

NEUTRAL HYDROGEN ABSORPTION IN MRK 6, NGC 3810, 1506+34, AND NGC 1068

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Received 15 November 1982; revised 13 April 1983

ABSTRACT

H I absorption has been reported in NGC 1068 and NGC 3810. The absorbing material in NGC 1068 has a low column density and is positioned in front of the compact nuclear source. Absorption in NGC 3810 occurs across a large fraction of the extended (4') radio source. Velocity offsets in NGC 3810 are due to disk rotation of the absorbing gas. Interpreting the features in these galaxies in terms of H I holes is considered implausible. H I absorption spectra are presented for Mrk 6 and a high resolution spectrum is given for 1506 + 34, suggesting the presence of distinct components in the 1506 + 34 absorption feature.

I. INTRODUCTION

A 21-cm hydrogen-line survey of extragalactic radio galaxies having known redshifts has resulted in six detections of absorption lines. Four of these lines have been reported previously, those being NGC 2377/3C178 (Roberts and Steigerwald 1977; Haschick, Baan, and Burke 1978; Haschick *et al.* 1980), Mrk 6 (Haschick, Baan, and Burke 1977; Heckman, Balick, and Sullivan 1978), 1506 + 34 (Baan, Haschick, and Greenfield 1978), and 3C293 (Baan and Haschick 1980; Haschick and Baan 1983). In this communication we present results of deep surveys of the radio galaxies 1506 + 34, Mrk 6, NGC 1068, and NGC 3810.

II. OBSERVATIONS

The observations were conducted using the 300-ft (91.5-m) transit telescope of NRAO* in Green Bank, West Virginia, the 1000-ft telescope of the National Atmospheric and Ionospheric Center† in Arecibo, Puerto Rico, and the Very Large Array of NRAO in Socorro, New Mexico.

The 300-ft observations were initially made in April and September of 1976 using a dual channel tunable 21-cm receiver ($T \sim 50$ K) and the 2×192 -channel autocorrelator spectrometer. Additional observations of Mrk 6 in August, 1976 employed the Mk II VLBI recording terminal and processor in the autocorrelation mode. Since June 1977 we have used the 6/25-cm dual channel cooled parametric up-converter amplifier with a system temperature of approximately 50–80 K. The sensitivity was ~ 1.1 K/Jy and ~ 1.27 K/Jy, respectively, for the

two systems. The 300-ft. was used to observe NGC 1068, Mrk 6, and NGC 3810.

The observations with the 1000-ft were performed in January 1978 and November 1979 using two different receivers. The first, a 21-cm micromega receiver (NGC 1068, NGC 3810), is an uncooled dual channel parametric amplifier, outfitted with a 16' circular line feed. The system had a sensitivity of 8.6 K/Jy and a system temperature of 80–120 K. The second, the 6/25-cm receiver (1506 + 34), was used with a 40' dual circular feed and had a sensitivity of 5.2 K/Jy at a system temperature of ~ 60 K.

The galaxies 1506 + 34 and NGC 3810 were observed in the radio continuum at 20 cm using, respectively, the VLA-A in March 1982 and the VLA-C in March 1983. Twenty seven telescopes were used in each configuration giving an angular resolution of 0".8 and 8".3, respectively.

III. RESULTS

a) Mrk 6

Mrk 6 (IC450) is classified as a class 2 Seyfert galaxy and is morphologically similar to NGC 1068 (Kachikian and Weedman 1971a). The sudden appearance of an entirely new set of hydrogen recombination lines in the spectrum of Mrk 6, blueshifted with respect to the main hydrogen lines by ~ 3000 km s⁻¹ (Kachikian and Weedman 1971b) has been interpreted as an extreme example of an asymmetry of the main lines and is an indication that real gas motions must be taking place (Adams 1972).

Radio emission from Mrk 6 was detected initially by Moffet in 1968 (see Weedman and Kachikian 1969). There is a radio double separated by $\sim 1''$ located within the error limits of the position given for the optical nucleus of Mrk 6 by Peterson (1973; Ulvestad, Wilson, and Sramek 1981). Extended double structure has been observed at 2695 MHz, and is thought to be the result of

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

†The Arecibo Observatory is part of the National Astronomy and Ionosphere Center (NAIC), which is operated by Cornell University under contract with the National Science Foundation.

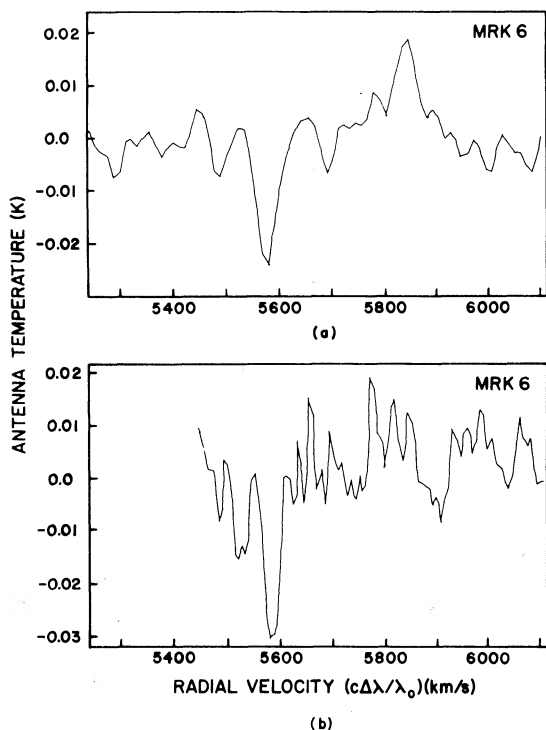


FIG. 1. Spectra of the neutral hydrogen in Mrk 6. The spectra were taken during 1976 using the NRAO 300-ft telescope and (a) a 10-MHz bandwidth and 80 minutes integration time, (b) a 5-MHz bandwidth and 120 minutes.

earlier activity within the nucleus of Mrk 6. The displacement of the extended component by 1 kpc from the nuclear source may be explained by the motion of the galaxy through the intergalactic medium.

21-cm spectra of Mrk 6 obtained with the 300-ft telescope during 1976 are presented in Fig. 1. A narrow absorption line is clearly visible at 5586 km s^{-1} in addition to a possible weak emission feature at 5850 km s^{-1} .

The results are summarized in Table I. These results were first announced by Haschick, Baan, and Burke (1977). The possible presence of emission has also been suggested by Heckman, Balick, and Sullivan (1978), but the emission in the spectrum could also be due to the Sb galaxy IC451 which is only 4.5 arcmin away. We use the optical velocity of 5636 km s^{-1} (Shuder 1980) as the systematic velocity of the system.

The determination of the optical depth for Mrk 6 is complicated by the presence of the weak extended radio component in addition to the double nuclear source. Extrapolation of the flux of the extended source measured by Sramek and Tovmassian (1974) to 21-cm wavelengths yields a flux density of $\sim 22 \text{ mJy}$. The depth of the absorption line (27 mJy) is greater than the total flux density of the extended source, which rules out absorption by a H I cloud covering the extended source alone. We thus assume that the absorption line in the spectrum of Mrk 6 is caused principally by a neutral cloud covering the nuclear source. The optical depth of the line is then 0.14 ± 0.03 and the column density of the absorbing cloud is $N_H/T_S = 7.7 \cdot 10^{18} \text{ H I atoms cm}^{-2} \text{ K}^{-1}$. The velocity of the absorbing cloud suggests a velocity of the cloud of 50 km s^{-1} towards the nucleus of the galaxy. But considering the uncertainties in the redshifts this relative radial velocity of the absorbing cloud cannot be considered very significant.

b) NGC 3810

The Sc galaxy NGC 3810 is pictured in *The Hubble Atlas of Galaxies* (Sandage 1961) as the Sc counterpart to the "two region surface brightness galaxies" such as the Sb galaxy NGC 1068. Like NGC 1068 it has a bright inner region surrounding the nucleus and fainter outer spiral arm structure. The object is a member of the Leo group. A H I emission profile of NGC 3810 has been published earlier by Dickel and Rood (1978).

Initial observations were done in May 1978 using the 300-ft NRAO telescope and in November 1979 using

TABLE I. Characteristic parameters of observed galaxies.

	Mrk 6	NGC 3810	B2 1506 + 34	NGC 1068
$M_{H I}/M_{\odot} 10^9$	0.4	2.6	8.2	> 0.65
Type	Sa:Sy2	Sc	Pec	Sb:Sy2
Inclination angle $i(^{\circ})$	53	42	—	39
Adopted distance (Mpc) ^a	106	18	245	21
$S(1400)(\text{mJy})$	297	184 + 18	130	1000
$V_{\text{opt}}(\text{km s}^{-1})$	5636 ± 56^b	988	13 550	1107
$V_{\text{em}}(\text{H I})(\text{km s}^{-1})$	5850	996	(13 669)	1136
$V_{\text{abs}}(\text{H I})(\text{km s}^{-1})$	5586 ± 6	$949 \pm 5, 1055 \pm 5$	$13 495 \pm 4$	1129 ± 5
H I absorption half-width (km s^{-1})	32 ± 5	66, 45	117	31
$V_{\text{em}} - V_{\text{abs}}(\text{km s}^{-1})$	-50^c	$-47, +59$	(-180)	-7
τ	0.14 ± 0.03	0.15, 0.09	0.45	0.014
$N_H/T_S(\text{H I atoms cm}^{-2} \text{ K}^{-1})$	$7.7 \cdot 10^{18}$	$1.1 \cdot 10^{19}, 5.2 \cdot 10^{18}$	$1.0 \cdot 10^{20}$	$8 \cdot 10^{17}$

^a $H_0 = 55 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

^b Shuder (1980).

^c $V_{\text{opt}} - V_{\text{abs}}$.

the NAIC 1000-ft telescope. The Arecibo results are presented in Fig. 2(a). The spectrum displays the characteristic emission profile for an edge-on-spiral galaxy. Superimposed on this profile is a dip in the spectrum at a velocity of 949 km s^{-1} and a possible depression at 1055 km s^{-1} . In Fig. 2(b) the 300-ft spectrum is presented, which shows a very pronounced feature at 949 km s^{-1} . The difference in the emission profiles for the 300-ft and 1000-ft data are mostly due to the difference in the beam size of the antennas. The discrepancy in the depth of the absorption features further suggests that the background continuum source has an extent larger than the 1000-ft beam, but smaller than the 300-ft beam.

The radio continuum flux at 2695 MHz has been measured by Dressel and Condon (1978) to be 62 mJy. Measurements on the 300-ft antenna yield a flux of $184 \pm 18 \text{ mJy}$ at 1415 MHz from the total power records and the spectral index is $\alpha = -1.69$. Early VLA observations of this galaxy suggested the presence of seven point sources distributed through the galaxy (van der Hulst, Crane, and Keel 1981). Recent VLA-C observations indicate that all the flux in NGC 3810 originates in an extended source, which is centered on the galaxy and has an extend equal to the optical extend of the galaxy (Fig. 3). The total flux density in the map is 110 mJy.

When comparing the two H I emission profiles one realizes that a large fraction of the emission could be missing in the spectra. Since the 300-ft beam encompasses the whole galaxy, one may estimate, using a symmetric emission profile, that as much as 10% of the pro-

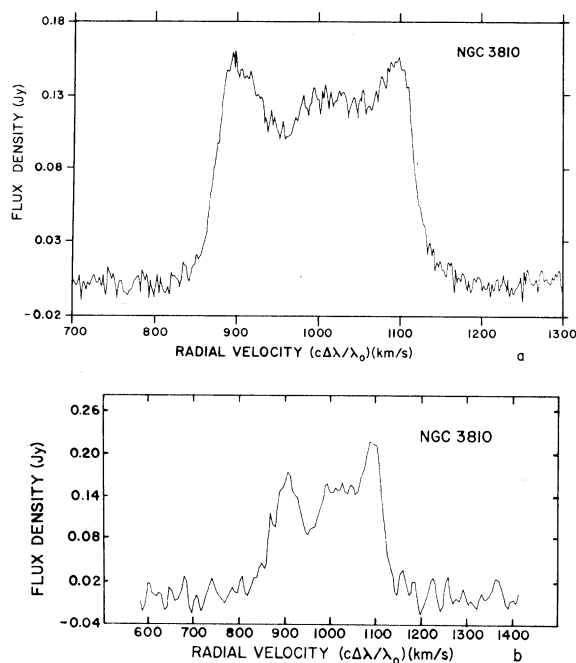


FIG. 2. Spectra of the neutral hydrogen in NGC 3810. (a) A spectrum taken in November 1979 using the 1000-ft Arecibo telescope. (b) A spectrum taken March 1978 with the NRAO 300-ft telescope.

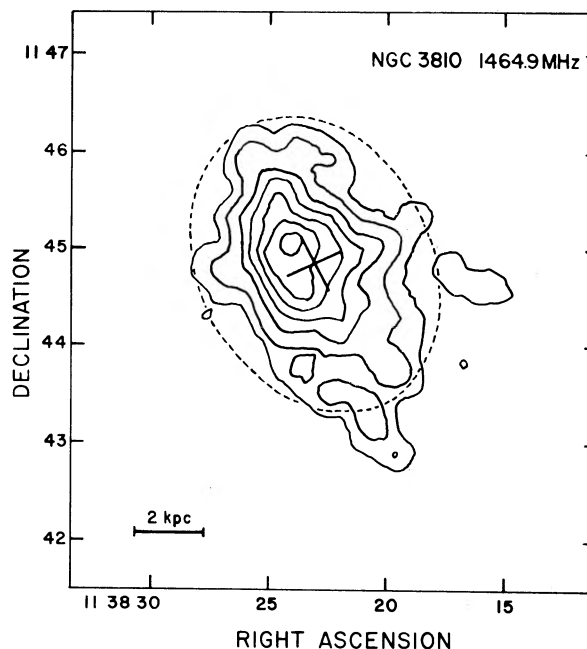


FIG. 3. The structure of the continuum source in NGC 3810 at 20-cm wavelength. This map was obtained with the VLA-C in March 1983. The contour levels are drawn at 0.5, 1, 2, 3, 4, 5, 6 mJy/beam. The cross marks the position of the optical nucleus. The extend of the optical image of NGC 3810 is indicated with the traced line.

file is missing on the blue side. This would indicate a velocity range for the absorption of at least 129 km/s . The width and uniform depth of the absorption features, and also the difference in the two profiles as noted above, suggest that the absorption occurs across a large fraction of the continuum source. This is supported by mapping results for the galaxy using the 1000-ft telescope, which indicate a large extend of the absorption. Also the depth of the absorption features is much more than the peak flux in the source. An alternative interpretation (a hole) seems rather implausible. There is no asymmetry in the optical image of the galaxy and there is no 30 Doradus-like region. It is therefore rather difficult to account optically for a possible 10% depletion of the neutral hydrogen. We therefore suggest that the features are indeed due to absorption. In fact the H I profiles are very similar to those for 3C178/NGC 2377 (Haschick, Baan, and Burke 1978), where NGC 2377 disk material absorbs the continuum spectrum from a background triple ($30''$) radio source 3C178 (Haschick *et al.* 1980).

The location of the absorbing gas is most likely in the disk, such that the velocity spread of the absorption is due to the disk rotation. The fact that the absorption appears asymmetric relative to the emission profile may be due to the offset position of the strongest disk emission. However, this may also suggest that the blue side of the profile is absorbed as well. The absorption in NGC 3810 provides unique opportunities for studying the dis-

tribution of the absorbing gas. Assuming a uniform section of the disk covering the extended continuum source we find that the optical depth for the strong and the possible weak features are 0.15 and 0.09, and the column densities are $1.1 \cdot 10^{19} T_S \text{ cm}^{-2}$ and $5.2 \cdot 10^{18} T_S \text{ cm}^{-2}$ (see Table I).

c) 1506+34

The Bologna radio source B2 1506 + 34 has been identified by Colla *et al.* (1975) with a 15.6-mag peculiar double galaxy. Colla *et al.* (1975) identify the radio source with a knot approximately three arcminutes northeast of the center of the optical image. Observations of this source using the VLA-A antenna at 6 and 20 cm have produced improved positions for the radio source of RA (1950) = $15^{\text{h}}06^{\text{m}}05^{\text{s}}.32$ and DEC (1950) = $34^{\circ}34'49''.3$. A map at 6-cm wavelength of 1506 + 34 is given in Fig. 4. The peak flux in the maps of 108 mJy at 20 cm and 29 mJy at 6 cm, as compared with single disk fluxes of, respectively, 130 and 45 mJy, indicate that the source is slightly resolved at both frequencies. An approximate size for the source at 6 cm is $1''.3$ (or 1.2 kpc assuming $H_0 = 55 \text{ km s}^{-1} \text{ Mpc}^{-1}$). A 21-cm spectrum of 1506 + 34 has been presented earlier (Baan, Haschick, and Greenfield 1978).

In November 1979 additional observations were done using the 1000-ft Arecibo telescope in order to further study the structure of the line (Fig. 5). The prominent absorption feature at $13\,495 \pm 4 \text{ km s}^{-1}$ has a full width at half-maximum power points of $\sim 117 \text{ km s}^{-1}$. A weak emission feature is seen in the spectrum at a velocity of $13\,650 \text{ km s}^{-1}$ and in other spectra also a possible feature appears at $13\,300 \text{ km s}^{-1}$, but this feature needs further investigation. The redshifted emission feature was suggested earlier on the basis of 300-ft observations

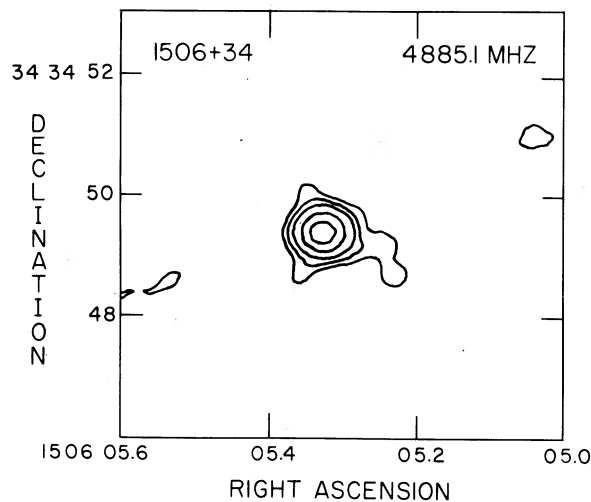


FIG. 4. The continuum structure of B2 1506 + 34 at 6-cm wavelength. This map was obtained in March 1982 using the VLA-A. The contour levels are drawn at 1, 2, 4, 10, 20 mJy/beam.

(Baan, Haschick, and Greenfield 1978) and is hereby confirmed. The redshifted emission represents a mass in neutral hydrogen of $8.2 \times 10^9 M_{\odot}$. Naturally this is a low value for a peculiar galaxy, but of course further emission could be hidden by the absorption feature. The optical radial velocity of $1506 + 34$ of 13550 km s^{-1} (Colla *et al.* 1975) agrees well with the velocity of the absorption feature and is also consistent with the location of the emission feature. The absorption line itself has a "flat" bottom, which may indicate that the line is a composite of several narrower components, typically of a half-width of 50 km s^{-1} and separated by $\sim 35 \text{ km s}^{-1}$. The shoulder on the blue side of the line indicates the presence of a distinct feature at $13\,421 \text{ km s}^{-1}$. Some important parameters are given in Table I.

d) NGC 1068

NGC 1068 is one of the most extensively studied galaxies in the Seyfert class and has been taken as a prototype of a class 2 Seyfert, although in some aspects it is the exception rather than the rule. Discrete gas clouds have been detected in the nucleus of this Sb spiral which are moving at high velocities (up to 600 km s^{-1} ; Walker 1968).

The radio structure of NGC 1068 has been studied by de Bruyn and Willis (1974) at 6 cm and by de Bruyn and Wilson (1976) at 20 cm. Most of the ~ 9 -Jy flux at 1415 MHz is due to an extended structure of 13 arcsec (1.5 kpc) at position angle $\sim 33^{\circ}$ (Wilson and Ulvestad 1982). A central component coincides with the optical nucleus and has a size of 0.7×0.3 arcsec ($77 \times 33 \text{ pc}$) in p.a. $\sim 28^{\circ}$ (Condon *et al.* 1982).

Spectra of NGC 1068 were taken at 1415 MHz on both the 300-ft (June 1977) as well as the 1000-ft (January 1978) telescopes and the 1000-ft spectrum is shown in Fig. 6. The spectrum shown has been smoothed using Hanning weighting and the effective resolution is 4.2 km s^{-1} . The integration time on the source position is 80 minutes and corresponds to seven days of observing

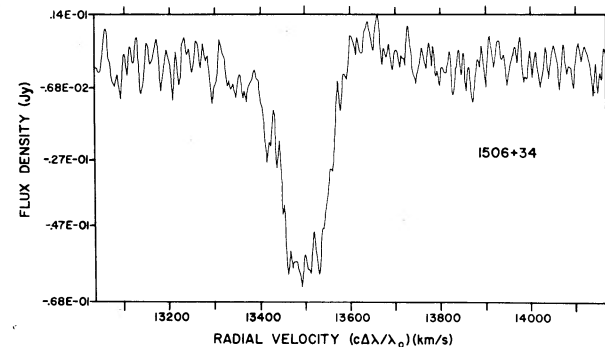


FIG. 5. Spectrum of the neutral hydrogen in B2 1506 + 34. The spectrum which was obtained in November 1979 using the 1000-ft Arecibo telescope, has been Hanning smoothed and has a 4.2-km/s velocity resolution.

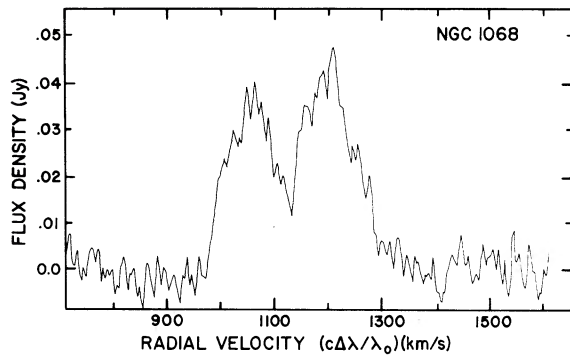


FIG. 6. Spectrum of the neutral hydrogen in NGC 1068. The spectrum was obtained in January 1978 using the 1000-ft Arecibo telescope. The effective velocity resolution is 4.2 km/s.

time on the 1000-ft antenna. A linear baseline has been removed from the spectrum.

Neutral hydrogen emission from NGC 1068 is clearly seen in the Arecibo spectrum. The centroid H I velocity is $1136 \pm 4 \text{ km s}^{-1}$, which is in good agreement with the optical velocity for the nucleus of 1107 km s^{-1} as derived by Walker (1968). The double-peaked emission profile characteristic of Sb spiral galaxies is slightly peculiar due to the fact that the relatively small Arecibo beam has sampled only the central part of the galaxy. However, there is the deep and sharp trough at the center of the emission profile at a velocity of 1129 km s^{-1} . A similar central depression was initially seen in our (1977) 300-ft spectrum, but naturally the feature is more pronounced in the 1000-ft spectrum. The sharpness and depth of this feature, which is almost 70% of the emission amplitude, leads to the conclusion that it is likely due to absorption of the flux of the nuclear source. Roberts and Steigerwald (1977) have attempted to explain the unusual profile of NGC 1068 as a similar profile as observed in M82, but distorted by absorption across the profile.

A possible alternative interpretation of the central depression in the H I profile could be the absence of emission from the central region ($\Delta V = 0$) of NGC 1068. This would require the presence of a H I ring structure as has been observed in other Sb galaxies and has been suggested earlier for NGC 1068 on the basis of its structure (Bosma 1978). However, the spectrum of a rotating ring of H I would have a shallow central section with relatively narrow sides and is not likely to have a narrow central feature as observed. Therefore we suggest that the central depression is indeed due to absorption. In order to exemplify this point further we present a position-velocity map of NGC 1068 made with the 1000-ft telescope (Fig. 7) (Giovanelli and Hardy 1983). The map was made along the major axis, which lies at PA = 70° . This map clearly suggests the presence of H I absorption at the center of the galaxy. Assuming that the feature is due to absorption of the core source of $\sim 1 \text{ Jy}$, we derive a column density of $8 \times 10^{17} T_S \text{ cm}^{-2}$.

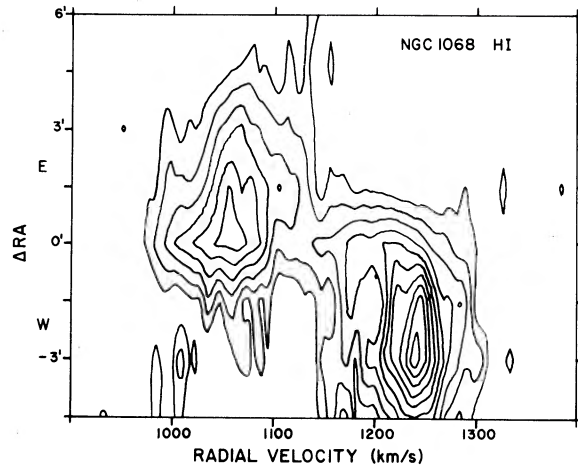


FIG. 7. Position-velocity map of NGC 1068. The positions were taken along the major axis of the galaxy, which is at P.A. = 70° . The data were obtained with the Arecibo telescope by Giovanelli and Hardy (1983). The contour levels are at 10-mJy intervals starting at 10 mJy.

This column density is an order of magnitude lower than that for the absorption observed in Mrk 6.

IV. SUMMARY

For NGC 1068 the velocity of the absorption feature is nearly the same as the emission velocity. The absorption velocities of Mrk 6 and 1506 + 34 are only discrepant when the optical velocity is taken to be the systemic velocity of the galaxy. But considering the uncertainty of the optical velocities and the ambiguity of the H I emission profiles we find no significant evidence for radial motions in these galaxies. This conclusion adds further weight to similar conclusions reached by Mirabel (1982) on the basis of all previously observed absorption features in radio galaxies. NGC 3810 is unusual in the sense that there may be absorption across a large region of the disk. The relative velocities of the absorbing clouds are therefore caused by motion in the disk.

The features for NGC 1068 and NGC 3810 have been interpreted as absorption. In both cases the notion of a neutral hydrogen "hole" seems rather implausible. However, it will be interesting to see whether irregular neutral hydrogen distributions or holes can indeed produce a feature in the emission profile, which looks perfectly like an absorption line. Interferometric observations will certainly help answer these questions.

The galaxies Mrk 6, NGC 3810, and NGC 1068 have relatively small inclination angles such that absorption in these systems could suggest the presence of halo gas. But the high values for the neutral hydrogen column density, observed for the first two galaxies, suggest that the absorbing gas must belong to the disk. The lower value for the column density in NGC 1068 would indeed be consistent with an absorbing halo cloud. Interferometric studies of NGC 3810 provide a unique chance to study the spatial distribution of the absorbing material.

The authors would like to thank Jacqueline van Gorkom for help with VLA observations and Riccardo Giovanelli for communicating observational data prior to publication.

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