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AN H I SURVEY OF HIGH-VELOCITY CLOUDS IN NEARBY DISK GALAXIES

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ABSTRACT

We observed 14 nearly face-on disk galaxies with the Arecibo 305 m telescope and found the double-horned H I profiles to have high-velocity wings in 10 of these galaxies. Such wings can be caused by high-velocity clouds, similar to those observed in our own Galaxy. Disk galaxy models were constructed that include both high-velocity clouds (modeled as a component of galactic gas with a velocity dispersion of either 30 or 50 km s^{-1}) and warped H I disks. We find that the high-velocity wings can be reproduced by models with high-velocity clouds but not by models with warps that are similar to those observed in other galaxies. If these wings are due to high-velocity clouds, then the mass of neutral hydrogen in high-velocity clouds for the 10 galaxies ranges from 6×10^7 $M_\odot$ to 4×10^9 $M_\odot$, which corresponds to 4%–14% of the total H I in these galaxies. The galaxies with no detected high-velocity wings are also those with the lowest far-infrared fluxes as measured by *IRAS*, which is consistent with the galactic fountain model in which the young stellar population (responsible for most of the far-infrared emission) produces supernovae which then provide the kinetic energy of the high-velocity clouds.

Subject headings: galaxies: ISM — galaxies: kinematics and dynamics — galaxies: spiral — radio lines: galaxies

1. INTRODUCTION

The high-velocity clouds of neutral hydrogen in our Galaxy dominate the kinetic energy of H I in noncircular motion and are an important though poorly understood component of Galactic gas. High-velocity clouds with $|v_{\rm LSR}| > 100$ km s^{-1} cover approximately 10% of the sky to a limiting column density of 2×10^{18} cm^{-2} (Wakker 1990) and are responsible for about 0.7% of the total neutral hydrogen flux density which we detect from the Galaxy. There are large numbers of high-velocity clouds at both positive and negative velocities and the clouds are found at all Galactic longitudes and latitudes, although they are concentrated toward the Galactic plane. Very high velocity clouds ($|v_{\rm LSR}| > 200$ km s^{-1}) are concentrated in the southern Galactic hemisphere and are probably material which has been tidally torn from the Magellanic Clouds (Murai & Fujimoto 1980; Wakker 1990). Some high-velocity clouds with low Galactic latitude are caused by the warped and flared disk of the Galaxy (Burton 1988 and references therein). Most of the high-velocity clouds have 100 km $s^{-1} < |v_{\rm LSR}| < 200$ km s^{-1}, are evenly distributed between the northern and southern Galactic hemispheres, and show the signature of Galactic rotation which implies that they are at distances greater than about 3 kpc. Such high-velocity clouds can be explained by the galactic fountain model (Shapiro & Field 1976; Bregman 1980), in which hot gas from superbubbles escapes from the Galactic disk, cools radiatively as it rises upward, and eventually recombines and returns to the disk ballistically. If this model is correct, then the total mass in extraplanar H I is estimated to be 5×10^8 $M_\odot$, about 10% of the total H I in the Galaxy (Wakker 1990). Most of this extraplanar gas does not have $|v_{\rm LSR}| > 100$ km s^{-1} because the gas spends much of its lifetime above the disk near the peak of its ballistic orbit. We shall hereafter use "high-velocity clouds" (HVCs) to denote a component of neutral hydrogen with a large velocity dispersion, such as the extraplanar gas which would be produced by a galactic fountain. In order to determine the mass in the HVC component and to test the galactic fountain model we need to know the distance to the high-velocity clouds, but it is difficult to determine the distance to HVCs in the Galaxy. Danly, Albert, & Kuntz (1993) have determined that the distance to High Velocity Cloud Complex M is $1.5 < z < 4.4$ kpc, but this is the only undisputed detection of an HVC in the absorption line spectrum of a Galactic halo star. We can avoid the problem of uncertain distances to galactic HVCs by studying HVCs in external galaxies.

High-velocity gas has been discovered in a few nearby galaxies through 21 cm radio telescope studies. Westerbork Synthesis Radio Telescope (WSRT) observations of NGC 6946 (Kamphuis & Sancisi 1993) detected about 5×10^8 $M_\odot$ of H I at high velocities, most of which is seen near holes in the H I distribution. Such holes have been detected in M31 (Brinks & Bajaja 1986) and M33 (Deul & den Hartog 1990), and it has been suggested that the H I holes are produced by supernovae and persistent stellar winds from large H II regions in the galactic disk. A large H I hole (1.5 kpc) detected in M101(Kamphuis, Sancisi, & van der Hulst 1991) is surrounded by a shell of 10^7 $M_\odot$ of neutral hydrogen expanding at about 50 km s^{-1}. The structure and symmetry of the H I hole suggest that it was produced by a large number of supernovae near the

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

TABLE 1

SAMPLE GALAXIES

Galaxy (1)	α (2000.0) (2)	δ (2000.0) (3)	$a \times b$ (4)	m_B (5)	V_H (km s^{-1}) (6)	Distance (Mpc) (7)	Type (8)
NGC 99	00^h23^m59^s.5	+15°46′10″	1′.4 × 1′.3	13.7	5311	110.0	Scd
NGC 765	01 58 47.4	+24 53 29	2.8 × 2.8	13.6	5119	105.4	Sbc
UGC 1546	02 03 21.0	+18 38 23	1.1 × 1.1	14.4	2369	49.9	Sc
NGC 1517	04 09 11.5	+08 38 52	1.1 × 1.0	14.1	3478	69.3	Scd
UGC 5288	09 51 17.2	+07 49 38	1.5 × 1.0	14.1	561	7.9	S
NGC 3344	10 43 30.6	+24 55 25	7.1 × 6.5	10.8	586	10.3	Sbc
NGC 3423	10 51 13.1	+05 50 32	3.8 × 3.2	11.5	1009	17.0	Scd
NGC 3507	11 03 25.5	+18 08 15	3.4 × 2.9	11.7	981	17.7	Sb
NGC 4136	12 09 17.6	+29 55 40	4.0 × 3.7	11.7	599	11.7	Sc
NGC 4254	12 18 49.2	+14 25 07	5.4 × 4.7	10.2	2407	46.6	Sc
NGC 5668	14 33 24.8	+04 27 02	3.3 × 3.0	12.0	1583	31.3	Sd
NGC 5921	15 21 56.2	+05 04 11	4.9 × 4.0	11.7	1488	30.3	Sbc
NGC 7292	22 28 24.9	+30 17 30	2.1 × 1.7	12.9	986	25.2	Im
UGC 12732	23 40 39.8	+26 14 08	3.0 × 2.8	13.8	750	19.8	Sm

NOTES.—Col. (2) right ascension; col. (3) declination; col. (4) major and minor axes; col.(5) apparent blue magnitude; col. (6) heliocentric velocity; col. (7) distance; col. (8) hubble type.

midplane of the disk. Very Large Array (VLA)[2] observations of NGC 628 by Kamphuis & Briggs (1992) found several high-velocity complexes which have a combined H I mass of about 2×10^8 $M_\odot$. These high-velocity complexes were detected earlier by using the Arecibo[3] telescope in a mapping mode in which data were taken at about 80 separate locations over the face of the galaxy (Briggs 1982). The symmetry of these complexes implies that they are due to a tidal disturbance. Large H I supershells which probably cannot have been produced by a combination of supernovae and stellar winds have been found in M101 (van der Hulst & Sancisi 1988) and NGC 4631 (Rand & van der Hulst 1993). These observations suggest that some high-velocity gas in external galaxies is produced by energetic stellar phenomena and other high-velocity gas is produced by external events such as tidal interactions and/or collisions with other galaxies. While such observations of individual galaxies are revealing, until now no survey for galaxies which contain high-velocity clouds has been attempted.

We observed a sample of nearly face-on nearby galaxies with the Arecibo 305 m telescope in order to search for evidence of high-velocity clouds. The signature of HVCs in an external galaxy should be evident in the net H I emission line profile obtained with a large filled-aperture radio telescope. The filled-aperture signature of a rotating disk of neutral hydrogen is a double-horned profile which decreases as a Gaussian at velocities $|v| > v_{\rm peak}$. The presence of HVCs will produce detectable low-intensity "wings" beyond the steeply decreasing double-horned H I profile. Such wings are distinguishable from a warp in the H I plane, which will appear as a small increase in the width of the profile (§ 4). Nearby ($v < 6000$ km s^{-1}) galaxies with 10^8 $M_\odot$ of hydrogen in HVCs will have wings at the 1–10 mJy level. The excellent, stable baselines now achievable with the Arecibo telescope allow us to perform observations with rms errors of less than 1 mJy per channel.

In this paper we discuss the results of our search for HVCs in 14 nearby galaxies (§ 2) with the Arecibo telescope (§ 3). We calculate model spectra of disk galaxies to help us determine the presence and amount of high-velocity gas in the galaxies (§ 4). We discuss the frequency of galaxies with HVCs, compare the kinetic energy in quiescent disk H I and in HVCs to the energy produced by Type II supernovae, and present a correlation between the integrated H I flux density from HVCs and the far-infrared flux from the galaxies (§ 5). Future papers will discuss optical observations of the galaxies obtained with the Michigan-Dartmouth-MIT Observatory 1.3 m telescope, VLA observations of NGC 5668 and UGC 12732, and WSRT observations of NGC 7292.

2. THE SAMPLE

Our sample is chosen from the Uppsala General Catalog of Galaxies (UGC) (Nilson 1973). In order to maximize the probability of detecting high-velocity clouds, we limit the sample to nearly face-on galaxies which have been previously detected in H I. We include galaxies with peak H I flux densities greater than 50 mJy, H I widths less than 250 km s^{-1}, and inclinations less than 45°. High-velocity clouds are easier to detect in nearly face-on disk galaxies because the velocities are expected to be nearly perpendicular to the disk. Our final sample is further restricted by the declination range accessible with reasonable zenith angle to the traveling feed system of the Arecibo 305 m telescope: $4° < \delta < 32°$. Galaxies that do not have double-horned H I profiles are excluded from our sample because it is difficult to construct unique models for such galaxies. We note that the two H I horns blend into one as the inclination of the galaxy approaches a face-on orientation so that galaxies with inclinations less than about 5° are excluded from our sample. Highly asymmetric H I profiles are difficult to model and may reflect encounters with other galaxies, so we exclude galaxies with such profiles from our sample. To lessen the likelihood of observing galaxies with asymmetric H I profiles, we avoided galaxies which are noted in the UGC as having possible nearby companions. This selection criterion does not mean that none of the sample galaxies have dwarf satellites such as the Magellanic Clouds but does eliminate pairs of large interacting galaxies.

The 14 galaxies with well-behaved emission-line profiles that comprise our sample are listed in Table 1. The distance in megaparsecs is computed from V_0/H_0, where V_0 is the radial velocity corrected to the rest frame of the local group (de Vau-

[2] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

[3] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a management agreement with the National Science Foundation.

couleurs, de Vaucouleurs, & Corwin 1976):

$$V_0 = V_H + 300 \sin l \cos b \text{ km s}^{-1} . \quad (1)$$

The heliocentric velocity, V_H, is listed in Table 1, and no corrections for a Virgocentric flow or for a flow due to a "great attractor" are made. $H_0 = 50$ km s^{-1} Mpc^{-1} is used throughout.

3. OBSERVATIONS

We observed our sample galaxies with the Arecibo 305 m telescope in the normal low-redshift H I mode. The observations were made in 1991 April and September using the total-power mode, alternating 5 minute On-source scans with 5 minute Off scans. We obtained 40 On-Off pairs of NGC 5668, reaching an rms noise level of about 0.6 mJy per 2 km s^{-1} channel; 10–20 On-Off pairs were obtained for most of the other target galaxies. The data were calibrated by observing continuum sources with the Arecibo POINTING program and with On-Off scans. A system temperature of better than 35 K was provided by GaAs FET amplifiers.

The spherical dish of Arecibo focuses incoming radiation of a given frequency to a line feed; we employed the dual-circular feed which is sensitive to both circular polarizations. The feed illuminates an annulus on the dish 200 m in diameter; it is tapered to attain a beamwidth (full width at half-power) of 3'.3 ± 0'.1 at 1411 MHz. The first sidelobe ring has a radius of about 5'.6 and is at a level of about −10 dB (Haynes & Giovanelli 1984). At the nominal optimum tuning of 1410 MHz, the gain is about 8 K Jy^{-1}. Most of the observations use a total bandwidth of 5 MHz, corresponding to about 1000 km s^{-1}.

The presence of high-velocity gas in an external galaxy produces a "wing" beyond the steeply declining H I profile (Fig. 1). In order to detect such wings and to discriminate between wings caused by a warp and wings caused by HVCs, we require a sensitive instrument with stable baselines. The Arecibo 305 m telescope satisfies both requirements, although care must be taken to determine whether detected wings are real features.

We made a concerted effort to minimize spurious effects. The observations were made at night to avoid the baseline distortions that occur when the sun is in distant sidelobes of the telescope. Some galaxies were observed with channel widths of both 2 and 4 km s^{-1} to ensure that the features were not dependent on the instrumental bandwidth. Almost all of our galaxies were observed on more than one night to decrease the probability that the features could be due to unpolarized interference. Since terrestrial interference tends to be polarized, it was identified and discarded by examining both polarizations before combining them. Some of our galaxies were checked by observations with an offset from the center to ensure that the high-velocity wings were not due to sidelobes on unrecognized companion galaxies. Some galaxies were observed with a small offset in the central frequency in order to be certain that the weak features of interest were not related to systematic irregularities in the baseline, such as those due to standing waves generated in the IF sections of the receiver, such as the cables. The cables are usually stable over the period of time it takes to do an On-Off pair and we found no significant differences between the scans with different central frequencies.

We found no baseline effects in our observations which would produce high-velocity wings. To test the quality of the Arecibo telescope baseline, we made two measurements of blank sky in On-Off mode and detected no signal in either of these observations. Such a test is not definitive if the galaxies have substantial continuum fluxes because the total power level would be different in the On and Off scans but only one of our galaxies has $F_{20\text{ cm}} > 150$ mJy (Condon & Broderick 1988). The baselines for all but two of our galaxies are well fitted by first-order polynomials. There are small nonlinearities in the blue side of the spectrum of NGC 765, although a first-order polynomial fits the red side of the spectrum well. A third-order polynomial was required to fit the baseline in NGC 4254, the galaxy which has strong continuum emission ($F_{20\text{ cm}} = 450$ mJy). In both cases the baseline fluctuations are of order 1 mJy in amplitude, smaller than that expected for HVC wings. If the high-velocity wings are a baseline effect, then we would expect to observe wings with negative flux density one-half the time, but we find no such "negative" wings. We find that the rms noise level decreases in inverse proportion to the square root of the observing time, as expected for a well-behaved system.

We also confirmed the Arecibo H I profile and high-velocity wings of one of our galaxies by making observations with a synthesis telescope. We observed NGC 5668 with the VLA in D configuration for 24 hours in 1991 April (Schulman et al. 1991). These observations have an rms noise level of 0.34 mJy beam^{-1} channel^{-1} (FWHM = 1', channel width = 10.4 km s^{-1}) and reproduce the H I profile detected at Arecibo. The VLA observations also detect a large amount of high-velocity material which is not discernible in a single-dish spectrum because most of the high-velocity material has the same line-of-sight velocity as quiescent disk H I. We conclude that the wings we have observed at Arecibo are not due to baseline or other instrumental effects.

The preliminary data reduction was performed at Arecibo Observatory using GALPAC routines in the Arecibo spectrum reduction package ANALYZ (Haynes & Giovanelli 1984). The On-Off pairs were combined to produce preliminary spectra; all such spectra for a single galaxy were added together, and a baseline was removed to produce a single spectrum for each galaxy. These spectra provide the starting point for our analysis to determine the presence or absence of high-velocity gas in these galaxies. The H I properties of our sample galaxies shown in Table 2 were determined at the University of Michigan using the program DRAWSPEC.[4] The integrated H I flux density listed in column (3) is a lower limit to the total integrated H I flux density unless the galaxy is significantly smaller than the Arecibo beam.

4. MODELS

We construct simple disk galaxy models in order to better understand how high-velocity gas from HVCs or a warp affects the H I profiles. We model the galaxies as rotating disks of H I and produce model spectra to compare to our observations. We can warp the outer disk of H I and also introduce extra-planar gas as a component with a larger velocity dispersion than that of the quiescent disk H I.

For these models we assume a rotation curve typical of spiral galaxies, with solid body rotation at small radii and approaching a constant value, v_{max}, at large radii:

$$v_{rot} = v_{max}\left(\frac{r/r_s}{1 + r/r_s}\right) , \quad (2)$$

[4] DRAWSPEC is a spectral analysis program developed by H. Liszt at the National Radio Astronomy Observatory.

TABLE 2

PROPERTIES OF SAMPLE GALAXIES

Galaxy (1)	F_{max} (mJy) (2)	$S_{\mathrm{H\,I}_{A0}}$ (Jy km s^{-1}) (3)	rms (mJy) (4)	ΔV_{ch} (km s^{-1}) (5)	$\frac{M_{HVC}}{M_{\mathrm{H\,I}}}$ (6)	M_{HVC} $10^8 M_\odot$ (7)	F_{FIR} (10^{-11} ergs cm^{-2} s^{-1}) (8)
NGC 99	79	9.9	1.00	2.134	0.12	33.3	4.5
NGC 765	113	11.1	1.01	2.132	0.13	37.8	2.6
UGC 1546	82	6.3	1.39	2.094	<0.03	<1.2	0.8
NGC 1517	82	11.0	0.85	2.109	0.14	17.8	19.6
UGC 5288	115	9.3	1.31	1.035	<0.04	<0.1	1.5
NGC 3344	252	29.6	0.99	2.068	0.08	0.6	46.3
NGC 3423	178	24.2	0.79	2.075	0.12	2.0	...
NGC 3507	111	12.3	1.81	2.075	<0.03	<0.3	...
NGC 4136	284	19.0	1.05	1.035	0.13	0.8	10.0
NGC 4254	205	36.6	1.38	2.094	0.07	13.3	178.0
NGC 5668	246	22.2	0.57	2.083	0.04	1.9	15.4
NGC 5921	134	16.2	0.89	4.166	0.04	1.5	22.3
NGC 7292	193	14.2	0.78	2.075	0.07	1.5	7.2
UGC 12732	216	21.3	0.76	2.072	<0.03	<0.5	1.1

NOTES.—Col. (2) peak H I flux density; col. (3) integrated H I flux density in the Arecibo beam; col. (4) rms noise per 2 km s^{-1} H I channel; col. (5) H I channel width; col. (6) mass ratio of H I in high-velocity clouds to total H I from the model fits; col. (7) mass of H I in high-velocity clouds in the Arecibo beam; col. (8) far-infrared flux (NGC 3423 and NGC 3507 were not observed by *IRAS*).

where r_s is taken to be 250 pc. This value is consistent with many of the rotation curves of Sbc to Scd galaxies given in Bosma (1978). The disk of the galaxy is inclined by an angle i,

$$i = i_0 + \Delta i[1 - e^{-(r/h_w)^w}] , \quad (3)$$

where i_0 is the inclination of the main body of the galaxy and Δi is the tip angle of the warped disk. The warp scale factor, h_w, is the radius at which the warp begins and is taken to be 14 kpc, a typical size for the optical disk of a late-type galaxy. We estimate that in NGC 4565, the warp sharpness parameter, w, has a value between 4 and 8 (data from Sparke & Casertano 1988). Our specification of the warp is a simple one in order to limit the number of free parameters in our models. We assume that the warp is exactly along the major axis to maximize its effect in the production of high-velocity wings. If the warp is not along the major axis, then the width of the H I profile is smaller, but the shape of the profile at low flux densities is not significantly different. A more complex model would include the effects of changing the line of nodes with radius. Such a changing line of nodes does not affect the shape of the H I profile in such a way that it could mimic the wings produced by high-velocity clouds.

The gas density distribution is

$$n(r) = n_0 e^{-r/h_2}[1 - Ae^{-(r/h_1)^2}] , \quad (4)$$

where the density scale length, h_2, is taken to be 4 kpc, a value consistent with many of the density distributions for Sbc to Scd galaxies given in Bosma (1978). The scale length can increase with radius (Hoffman et al. 1993) in the outer disks of galaxies, but the H I density beyond 15 kpc is small, and so keeping h_2 constant should not significantly affect the H I profile. We determine n_0 by measuring the integrated H I flux density in the Arecibo beam, $S_{\mathrm{H\,I}_{A0}}$. The second term in equation (4) creates an H I hole in the center of the galaxy with maximum fractional depth equal to A. Such holes are found in disk galaxies (Giovanelli & Haynes 1988), but models with and without the H I holes have nearly identical H I profiles in the wings so we have taken A to be 0.

The H I is assumed to exist in two velocity components, distributed such that the emission line shape is

$$P(v) = \frac{1}{\sqrt{2\pi}(\sigma_1 + c_2\sigma_2)} (e^{-v^2/2\sigma_1^2} + c_2 e^{-v^2/2\sigma_2^2}) . \quad (5)$$

The velocity dispersion of the quiescent disk H I component, σ_1, is approximately 10 km s^{-1}, while the velocity dispersion of the HVC component, σ_2, is taken to be either 30 or 50 km s^{-1}. The HVC mass parameter, c_2, is determined by fits to the data and falls in the range 0.0 to 0.06. The HVCs are thus represented as a corotating population with a Gaussian velocity dispersion such that the mass ratio of the quiescent H I to the HVC component is $(\sigma_1/c_2\sigma_2)$. Our specification of the HVC component is simple in order to limit the number of free parameters in our models because a more realistic model would include a mass and velocity distribution with a variety of parameters.

The 21 cm line profile is calculated by integrating the column density averaged over the radio telescope beam as a function of velocity and convolving it with the line shape:

$$S_v(v) \propto \int_{-\infty}^{+\infty} \left\{ \int_0^{r_{max}} \frac{rn(r)dr}{\sqrt{[v_{rot}(r) \sin i]^2 - v'^2}} \right\} P(v - v')dv' , \quad (6)$$

where v_{rot} is related to v_{max} by equation (2). The integrand is evaluated only where $v' > v_{rot}(r) \sin i$. This method assumes that the optical depth is low, which is a satisfactory assumption since the galaxies are nearly face-on. We have taken r_{max} to be 20 kpc (Hoffman et al. 1993) or the length corresponding to 1'.7 at the distance of the galaxy, whichever is smaller. For nearby galaxies, the value of r_{max} chosen has a measurable effect on the derived inclination but no effect on the determined amount of HVC material. We do not take into account that the galaxies are only approximately centered in the beam, which can lead to asymmetric horns and slightly different geometric and kinematic parameters from those we determine. Such pointing errors do not affect our primary goal, the study of the high-velocity wings.

The results are relatively insensitive to most of the parameters in our disk galaxy models (r_s, h_w, h_1, h_2, A, and r_{max}). A first approximation to the inclination is obtained from Huchtmeier & Richter (1989), and a first approximation to v_{max} is obtained from the Tully-Fisher relation for spiral galaxies (Rubin et al. 1985), using the Sc relation for galaxies later than Sc. We took v_{max} for NGC 4254 from recent VLA observations (Phookun, Vogel, & Mundy 1993, hereafter PVM). Since we are primarily interested in the wings and most galaxies do not have perfectly symmetric profiles, we do not attempt to model the H I profile within about 20 km s^{-1} of the systemic velocity. Fine adjustments are made to v_{max} sin i until the model spectrum reproduces the velocity separation between the horns in the observed spectrum; the observations are not sensitive to v_{max} or i individually, only to the product v_{max} sin i. We adjust σ_1 upward or downward from 10 km s^{-1} until the width of the model spectrum is the same as the width of the observed spectrum. Galaxies with high-velocity wings require HVCs to fit the H I profile. We chose σ_2 to be either 30 or 50 km s^{-1}, depending on the shape of the wings, and we adjust c_2 upward until the observed wings are reproduced. We then adjust the integrated flux density slightly, so that the model has the same peak flux density as the observations.

The signature of high-velocity clouds is quite different from the signature of a warp, as illustrated by Figure 1. The parameters of the 30 km s^{-1} HVC model (*dashed line*) are listed in Table 3, the model without high-velocity material (*solid line*) is identical except that $c_2 = 0$, the 50 km s^{-1} HVC model (*dash-dot line*) has $\sigma_2 = 50$ km s^{-1} and $c_2 = 0.03$, and the warp model (*dotted line*) has $\Delta i = 8°$, $w = 4.0$, $i = 14°$, and $\sigma_1 = 7$ km s^{-1}. The signature of HVCs is quite distinctive, although it is difficult to distinguish between a galaxy with a warp and a galaxy with a smaller σ_1 and inclination.

We have considered the effects of warped H I disks on the observed profiles of our sample and have concluded that any effects are small. Most, if not all, late-type galaxies have warps (Bosma 1991), and both NGC 3344 (Briggs 1990) and NGC 5668 (Schulman et al. 1991) have reported warps. H I disks become warped near or beyond the optical radius of the galaxy and nine of our 14 galaxies have optical diameters comparable to or larger than the Arecibo beam. Of the remaining five galaxies, one-half would be expected to have warps into the plane of the sky, producing velocities closer to the systemic velocity rather than farther from the systemic velocity. About one-half of the galaxies will have weak or very weak warps

TABLE 3

MODEL PARAMETERS

Galaxy (1)	v_{max} (km s^{-1}) (2)	S_{HI} (3)	i (4)	σ_1 (km s^{-1}) (5)	σ_2 (km s^{-1}) (6)	c_2 (7)
NGC 99	170	10.1	21°	15	50	0.04
NGC 765	230	12.1	15	10	30	0.05
UGC 1546	110	6.2	21	9	30	<0.01
NGC 1517	140	11.9	37	12	50	0.04
UGC 5288	70	8.4	40	7	30	<0.01
NGC 3344	200	29.8	22	10	30	0.03
NGC 3423	130	23.2	33	13	30	0.06
NGC 3507	160	12.5	26	10	30	<0.01
NGC 4136	100	23.4	23	10	30	0.05
NGC 4254	150	33.1	43	13	50	0.02
NGC 5668	140	22.6	18	13	50	0.01
NGC 5921	200	17.5	24	11	50	0.01
NGC 7292	100	14.6	17	13	50	0.02
UGC 12732	100	20.9	27	13	30	<0.01

NOTES.—Col. (2) rotational velocity of disk; col. (3) integrated H I flux density in the Arecibo beam; col. (4) inclination of galactic disk; col. (5) velocity dispersion of quiescent disk H I; col. (6) velocity dispersion of high-velocity component; col. (7) amount of H I in high-velocity component.

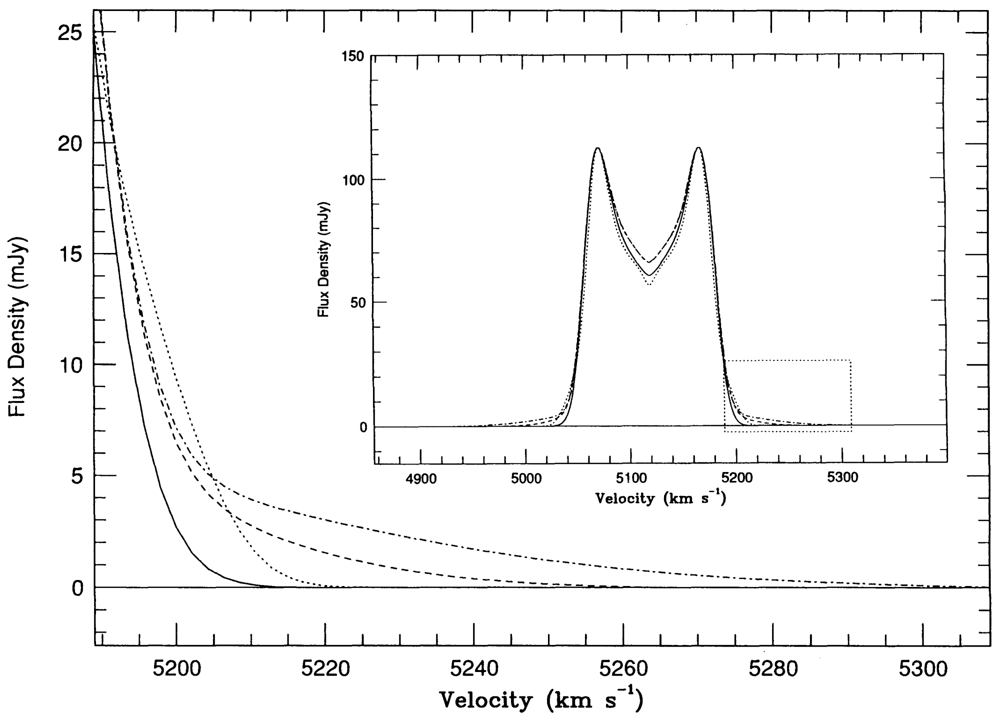

FIG. 1.—Wings of four H I profiles produced by different disk galaxy models of NGC 765: a model with no high-velocity material (*solid line*); a model with a warp along the major axis (*dotted line*); a model with high-velocity clouds having a velocity dispersion of 50 km s^{-1} (*dashed line*); and a model with high-velocity clouds having a velocity dispersion of 30 km s^{-1} (*dash-dot line*). The inset shows the entire H I profiles, and the dotted box indicates the magnified region.

(Bosma 1991), and perhaps one-half will have warps aligned too close to the minor axis to produce large shifts in velocity. We estimate that there may be one galaxy in our sample with an H I profile that is significantly affected by a warped disk, but such a warped disk will not produce wings similar to those produced by HVCs (Fig. 1). There are no galaxies in our sample which require warped disks to fit the H I spectra, and so we have fitted the observed spectra with models that do not have warped disks.

5. RESULTS AND DISCUSSION

Our best-fit model parameters for the 14 galaxies (Table 3) show that four galaxies are well fitted by models without HVCs, and the remaining 10 galaxies are well fitted by models with an HVC component having a velocity dispersion of either 30 or 50 km s^{-1}. The difference between models with and without HVCs is illustrated in the H I spectrum of NGC 99 (Fig. 2), where one model spectrum was produced with an HVC component with a velocity dispersion of 50 km s^{-1} while the other was produced by a model with no high-velocity gas. Note the high-velocity wings from 5180 to 5230 km s^{-1} and 5400 to 5450 km s^{-1}. Another example of the presence of HVC material is the H I spectrum of NGC 765 (Fig. 3), where one model spectrum was produced with an HVC component with a velocity dispersion of 30 km s^{-1} while the other was produced by a model with no high-velocity gas; high-velocity wings extend from 5010 to 5040 km s^{-1} and 5200 to 5230 km s^{-1}. One of the galaxies without HVC material is UGC 1546 (Fig. 4), which shows no high-velocity wings and is well fitted with a model spectrum without high-velocity material.

NGC 4254 was recently observed with the C and D arrays of the VLA by PVM, who find H I clouds superposed on and beyond the H I disk, at velocities up to 150 km s^{-1} from the systemic velocity of the disk. The mass in these clouds is about $2 \times 10^8\ M_\odot$, and PVM suggest that the clouds may be the remnants of an entity that was tidally disrupted by NGC 4254 (Fig. 5), which is shown with a model spectrum produced with an HVC component with a velocity dispersion of 50 km s^{-1}. In addition to the emission from our HVC model, there is excess H I emission on the red side of the spectrum, at velocities similar to the infalling gas detected by PVM.

The fraction of H I in the HVC component (col. [4] in Table 2) is given by the model fits:

$$\frac{M_{\rm HVC}}{M_{\rm H\,I}} = \frac{c_2 \sigma_2}{\sigma_1 + c_2 \sigma_2} . \qquad (7)$$

The mass of high-velocity material that we detect in distinct wings is a factor of 4 to 13 less than the total HVC mass determined from our models, because most of this high-velocity material has the same line-of-sight velocity as quiescent disk H I. The mass determined in our models is a lower limit to the actual HVC mass since some of the galaxies (such as NGC 4254) have excess emission in one of the wings of the H I profile. In addition, if some of our sample galaxies do have warps which affect the H I profile, then the σ_1 we determine is too high, and thus the fraction of H I in the HVC component that we determine is too low.

We detect high-velocity gas in 10 of 14 galaxies and estimate that 4% to 14% of the integrated H I flux density from these

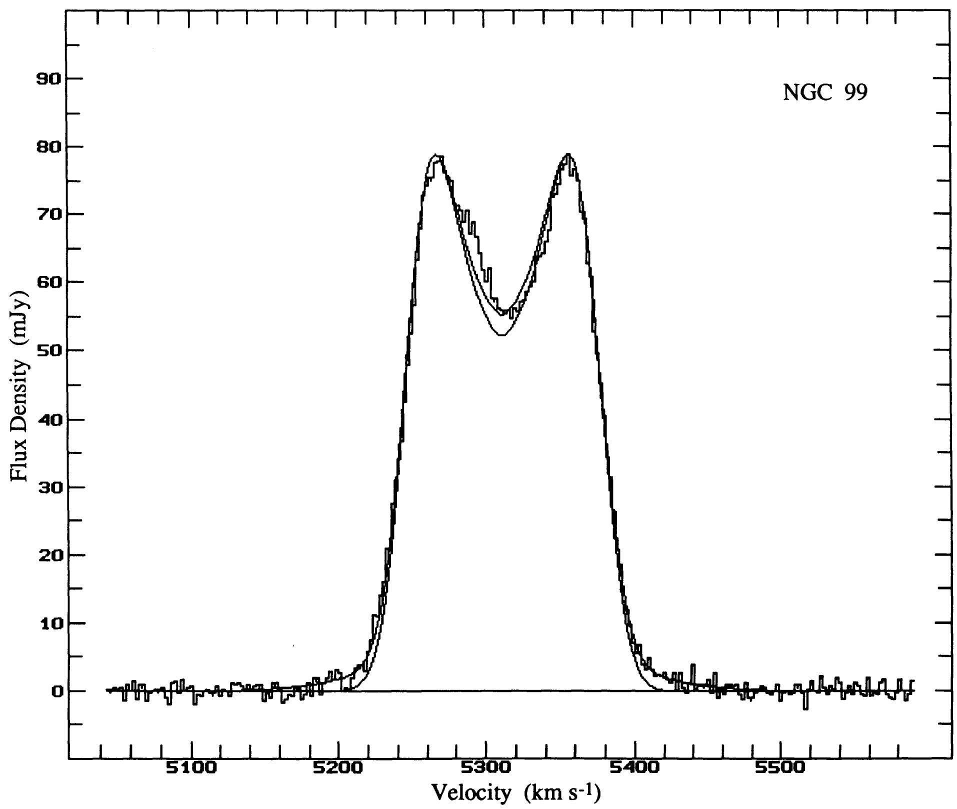

FIG. 2.—Observed and model H I profiles for NGC 99. One model spectrum was produced by a disk galaxy model with a high-velocity cloud component having a velocity dispersion of 50 km s^{-1}, and the other model spectrum was produced by a model without any high-velocity clouds. A linear baseline has been subtracted from the observed spectrum.

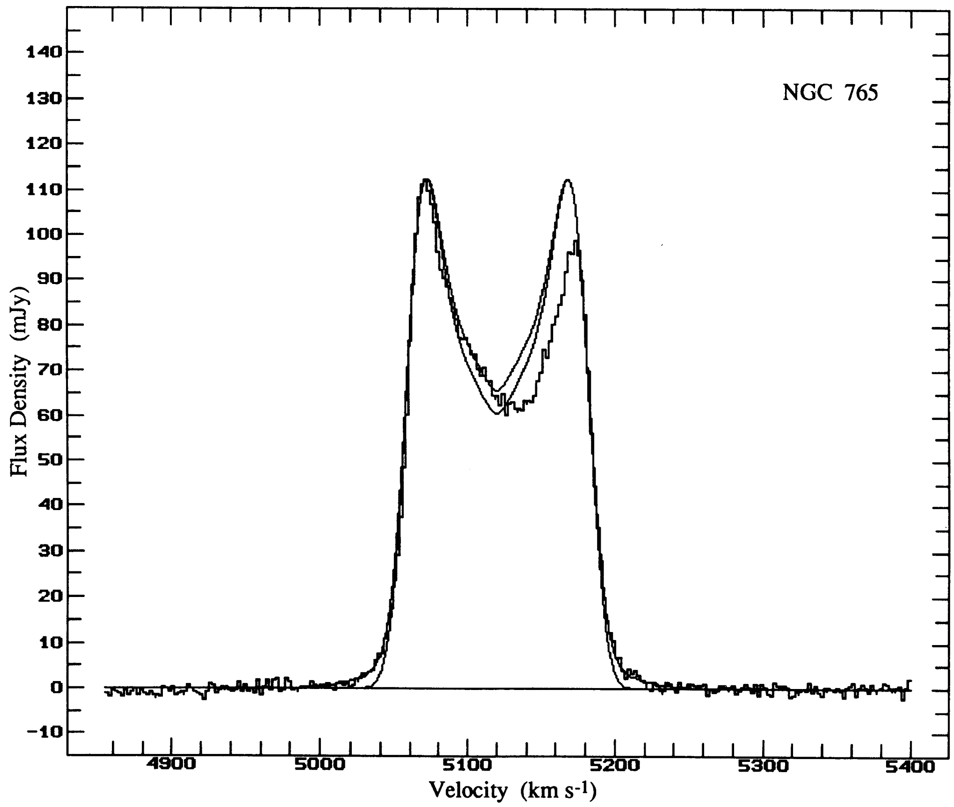

FIG. 3.—Observed and model H I profiles for NGC 765. One model spectrum was produced by a disk galaxy model with a high-velocity cloud component having a velocity dispersion of 30 km s^{-1}, and the other model spectrum was produced by a model without any high-velocity clouds. A linear baseline has been subtracted from the observed spectrum.

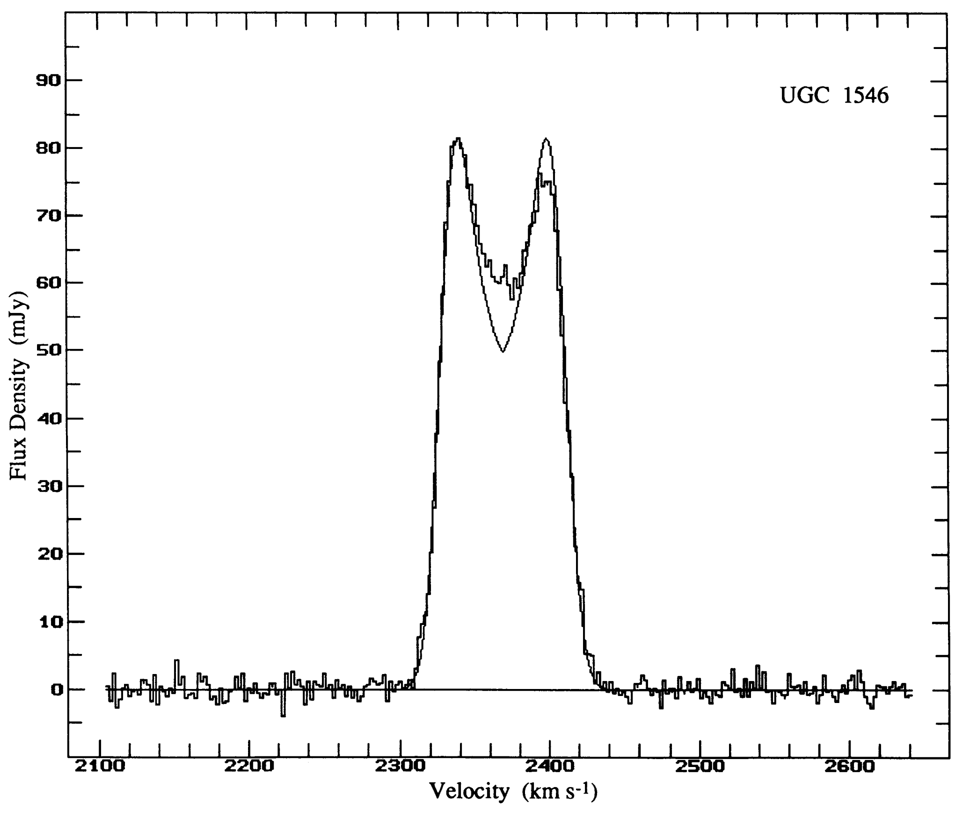

FIG. 4.—Observed and model H I profiles for UGC 1546. The model spectrum was produced from a disk model without either high-velocity clouds or a warped H I disk. A linear baseline has been subtracted from the observed spectrum.

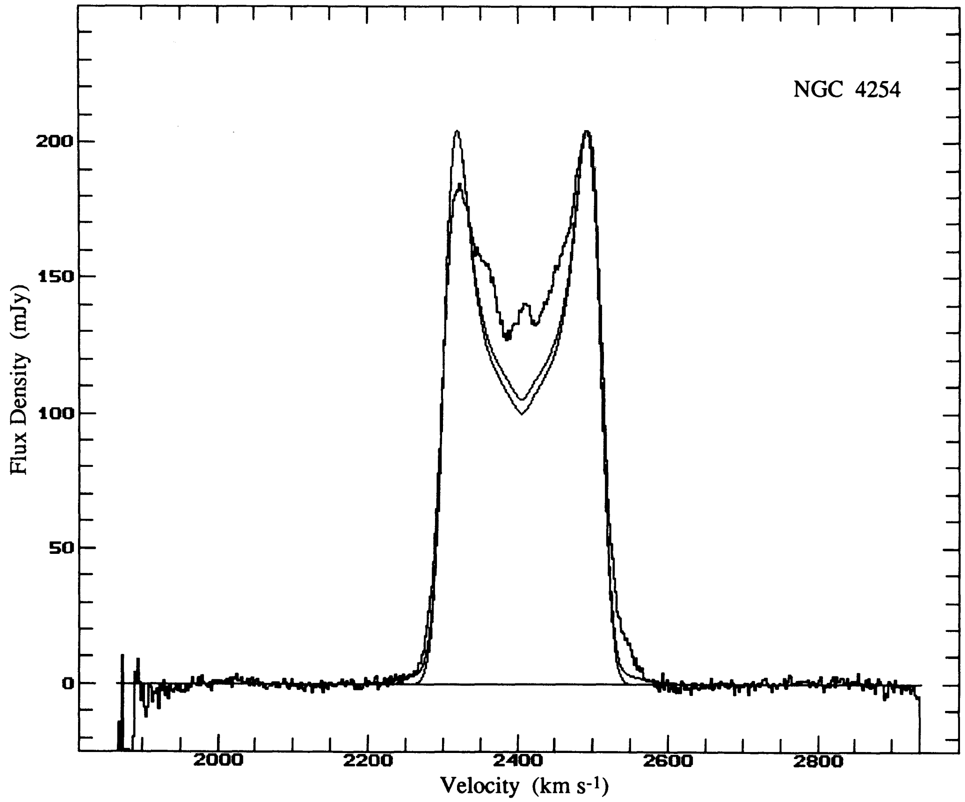

FIG. 5.—Observed and model H I profiles for NGC 4254. The model spectrum was produced from a disk model with a high-velocity cloud component having a velocity dispersion of 50 km s^{-1}. A third-order polynomial baseline has been subtracted from the observed spectrum. Note the exces H I emission near 2550 kn s^{-1}.

galaxies is from HVCs with a corresponding total mass between 6×10^7 $M_\odot$ and 4×10^9 $M_\odot$. The HVC component may be the extraplanar gas that has been observed in our galaxy (Wakker 1990), in NGC 891 (Rupen 1991), and in NGC 6946 (Kamphuis & Sancisi 1993). Wakker (1990) constructed a galactic fountain model to reproduce the observed distribution of Galactic HVCs, and he estimates that there is 5×10^8 $M_\odot$ of extraplanar H I in our Galaxy, which is about 10% of the total H I in the Galaxy and close to the mean HVC mass we find for the galaxies in our sample that have high-velocity wings. The typical distance to galactic HVCs in Wakker's models is 10–20 kpc, and since our observations are consistent with his findings, we conclude that it is likely that the HVCs are a galaxy-wide phenomenon commonly found in late-type galaxies. Wakker's models also require the Magellanic Stream to fit the observed distribution of galactic high-velocity clouds. While we do not attempt to model infalling material in our sample galaxies, we can detect such material as excess H I in one of the wings of the profile (as in NGC 4254).

The random kinetic energy in quiescent disk H I and HVCs for the sample galaxies, listed in Table 4, is calculated by

$$E_j = \frac{M_{\rm H\,I}\sigma_{j^2}}{2} \frac{c_j \sigma_j}{\sigma_1 + c_2 \sigma_2}, \qquad (8)$$

where $j = 1$ represents the quiescent H I component (c_1 is defined to be unity) and $j = 2$ represents the HVC component. The kinetic energy in HVCs exceeds the energy in quiescent disk H I in most cases, indicating that a significant energy transfer into the interstellar medium is required to generate these high-velocity clouds. The free-fall time from 1 kpc above the disk is about 25×10^6 yr, and we take this to be a characteristic timescale for the HVC component. The energy released by Type II supernovae during this period of time was estimated using supernova rates from van den Bergh & Tammann (1991) and is listed in Table 4. The kinetic energy in HVCs can be produced by supernovae alone if only a few percent of the released energy is transferred to the interstellar medium as kinetic energy.

Far-infrared (FIR) emission is a good tracer of star formation (Thronson & Telesco 1986) and since the galactic fountain model predicts a relationship between the mass of HVCs and the amount of star formation (supernovae) in a galaxy, we would expect a relationship to exist between the integrated HI flux density from HVCs and the FIR flux. The IRAS satellite obtained flux densities in four broad bands centered at 12 μm, 25 μm, 60 μm, and 100 μm (Neugebauer et al. 1984), and we can estimate the FIR flux in a band of width 80 μm and centered at 82.5 μm:

$$F_{\rm FIR} = (3.25 \times F_{60\,\mu\rm m} + 1.26 \times F_{100\,\mu\rm m}) \times 10^{-11} \text{ ergs cm}^{-2}\text{ s}^{-1} \qquad (9)$$

(Rice et al. 1988), where $F_{60\,\mu\rm m}$ and $F_{100\,\mu\rm m}$ are expressed in janskys. We use nonparametrical statistical tests that include upper limits to determine whether a correlation exists between the FIR flux and the amount of HVC material in our sample galaxies. The particular methods employed are from ASURV Rev 1.2 (Isobe & Feigelson 1990), which implements the methods presented in Isobe, Feigelson, & Nelson (1986). The FIR fluxes for the nine brightest galaxies are obtained from the *IRAS* Point Source Catalog (as described in Beichman et al. 1988). The FIR fluxes for UGC 1546, UGC 5288, and UGC

TABLE 4
ENERGY IN GALACTIC COMPONENTS

Galaxy (1)	$E_{q\text{H I}}$ (10^{53} ergs) (2)	E_{SN} (10^{53} ergs) (3)	E_{HVC} (10^{53} ergs) (4)	$E_{\text{HVC}}/E_{q\text{H I}}$ (5)	$E_{\text{HVC}}/E_{\text{SN}}$ (6)
NGC 99	560	17000	830	1.5	4.9%
NGC 765	250	17000	310	1.2	1.8%
UGC 1546	$\gtrsim$29	1900	<11	<0.4	<0.6%
NGC 1517	150	4700	520	3.5	11.1%
UGC 5288	$\gtrsim$0.6	62	<0.5	<0.8	<0.8%
NGC 3344	6.8	2200	5.5	0.8	0.3%
NGC 3423	24	3100	18	0.8	0.6%
NGC 3507	$\gtrsim$8.8	650	<2.4	<0.3	<0.4%
NGC 4136	5.3	1200	8.5	1.6	0.7%
NGC 4254	290	78000	330	1.1	0.4%
NGC 5668	83	6700	47	0.6	0.7%
NGC 5921	40	8300	38	1.0	0.5%
NGC 7292	33	1900	38	1.2	2.0%
UGC 12732	$\gtrsim$32	520	<4.0	<0.1	<0.8%

NOTES.—Col. (2) kinetic energy in quiescent disk H I; col. (3) energy produced by Type II supernovae in 25×10^6 yr; col. (4) kinetic energy in high-velocity clouds; col. (5) ratio of high-velocity cloud to quiescent H I kinetic energy; col. (6) ratio of kinetic energy in high-velocity clouds to energy produced by Type II supernovae in 25×10^6 yr.

12732 are measured from IPAC[5] Full Resolution Coadded (FRESCO) images because these galaxies are too faint to be in the Point Source Catalog. Two of our galaxies, NGC 3423 and NGC 3507, are in the area of the sky not observed during the *IRAS* all-sky survey; see Fullmer et al. (1989) for more details. The generalized Kendall's τ correlation test reveals a correlation at the 96% confidence level between F_{FIR} and S_{HVC}. Since this could be due to larger galaxies having more infrared emission and more H I, we normalized both fluxes by the "size" of the galaxy. We divide F_{FIR} by the optical surface area of the galaxy ($\pi ab/4$) and S_{HVC} by the surface area of the galaxy or the area of the Arecibo beam, whichever is smaller, because the FIR flux is measured over the entire galaxy, but the H I flux density of HVCs has only been determined within the Arecibo beam. We find a correlation at the 96% confidence level between F_{FIR}/(area) and S_{HVC}/(area), suggesting that there may be a relationship between the degree of star formation and the amount of HVC material. Of the four galaxies that do not have observed high-velocity wings, one was not observed by *IRAS* and the other three have the lowest FIR fluxes in our sample.

Synthesis telescope observations will allow us to better determine the amount of high-velocity material, and optical observations will allow us to better determine the amount of star formation. Dettmar (1993) finds that the presence of extraplanar Hα filaments and diffuse ionized gas in spiral galaxies is related to the FIR luminosity, supporting the conclusion that at least some of the HVCs we detect are due to a galactic fountain. There is also a correlation between FIR emission and the presence of disturbing companions since infalling material triggers star formation, but this star formation is likely to produce supernovae that produce superbubbles which break out of the disk, producing more HVCs. In our own Galaxy a combination of a warp, infalling material tidally torn from the Magellanic clouds, and a galactic fountain are required to explain all of the HVCs and it seems likely that a combination of phenomena is also required to explain the HVCs in other galaxies.

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6. SUMMARY

We obtained very sensitive observations of 14 nearly face-on disk galaxies with the Arecibo 305 m telescope and found high-velocity wings in the H I spectra of 10 of these galaxies. To analyze the H I profiles, we constructed disk galaxy models which include both warped H I disks and HVCs. Four galaxies have no detected high-velocity material and the other 10 galaxies have spectra which are well fitted by models that have HVCs but not warped H I disks. The mass of hydrogen in HVCs for the 10 galaxies ranges from $6 \times 10^7\ M_\odot$ to $4 \times 10^9\ M_\odot$, which corresponds to 4% to 14% of the total H I in the galaxies. The integrated H I flux density from HVCs is correlated with the *IRAS* FIR flux at the 96% confidence level. Our findings are consistent with the predictions of the galactic fountain model in that HVCs are common in disk galaxies, and the mass of H I in HVCs is related to the amount of star formation. In principle, it is very difficult to determine with a single-dish telescope whether the HVCs are due to galactic fountain gas, infalling material from an interaction (unless the gas is quite asymmetric in velocity, as appears to be the case for NGC 4254), some other phenomenon, or a combination of phenomena. If our Galaxy is typical of our sample galaxies, then the HVCs in our own Galaxy are a disk-wide phenomenon with a characteristic distance of between 10 and 20 kpc.

Further observations can improve our understanding of the HVC phenomena in other galaxies. H I synthesis imaging with the VLA and WSRT will permit a measurement of the total mass in HVCs which will be independent of the models that we adopted to fit the Arecibo spectra and will allow us to determine whether the distribution of clouds is consistent with the galactic fountain or infall models. Our initial synthesis observations support the results from the filled-aperture data (Schulman et al. 1991). Hα imaging will provide a better tracer of star formation than the *IRAS* total FIR flux densities and will allow us to better determine the supernova rate. Such observations can better determine whether there is a strong correlation between HVC integrated flux density and Hα flux and whether there is a correlation between the location of HVCs in the H I maps and the location of Hα sources.

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