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NEUTRAL HYDROGEN ABSORPTION BY GALAXIES AND IMPLICATIONS FOR THE SOFT X-RAY BACKGROUND

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ABSTRACT

We have searched for neutral hydrogen absorption in the 21 cm spectra of 59 radio continuum sources in the proximity of spiral and lenticular galaxies using the Arecibo radio telescope. Searches of this type are of importance not only for establishing the properties and the extents of halos and outer disks of galaxies but also for defining the intensity of the extragalactic ionizing flux. Five galaxies showed possible but uncertain absorption; three of these were reobserved at the VLA, and in the case of 3C 275.1/NGC 4651 the absorption appears to be confirmed. For the 54 other sources we find either that the column density of the neutral hydrogen in the intervening material is well below 2×10^{19} cm^{-2} or that the spin temperature is at least one order of magnitude above the microwave background temperature. For these cases we show that subthermal effects are not hiding appreciable amounts of neutral hydrogen. Upper limits for $N_{\rm H\,I}$ obtained from emission studies should therefore be reliable. Moreover, from good constraints on the spin temperature in the outer H I disk of M33 (NGC 598) we estimate that the soft X-ray background must be at least as strong as predicted by extrapolations of the hard X-ray spectrum down to 13.6 eV if no other heat sources are present.

Subject headings: cosmic background radiation — galaxies: interstellar matter — quasars — radio sources: galaxies — radio sources: 21 cm radiation

I. INTRODUCTION

The high frequency of broad-line optical absorption systems seen in the spectra of distant quasars (Young, Sargent, and Boksenberg 1982; Briggs and Wolfe 1983; Wolfe 1986) suggests that very extended H I distributions around galaxies were common at early epochs. At the present epoch, while many spiral galaxies are known to have high-density gaseous disks of neutral atomic hydrogen (with column densities of order $N_{\rm H\,I} \sim 10^{20-21}$ cm^{-2}) extending slightly beyond their optical disks, only rarely have even the deepest searches for H I emission detected neutral hydrogen disks or outer rings much farther out (Briggs 1982; Blitz, Fich, and Kulkarni 1983; Corbelli, Schneider, and Salpeter 1989). When neutral hydrogen emission at high column densities is found much beyond the optical disk, it is generally related to tidal disturbances in groups of galaxies (Weliachew, Sancisi, and Guelin 1978; Sancisi 1983; Haynes, Giovanelli, and Roberts 1979; Haynes 1981). This raises questions about what has become of the extended H I gas distributions: has the gas been removed, has it become ionized, or are subthermal effects suppressing H I emission? To begin to determine how much low column density gas, neutral or ionized, lies outside the optical disks of present-day spiral and lenticular galaxies, searches for H I in emission need to be complemented with absorption studies to determine the 21 cm spin temperature and to establish whether subthermal effects are suppressing H I emission.

Several studies have uncovered quasar/galaxy pairs in which 21 cm absorption has been detected against the radio continuum of the quasar along a line of sight outside the optical image of the galaxy, and at a redshift close to that of the galaxy (Haschick and Burke 1975; Rubin, Thonnard, and Ford 1982; Haschick, Crane, and Baan 1983; Carilli and van Gorkom 1987). This might suggest that neutral hydrogen clouds are fairly common at large galactocentric distances. Arecibo observations of H I absorption in the pair 3C 232/NGC 3067 were used to argue in favor of a very extended disk around NGC 3067 (Rubin, Thonnard, and Ford 1982). The strong absorption relative to the weak emission detected in the Arecibo beam seemed to imply that the spin temperature of the 21 cm H I emission was subthermal, i.e., much lower than the gas kinetic temperature. However, a recent VLA investigation of this system (Carilli, van Gorkom, and Stocke 1989) shows that the absorption is produced by a high column density feature in an H I "tail," which lies along the line of sight to the quasar, and which is probably of tidal origin. The low H I emission measured at Arecibo was a result of beam dilution.

The aim of the present study is to establish the frequency of absorption in close quasar/galaxy pairs, and to investigate both the emission and absorption properties of the gas at large galactocentric radii. This may permit us to learn whether most of the neutral hydrogen found outside the optical image of a galaxy is due to transient phenomena like tidal encounters or whether there are more extended H I disks rendered nearly invisible in emission by subthermal effects.

We have searched for H I absorption in the 21 cm spectra of 59 radio sources that lie close to the optical image of a galaxy, and we have a fairly definite detection in one of these. In § II we review how the conditions of the hydrogen in outer disks differ from those inside the stellar disk because of the lower surface density and different energetic inputs for the gas. Violent phenomena in the stellar disk, like supernova explo-

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sions, can affect the distribution of hydrogen in outer disks, and the extragalactic ionizing flux limits the survival of low-column-density neutral hydrogen. Even though most of the results of our search, described in § III, are negative, the upper limits to the 21 cm optical depth have implications for the energetics of galaxies, and they can be used to put constraints on the very uncertain value of the extragalactic soft X-ray background radiation (Silk and Sunyaev 1976; McCammon *et al.* 1983; Chevalier and Frasson 1984; Melott, McKay, and Ralston 1988) as we discuss in § IV.

II. NEUTRAL HYDROGEN CONDITIONS OUTSIDE THE STELLAR DISK

Searches for H I emission from low column density neutral hydrogen outside the stellar disks of galaxies are frequently made in order to find dynamical masses of galaxies out to large radii. But to determine the total amount of neutral hydrogen in these outer regions, absorption measurements are also needed to establish the spin temperature of the gas: when the spin temperature is sufficiently close to the 3 K background, the observed H I emission will be suppressed. Fortunately, in such a subthermal state there is also an enhancement of H I absorption. Measurements of the H I spin temperature in the outer disk allow us also to constrain possible energy inputs and physical conditions there.

The absence of massive stars in outer regions removes the possibility for direct energetic input to the gas from stellar winds, supernova blastwaves, etc. The general lack of stars lessens the surface gravity in the disk so that the self-gravity of the gas may be the primary source for maintaining the disk (if the dark matter distribution is not very flat). Typical volume densities of neutral hydrogen, $n_{\rm H\,I}$, will also be much lower in the outer disk. At low densities, the infrequency of collisions between atoms can disengage thermodynamic equilibrium between the populations of the 21 cm hyperfine spin states and the gas kinetic temperature, potentially allowing the H I to thermalize with the 3 K background and become invisible in emission. However, the soft X-ray background interacts with neutral hydrogen atoms, providing an important source of Lyα photons, which can help to reestablish thermodynamic equilibrium (Watson and Deguchi 1984; Deguchi and Watson 1985).

In general, the kinetic temperature can be expressed in terms of the spin temperature as

$$T_K = \chi T_S\,, \tag{1}$$

where χ (=1 for a thermalized medium) depends on the spontaneous and collisional de-excitation probabilities as well as on the color and intensity of Lyα radiation (Field 1959). The optical depth at the center of the 21 cm absorption line, τ_0, and the brightness temperature, T_b, can be expressed in term of T_S as

$$\tau_0 = \frac{5.14 \times 10^{-19}}{W} \frac{N_{\rm H\,I}}{T_S} \tag{2}$$

$$T_b(v) = 5.49 \times 10^{-19} \frac{T_S - T_R}{T_S} N_{\rm H\,I}(v) \tag{3}$$

(Spitzer 1978; Watson and Deguchi 1984), where W is the half-power width of the 21 cm absorption line in km s^{-1} and T_R is the temperature of the microwave background radiation. Any subthermal deviations from the kinetic temperature will increase the optical depth of the medium, so that the level of absorption may be enhanced even in a low-density warm medium where a considerable number of Lyα photons are generated through collisional excitation of H I atoms by thermalized electrons (Spitzer 1978). On the other hand, subthermal suppression of the emission only occurs when the spin temperature is close to T_R. When the gas density is less than $\sim 10^{-3}$ cm^{-3} or temperatures are below ~ 30 K—conditions that might occur outside a galaxy's stellar disk—the spin temperature may approach the background radiation temperature, unless the ionizing background flux in the soft X-ray range is strong enough to repopulate the hyperfine states via Lyα photons generated after recombinations.

Using the results of Bonilha *et al.* (1979) to compute the average number of times a Lyα photon is scattered before it escapes from the medium, we can estimate the Lyα pumping of the 21 cm hyperfine levels from the de-excitation probabilities of the hyperfine triplet states for given values of T_K and $N_{\rm H\,I}$. In order to estimate the thermal properties of neutral hydrogen in outer regions we consider first a simple model in which the main heating sources for the medium are photoionizations by background soft X-rays. We suppose that the gas in outer disks has $\frac{1}{2}$ solar metallicity and that it is distributed according to self-gravity and to a spheroidal distribution of dark matter ($V_{\rm rot} = 100$ km s^{-1}, $b/a \sim \frac{1}{4}$).

If there is no external pressure to compress the medium and the soft X-ray background is less than that predicted by the spectrum of more energetic X-rays (Schwartz 1978) extrapolated down to 200 eV, then Lyα pumping will not be efficient in eliminating subthermal effects on the brightness temperature of the 21 cm line. These conditions arise for $N_{\rm H\,I} \leq 10^{19}$ cm^{-2} and the medium then should be more easily detectable in absorption. Even if the heat input is as big as that predicted by an extrapolation of the Schwartz law down to 13.6 eV, the optical depth at the line center will still be $\tau_0 > 0.01$ for $N_{\rm H\,I} > 10^{18}$ cm^{-2}, because cold phase neutral hydrogen with $T_K < 40$ K exists when the thermal pressure of the neutral gas is more than ~ 50 K cm^{-3} (see, e.g., Kulkarni and Heiles 1988 for a review of the various hydrogen phases in the ISM).

Smaller optical depths are typical for a medium where the neutral hydrogen is in its warm phase ($T_K \sim 10^4$ K). Still, in this case T_S may be as small as $0.01\,T_K$ if the pressure is low enough and if the intensity of the soft X-ray radiation is not much stronger than predicted by the Schwartz law extrapolation down to 13.6 eV. The optical depth of neutral hydrogen at column densities $\sim 10^{19}$ cm^{-2} could then be ~ 0.01. Twenty-one centimeter absorption might thus be detectable for a wide range of H I column densities and temperatures.

H I absorption measurements for the strongest background source next to M33 (NGC 598), which lies behind a region where the H I column density is $\sim 10^{19}$ cm^{-2} (see § III), can be used to constrain the intensity of heating sources in these outer regions. Tidal interactions or outer galactic fountains (Corbelli and Salpeter 1988; Charlton and Salpeter 1989) might have released heat in outer regions of galaxies in addition to soft X-rays. However, if the injection temperature of gas into the halo via supernovae is only a few million degrees, cooling flows with consequent formation of cold, extended outer disks, could have formed. Injection temperatures of the order of 3×10^6 K, with a mass flow rate of 10 H cm^{-2} s^{-1} or greater, can in fact build up an H I disk at temperatures $T \sim 20$ K and $N_{\rm H\,I} > 10^{19}$ cm^{-2} (Corbelli and Salpeter 1988), which again, would be readily detectable in absorption at 21 cm.

III. THE DATA

The sample selected for the 21 cm absorption search comprises 59 background continuum sources along lines of sight in the vicinity of lenticular and spiral galaxies. Because we were primarily interested in searching for neutral hydrogen absorption due to material lying within a few Holmberg radii outside the stellar disk, most of the selected background sources are at a projected distance from the galaxy between 1 and 3 optical radii. The sample was based in large part upon previous radio continuum surveys of galaxies designed to detect continuum radiation from the galaxies themselves or to look for excess counts of radio sources associated with the galaxies. Most of the sources were selected from surveys by Willis (1976), Hummel (1980), and Condon and Broderick (1985).

Table 1 lists basic parameters for all of the galaxies in our sample which have one or more nearby background sources. The data for NGC 7413, which is not listed in the UGC catalog, have been taken from Arp *et al.* (1972).

TABLE 1

GALAXIES WITH NEARBY BACKGROUND SOURCES

NGC (1)	UGC (2)	R.A. (3)	Dec. (4)	Type (5)	$2a$ (6)	b/a (7)	α (8)	V_{hel} (km s^{-1}) (9)	$\int S_{\rm H\,I}dv$ (Jy km s^{-1}) (10)
	U477	004335.1	+191300	S	$3'.5$	0.23	167	2657	34.2
N474	U864	011731.7	+030917	S0	10.0	0.90		2359	3.3
N598	U1117	013102.4	+302400	Sc	73.0	0.62	23	−180	11,000
N628	U1149	013401.0	+153138	Sc	12.0	1.00		662	469.8
N660	U1201	014021.0	+132319	SBa	10.0	0.45	170	852	150.3
N959	U2002	022921.0	+351626	Sc/Irr	2.6	0.58	65	609	11.9
N972	U2045	023116.6	+290535	Sa-b	3.7	0.46	152	1550	9.7
	U2174	023904.9	+321000	Sc/SBc	2.3	0.96		∼5150	<8.5
N2608	U4484	083215.3	+283847	SBb/c	2.5	0.72	60	2134	4.4
N2903	U5079	092919.9	+214319	Sb/Sc	13.3	0.45	17	555	239.
N3351	U5850	104119.3	+115803	SBb	8.5	0.59	13	779	72.
N3547	U6209	110718.8	+105940	S	2.1	0.43	7	1614	10.0
N3623	U6328	111618.6	+132200	Sa	9.5	0.24	174	813	14.0
N3627	U6346	111737.9	+131608	Sb	9.0	0.47	173	736	38.6
N3628	U6350	111739.6	+135148	Sb	15.5	0.28	104	846	348.6
N4321	U7450	122023.2	+160600	Sc	6.8	0.85	30	1575	48.4
N4548	U7753	123255.1	+144620	SBb	5.5	0.82	150	484	7.8
N4569	U7786	123418.7	+132618	Sb	11.4	0.41	23	−236	6.9
N4631	U7865	123941.5	+324854	Sc	17.0	0.21	86	613	639.
N4651	U7901	124112.5	+164005	Sc	3.9	0.64	80	797	57.2
N4725	U7989	124759.9	+254820	Sb/SBb	12.0	0.75	35	1210	88.3
N4826	U8062	125416.9	+215718	Sb	10.0	0.50	115	410	51.2
	U8273	130934.1	+210333	S0	1.0	0.40	164	∼9050	
N5645	U9328	142810.7	+072950	SB	3.2	0.53	80	1363	18.0
N5773	U9571	145023.2	+300040	S	1.1	1.00		∼6950	
N5936	U9867	152739.7	+130940	SBb	1.3	0.92		3986	2.0
N6045	U10177	160256.0	+175342	Sb/c	1.1	0.20	82	10025	<2.7
	U11017	175013.5	+295227	SBc/Irr	1.8	0.56	165	∼4600	
N6509	U11075	175658.5	+061720	Sc	1.6	0.81	105	1817	37.8
	U11811	214505.7	+183010	Sc/Irr	1.0	0.30	74	∼6500	
	U12081	223134.9	+095447	Sa/b	1.3	0.19	132	∼11650	
N7331	U12113	223447.7	+340935	Sb	11.4	0.35	171	822	162.2
N7337	U12120	223509.2	+340648	SBa	1.2	0.83		6900	<0.9
N7413		225233.8	+125713	S0	0.5	0.60	70	9740	
N7490	U12379	230501.0	+320618	Sb	3.0	0.93		6214	
N7500	U12399	230759.1	+104423	S0	2.1	0.52	125	∼10600	
N7537	U12442	231201.9	+041333	Sb	2.1	0.24	79	2654	21.0
	U12552	231933.4	+124539	Sa/b	1.8	0.14	169	∼3600	<7.9
	U12667	233119.8	+294659	Sc	1.6	0.56	142	∼3750	
	U12886	235657.4	+175523	Sb/c	1.6	0.69	110	∼6630	

NOTES.—Cols. (1) and (2).—NGC and UGC numbers of the galaxy (Nilson 1972). Cols. (3) and (4).—Coordinates (epoch 1950) of the galaxy (Huchtmeier and Richter 1989; Dressler and Condon 1976). Col. (5).— The Hubble type as given by Nilson (1972). Col. (6).—The blue diameter of the galaxy in arcminutes (Nilson 1972). Col. (7).—The ratio between the blue minor and major axis (Nilson 1972). Col. (8).—The position angle α (see Fig. 1) of the major axis of the galaxy, unless it is face-on, from Nilson (1972). Col. (9).—The heliocentric velocity of the galaxy in km s^{-1} (Huchtmeier and Richter 1989, when available; otherwise an approximate value has been found at Arecibo during the observing session). Col. (10).—The integrated flux density of H I in Jy km s^{-1} (Huchtmeier and Richter 1989).

a) Arecibo Observations

For this search we employed the 305 m radio telescope of the Arecibo Observatory[2] during 1987 May. We chose the dual-circular polarization feed for its high sensitivity. A bandpass of 5 MHz was centered on the velocity of each galaxy with two banks of 1024 channels each in the autocorrelation spectrometer, one for each polarization. After a single Hanning smoothing the effective resolution was 8.8 kHz or ~ 2 km s^{-1}. This spectral resolution should be sufficient for detection of absorption because even if the temperature is very low, turbulent motions will increase the line width. Previously detected H I absorption features in outer regions (see § I) have also been wider than our resolution. We used the standard ON-OFF total power technique for all measurements.

Some spectra showed H I emission in the direction of the background source. In general, we would still expect to be able to determine whether or not absorption was present since the galaxy's H I emission averaged over the entire Arecibo beam tends to be much wider and smoother than an absorption feature toward a small angular-diameter background source. Several of these spectra showed structure within their emission that could have been produced by absorption. We attempted to confirm these features by making offset observations with the telescope pointed farther away from the center of the galaxy while maintaining the background source within the half-power beamwidth in order to reduce the contribution of confusing H I emission. In five cases we still found possible absorption features; the three most suspicious of which were reobserved at the VLA (see § III*b*). The data for the background sources and their spectra are given in Table 2. The geometry of the relative location of galaxy and quasar is illustrated in Figure 1.

The limiting H I column density and optical depth (cols. [13] and [14]) are based on the larger of the rms noise or any H I features in our spectra. If no emission was detected, a 3 σ upper limit to the column density was computed as

$$N_{\rm lim} = 1.46 \times 10^{19}\ {\rm cm}^{-2}\, \frac{2\Delta V \times (3\ {\rm rms})}{\sqrt{\Delta V/{\rm res}}} \qquad (4)$$

where we have assumed a forward gain of 8 K Jy^{-1}, rms (col. [6]) is in Jy, res is the spectral resolution, and ΔV is the velocity width (in km s^{-1}) over which emission would be expected in the direction of the background source. Since the background sources lie outside the optical image of the galaxy where the full rotation width of the galaxy is not appropriate, we use $\Delta V = 100$ km s^{-1} as an estimate of the typical kinematic line width that might have been expected within the Arecibo beam. The extra factor of 2 in equation (4) accounts for the typical variations due to baseline subtraction.

If emission was detected, we list the column density corresponding to the observed brightness temperature assuming no subthermal effects. The detected emission will generally give an upper limit to the column density since the measured flux is dominated by emission from regions of the galaxy's inner disk that are subtended by the telescope's 3.'3 diameter beam. However, if the region being observed is smaller than the beam size, beam dilution can result in a low value of the column density. In particular, the listed column densities will be too low when the galaxy's size (r in Table 1) and the separation

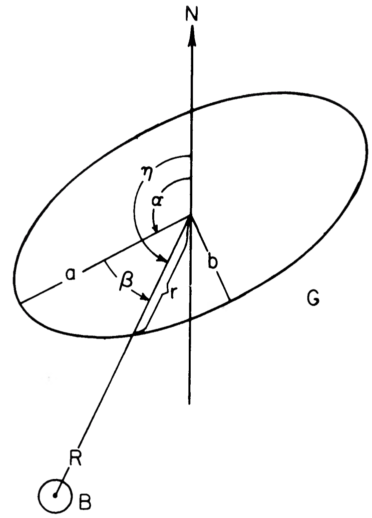

FIG. 1.—Geometry of the galaxies and background sources. The position of a background source B is shown with respect to a galaxy G having a semimajor axis a, semiminor axis b, and position angle α on the plane of the sky, the position angle of the background source is shown by η, β is the angle between the source position and the galaxy major axis, R is the distance between the background source and the center of the galaxy on the plane of the sky, and r is the distance between the center of the galaxy and its projected optical edge in the direction of the background source.

from the background source (R in Table 2) are both smaller than the beam. In addition, if the outer regions of the observed galaxies have strong clumping, beam dilution could allow higher column densities, but statistically for many lines of sight, this effect should average out.

One background source received further study at Arecibo. After mapping the emission in the region surrounding the strong background source close to M33 (NGC 598) during 1988 November, using the low-sidelobe flat feed at Arecibo (see Corbelli, Schneider, and Salpeter 1989 for the flat-feed characteristics), we found that the H I distribution there was smooth enough for an ON-OFF type of measurement to be made in order to subtract the emission. Therefore, in addition to the on-source spectrum we obtained spectra at two adjacent points at the same radial distance from the center of M33. After taking the average of the two polarizations and the weighted average of several 5 minute scans at each position, we obtained an rms of 1.8 mJy for the spectral resolution of 4 km s^{-1}. Using the average of the two adjacent spectra as an off-source spectrum, the H I emission within M33 could be subtracted. The ON spectrum, the two OFF spectra, and their difference are shown in Figure 2. Baselines were subtracted from each 5 minute scan in regions of the spectrum away from any H I emission (primarily outside the portions of the average spectra shown in Fig. 2). A possible weak negative feature is visible within the ON-OFF spectrum, but this may be produced by imperfect subtraction, and in any case it is weaker than 3 σ and at a different velocity from the mean of the emission. The limit on the peak optical depth found is $\tau < 0.004$ (3 σ limit), while the H I column density on-source is $N_{\rm H\,I} = (1.6 \pm 0.5) \times 10^{19}$ cm^{-2}.

None of the 59 sources examined shows an indisputable absorption feature, although for five cases we could not exclude there being neutral hydrogen absorption lines at a level of 3–5 times the rms noise because of confusion with the galaxy's own H I emission. The possible absorption features

[2] The Arecibo Observatory is a part of the National Astronomy and Ionospheric Center operated by Cornell University under contract with the National Science Foundation.

TABLE 2

LIMITS ON ABSORPTION AGAINST BACKGROUND SOURCES

Galaxy (1)	Source R.A. (2)	Source Dec. (3)	S_0 (mJy) (4)	S_1 (mJy) (5)	*rms* (mJy) (6)	η (7)	β (8)	R (9)	R/r (10)	R/a (11)	S_{HI} (mJy) (12)	$\log N_{lim}$ (cm^{-2}) (13)	τ_{lim} (14)
U477	004332.1	+191313[d]	210[d]	200	3.3	287	60	0'.7	1.6	0.4	100	20.46	0.050
N474	011810.8	+030021[e]		440	14.8	132		13.2	2.6	2.6		19.26	0.101
N598	012816.1	+305554[g]	80[g]	80	4.0	312	71	48.0	2.1	1.3	190	19.98	0.150
	013150.2	+294818[g]	140[g]	200	2.7	164	39	37.2	1.3	1.1	300	20.35	0.041
	013327.7	+310935[g]	150[g]	230	1.8	35	12	55.3	1.6	1.5	11	19.04	0.023
	013404.6	+295918[g]	1220[g]	1320	1.7	122	81	46.4	2.0	1.3	25	19.20	0.0039
	013418.5	+310730[g]	280[g]	400	1.2	44	21	60.7	1.8	1.7	8	18.93	0.0090
	013436.5	+304648[g]	130[g]	200	3.8	64	41	51.5	1.8	1.4	19	19.12	0.057
N628	013131.0	+152716[e]		163	1.8	263		36.4	6.1	6.1		18.35	0.033
	013141.5	+155650[e]		210	4.1	307		42.0	7.0	7.0		18.71	0.059
	013218.0	+152220[e]	78[f]	107	1.2	249		26.5	4.4	4.4		18.17	0.034
	013240.6	+151444[e]	127[f]	135	1.1	229		25.7	4.3	4.3		18.13	0.024
	013408.8	+150600[f]	75[f]	77	1.9	176		25.7	4.3	4.3		18.37	0.074
N660	013938.1	+131240[e]		322	1.6	224	54	14.9	5.7	3.0		18.30	0.015
N959	022922.7	+351821[c]	670[c]	250	7.2	10	55	1.9	2.3	1.5		18.95	0.086
N972	023113.0	+290458[a]	290[c]	250	2.6	232	80	1.0	1.2	0.5	48	20.19	0.031
U2174	023903.4	+321237[c]	720[c]	1000	5.9	353		2.6	2.3	2.3	22	19.53	0.018
N2608	083209.2	+283540[f]	254[f]	276	0.9	203	37	3.4	3.1	2.7	3	18.05	0.010
N2903	092748.0	+214816[e]	222[f]	261	0.8	283	86	21.9	7.3	3.3		18.00	0.0092
	092925.9	+212602[e]	481[f]	537	1.2	175	22	17.3	3.2	2.6		18.17	0.0067
	092932.8	+214942[e]	105[f]	125	1.1	25	8	7.1	1.1	1.1	330[h]	20.54	
N3351	104139.0	+120156[f]	130[f]	74	3.9	51	38	6.2	1.9	1.5	20	18.94	0.158
	104151.9	+115405[f]	190[f]	257	2.8	116	77	8.9	3.5	2.9		18.54	0.033
N3547	110713.6	+110038[c]	1500[c]	1200	5.4	307	60	1.6	3.2	1.5	43	19.96	0.014
N3623	111527.5	+131253[e]	280[f]	277	1.3	234	60	15.4	11.7	3.2		18.21	0.014
N3627	111753.8	+125737[e]	320[f]	315	1.4	168	5	18.9	4.3	4.2	8[h]	18.63	
	111804.8	+132152[e]		130	1.4	49	56	8.7	3.6	1.9	4	18.86	0.032
N3628	111821.3	+134337[e]		100	2.1	129	25	13.0	3.0	1.7	9	19.21	0.063
N4321	122042.6	+155822[f]	73[f]	78	1.2	149	61	8.9	3.0	2.6	4	18.46	0.046
	122120.0	+162446[e]	679[f]	648	2.7	36	6	23.2	6.8	6.8		18.52	0.013
N4548	123249.0	+145717[e]	150[f]	147	1.2	352	22	11.0	4.2	4.0		18.17	0.024
	123337.1	+143928[e]		137	3.3	124	26	12.3	4.7	4.5		18.61	0.072
N4569	123407.0	+131518[c]	300[c]	450	3.0	194	9	11.4	2.1	2.0		18.57	0.020
N4631	123642.3	+324656[e]	771[f]	775	4.0	267	1	37.7	4.5	4.4		18.69	0.015
	124021.2	+331502[e]	240[f]	212	1.8	18	68	27.4	14.6	3.2	6	18.46	0.025
	124113.5	+324044[f]	58[f]	41	3.1	113	27	21.0	5.9	2.5	70	19.71	0.227
N4651	124127.5	+163916[e]	2760[f]	2972	2.5	103	23	3.7	2.1	1.9	60[h]	19.99	
N4725	124650.5	+254930[f]	111[f]	109	0.9	274	59	15.7	3.3	2.6		18.05	0.025
	124931.2	+255025[f]	290[f]	271	2.3	84	49	20.7	4.1	3.4		18.45	0.025
N4826	125607.3	+213518[e]	447[f]	506	3.8	131	16	33.8	7.5	6.8		18.67	0.023
U8273	130931.6	+210430[c]	500[c]	400	7.1	328	16	1.1	2.6	2.2		18.94	0.053
N5645	142733.4	+072826[a]	1200[c]	1200	4.3	261	1	9.4	5.8	5.8		18.73	0.011
N5773	145027.3	+300127[c]	280[c]	280	2.9	49		1'.2	2.2	2.2		18.55	0.031
N5936	152737.0	+130847[c]	150[c]	150	1.5	217	37	1.1	1.7	1.7	25[h]	19.47	
N6045	160255.3	+175234[c]	760[c]	900	3.9	153	71	1.1	9.5	2.0		18.68	0.013
U11017 ...	174953.7	+295148[c]	970[c]	970	8.2	261	84	4.3	8.6	4.8		19.01	0.025
N6509	175706.0	+061726[c]	710[c]	690	7.5	87	18	1.9	2.4	2.3	135	20.40	0.033
U11811 ...	214457.5	+183005[c]	260[c]	300	2.2	268	14	1.9	4.8	3.9		18.43	0.022
U12081 ...	223128.0	+095255[c]	450[c]	380	2.9	222	90	2.5	20.2	3.9		18.55	0.023
N7331	223337.2	+335854[e]	146[f]	168	1.9	234	63	18.1	8.2	3.2		18.37	0.034
	223436.0	+340518[e]	148[f]	148	1.6	209	38	4.9	1.7	0.9	80[h]	20.35	
N7337	223452.0	+340811[c]	510[c]	300	5.3	290		3.8	6.3	6.3		18.82	0.053
N7413	225234.5	+125734[b]		3570	7.0	26	44	0.4	2.1	1.6		18.94	0.0059
N7490	230451.5	+321500[e]		640	4.9	347		8.9	6.0	6.0		18.78	0.023
N7500	230805.0	+104327[e]		400	2.5	123	2	1.7	1.6	1.6		18.49	0.019
N7537	231208.8	+041606[c]	170[c]	140	5.0	34	45	3.1	8.9	2.9	112	20.60	0.107
U12552 ...	231933.0	+124812[e]		120	3.5	355	6	2.6	3.6	2.9		18.64	0.088
U12667 ...	233125.7	+294806[e]		280	4.1	49	87	1.7	3.8	2.1	43	19.86	0.044
U12886 ...	235649.0	+175445[e]		600	3.8	252	38	2.1	3.1	2.6	33	19.67	0.019

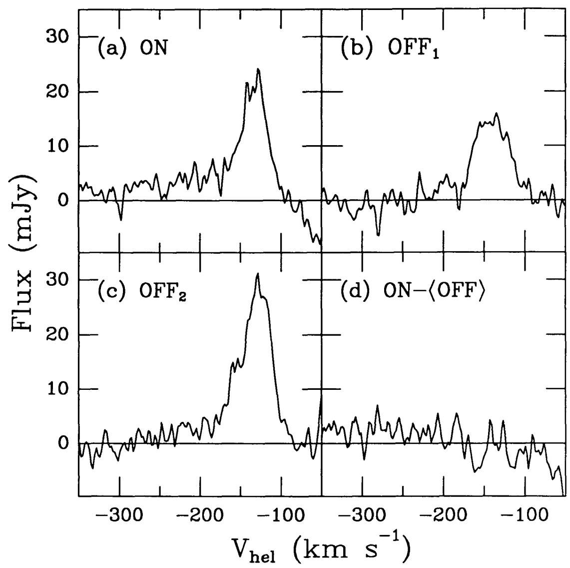

FIG. 2.—H I spectra in the vicinity of the strongest background source near M33 (R.A. = 01ʰ34ᵐ05ˢ = 29°59′18″). Panel (*a*) shows the H I emission spectrum taken ON source. Panels (*b*) and (*c*) show H I emission spectra taken in nearby locations, respectively, at R.A. = 01ʰ34ᵐ13ˢ Decl. = 30°02′08″ and at R.A. = 01ʰ35ᵐ57ˢ Decl. = 29°56′38″. Panel (*d*) shows the difference between (*a*) and the average of (*b*) and (*c*).

are in the spectra of NGC 2903, NGC 3627, NGC 4651 (3C 275.1), NGC 5936, and NGC 7331 and are noted in Table 2 by footnote *h*. Since these features could not be unambiguously distinguished from either absorption or kinematic structure within these galaxy's emission profiles, we exclude them from the remaining analysis in § IV; however we were able to reobserve the three most suspicious cases at higher spatial resolution.

b) VLA Observations: Preliminary Results

In order to test whether weak features in our emission-contaminated spectra are due to absorbing neutral hydrogen in the proximity of the optical disk of external galaxies, observations must be made with higher spatial resolution in order to reduce the confusing H I emission. For three quasar/galaxy pairs with suspected absorption features, we made observations with the VLA[3] in its C configuration in 1989 August. Twenty-seven antennas and two polarizations were used. On-line Hanning smoothing with 128 spectral channels over a 1.56 MHz bandpass yielded a velocity resolution of ∼2.5 km s^{-1}. Standard amplitude, phase, and bandpass calibration were performed with nearby strong continuum sources. The fields were centered on the continuum sources closest to NGC 4651, NGC 5936, and NGC 7331. The more distant southern source associated with NGC 7331 was not in the field of view. In addition to producing bandpass-calibrated, naturally weighted maps, we constructed emission-line maps by subtracting from each channel map the continuum as averaged over the entire bandpass for NGC 4651 and NGC 7331 and as averaged over channel maps on either side of the channels containing H I emission in NGC 5931. Unfortunately, NGC 4651 and NGC 7331 had H I emission spread over too wide a velocity range to fit within our bandpass, and a wider bandpass would have forced us to use too coarse a velocity resolution. For these two galaxies we therefore observed only the H I emission over the half of the velocity range that corresponded to the side of the galaxy where the background source was located. The lack of adequate line-free channels necessitated some self-subtraction of the H I emission, but this was significant only near the centers of the galaxies, and we were able to correct this fairly well (for purposes of estimating the total H I emission) by an iterative procedure.

The background sources next to NGC 5936 and NGC 7331 displayed typical double-lobed structures at the respective synthesized beam resolutions of 30″ × 20″ and 25″ × 20″. The continuum emission listed in Table 2 for the NGC 5936 observation proved, however, to be divided almost equally between a probable nuclear source close to the optical center of the galaxy and the background source near the quoted coordinates in Table 2. After cleaning and summing the separate

[3] The Very Large Array is a facility of the National Radio Astronomy Observatory (NRAO) operated by Associated Universities, Inc., under contract with the National Science Foundation.

NOTES TO TABLE 2

[a] Data from the present Arecibo observations.
[b] Arp *et al.* 1972.
[c] Condon 1986.
[d] Condon and Broderick 1985.
[e] Douglas *et al.* 1980.
[f] Willis, Oosterbaan, and De Ruiter 1976.
[g] Wright, Warner, and Baldwin 1972.
[h] Possible absorption. N4651, N5936, and N7331 were also observed at the VLA. See text.

NOTES.—Data in cols. (1)–(14) follows: Col. (1).—Name of the galaxy near the line of sight to the background source. Cols. (2) and (3).—Coordinates of the background source. Col. (4).—Flux density of the source in mJy as quoted in the reference given in the lettered footnotes, usually measured at 1400 MHz. Col. (5).—Flux density of the source in mJy measured at Arecibo from our ON-OFF spectra. This method is subject to possible systematic errors if continuum sources are present in our OFF scans, but it is otherwise the most direct measure of the detected flux density at the time of observation and generally is in good accord with the values in col. (4). Col. (6).—The rms of the spectrum's baseline in mJy. Col. (7).—Position angle η of the background source relative to the center of the galaxy in degrees east of north (see Fig. 1). Col. (8).—Position angle β of the background source relative to the galaxy's major axis position (see Fig. 1). Col. (9).—The separation R, in the plane of the sky, of the background source from the center of the galaxy in arcminutes (see Fig. 1). Col. (10).—Ratio between R and the galaxy's optical extent r in the direction of the source (see Fig. 1), which indicates the relative separation of the source from the center in the plane of the galaxy's disk. Col. (11).—Ratio between R and the semimajor axis a, which indicates the relative separation of the source with respect to any spherically distributed matter. Col. (12).—Peak in mJy of any H I emission detected above the 3 σ level in our observation in the direction of the background source. Footnote *h* indicates a possible absorption feature in the spectrum. Col. (13).—Limiting H I column density in the direction of the background source. If no emission was detected, a 3 σ upper limit was computed (see text). Col. (14).—Limiting value to the optical depth evaluated as $\tau_{\rm lim} = 3 \times {\rm rms}/S_1$. It is given for only those cases where no absorption features were suspected in the spectrum.

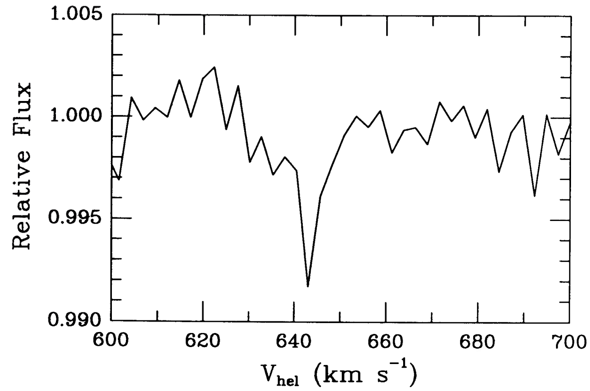

FIG. 3.—Spectrum of 3C 275.1 in the velocity range of NGC 4651, from VLA observations at $\sim$2.5 km s^{-1} resolution. The vertical scale has been normalized to the continuum flux density.

channel maps (averaged to 20 km s^{-1} resolution), we found a total H I column density of $\sim 2.5 \times 10^{20}$ cm^{-2} at the position of the background source. (Note that this value is higher than our Arecibo measurement, which is affected significantly by beam dilution because of the combination of a small angular size of the galaxy and a small angular separation from the source.) For NGC 7331, no H I emission was detected at the position of the background source to a limiting column density of 10^{20} cm^{-2} after similar cleaning and summing. No absorption features were detected in the spectra of either of these background sources at the position of their peak emission or after averaging over the region of observed continuum emission. Three-sigma limits on the absorption of 8% and 6% were found for NGC 5936 and NGC 7331, respectively. It may be possible that nuclear absorption in NGC 5936 accounts for our Arecibo result, or peculiar structures in the H I emission may account for the suspected absorption features in both galaxies. The resultant limits on the optical depths are similar to the Arecibo results for other sources.

The background source close to NGC 4651 is the well-known quasar 3C 275.1 (see Stocke, Burns, and Christiansen 1985, for a VLA map), where others have already searched for H I absorption from gas associated with NGC 4651 (Haschick and Burke 1975). The structure of the quasar was only slightly resolved with our 25" × 20" synthesized beam. As can be seen in Figure 3, the spectrum at the position of the quasar shows a dip at $\sim$643 km s^{-1}. In the continuum-subtracted channel at 643 km s^{-1}, the negative dip at the location of 3C 275.1 was the most extreme point in the line-free regions of the map, measuring -11.5 mJy beam^{-1} relative to an rms of 2.7 mJy beam^{-1} in the surrounding area. The feature also appeared to be present in both the beginning and ending halves of the data, and no significant variations in the bandpass calibration at this velocity appeared to be present (<0.2% variations in any calibration scan). Formally, we find a peak optical depth $\tau = 0.0077 \pm 0.0014$ in the spectrum averaged over the source, and $\tau = 0.0064 \pm 0.0015$ in the channel map at the position of peak emission (1 σ errors). The deepest point in the spectrum thus reaches $\sim$5 times the rms noise with a line width of $\sim$5 km s^{-1}, which at the spectral resolution of 2.5 km s^{-1} may be unresolved. Haschick and Burke (1975) quote an essentially consistent upper limit of $\tau < 0.0068$ at a resolution of 2.8 km s^{-1}; their observation was made with the Green Bank 91 m telescope and must therefore have been significantly contaminated with H I emission. Given that the velocity of the absorption is appropriate for an extrapolation from the velocity field seen within the galaxy's disk (see Warmels 1988), we believe this feature is real, although we intend to make confirming observations with greater sensitivity.

In the present observations, after cleaning and summing, no H I emission was visible at the location of the quasar. Because of the great strength of the continuum source in this case, our integration time was relatively short, and the minimum detectable column density was only 1.3×10^{20} cm^{-2}, similar to the limiting value in maps published by Warmels (1988) for this galaxy, although in both cases this limit could be too low due to the spatial filtering of these synthesis instruments. The Arecibo observation gives a detected column density of 9.8×10^{19} cm^{-2}, which is effectively an upper limit since it is dominated by emission from the interior of the galaxy. There is no evidence of a clumpy structure in the VLA and Westerbork maps of NGC 4651 in the direction of 3C 275.1; thus, unlike 3C 232/NGC 3067 the absorption may be associated with a generally extended gaseous disk, and our Arecibo limit on the column density is probably reasonable. This limit on the H I emission would imply only that $T_S \lesssim 1450$ K, but the 5 km s^{-1} line width would already indicate that $T_k \lesssim 530$ K. Extrapolating the falloff in H I column density from within the disk out to the position of 3C 275.1 also suggests a spin temperature of perhaps a few hundred K. In any case, a more complete analysis awaits more sensitive, higher velocity resolution observations, but it does not appear that subthermal effects are required to explain the level of absorption apparently detected in this system.

IV. ANALYSIS AND DISCUSSION

Our examination of 59 radio continuum sources shows no evidence of strong 21 cm H I absorption by any of the corresponding galaxies' outer disks. The rarity of absorption indicates that (1) H I at low column densities in the outer parts of disks does not have a low spin temperature, (2) H I emission measurements are therefore reliable, and (3) the occasional detections of strong absorption outside of optical disks are probably due to uncommon sources of high column density gas such as gas removed from the inner disk via tidal interactions.

From the Arecibo search in the lines of sight to 54 background sources lying in the proximity of galaxies we have found no evidence for neutral hydrogen absorption and have upper limits τ_{lim} to the absorption optical depth. For each we can estimate a value or an upper limit for the emission brightness temperature T_b along the line of sight and a corresponding H I column density N_{lim}, assuming no subthermal effects on the emission (see Table 2). The Arecibo beam is so large that the detections of neutral hydrogen will be significantly contaminated from brighter regions closer to the center of the galaxy, so that T_b is in some respects an upper limit in these cases too, except for the largest angular diameter galaxies like M33 or NGC 4631, where the values should be accurate. Beam dilution may alternatively give us an artificially high or low limit on the column density if the interstellar medium is clumped within the beam. By studying a large sample of quasar/galaxy pairs, though, such statistical fluctuation should average out.

In order to examine the possible values of the spin temperature and H I column density, we define a reference value of the temperature T_{lim} for our upper limits by the relation

$$\frac{N_{lim}}{T_{lim}} = 1.95 \times 10^{18} W \tau_{lim} , \qquad (5)$$

where $N_{\rm lim}$ is in cm^{-2}, $T_{\rm lim}$ is in K, and W is the line width in km s^{-1}; i.e., $T_{\rm lim}$ would be the spin temperature for a column density $N_{\rm lim}$ producing optical depth $\tau_{\rm lim}$. In order to evaluate $T_{\rm lim}$ we use a velocity width W of 4 km s^{-1} for the expected absorption feature, as suggested by previous detections (Rubin, Thonnard, and Ford 1982; Carilli and van Gorkom 1987). When the calculated value of $T_{\rm lim}$ would exceed 300 K we instead use a larger value of the velocity width $W = 8$ km s^{-1} to remain consistent with a thermally broadened line.

For these 54 lines of sight we have pairs of values $N_{\rm lim}$, $T_{\rm lim}$; scatter plots of which are shown in Figure 4. The triangular symbols show all cases where no H I was detected in emission, H I emission was present in the spectra of sources shown by circles, and results for the VLA observations are shown by squares and a star. The filled symbols refer to sources where the angular resolution of our observations was sufficiently good that the detected column density of H I is probably close to the actual H I column density in the line of sight to the background source: these include the Arecibo observations of the two largest galaxies in our sample, M33 and NGC 4631, and the VLA observation of NGC 5936. Note that except for the two or three lowest (and lowest quality) points, we have the inequality $T_{\rm lim} \gg T_R \simeq 2.7$ K. In particular, this is true for the filled circles in Figure 4, where $T_{\rm lim}$ should be a good lower limit to the actual spin temperature.

The quantity $T_{\rm lim}$ as we have defined it is somewhat peculiar since in most of the cases it depends on dividing two upper limits. It would be further complicated if the spin temperature were very low and the H I emission were suppressed, in which case the "upper limit" $N_{\rm lim}$ would not be any kind of limit at all! However, we can use the values of $T_{\rm lim}$ and $N_{\rm lim}$ to place several constraints on the possible pairings of the actual spin temperature and H I column density, and directly rule out the possibility of suppression of the H I emission from regions of column density greater than $\sim 10^{18}$ cm^{-2}.

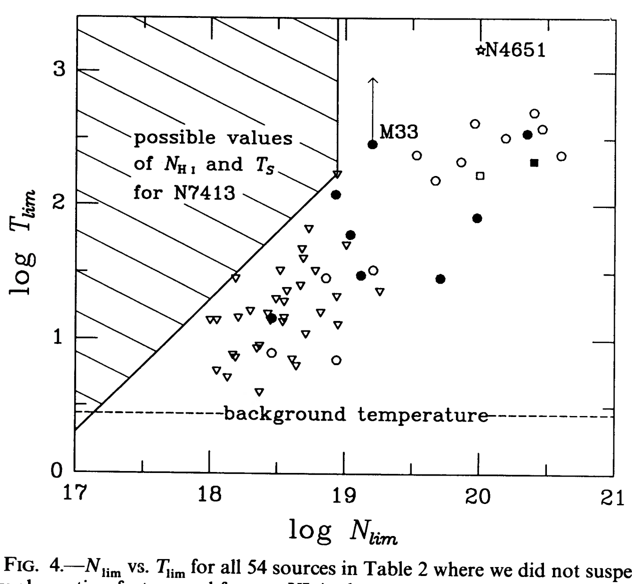

FIG. 4.—$N_{\rm lim}$ vs. $T_{\rm lim}$ for all 54 sources in Table 2 where we did not suspect any absorption feature and for our VLA observations. Triangles mark values where no H I emission was present in the spectrum, circles mark values where some H I was detected in emission, and squares and star mark VLA observations. The filled symbols represent observations with good estimates of the local $N_{\rm H\,I}$, which then give lower limits on T_S as illustrated for the strongest continuum source associated with M33. The open symbols have upper limits on both the H I emission and absorption, which yields a range of possible values for $N_{\rm H\,I}$ and T_S as illustrated for the continuum source associated with NGC 7413. The apparent absorption in NGC 4651 gives an upper limit to $N_{\rm H\,I}/T_S$ as is shown by a star (but see text). The dashed line at the bottom of the figure indicates the blackbody temperature of the cosmic microwave background.

Irrespective of subthermal effects, the absorption limits require that the true column density $N_{\rm H\,I}$ and the spin temperature T_S in each case satisfy the inequality

$$\frac{N_{\rm H\,I}}{T_S} < \frac{N_{\rm lim}}{T_{\rm lim}} . \qquad (6)$$

Thus for each line of sight, the possible pairings of $N_{\rm H\,I}$ and T_S must lie above and to the left of a line of unit slope passing through $N_{\rm lim}$, $T_{\rm lim}$ (see Fig. 4). In order for the emission to be suppressed, T_S must be close to T_R (shown as a horizontal dashed line in Fig. 4), but this can only occur for low values of $N_{\rm H\,I}$ approximately less than 10^{18} cm^{-2} for any of the lines of sight observed. The value of $N_{\rm H\,I}$ must also lie to the left of $N_{\rm lim}$ by the inequality

$$N_{\rm H\,I} \leq N_{\rm lim} , \qquad (7)$$

which holds unless T_S is close to T_R, and as we have just shown, such a suppression could only be possible at column densities lower than $N_{\rm lim}$ for any of the points in Figure 4, so that equation (7) applies. The region of possible values of T_S and $N_{\rm H\,I}$ for the open symbols in Figure 4 is thus bounded by two limits; this is illustrated in the figure for the continuum source associated with NGC 7413.

Previous H I emission studies with good sensitivity (Briggs *et al.* 1980; Hewitt, Haynes, and Giovanelli 1983; Huchtmeier and Seiradakis 1985; Bothun 1985; Carilli, van Gorkom, and Stocke 1989) have shown that a small fraction of lines of sight outside the optical disks of galaxies show quite large column densities, $N_{\rm H\,I} \geq 10^{20}$ cm^{-2}, but most lines of sight have less than $\sim 2 \times 10^{19}$ cm^{-2}. In spite of the large area represented by regions of possible low column density, they would contribute little to the total H I mass unless subthermal emission suppression was occurring. One important conclusion of our study is therefore that subthermal effects do not hide a sizeable fraction of the hydrogen mass and can therefore be neglected for emission studies but not necessarily for 21 cm absorption lines.

For the filled points in Figure 4*b* and several other points in the upper part of the diagram $N_{\rm lim}$ should be a good estimate of $N_{\rm H\,I}$, yet no absorption was seen. For several of those points then $T_S \geq T_{\rm lim} \sim 100$ K. This suggests that the H I in the outer regions may generally be in a warm phase (Dickey and Brinks 1988).

Focusing on the observations of the strongest background source near M33, where we have a good estimate of the H I column density well outside the optical disk, we can examine the thermal status of the neutral hydrogen in a place where it is not likely to be contaminated by a significant stellar radiation field. As described in § III, the column density in the outer disk of M33 in the direction where the background source is located does not yet decline steeply and the H I distribution appears to be smooth. $N_{\rm H\,I}$ is then close to what we measured with the flat feed beam, $\sim 1.6 \times 10^{19}$ cm^{-2}. In order to explain the absence of any absorption feature at the level of 3 σ, the spin temperature must be at least 250 K (assuming a velocity width of 8 km s^{-1}). We suspect therefore that the hydrogen is in its warm phase with $T_K \sim$ 3000–10,000 K. If the main source of heating is soft X-rays from the background, then in order to suppress strong subthermal effects on the absorption line that would bring τ_{lim} above 0.004, the soft X-ray background should be at least as strong as that predicted by extrapolation of the Schwartz law down to 13.6 eV.

The preliminary results of our VLA observations of NGC 7331 and NGC 5936 are shown in Figure 4 by square symbols. In the case of NGC 7331, we have limits on both the emission and absorption, while for NGC 5936 we have a good estimate of the column density, giving us a lower limit on the spin temperature. The absorption and emission limits for NGC 4651/3C 275.1 are shown by a star in Figure 4. The current limit on the column density of H I along the line of sight to 3C 275.1 only constrains T_S in the apparent absorption feature in NGC 4651 to be ~ 1450 K or less, although the line width implies it should be considerably smaller (see § III*b*). The possibility of partial coverage of the background source further complicates the interpretation of this probable absorption system; we defer further discussion of this system until more sensitive confirmation of the absorption has been obtained.

From our search we conclude that cold gas at column densities greater than 10^{19} does not normally extend much farther out than the optical disk of a galaxy, and subthermal effects do not hide a substantial fraction of neutral hydrogen. This, together with the limit on absorption in the spectrum of the strong background source close to M33, suggests that neutral hydrogen in the outer regions of galaxies is generally warm. In order for the hydrogen outside the stellar disk with $N_{\rm H\,I} \geq 10^{19}$ cm^{-2} to be in a thermally stable phase and still have a high spin temperature, a nonnegligible extragalactic flux of X-rays or some other energy source is required. One other such heating source for the outer disk may come from the inner disk: if only a small fraction of supernova energy reaches the outer regions via galactic fountains, it would be sufficient for warming the neutral gas. In order to put better constraints on the X-ray background we must therefore analyze these other energy sources (Corbelli and Salpeter 1990) and see which gives the best fit to the observed properties of the neutral hydrogen outside the stellar disk.

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