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A SURVEY OF NEUTRAL HYDROGEN ABSORPTION IN THE NUCLEI OF ACTIVE SPIRAL GALAXIES

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ABSTRACT

Nineteen spiral and irregular galaxies with bright continuum nuclei have been observed with the VLA to search for absorption at $\lambda = 21$ cm by cool atomic hydrogen in or in front of the nuclei. Most of these galaxies show activity at other wavelengths, such as Seyfert nuclei, intense far-IR emission, and X-ray emission. Fifteen absorption lines were detected, and six tentatively detected, in 15 of these galaxies. The VLA eliminates confusion due to H I emission from the galaxy disks and so permits accurate measurement of the velocity centers, widths, and integrals of the absorption lines. The line centers are offset from the systemic velocities by as much as 500 km s^{-1}. Infall is more common than outflow at these high velocities, although the more common lines with offsets of less than 100 km s^{-1} are evenly distributed between infall and outflow. Some lines are broad (more than 100 km s^{-1}); about half have σ_v greater than 30 km s^{-1}. Equivalent widths are much larger than for a spiral disk like that of the Milky Way; probably the absorption is arising not in the disks, but in circumnuclear clouds, or in some cases perhaps in an intervening system falling toward the active nucleus. Simple order-of-magnitude calculations suggest accretion rates of $\sim 1\ M_\odot$ of H I per year onto the nucleus.

Subject headings: galaxies: internal motions — galaxies: nuclei — radio sources: 21 cm radiation

I. INTRODUCTION

There are several types of extragalactic λ-21 cm absorption lines, distinguished by the relation of the absorbing gas to the background continuum. Several lines have been found at very high redshift in the spectra of quasars; these often correspond to optical absorption systems (reviewed by Roberts and Steigerwald 1977; Wolfe, Briggs, and Jauncey 1981). At lower redshifts, some absorption lines are associated with known galaxies intervening in front of much more distant, unrelated continuum sources (Briggs and Wolfe 1983; Briggs 1983). A different situation is when the absorbing gas and the continuum emission are both intrinsic to the same galaxy. A particularly simple case of this is absorption by gas in an active spiral galaxy of continuum radiation from the nucleus. Many Seyferts and starburst galaxies, including several of the novel *IRAS* galaxies, have compact, bright centimeter wave sources in their nuclei (Condon *et al.* 1982) which make good background sources for studying the absorption by the intervening gas in the galaxy. In this paper I report results from a VLA survey of absorption toward the nuclei of 19 active spirals; the discussion section includes results from earlier observations to study the statistical properties of a larger sample of lines.

To detect 21 cm absorption in other galaxies needs both sensitivity and high angular resolution. The first is needed because the nuclear continuum sources are so weak, typically only a few hundred mJy or less, and the lines are themselves weak, with optical depths of a few tenths or less, so a large total collecting area is required. For example, the pioneering work of Haschick (1977) with the Green Bank interferometer was hampered by the low sensitivity of the telescope; in spite of this handicap a few lines were detected, but the instrument was not capable of amassing a sample of lines large enough to be of statistical value. Westerbork has turned up several lines (Bosma, Ekers, and Lequeux 1977), but here also long integration times are needed, and signal-to-noise ratios are still not high.

Sensitivity is not a problem for Arecibo, whose collecting area is so huge that it can detect a line as weak as $\tau = 0.01$ toward a source as faint as 10 mJy in only 5 minutes of integration. But this is seldom possible for Arecibo because of confusion between emission and absorption. Most spiral galaxies have 21 cm emission much stronger than the 100 μJy which would be the depth of such an absorption line. (This much emission would come from only about $10^7\ M_\odot$ of H I at 100 Mpc distance if confined to a 40 km s^{-1} spectrometer channel; typical spirals may have 100 times this much.) The Arecibo beam is so large that most galaxies are unresolved, so it is impossible to separate the absorption toward the compact nuclear continuum source from the emission from the much larger galaxy disk. Some of the stronger continuum sources in galaxies do show absorption at Arecibo (discussed below, Table 3), but in most cases the absorption is so blended with emission that it is impossible to measure accurately the center, width, or area (equivalent width) of the absorption lines.

The VLA[1] (Thompson *et al.* 1980) is the only telescope which can provide both the sensitivity (due to its large total collecting area) and the resolution (a few arcseconds at 21 cm) to be able to measure sensitive absorption spectra unconfused by emission. The telescope and observing parameters for this survey are described in § II, which also contains discussions of the galaxies searched and the spectra measured. Section III presents a summary of the resulting distribution of line parameters, including well-determined lines from the literature, to try to deduce the dynamics of the absorbing gas relative to the disk and nucleus of the active galaxy. Section IV gives a brief discussion of the probable physical parameters of the clouds seen in absorption, depending on their location. Section V summarizes the results.

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II. OBSERVATIONS

a) General Discussion

The indispensible feature of the VLA for extragalactic 21 cm absorption studies is its high resolution. The synthesized beam is almost as small in solid angle as the nuclear continuum sources in many of the galaxies observed, so only absorption is seen, no emission. Even in cases where the nuclear source is much smaller than the VLA beam, emission which is spread over angles much larger than the beam is canceled out by the positive and negative interferometer sidelobes.

These spectra were taken in 1982 August and October, when the VLA was in B array, which has a synthesized beam size of about 4″. The continuum source was set at the map phase center, and the program PASSUM was used to construct the spectrum at that point. As explained by Dickey (1982), this technique gives simply the spectrum toward a single synthesized beam area at the map center, avoiding the multiple Fourier inversion and cleaning normally needed for spectral line mapping. The bandpass shape was calibrated in real time by dividing the cross-correlation functions of each antenna pair by the rms of the autocorrelation functions of the individual antenna bandpasses (line option B, see Rots and Hjellming 1982). The velocity resolution was 42 km s^{-1} and the total bandwidth was 1312 km s^{-1} (6.125 MHz).

Table 1 lists the galaxies searched for absorption, the velocity range covered, the spectral rms noise level achieved, and the continuum flux detected. The continuum fluxes must not be taken very seriously because of the PASSUM technique used to reduce the data; extended flux even slightly larger than the synthesized beam is eliminated. The solid angles listed on Table 1 come from the literature (references given); accurate flux measurements may be found in the references as well. The selection of galaxies to be observed was not intended to be in any sense a complete sample; galaxies which showed a suggestion of absorption from single-dish H I observations or molecular line studies were selected, and otherwise spirals with the most intense, compact nuclear continuum were chosen. The relatively high rate of detection of absorption lines in these observations is due to this selection of objects most likely to show absorption.

Spectra with clear detections of H I absorption are shown in Figure 1. Spectra which show lines with poor signal-to-noise ratio are shown in Figure 2; these may be considered tentative detections. In Figure 1 the arrows mark the systemic velocities of the galaxies, as determined for the disks as a whole by 21 cm emission studies, or, where these are not available, as determined optically. Gaussians have been fitted to the absorption lines; best-fit values of the Gaussian peak $A_{\max}$, center velocity V_0, and half-width σ_v are listed in Table 2. The error bars are the formal 1 σ errors of the fit or the 1 σ noise level, whichever is greater. Also listed in Table 2 is the equivalent width (i.e., the velocity integral of the absorption spectrum), expressed as the line-of-sight integral of density divided by temperature using

$$\frac{N}{T} = 1.82 \times 10^{18}\ \mathrm{cm}^{-2}\ \mathrm{K}^{-1} \times \int_{\infty}^{\infty} \tau(v)dv$$

(e.g., Dickey, Salpeter, and Terzian 1979). Finally, the value for the velocity offset ΔV, defined as the line velocity minus the systemic velocity, is given also in Table 2. For lines whose width is only two channels or less (i.e., $\sigma \lesssim 50$ km s^{-1}), the Gaussian fitting program I have used has trouble finding σ. I have simulated this with artificial Gaussians superposed on random noise. When the signal-to-noise ratio is 3 or less, then the fitted values of σ become unreliable, as do the peaks. Even for low signal-to-noise ratio, however, the velocity center and the velocity integral (equivalent width) of the line are generally well determined. For signal-to-noise ratio of 5, the fitted value of σ is reliable as long as σ is larger than the channel width; for σ less than the channel width, the fitting program arbitrarily varies the peak and σ, keeping the values integrated over the velocity channel roughly constant. This can give an unreasonably narrow, very deep line. In these cases I have fixed σ at 20 km s^{-1}

b) Discussion of Individual Sources

NGC 449 (*Markarian 1*).—This galaxy was detected in 21 cm emission by Heckman, Balick, and Sullivan (1978) at Arecibo, with a center velocity of 4780 km s^{-1}, only 13 km s^{-1} from the optical redshift. The VLA absorption line is tentative, not because the absorption is weak (almost 10%), but because the continuum is faint (approximately 30 mJy). This is significantly less than de Bruyn and Wilson (1976) measured using Westerbork, which implies that the rest of the continuum emission is spread over a larger area of 10″–15″, too large for the B array using PASSUM. A broader H I emission line was measured by Bierman, Clark, and Fricke (1979), with a significantly redder line center. The signal-to-noise ratio in the latter spectrum is not as good as in the former, so I shall use the Heckman, Balick, and Sullivan (1978) results to determine the systemic velocity and total H I mass.

NGC 520 (*Arp 157*).—This extraordinary galaxy appears on the Arp (1966) plate to be a collision or superposition of galaxies. It is difficult to define an inclination in this case or to classify the system, although there are a very prominent dust lane across the center and the suggestion of disrupted spiral arms, so it is clearly of spiral type. It has often been studied in the radio continuum and 21 cm line, and absorption was detected at Arecibo by several groups (Mirabel 1982; Thuan and Wadiak 1982). The VLA absorption measured here confirms the earlier detection (Dickey 1982) and shows more clearly the multiple components which were suspected earlier. At least three Gaussian components are needed to fit the highly asymmetric line, but it may be that these fits do not correspond to real clouds. The velocity distribution of the absorbing gas may be intrinsically skewed with a long tail of blueshifts. Higher resolution data may permit a detailed model of this gas flow. The deepest absorption is more than 100 km s^{-1} redder than the systemic velocity, which I take from Shostak (1978); none of the several other systemic velocity measurements (see Bottinelli, Gouguenheim, and Paturel 1982) are as high as the absorption.

NGC 2110.—This galaxy has been discussed at length by Ulvestad and Wilson (1983) and Wilson and Baldwin (1985), who take it to be a prototype for a class of galaxies with X-ray–emitting nuclei but narrower nuclear optical lines than type 1 Seyferts. The lines are weak ($\tau = 0.03$ to 0.04), but the nuclear emission is quite strong, allowing a reasonably confident detection. Wilson and Baldwin (1985) have determined the velocities of the O III and Hβ emission across the disk of this galaxy; they find a curious offset of $1\farcs7$ between the kinematic center and the nucleus seen in the optical and radio continuum. The center of the rotation system appears to be at 2402 ± 15 km s^{-1}, whereas the velocity at the nucleus is 2232 km s^{-1}, 170 km s^{-1} less. The 21 cm absorption lines are

TABLE 1

GALAXIES SEARCHED FOR ABSORPTION

Galaxy Name	Type	Inclination	Other Names	(1950) α	Position δ	Search (heliocentric) velocity range	σ_τ	$S_{\rm cont.}$ mJy	$\Omega_{\rm cont.}$ (arc sec)^2	$M_{\rm HI} \times 10^8\ M_\odot$	Continuum References
NGC 449	SBO/SBa Seyf 2	44±10	Mkn 001	$01^h13^m19.56$	+32°49'32.9	3910-5010	0.034	30	<0.04	13	1,5,10
NGC 520	Pec/Irr	63±2	Arp 157	01 21 59.62	+03 31 53.0	1700-2800	0.027	134	5	62	5,12,14
NGC 2110	Sa?/Seyf2	?		05 49 46.38	-07 28 01.4	1680-2790	0.007	187	2		3
IC 0450	SO-a	52±6	Mkn 006	06 45 43.93	+74 29 09.7	5030-6130	0.010	324	0.2		1,4,7,10
NGC 2623	Sc/Pec	34±13	Arp 243	08 35 25.28	+25 55 50.2	4970-6080	0.026	261	0.2	30	5,12,14
NGC 2782	S pec	41±5	Arp 215	09 10 53.60	+40 19 15.19	1990-3170	0.058	48	10	45	1,11,15
NGC 3227	Sb Seyf2	45±4	Arp 94	10 20 46.77	+20 07 06.30	710-1900	0.032	172	0.5	9	1,5,10,11,12,15
NGC 3504	Sa/SBb	36±5		11 00 28.54	+28 14 31.26	960-2060	0.023	100	<0.01	7	1,5,9,10,15
NGC 3690	Sb/Irr	37±8	Arp 299 Mkn 171	11 25 44.20	+58 50 18.0	2430-3530	0.009	311	0.6		1,6,9,10,15
NGC 3894	SO pair	47±5		11 46 10.41	+59 41 37.1	2670-3790	0.008	506	<20		12
NGC 4151	Sab/Seyf	42±4		12 08 01.03	+39 41 02.0	420-1530	0.007	344	≤10	18	2,7,10,11,12,16
NGC 4194	Pec/Irr	47±5	Arp 160 Mkn 201	12 11 41.24	+54 48 16.3	1320-3750	0.041	90	<20	14	10,12
NGC 4594	Sa/pec	63±1	M 104	12 37 23.40	-11 20 54.5	540-1700	0.027	90	10^{-5}	5	8,11,12,15
NGC 5506	Sa	69±2	Mkn 1376	14 10 39.17	-02 58 27.0	1180-2290	0.009	245	<0.1		1,10,15
NGC 5675	S			14 30 36.33	+36 31 18.5	3610-4760	0.015	55.5	10^{-5}		5,12,14
IC 4553	pec		Arp 220	15 32 46.91	+23 40 07.8	4840-5950	0.008	221	0.6		5,12,14
UGC 10599	pec		Mkn 501	16 52 11.75	+39 50 24.6	9500-10600	0.003	1390	<20		12
NGC 6500	Sa	39±8		17 53 48.14	+18 20 39.8	2050-3150	0.022	166	10^{-5}	51	5,12,13,14
NGC 7674	Sa/Sb	17±12	Arp 182 Mkn 533	23 25 24.40	+08 30 12.7	8170-9280	0.022	195	0.2	400	5,12,14

REFERENCES.—(1) van der Hulst *et al.* 1981. (2) Booler *et al.* 1982. (3) Ulvestad and Wilson 1983. (4) Ulvestad *et al.* 1981. (5) Jones *et al.* 1981. (6) Gehrz *et al.* 1983. (7) Preuss and Fosbury 1983. (8) Graham *et al.* 1981. (9) Hummel *et al.* 1982. (10) Wilson and Meurs 1982. (11) Hummel 1980. (12) Condon and Dressel 1978. (13) Hummel *et al.* 1984. (14) Condon 1980. (15) Condon *et al.* 1982. (16) Johnston *et al.* 1982.

centered at 2506 and 2589 km s^{-1}, which is close to the extreme of about 2600 km s^{-1} seen 4″–6″ to the southeast in the optical emission lines. The radio continuum source is compact enough to isolate the absorption to within about 1″ of the optical nucleus. For consistency with the other galaxies, where the 21 cm rotation curve is used to define the systemic velocity, I use 2402 km s^{-1} for the systemic velocity here. It is possible that the two lines seen in this spectrum are in fact one line, with a strong noise spike at 2550 km s^{-1}. In this case the true line would have its center at ~2550 km s^{-1} and equivalent width of about 1.5×10^{19} cm^{-2} K^{-1}. Classification is a problem for this galaxy, considering the results of McClintock *et al.* 1979, Bradt *et al.* 1978, and Wilson and Baldwin (1985); I shall assume it to be Sa, but this should be confirmed by careful morphological study.

IC 450 (*Markarian 6*).—Absorption at 21 cm has been

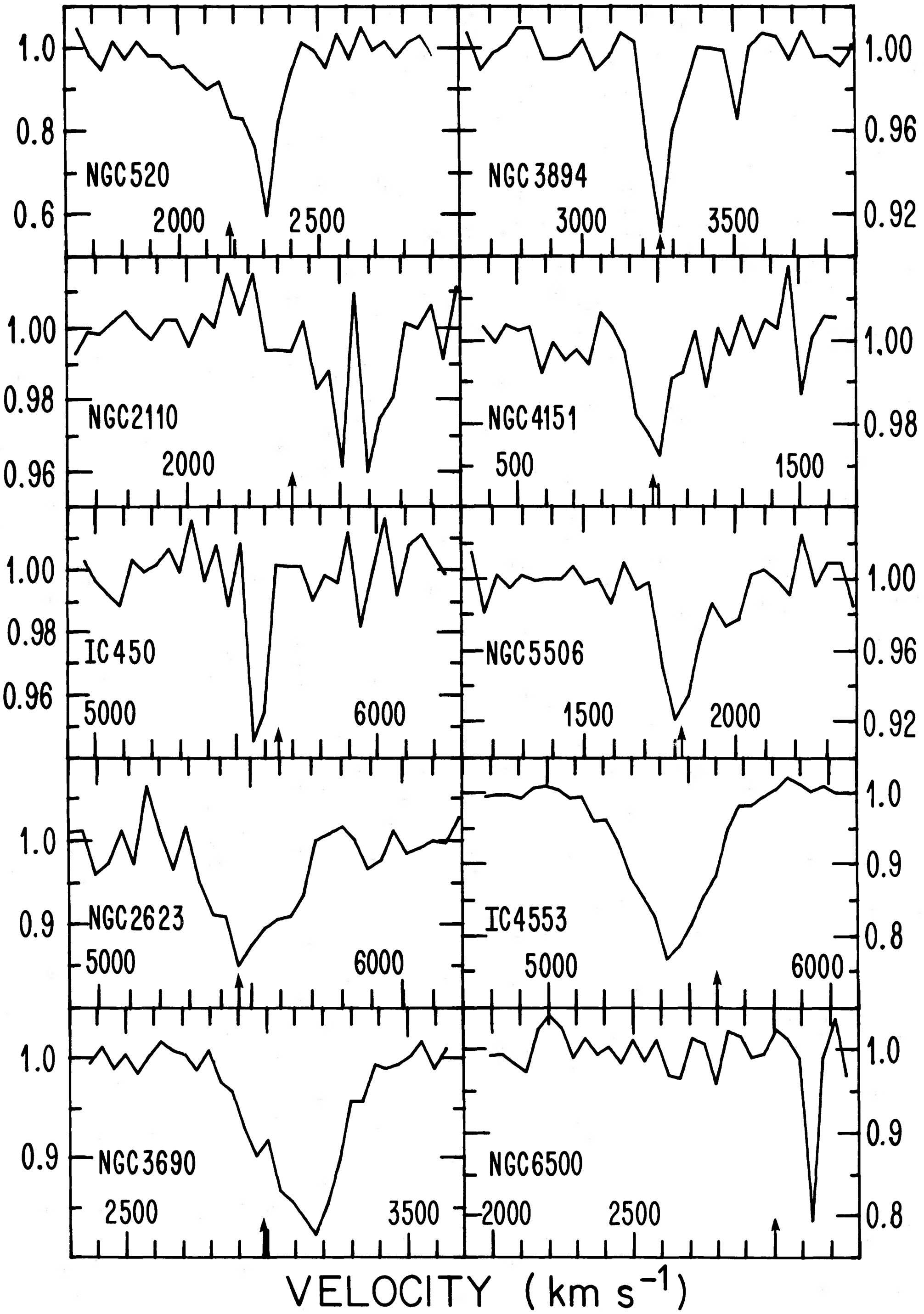

FIG. 1.—21 cm absorption lines detected toward active nuclei of spiral galaxies. The abscissa scale is the radial velocity ($c\Delta\lambda/\lambda$). The ordinate is relative absorption ($e^{-\tau}$). The small arrows mark the systemic velocities of the galaxies.

detected in this galaxy in several previous studies (Haschick, Baan, and Burke 1976; Haschick 1977; Heckman, Balick, and Sullivan 1978), but the new spectrum has much better signal-to-noise ratio than earlier measurements, so the center velocity and equivalent width can be well determined. (Earlier VLA spectra showed a hint of absorption at the 2 σ level.) Here again the determination of the systemic velocity is difficult, because single-dish spectra are dominated by the absorption, which overwhelms the emission (a rare situation). I adopt the optical determination of 5660 km s^{-1} (cf. Heckman, Balick, and Sullivan 1978), but, as Haschick (1977) discusses, there are other optical measurements giving higher values by as much as 100 km s^{-1}.

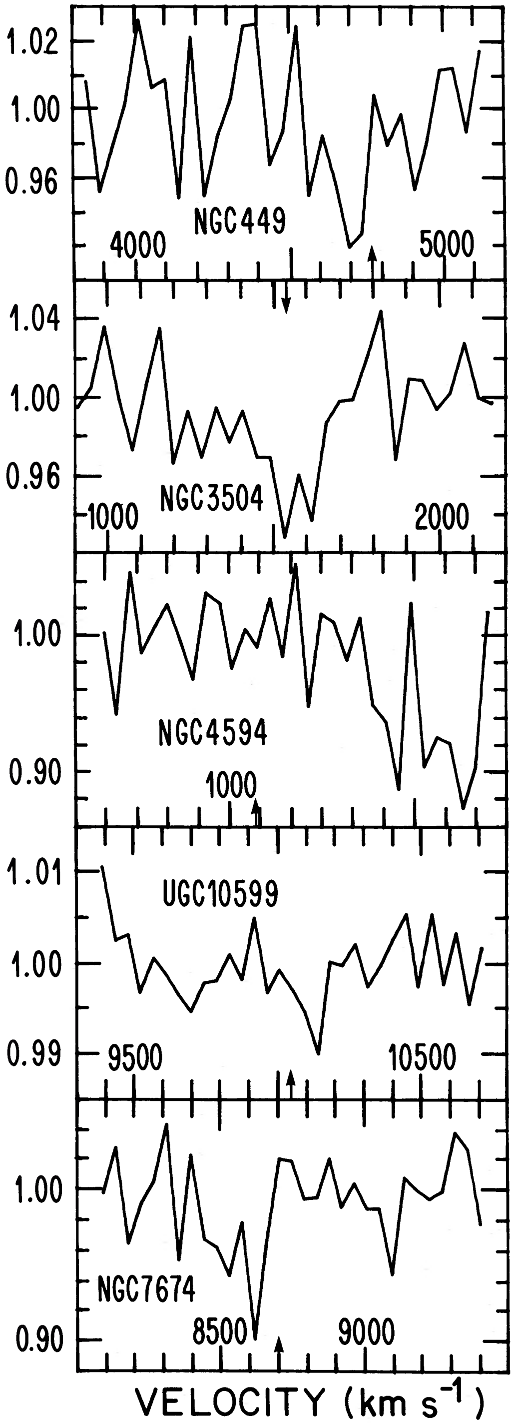

FIG. 2.—Tentative detections of absorption. The notation is the same as in Fig. 1.

NGC 2623 (*Arp 243*).—Single-dish profiles from Arecibo show absorption mixed with emission in this galaxy (Bieging and Biermann 1977; Mirabel 1982), so again for a systemic velocity I use the optical redshift. This is clearly an interacting pair of spirals, in which there may have been a burst of star formation about 10^8 yr ago (Larson and Tinsley 1978). This is a good example of the necessity for interferometer measurement of H I absorption in spirals, since in the single-dish spectrum the emission fills in the center velocities of the absorption line, making it appear to be two lines, one on each side of the optical systemic velocity. Obviously, the single-dish determinations of the equivalent width and the total H I emission are not reliable.

NGC 3504.—The systemic velocity for this galaxy comes from the Nançay spectrum by Bottinelli, Gouguenheim, and Paturel (1980). This galaxy has a very bright, compact nuclear source of size $\sim$0″.2 but shows no VLBI fringes. The nuclear emission region is therefore smaller than about 20 pc but larger than about 5 pc, assuming a distance of 20 Mpc. The absorption line is weak, and the signal-to-noise ratio is not very high, so this line also might be considered a tentative detection.

NGC 3690.—This starburst galaxy is bright in the radio and infrared and has bright optical emission lines (reviewed by Gehrz, Sramek, and Weedman 1983). A recent burst of star formation may explain most, but not all, of the radio continuum emission; one flat spectrum point source, unresolved with a beam of 0″.7, does not fit a starburst model. The redshift comes from the optical observations of Gehrz, Sramek, and Weedman (1983); I have not found a 21 cm emission detection of this interesting multiple system. The Arp atlas plate shows two interacting spiral galaxies, which may be superposed along the line of sight. This is a good example of an interacting system where the H I of the intervening galaxy may be absorbing continuum from the other. Although the absorption line is clearly asymmetric (it has a blue tail), I have only fitted a single Gaussian component. With better signal-to-noise ratio, at least one more component should be tractable.

NGC 4151.—This well-known nearby Seyfert has been studied in 21 cm emission by many authors (reviewed by Bottinelli, Gouguenheim, and Paturel 1982); recently a VLA synthesis map of the emission has been made by Liszt and Dickey (1986). Absorption toward the nucleus was tentatively detected by Bosma, Ekers, and Lequeux (1977) and by Dickey (1982). This detection is now firm, with the center velocity and width well determined. Continuum synthesis shows that the nuclear source is quite compact (Johnston *et al.* 1982; Booler, Pedlar, and Drake 1982); most of the flux detected here is contained within 3″ × 5″ in the nucleus. About 70 mJy is in two very compact (<0″.25) point sources, at least one of which is a VLBI source (Preuss and Fosbury 1983) and therefore a few parsecs or smaller in physical size.

NGC 4594 (*M104*).—This well-known Sa (the "Sombrero") has been mapped in 21 cm emission and in optical absorption lines by Faber *et al.* (1977). The emission is weak, showing little more than two spikes at 739 and 1448 km s^{-1}. The nuclear continuum is also weak, and therefore the absorption sensitivity is poor (rms 0.027). If the absorption lines are real,

TABLE 2

Absorption Lines Detected

Galaxy	$V_{\rm sys}$	Reference	$A_{\rm max}$	N/T_S (10^{19} cm^{-2} K^{-1})	$v_{\rm cen}$	σ_v	$\Delta V = v_{\rm cen} - v_{\rm sys}$
Positive Detections:							
NGC 0520	2193	1	0.37 ± 0.05	12.3 ± 0.1	2313 ± 15	31 ± 15	+120
			0.12 ± 0.05	...	2209 ± 15	<20	+16
			0.09 ± 0.03	...	2160 ± 58	146 ± 81	−33
NGC 2110	2402	2	0.040 ± 0.007	0.9 ± 0.04	2589 ± 15	<20?	+187
			0.039 ± 0.007	...	2506 ± 15	<20	+104
IC 0450	5660	3	0.06 ± 0.01	0.6 ± 0.05	5576 ± 15	23 ± 15	−84
NGC 2623	5435	4	0.13 ± 0.03	6.7 ± 0.1	5499 ± 15	108 ± 17	+64
NGC 3690	2996	5	0.18 ± 0.07	9.4 ± 0.05	3161 ± 15	88 ± 15	+165
NGC 3894	3256	5	0.09 ± 0.01	1.8 ± 0.04	3255 ± 15	33 ± 15	−1
			0.034 ± 0.008	...	3502 ± 19	<20	+246
NGC 4151	980	6	0.028 ± 0.007	0.6 ± 0.04	977 ± 15	52 ± 15	−3
NGC 5506	1815	7	0.084 ± 0.009	2.3 ± 0.05	1811 ± 52	48 ± 15	−4
			0.033 ± 0.010	...	1980 ± 15	27 ± 15	+165
IC 4553	5600	8	0.22 ± 0.015	11.4 ± 0.04	5438 ± 15	118 ± 15	−162
NGC 6500	3004	4	0.21 ± 0.02	1.6 ± 0.12	3124 ± 15	<20	+120
Tentative Detections:							
NGC 0449	4780	3	0.09 ± 0.04	1.7 ± 0.2	4698 ± 23	40 ± 28	−82
NGC 3504	1531	9	0.06 ± 0.02	1.7 ± 0.1	1548 ± 24	75 ± 27	+17
NGC 4594	1090	10	0.12 ± 0.02	4.7 ± 0.15	1630 ± 15	68 ± 17	+540
			0.11 ± 0.03	...	1427 ± 103	31 ± 9	+337
UGC 10599	10050	11	0.010 ± 0.002	0.06 ± 0.02	10119 ± 15	<20	+69
NGC 7674	8709	12	0.06 ± 0.02	1.6 ± 0.12	8572 ± 24	69 ± 19	−137

References.—(1) Shostak 1978. (2) Wilson and Baldwin 1985. (3) Heckman *et al.* 1978. (4) Mirabel 1982. (5) de Vaucouleurs and de Vaucouleurs 1967. (6) Fisher and Tully 1981. (7) Thuan and Wadiak 1982. (8) Stocke *et al.* 1978. (9) Bottinelli *et al.* 1980. (10) Faber *et al.* 1977. (11) Wills and Wills 1974. (12) Chincarini and Rood 1976.

they are at surprisingly high relative velocity, as large or larger than the rotation velocity of the H I disk. The central source is very small, less than a parsec in size (Graham, Weiler, and Wielebinski 1981; Shaffer and Marscher 1979). The absorption should be studied further in hopes of probing what is evidently a deep potential well in the nucleus of this galaxy.

NGC 5506.—This strong X-ray–emitting irregular galaxy has been observed optically by Wilson *et al.* (1976) and by others (reviewed by Thuan and Wadiak 1982). The emission spectrum measured by the Green Bank 140 foot (43 m) telescope (Thuan and Wadiak 1982) shows an absorption valley, although like other single-dish absorption spectra the line parameters cannot be estimated accurately because of the blending with emission. The VLA spectrum shows two separate lines, one centered almost exactly on the systemic velocity taken as the center of the 140 foot emission, the other about 160 km s^{-1} redder. This latter line is weak and might be classed as a tentative detection.

IC 4553 (*Arp 220*).—This very strong absorption line probably corresponds to the molecular cloud emitting the intense OH lines at 1665 and 1667 MHz detected by Baan, Wood, and Haschick (1982). *IRAS* observations show this peculiar galaxy to be 80 times more luminous at 60 μm than in the blue (Houck *et al.* 1984; Soifer *et al.* 1984), which makes it one of the most luminous far-infrared galaxies known. It is interesting that Mrk 231 and NGC 6240, which also show deep H I absorption lines toward their bright radio-continuum nuclei, are also intense infrared emitters. It is possible that the presence of dense neutral gas clouds in or near the active nuclei of such galaxies is a factor in producing their tremendous infrared luminosities. The Arecibo H I spectrum (Mirabel 1982) shows in this case absorption with no emission, with an even broader line width than that detected here. The equivalent width (line integral) gives 1.1×10^{20} cm^{-2} K^{-1} (about the same as found by Mirabel). If we assume that the temperature derived from the far-infrared spectrum for the dust (47–62 K) is the same as for the neutral hydrogen, then the H I column density to the nucleus is about 6×10^{21} cm^{-2}. This combined with the conversion factor from Bohlin, Savage, and Drake (1978) implies reddening ($B-V$) of 1.25 mag, but this must be considered a lower limit because, first, the H I column density includes only the cold, absorbing gas, which may be a small fraction of the total H I, and second, the ratio of molecular to atomic gas may be much higher in this region of intense star formation than in the solar neighborhood sample used by Bohlin *et al.* So a more reasonable estimate of $B-V$ in this case is perhaps 3–10 mag, depending on the H I to H_2 ratio.

UGC 10599 (*Mrk 501, 4C 39.49*).—This distant Seyfert has not been detected in H I emission, even from Arecibo (Heckman, Balick, and Sullivan 1978). The intense radio continuum source was studied by Condon and Dressel (1978), and by Biermann *et al.* (1980), who classify it as a BL Lac object. The redshift is from Wills and Wills (1974). The classification is in question: it may not belong in a survey of active spirals like this one, but rather in a survey of radio galaxies (e.g., Shostak *et al.* 1983), but since it is a Markarian with some Seyfert properties it might well be classified as a spiral if it were closer.

NGC 6500.—This Sa galaxy has an extremely compact, intense radio continuum source in its nucleus (Jones, Sramek, and Terzian 1981), with size of only a few parsecs or less, which gives most of the continuum flux detected here. Unfortunately, the redshift of this galaxy puts it close to a strong interference signal at about 1403.5 MHz. The observation was repeated three times with different center frequencies; the least polluted spectrum is shown in Figure 1. The line at 3115 km s^{-1} was detected in all three observations, although in the other two observations several spurious lines were also seen, probably coming from aliasing of the interference spike. I am fairly confident that the 3115 km s^{-1} line is real; but in the presence of interference, normal statistical detection criteria do not apply, so this line must remain slightly suspect.

NGC 7674 (*Arp 182*, *Mrk 533*).—This spiral is classified Sa by de Vaucouleurs, de Vaucouleurs, and Corwin (1976) and SBb by Nilson (1973). Based on the Arp atlas photograph, I prefer the latter. Mirabel (1982) also detected absorption blended with emission at the same velocity as the principal feature on Figure 2. The continuum source is compact (Condon 1980), but not extremely compact (Jones, Sramek, and Terzian 1981), i.e., diameter in the range 50–150 pc.

III. RESULTS

Many other studies have been made of H I absorption toward the nuclei of active galaxies (reviewed recently by Heckman *et al.* 1983), using various telescopes. As discussed above, because of confusion by H I emission, observations with large single-dish telescopes such as Arecibo may be unable to give accurate values for the center velocities or equivalent widths of the absorption lines, even though the signal-to-noise ratio and velocity resolution may be much better than the VLA can achieve. To get the largest sample of absorption lines possible, I have augmented the VLA survey by studying the spectra in the literature and selecting those taken by interferometers with high enough resolution to be unconfused by H I emission plus a few taken by single-dish telescopes for which there is very deep absorption and little or no emission apparent. In addition, a few galaxies show H I absorption confused by emission, but also show OH absorption (Rickard, Bania, and Turner 1982; Baan *et al.* 1985). In these cases, the radial velocity of the OH may be used to pinpoint the center of the H I absorption line (Dickey, Crovisier, and Kazes 1981), although it is still impossible in these cases to tell the width or integral of the H I absorption accurately. Table 3 lists the absorption lines chosen from the literature which seem to have accurate, reliably determined centers, widths, and optical depths.

In Table 3, spiral and irregular type galaxies are arbitrarily separated from elliptical and S0 types. This separation is intended to distinguish Seyfert and starburst nuclei on the one hand from radio galaxies on the other. There may be no astrophysical basis for this distinction between nuclei, but at least there are average differences between the gas contents of the disks of spirals and of ellipticals or S0's. In any case, classification of some interacting systems is difficult, and there are disagreements about a few of these galaxies.

Figure 3 (*top*) shows the distribution of velocity offsets ΔV (defined as in Table 2 to be line center velocity minus systemic velocity). Different shading distinguishes spirals observed with the VLA in this survey, spirals from Table 3, and ellipticals and S0's. In all three groups there is a preference for infall of gas toward the nucleus over outflow (positive ΔV). This preference has been noted before (Dickey 1982; Heckman *et al.* 1983), but with insufficient numbers of galaxies to allow statistical confidence. The asymmetry of the distribution shown in Figure 3 (*top*) is fairly convincing; the mean ΔV for the 24 lines in spirals is 52 ± 22 km s^{-1}; including the ellipticals and S0's it is 72 ± 22 km s^{-1}, where the formal errors are the standard deviation of the distribution divided by the square root of the number of samples. In fact, this may be an overestimate of the uncertainty, because the distribution of ΔV seems to show two parts: a symmetric, roughly Gaussian function centered at about 0 km s^{-1} with half-width slightly less than 50 km s^{-1}, plus a long tail toward only positive velocities with character-

TABLE 3

ABSORPTION LINES FROM OTHER STUDIES

Name	Type	Inclination	Continuum Solid Angle (arcsec^2)	N/T (10^{19} cm^{-2} K^{-1})	$A_{\max}$ ($1 - e^{-\tau}$)	σ_v (km s^{-1})	ΔV (km s^{-1})	Reference
UGC 6081	S	...	...	4	0.26	42	−40	1, 2
NGC 1068	Sb	32°	1	2.7	0.02	60	+20	3, 4
NGC 3628 = Arp 317	Sb	76	1	7.5	0.44	93	+18	5
NGC 3079	Sb	77	...	10	0.19	85	+10	6
					0.16	40	+90	
NGC 253	Sc	73	400	34.	...	25	−47	7
Mkn 231	Sc	47	0.1	2.7	0.1	150	+338	3, 5
NGC 4945	Scd	77	...	66	...	28	+37	7
NGC 6240 = Arp 193	Irr	58	1	7.7	0.14	300	−42	5, 8
IC 883	Pec	45	...	3.2	0.07	57	+56	8
NGC 1275	Pec	...	...	0.4	0.004	191	+142	9
NGC 5128 = Cen A	S0*p*	80	...	50	0.72	17	+3	10
					0.48	24	+26	
					0.29	16	+45	
NGC 3034 = M82 = 3C 231	I0-E	56	40	9.3	0.54	20	+110	11
					0.48	30	−85	
NGC 5318	S0	52	~0.0001	0.9	0.015	26	+82	12
NGC 1052	E4	...	~0.0001	0.07	0.01	50	−20	13
					0.01	50	+105	
NGC 315	E-S0	...	~0.0001	0.4	0.87	1.1	+491	13, 14
					0.21	1.1	+494	
3C 293	E(Sb?)	...	4	1.6	0.085	41	+9	15
					0.03	135	−109	
					0.005	200	+159	

REFERENCES.—(1) Bothun and Schommer 1983. (2) Williams and Brown 1983. (3) Haschick 1977. (4) Liszt and Dickey 1986. (5) Dickey 1982. (6) Irwin, Taylor and Seaquist 1984. (7) Gardner and Whiteoak 1974. (8) Heckman *et al.* 1983. (9) Crane *et al.* 1982. (10) van der Hulst *et al.* 1983. (11) Weliachew *et al.* 1984. (12) Mirabel 1983. (13) Shostak *et al.* 1983. (14) Dressel *et al.* 1983. (15) Baan and Haschick 1981.

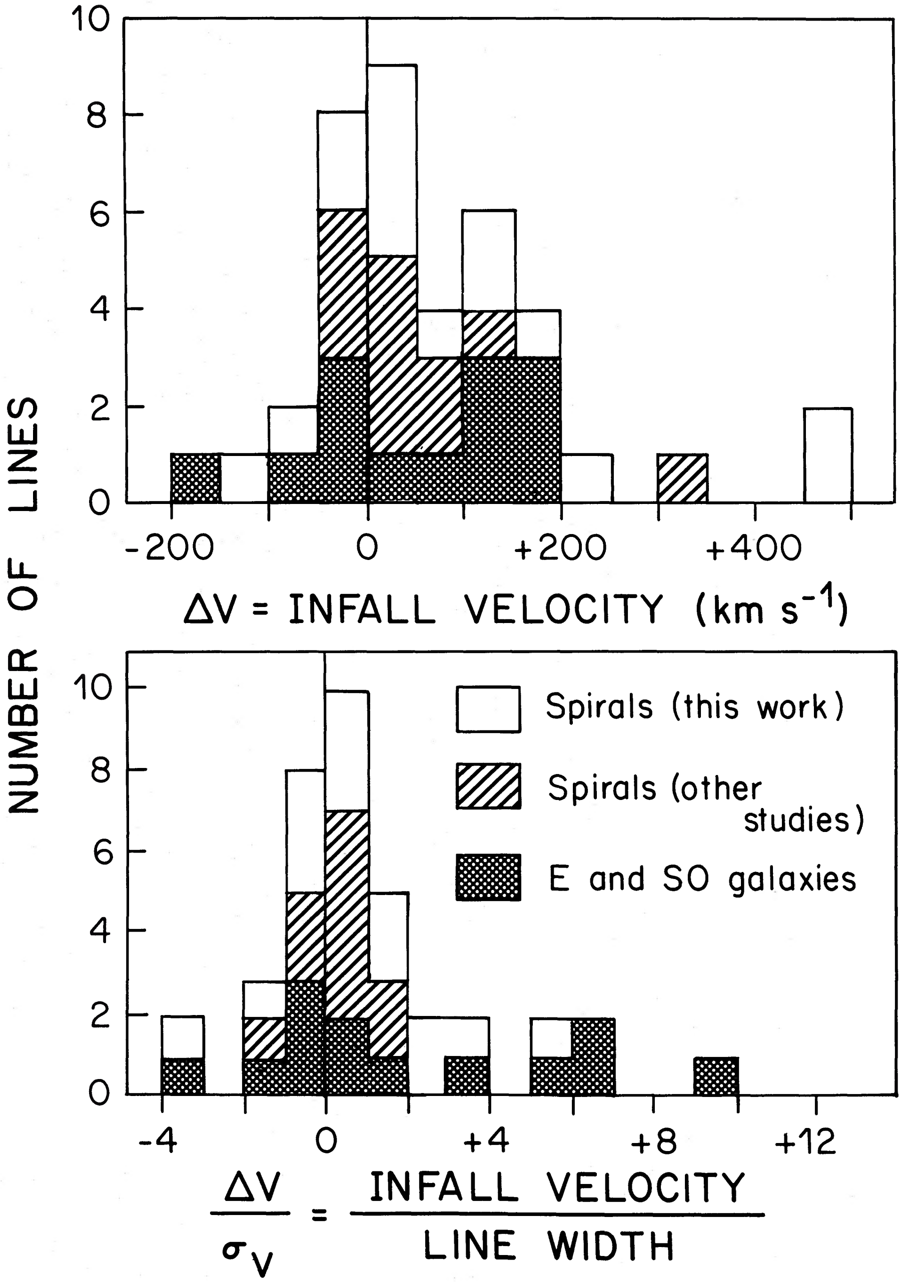

FIG. 3.—The distribution of radial velocities relative to systemic velocities for absorption lines toward active nuclei. Positive values represent infall of gas toward the nucleus, negative values represent outflow. (*top*) Velocity of infall in km s^{-1}; (*bottom*) infall velocity normalized by the half-width σ_v of the absorption line (see Table 2). Tentative detections are not included, but results of other studies (Table 3) with very reliable line centers and widths are shown with different shading.

istic width of perhaps 200 km s^{-1}. Tentative detections are not included in Figure 3, but they also show a bias toward positive ΔV.

Another way to test for a preference for infall velocities is to look at the distribution of $\Delta V/\sigma_v$, i.e., the velocity offset in units of the line width for each absorption line. This distribution is shown in Figure 3 (*bottom*). Again there is an excess of lines with positive velocities, implying a preference for infall. The mean is 1.6 ± 0.5, but again the distribution may be made up of two components: a symmetric part with width of ~0.7–0.9, plus a positive-going tail extending to +12. (This does not include the two very narrow lines toward NGC 315, for which $\Delta V/\sigma_v = \sim +450$.) Here again the asymmetry is evident in spirals alone, although it is more pronounced when E's and S0's are included. This figure demonstrates that the bias toward positive ΔV values is not due to a slight shift of line centers by much less than the widths of the lines. All lines with $|\Delta V/\sigma_v| > 1$ are offset from zero by more than their widths.

Figure 4 shows the distributions of equivalent width (N/T) and velocity offset (ΔV) with galaxy type. (Galaxies classified peculiar or without morphological type are not shown.) In the upper panel there is an apparent correlation between N/T and galaxy type, with Sc's and Irregulars having the highest equivalent widths. This should not be taken seriously, because

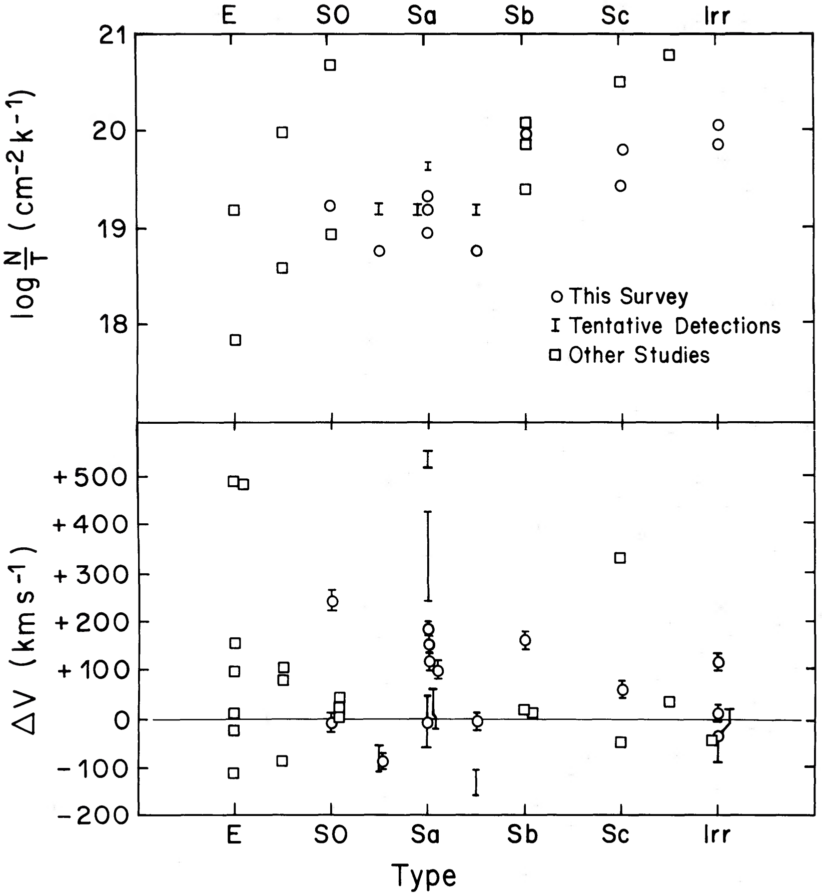

FIG. 4.—The distribution of equivalent width and infall velocity with galaxy type. (*top*) Equivalent width, $\int (1 - e^{-\tau})dv \propto N/T$, of the absorption lines. Different symbols represent lines chosen from different studies. The lower figure shows the infall velocity ΔV (as in Fig. 3 [*top*]) vs. galaxy type.

of the observational selection for weak lines toward E's and S0's, which have much stronger nuclei than Sc's, Sd's, or Irr's. The absence of points on the lower right of Figure 5 (*top*) is explained by this observational selection. Without that effect there is no obvious correlation of N/T with galaxy type, which suggests that the absorption is not coming from the galaxy disks, since emission studies of much larger samples of normal spirals show distinct correlation between hydrogen mass and galaxy type (e.g., Roberts 1969).

The lower panel of Figure 4 shows the distribution of line center–velocity offsets (ΔV) with galaxy type. This shows as clearly as Figure 3 the preference for positive ΔV's. This preference is shared by all galaxy types, although the statistics are not yet good enough to make a quantitative measure of $\langle \Delta V \rangle$ versus type.

Figure 5 (*top*) shows the behavior of the equivalent width (ΔV) versus inclination for those galaxies with axis ratios given by de Vaucouleurs, de Vaucouleurs, and Corwin (1976). There is not an overwhelming correlation between these two quantities, which suggests strongly that the absorption is not coming from the disks. Upper limits for galaxies observed at the VLA are included. The solid curve shows the average local Galactic absorption (Crovisier 1981), assuming a homogeneous disk of gas viewed at various angles. Many of the galaxies with absorption detected show much more absorption (factor of 10–100) than the Milky Way disk would give viewed at the same inclination. However, these galaxies do not contain more total hydrogen than the Milky Way, as measured by single-dish studies (Table 1, next to last column). So there is more concentration of gas along the lines of sight to the nuclei of these active galaxies than would be expected for a homogeneous disk by more than an order of magnitude. This fact is illustrated in Figure 5 (*bottom*), which plots the total absorption (equivalent width N/T) divided by the total (single-dish measured) emission M_{H} for several of the galaxies detected at the VLA. The Milky Way absorption (assuming total H I mass $M_{\mathrm{H\,I}} \approx 3 \times 10^9\ M_\odot$, Burton and Gordon 1978) is shown by the solid line, which assumes opacities like those observed in the solar neighborhood averaged over a homogeneous disk. The point of Figure 5 is that in these galaxies the absorbing gas does not seem to be part of the normal spiral disk; it is too much concentrated along the line of sight to the nucleus. This is indirect evidence that the absorbing gas is confined to a cloud near the nucleus, or alternatively it is in an intervening cloud which is not part of the disk of the spiral. Among the lines detected there may be cases of both kinds.

IV. DISCUSSION

The VLA observations of absorption lines toward active nuclei discussed above give accurate values of equivalent width, line center velocity, and velocity width, as far as the sensitivity and velocity resolution permit, but they do not tell the distance of the absorbing gas from the nucleus. Physical interpretation of the line widths and the noncircular velocities with their apparent preference for infall to outflow depends on whether the H I is in a cloud surrounding the nucleus, with radius of a few hundred parsecs, perhaps, or far from the nucleus in a cloud which happens to intervene, perhaps as the result of a collision or merger of two systems. One way to distinguish these two is on the basis of line width σ_v.

If we assume spin temperature in the absorbing gas of 100 K, then the equivalent widths for the detected lines give column densities ranging from 6×10^{20} cm^{-2} to 1.1×10^{22} cm^{-2} with typical values of about 6×10^{21} cm^{-2}. Assuming path length through the absorbing gas of r_{100} (in units of 100 pc), the typical space density in the cloud is

$$n \approx \frac{20 \text{ cm}^{-3}}{r_{100}} .$$

If the absorbing cloud is spherical and centered on the continuum source, it would have H I mass

$$M_{\text{H I}} \approx 2 \times 10^6 \, M_\odot \times r_{100}^2 .$$

If the cloud were intervening, this changes slightly, because the path length is then $2r_{100}$, so the density and mass are half the above values. So far, these are not unreasonable values for galactic molecular clouds with atomic envelopes, assuming $0.1 \lesssim r_{100} \lesssim 1$.

The difference between the clouds seen here and ordinary galactic interstellar clouds is the line widths. Absorption lines with widths broader than ~ 5 km s^{-1} are not seen in our Galaxy (Crovisier 1981, Dickey *et al.* 1983). Line widths broader than this must be due to turbulence or bulk motions,

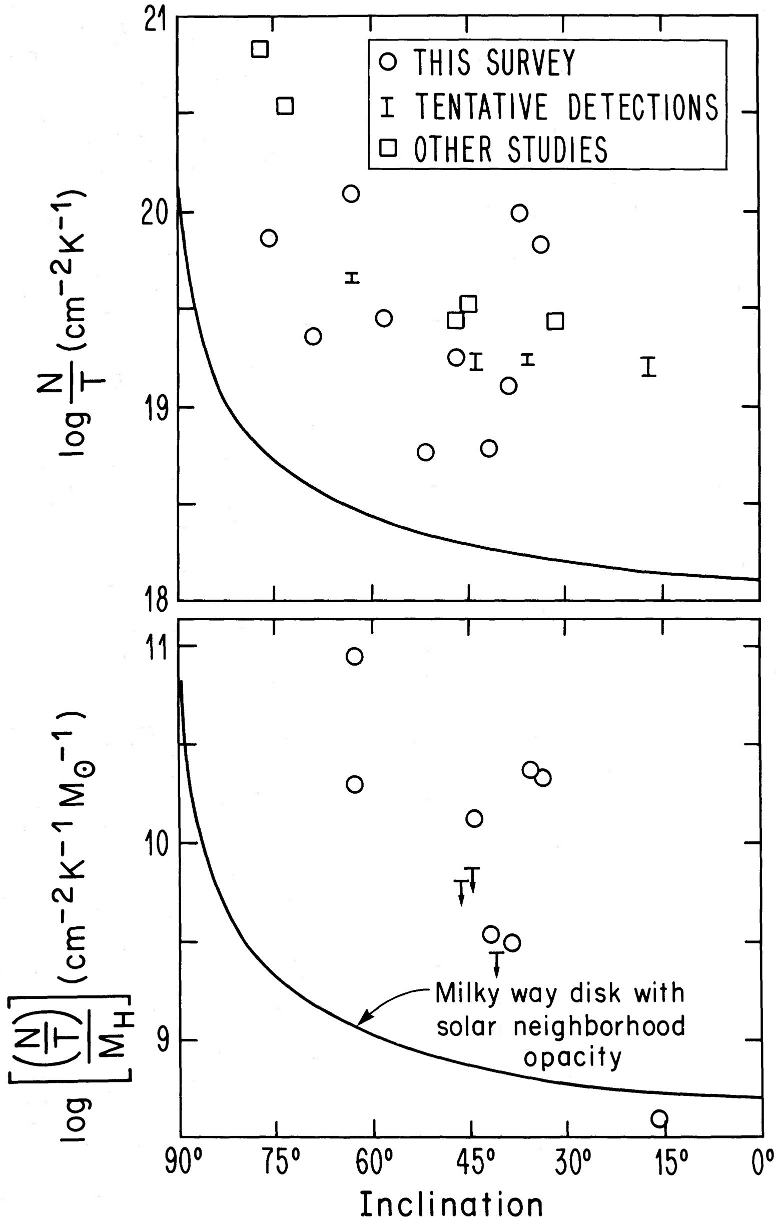

FIG. 5.—Equivalent width vs. inclination. (*top*) Equivalent width, $\int (1 - e^{-\tau})dv \propto N/T$, relative to the inclination of the galaxy, based on the axis ratio (de Vaucouleurs, de Vaucouleurs, and Corwin 1976). (*bottom*) Equivalent width divided by the total H I mass of the galaxy, measured by single-disk emission studies. This shows that the strong absorption cannot be explained by an H I–rich disk. The curves represent typical Milky Way values (Liszt *et al.* 1983).

since the optically thick gas must be cooler than a few hundred K, and to have neutral gas at all requires $T \lesssim 10^4$ K, which would give thermal width of only ~ 10 km s^{-1}. Ordinary circular rotation of the galaxy disks cannot significantly broaden lines, because the nuclear continuum source is so small (a few hundred parsecs) that a narrow column of gas is all that is sampled in absorption. Circular rotation is very nearly perpendicular to the line of sight throughout this column. Even at 90° inclination, a rotation curve like that of our Galaxy would broaden the lines by only 10–15 km s^{-1}, assuming a nuclear source size less than or equal to 300 pc. This does not apply to a compact nuclear disk with radius 1 kpc or less. To gravitationally confine a system with bulk motions of 30–150 km s^{-1} requires considerable mass; assuming $\sigma_v^2 \approx GM/r$, then

$$M_{\rm tot} \cong 10^7\ M_\odot \times r_{100}\,\sigma_{30}^2\ ,$$

where σ_{30} is the line width in units of 30 km s^{-1}. Such a mass concentration ($> 10^7\ M_\odot$ within a few hundred parsecs) is not known in our Galaxy, except perhaps in the Galactic center. The most plausible sites for the absorbing gas in galaxies showing lines broader than 30 km s^{-1} are therefore the nuclear regions. Absorption lines much narrower than 30 km s^{-1} (e.g., those in NGC 315, Dressel, Bania, and Davis 1983) may well be intervening clouds of much smaller total mass.

For the typical cloud parameters summarized above, we may estimate a rough accretion rate onto the nuclear object if the absorbing gas is in a circumnuclear cloud. Given ΔV_{100}, the measured velocity offset between the systemic and the line center velocities in units of 100 km s^{-1}, the accretion rate is

$$\dot{M} = \Delta V_{100}\, r_{100} (M_\odot\ {\rm yr}^{-1})$$

averaged over the infall time $t = \Delta V_{100}/r_{100} \times 10^6$ yr. Since $\Delta V_{100} \approx 1$ in many cases, this would give plausible accretion rates for active nuclei ($\sim 1\ M_\odot$ yr^{-1}), assuming $r_{100} \approx 1$.

Lines narrower than 30–40 km s^{-1}, which by the arguments given above need not be circumnuclear but may intervene at any distance from the nucleus, also show more cases of infall than outflow. There are several possible explanations for this, even assuming that these clouds are far from the active nucleus. If some of these absorption lines occur in accretion flows onto active galaxies (e.g., NGC 1275, Hu *et al.* 1983), then infall velocities of several hundred km s^{-1} are to be expected. If the active system consists of two colliding galaxies, then we would also expect to see an asymmetry, assuming that the collision disrupts the intervening galaxy. Encounters so distant that tidal disruption does not occur would be symmetric between positive and negative radial velocities, just as, for example, statistics of absorption lines through comets transiting in front of the Sun would in principle give a symmetric distribution of possitive and negative heliocentric velocities. Even in an isolated galaxy with no accretion, it is possible to get noncircular motion of gas in the disk as a response to an axially asymmetric mass distribution (Sanders and Huntly 1976), as is the case in barred spiral galaxies (van Albada and Roberts 1981). It is even possible in these models to get an asymmetric distribution between inward and outward motions in a galaxy whose gas flow is in equilibrium with closed orbits. Two different models for the kinematics of the disk of NGC 5383 (Roberts, Huntley, and van Albada 1979; Sanders and Tubbs 1980) both predict radial velocities as high as 150 km s^{-1} near the bar. But the alignment needs to be very good between the bar and our line of sight to see even as much as 100 km s^{-1}, and of course the galaxy inclination needs to be high. It would be interesting to search for absorption in a sample of barred spirals to test these models (they seem to disagree on whether infall or outflow at velocities greater than 100 km s^{-1} is more common). But since only two of the galaxies in this survey are classified as barred (both are only tentative detections and thus are not included in Fig. 3), the preference for positive ΔV in Figure 3 cannot be explained simply by equilibrium gas flow in ordinary barred spiral disks.

The assumption used above to derive column densities from the observed equivalent widths is that the spin temperature is about 100 K, typical for cool galactic clouds. This may be incorrect for at least three reasons. In normal galactic conditions the spin temperature is nearly equal to the kinetic temperature, since collisions dominate both the excitation and de-excitation of the hyperfine levels; if this is true also in these active galaxy clouds, then the assumption is that the clouds have kinetic temperatures of ~ 100 K. This may be incorrect; the kinetic temperature may in principle be as hot as 10,000 K without too much of the collisional ionization of hydrogen that would eliminate the 21 cm line. In that extreme case, the column densities implied by Table 2 would be as high as 10^{23} atoms cm^{-2}. With high velocity resolution, it is possible to set upper limits on the kinetic temperature from the velocity width of the 21 cm line, but unfortunately in this experiment the resolution is not high enough to tell whether the gas is cooler than 10,000 K, so this is not useful in limiting the column density.

In the vicinity of an intense continuum source, two effects of the radiation field can cause the spin temperature to deviate from the kinetic temperature (Field 1958). The first is the redistribution of atoms between the hyperfine levels by Lyman-α radiative excitation from the ground state followed by spontaneous emission. This can either increase or decrease the spin temperature, depending on the detailed shape of the spectrum near 10.6 eV (Bahcall and Ekers 1969). For a typical power-law continuum spectrum, the effective temperature of the radiation field at Lyman-α is 2–4 × 10^4 K; in the extreme where collisions are unimportant, the spin temperature may rise to this value, with a result similar to that in the preceding paragraph: the column densities must be 200–400 times higher than those assumed in the simple models above. Even without Lyman-α, the intense continuum radiation at $\lambda = 21$ cm from the active nucleus can also change the spin temperature, as discussed by Wolfe (1979). This becomes important when the stimulated emission rate becomes greater than the spontaneous emission rate. This also will increase the spin temperature above the kinetic temperature, by an amount proportional to the phase space density of 21 cm photons (Bahcall and Ekers 1969). To estimate the strength of this effect requires knowledge of the distance from the cloud to the continuum source. For some objects it might even be possible to set a lower limit on this distance from the simple presence of 21 cm absorption, if the column density of neutral hydrogen could be independently measured, e.g., by Hα absorption.

V. SUMMARY

This survey used the VLA to study 21 cm absorption in front of the nuclei of Seyferts and other active spirals to probe the dynamics of the gas in these systems, the effects of tidal interaction with companions, and the rate of gas accretion onto the central source. The high angular resolution of the VLA (4″ in this experiment) is needed to separate the absorption toward the continuum nucleus from the emission by the hydrogen in the larger spiral disk. The VLA can measure accurately the center velocity, line width, and integral (equivalent width) of the absorption lines, which is usually impossible for a single-dish telescope. Ten galaxies show clear absorption (Fig. 1), and five more show tentative lines (Fig. 2), out of 19 searched; but these candidates were selected as the most likely to show absorption, either because of apparent absorption in Arecibo spectra or because of their strong, compact nuclear continuum sources, so the sample is far from complete or unbiased.

Differences between the center velocities of the absorption lines and the systemic velocities of the galaxies imply noncircular motion for the absorbing gas. The distribution of these differences (Fig. 3) suggests that infall with velocities 100–300 km s^{-1} is more common than outflow at similar velocities, although cases of both types are seen. The distribution of noncircular velocities appears to be made up of two parts: the first is symmetric about 0 with width of about 50 km s^{-1}, which may be due to errors in determining the systemic velocity; the second is asymmetric, with more lines at positive velocities than negative, and extends to several hundred km s^{-1}. This preference for infall is suggestive, but statistically there are not yet enough lines to make it entirely conclusive.

The velocity widths of the lines detected are quite different from Milky Way absorption lines. Even though the velocity resolution of this experiment (40 km s^{-1} channels) is relatively poor, many lines are resolved in velocity, and several have widths (σ_v) greater than 100 km s^{-1} (Fig. 4). If these widths are due to internal motions of the gas clouds (e.g., rotation, turbulence) which are in virial equilibrium with gravitational forces, the mass required inside the clouds is 10^7 $M_\odot$ or more. This suggests that in at least some cases the absorbing gas clouds are in the inner few hundred parsecs of the active galaxies, surrounding the active nuclei. Narrower lines may come from intervening clouds far from the active nuclei.

There is no clear dependence of equivalent width or velocity width on galaxy inclination. Neither is there a dependence on the solid angle of the continuum source, although there are few cases for which the solid angle is well known. The lack of such correlations suggests that the absorbing gas is not ordinary disk gas like the interstellar medium of the Milky Way. In fact, the total absorption (equivalent width) is much more than the Milky Way disk would show when viewed at the inclination angles of these galaxies (Fig. 5 [*top*]). This is not simply because these galaxies have more gas. In some cases we have measurements of the total H I mass from single-dish emission studies, even dividing by this the absorption is much more than the Milky Way would show (Fig. 5 [*bottom*]). This means that the absorbing gas is more concentrated along the line of sight than it would be simply by the disk of the spiral galaxy. Probably it is confined to a smaller volume in the vicinity of the active nucleus. Alternatively, it may be contained in an intervening galaxy which is interacting with the spiral containing the active nucleus.

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