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Neutral Hydrogen in Elliptical Galaxies with Nuclear Radio Sources and Optical Emission Lines

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NEUTRAL HYDROGEN IN ELLIPTICAL GALAXIES
WITH NUCLEAR RADIO SOURCES AND OPTICAL EMISSION LINES

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ABSTRACT

We have made an HI detection survey of eleven elliptical galaxies with powerful nuclear radio sources, using the 305m antenna of Arecibo Observatory, to test the hypothesis that large HI mass is conducive to the formation of nuclear radio sources in elliptical galaxies. HI was detected in emission in UGC 09114 and was possibly detected in absorption in UGC 06671. Observations of the remaining galaxies were not sensitive enough to support or refute the hypothesis. We have combined our data with data from other HI surveys and spectroscopic surveys to search for correlations of HI mass with other galactic properties and environmental conditions. We find strong correlations of [OII] λ3727 emission with HI content and with nuclear radio power. The latter two properties may simply indicate, respectively, whether a significant amount of gas is available to be ionized and whether energy is provided by nuclear activity for ionization. We find no dependence of HI content on optical luminosity or on degree of isolation from other galaxies.

Subject headings: galaxies: general - interstellar: matter - radio sources: 21 cm radiation

I. INTRODUCTION

Over the past several years, increasingly sensitive searches have been made for 21 cm emission from neutral hydrogen in elliptical galaxies. Emission has been detected in several galaxies, which have 5×10^8 to 5×10^9 $M_\odot$ of HI. Upper limits between 10^7 $M_\odot$ and 2×10^9 $M_\odot$ have been set for the HI mass in about 35 other galaxies. (A Hubble constant of 55 km s^{-1} Mpc^{-1} is assumed here and throughout the paper.) Since mass loss from stars should provide about 10^8 $M_\odot$ of hydrogen in a galaxy of luminosity 10^{10} $L_\odot$ in only 10^9 years (Faber and Gallagher 1976), either an efficient gas removal mechanism must operate in most E galaxies, or the gas must exist in some unobservable form. Gas could be removed from cluster galaxies by ram pressure as the galaxies move through an intracluster medium (Gisler 1976; Lea and DeYoung 1976). Where such external sweeping does not occur, gas could be removed from the system by the formation of low mass stars (Jura 1977) or by expulsion via supernova-driven winds (Mathews and Baker 1971; Gisler 1976; Sanders 1981). When winds are not active, the gas could remain in the galaxy in the form of a hot plasma (Sanders 1981).

Among the few elliptical galaxies with detected 21 cm emission are two galaxies with fairly powerful nuclear radio sources. NGC 1052 and NGC 4278 emit 6×10^{22} WHz^{-1} and 1×10^{22} WHz^{-1} at 2380 MHz (Condon and Dressel 1978) and contain 2×10^9 $M_\odot$ (Fosbury et al. 1978) and 5×10^8 $M_\odot$ (Knapp et al. 1978) of HI, respectively. No other elliptical galaxies with radio sources this powerful have been observed with enough sensitivity to detect an HI mass comparable to that in NGC 4278. Since powerful radio continuum emission and detectable 21 cm line emission are both uncommon among elliptical galaxies, their unlikely coincidence in these galaxies suggests that nuclear activity and HI content may be related in E galaxies.

To test whether large HI mass is a necessary or frequently occurring auxillary to powerful nuclear radio emission in E galaxies, we have searched for HI in eleven E galaxies with nuclear radio power $P_{2380} > 10^{22}$ WHz^{-1}. Since powerful radio sources are generally found in very luminous E galaxies (Dressel 1981), our survey also makes a substantial contribution to the number of luminous E galaxies that have been searched for HI. We have also made spectrophotometric observations of several of the galaxies in our survey, and can discuss the relationship of ionized gas content (evidenced by [OII] λ3727 emission) to neutral gas content in E galaxies.

Our 21 cm line observations are described in the following section; the observational results and other characteristics of the galaxies are presented in Section III. In Section IV, we describe a sample of elliptical galaxies compiled from our own and other observing programs, which can be used to test possible correlations of HI mass with other parameters. We consider, in turn, the relationship of HI mass to nuclear radio emission, to optical luminosity, to the environment of the galaxy, and to ionized gas content. We briefly summarize our observational results and present the conclusions of our correlation studies in Section V.

II. OBSERVATIONS

Elliptical galaxies with powerful nuclear radio sources are fairly rare and tend to be relatively distant. For this reason, they have generally not been included in HI surveys of E galaxies, which have concentrated on very nearby galaxies. Since detections or low upper limits to HI masses in distant galaxies require good sensitivity, and since an extensive list of radio-emitting elliptical galaxies (Dressel and Condon 1978) already exists for the declination range observable at Arecibo Observatory, we chose to conduct our search for HI in radio-emitting elliptical galaxies at Arecibo.[1]

A galaxy was selected for observation from the Dressel and Condon (1978) radio continuum survey if: 1) it has been classified as an E galaxy by Nilson (1973); 2) it is stronger than 20 mJy at 2380 MHz; and 3) it has a compact component more powerful than 10^{22} WHz^{-1} which accounts for a substantial fraction (generally all) of the flux density. The latter information was obtained from NRAO interferometer observations and VLA observations (Condon and Dressel 1978 and unpublished) of the galaxies. Nearly all of the galaxies meeting these criteria were actually observed.

The observations were made during the period of June 4 to June 11, 1981. We used the frequency-tunable dual circular polarization line feed, which gave a response of 8.3 KJy^{-1} at small zenith angles and at frequencies near the chosen optimum value of 1388 MHz. The half-power beamwidth was 3.2', which is greater than the Nilson (1973) blue diameters of the galaxies we observed. Galaxy positions were known to 4 arcsec r.m.s. error in each coordinate (Dressel and Condon 1976). The r.m.s. pointing error was 17 arcsec below zenith angles of 15^o, where most of the observations were made. The GaAsFET receiver, a recent addition to the observatory, had a system temperature of 38K at small zenith angles. For each polarization, two spectra were independently amplified and detected. The channel spacing was 39 kHz, and the total bandwidth was 10 MHz ($\sim$ 2000 km s^{-1}).

The observations consisted of five-minute total power scans of the galaxies, paired with five minute scans of blank sky at the same telescope coordinates to determine the instrumental profile. Noise diode measurements and continuum source observations were used to calibrate the spectra;

[1]Arecibo Observatory is part of the National Astronomy and Iononosphere Center, which is operated by Cornell University under contract with the National Science Foundation

corrections were then made for the dependence of gain on zenith angle. Acceptable scans of each galaxy were averaged together and corrected for the instrumental profile. A polynomial baseline was removed from each spectrum, and the data were smoothed over 8 channels (64 km s^{-1}). The r.m.s. fluctuations in flux density across each spectrum were then measured, excluding the central part of the spectrum if a line possibly existed there.

III. RESULTS

a) The Total Sample

For an optically thin gas, HI mass is related to observable parameters by

$$M_{HI} = 236\ D^2 \int S_\nu\ dv\ M_\odot$$

where D is the distance to the galaxy in Mpc, S_ν is the flux density in the emission line in mJy, and v is velocity in km s^{-1}. For galaxies with no obvious HI emission or absorption, we chose to compute an upper limit to the HI mass by assuming a flux density limit of three times the r.m.s. fluctuations in the spectrum and a line width of 450 km s^{-1}. The computed mass or mass limit will be too small if the HI emission is resolved or if significant absorption of the nuclear continuum source is occurring. Of course, it is unlikely that emission line fluxes, which depend only on HI mass for an optically thin gas, are fortuitously being just cancelled in many cases by absorption, which depends on HI mass and distribution and on continuum flux.

Optical and radio data are presented for the galaxies in our observing program in Table 1. The UGC and NGC or IC numbers are given in columns 1 and 2. The Nilson (1973) blue major diameter is given in column 3, for comparison with the half-power beamwidth of 3.2'. In column 4 is the optically measured heliocentric radial velocity, kindly provided by J. Huchra for most of the galaxies. For column 5, the distance to the galaxy has been computed from the radial velocity corrected for motion with respect to the Local Group (Δv = 300 sin ℓ cos b km s^{-1}) assuming H_0 = 55 km s^{-1} Mpc^{-1}. The 2380 MHz flux density of the galaxy (Dressel and Condon 1978) is given in column 6. The 2380 or 5000 MHz flux density originating in a nuclear component less than a few arcseconds in diameter (Condon and Dressel 1978 and unpublished) and the log of the power of the nuclear component are listed in columns 7 and 8. (For $-0.7 <$ spectral index $< +0.7$, log P_{5000} differs from log P_{2380} by $\lesssim 0.2$). In column 9 is the B luminosity of each galaxy, computed from the Zwicky photographic magnitude (Zwicky et al. 1961-1968) corrected for scale errors (Peterson 1979) and for galactic extinction ($\Delta m = -0.26$ csc $|b|$). Corrected Zwicky magnitudes were converted to B_T^o (de Vaucouleurs et al. 1976) by the subtraction of 0.05 mag (Section IV). Luminosities were computed assuming that the B magnitude of the sun is 5.48 mag (Allen 1973). The HI mass and HI mass-to-luminosity ratio, or upper limits, are shown in columns 10 and 11. For galaxies with spectrophotometric data (O'Connell and Dressel 1978 and in preparation), the equivalent width of the [OII] λ3727 line is listed in the last column.

One galaxy, UGC 09114, was convincingly detected in emission. Another galaxy, UGC 06671, may have been detected in absorption. These galaxies are discussed at length below. Neither emission nor absorption was detected in any other galaxy. UGC 00597 was initially included in the observing program, but had to be dropped because of persistent problems with interference.

b) UGC 09114

UGC 09114 is the most distant elliptical galaxy yet detected in HI emission. It necessarily has one of the largest masses of HI yet detected:

2.4×10^9 $M_\odot$. The mass may even be larger, as explained above, if the line-emitting region is resolved or if absorption of the nuclear continuum source is significant. The line is quite convincingly detected, with a peak flux density 7 to 8 times the r.m.s. noise.

In Figure 1a, the data are shown for the four simultaneously accumulated spectra prior to baseline removal and smoothing. In Figure 1b, the data are shown after averaging the four spectra, removing a third order baseline and smoothing over 32 km s^{-1}. A tick mark indicates the optically measured heliocentric velocity of the galaxy, which is 7570 ± 28 km s^{-1} (J. Huchra, private communication). The formal width of the emission line at 20% intensity is about 330 km s^{-1}, but the value of this parameter depends rather sensitively on the selection of the baseline. We removed a third order baseline because of obvious curvature in the raw spectrum, but in doing so we may have subtracted out a broad component of the emission line.

To verify that 09114 is the source of the emission, rather than some neighboring spiral galaxy in the main beam or side lobes, we observed all galaxies within 15' of 09114 listed in either the Uppsala General Catalog (Nilson 1973, complete to 14.5 mag) or the Zwicky catalog (Zwicky et al. 1961-68, complete to 15.5 mag). Emission lines about 200 km s^{-1} wide were detected at 7835 km s^{-1} in UGC 09108 and at 8020 km s^{-1} in a galaxy at 14^h 11.6^m $+03^o27'$, well displaced from the emission line centered at 7592 km s^{-1} in 09114. In the two remaining galaxies that were searched, UGC 09118 and a galaxy at 14^h 12.0^m $+03^o25'$, no emission was detected.

Given the rather large amount of HI that has been found in UGC 09114, we need to confirm its classification as an elliptical galaxy. Our reference for this classification is Nilson (1973), who examined prints of the Palomar Sky Survey. To check the reliability of Nilson's estimates of Hubble types, we have compared his classifications to those of Sandage and Visvanathan (1978) and Sandage (1978). For the last two papers, Hubble types were estimated from large-scale reflector plates taken at Mount Wilson and Palomar for the purpose of classification.

Sandage and Visvanathan determined Hubble types for comparable numbers of E and SO galaxies and for a few early-type spirals. Of the 28 galaxies fainter than m_{pg} = 13.0 which are classified as E by Nilson and which are included in Table I of Sandage and Visvanathan, 25 are also classified as E by the latter authors; the remaining three are classified as E/SO, SO/E, and SO. (We have confined our attention to magnitudes not too different from that of 09114, which has m_{pg} = 14.4.) Thus, Nilson's "E" galaxies rarely appear to be SO galaxies on better plate material.

To test for contamination of Nilson's "E" sample by galaxies of type other than SO, we have examined Sandage's (1978) data for galaxies of all types. Seven galaxies called E galaxies by Nilson are included among the 624 galaxies in Sandage's Table IV. Six of these are described as E galaxies by Sandage, and one as SO. Thus, Nilson does not often mistake either SO galaxies or galaxies of any other type for E galaxies. Seven additional galaxies which are common to the compilations of both Sandage and Nilson, and which are classified as E by Sandage, are classified mostly as SO by Nilson (5 SO, 1 SO-a, 1 S...). Nilson is thus very sparing with the 'E' classification, and tends to assign later types than Sandage does. In summary, the above discussion indicates that the reliability of Nilson's classification of 09114 as an E galaxy is fairly high.

There are several additional observations which indicate that 09114 is probably at least an E or SO galaxy, rather than a galaxy of later type:

1) K. Kingham has photographed 09114 with the Fan Mountain 40-inch

reflecting telescope at the University of Virginia. There is no strong concentration of light in the central 10 arc seconds of the image, such as one would have expected to find in a spiral galaxy.

2) The optical spectrum of the nuclear region of 09114 is like that of a normal elliptical galaxy, except for a fairly strong [OII] $\lambda3727$ emission line (O'Connell and Dressel, in preparation). Such a spectrum is typical of E and S0 galaxies with compact nuclear radio sources, although it could also belong to an early spiral.

3) Finally, the radio spectrum of this object is inverted, with the flux density increasing from 30 mJy at 2380 MHz (Dressel and Condon 1978) to 75 mJy at 5000 MHz (R. Porcas, private communication, and Dressel, in preparation). Nuclear radio sources in E and S0 galaxies nearly always have flat or inverted spectra; those in spiral galaxies usually have steep spectra. For example, in interferometer observations of an optically complete sample of galaxies with $S_{2380} \gtrsim 30$ mJy, Condon and Dressel (1978) found that powerful nuclear sources in E and S0 galaxies had flat spectra ($-0.5 < \alpha < 0.0$ for $S_\nu = k\nu^\alpha$) or inverted spectra ($\alpha > 0.0$) in 16 out of 19 cases, while only one powerful nuclear source out of five in spiral galaxies had a flat spectrum, and none had an inverted spectrum.

The measured flux densities of 09114 indicate a radio spectrum so remarkably inverted that it will be of great interest to better define the spectrum over a wider range of frequencies. The spectral index between 2380 MHz and 5000 MHz is $+1.2\pm0.1$. For comparison, in interferometer observations of 61 galaxies with powerful compact radio sources, Condon and Dressel (1978) found no sources to have spectral indicies more inverted than +0.6 between 2695 and 8085 MHz. Thermal absorption by the detected HI cloud is an implausible cause of the inverted spectrum, since a high emission measure would be required to suppress the continuum flux, while a low column density is required to avoid making an HI absorption line. The source in 09114 may be similar to compact synchrotron self-absorbed components that exist in other galaxies, but must be unique in having no larger component or halo, which would steepen the spectrum.

c) UGC 06671

We have possibly detected an HI absorption line in UGC 06671. To support the classification of 06671 as an E galaxy, we again refer to the reliability of Nilson's classification of E galaxies. In addition, the radio continuum spectrum suggests that 06671 is probably an E or S0 galaxy: the spectral index between 2380 and 8085 MHz is 0.0 (Condon and Dressel 1978).

The four simultaneously accumulated spectra are displayed in Figure 2a, corrected for the instrumental profile as determined from the reference scans. Figure 2b shows the spectrum after averaging, removing a second-order baseline, and smoothing over 64 km s^{-1}. A tick mark indicates the optically measured velocity of the galaxy, which is 9051±41 km s^{-1} (J. Huchra, private communication). The maximum depth of the line, 0.9 mJy, is 3.1 times the r.m.s. fluctuations in the baseline of the smoothed spectrum. Because of the low signal-to-noise ratio and baseline curvature in the spectrum, more observations should be made to confirm or refute this marginal detection.

Assuming for the moment that the measured depth and integrated flux of the absorption line are aproximately correct, one can calculate the optical depth and HI column density along the line of sight to the nuclear continuum source. The ratio of the greatest absorbed flux density (0.9 mJy) to the unabsorbed flux density (55 mJy) imply a maximum optical depth of 0.016. The integrated absorbed flux (230 mJy km s^{-1}), taken together with the unabsorbed flux density and the spin temperature, imply an HI column density of 8×10^{18}

T_{spin} cm^{-2}. If the observed absorption line has been "filled in" to some extent by 21 cm line emission from the gas, these values of optical depth, absorbed flux, and column density are too small. They are still correct to within a factor of two, however, even if the HI mass is fairly high (~ 10^9 $M_{\odot}$).

The column density of the gas in 06671 cannot be calculated until the spin temperature of this gas is determined. The kinetic temperature of the gas may be $\lesssim$ 10,000K. At higher temperatures the gas would be ionized; lower temperatures might be reached very slowly, due to the low cooling rate of hydrogen below 10,000K (Dalgarno and McCray 1972) and to the heat input from supernovae and from cloud collisions (Gunn 1979). While the kinetic temperature may thus be fairly high, the spin temperature is probably much lower than the kinetic temperature. The spin temperature approaches the kinetic temperature only when the gas is dense and collisions are frequent; i.e., when n_{HI} (cm^{-3}) >> 0.002 $(T_{kinetic})^{1/2}$ (Kaplan and Pikelner 1970). The HI cloud in 06671 would have to be much more massive or much more compact than the one in NGC 4278 (Raimond et al. 1981) in order for this condition to be met.

Assuming for the sake of argument a spin temperature ~ 100K, one deduces a column density of 8 x 10^{20} cm^{-2} along our line of sight to the nucleus of 06671. This is three times higher than the maximum column density observed in emission in NGC 4278, and ~ 15 times higher than the column density to the nucleus of this galaxy (Raimond et al. 1981). Therefore, either 1) 06671 has an HI mass several times greater than that of NGC 4278, which has M_{HI} ~ 5 x 10^8 $M_{\odot}$; or 2) the real or projected distribution of HI in 06671 is quite different from that of NGC 4278; or 3) the column density to the nucleus of NGC 4278 has been underestimated by failure to take into account absorption of the nuclear continuum source; or 4) the spin temperature of 06671 is less than 100K; or 5) the marginally detected absorption line in 06671 is spurious. We will make further observations at Arecibo to check the last alternative.

III. STATISTICAL STUDIES

Searches for neutral hydrogen in elliptical galaxies, with largely negative results, have triggered much discussion of the formerly unsuspected scarcity of HI in most E galaxies and of the consequently surprising detections of HI in some E galaxies. Various scenarios of the evolution of a gaseous medium in elliptical galaxies have been proposed, usually involving the continuous or episodic removal of gas by an internal or external wind.

Now that a large body of data exists, a number of questions should be addressed. For example, is sweeping by an external medium an important gas removal mechanism in loose clusters and groups, wherein the majority of galaxies reside, or does the opportunity to accrete gas in small groups result in a higher proportion of elliptical galaxies with detectable HI? Is there a clear tendency for massive galaxies to retain their gas or to accrete external gas? Is large HI content a necessary condition for the generation of a nuclear radio source? To what extent are neutral and ionized gas content correlated in elliptical galaxies, and what is thereby implied about the total gas content of most elliptical galaxies?

a) The Data

To attempt to answer the foregoing questions, we have combined our data for luminous radio-emitting elliptical galaxies with data for E galaxies that have been observed by others. All elliptical galaxies with published HI detections or upper limits better than $2.5 \times 10^9 M_\odot$ have been included in our compilation. For the sake of consistency, upper limits have been converted to our system: three times the r.m.s. noise, with an assumed velocity width of

450 km s^{-1} and a Hubble constant of 55 km s^{-1} Mpc^{-1}. Galaxies have been excluded if they are classified as anything but elliptical by Nilson (1973), de Vaucouleurs et al. (1976), Humason et al. (1956), or Sandage and Visvanathan (1978). NGC 3226 has also been excluded, because it is interacting with the Seyfert galaxy NGC 3227 (Knapp et al. 1978).

The data for the galaxies are shown in Table 2, in the same format as the data in Table 1. References for the HI data are given in an additional column. Galaxies with detected HI are at the end of the table. When doubt existed over the distance to an undetected galaxy, the largest published distance found among the references was used, to give the most conservative HI mass limit.

In the column concerning [OII] λ3727 emission, detection (*) or non-detection (-) by Humason et al. (1956) is indicated, or the equivalent width of the line is given (O'Connell and Dressel, in preparation; Osterbrock (1960) for NGC 4125). Flux densities at 2380 MHz (Dressel and Condon 1978) are given for most galaxies; flux densities at 5000 MHz (Disney and Wall 1977) are given for a few southern galaxies. Nuclear flux densities at 2380 MHz are given if known (Condon and Dressel 1978); nuclear flux densities at 5000 MHz (Condon and Dressel unpublished) or 1400 MHz (Hummel 1980) are given otherwise. Nuclear radio power is listed for all galaxies known to have a nuclear source; upper limits to nuclear radio power are calculated from 2σ upper limits to the total flux density for undetected galaxies.

Major blue diameters are taken from Nilson (1973) or de Vaucouleurs et al. (1976). To convert corrected Zwicky magnitudes, m_z, to B_T^o magnitudes for Table 1, the difference between m_z and B_T^o was examined for the 28 galaxies in Table 2 with measurements in both magnitude systems. The median value of $B_T^o - m_z$ is -0.05, and the dispersion is 0.25 mag.

In other publications, authors have calculated upper limits to HI mass by assuming line widths of about 300 km s^{-1}, or line widths proportional to the fourth root of the optical luminosity--i.e., proportional to the stellar velocity dispersion (Faber and Jackson 1976). Neither assumption is a good fit to the existing data. Widths of emission lines detected in elliptical galaxies (Tables 1 and 2) are shown as a function of the fourth root of B luminosity on logarithmic scales in Figure 3. Virtually all of the detected HI lines have widths greater than 300 km s^{-1}, and there is no obvious proportionality between line width and luminosity to the quarter power. For want of an accurate predictor of HI emission line width, we have chosen a value near the median of the observed values, 450 km s^{-1}, for determining upper limits to emission line fluxes and HI masses.

It is possible that a correlation between HI line width and optical luminosity has been obscured by measuring errors, since very broad wings could be mistaken for baseline curvature. This could certainly be the case for UGC 09114, for example. However, given the complicated kinematical situation in NGC 4278 (Raimond et al. 1981), it is not clear that one should expect a close relationship between observed HI velocity dispersion and stellar velocity dispersion. The observed HI velocity dispersion in NGC 4278 may be due largely to the rotation of a disk-like distribution which is non-coaxial with the stellar rotation axis (Raimond et al. 1981) or to radial inflow of gas (Sanders 1981). The relationship between the gas and stars is thus unclear, and projection effects could play a large role in determining the observed line width.

b) HI Mass and Nuclear Radio Power

The primary motivation of our observing program was to determine whether a large reservoir of neutral hydrogen is a necessary ingredient for the formation of a compact nuclear radio source in an elliptical galaxy. The detection of HI in two nuclear source galaxies in some of the earlier HI surveys suggested such a connection. Our 21 cm detection of a very large HI mass in the radio source elliptical galaxy UGC 09114 is also suggestive. Perhaps these galaxies emit radio waves as some of the gas is accreted by a central massive object (Gunn 1979).

To examine the relationsnip of nuclear radio emission to HI content in elliptical galaxies, we have plotted HI mass against nuclear radio power in Figure 4 for the galaxies in Tables 1 and 2. Dots represent HI detections; horizontal arrows are appended to indicate upper limits to nuclear radio power. Inverted carets indicate upper limits to HI mass for galaxies with detected nuclear radio sources. Diagonal arrows indicate upper limits to both HI mass and nuclear radio power for galaxies undetected in both line and continuum surveys. All but two of the galaxies with $\log P_\nu$ (WHz^{-1}) > 22.3 are members of our observing program at Arecibo.

The data, at best, are consistent with the existence of a maximum attainable radio power which increases with increasing HI mass. Of course, the apparent existence of such a relationship could be produced by a selection effect. Galaxies with powerful nuclear sources are rare and tend to be distant; to detect small HI masses or to set good upper limits to the HI mass in these galaxies is therefore difficult. A factor of two improvement in the sensitivity of the HI observations of the undetected galaxies with active nuclei in Figure 4 would probably allow one to make a fairly definitive statement about the relevance of HI mass to nuclear activity. Another observing session would not necessarily improve the sensitivity significantly for galaxies that already have long integration times, however, since receiver instability and standing waves from the continuum emission contribute to the observed fluctuations in the spectra. The best course to take in the future, therefore, may be to reobserve a few galaxies with the shortest integration times, and to observe other radio-emitting galaxies with low velocities (where possible) and with favorable declinations for the instrument being used. In summary, the existing data are consistent with and perhaps even suggestive of a relationship between HI mass and nuclear radio power, but the existence of such a relationship has by no means been proved.

c) HI Mass and Optical Luminosity

Predictions have been made about a correlation, or lack of one, between gaseous mass and total galactic mass in elliptical galaxies. Some models of supernovae-driven galactic winds (Mathews and Baker 1971; Gisler 1976) predict that gas should be found only in fairly massive galaxies. Massive galaxies have larger binding energies which cannot be overcome by typical rates of supernova heating per mass of gas produced. The retained gas is initially hot, due to the high velocity dispersion of the stars that shed it, and may or may not recombine to become observable as HI. Mathews and Baker originally objected that recombination and cooling would lead to the formation of early-type stars, in conflict with optical observations. However, Jura's (1977) discussion of the possibility of preferential formation of low mass stars in elliptical galaxies circumvents this problem.

In another galactic wind model (Sanders 1981), the supernova rate in elliptical galaxies is usually too low to drive a wind. Hot gas accumulates until the density becomes high enough for cooling, recombination, and collapse to occur. Massive stars form and evolve to become supernovae, which temporarily drive a wind that rids the galaxy of gas. This cycle occurs repeatedly. In this scheme, the mass of HI in a galaxy depends much more critically on the time of observation than on the mass of the galaxy. (See

Sanders (1981) for caveats about galaxies of extremely low or high mass, which are beyond the limits of our sample.)

The evolution of elliptical galaxies in clusters is complicated by ablation of gas during motion of the galaxies through an intracluster medium. Since intracluster gas exists even in fairly poor and open clusters (Burns et al. 1981), field galaxies may exhibit a closer relationship between gaseous mass and total mass than cluster galaxies do. It may therefore be useful to consider the data for field galaxies and for cluster galaxies separately.

To determine whether only massive galaxies retain gas, or whether any other relationship between neutral gas content and galactic mass exists, we have plotted HI mass-to-luminosity ratios as a function of luminosity in Figure 5 for the galaxies in Tables 1 and 2. Galaxies which belong to the field according to Zwicky et al. (1961-1968) are indicated by open circles; galaxies belonging to Zwicky clusters or to the Virgo cluster are represented by filled circles; a few galaxies which lie outside the region examined by Zwicky are indicated by asterisks. (UGC 01503 has been counted as a field galaxy; although it lies just on the defining contour of a Zwicky cluster, it has been classified as an isolated galaxy by Karachentseva (1973).)

Limits to the HI mass-to-luminosity ratio lower than 0.01 $M_\odot/L_\odot$ have been set for galaxies spanning four absolute magnitudes. Detections, mostly between 0.01 and 0.06 $M_\odot/L_\odot$, have also been made over most of this range. There is thus no evidence in Figure 5 for a relationship between HI mass and total mass (or luminosity) in elliptical galaxies, either in clusters or in the field. Models in which galactic mass is the most critical parameter in determining HI mass are therefore inconsistent with the data. Models predicting large differences in the properties of E galaxies of the same mass (e.g., differences in supernova rate or stellar mass loss rate), or evolving models in which HI content changes greatly with time (Sanders 1981) are favored.

d) HI Mass and Cluster Membership

Galaxies in clusters are expected to lose at least part of their gas due to the pressure exerted by the intracluster medium through which they are moving. Ablation of gas is more complete for higher galactic velocities, lower stellar mass loss rates, and greater densities of intracluster gas (Gunn and Gott 1972; Gisler 1976). Most galaxies in rich clusters are expected to lose gas from their outer parts, but retain a gaseous core. In less rich clusters, such as those cataloged by Zwicky et al. (1961-1968) but not by Abell (1958), most galaxies may retain a significant fraction of their gas. A galaxy of mass 10^{11} $M_{\odot}$ moving through a cluster medium of density $\lesssim 10^{-4}$ cm^{-3} at 500 km s^{-1} should retain one-third or more of its gas, according to Gisler's (1976) model.

The data in Figure 5 are ambiguous with respect to the significance of ablation in Zwicky clusters. Cluster galaxies account for 75% of the sample in the northern sky. They number 3 of the 5 HI detections in the northern sky (discounting UGC 06671). The relative detection rates of cluster and field E galaxies (admittedly derived from small numbers) thus give no indication of significant gas-stripping of galaxies in Zwicky clusters. It is note-worthy, however, that UGC 01503, an unusually isolated galaxy (Karachentseva 1973), has by far the largest detected HI mass and HI mass-to-luminosity ratio (Haynes and Giovanelli 1981) in the sample.

Because of the far-reaching implications of the large HI mass of 01503, it is important to verify that this galaxy is actually an elliptical galaxy, and to determine whether other isolated elliptical galaxies have anomalously large HI masses. Haynes and Giovanelli (1981) reported detections of large HI masses in two other isolated elliptical galaxies, UGC 06777 and 12541, but the classifications of these galaxies are in dispute. Nilson (1973) described both of them as compact galaxies of indeterminate type. (They have therefore not been included in our Table 2.) The HI lines in UGC 01503, 06777, and 12541 have widths of 200 to 300 km s^{-1}, and thus are narrower than the lines in all the other elliptical galaxies with detected HI (Figure 3). Lines of this width are often found in S0, spiral, and irregular galaxies, however (Bieging and Biermann 1977; Bottinelli et al. 1980; Shostak 1978). Finally, UGC 06777 has a strongly pronounced double-peaked HI profile, similar to the profiles of many spiral galaxies. Therefore, either these galaxies are not elliptical galaxies, or they differ from other elliptical galaxies in both the mass and the dynamical properties of their HI distributions.

UGC 01503 has no neighboring galaxies brighter than 15.7 magnitudes within a projected distance of 1.2 Mpc. The next most isolated galaxies in the northern sky in Tables 1 and 2 are UGC 11718 and UGC 12841, which have no neighbors brighter than 15.7 magnitudes within projected distances of 1.0 Mpc and 0.7 Mpc, respectively. Neither of these galaxies has been detected in an HI survey. UGC 11718 has $M_{HI} < 5 \times 10^8$ $M_\odot$ and $M_{HI}/L_B < .004$ $M_\odot/L_\odot$; UGC 12841 has $M_{HI} < 2 \times 10^9$ $M_\odot$ and $M_{HI}/L_B < .023$ $M_\odot/L_\odot$. Some quite isolated elliptical galaxies thus have moderate to low ratios of HI mass to luminosity. In any case, while it may yet be proved that elliptical galaxies in rich clusters or in extremely isolated regions have unusual HI properties, there is no evidence for a strong dependence of HI mass on environmental conditions over the range of less extreme environments occupied by most of the galaxies in our sample.

e) HI Mass and λ3727 Emission

In their study of the elliptical galaxy NGC 1052, Fosbury et al. (1978)

noted that all five of the elliptical galaxies with HI detected to date had optical emission lines, indicative of high HII content. Subsequently Knapp, Kerr, and Henderson (1979) completed a large 21 cm survey of elliptical galaxies and speculated that the HI and HII contents of elliptical galaxies are unrelated. We wish to address this question again, now that larger samples of galaxies have been searched for 21 cm emission and for optical emission lines.

As a tracer of HII in elliptical galaxies we will use the [OII] blended emission line at 3727 A. Once-ionized oxygen and ionized hydrogen tend to coexist because the ionization potentials of these elements are nearly equal, and the λ3727 line is generally the strongest emission line in the spectra of elliptical galaxies (Osterbrock 1960). Information about the strength of the λ3727 line for the galaxies in our statistical sample, mostly from Humason, Mayall, and Sandage (1956) and O'Connell and Dressel (1978 and in preparation), is included in Tables 1 and 2. Humason, Mayall, and Sandage report only detection or nondetection of the λ3727 line, and have a nonuniform detection limit. A uniform detection limit of about 5 A is not a bad assumption, however. Among the E and S0 galaxies with λ3727 equivalent width measured by O'Connell and Dressel or by Osterbrock (1960), 14 out of 16 with $W_\lambda < 5$ A were undetected by Humason, Mayall, and Sandage and 8 out of 10 with $W_\lambda > 5$ A were detected.

The values of HI mass to luminosity, or upper limits, are shown in Figure 6 for the galaxies in Tables 1 and 2. Weak 3727 emitters ($W_\lambda < 5$ A) are grouped on the left, and strong 3727 emitters ($W_\lambda \gtrsim 5$ A) on the right. The coincidence of strong λ3727 emission and detected HI emission is quite striking. Given the HI detection rate of 19% for the galaxies in the figure, the binomial probability of finding 7 or more detected galaxies among the 11 with strong λ3727 emission is 0.0014. This statistic could be misleading if galaxies with λ3727 emission were searched for HI with better sensitivity than other galaxies were. Considering only detected galaxies and galaxies known to have $M_{HI}/L_B < 0.015\ M_\odot/L_\odot$, we still find a significant result: 22% of these 32 galaxies have $M_{HI}/L_B > 0.015\ M_\odot/L_\odot$; the binomial probability of finding 5 or more galaxies with $M_{HI}/L_B > 0.015\ M_\odot/L_\odot$ among the 8 with strong λ3727 emission is 0.016. The neutral gas content and ionized gas content of elliptical galaxies is thus significantly correlated.

O'Connell and Dressel (1978) have shown that the existence of λ3727 emission is extremely well correlated with the existence of compact radio sources in elliptical galaxies. The above discussion shows that λ3727 emission and HI content are strongly correlated in elliptical galaxies. Why then have we not yet seen a significant correlation between HI content and compact radio sources in eliptical galaxies? Perhaps more sensitive 21 cm observations of radio-emitting galaxies are needed. Alternatively, perhaps no significant correlation exists.

To have a strong λ3727 emission line, an elliptical galaxy must have an unusually large mass of gas or an unusually powerful source of ionization. Unusually powerful sources of ionization may in some cases be traceable to nuclear activity which is evidenced by radio emission. In NGC 1052, for example, the relative forbidden line intensities indicate that the line-emitting gas has been ionized by shocks driven by the radio-emitting relativistic electrons (Fosbury et al. 1978). The same process is probably occurring in NGC 4278: the five forbidden lines observed by Osterbrock (1960) have the same intensity ratios, to within a few percent, as the lines in NGC 1052 do. The SO galaxy NGC 3998 also has a nuclear radio source and a forbidden line spectrum characteristic of shock ionization (Blackman et al.

1981).

One might therefore expect to find λ3727 emission in elliptical galaxies with large HI content or with powerful nuclear radio sources. HI content and nuclear radio power could thus each be correlated with λ3727 emission, but not necessarily with each other.

In Table 3 we have listed the λ3727 equivalent width, the nuclear radio power, and the HI mass-to-luminosity ratio for all galaxies in Tables 1 and 2 known to have a λ3727 equivalent width > 4A . We expect Table 3 to be reliable, but not necessarily complete. That is, all of the Humason, Mayall and Sandage (1956) detections probably have $W_\lambda(3727) > 4A$ and belong in the table; but a few of the non-detections and unobserved galaxies probably also have $W_\lambda(3727) > 4A$ and are missing from the table.

All but one of the thirteen line-emitting galaxies in Table 3 has a nuclear radio source and/or detected HI emission. Moreover, the largest measured equivalent widths occur in the galaxies which have both a nuclear radio source and detected HI emission. The occurrence of fairly strong or exceptionally strong λ3727 emission may thus be a simply predictable consequence of HI mass (i.e., amount of gas available for ionization) and nuclear radio power (i.e., strength of ionizing agent). An implicit assumption is that either all elliptical galaxies have $\gtrsim 5 \times 10^4$ $M_\odot$ of nuclear gas, or that at least elliptical galaxies with compact radio sources have this much nuclear gas, since $\gtrsim 5 \times 10^4$ $M_\odot$ of ionized gas is implied by the detected λ3727 line fluxes. A correlation of total gas content and nuclear radio power is not required by either the optical emission line data or the 21 cm line data, but cannot be excluded either. The HI mass limits are not very low for some of the galaxies in Table 3 that are listed as nuclear radio sources but not as HI detections; some of these galaxies could still contain a respectable mass of hydrogen.

V. CONCLUSIONS

We have made a 21 cm line survey of eleven elliptical galaxies with powerful nuclear radio sources to test whether nuclear radio emission is related to HI content in E galaxies. We detected the galaxy UGC 09114 in emission, and possibly detected UGC 06671 in absorption. UGC 09114 has one of the largest HI masses yet to be found in an elliptical galaxy: 2.4×10^9 $M_\odot$. The 21 cm absorption line in 06671, if real, is the first to be reported in an elliptical galaxy, and indicates a hydrogen column density of 8×10^{18} T_{spin} cm^{-2}. These detections, together with earlier detections of the radio-emitting galaxies NGC 1052 and NGC 4278, are suggestive of a connection between HI content and radio power, but the observations of the remaining galaxies in our program were not sensitive enough to confirm or refute the existence of such a connection.

We have combined our results with the results of other HI surveys of elliptical galaxies to study the relationship of HI mass to other galactic properties and environmental properties. We note the following:

1) Large HI masses (5×10^8 $M_\odot$ to 2×10^9 $M_\odot$) have been detected in several E galaxies with nuclear radio sources. No E galaxy with a powerful nuclear radio source has yet been found to have a small HI mass, but this is due largely to the difficulty of detecting small masses, or setting low limits, in relatively distant galaxies.

2) No direct relationship between HI mass and optical luminosity (i.e., total galactic mass) is apparent in the data.

3) Over the range of environments occupied by most galaxies, from the Zwicky field to medium compact Zwicky clusters, there is no obvious relationship between HI mass and environment.

4) [OII] λ3727 emission, a tracer of HII, is unusually strong in E galaxies with large HI mass and in E galaxies with nuclear radio emission. It is strongest in galaxies with both large HI mass and nuclear radio emission. The relationship between λ3727 emission and HI mass is not surprising; the relationship between λ3727 emission and radio emission can be understood if radio emission indicates the existence of an additional source of ionization not found in radio-quiet galaxies.

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FIGURE CAPTIONS

Figure 1a) - Four simultaneously accumulated spectra of UGC 09114, corrected for instrumental profile.

Abscissa: autocorrelator channel number

Ordinate: relative intensity, I_ν, within each quadrant of the autocorrelator.

Figure 1b) - Spectrum of UGC 09114 after calibrating, averaging, removing a third order baseline, and boxcar smoothing over 32 km s^{-1}.

Abscissa: radial velocity in km s^{-1}

Ordinate: flux density in mJy

Figure 2a) - Four simultaneously accumulated spectra of UGC 06671, corrected for instrumental profile.

Abscissa: autocorrelator channel number

Ordinate: relative intensity, I_ν, within each quadrant of the autocorrelator.

Figure 2b) - Spectrum of UGC 06671 after calibrating, averaging, removing a second order baseline, and boxcar smoothing over 64 km s^{-1}.

Abscissa: radial velocity in km s^{-1}

Ordinate: flux density in mJy

Figure 3 - HI line width as a function of B luminosity to the quarter power for the galaxies in Table 1 and 2 with detected HI emission.

Abscissa: log $(L_B/L_0)^{0.25}$

Ordinate: (log) line width in km s^{-1}

Figure 4 - Hydrogen mass versus nuclear radio power at 2380 MHz (or 1400 or 5000 MHz) for the galaxies in Tables 1 and 2.

Abscissa: log of the radio power in WHz^{-1}

Ordinate: log of the hydrogen mass in units of solar mass.

Symbols:

filled circle only = detected HI, detected nuclear radio source

filled circle + horizontal arrow = detected HI, upper limit to nuclear radio power

inverted caret = upper limit to HI mass, detected nuclear radio source

diagonal arrow = upper limit to HI mass, upper limit to nuclear radio power

Figure 5 - Hydrogen mass-to-B luminosity ratio as a function of B luminosity for the galaxies in Tables 1 and 2.

Abscissa: log of L_B in solar units

Ordinate: M_{HI}/L_B in solar units

Symbols:

filled circle = Virgo cluster member or Zwicky cluster member

open circle = Zwicky field galaxy

asterisk = galaxy outside the region cataloged by Zwicky et al. (1961-1968)

appended arrow = upper limit to M_{HI}/L_B

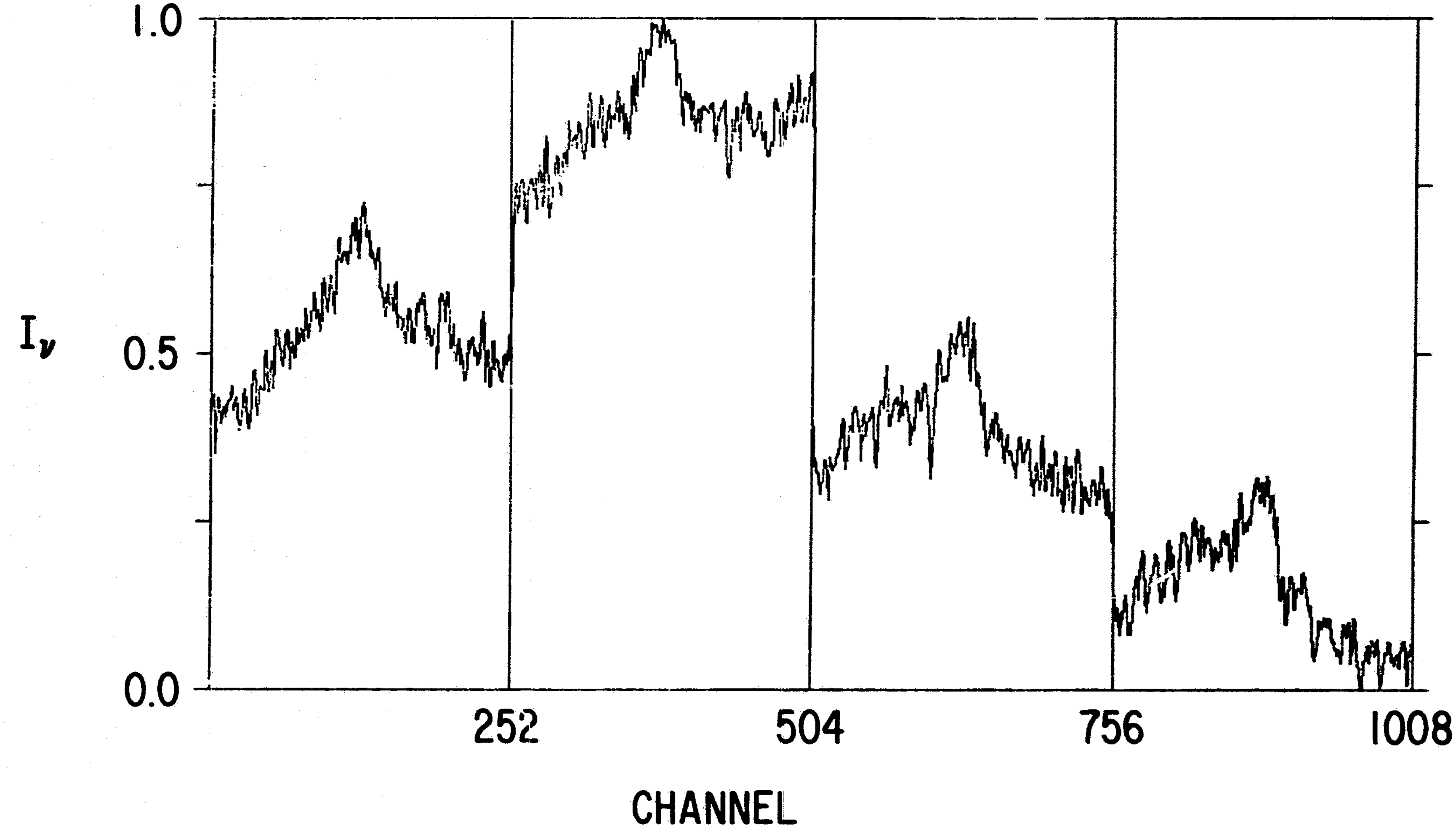
Figure 6 - HI mass-to-B luminosity ratios for galaxies in Tables 1 and 2 with $W_\lambda(3727) < 5$ Å (left portion of graph) and with $W_\lambda \gtrsim 5$ Å (right portion).

Ordinate: M_{HI}/L_B in solar units

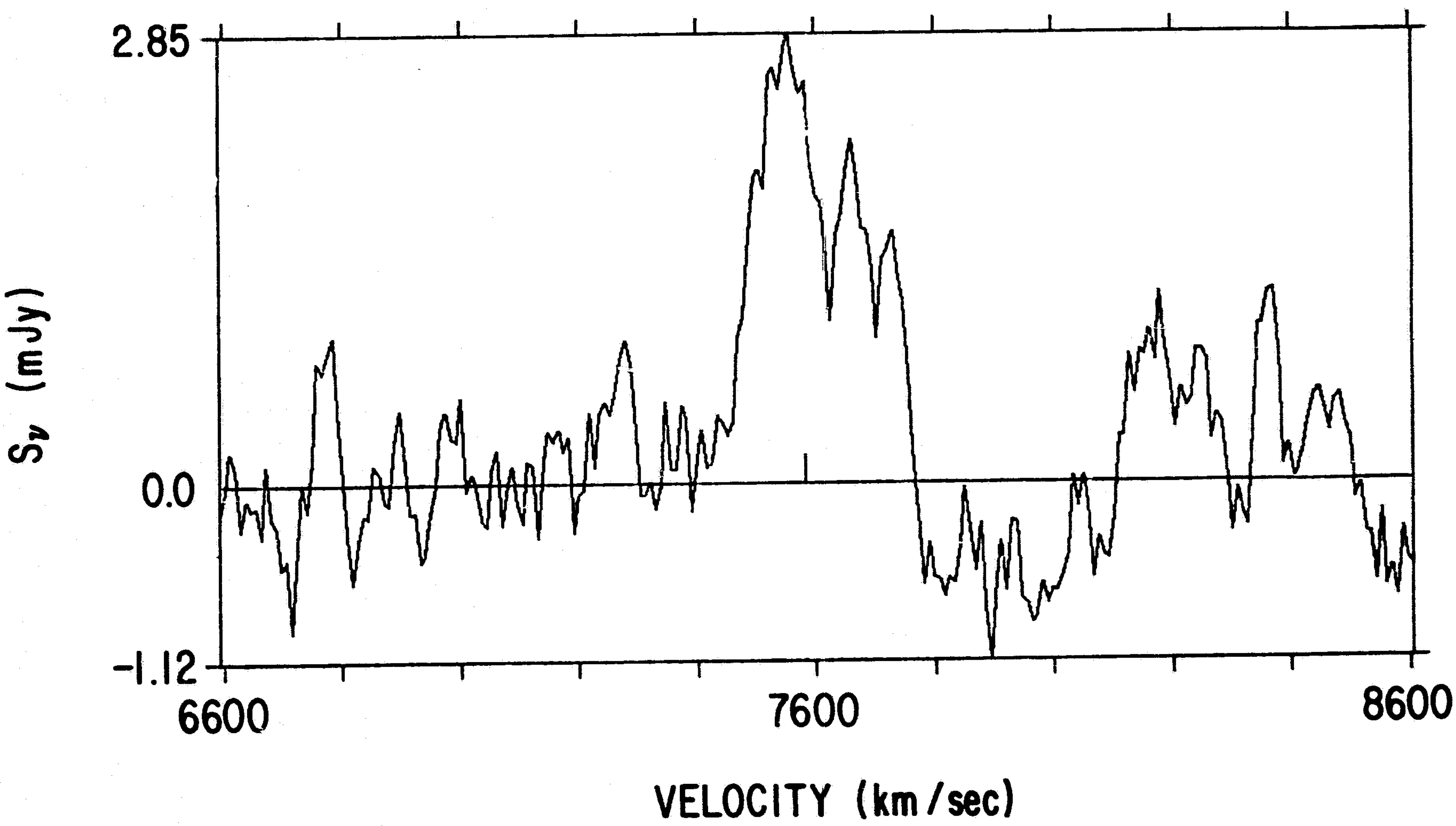
Symbols:

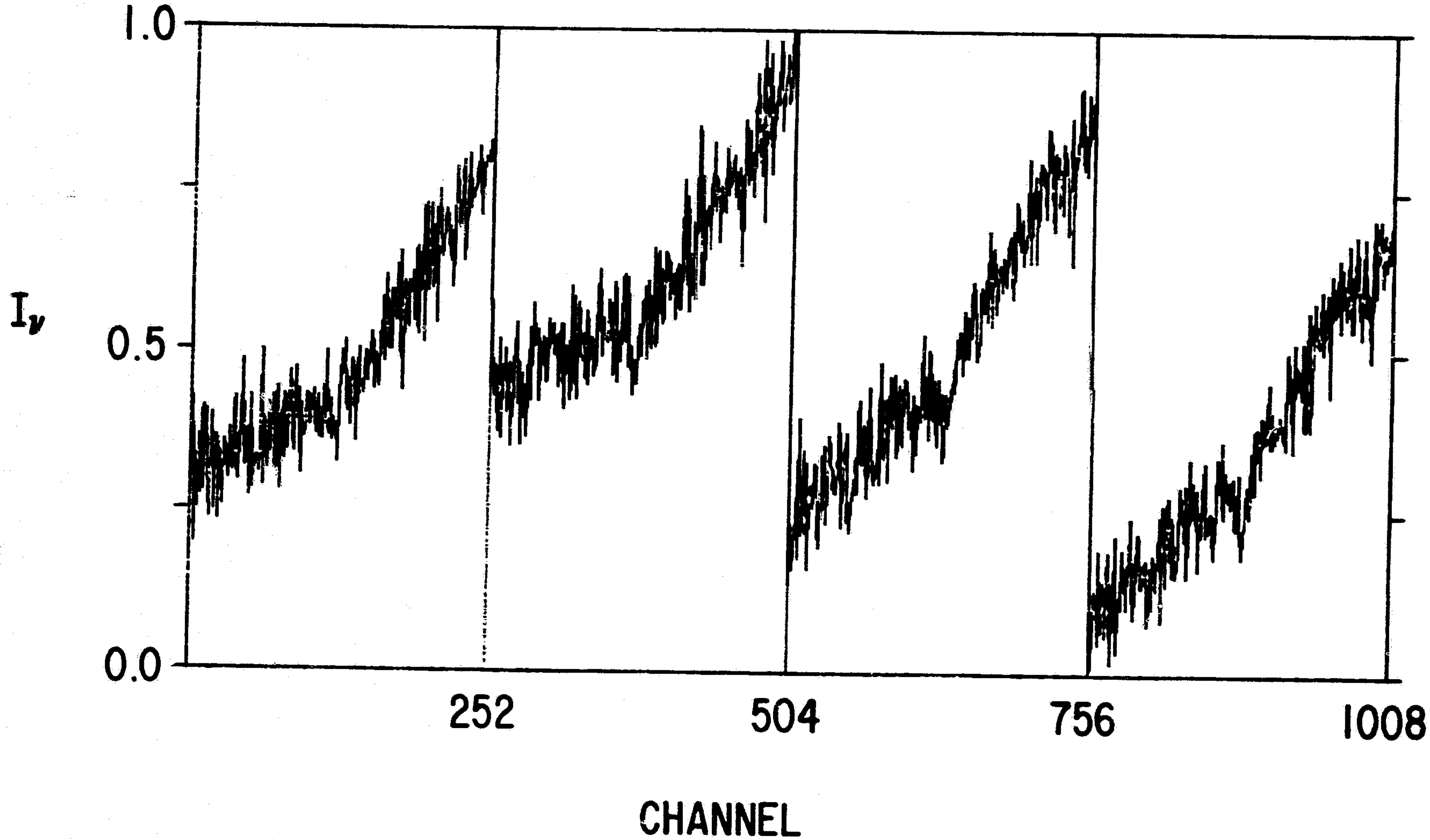
filled circle = detected HI mass

inverted caret = upper limit to HI mass

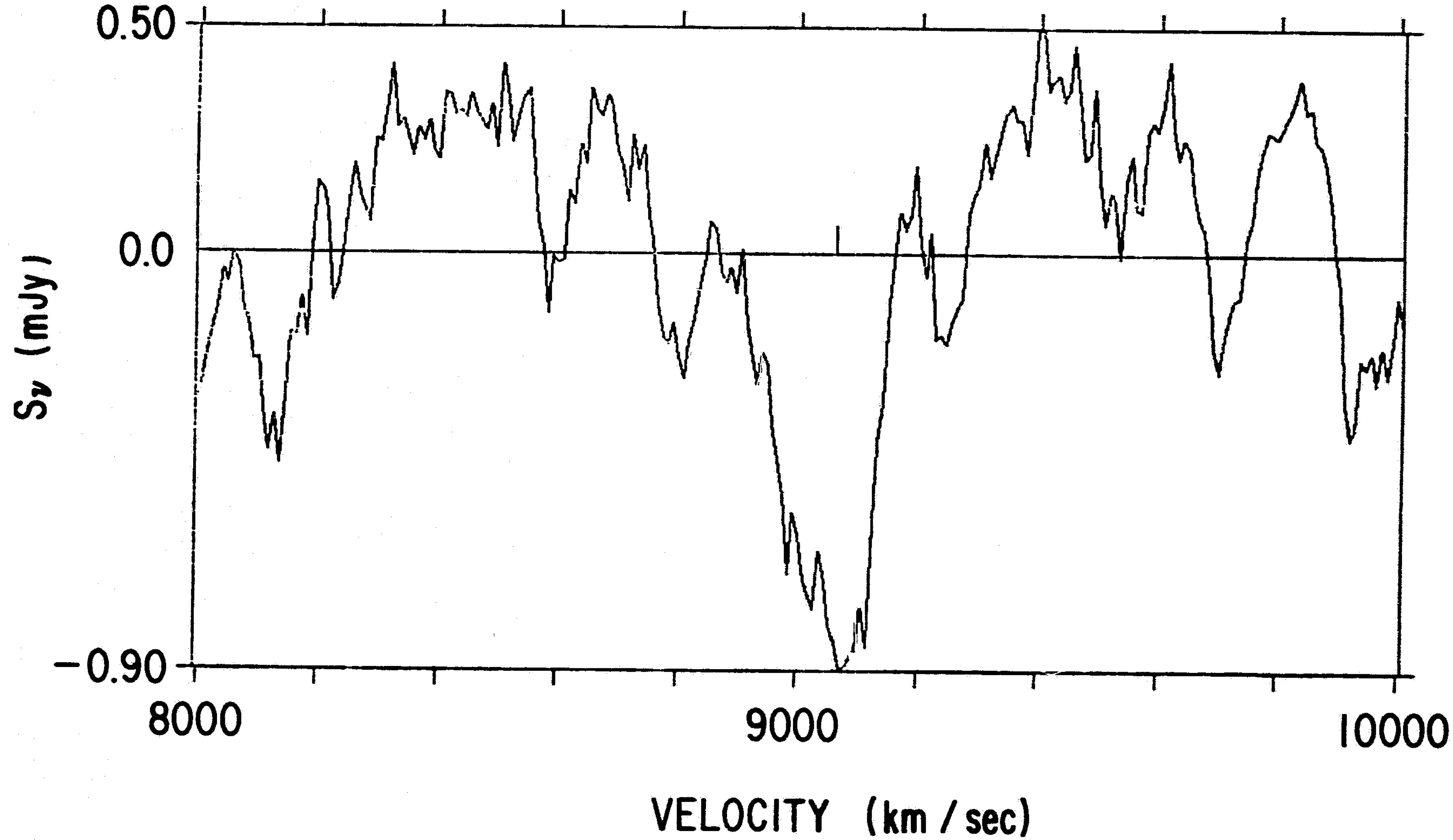


1.0
0.5
0.0
I_ν
252
504
756
1008
CHANNEL


2.85
0.0
-1.12
6600
7600
8600
VELOCITY (km/sec)
Sν (mJy)



1.0
0.5
0.0
I_ν
252
504
756
1008
CHANNEL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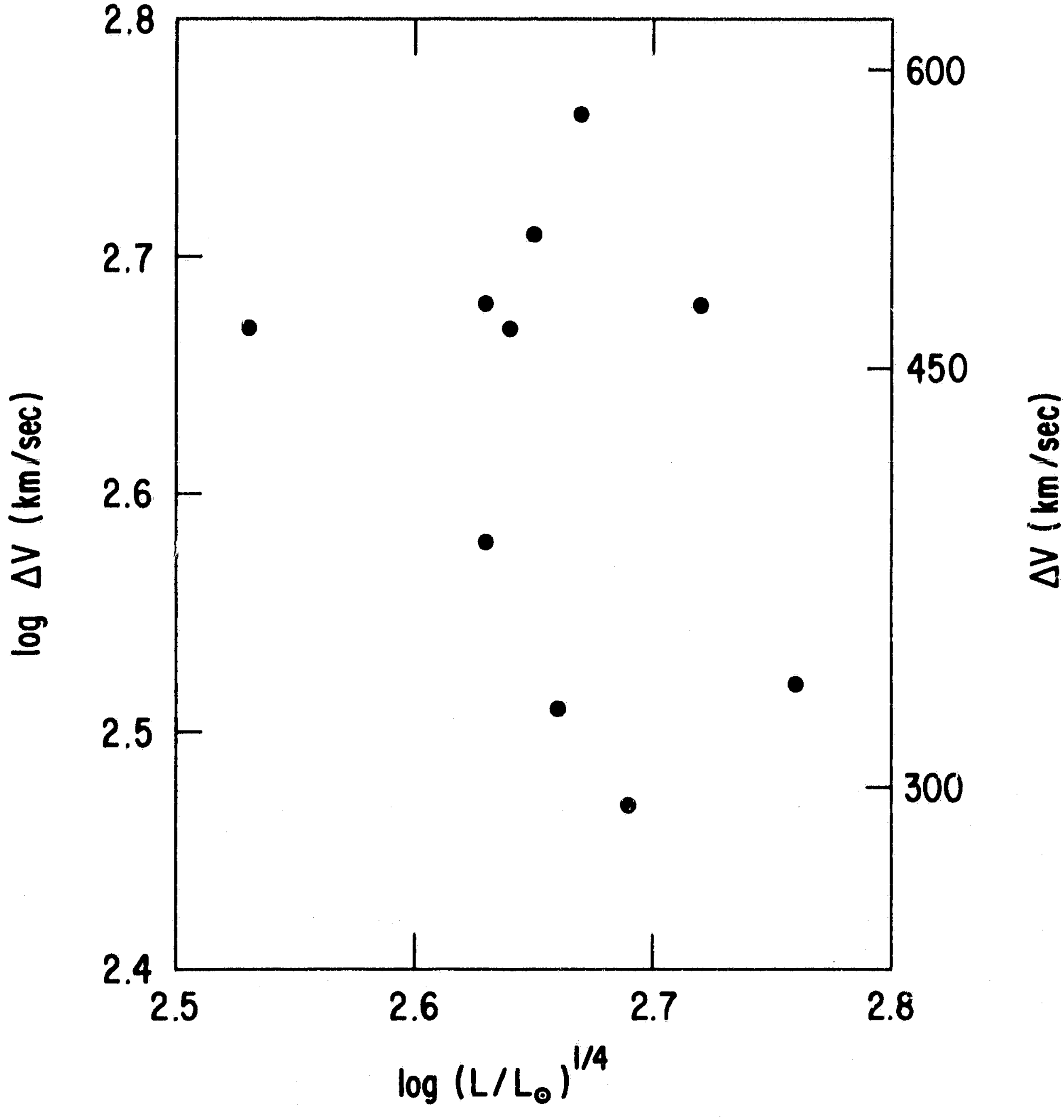
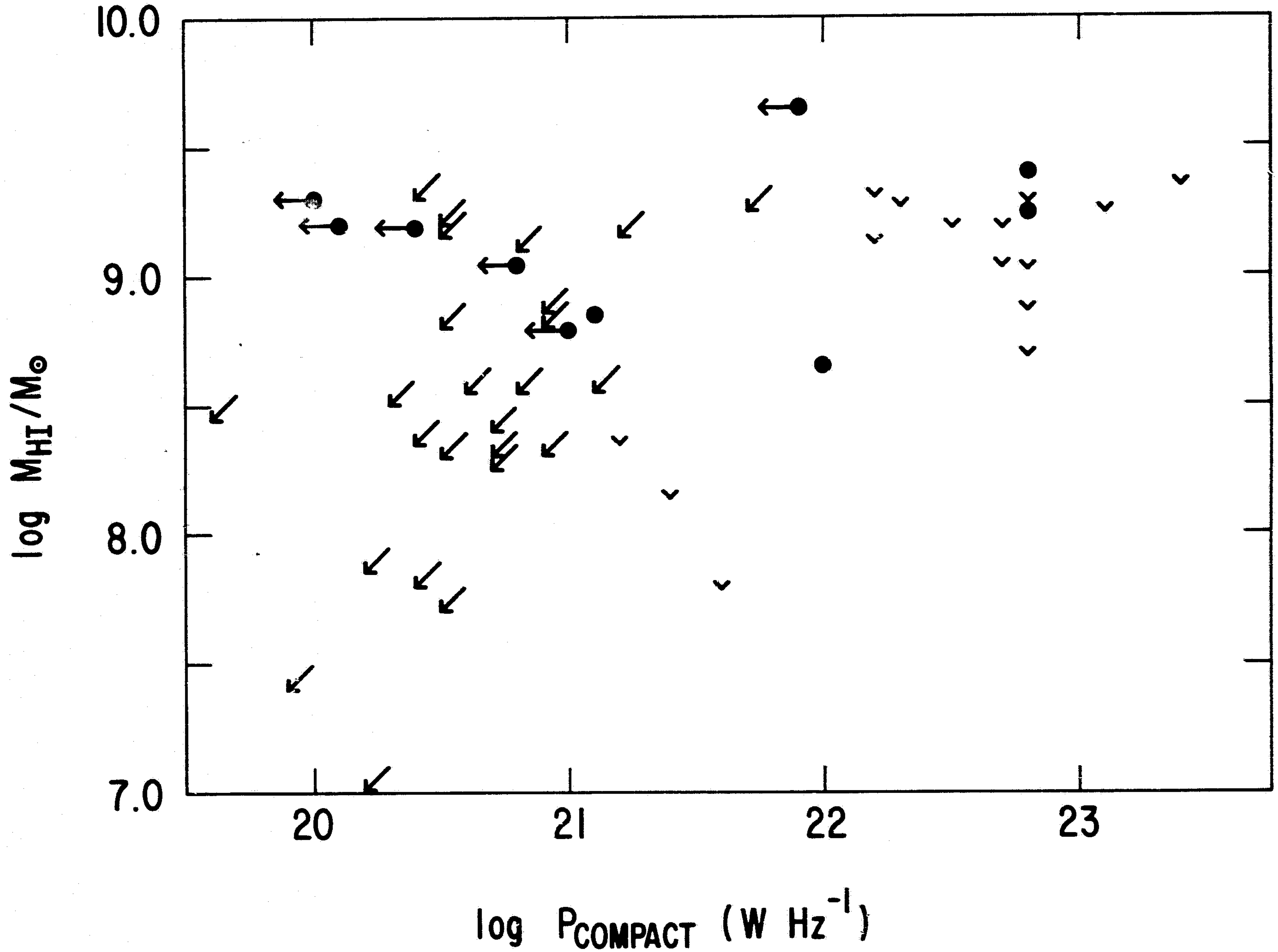
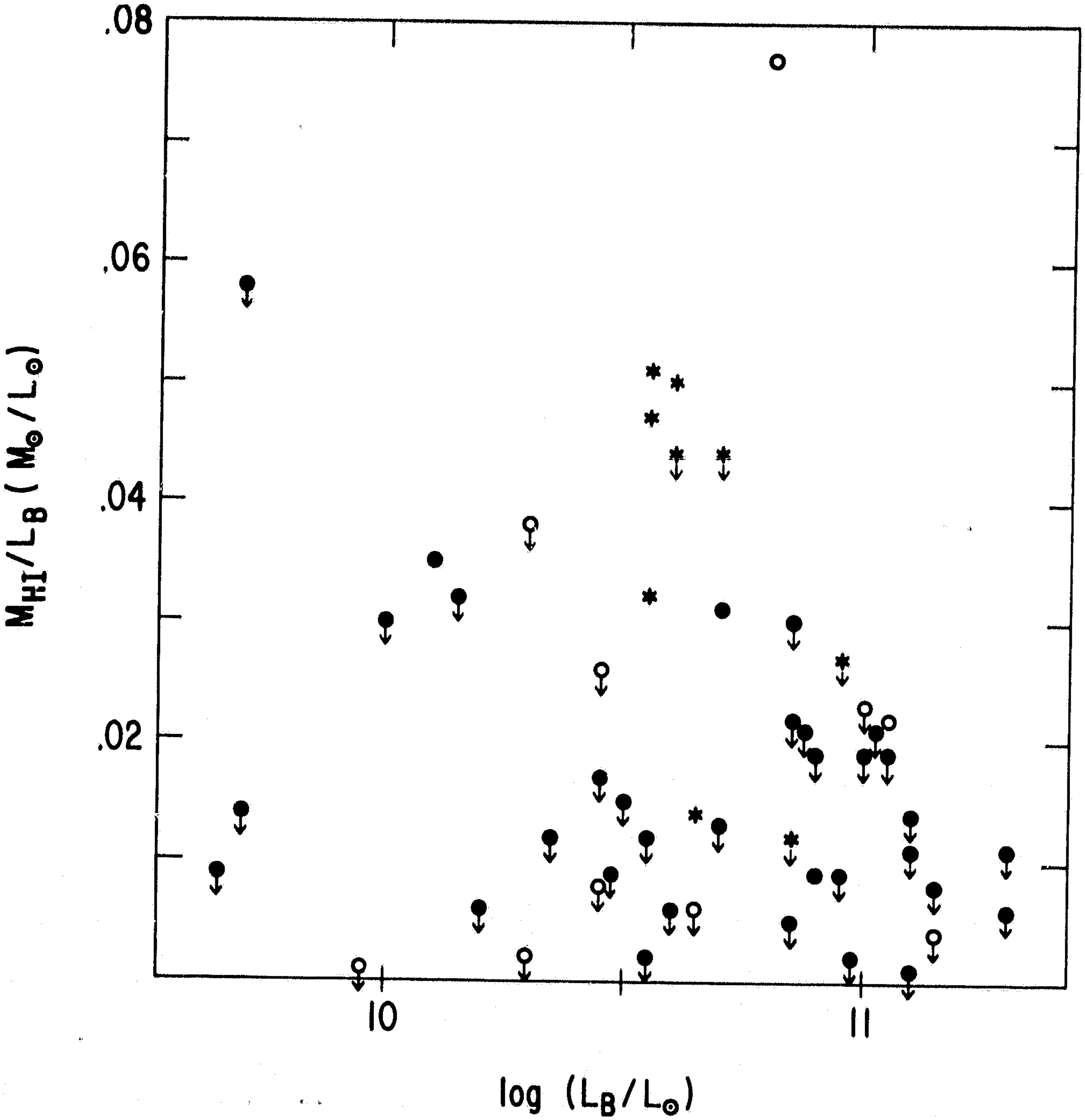
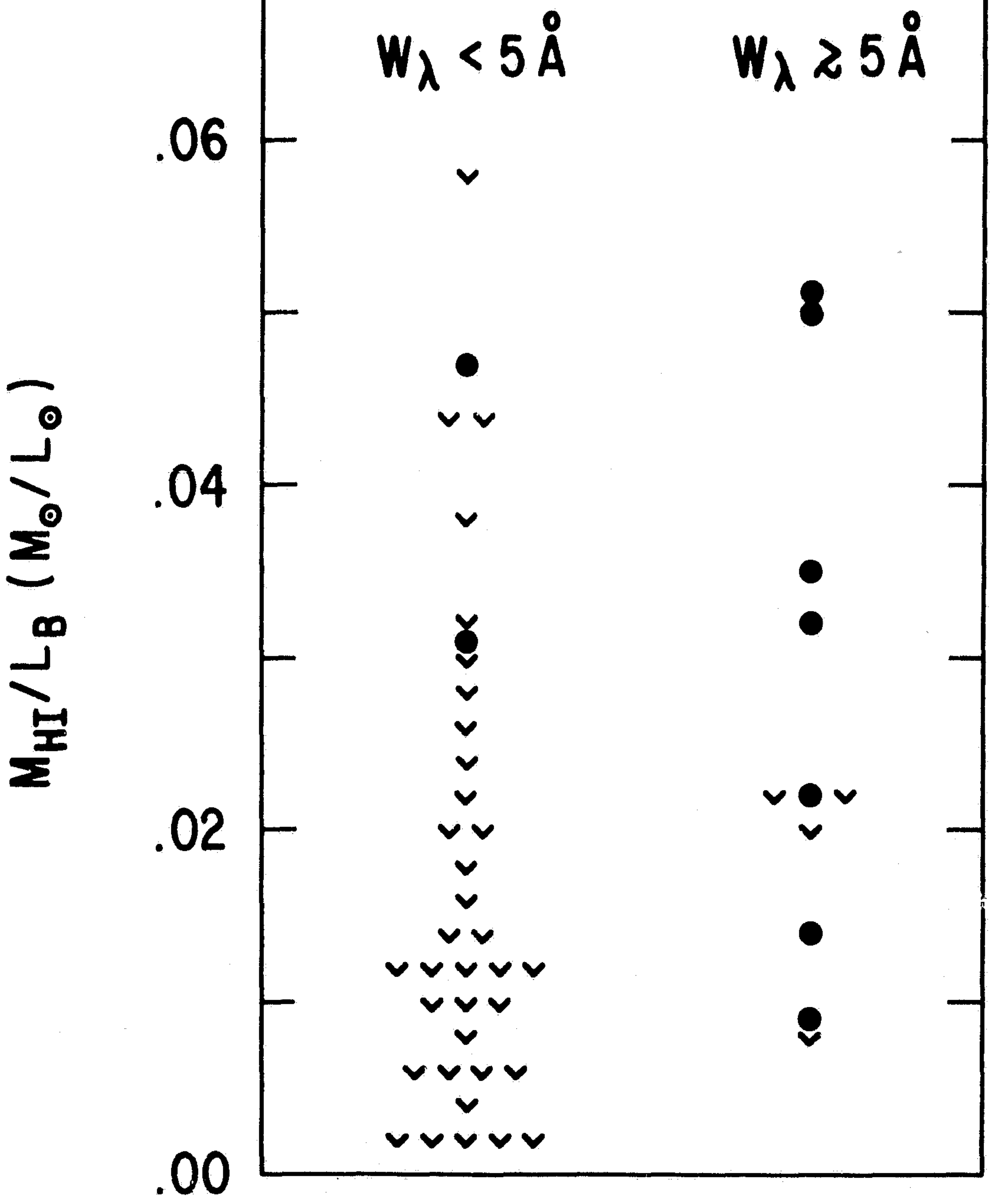
0.0
−0.90
S_ν (mJy)
8000
9000
10000
VELOCITY (km / sec)


2.8
2.7
2.6
2.5
2.4
600
450
300
log ΔV (km/sec)
ΔV (km/sec)
2.5
2.6
2.7
2.8
log $(L/L_\odot)^{1/4}$


10.0
9.0
8.0
7.0
log $M_{HI}/M_{\odot}$
20
21
22
23
log $P_{COMPACT}$ (W Hz^{-1})



.08
.06
.04
.02
10
11
M_{HI}/L_B ($M_\odot/L_\odot$)
log ($L_B/L_\odot$)



$W_\lambda < 5$ Å
$W_\lambda \gtrsim 5$ Å
.06
.04
.02
.00
M_{HI}/L_B ($M_\odot/L_\odot$)

TABLE 1: RADIO AND OPTICAL DATA FOR THE PROGRAM GALAXIES

UGC#	NGC/IC #	MAJOR DIAMETER (arcmin)	$V_{\odot}$ (km s^{-1})	DISTANCE (Mpc)	S_{total} (mJy)	$S_{compact}$ (mJy)	log $P_{compact}$ (WHz^{-1})	L_B ($10^{10}L_{\odot}$)	M_{HI} ($10^8 M_{\odot}$)	M_{HI}/L_B ($M_{\odot}/L_{\odot}$)	λ3727
01308		2.3	5173	97	26	18[a]	22.3[a]	6.7	<20.	< .030	
02112	1004	1.8	6480	119	85	36[a]	22.8[a]	10.	<19.	< .019	< 1A
03063	1587	1.8	3667	66	87	87	22.7	7.8	<16.	< .021	7A
04859	2783	2.1	6713	121	28	28	22.7	14.	<11.	< .008	9A
06671	3826	0.9	9051	164	53	53	23.2	13.	---[b]		
07378	4272	1.0	8453	155	40	40	23.1	13.	<18.	< .014	
08779	1948	1.2	6912	125	31	31	22.8	8.5	< 7.6	< .009	< 1A
09114	1989	1.3	7570	137	30	30	22.8	11.	24.	.022	23A
11718	7052	2.5	4920	95	158	61	22.8	14.	< 5.0	< .004	4A
12269	7436	2.	7409	139	28	28	22.8	19.	<11.	< .006	
12727	7728	1.0	9498	177	386	73	23.4	21.	<23.	< .011	< 1A

a) At 5000 MHz

b) Possibly detected in absorption; see text

TABLE 2: RADIO AND OPTICAL DATA FOR OTHER GALAXIES

UGC#	NGC#	MAJOR DIAMETER (arcmin)	$V_\odot$ (km s^{-1})	DISTANCE (Mpc)	S_{total} (mJy)	$S_{compact}$ (mJy)	LOG $P_{compact}$ (WHz^{-1})	L_B ($10^{10}L_\odot$)	M_{HI} ($10^8M_\odot$)	M_{HI}/L_B ($M_\odot/L_\odot$)	λ3727[c]	REF
	720	4.4[d]	1808	33	4[a]		<21.0	7.4	< 9.0	<.012	---	SRP
01631	821	3.3	1778	34	-3		<20.8	4.5	< 2.6	<.006	---	KKW
04619	2672	<2.3	4223	75	4		<21.8	11.	<23.	<.021	---	KKW
04763	2749	1.8	4236	75	46	46	22.5	7.3	<16.	<.022	8A	KKH
05562	3193	2.5	1371	21	-4		<20.3	1.5	< 0.94	<.006	---	KKW
05899	3377	4.0	718	11	5		<20.3	.87	< 0.12	<.001	---	KKH
05902	3379	3.8	885	11	-1		<20.0	2.0	< 0.33	<.002	---	KKW
	3585	2.9[d]	1491	23	0[a]		<20.6	4.8	<21.	<.044	---	GFB
06299	3608	3.0	1210	25	5		<21.0	2.0	< 7.5	<.038	---	KS
06368	3640	4.5	1354	22	9		<20.9	3.0	< 4.5	<.015	---	SRP
	3923	2.9[d]	1788	27	2[a]		<20.6	.14	<18.	<1.3	---	BGH
07118	4125	6.0	1339	27		<10[b]	<20.9	7.9	<15.	<.019	10A	G
07488	4365	5.5	1183	20	1		<20.6	4.1	< 2.6	<.006	---	HTW
07517	4387	1.5	511	20	1		<20.6	.48	< 0.63	<.013	---	KKH
07532	4406	12.	-341	20	5		<19.7	6.9	< 3.7	<.005	---	KS
07610	4458	1.5	383	20	-1		<20.5	.52	< 0.75	<.014	---	KKH
07629	4472	8.	935	20	132	55[a]	21.4[a]	13.	< 1.4	<.001	<1A	HTW
07631	4473	3.6	2275	20	-1		<20.5	2.9	< 2.7	<.009	---	HTW
07645	4478	1.7	1482	20				1.0	< 3.0	<.030	---	HTW
0766[illegible]	4494	4.5	1307	17	3		<20.6	2.9	< 7.5	<.026	---	GFB

07759	4551	1.1	978	20	4		<20.8	.52	< 3.0	<.058	---	KS
07760	4552	3.4	239	20	92	92	21.6	3.5	< 0.62	<.002	---	KKH
07858	4621	4.5	414	20	-3		<20.4	3.5	< 4.2	<.012	---	KS
07898	4649	7.	1200	21	27	27	21.2	10.	< 2.3	<.002	---	KKW
07914	4660	2.4	1017	20	2		<20.7	1.4	< 4.5	<.032	---	KS
	4697	6.0[d]	1308	24	-3[a]		<20.5	9.0	<24.	<.027	---	GFB
08745	5322	6.	1902	38	87[b]	87[b]	22.2[b]	13.	<14.	<.011	---	SRP
09183	5576	3.0	1528	27	0		<20.8	2.9	< 2.2	<.008	---	KKW
09308	5638	2.3	1677	31	6		<21.2	2.7	< 4.5	<.017	---	KKW
	5812	2.4[d]	2066	37	1[a]		<21.3	4.1	<18.	<.044	---	SRP
09678	5831	2.0	1684	31	1		<21.0	2.2	< 2.6	<.012	---	KKW
	5846A	0.5[d]	2291	31				.45	< 0.42	<.009	---	KKH
	6927A	0.8[d]	4277	82					<18.		---	KKW
12531	7626	2.4	3439	63	165	33[a]	22.2[a]	11.	<21.	<.019	<1A	KKW
12841	7785	1.8	3846	73	19		<22.1	10.	<23.	<.023	---	KKW
01503		1.0	5087	96	1		<21.9	6.0	46.	.077		HG
	1052	2.9[d]	1439	26	704	704	22.8	3.5	18.	.051	58A	FMGD
	2974	3.4[d]	1998	34	4[a]		<21.0	4.5	6.1	.014	*	BGb
	3904	2.2[d]	1613	31	-5[a]		<20.1	3.4	16.	.047	---	BGa
	3962	2.9[d]	1822	29	-9[a]		<20.0	4.0	20.	.050	*	BGc
	4105	2.4[d]	1895	31	1[a]		<20.8	3.4	11.	.032	*	BGb
07386	4278	3.5	659	15	434	434	22.0	1.3	4.6	.035	40A	KKW
07878	4636	7.	979	20	64	≲5[a]	≲20.4[a]	4.8	15.	.031	4A	KFG
09706	5846	3.0	1713	34	20	10[a]	21.1[a]	7.9	7.0	.009	*	BGb

a) At 5000 MHz

b) At 1400 MHz

c) (*,-) indicates (detection, nondetection) by Humason, Mayall, and Sandage (1956)

d) From deVaucouleurs et al. (1976)

References:

BGa Bottinelli and Gougenheim 1977

b 1979a

c 1979b

BGH Bottinelli, Gougenheim, and Heidmann 1973

FMGD Fosbury, Mebold, Goss, and Dopita 1978

G Gallagher, J.S. 1972

GFB Gallagher, Faber, and Balick 1975

HG Haynes and Giovanelli 1981

HTW Huchtmeier, Tammann, and Wendker 1975

KFG Knapp, Faber, and Gallagher 1978

KKH Knapp, Kerr, and Henderson 1979

KKW Knapp, Kerr, and Williams 1978

KS Krumm and Salpeter 1979

SRP Shostak, Roberts, and Peterson 1975

TABLE 3: RADIO POWER AND HI MASS-TO-LUMINOSITY RATIOS FOR GALAXIES WITH λ3727 EMISSION

UGC/NGC#	W_{λ} (3727)[a]	log $P_{compact}$ (WHz^{-1})	M_{HI}/L ($M_{\odot}/L_{\odot}$)
a) Galaxies with nuclear radio sources and detected HI:			
U09114	23A	22.8	.022
N 1052	58A	22.8	.051
N 4278	40A	22.0	.035
N 5846	*	21.1	.009
b) Galaxies with nuclear radio sources:			
U03063	7A	22.7	<.021
U04763	8A	22.5	<.022
U04859	9A	22.7	<.008
U11718	4A	22.8	<.004
c) Galaxies with detected HI:			
N 2974	*	<21.0	.014
N 3962	*	<20.0	.050
N 4105	*	<20.8	.032
N 4636	4A	$\lesssim$20.4	.031
d) Other galaxies:			
N 4125	10A	<20.9	<.019

a) * indicates detection by Humason, Mayall, and Sandage (1956).

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