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RADIO STRUCTURE AND OPTICAL KINEMATICS OF THE cD GALAXY HYDRA A (3C 218)

R. D. EKERS[1,2]
National Radio Astronomy Observatory, Socorro, NM[3]
AND
S. M. SIMKIN[1,4]
Department of Astronomy and Astrophysics, Michigan State University
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ABSTRACT

We present a 1400 MHz map of the radio source Hydra A with 50″ resolution which shows that this object is a "3C 31" type source (unusual for an object of such high luminosity). Optical velocity measurements indicate that the central, optical galaxy consists of a rapidly rotating core of stars and gas embedded in a nonrotating stellar envelope. In addition, there is evidence for a region of nonrotating, higher-excitation gas, redshifted relative to the rotating system by $\sim$400 km s^{-1}. The position angle of the major axis of the radio core is aligned with the optical rotation axis. This result, combined with measurements from earlier studies, suggests that the more powerful radio sources have their radio structure more closely aligned with their rotation axes than do the weaker ones.

Subject headings: galaxies: individual — galaxies: internal motions — galaxies: structure — radio sources: galaxies

I. INTRODUCTION

Although Hydra A was one of the first extragalactic radio sources identified (Mathews, Morgan, and Schmidt 1964), and is the seventh brightest source in the 3C catalog (Edge *et al.* 1959), its southern declination ($-12°$) makes it unsuitable for mapping with the E-W earth rotation synthesis telescopes in the Northern Hemisphere. Models, and very low resolution maps, by Fomalont (1971) at 1400 MHz, and Stull *et al.* (1975), at 5 GHz, suggest that it is a "core-halo" source with a $\sim$2.5′ halo. Earlier observations by Bash (1968) at 2.7 GHz indicate that the core is a 15″ double. Because the haloes of most "core-halo" sources found in these earlier observations often exhibit complex, even bilobal, structure when mapped in more detail, we felt that a more detailed map of this object might also reveal a more complex structure. Such detailed radio structure was of particular interest because recent optical spectroscopy of the parent galaxy (Simkin 1979; hereafter SMS) has shown that it has a rotation axis in PA 29° ± 9, close to the major axis of the core radio source measured by Fomalont (1971). Thus, we obtained a medium resolution (50″) map with the Fleurs Synthesis Telescope, to try to resolve any intermediate-scale features in the object's radio halo and to examine their relationship to the optical rotation axis. In addition, further optical spectra were obtained to try to clarify the relation between the galaxy's radio structure and the peculiar emission-line pattern observed in its nucleus (SMS). These new measurements show that:

1. The large-scale radio structure seems to be that of a head-tail or "3C 31" type radio galaxy with the head extended in the position angle of the optical rotation axis;
2. The optical core of the galaxy, which is in rapid rotation, is surrounded by a relatively stationary envelope of stars and gas; and
3. The fainter component of the apparent double optical nucleus differs in velocity from that of the brighter component by $\sim$500 km s^{-1}.

The kinematical structure of Hydra A is similar to that of the cD radio galaxies 3C 98, 3C 184.1, and 3C 390.3.

II. RADIO OBSERVATIONS

Hydra A was observed with the Fleurs Synthesis Telescope (FST) at a frequency of 1415 MHz (cf. Frater 1973; Frater *et al.* 1976; and Christiansen *et al.* 1977 for details). Measurements were made by tracking the source for 8 hours with both the E-W and N-S arms, to obtain the best possible spatial coverage of this near-equatorial source. A failure in the automatic tracking of one of the large dishes during the E-W observations led to some gaps in the tracks in the

[1] The observations in this paper were obtained while the authors were on the staff of Mount Stromlo and Siding Spring Observatories (MSSSO).
[2] Kapteyn Astronomical Institute, Groningen, Netherlands until 1979 September.
[3] The National Radio Astronomy Observatory is operated by Associated Universities, Incorporated, under contract with the National Science Foundation.
[4] Guest Investigator, Hale Observatories, 1978–1980.

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visibility plane. However, this did not significantly affect the accuracy of the final map.

Calibration and Fourier inversion of the radio measurements were done using a PDP-11/20 at the University of Sydney. The final analysis of the map was done at the University of Groningen, using the interactive reduction programs described by Ekers, Allen, and Luyten (1973). This peripatetic reduction sequence was accomplished almost painlessly by transporting the data from Australia to the Netherlands using a FITS standard tape, written by Dennis Warne at MSSSO. (See Wells, Greisen, and Harten 1981 for the FITS standard).

The original Fleurs radio map is shown in Figure 1*a* (Plate 6) superposed on a IIa-J Palomar Schmidt image of the optical galaxy. At this resolution, the "halo" component of the radio source has the appearance of a classical "head-tail" galaxy. The lowest contour in Figure 1*a* is about 2.5% of the brightest peak in the map. This ratio is comparable to the expected dynamic range of the FST. There is a slight negative hole to the north in a position symmetric with respect to the southern "tail." This could be caused by a phase error in the N-S observations giving antisymmetric sidelobes from the strong central source. For these reasons, we were not completely confident about the reality of the tail to the south or the absence of any corresponding feature to the north (which would be expected of a double-lobed system). To obtain a better estimate of the reliability of the features seen in Figure 1*a*, we performed the following two tests on the data:

1. We rotated the original "dirty" map by 180° and added the rotated map to the original map. This has the effect of zeroing the phases in the Fourier transform of the map and should eliminate any spurious features due to phase errors (at the expense of increasing the noise and making a purely symmetric image). This composite map was then cleaned. The final cleaned version showed an even stronger extension to the south than the map in Figure 1*a*, proving that the extended feature cannot come from a phase error.

2. Since the above test produces a symmetric map, it gives no information about the possibility of a northern extension similar to the southern "tail." To investigate this latter possibility, the original dirty map was cleaned down to a level just above that of the noise and error lobes, and then this residual map (dirty map − clean components) was rotated by 180° and averaged with the unrotated residual map. The clean components were then restored to the resulting "phase zeroed" background. The map produced by this operation is shown in Figure 2*b* (with the original cleaned map in Fig. 2*a* for comparison). Whereas the positive and negative "ears" to the NW and SE disappear and are certainly due to phase errors, the southern feature is still present, and any similar feature to the north is still below the noise level. We cannot exclude the possibility of a weaker extension to the north. However, if the extended structure in Hydra A is bilobal, any northern lobe must be at least a factor of 2 fainter than the southern lobe.[5]

The total flux from the core source and the tail was obtained by integrating over the relevant areas in the map. The resulting flux densities, measured angular sizes, and total power are listed in Table 1. The flux scale used

[5] Recent VLA observations (J. Dreher 1982, private communication) show that there is an extension to the north just below the lowest contour in Figure 1. This makes the "head-tail" interpretation unlikely.

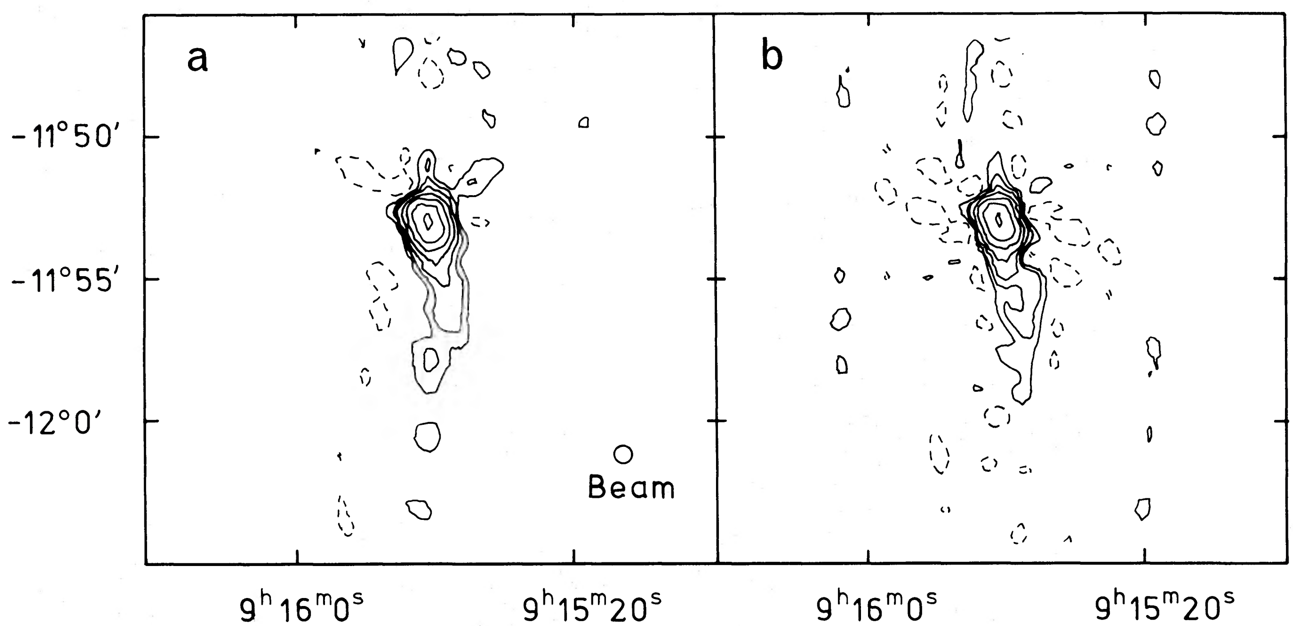

FIG. 2.—Same contours as in Fig. 1; (*a*) before and (*b*) after zeroing the phases in the Fourier transform of the background

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TABLE 1

OBSERVED PARAMETERS
($h \equiv H_0/100$ km s^{-1})

Parameter	Value	
Optical		
Redshift	0.053	
Distance (Mpc h^{-1})	162	
m_B (mag)[a]	14.58	
M_B [mag + 5 log (h)]	-21.43	
Optical rotation axis (deg N of E)	29 ± 9	
Max rotation velocity (km s^{-1}) (center to edge of core)	175 ± 50	
Radio		
	Head	Tail
Flux density at 1415 MHz (Jy)[b]	39.0 ± 3.0	6.6 ± 2.4
P_{1415} (W Hz^{-1} sr^{-1}) h^{-2}	1.0×10^{25}	1.6×10^{24}
Luminosity[c] (ergs s^{-1}) h^{-2}	1.9×10^{43}	3.3×10^{42}
Angular size (arcsec)	72	240
Position angle (deg N of E)	24 ± 5	$30 - 0$
Linear size (kpc h^{-1})	56	187

[a] Sandage 1973.
[b] 1 Jy = 10^{-26} W m^{-2} Hz^{-1}.
[c] Luminosity based on an assumed spectral index of -0.9.

in the FST measurements is based on an assumed flux of 16.4 Jy for the source PKS 1934−63 and could be uncertain by as much as 5%. The apparent position angle of the core source was estimated from the original long-baseline visibility amplitudes and the position angle of the tail was measured from the cleaned map. These parameters are also listed in Table 1.

The measured fluxes in Table 1 are comparable to the values of 34 Jy for the core and 12 Jy for the halo in the model for this source constructed by Fomalont (1971). This agreement is within the combined uncertainty of the flux calibration and the somewhat arbitrary definition of "core" and "halo" (or head and tail) and suggests that the tail we see corresponds to Fomalont's halo.

III. OPTICAL OBSERVATIONS

Hydra A appears to have a double optical nucleus (Dewhirst 1959). The position angle of this double (125°) is almost normal to that of the rotation axis (29° ± 9, SMS). In addition, there is a faint optical knot aligned with this pair on the NW side of its brighter component (marked with a cross in Fig. 1), and the outer envelope of the galaxy appears to be elongated in the same position angle (Fig. 1*a*). Finally, the internal kinematics of the nuclear region seem to be as complex as its spatial appearance. Relative velocities from emission lines of Hβ and [O III] on low-dispersion spectra of this region differ by as much as 250 km s^{-1} (SMS, Fig. 7*b*).

To examine these optical peculiarities more closely, two high-dispersion spectra were obtained in position angle 115° with the Palomar 5 m SIT spectrograph (1979 January). The spectrograph slit was set to cut through the NE side of the fainter nuclear component and the center of the brighter component. A gray scale print of the sum of these two spectra is shown in Figure 3*b*. A similar print of the sum of three lower-dispersion spectra of the nucleus is reproduced in Figure 3*a*. These latter spectra were taken in position angle 140°, through the brighter nuclear component and the SE edge of the fainter one. The prints in Figure 3 show that the fainter component of the double nucleus has an absorption line spectrum with a redshift similar to that of the brighter component.

The Hβ and [O III] emission lines shown in Figure 3*b* (Plate 7) were measured using the techniques described in SMS. These measurements are plotted in Figure 4*a*. Inspection of the [O III], λ5007 line in Figure 3*b* shows that the velocity field of the ionized gas is double-valued on the NW side of the core. The peak velocity separation between the two emission line regions on this side is ~460 km s^{-1}. This narrows to ~300 km s^{-1} on the SE side. This double-peaked velocity appears to be the explanation for the notably widened [O III] line observed at lower dispersion (SMS, Fig. 6). An intensity plot of the nuclear region of the spectrum in Figure 3*b* is presented in Figure 5, where the separation and nearly equal intensity of the two [O III], λ5007 components is clearly shown. The Hβ line in Figure 5 has the same velocity as the short wavelength component of the λ5007 line. Thus, the two regions giving rise to the [O III] emission must have quite different excitation conditions, since H$\beta \approx$ [O III] in the low-velocity region and H$\beta \gg$ [O III] in the high-velocity region. The long wavelength component of the λ5007 line exhibits little or no differential motion from one side of the optical core to the other. The short wavelength component, on the other hand, appears to reflect the same differential velocities seen in the stellar absorption lines.

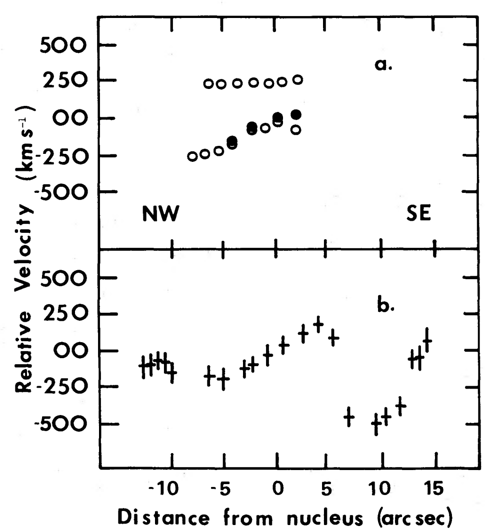

FIG. 4.—Relative velocities of the gas (Fig. 4*a*) and stars (Fig. 4*b*) along the major axis of Hydra A. *Open circles*: [O III]; *filled circles*: Hβ. The absorption-line errors are indicated by the size of the crosses. The zero point has been set by assuming that emission- and absorption-line velocities showing rapid rotation have the same mean velocity (see text).

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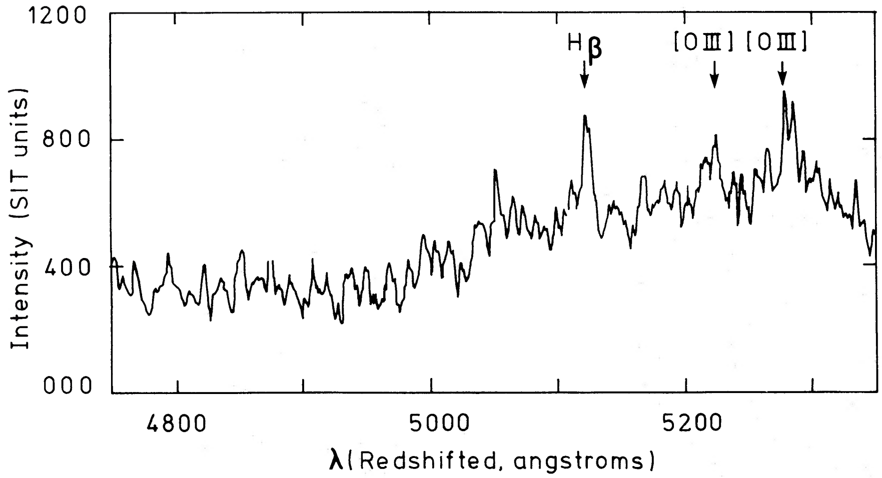

FIG. 5.—Relative intensities of the emission lines in the nucleus of Hydra A from the spectrogram shown in Fig. 3*b*

It is not possible to compare these [O III] emission-line velocities directly with absorption line velocities for the same position angle, because the high dispersion spectra do not have a high enough signal-to-noise to yield accurate absorption line measurements. The lower-dispersion spectra in position angle 140° do cover a similar area in the inner regions of the galaxy, and these were remeasured for comparison. Because we now have much better two-dimensional reduction and display routines than when the data presented in SMS were measured, we were able to measure absorption line velocities over a much greater radial distance in position angle 140° than those reported previously. It is clear from the print in Figure 3*a* that the CaH, and CaK lines can be traced well beyond the core of the galaxy. We measured these lines by windowing the data in the region of CaH, and CaK and then applying reduction procedures similar to those described in Simkin (1974). The relative velocities of the stars at various radial distances are plotted in Figure 4*b* as + signs. The absorption line velocities in the core of the galaxy agree with those previously reported (SMS). In Figure 4*a* the emission-line velocity system from position angle 115° with the stronger gradient has been shifted in zero point to correspond with the absorption-line velocities from position angle 140° shown in Figure 4*b*.

It is not possible to determine absolute zero points for this type of velocity measurement to better than 150 km s^{-1}. This type of zero point uncertainty is inherent in the different techniques used to measure positions for absorption and emission lines and would even be present if the different measurements were all made on the same spectrogram. It can be reduced only by obtaining spectrograms with higher signal-to-noise and much higher dispersion than those discussed here, but such high quality spectra are beyond the capabilities of present instruments and observing limitations.

In the present case, the nominal velocity difference between the absorption- and emission-line velocity systems shown in Figure 4 is 90 ± 150 km s^{-1}. The similar shapes for the inner parts of the two velocity curves make plausible the zero point shift incorporated into the plotted data. A less plausible interpretation is that the higher redshift emission line system (without a steep velocity gradient) is associated with the nucleus, and that the system *with* the velocity gradient is blue-shifted with respect to the nuclear velocity. In this case, the latter (gaseous) system would have a systemic velocity similar to that of the secondary nucleus. The following will be based on the assumption that the data, as plotted, represent the correct picture. This should be regarded as tentative until more precise measurements are available.

In addition to the velocity zero point uncertainty, there is also some uncertainty about the physical position of the true "nucleus". In Figure 4, the zero point in velocity and radius has been chosen as that velocity which corresponds to the brightest part of the optical core.

However, because of the peculiar, multicomponent appearance of this system, this peak intensity may not correspond to the dynamical center of the system. Indeed, if the outermost absorption line velocities plotted in Figure 4 do represent a stationary, systemic velocity for the envelope, a better choice for the center may be the point -70 km s^{-1}, $-1''.9$ on this plot.

Two features of the absorption line velocities in Figure 4*b* are noted for future reference:

1. Beyond 7″ in radius the absorption line velocities no longer show differential motion, but drop back to the velocity at the center of the core.
2. The absorption line velocities from the "secondary nucleus" (at $+10''$ and -500 km s^{-1} in Fig. 4) are kinematically separate from the stellar velocities in both the galaxy core and the envelope.

IV. DISCUSSION

From the data presented here, Hydra A appears to present several unusual features which set it apart from other strong radio galaxies.

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a) *The Radio Structure*

The most obvious interpretation of the maps in Figures 1 and 2 is that Hydra A is a head-tail galaxy. Alternatively, since our data do not exclude the possibility of a faint northern extension, the structure may be that of a "3C 31" system, with higher surface brightness in the inner regions and lower surface brightness further from the center.[6] The optical galaxy associated with Hydra A is highly luminous ($M_B = -21.4$; Table 1) and is the dominant member of a poor cluster (Bautz-Morgan type I, Abell richness class O, Sandage and Hardy 1973). This combination of optical and radio properties appears to be unusual in two respects.

1. Head-tail and 3C 31-type radio galaxies are all members of Farnaroff and Riley's (1974) Class I, which consists of objects with relatively low radio luminosities ($P_{1400} \leq 10^{24}$ W (Hz sr)$^{-1}$, with $H_0 = 100$ km s^{-1}). Hydra A has a luminosity of $P_{1400} \sim 10^{25}$ W (Hz sr)$^{-1}$ (Table 1), a factor of 10 brighter than any other known member of this class.

2. Some authors (Rudnick and Owen 1977; Simon 1979; and Valentijn 1979) have noted that head-tail galaxies are never associated with a dominant cluster galaxy. This fits with a picture of head-tail galaxies which attributes their asymmetrical structure to relative motion between the galaxy and the gas in the cluster, since dominant cluster galaxies are found at the center of the cluster and are, presumably, relatively stationary. Hydra A, however, is associated with the dominant galaxy in its cluster. Thus, unless there is a faint, undetected N counterpart of the southern extension seen in Figure 1, Hydra A is a striking exception to the above rules, suggesting that either this cD galaxy is moving through the center of its cluster or the conventional explanation for head-tail structure is inadequate.

[6] The recent VLA observations noted previously show that Hydra A is of the "3C 31" type. Consequently, the problem discussed in point 2, below, is resolved.

In addition, the radio structure of Hydra A reported here adds to the evidence for a significant link between the total power of a radio source and the relationship between the internal kinematics of its optical galaxy and orientation of its radio features. The position angle for the core source listed in Table 1 lies within 10° of the position angle for the rotation axis of the optical galaxy. This determination brings to 15 the number of radio galaxies with well-measured rotation axes. The distribution of the differences between the optical rotation axis and the radio axis of the inner part of the radio structure for these 15 objects is shown in Figure 6. There is a notable separation of the sources into two groups: The more powerful radio galaxies, [$P_{1400} > 10^{24}$ W (Hz sr)$^{-1}$], have radio axes which are aligned with their rotation axes, while the less powerful objects exhibit a significant degree of misalignment. It is important to note that the correlation shown in Figure 6 is *not* associated with radio morphology but with radio power. The good alignment seen for Hydra A along with the core-brightened radio structure which we have found for this object makes this distinction clear.

In Figure 6 the position angle differences derived from emission lines rather than absorption lines are marked with an asterisk. It is evident that this distribution is similar for both emission line and absorption line axes. This is also demonstrated by the measurements reported in SMS, where rotation axes derived from both emission lines and absorption lines in the same systems were coincident.

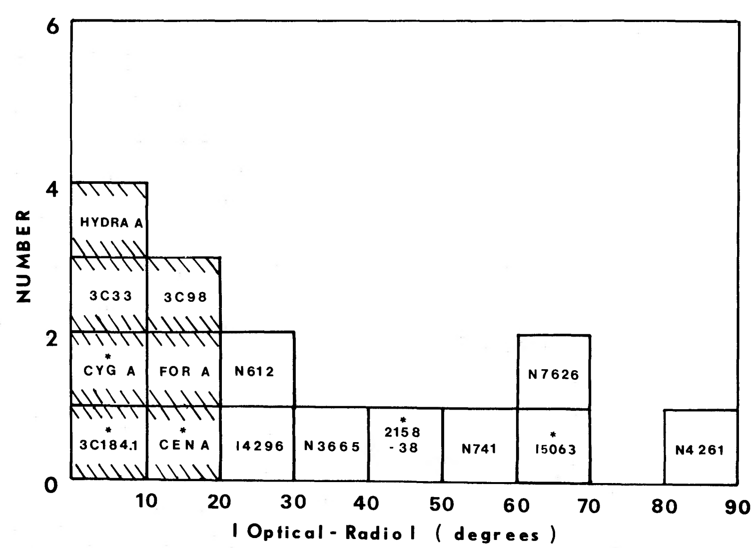

FIG. 6.—The absolute difference between PA of the optical rotation axis and the inner radio axis for 15 galaxies. Objects with $P_{1400} \geq 10^{24}$ W (Hz sr)$^{-1}$ are cross-hatched. Those differences derived from emission-line rotation axes are marked with an asterisk. Data are taken from Efstathiou *et al.* 1980, Fosbury 1981, Danziger, Goss, and Wellington 1981, Graham 1979, Goss *et al.* 1981, Jenkins and Scheuer 1980, Jenkins 1981, Schweizer 1980, and Simkin 1979.

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b) *The Optical Kinematics*

Hydra A seems to present a kinematical picture which is more complex than any of the currently popular "scenarios" which attempt to explain the known association between cD galaxies and extended sources.

The velocity pattern shown in Figure 4 is very similar to that found in the nonnuclear regions of some other strong radio galaxies. For example, comparing the velocities in Figure 4 with those found in 3C 98 (SMS) shows that both galaxies have a rapidly rotating, inner core of stars and gas. In addition, in line of sight with this core but at significantly different radial velocities lies a region of ionized gas whose excitation conditions differ from those of the gas associated with the core. Finally, the region outside the core has the same radial velocity as the nucleus, with little or no rotational motion. This velocity pattern appears to be present in 3C 184.1 and 3C 390.3 (S. M. Simkin, unpublished measurements) as well as in Hydra A and 3C 98. These similarities suggest that a rapidly rotating inner core and nonrotating outer envelope in a galaxy may be characteristics which establish or reflect a physical environment favorable to the development of radio sources. As noted previously (SMS), the observed rotational velocities in these cores are much larger than those observed in normal E galaxies. This is consistent with the long-standing observation (Mathews, Morgan, and Schmidt 1964) that strong radio sources are associated with cD galaxies. The present measurements show that the "D" component in Hydra A is associated with the rotating core described above, while the "c" envelope corresponds to the slowly-rotating outer region.

Although the radio-optical structure presented here for Hydra A does not fit nearly into any of the current theoretical discussions about the origin of active radio galaxies, it does have features which can be plausibly associated with different aspects of several theoretical scenarios.

In particular, three features found in these observations of Hydra A point towards the following:

1. The secondary nucleus and structure of the surrounding cluster of galaxies suggest that this cD galaxy may be an object formed by "cannibalism" (cf. Ostriker 1977 and references therein).

2. The velocity pattern in the ionized gas (Fig. 4*a*) can be interpreted as coming from two distinct regions: a rotating disk (the blueshifted velocity group) and an infalling component (the redshifted group). Several authors (cf. Gunn 1979) have suggested that gas from a disk in an active galaxy may be fed into its nucleus by perturbations from a nonaxisymmetric, gravitational potential. To date the evidence available suggests that such a driving mechanism works best when the non-axisymmetric perturbation moves in a direct path with an angular velocity close to that of the rotating gas in the disk (Toomre and Toomre 1972; M. P. Schwarz, reported in Simkin, Su, and Schwarz 1980). The velocity for the secondary nucleus of Hydra A, however, appears to be retrograde with respect to the velocities in the gaseous disk.

3. Finally, it is clear from Figure 1 that the outer stellar envelope in Hydra A is extended *in a direction roughly perpendicular* to the rotation axis of the central core. The velocity measurements for the outer envelope, however, imply that this large-scale component either has a different rotation axis or exhibits only minimal rotation. In the former case, the outer parts of the galaxy may well be in prolate rotation. This would fit a picture for radio galaxy kinematics recently developed by Van Albada, Kotanyi, and Schwarzschild (1982), which appears to be quite different from the infall model previously discussed.

c) *Additional Observations*

Thus, the present data are compatible with parts of several theoretical pictures for radio galaxies, some of which appear to be contradictory. The following additional data seem to be necessary in order to resolve this confusion:

1. Measurement of the velocities of the other galaxies in the cluster surrounding Hydra A would establish whether the radio galaxy is indeed a cluster member and whether the relative velocity between the "secondary nucleus" and the main galaxy is in the same range as the cluster's velocity dispersion.

2. More detailed, very high resolution spectroscopy to establish the precise relationship between the ionized gas velocities and the stellar velocities in the cores of radio galaxies which have velocity patterns similar to those in Hydra A, would establish whether the double-valued emission-line velocities in these systems are consistent with infalling gas.

3. More extensive observations of the stellar velocities in the outer envelope of Hydra A and other cD radio galaxies will resolve the question of whether these objects are in an equilibrium state or an unstable state of gaseous infall (see § IV*b*, above).

V. CONCLUSIONS

The structural data presented here suggest that Hydra A has an unusual morphology, since other radio sources of comparable power have well-collimated, edge-brightened radio structure. The contradiction between the high optical and radio luminosity of Hydra A and its apparent "luminosity class I" radio structure may mean that our present descriptive generalizations about radio morphology may not be correct. More detailed radio observations of this galaxy are necessary, however, before we can decide just where these need revision.

The velocity data presented here seem to provide important clues about the mechanism which enables cD galaxies to become radio galaxies. They suggest that the conditions which produce radio galaxies may be related to the dynamical effects of a rapidly rotating core of stars and gas embedded in an outer envelope of material which is relatively stationary. More detailed observations on a much broader sample of radio galaxies are needed before these suggestions can be confirmed. Such optical

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data are not easily acquired since even a relatively bright object such as Hydra A requires lengthy observations with large aperture telescopes to provide the necessary high dispersion spectra. The data presented here suggest, however, that such lengthy observations would be worthwhile.

Finally, the close alignment between the axis of the present radio structure and the optical rotation axis for this object is characteristic of that found for other powerful radio sources. This implies that the mechanism responsible for the alignment of radio and rotation axes is related to the radio *power* of a source and *not* its radio morphology.

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R. D. Ekers: National Radio Astronomy Observatory, P. O. Box O, Socorro, NM 87801

S. M. Simkin: Department of Astronomy and Astrophysics, Michigan State University, East Lansing, MI 48824

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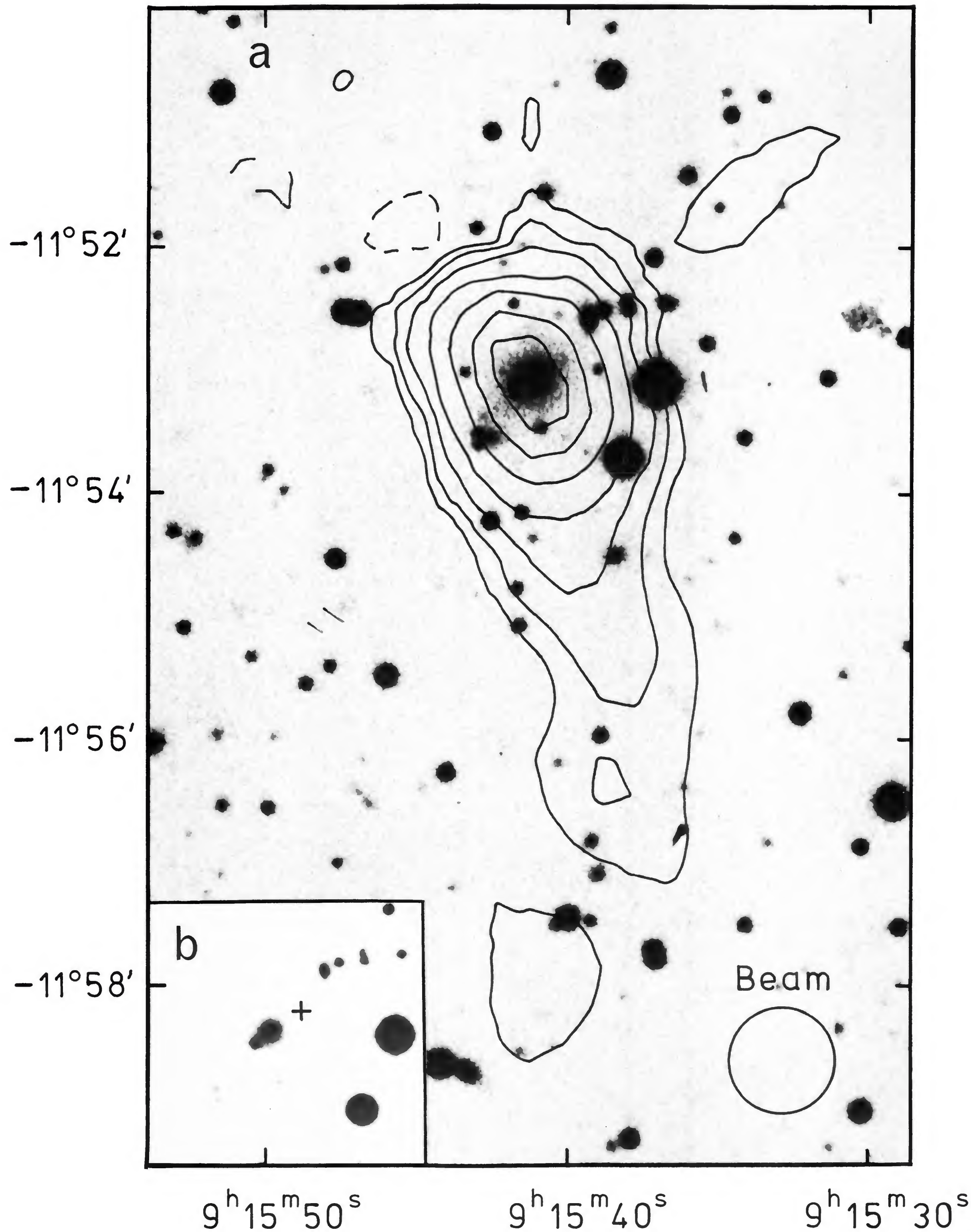

FIG. 1.—(*a*) 1400 MHz contours on a deep, IIIa-J, Palomar Schmidt plate of Hydra A. Contours: −0.45 (*dashed*), 0.45, 0.90, 1.80, 3.60, 7.20, 12.0, and 17.4 Jy/beam area. (*b*) The optical core, same scale as Fig. 1*a*. Half-power beamwidth = 50″.

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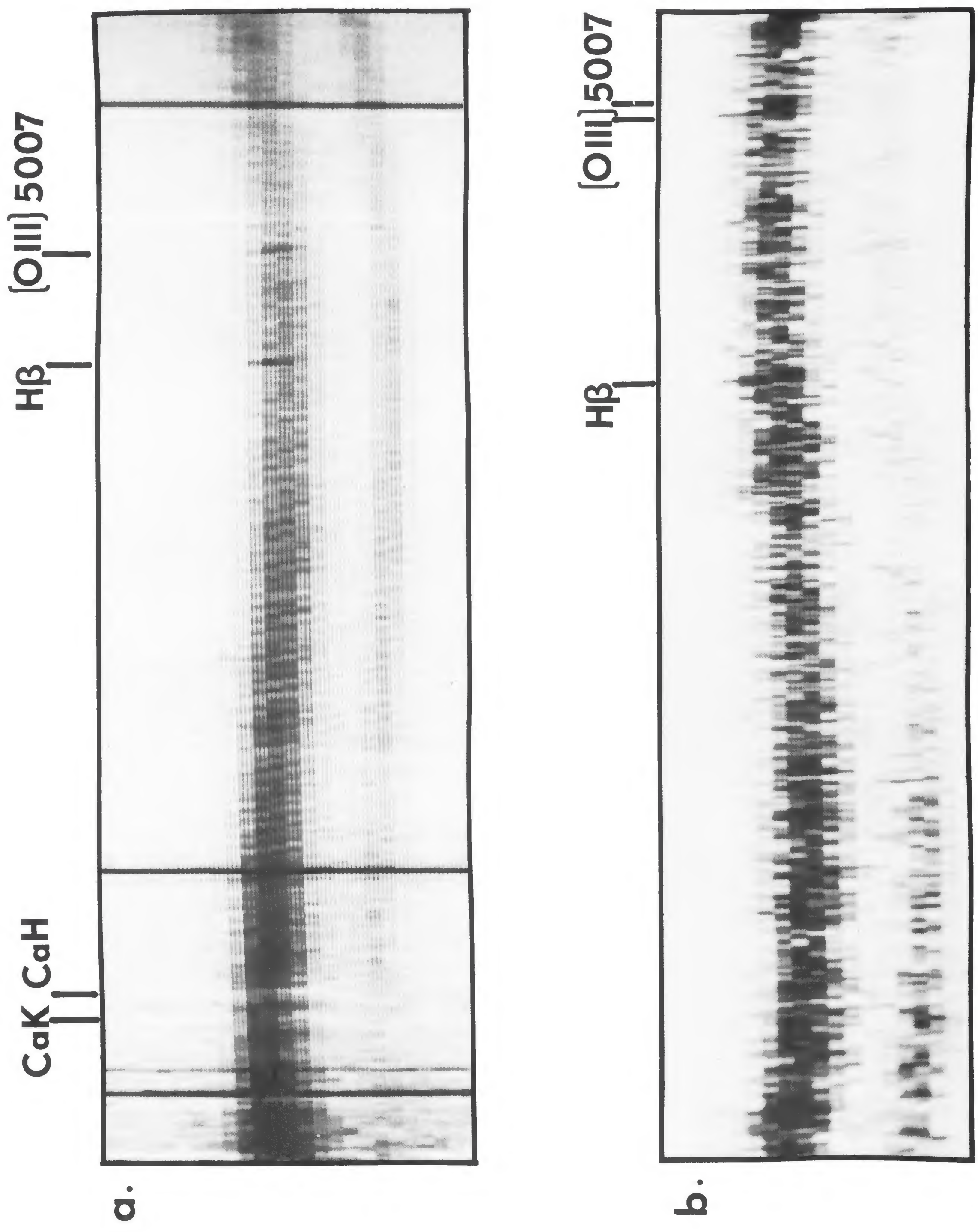

FIG. 3.—SIT spectra of the optical data: (*a*) in PA 140°, ~2.8 Å per pixel, and (*b*) in PA 115°, ~1.3 Å per pixel

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