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# A SEARCH FOR H I IN INTERCLUSTER AND COSMIC VOID SPACES

NOAH BROSCH
The Wise Observatory, Israel
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## ABSTRACT

A sample of radio-loud QSOs has been examined for the presence of narrow 21 cm H I lines originating in the redshift range from 3000 to 10,000 km $s^{-1}$ with the Arecibo radio telescope. No probable or definite absorption or emission lines have been found, putting stringent limits on the volume density of small neutral hydrogen clouds or gas-rich dwarf galaxies, both in the void toward Perseus-Pisces and in the nearby superclusters.

*Subject headings:* galaxies: clustering — galaxies: intergalactic medium — quasars — radio sources: 21 cm radiation

## I. INTRODUCTION

Studies of the three-dimensional distribution of galaxies show that on scales larger than a few Mpc, the universe, as probed by light-emitting matter, is far from uniform. Clusters and superclusters of galaxies seem to be arranged in long and narrow filaments that border huge regions, of scales from Mpc to tens and possibly hundreds of Mpc, that seem to lack appreciable manifestations of luminous matter. These empty regions are called voids. Recent observational, albeit somewhat controversial, evidence locates the luminous matter on thin walls of bubble-like structures that fill the universe (de Lapparent, Geller, and Huchra 1986).

The importance of determining the contents of voids cannot be overstressed. Theoretical scenarios that produce such large features rely on phenomena occurring in early stages of the formation of the universe (e.g. Zel'dovich, Einasto, and Shandarin 1982). Some questions related to this issue include: (*a*) how empty are the voids; (*b*) if diffuse matter is present, what is its chemical composition; and (*c*) what fraction of this material is ionized. The answers to these questions will tell, among other things, how and when the luminous galaxies formed and will indicate which of the forming mechanisms of the large-scale structure that were proposed so far may be correct.

A few attempts have been made to detect faint, yet luminous, objects residing in nearby voids. The results are at best ambiguous, indicating the possible presence of *some* galaxies in regions identified as voids. Balzano and Weedman (1982) and Sanduleak and Pesch (1982) claimed that emission-line galaxies were observed in the Bootes void. Their results were contested by Thompson (1983), and furthermore, the borders of the Bootes void were revised by Kirshner *et al.* (1984). Recently, *some* emission-line galaxies were indeed located within the revised borders of the Bootes void (Moody *et al.* 1987; Strauss and Huchra, 1988).

General ideas on the different distributional properties of galaxies have met with similar degrees of success. Davis and Djorgovski (1985) suggested that the clustering properties of high–surface brightness and low–surface brightness (LSB) galaxies are different. They proposed that, as LSBs cluster less than their more luminous relatives, they may reside even in voids, where their presence will be undetected (or undetectable) because of their extreme surface faintness. This has been shown not to be the case by the recent redshift survey of LSB galaxies done at 21 cm (Bothun *et al.* 1985, 1986).

There is a possibility that matter is present in voids, but that due to some unknown biasing process it has been unable to condense into luminous galaxies (Rees 1986). Thus a relevant question may be to what degree are the voids free of diffuse (baryonic, but nonluminous) matter. This matter may be either neutral or ionized, may have primeval abundances, or may be enriched with "metals." Searches for such candidate fillers of voids are related to the determination of the nature of matter producing the intervening absorption systems in QSO spectra.

The consensus in the literature has been that the sharp QSO absorption lines of type II, i.e., those with $z_e - z_a > 0.1z_e$, is the emission-line redshift and $z_a$ is the absorption-line redshift, originate in low-density intervening material. Bahcall and Spitzer (1969) suggested that the absorption systems showing metallic lines originate in gaseous halos of intervening galaxies. The "unidentified" lines shortward of the intrinsic Lyman-α emission have been associated with intervening gas clouds of small optical depth, so no lines but Lyα emerge (Lynds 1971), or to gas with primordial abundance, i.e., lacking appreciable amounts of metals (Boksenberg 1978).

The same ambiguity of results is the case for searches for absorption produced by H I. Field (1962) searched for intervening 21 cm absorption toward Cygnus A and put an upper limit of $2.4 \times 10^{-4}$ to the opacity of uniformly distributed neutral hydrogen. Koehler and Robinson (1966) found H I in absorption in the Virgo cluster, but not in the Fornax cluster of galaxies. In general, searches for 21 cm absorptions concentrated on identified clusters of galaxies or on absorption systems of QSOs identified previously by optical or UV observations.

In the latter case, some examples are the work of Perrenod and Chaisson (1979), with upper limits as low as $1.6 \times 10^{19}$ $cm^{-2}$ toward a few absorption systems observed in high-redshift QSOs, and the detection of 21 cm absorption in PKS 1331+170 by Wolfe and Davis (1979) with $\tau(21) = 0.02$. Moreover, Wolfe (1980) reported on a search for 21 cm absorption associated with Mg II λλ2796, 2803 and Fe II λλ2344–2600 absorption systems, which yielded only one H I absorption in PKS 1229−02 out of 16 different Mg II and Fe II systems looked at, and of a 21 cm absorption in AO 0235+164 (Wolfe *et al.* 1978). Finally, Wolfe *et al.* (1985) found a 21 cm absorption feature in PKS 0458−02, with ≃0.2 absorption. However, as mentioned before, these searches were directed toward previously identified features. No attention was specifically being paid to voids and adjacent superclusters, with the exception of the search for wide 21 cm lines in absorption in the spectra of background QSOs, produced by diffuse hydrogen clouds in superclusters (Altschuler, Davis, and Giovanardi 1987).

In order to study the content of voids, Brosch and Greenberg (1983) proposed to look for optical and UV absorption lines produced by matter in nearby, well-identified voids, in the spectra of QSOs located well beyond those voids. Nearby in this context means closer than $\simeq 150h^{-1}$ Mpc ($h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$), because the identification of voids relies on extensive redshift surveys of luminous galaxies, and to this redshift limit the completeness is reasonable. At higher redshifts, considerable numbers of fainter galaxies may be missed by magnitude-limited surveys.

Brosch and Gondhalekar (1984, hereafter Paper I) and Gondhalekar and Brosch (1986, hereafter Paper II) reported on the identification of a few Ly$\alpha$, Si IV and C IV absorption systems showing at void redshifts in *IUE* spectra of background QSOs. These detections have been interpreted by Ozernoi and Chernomordik (1986) as indicating that either the voids are filled with ionized and very low density gas, or that large numbers of dwarf galaxies abound in the voids, as many as 300 Mpc$^{-3}$ or more.

The search for neutral hydrogen in the voids has not been as successful. Krumm and Brosch (1984) looked for 21 cm emission in the Perseus-Pisces and in the Hercules voids, and put upper limits to the number of large ($>10^{10}$ $h^{-2}$ $M_\odot$) H I clouds. Hulsbosch (1987) found no clouds larger than about $3.10^{10}$ $h^{-2}$ $M_\odot$ in emission in the Perseus-Pisces void, confirming the previous results. These results indicate that the cosmic voids are not "filled" by large H I clouds. This is apparently confirmed by the recent results of the search for galaxy-sized H I clouds by Henning and Kerr (1988), where a single candidate cloud has been found and possibly identified with a faint, blue galaxy.

In order to search for 21 cm clouds not associated with luminous galaxies and residing in voids, I attempted to observe narrow 21 cm absorption and emission lines toward radio QSOs located beyond the Perseus-Pisces supercluster and associated void. The advantage in observing toward known background radio sources is that, in this way, if the conditions are favorable, absorption lines can be observed against the continuum. The sample of objects and the observing techniques are described in § II. No clouds were detected, but one of the emission detections reported by Hulsbosch (1987) was confirmed as produced by the galaxy UGC 00749. These results are presented in § III. The implications of the lack of detections, compounded with the apparent presence of UV absorption lines of ionized metals, are discussed in § IV.

## II. OBSERVATIONS

### *a) The Sample*

The search for absorption features produced by intervening matter in the spectrum of a background source and the study of weak emission lines are easier if a detection system with the highest possible sensitivity is used. For frequencies near 1400 MHz, the Arecibo[1] radiotelescope is unequalled. The location of the instrument at latitude 18° and its limitation to object zenith distances smaller than 20° imply that of the four voids identified in Brosch and Greenberg (1983) only the one in Perseus-Pisces (PPV) is fully accessible. Although other voids, like Bootes, may be more suitable for such a search, as UV absorption systems at the redshift of the void have been observed in a number of QSOs beyond it (Paper II), some evidence for the presence of *ionized* gas is available for the PPV as well (Paper I). This shall be discussed in conjunction with the results of the 21 cm search in § IV.

These reasons dictate that the search be concentrated toward radio QSOs beyond PPV. The right ascension borders of the void, as identified by Einasto, Joeveer, and Saar (1980), are $0^h \rightarrow 2^h$. This identification relies on the distribution of the Zwicky clusters, not on the actual distribution of galaxies, which usually are less concentrated. The void borders of Einasto *et al.* shall be referred to here as "the large PPV." They are, for completeness, $0^h < \alpha < 2^h$; $0° < \delta < 20°$; 6500 km s$^{-1}$ $< v <$ 9500 km s$^{-1}$.

Recently, Haynes and Giovanelli (1986) used redshift information of more than 2700 galaxies to map the three-dimensional distribution of objects in the neighborhood of the large PPV. Their Figure 3 shows the distribution of galaxies with $0° < \delta < 20°$ to 12,000 km s$^{-1}$. At least two regions empty of galaxies are easily identified; the more prominent one is at $23^h40^m < \alpha < 01^h30^m$ and 3000 km s$^{-1}$ $< v <$ 4000 km s$^{-1}$. The second, less prominent void, is located at about the same right ascension range, but spans a redshift range of 6500 km s$^{-1}$ $< v <$ 9500 km s$^{-1}$. I shall refer to these voids as "the small PPV 1" and "the small PPV 2," respectively. Note that, but for a small right ascension shift, the large PPV and the small PPV 2 have identical borders.

When planning an extensive search for features arising from matter in voids, it is advisable to observe some comparison regions that, with a high degree of certainty, are *not* in voids. Thus I decided to survey objects in the entire right ascension range from $22^h$ to $4^h$ and declination range from 0° to 20°. This includes the Perseus-Pisces supercluster, the Local Supercluster, and parts of the Pegasus supercluster.

A survey of the kind described here should comprise entirely the velocity range of the voids observed. In view of the definition of the large PPV, and of the subsequent identification of the two smaller PPVs, it seemed imperative to ensure that the frequency spread of the resultant spectra would be wide enough to accommodate all these features. In fact, it seemed indicated to *extend* the velocity coverage to include both the nearby supercluster and the background supercluster on both sides of the PPV. This imposes some constraints on the range of frequencies to be searched.

As probes of the intercluster and supercluster matter I chose QSOs from the catalog compiled by Véron-Cetty and Véron (1985). The selection criteria for the targets were (*a*) position within the stated ($\alpha$, $\delta$) limits, (*b*) redshift larger than $\simeq 0.2$, and (*c*) 21 cm flux, as extrapolated from the 11 cm flux in the catalog and with the 6 to 11 cm spectral index, higher than $\simeq 0.2$ Jy and lower than $\simeq 1.5$ Jy.

The reason for imposing a lower limit on the emission redshift is to avoid misidentifying an absorption feature as due to intervening matter in the PPV, when in fact it is produced by QSO ejecta. If the absorption line conforms to the class II definition (cf. Perrenod and Chaisson 1979), then the appearance of a narrow feature would require a high degree of coherence in momentum space, which seems rather unlikely.

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

The flux limits set in criterion (*c*) arise because of the need of a minimal signal level in the continuum of the source toward which an absorption is sought, in order to minimize the observing time spent on the source and, on the other hand, to be not so strong as to set up standing waves in the telescope feed; this may happen when observing too strong a source and may corrupt the baseline of the observation.

Table 1 shows the sources observed in this program. One object (III Zw 2) was included in the sample to be observed despite its low emission redshift, $z_e = 0.089$, because of the presence of Si IV and C IV absorption features at $z_a \simeq 0.03$ identified in Paper I as originating from the PPV. Note that even in this case the UV absorption system complies with the requirements of the class II criteria.

Table 1 gives, besides the 1950 coordinates of the objects, the expected 21 cm flux, which was calculated as explained above. The list is by no means a "complete" sample. The reasons are that the original catalog from which the sources were selected is not complete in itself and also that many objects, for which Véron-Cetty and Véron give no radio spectral index, were not included. In spite of these reasons, the number of targets is sufficient to obtain a preliminary idea on the statistical properties of absorption clouds.

In order to detect an absorption feature produced by a foreground H I cloud, in the spectrum of a background source, a number of conditions must be fulfilled. In particular, the source size should be smaller than the cloud diameter, and the cloud itself must be small with respect to the size of the beam. About half of the sources in Table 1 are known to be small, with largest sizes of order a few arcsec, as can be seen either in Barthel and Miley (1988), in Barthel (1984), or in Ulvestad *et al.* (1981). Others are not mentioned in the sources I consulted. Here I assume that *all* are small, compared with the Arecibo beam.

TABLE 1

RADIO-LOUD QSOs AND AGNs OBSERVED IN THIS STUDY

| Object | z(em) | S21 | N | R8[a] | R32[a] | Name |
|---|---|---|---|---|---|---|
| Q2120+1651.... | 1.805 | 1.95 | 3 | 10 | 9 | 3C 432.0 |
| Q2131+1733.... | 1.215 | 0.45 | 2 | 44 | 36 | 4C 17.87 |
| Q2201+1711.... | 1.076 | 0.65 | 3 | 16 | 8 | PKS 2201+17 |
| Q2222+0511.... | 2.324 | 0.83 | 2 | 22 | 13 | PKS 2222+05 |
| Q2248+1915.... | 1.806 | 0.80 | 2 | 19 | 17 | 4C 19.74 |
| Q2251+1120.... | 0.323 | 1.44 | 3 | 10 | 8 | PKS 2251+11 |
| Q2254+0727.... | 0.496 | 0.92 | 2 | 39 | 31 | PKS 2254+07 |
| Q2305+1845.... | 0.313 | 0.76 | 3 | 16 | 13 | PKS 2305+18 |
| Q2308+0951.... | 0.432 | 0.47 | 3 | 24 | 18 | 4C 09.72 |
| Q2320+0755.... | 2.090 | 1.05 | 2 | 16 | 13 | PKS 2319+07 |
| Q2344+0914.... | 0.677 | 1.53 | 2 | 10 | 9 | PKS 2344+09 |
| Q2345+0608.... | 1.546 | 0.77 | 2 | 28 | 22 | PKS 2345+06 |
| Q2354+1429.... | 1.010 | 1.03 | 2 | 18 | 14 | PKS 2354+14 |
| Q0003+1553.... | 0.450 | 0.72 | 2 | 20 | 16 | PKS 0003+15 |
| Q0007+1041.... | 0.089 | 0.12 | 3 | 46 | 36 | III Zw 2 |
| Q0007+1707.... | 1.601 | 0.68 | 2 | 22 | 17 | PKS 0007+17 |
| Q0033+1536.... | 1.160 | 0.54 | 2 | 36 | 28 | MC 0033+15 |
| Q0033+0951.... | 1.918 | 0.50 | 2 | 23 | 18 | 4C 09.01 |
| Q0041+1154.... | 0.228 | 0.68 | 2 | 23 | 18 | MC 0041+11 |
| Q0109+1737.... | 2.157 | 0.59 | 3 | 25 | 20 | PKS 0109+17 |
| Q0146+0541.... | 2.345 | 0.44 | 3 | 22 | 17 | PKS 0146+05 |
| Q0158+1822.... | 0.799 | 1.18 | 3 | 13 | 10 | PKS 0158+18 |
| Q0212+1708.... | 0.472 | 0.69 | 3 | 22 | 17 | MC 0212+17 |
| Q0214+1050.... | 0.408 | 1.25 | 2 | 16 | 13 | PKS 0214+10 |
| Q0223+1120.... | 0.924 | 0.41 | 2 | 31 | 25 | MC 0222+11 |
| Q0238+1005.... | 1.816 | 0.33 | 3 | 36 | 28 | MC 0238+10 |
| Q0353+1223.... | 1.616 | 0.67 | 1 | 37 | 28 | PKS 0353+12 |
| Q0404+1742.... | 1.712 | 0.44 | 2 | 25 | 19 | MC 0404+17 |

[a] R8 and R32 are $10^4$ times the root mean square deviations from the mean of 1.0 of the antenna temperature in the final, baselined, total power spectra, with spectral resolution of 8 or 32 km s$^{-1}$. The derivation of this quantity is explained in § III*a*.

Suppose that the situation in reality is that of a small H I cloud, located in the void or in the supercluster, seen against the strong radio background of the target QSO. If the cloud is small relative to the beam size but larger than the radio QSO's size, an absorption feature may be detected in the baselined spectrum. Specifically, the cloud needs to be smaller than about 6 kpc, at the typical distances covered by this survey, to have a beam filling factor smaller than 0.01, i.e., some 30" in diameter. This will be justified *a posteriori* by arguing that the results presented here are most relevant to the space density of dwarf galaxies, with sizes less than about 6 kpc (§ IV*a*). The hidden assumption is that there is only one such cloud in the beam, so that C, the covering factor by the H I, is small.

The restriction may be expressed in the form $\Delta T_{em}/\Delta T_{abs} = C(T_s/T_a)$, where $T_s$ is the spin temperature, which may reach 1000 K, and $T_a$ is the antenna temperature, typically 7 K. Thus, provided $C < 0.01$, the absorption will dominate over the emission.

### b) *The Observational Procedure*

The Arecibo radiotelescope and its performance are described in Haynes and Giovanelli (1984) and in Schneider (1985). I used the 22 cm receiver with the 40 MHz correlator with 2048 channels. The receiver has a forward gain of 6.5–7.5 K Jy$^{-1}$ from 1365 MHz to 1385 MHz. Half of the 2048 channels were set to observe a 20 MHz bandwith in one polarization, while the other half were set to observe the same frequency band in the orthogonal polarization. The channel spacing in frequency was thus 19.531 kHz.

The survey was conducted by observing each object twice. One such individual observation consisted of a 5 minute integration on source (ON scan) and a 5 minute integration off source (OFF scan) with the telescope feed tracking the same declination and zenith distance as for the ON scan. The local oscillator was reset after the first ON-OFF pair so as to provide two radial velocity segments, one centered at 8750 km s$^{-1}$ and the second centered at 5250 km s$^{-1}$, while the 40 foot (12.2 m) dual circular feed was refocused to the new central frequency. All velocities in this paper are heliocentric. The entire frequency space searched in the present survey was from 1405.976 to 1370.151 MHz. This corresponds, in redshift space, to $0.010 < z < 0.035$ (3050 km s$^{-1}$ $< v <$ 10600 km s$^{-1}$). The overlap between the two 20 MHz frequency bands was 4.175 MHz $\simeq$ 900 km s$^{-1}$.

In actual observation, it was found that the frequency ranges 1393.4–1394.2 MHz and 1399.8–1400.2 MHz were affected by strong interference, probably from nearby radar transmitters. These frequency segments were excised from the data and were replaced by neighboring values.

The spectra were Hanning-smoothed once, to reduce ringing due to the excised interference spikes and to improve the signal-to-noise ratio. This reduces the effective velocity resolution to about 8.2 km s$^{-1}$. The two correlator halves of orthogonal polarizations were averaged, after subtracting the OFF from the ON scans, in a total power configuration. The resultant spectrum was corrected for bandpass response by dividing each total power spectrum with a smoothed version of itself. The smoothing was done with a boxcar averaging of 99 channels = 1.934 MHz width $\simeq$ 420 km s$^{-1}$. This procedure, although straightforward and unbiased, limits the detection of *wide* features in the spectrum. In particular, because of this reason, I did not search the final spectra for features wider than $\simeq 100$ km s$^{-1}$. The end segments of each ON-OFF, baseline-compensated spectrum were excised to eliminate end-of-bandpass effects. This amounted to 0.39 and 1.62 MHz.

The result of the baseline compensation operation, after combining the two frequency segments with equal weights in the overlap region in a single, baselined, spectrum, is a spectrum-like vector covering $\simeq 7200$ km s$^{-1}$ (34.2 MHz) with an effective resolution of $\simeq 8$ km s$^{-1}$, and centered at $\simeq 7150$ km s$^{-1}$.

Note that the result of the baseline compensation is not a proper spectrum, but the ratio $\Delta T/\langle T \rangle$ at any spectral point, where $\langle T \rangle$ is the mean local antenna temperature in a given $\sim 100$ channel wide segment, and $\Delta T$ is the local deviation from this mean antenna temperature. This peculiar baseline compensation is useful when searching for narrow lines of small equivalent width, such as those expected here. In order to rule out "false alarm" detections, most objects were observed more than once. This proved to be useful in rejecting apparent detections in a number of cases. Figure 1 demonstrates the final stage of data reduction.

Note also that the procedure selected for baseline compensation allows for a straightforward estimation of the error in the measurement, without having to consider individual sources of noise. The expectation is that a noiseless system will show a flat response after the division by the smoothed baseline. The fluctuations seen on top of the flat baselined power spectrum ($\Delta T$), imply that a number of noise sources combine to reduce the sensitivity of the system for detecting narrow absorption (and emission) features. Thus, by measuring the rms scatter of the normalized antenna temperature ($\Delta T/\langle T \rangle$), an upper limit for the detection of such features can be obtained.

The acceptance criteria for one line of $\lambda = 21$ cm were set before the start of the observations to a situation where (*a*) a change must be at least 3 $\sigma$, where $\sigma$ is the measured rms scatter of the normalized antenna temperature from the 1.0 average, assuming a normal distribution of residuals; (*b*) the change should appear in both polarization halves of the correlator; and (*c*) the change should appear in more than one spectral observation, possibly with less than 3 $\sigma$ amplitude but at the same frequency. The reasons for the restrictiveness of these acceptance criteria were that the mere detection of 21 cm absorption or emission features arising from matter not associated with galaxies has strong cosmological implications, as was explained in § I, and it was felt that it is better to err on the safe side and reject features that are not very convincing than to accept observational artifacts.

## III. RESULTS

### *a) Upper Limits*

All spectra of a single object were averaged with equal weights to one final spectrum for each object. Table 1 presents the results of the survey, in the form of rms deviations from the mean of 1.0 of the final spectra, for the full resolution after processing (8.2 km s$^{-1}$) and after Hanning-smoothing twice to an effective resolution of 32.4 km s$^{-1}$.

The 3 $\sigma$ upper limits to the optical depth of any absorption feature have been obtained from the normalized rms antenna temperature $\Delta T/\langle T \rangle$, as

$$\tau = -\ln\left[1\text{-}3\left(\frac{\Delta T}{\langle T \rangle}\right)\right] . \quad (1)$$

The corresponding upper limit of the neutral hydrogen column density $N_{\rm H}$ is obtained from

$$N_{\rm H} = 1.83 \times 10^{18} T_s \tau \Delta v \text{ cm}^{-2} . \quad (2)$$

Here $T_s$ is the spin temperature and $\Delta v$ is the width of the putative absorption feature, taken to be the effective resolution of the spectrum.

The rms normalized antenna temperature, averaged over all objects in Table 1, is $(2.7 \pm 2.0) \times 10^{-5}$. This corresponds to a 3 $\sigma$ upper limit to the optical depth, as defined above, of $8 \times 10^{-3}$, or to a 3 $\sigma$ upper limit of H I column density of

$$N_{\rm H} < 1.3 \times 10^{17} T_s \text{ cm}^{-2} \quad (3)$$

for the $\simeq 8$ km s$^{-1}$ resolution data. For the objects with the lowest rms antenna temperature, this decreases to $4.8 \times 10^{16} T_s$ cm$^{-2}$. The Hanning-smoothed data with $\simeq 33$ km s$^{-1}$ resolution has lower rms antenna temperatures, with an average 3 $\sigma$ upper limit of H I at $N_{\rm H} < 4.2 \times 10^{17} T_s$ cm$^{-2}$, higher than the upper limit for the $\simeq 8$ km s$^{-1}$ data, because of the larger $\Delta v$ factor is the derivation of $N_{\rm H}$. A similar behavior has been noticed by Perrenod and Chaisson (1979) in their search for 21 cm absorptions in high redshift quasars.

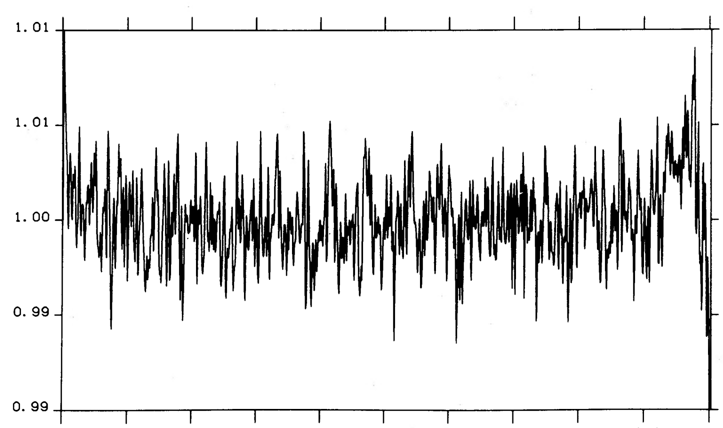


FIG. 1.—Example of final stage of reduction: baselined total power scan of Q2201+1711

### b) *Detections*

Hulsbosch (1987) reported the possible detection of emission features in PPV, observed with the Dwingeloo radio telescope. He observed one location more than once and apparently the detection was confirmed. As the Dwingeloo radiotelescope has a 30′ wide beam, I decided to observe all locations observed by Hulsbosch from Arecibo with the same experimental setup as used for the main survey. The only difference was at the processing stage, where the baseline compensation was performed by subtracting a third-degree polynomial best fitted to the observations. In the absence of a strong continuum signal in the ON position, the total power spectra were essentially flat, with the exception of some low-level oscillatory behavior, presumably induced by the radar interference reported above.

All Hulsbosch's (1987) positions but one showed no emission, to a 3 $\sigma$ limit of $\simeq 10$ mJy per resolution element (8.2 km $s^{-1}$) per beam area. The location was observed twice by him, and, where he reported a detection, it coincides with the galaxy UGC 00749. This is an "integral sign" galaxy (Nilson 1973) that was detected in 21 cm emission by R. Giovanelli (private communication). In Figure 2, I present the H I profile resulting from the average of four 5 minute ON and 5 minute OFF integrations, with the local oscillator set to center the 20 MHz bandwidth at 6900 km $s^{-1}$. I checked also the position of the companion galaxy, UGC 00747, that could have contributed 21 cm emission in the Dwingeloo beam. No detection was obtained from this object in the entire velocity band from $\simeq 3000$ to $\simeq 8000$ km $s^{-1}$, to a 3 $\sigma$ uper limit of $\simeq 10$ mJy per resolution element.

## IV. DISCUSSION

### a) *The* H I *Upper Limits*

The stated aim of this survey was to detect small H I clouds that are not related to luminous galaxies. Here I estimate the expected number of such clouds.

Each line of sight toward a QSO probes a distance of (106–30.5)$h^{-1} = 75.5h^{-1}$ Mpc. The actual volume sampled by each line of sight depends on the impact parameter expected from an H I cloud; for a cloud with radius $r$ the sampled volume is $2.4 \times 10^{-4}(r/1 \text{ kpc})^2\ h^{-1}$ Mpc$^3$. Large galaxies ($r \simeq 15$ kpc), which imply large search volumes, are relatively rare with a volume density of $\simeq 10^{-2}$ Mpc$^{-3}$. Assuming such galaxies are

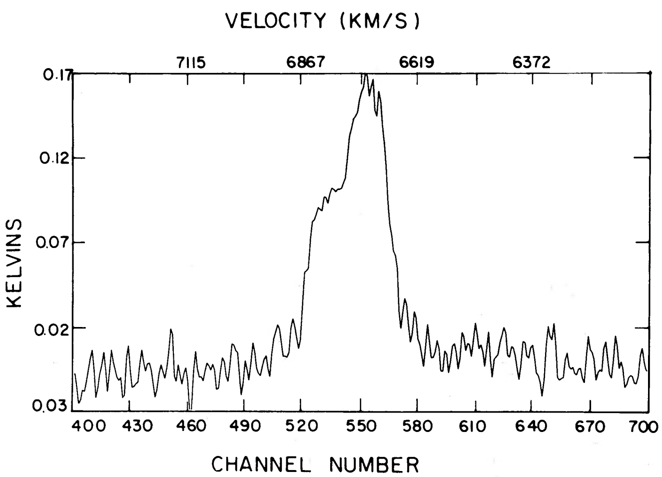


FIG. 2.—Velocity profile of UGC 00749

subluminous in the voids, to prevent their being detected easily by optical means, would yield only $5 \times 10^{-2}$ detections per line of sight, or an expected total of about one for the whole survey. It is possible that such low expected values may have escaped detection altogether, besides invoking the unpalatable choice of underluminous large galaxies. Note also that the lack of detections limits the space density of huge subluminous galaxies similar to Malin 1 (Bothun *et al.* 1987) to less than $10^{-3}$ $h^3$ Mpc$^{-3}$.

If, however, dwarf galaxies (DGs) are very abundant, and if, as Dekel and Silk (1986) suggest, they should be formed everywhere, their sheer numbers may prevail despite their small size, and absorption lines may be detected. To estimate this possibility, the size distribution and the volume density of dwarf galaxies are considered.

Recently Tyson and Scalo (1988, hereafter TS) found that the distribution function of galactic radii for DGs should behave as:

$$f(r) = 3\left(\frac{r}{1 \text{ kpc}}\right)^{-4.2} . \qquad (4)$$

The lower limit of a DG radius, taken in TS to represent the threshold surface density of H I where star formation ceases, $N(\text{H I}) = 5 \times 10^{20}$ cm$^{-2}$, was found to be smaller than 0.5 kpc, possibly as low as 0.2 kpc. In the latter case, the volume density of DGs could be as high as 160 Mpc$^{-3}$!

The observations of H I absorptions reported here are sensitive to lower column densities than the star formation cutoff adopted by TS; thus the lower limit of the radii may be extended. Following the guidelines of TS and assuming that $N$(H I) scales as the surface brightness, which in turn has the behavior of an exponential disk:

$$I(r) = I_0 \exp(-\alpha r) \qquad (5)$$

with a scale length $\alpha^{-1} = 1$ kpc. I find that the upper limit of detectable neutral hydrogen reported here of $\simeq 10^{17} T_s$ cm$^{-2}$ implies the extension of the lower limit of the radii from $r_{\text{TS}}$ to

$$r_L = r_{\text{TS}} + 8.5 - \ln(T_s) \text{ kpc} . \qquad (6)$$

The proper choice of spin temperature of neutral hydrogen in extragalactic objects is difficult and has been discussed several times in contexts similar to that of the present paper. One of the latest contributions to the subject is by Watson and Deguchi (1984) about the Leo cloud and concludes that $T_s$ may range anywhere from $\simeq 10$ K up to $10^3$ K. Therefore $r_L = r_{\text{TS}} + (1.6\text{–}6.2)$ kpc. For both $r_{\text{TS}}$ values of 0.2 and 0.5 kpc, $r_L$ is larger than or of order 2 kpc. I adopt therefore a 2 kpc lower limit of radius for DGs (10″ at the typical survey distance), where the neutral hydrogen surface density drops to $10^{17} T_s$ cm$^{-2}$. This brings the volume sampled by each line of sight to at least $10^{-3}\ h^{-1}$ Mpc$^3$.

The total number of lines of sight surveyed here is 27 (equal to the number of entries in Table 1). Therefore the total surveyed volume is larger than $\simeq 3 \times 10^{-2}\ h^{-1}$ Mpc$^3$. If the number of DGs is indeed $\simeq 160$ Mpc$^{-3}$ as TS calculated, then some five absorption features should have been detected in this survey, whereas none has been. Note also that if the number density of DGs is as large as proposed by Ozernoi and Chernomordik (1986, hereafter OC), 300 Mpc$^{-3}$, then about nine features should have been observed in this survey.

Consider also the possibility that dwarf galaxies are distributed more or less uniformly in space, but may change their appearance from dwarf ellipticals in clusters of galaxies to gas-rich irregulars in the intercluster space due perhaps to ram pressure stripping in the cluster environment. The structural properties of dwarf spheroidal galaxies and late-type dwarfs are similar (Kormendy 1987), thus a comparison based on cluster data is valid. The luminosity function of dwarf galaxies has been studied by Sandage, Binggeli, and Tammann (1985, hereafter SBT) in the Virgo cluster and for the dE galaxies in the sample has the form

$$\phi(M) = \text{dex}\,[0.14(14.3 - M)]\,. \tag{7}$$

The SBT luminosity function is determined for galaxies brighter than $M_B \simeq -12$. But even fainter galaxies exist, such as M81 dwA with $M_B = -11.0$ (Sargent, Sancisi and Lo 1983), and the dwarfs of the Local Group, of which at least 13 are fainter than $-12$ absolute magnitude. This justifies the extension of the Virgo luminosity function to fainter galaxies, although it should always be kept in mind that at very faint magnitudes dwarf galaxies and globular clusters could be confused.

The volume density of dE+Im galaxies in the Virgo standard region is $\simeq 33$ Mpc$^{-3}$ for $M_B < -12$ (SBT). Going to dwarfs as faint as $M_B \simeq -10$ would double the volume density and would bring the number of such objects expected in the survey sight lines to approximately four. The lack of detections shows again that the nature of objects present in the intercluster space is different from that of "normal" dwarf galaxies. Some speculations on this nature shall be offered below.

In one instance, the AGN III Zw 2 was reported in Paper I to show absorption lines from C IV and Si IV at the redshift of the PPV. It was not possible to detect Lyman-$\alpha$ in absorption, as this object has a strongly decreasing flux shortward of its intrinsic Lyman-$\alpha$. We have derived in Papers I and II the column density of hydrogen from the cases where Lyman-$\alpha$ *has* been detected, by assuming damped Lyman lines. This amounted typically to $\simeq 10^{19}$ cm$^{-2}$ which, together with the limit derived above, indicates $T_s > 100$ K. If, however, the Ly$\alpha$ lines are not saturated, as proposed by OC, the column density of hydrogen is lower, $\simeq 10^{14}$ cm$^{-2}$, and the derivation of the spin temperature is meaningless.

We cannot determine unambiguously from the *IUE* spectra whether Ly$\alpha$ is saturated or not. Better spectral resolution is required for this. The UV spectra, on the other hand, do not confirm either of the two possibilities put forward by OC. If the absorption lines were formed by numerous dwarf galaxies uniformly distributed in the void, the lines should have been broadened to the full cosmological width of the void, some 3000 km s$^{-1}$. This is easily resolved by *IUE* (6 Å resolution at 1550 Å is 1200 km s$^{-1}$). A similar argument can be put forward for the second possibility proposed by OC, that the absorption lines are formed in a dense shell around the void. In this case the two sides (near and far) of the void ought to produce similar lines, separated by two resolution elements of *IUE*, thus again easily detectable.

In Papers I and II we argued that because the UV absorption lines showed different behavior toward different QSOs behind the same void, to the degree of not exhibiting C IV and Si IV absorptions at all in some cases, the ionized gas within the voids should be localized and not permeating the voids. The picture that emerges from these data is of some (small?) clouds, composed of (dense?) highly ionized, metal-enriched gas. One theoretical model which fits this description is that of the dark minihalos containing hot gas that was proposed by Rees (1986) in a cold dark matter cosmological scenario, with the only difference that here the halos should contain metals. These entities, says Rees, are more likely to survive being incorporated in larger structures if they are located in voids. Thus a test of this could be a search for absorption lines as reported in Papers I and II which is not limited to nearby voids, but which comprises nearby (super)clusters as well.

### *b) The Case of U00749*

It was reported above that of all Hulsbosch's possible detections only the one corresponding to U00749 was confirmed. The centroid of the velocity profile is at $6760 \pm 10$ km s$^{-1}$. The location, at $01^h08^m56^s$ and $+01°03'21''$ and at this redshift, corresponds to the near edge of the small PPV 1. Figure 3 of Haynes and Giovanelli (1986) demonstrates that the near edge of this void is *defined*, at this right ascension, by a single object that presumably is UGC 00749. The galaxy appears to be rather isolated, with the possible exception of its undetected neighbor UGC 00747. It is therefore possible that U00749 is a genuine galaxy in the void, although not in a central position. Thus a listing of its observational properties may be worthwhile.

The velocity profile of the galaxy, shown in Figure 2, is broad, with a full width at the 0.20 level of $\simeq 220$ km s$^{-1}$. The profile is asymmetric, with a low-velocity peak next to a high-velocity plateau, both with a similar width. This may be the result of a major warp of the galaxy disk, although such a feature is not immediately apparent in the optical picture. The appearance of the galaxy on the Palomar Sky Survey prints is peculiar, as noted also in the UGC; "integral-shaped, patchy, spiral arm to southwest (bridge to U747?), blue condensation 0'.15 × 0'.15 attached at northern side, companion ?" The northern arm, with the blue condensation, appears thicker than the opposite arm and is also shorter.

U00749 shows signs of intense star formation. Not only the presence of the "blue condensation" points to this, but also its being an *IRAS* point source (IRAS 01089+0103), with fluxes of 1.35 Jy at 60 $\mu$m and 2.66 Jy at 100 $\mu$m. At the 21 cm redshift, the distance is $D = 67.6h^{-1}$ Mpc. The 80 $\mu$m luminosity is given by

$$L_{\rm IR} \simeq 6 \times 10^5 D^2 (2.58 f_{60} + f_{100})\, L_\odot\,. \tag{8}$$

This amounts to $1.7 \times 10^{10}\, h^{-2}\, L_\odot$. The blue magnitude of the galaxy, from UGC, is 14.2. At its distance, the blue luminosity is $L_B \simeq 1.3 \times 10^{10}\, h^{-2}\, L_\odot$. The high ratio of $L_{\rm IR}$ to $L_B$ is another indication of intensive star formation and should be compared with the typical value of 0.4 for Shapley-Ames galaxies (de Jong *et al.* 1984).

The total hydrogen content is obtained from

$$M(\text{H I}) = 2.36 \times 10^5 D^2 \int S\, dv\, M_\odot\,. \tag{9}$$

The flux integral, from the profile in Figure 2, is $4.3 \pm 0.8$ Jy km s$^{-1}$. Thus $M(\text{H I}) \simeq (4.6 \pm 0.9) \times 10^9\, h^{-2}\, M_\odot$. The ratios $M_{\rm H}/L_B$ and $M_{\rm H}/L_{\rm IR}$ are 0.3 and 0.4, respectively

The thick central lens shows signs of a dust lane, starting from the joinure of the fainter and thinner southern arm to the center of the galaxy. The peculiar shape and the signs of enhanced star formation may indicate a kinship between this galaxy and others found in voids (Moody *et al.* 1987; Strauss and Huchra 1988).

## V. CONCLUSIONS

1. A search for 21 cm absorption lines at redshifts of well-defined nearby voids and superclusters, sensitive to H I in dwarf galaxies, yielded no detections in 27 different sight lines.

2. The lack of detections, compared with the values expected from different predictions of the volume number density of dwarf galaxies in the universe, indicates that theories attempting to explain the Lyman-$\alpha$ forest by large numbers of gas-rich dwarf galaxies probably overestimate their numbers.

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NOAH BROSCH: Wise Observatory and the School of Physics and Astronomy, Beverley and Raymond Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel