650
Typical emission-line widths (km s^{-1}): $r \geq 3$ kpc	350	100
Radius (kpc) at maximum velocity	9	2–3
Total line luminosity (ergs s^{-1})[c]	(10^{44})	10^{44}
Radio Core		
Morphology	**Z**-shaped	**H**-shaped
Spectral index ($S\nu \sim \nu^{-\alpha}$)	0.7	0.9
Size (kpc)	1.5	3
Monochromatic power at 1.4 GHz (W Hz^{-1})	$10^{25.1}$	$10^{24.9}$
Total luminosity (ergs s^{-1})[d]	2.3×10^{42}	1.3×10^{42}
H I absorption (width km s^{-1})	strong (480)	weak (−)
Position Angles (Degrees) of Major Axes of Radio and Optical Features		
Dust lane	13[e]	120
Radio core	93	43
Radio bridges/tails	125	138
Line emission: inner ~3 kpc	(30–75)[f]	53
Line emission: outer region	75	115
Galaxy	60	75

Note.—Assuming $H_0 = 75$ km s^{-1} Mpc^{-1}.

[a] For references see BFC, Baan and Haschick 1981, or this paper.

[b] For references see Heckman *et al.* 1982.

[c] Approximate values assuming case B recombination (Osterbrock 1974) and after applying a reddening correction which for 3C 293 was assumed to be the same as for 3C 305 ($E_{B-V} = 0.85$).

[d] From 10^7 Hz to 10^{11} Hz. Assuming minimum energy conditions and equal energies in protons and electrons.

[e] Within ~3 kpc radius.

[f] Uncertain because of irregular obscuration.

central dust lane makes this identification somewhat uncertain.

We have determined the Hα + [N II] flux from several regions of the disk (labeled A, B, and C in Fig. 1*b*) by integrating over the appropriate regions. The fluxes are: 2.3×10^{-14} ergs cm^{-2} s^{-1} (A), 3.8×10^{-14} ergs cm^{-2} s^{-1} (B, the nuclear region), and 1.9×10^{-14} ergs cm^{-2} s^{-1} (C). The errors are probably less than 25% of these values. The total Hα + [N II] flux (~8×10^{-14} ergs cm^{-2} s^{-1}) is in excellent agreement with that obtained by Yee and Oke (1978) from photoelectric spectrophotometry (~7×10^{-14} ergs cm^{-2} s^{-1}) after taking into account the probable absence of other emission lines in their relatively broad-band (~160 Å) data. The Hα + [N II] luminosity implied is ~3×10^{41} ergs s^{-1}. Given the dusty appearance of the galaxy and by analogy to 3C 305 (Heckman *et al.* 1982), the *total* emission-line luminosity is likely to be much greater than the radio luminosity (Table 2).

b) *Spectroscopy*

The velocities and velocity widths of the line-emitting gas in 3C 293 as measured along the major and minor axes are shown in Figure 3. We note the following:

1. Along the major axis of the galaxy (P.A. 60°/65°), the plot of gas velocity as function of distance from the nucleus strongly resembles the rotation curve of a normal disk galaxy. The curve is symmetric with respect to the systemic velocity of the galaxy (~13,500 km s^{-1}, from Burbidge 1967 and Baan and Haschick 1981). Although the velocity gradient appears steepest in the inner ±2″, the relative velocity continues to rise out to ~10″ (~9 kpc) from the nucleus, reaching a peak of ±300 km s^{-1}. The total velocity range seen in the gas is thus rather similar to that seen in the H I absorption.

2. There is only marginal evidence for a velocity gradient along the galaxy minor axis (P.A. 150°).

1984ApJ...277...82V

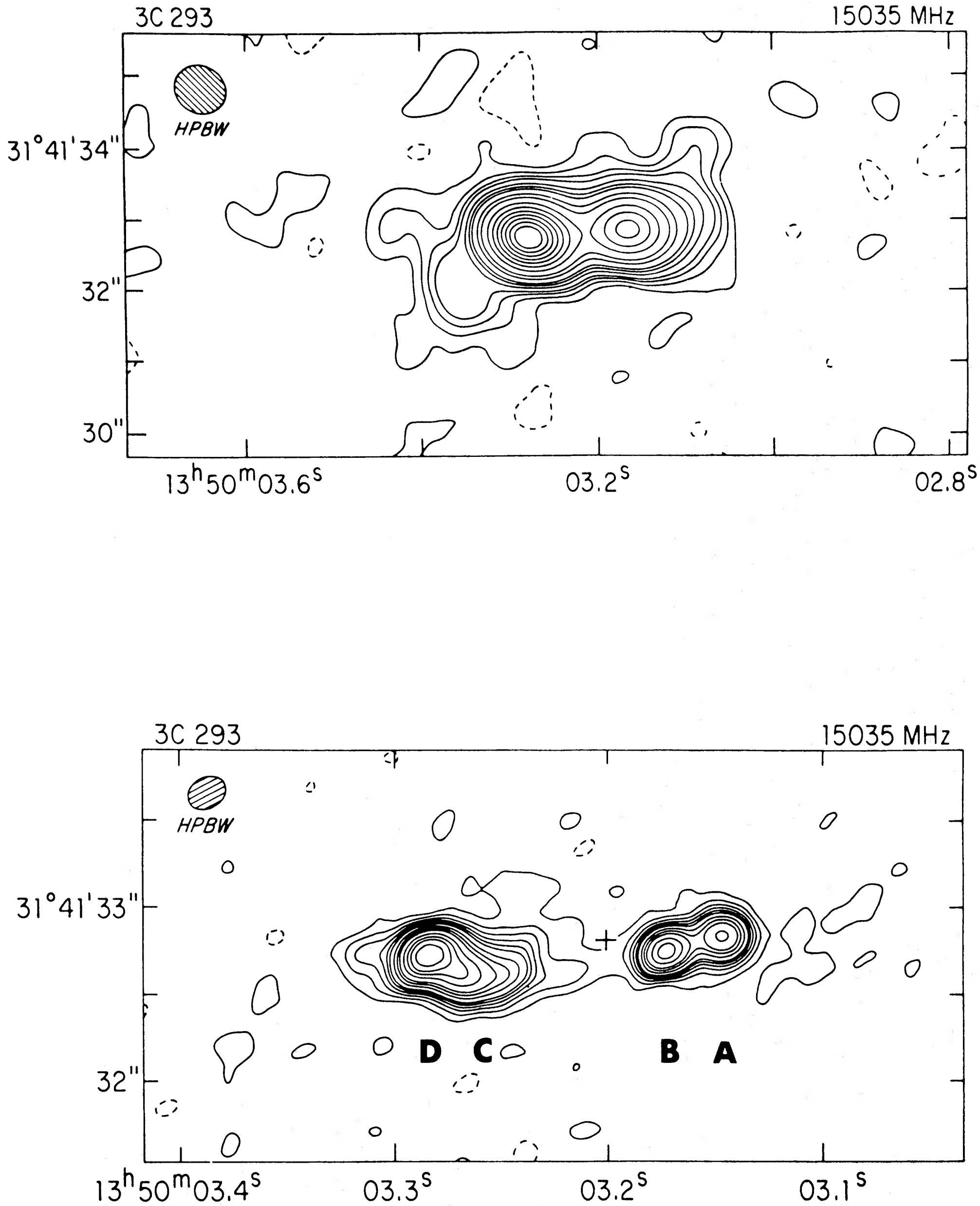

FIG. 4.—Reproductions of two 2 cm VLA maps of the core component of 3C 293 (BFC) which show the **Z**-shaped morphology of the core (*top*) and the compact components (*bottom*). The resolution (FWHM) is, respectively, ~0″.7 and ~0″.2. The **Z**-structure in the low-resolution map is confirmed by MERLIN observations at 18 cm (BFC). The contours are at −1%, 1%, 2%, 3%, 4%, 6%, 8%, 10%, 15%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the peak intensity of 324 mJy per beam (*top*) and at −4, 4, 8, 12, 16, 24, 32, 40, 48, 64, 80, 96, and 120 mJy per beam (*bottom*).

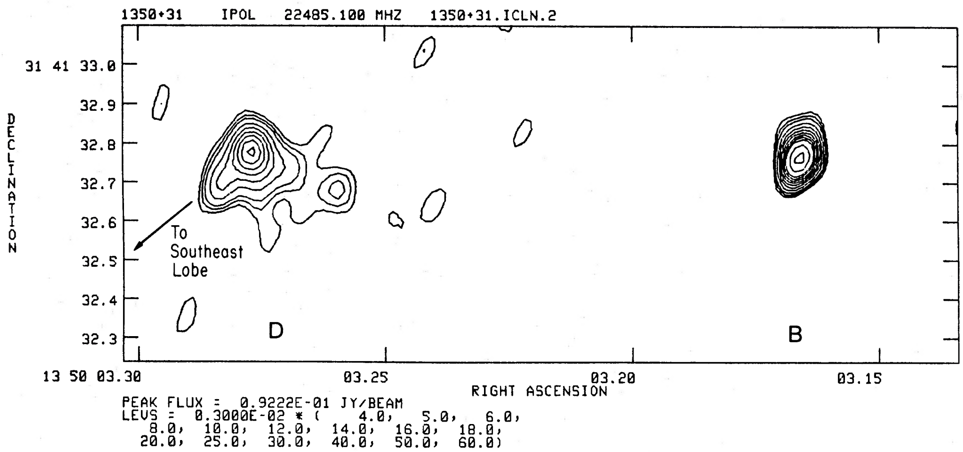

FIG. 5.—Reproduction of a 1.3 cm VLA map with ~0″08 resolution from van Breugel *et al.* (1984*b*). The contours are 12, 15, 18, 24, 30, 36, 42, 48, 54, 60, 75, 90 mJy per beam. Components A and C (see Fig. 4) were resolved and below detection level.

3. The line widths are comparable in magnitude to the velocity gradients and are typically 300–400 km s^{-1} FWHM, except for the [O III] λ5007 line in the nucleus (570 km s^{-1} FWHM).

4. The spatial intensity distribution differs somewhat for the various emission lines. We find that the [O II] λ3727 intensity is maximal ~2″–3″ NE of the nucleus, the [O III] λ5007 intensity is maximal ~1″ NE of the nucleus, and the Hα + [N II] emission peaks at the nucleus. This presumably reflects the differential extinction produced by the dust lane, which appears most conspicuous SW of the nucleus (see Fig. 1*a*).

c) *Review of Radio Morphology*

The radio morphology of 3C 293 is summarized in Figures 4 and 5 and Table 2, and has been discussed extensively by BFC. The salient properties are:

1. A strong, kiloparsec-scale, steep-spectrum core consisting of four high-brightness components (A, B, C, D in the notation of BFC). We identify component B as the nucleus since it is the most compact component and may exhibit the flattest radio spectrum (see van Breugel *et al.* 1984*b* for details).

2. A weak set of outer lobes whose radio morphology is not unusual. The total size of 3C 293 is ~175 kpc.

3. A gross misalignment of some 35° between the morphological axes of the kiloparsec-scale core and the outer lobes. To the east of the nucleus, the change in position angle is very abrupt and occurs within knot D (see Fig. 5 and compare with Fig. 4). We do not detect knot A (the western feature) in our high-resolution radio map (Fig. 5) and so do not know whether an equally abrupt change in position angle occurs there.

IV. DISCUSSION

a) *Comparison with 3C 305*

There are remarkable similarities between several of the properties of 3C 293 and those of 3C 305, a peculiar radio galaxy which has recently been the subject of intensive investigation (Heckman *et al.* 1982). From Table 2 several common properties can be noted.

First, both radio sources have relatively high monochromatic luminosities and are dominated by kiloparsec-scale radio emission. Such a situation is rarely observed in strong radio galaxies, most of whose radio emission is usually produced *outside* the optical galaxy. We note that in 3C 293 an outer component does exist but that it is weak.

Second, both galaxies have strong extended emission-line regions which are large and of roughly the same size (~12 kpc). Again, such large line-emitting regions are rarely seen in radio galaxies.

Third, in both emission-line regions the velocity distributions have similar characteristics and suggest that the line-emitting gas is rotating.

Fourth, in both objects wider emission lines are observed in regions of strong radio emission.

Fifth, both radio galaxies have optically disturbed appearances disfigured by pronounced dust lanes.

Sixth (as to be expected from the similarity in the observed radio and optical parameters), the calculated values for the intrinsic parameters such as luminosities and pressures are comparable.

These various similarities suggest that in explaining 3C 293 we should prefer interpretations that can also be applied to 3C 305.

b) *Kinematics of the Line-emitting Gas*

Any model for the kinematics of the emission-line gas in 3C 293 must explain the strong velocity gradient along the galaxy major axis (plus the very much weaker gradient along the minor axis), as well as the relatively broad lines seen through most of the line-emitting region.

The systematic velocity gradient could be due either to rotation or to radial motion. We favor the former explanation because (*a*) the maximum gradient is apparently along the galaxy major axis (60°), and (*b*) the shape and amplitude of the velocity curve (Fig. 3) strongly resemble rotation curves of disk galaxies (see, for example, Bosma 1982; Rubin, Ford, and Thonnard 1980).

Interpreted as rotation, the shape of the rotation curve would imply nearly solid-body rotation out to a radius of ~9 kpc, within which the virial mass must rise roughly linearly with radius. Inside this radius the enclosed virial mass would then be $M_{\rm vir} \sim 2 \times 10^{11} M_\odot$, taking the inclination of the emission-line gas disk from the observed eccentricity of the galaxy and assuming spherical symmetry for the gravitating mass.

Interpretation of the kinematics as rotation is in accord with the H I absorption-line data presented by Baan and Haschick (1981) if the narrow, deep absorption component at 13,500 km s^{-1} (the systemic velocity) is seen against the intense radio core, with the blue and red "wings" in the absorption profile arising in disk gas located to the west and east of the nucleus, respectively. VLA observations (J. H. van Gorkom, private communication; Shostak *et al.* 1983) show that the relatively strong, blueshifted absorption trough (see Baan and Haschick 1981) is indeed situated to the west of the galaxy nucleus. The stronger absorption to the blue can therefore be directly related to the stronger dust obscuration to the west of the galaxy's nucleus.

The origin of the relatively great widths of the emission lines is not clear-cut. Fosbury *et al.* (1982) have advocated a model for the radio galaxy PKS 2158 − 380 in which line-of-sight effects associated with viewing a warped disk can produce the appearance of broad emission lines in the absence of strong noncircular gas motions. At first sight, this model appears promising for 3C 293 given the disturbed optical morphology of the galaxy. However, in the Fosbury *et al.* model, the production of a warped disk involves differential precession of a disk of gas whose rotation axis is misaligned with the symmetry axis of the gravitational potential. 3C 293's disk appears to be in nearly solid-body rotation (so the disk should precess as a unit). Moreover, the disk axis and galaxy optical axis appear to be rather well aligned.

We favor a model in which the broad emission lines are indicative of true noncircular gas motions induced through an interaction with the radio plasma. We can cite the following evidence in favor of this model:

1. There is a statistical relationship between the width of the kiloparsec-scale emission lines and the power of the associated radio emission in a large sample of active galaxies (Wilson and Willis 1980; Heckman *et al.* 1981).

2. There is a strong similarity between 3C 293 and 3C 305. In the latter, the greater angular size of the radio source allowed us to demonstrate a detailed correspondence between the width of the emission lines and the power of the adjacent radio emission. In 3C 293, the [O III] λ5007 line is indeed broadest (FWHM of 570 km s^{-1} versus 300–400 km s^{-1} elsewhere) in the region of most intense radio emission. The low-resolution maps of BFC show also weak radio emission, linking the core with the lobes, in the regions with line-emitting gas *outside* the inner few kiloparsecs.

3. The spectrophotometric data of Yee and Oke (1978) show that the emission-line gas is not likely to be photoionized by a compact nuclear source (no nonstellar continuum was detected in 3C 293). Thus, a *local* source of ionization related to the radio source may be responsible (cf. the discussion of the very similar case of 3C 305 in Heckman *et al.* 1982). If the radio source *ionizes* the gas, it may *accelerate* it as well.

c) *The Nature of the Ambient Medium*

The gaseous medium within which 3C 293 is immersed is likely to play a crucial role in determining the properties of both the radio continuum and optical line emission. In our Galaxy, the interstellar medium is very inhomogeneous and consists of several phases (e.g., McKee and Ostriker 1977). The interstellar medium surrounding 3C 293 is very definitely "multiphase" since optical emission-line gas ($T \sim 10^4$ K), absorbing H I ($T \sim 10^2$ K), and dust clouds ($T \sim 10$ K?) are all present. In view of the controversy over the properties of the various phases and their relative importance in our own Galaxy, and in view of our ignorance concerning the degree to which the properties of our Galaxy can be assumed to apply to 3C 293, we will simply characterize the interstellar medium in 3C 293 as a two-phase, cloud-intercloud medium. Since the core of 3C 293 resides in the inner few kiloparsecs of VV 5-33-12, it is likely that most of the "clouds" are molecular clouds (cf. Liszt and Burton 1978; Rickard *et al.* 1977; Bieging *et al.* 1981). Such clouds, by analogy to our own Galaxy, might have typical diameters of ~40 pc, masses of 10^5–10^6 $M_\odot$, densities of 10^2–10^3 cm^{-3}, and volume filling factors of ~1% (Blitz 1982; Sanders 1982).

d) *The Radio Source*

i) *Introduction*

In the previous section we have presented evidence that the emission-line gas in 3C 293 has the kinematics and morphology of a rotating disk, and that the radio and optical emission are in some way related. In this section we will explore in more detail the consequences of this disk for the radio source, whose core it encompasses. Given the strong similarity to 3C 305 we will adopt the same general scenario as proposed for this source by Heckman *et al.*: the intense, small-scale radio emission in 3C 293 is the result of the vigorous interaction between normal twin radio jets and an unusually dense ambient medium (the rotating disk gas). Similar models have also been put forward to explain the linear, kiloparsec-sized radio features in some Seyfert galaxies (Wilson and Ulvestad 1982; Pedlar *et al.* 1982). Wilson and Ulvestad (hereafter WU) also applied their model to 3C 293 to explain its radio morphology.

ii) *Jets Propagating through an Inhomogeneous Disk*

The pressures in the radio core components ($nT \approx 10^8$–10^9 K cm^{-3}; BFC) and the emission-line clouds (probably $nT \approx 10^7$–10^8 K cm^{-3} by analogy to 3C 305, Heckman *et al.* 1982, and other active nuclei, Koski 1978) exceed the thermal pressure in the interstellar medium of our own Galaxy by factors of 10^4–10^5. Thus, unless the conditions in the disk of VV 5-33-12 are very much different from those in our Galaxy, neither the radio core nor the emission-line clouds are statically confined.

Instead the radio core components may be confined by ram pressure or may be transient. We suggest that components A, D, and possibly C also are associated with strong shocks which are caused by the collision of the jets with massive (molecular?) clouds. Such a model has, for example, also been proposed for the knots in the jet of M87 (Blandford and Königl 1979). Downstream from these shocks, i.e., west and east from A and D, respectively, the jets may have lost sufficient momentum that external pressures can subsequently influence the jet trajectories: dynamic pressure of the rotating disk gas and/or static pressure of a hot circumgalactic gaseous halo may have caused the jets to curve following the "sweeping" model of WU or the "refraction" model of BFC, respectively. Note that the maps by BFC show indeed that the radio jets curve significantly west (east) of A (D). Thus the basic interpretation of the structure of component D (Fig. 5) is that it is a shock in a jet triggered by a collision with a cloud, perhaps at the northern bright spot of D. Near D, or slightly farther downstream, the jet bends toward the southeastern lobe. (The faint radio emission visible in the low-resolution maps of BFC to the east and southeast of D is below the detection limit in the 1.3 cm VLA map in Fig. 5.)

To explain the optical line emission associated with jets and hot spots, such as, for example, in 3C 277.3, it has been proposed that the line-emitting gas has been entrained by the jets (Miley *et al.* 1981; De Young 1981). The entrainment of gas may occur in the nucleus, in the interstellar medium, or in a circumgalactic halo. It would take place at the interface of the jets and the ambient medium and therefore would naturally explain the predominant occurrence of line-emitting gas near the edges of bright radio source components (van Breugel and Heckman 1982; De Young 1982). This entrainment process involves shock heating, acceleration, and subsequent cooling of the gas.

Detailed models of jets by Norman *et al.* (1982) show how such an entrainment of gas might occur. A bow shock in front of the "working surface" (Mach disk) of a jet heats and accelerates the ambient gas. This gas may subsequently be mixed with back-flowing jet material in a laterally expanding cocoon (component C in 3C 293?) surrounding the jet. The entrainment efficiency and backflow velocity depend on the Mach number of the jet and its density relative to that of the external medium.

The above models presume a homogeneous environment and no jet bending (by whatever mechanism). Yet we know that in VV 5-33-12 the disk is *not* homogeneous and that the jets *do* bend through large angles. In the absence of such models we suggest the following simple working hypothesis. Massive clouds collide with the jet somewhere along its path because of the rotation of disk. At these locations the jet may deflect, and a strong shock in the jet (A, D) is accompanied by an external "bow shock" rather similar to the situation at the end of a jet. Such a bow shock in the inhomogeneous disk gas may resemble in some ways supernova remnants: fast shocks propagating relatively unhindered through the intercloud medium driving slow, radiative shocks into clouds (McKee and Ostriker 1977; McKee, Cowie, and Ostriker 1978).

The kinematics of the emission-line clouds in VV 5-33-12 may arise naturally in such a model. By analogy to our own Galaxy, radiative atomic shocks, which produce observable optical line emission, have velocities of 30–200 km s^{-1} (McKee and Hollenbach 1980): low-density clouds have high-velocity (>200 km s^{-1}) shocks driven into them, producing postshock temperatures which are too high for effective radiative cooling, while very dense clouds will have low-velocity ($\leq$30 km s^{-1}) shocks driven into them, which do not heat the postshock gas to high enough temperatures to produce optical line emission.

Thus if a range in cloud densities (n_C) is present in the disk of VV 5-33-12, then only those clouds with n_C large enough that v_C is in the range of a few tens to a few hundred km s^{-1} will be expected to radiate optical emission lines. Since the shocks will accelerate the clouds to velocities comparable to the shock velocity, we expect the population of optically emitting clouds to have a velocity dispersion (σ) of the same order. This is consistent with our observations: $\sigma \approx 100$–250 km s^{-1}.

The cloud and intercloud shock velocities are related by $v_{IC} = v_C(n_C/n_{IC})^{1/2}$. This follows from the conservation of momentum (McKee, Cowie, and Ostriker 1978). Here n_C/n_{IC} is the cloud-intercloud density contrast. Taking $n_C/n_{IC} \approx 10^4$, as in our Galaxy, then $v_{IC} \approx 10^4$–$10^{4.5}$ km s^{-1} in VV 5-33-12. In other words, the bow shocks associated with components A and D, and therefore these components themselves, probably move through the disk with a velocity of 10^4–$10^{4.5}$ km s^{-1}. At such a velocity, these components can be confined by ram pressure if $n_{IC} \approx 10^{-2}$ cm^{-3} (within a factor of 10). For comparison: McKee and Ostriker (1977) estimate $n_{IC} \approx 10^{-2.5}$ cm^{-3} in our Galaxy.

Because the shocks in the ambient medium are ultimately driven by the jets, the jet material must have a velocity $v_J \geq 10^{4.5}$ km s^{-1}. To power the radio emission at an efficiency of ϵ with the bulk kinetic energy of outflowing jet material requires $\frac{1}{2}\epsilon \dot{M}_J V_J^2 = 1.5 \times 10^{-26} L_R$ ergs s^{-1} ($\dot{M}_J$ is the mass-flux rate in solar masses per year; V_J is the jet velocity in km s^{-1}; L_R is the total radio luminosity in ergs s^{-1}) or

$$V_J = 2600 \dot{M}_J^{-1/2} \epsilon^{-1/2} \text{ km s}^{-1} .$$

Taking $V_J \geq 10^{4.5}$ km s^{-1} and $\dot{M}_J$ of 1 $M_\odot$ yr^{-1} would imply $\epsilon \leq 0.02$. Thus, even an inefficient jet (ϵ small) would not require an excessive mass flux.

iii) *Morphology*

The intense radio core of 3C 293 is significantly misaligned with the faint outer radio lobes and displays a slight **Z**-shaped morphology (BFC). Two mechanisms have been advanced to explain this misalignment. BFC propose that the radio jets "refract" (are buoyantly deflected) in a hypothetical circumgalactic gaseous halo. The principal evidence for this is the fact that the jet bends toward the projected minor axis of the galaxy, as would be expected in a model of this kind. Alternatively, by analogy to some Seyfert radio sources, WU suggest that the bending is due to the transverse ram pressure (sweeping effect) of rotating disk gas. Our discovery of a rapidly rotating gaseous medium in 3C 293 would support the WU hypothesis. Moreover, the rotation is probably counterclockwise, as inferred from the gas kinematics and dust lane geometry, which is in the correct sense to produce the observed bending of the radio source.

We can briefly evaluate the WU model quantitatively. For a jet with a kinetic energy flux (luminosity) of L_J and a velocity V_J, bending will occur over a distance comparable to the jet diameter (d_J) if the transverse momentum flux of the disk material (with particle density n_D [in cm^{-3}] and rotation velocity V_D [in cm s^{-1}]) is comparable to or greater than the outward momentum flux in the jet. This can be expressed as

$$\frac{L_J}{V_J} \leq \frac{\pi}{8} m_H n_D V_D^2 d_J^2 \text{ dyn} .$$

Significant jet bending apparently occurs just outside the bright core at a distance of $\sim$2 kpc from the nucleus, in a region where we estimate $V_D \sim 100$ km s^{-1} and $d_J \sim 0.1$ kpc. The total radio luminosity outside the core is only $\sim 20\%$ of that of the whole source (BFC). Thus, on average, per jet one has $L_J = 0.2 \times 10^{42} \epsilon^{-1}$ ergs s^{-1}. This allows one to rewrite the bending condition as

$$n_D \geq 40\epsilon^{-1}\left(\frac{V_J}{10^4}\text{ km s}^{-1}\right)^{-1}\text{ cm}^{-3} .$$

For the WU model to be applicable to 3C 293, it would appear that large gas densities are required, even if the efficiency of the jet is high (ϵ large) and its velocity large. For example, a lower limit is $n_D \geq 1\epsilon^{-1}$ cm^{-3} because $V_J \leq c$, where c is the velocity of light. Note that in terms of the transverse force exerted by the disk gas, it is the *average* density in the disk that is important ($n_D = f_C n_C + f_{IC} n_{IC}$, where f_C and f_{IC} are the filling factors for the cloud and intercloud medium). In the central region of our Galaxy, or other spiral galaxies, $n_D \sim 10$ cm^{-3} (Liszt and Burton 1978; Bieging *et al.* 1981).

Using a similar value for the inner few kiloparsecs in VV 5-33-12, one finds $\epsilon V_J \geq 4 \times 10^4$, or 4×10^4 km s$^{-1} \leq V_J \leq c$, $\epsilon > 0.1$, and $\dot{M}_J \leq 10^{-2}\ M_\odot$ yr^{-1}.

We conclude that within the framework of such a simple model, only a very light, fast, and efficient jet might be bent by the disk.

V. CONCLUSIONS

We have presented radio and optical data concerning the parent galaxy (VV 5-33-12) and the associated radio source, 3C 293. These data provide strong evidence that the powerful, kiloparsec-sized radio core of this source is immersed in a rapidly rotating gaseous disk.

We have argued that the relatively broad lines throughout the disk are probably due to the transfer of kinetic energy from radio jets to the ambient medium. This idea is supported by the fact that the [O III] lines are widest near the radio core, by the similarities to 3C 305, and by the general radio power–to–line width correlation which seems to exist for steep-spectrum, kiloparsec-sized radio sources.

We find that it is unlikely that the radio core components of 3C 293 are confined by static pressure. Instead, we suggest that, by analogy to supernova remnants, the radio and optical emission is associated with shocks which propagate through a two, or more, phase interstellar medium. The presence of a rotating disk with dust and neutral gas, besides the hotter line-emitting gas, suggests that such clouds may be present in VV 5-33-12. Fast, "nonradiative" shocks propagate through a hot intercloud medium driving slow (~ 200 km s^{-1}), "radiative" shocks into cool, dense clouds. The radio emission in the core component of 3C 293 may be associated with either of these types of shocks; the optical line emission is presumably associated with the latter.

We have shown that the rotation of the disk is in the correct sense to attribute the observed misalignment between the radio core and the outer lobes to the transverse force exerted by the rotating disk gas on jets which propagate through it (WU). Simple considerations lead us to believe that, for average gas densities in the disk similar to that in our own Galaxy, the jets must be light, fast, and efficient in producing radio emission.

The resemblance of 3C 293 in many of its radio and optical properties to 3C 305 suggests a rather similar scenario for its origin and evolution. Interaction with a nearby companion may have triggered the onset of nuclear activity some 10^8 yr ago or less (the galaxy crossing time). Twin jets were ejected from the nucleus at a substantial angle to the rotation axis of the 3C 293 gaseous "accretion" disk, which may have formed as a result of the tidal interaction. The subsequent interaction between the jet and disk material resulted in the observed radio and optical emission and allowed the jets to be deflected. The interaction was not, however, vigorous enough to entirely brake the jets (as apparently occurs in 3C 305), and they were able to pierce the disk and fuel the development of faint outer radio lobes.

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H. Butcher: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726-6732

T. M. Heckman: Astronomy Program, University of Maryland, College Park, MD 20742

G. K. Miley: Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands

W. J. M. van Breugel: Steward Observatory, University of Arizona, Tucson, AZ 85721