THE ASTROPHYSICAL JOURNAL, 243:L23–L26, 1981 January 1

UPPER LIMITS ON THE SPACE DENSITY OF INTERGALACTIC NEUTRAL HYDROGEN CLOUDS

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Received 1980 July 21; accepted 1980 September 19

ABSTRACT

A survey in the 21 cm line of H I of 153 square degrees of sky out to a distance corresponding to 3000 km s^{-1} and with a limiting sensitivity of $3 \times 10^6 D^2\, M_\odot$ has failed to turn up any convincing detections that are unassociated with a visible counterpart. These results, combined with previous limits, lead to the conclusion that the mass in intergalactic H I clouds in the interval $10^7\, M_\odot$ to $10^{10}\, M_\odot$ is less than 6% of the mass in galaxies and less than 5×10^{-4} times the density required for a closed universe (assuming $H_0 = 100$ km s^{-1} Mpc^{-1}).

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

I. INTRODUCTION

Since the landmark analysis by Gunn and Peterson (1965) which established a limit on the Lα absorption trough in the spectrum of a QSO, it has been evident that the density of uniformly distributed intergalactic neutral hydrogen is very low. Subsequently, there have been attempts to observe discrete H I clouds, either in absorption of the 21 cm line against distant radio continuum sources or in 21 cm emission. The only noncontroversial detections have been in the vicinity of galaxies (Roberts 1968; Davies 1974; Mathewson, Cleary, and Murray 1974; Burke 1978; Haynes, Giovanelli, and Roberts 1979). Neutral hydrogen in emission has been observed in the direction of the Sculptor group (Mathewson, Cleary, and Murray 1975) and somewhat removed from M33 (Wright 1974), but these clouds may actually be associated with our own Galaxy (Haynes and Roberts 1979; Wright 1979). There has been a failure to detect isolated H I clouds unambiguously, in spite of several recent surveys that have achieved extensive sky coverage (Shostak 1977; Materne, Huchtmeier, and Hulsbosch 1979; Lo and Sargent 1979; Haynes and Roberts 1979).

As a by-product of a program by the authors to determine the redshifts of nearby galaxies, roughly 153 square degrees of sky have been observed to a depth of 30 h^{-1} Mpc ($h = H_0/100$) and with a limiting sensitivity of $3 \times 10^6 D^2\, M_\odot$ (D is the distance in Mpc). This combination of volume explored and sensitivity represents a substantial gain over the earlier surveys.

In several instances, signals were detected from areas that are empty fields on the Palomar Sky Atlas. However, either faint dwarf galaxies were discerned on deeper plates (e.g., at 0907.5–3309) or the emission was ultimately found to append to a visible galaxy (e.g., NGC 2146, Fisher and Tully 1976). A few marginal signals have not been confirmed or rejected. However, with 98% of the survey satisfactorily completed, there is no convincing detection unassociated with an optical counterpart.

[1] Operated by Associated Universities, Inc., under contract with the US National Science Foundation.

II. OBSERVATIONS

Observations were made with the 91 m and 43 m telescopes at Green Bank, in each instance with the same dual-channel paramp with a system temperature of 50 K and with the same adjacent sky reference technique. The procedures and calibrations are described by Fisher and Tully (1975). Integration times on the 91 m telescope were 4 minutes on and 4 minutes off, while on the 43 m telescope they were 1 hr on and 1 hr off. Given the ratio of the telescope apertures, the sensitivity to an unresolved source was about the same for both telescopes. The standard bandwidth was 17 MHz centered to provide coverage from −300 to +3000 km s^{-1}.

With spectral resolution of 104 kHz (22 km s^{-1}), a 0.09 Jy source in the center of the beam would represent a threshold (5 σ) detection. The average response to a point source randomly placed in a circular beam is 70% of the beam-center response, so the effective flux density limit is $S_{\min} = 0.13$ Jy. The H I mass is determined by summing flux densities, S, over all velocities:

$$M_{\rm H} = 2.36 \times 10^5 D^2 \int S dv\, M_\odot\,, \qquad (1)$$

where S is in janskys, v is in km s^{-1}, and D is in Mpc. If the expected line-profile width were 100 km s^{-1}, the minimum detectable H I mass would be $3 \times 10^6 D^2\ M_\odot$. A line width exceeding 100 km s^{-1} would not be expected of an intergalactic cloud in which most of the mass is in the form of neutral hydrogen (certainly not for clouds with $M_H < 10^9\ M_\odot$), so this minimum detectable mass is considered conservative.

Some 1430 galaxies were observed with the 91 m telescope and a half-power beam width (HPBW) of 10′.8, while 290 galaxies were observed with the 43 m and a HPBW of 21′. A single observation involved an "on" and an "off" beam, so the total sky coverage was 72 and 56 square degrees with each of the respective telescopes. In addition, a deliberate search was conducted with the 91 m telescope for optically invisible galaxies or H I clouds in the vicinity of the M81 group. With the same integration times and bandpass used in the main program, 970 beam areas or 25 square degrees were observed, and with effectively twice the integration time but half the bandpass (coverage to +1300 km s^{-1}) 770 beam areas or 20 square degrees were observed. Except for emission in close proximity to M81 already reported by Davies (1974), there were no firm detections.

The sky coverage, redshift coverage, and sensitivity of the present survey are compared in Table 1 with results from the earlier investigations.

III. RESULTS

If intergalactic H I clouds are randomly distributed, the probability of the detection of a cloud within a given mass interval is $\phi(M_H) \times V(M_H)$, where ϕ is the luminosity function and a volume V has been observed that is dependent on cloud mass. Shostak (1977) chose to define an upper limit to the function ϕ such that, over all mass intervals, there was only a 1% probability on the basis of Poisson statistics that his function was an underestimate of the true space density. Phrased differently, if ϕ is as large as his limit, then the probability of *not* detecting anything over all mass intervals is only 1%. However, this choice of 1% is arbitrary. If observations by different observers are to be intercompared, there is the difficulty that sensitivity and bandpass limits differ; so each observer is sensitive to a slightly different mass range.

For simplicity, in this *Letter* ϕ has been defined such that $\phi V = 1$. In fact, this definition is the same as Shostak's (1977) to within 15%. In this case, the Poisson probability of more than four detections in a specific mass interval in the volume surveyed is 4×10^{-3}. The choice of the mass interval to be a mass decade establishes the scale for ϕ. Consequently, if ϕ describes the actual luminosity function, then across three decades there is a 50% probability of more than two detections in the volume surveyed, but the chance of there being more than seven is only 1%. These limits are in line with the number of possible detections near the survey limit that have not been confirmed. By comparison, if the actual frequency of H I clouds is *twice* the limit that has been proposed, there is a 50% probability that more than five detections would have been recorded and a 1% probability there would have been more than 12. Phrased in the manner Shostak (1977) preferred, the probability is 95% that the true number density is less than the limits set here across the interval $10^7 h^{-2} < M_H < 10^{10} h^2 - M_\odot$.

An H I cloud of mass M_H can be observed to a distance D determined from equation (1). A volume $V = \pi\theta^2 D^3/12$ is explored in each beam, where θ is the half-power beam width, and the distance cannot exceed the limit $30h^{-1}$ Mpc imposed by the receiver bandwidth. Consequently, $\phi = 1/V$ can be calculated as a function of M_H.

The results are summarized in Figure 1. Clouds with H I masses exceeding $3 \times 10^9 h^{-2}\ M_\odot$ can be observed to the limiting distance established by the receiver bandwidth; so, for greater masses, $\phi = 1/V =$ constant. For lower masses, $1/V \propto M_H^{-3/2}$. At velocities corresponding to distances less than $2h^{-1}$ Mpc, detections might be lost because of local emission. This limit roughly corresponds to $M_H = 10^7 h^{-2}\ M_\odot$.

For comparison, the results of the earlier surveys have been included in Figure 1. All data have been adjusted to a Hubble constant of $100h$ km s^{-1} Mpc^{-1}, and flux density limits have been adjusted to reflect the assumption that the flux is distributed over 100 km s^{-1}. Estimates have been made of the area each author surveyed, the system sensitivity, and the redshift cutoff. Beam-centering and one-bit autocorrelator sensi-

TABLE 1

COMPARATIVE SYSTEMS PARAMETERS

Reference	S_{min} (Jy)	Sky Coverage (sq. deg.)	Bandpass Limiting Distance (h^{-1} Mpc)	$D(M_H)$ [$10^{-4}\sqrt{(M_H)}$ h^{-1} Mpc]
Haynes and Roberts...	0.32	50	15.5	3.6
	0.32	10	21	3.6
Lo and Sargent........	0.8	175	7	2.3
	0.8	72	9	2.3
Materne *et al*..........	0.4	17	16	3.3
Shostak...............	0.26	79	14	4.1
	0.33	64	28	3.6
	0.09	20	30	6.7
This paper............	0.13	153	30	5.7
	0.09	20	13	6.7

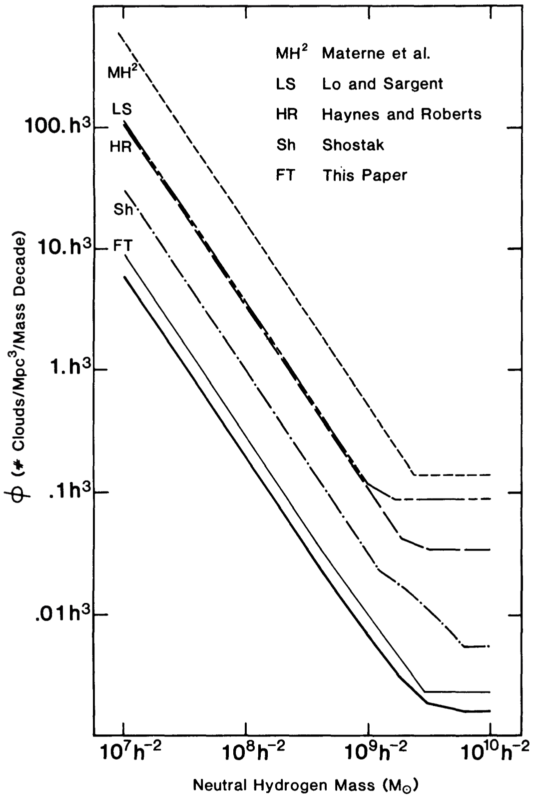

FIG. 1.—Upper limits to the luminosity function describing the space density of intergalactic H I clouds as a function of cloud mass. Limits from investigations discussed in the literature and from the observations described in this *Letter* are plotted separately. The combined data from the three most sensitive surveys lead to the lowest limit that is plotted.

tivity corrections have been made, where appropriate. Often the earlier investigations did not use set bandwidths, so the curves in Figure 1 are only crudely descriptive.

The lowest curve in Figure 1 represents the limiting luminosity function that can be derived by combining the data presented by Shostak (1977), by Haynes and Roberts (1979), and in this *Letter*. The summation is given by:

$$\phi = 1/\sum_i V_i = 1/\sum_i (1/\phi_i) .$$

The data by Lo and Sargent (1979) and by Materne, Huchtmeier, and Hulsbosch (1979) were not included in order not to repeat regions surveyed by Haynes and Roberts, but the final curve would not be lowered significantly if their results were incorporated. Figure 2 illustrates the upper limit to the H I *mass* density corresponding to the lowest curve in Figure 1. In the mass regime where survey volumes are limited by sensitivity rather than by bandpass, $M_H/V \propto M_H^{-1/2}$.

IV. CONCLUSIONS

The earlier surveys had already established that there could not be substantially more mass located in

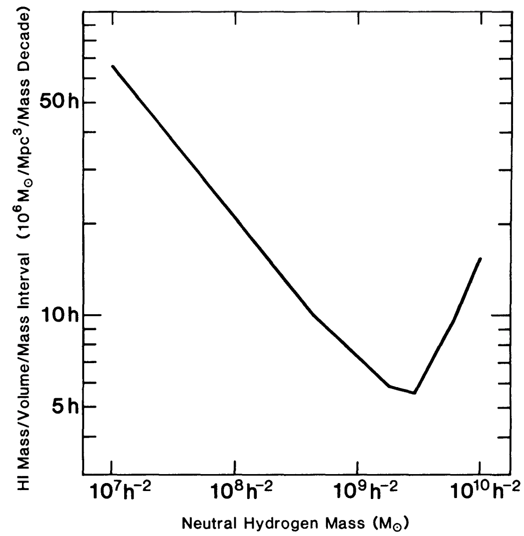

FIG. 2.—The limit established by combining data from the three most sensitive surveys is reinterpreted as an upper limit to the *mass density* as a function of cloud mass.

neutral hydrogen clouds $M_H > 10^7 h^{-2} M_\odot$ than is conventionally taken to exist in luminous galaxies. It is now shown that the mass located in clouds with $M_H > 10^7 h^{-2} M_\odot$ is *negligible* compared with the conventional mass associated with galaxies. An upper limit for the mass density in clouds in the range $10^7 h^{-2}$ to $10^{10} h^{-2} M_\odot$ is $\rho_{H\,I} < 9 \times 10^{-33} h$ g cm^{-3}. Assuming dark clouds exceeding $10^{10} h^{-2} M_\odot$ are unlikely to exist, then the upper limit to the density of neutral clouds integrated over all mass intervals is dominated by the choice of the low-mass cutoff. The limit for $\rho_{H\,I}$ can be compared with the density of mass in galaxies, ρ_g, accepting the luminous density given by Felten (1977), a mass-to-light ratio of $10h$, and a correction of 0.3 mag to account for inclination absorption effects: $\rho_{H\,I}/\rho_g < 0.06h^{-1}$. The limit for $\rho_{H\,I}$ can also be compared with the critical density for the closure of the universe, ρ_c: $\rho_{H\,I}/\rho_c < 5 \times 10^{-4} h^{-1}$.

The comparison with luminous galaxies resulting from this survey is significant because the observations were distributed like the galaxies; i.e., the observations were neither restricted to prominent groups nor were they made at random. While no intergalactic clouds were detected, a couple dozen visible galaxies were observed by accident either because they lie in a reference beam or in the line of sight of a survey candidate or were picked up in the search of the area of the M81 group. It might be remarked that our upper limits on the relative occurrence of H I clouds compared with galaxies is conservative in the sense that our beam positions are on or near known galaxies; and, if H I clouds and galaxies are correlated like galaxies with galaxies, then we systematically observed at locations where the detection expectations were higher than average. However, since along each line of sight most of the volume surveyed is at large distances from the associated galaxy, a more sophisticated analysis based on the galaxy-galaxy correlation function did not seem worthwhile.

Given that neutral hydrogen has been detected from galaxies which are of such low surface brightness as to be *almost* invisible, surely at some point H I will be detected in a blank field, even though the interpretation need not be that the source is entirely composed of gas.

Martha Haynes kindly provided unpublished details concerning the observing procedures, integration times, and sky coverage of the Haynes and Roberts survey. This research was supported in part by NSF grant AST 76-12159.

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