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A SEARCH FOR ATOMIC HYDROGEN FROM EVOLVED STARS AND PLANETARY NEBULAE

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ABSTRACT

With the 1000 foot (305 m) Arecibo antenna, we searched for 21 cm wavelength radiation from atomic hydrogen in expanding envelopes around a total of 13 red giant stars and planetary nebulae. For some stars (e.g., IRC +10216, IRC +10011) upper limits on the mass of atomic hydrogen in the circumstellar envelopes are a few percent of the total envelope mass estimated from other considerations. Toward α Ori intense, patchy background emission precludes a definitive estimate of the atomic hydrogen content in the envelope. No 21 cm radiation was detected that is directly associated with the planetary nebulae NGC 6210, NGC 6572, NGC 6720, and NGC 2346. Possible 21 cm absorption of the continuum radiation from NGC 6572 by foreground hydrogen would suggest a distant location for this nebula.

Subject headings: radio sources: 21 cm radiation — stars: circumstellar shells — stars: late-type

I. INTRODUCTION

Recent advances in optical, infrared, and millimeter wavelength astronomy have generated considerable interest in circumstellar matter about evolved giant stars. Because this matter is not gravitationally bound, its distribution and composition with radius can tell us about the stellar history. Observations of the dust and gas are sensitive to material that has been ejected within the past ~100 years (Sutton *et al.* 1979; Betz, McLaren, and Spears 1979; Ridgway *et al.* 1976) and over much longer time scales up to ~10^4 years (Bernat *et al.* 1978; McMillan and Tapia 1978; Wannier *et al.* 1979). We searched for atomic hydrogen from various evolved stellar objects to specify more precisely conditions in the circumstellar envelopes. To the best of our knowledge neither atomic nor molecular hydrogen has ever been seen directly in the circumstellar shell around an evolved star.

In no case did we detect hydrogen that is unambiguously associated with an evolved stellar object. In some cases where 21 cm wavelength emission due to background and foreground hydrogen is small at the relevant radial velocities we are able to show that at most ~10% of the hydrogen in the envelope is atomic rather than molecular (if mass-loss rates for these objects are as large as is commonly believed). For some stars such as α Ori, extensive background emission introduces considerable ambiguity into the analysis. However, our results are probably at best only marginally consistent with the mass-loss rate from α Ori estimated by Bernat (1977).

In § II we discuss the equipment and the observational procedure and results. Section III is a discussion of the observations and § IV a short summary.

II. OBSERVATIONS

Observations were carried out with the 1000 foot (305 m) Arecibo telescope. At the frequency of 1420.4058 MHz the full half-power beam width is $3'.2$ at moderate zenith angles. The peak gain at this frequency is ~8 K Jy^{-1} and the aperture efficiency is ~65% based on illumination of a 700 foot (214 m) diameter area by a 40 foot (12 m) circularly polarized line feed. The receiver consisted of a parametric amplifier (system temperature ~70 K) followed by a 1008 channel autocorrelator. We used a 2.5 MHz bandpass which yielded a channel spacing of 2.44 kHz (~0.5 km s^{-1}). We frequency-switched, and most of the data were taken so that the stellar velocity fell in both the signal and reference bands.

The typical observing procedure was to alternate ON-source measurements of a few minutes duration with OFF-source measurements of equal duration at four positions displaced by $\pm 3'.5$ in R.A. and in decl. The OFF's were subtracted from the adjacent ON's and the resulting spectra were averaged together. Calibration was by means of a noise tube that was switched on during half of the observing time.

The observational results are summarized in Table 1, and a few examples are shown in Figures 1, 2, and 3, where the "difference" spectra are the averaged ON-OFF's. For each object in Table 1 we give, in column (4), the range in radial velocity over which the limits to T_B in column (5) apply. The center value of V_{lsr} is the systemic velocity of the star with respect to the local standard of rest. The total radial velocity range corresponds, more or less, to twice the outflow velocity of the circumstellar or ionized matter. The limit to T_B is the maximum brightness temperature that a 21 cm wavelength line could have if it has the same central radial velocity and expansion velocity as matter known to exist about the star. In column (6) we give estimated distances between the Earth and the

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TABLE 1

SUMMARY OF THE RESULTS

Source (1)	R.A. (1950) (2)	decl. (1950) (3)	$V_{\rm LSR}$ (km s^{-1}) (4)	T_B (K) (5)	Distance (pc) (6)	$M_{\rm H}/M_{\rm total}$ (7)
IRC + 10011	$01^h03^m48^s$	+12°19′45″	+11 ± 15	<0.1	500	<0.025[b]
NML Tau	03 50 43.7	+11 15 30	+34 ± 20	<0.15	400	<0.1[c]
α Tau	04 33 02.9	+16 24 38	+42 ± 10	<0.25	21	...
CRL 618	04 39 34	+36 01 16	−25 ± 20	...[a]	2000	...
α Ori	05 52 27.8	+07 23 58	+7 ± 10	...[a]	200	...
NGC 2346	07 06 50	−00 43 29	+42 ± 15	<0.5	1150	<0.6[a]
IRC + 10216	09 45 15	+13 30 40	−26 ± 16	<0.1	200	<0.015[a]
IRC + 30219	10 13 12	+30 49 24	−1.5 ± 17	<0.2	500	<0.15[c]
NGC 6210	16 42 24	+23 53 17	−36 ± 20	<0.15	1050	<0.25[a]
NGC 6572	18 09 42	+06 50 37	−9 ± 8	<0.1	1000	<0.15[a]
NGC 6720	18 51 44	+32 57 51	−21 ± 20	<0.2	810	<0.2[a]
M1-92	19 34 18	+29 06 05	+2 ± 12	<0.5	500	...
CRL 2688	21 00 20	+36 29 45	−32 ± 18	<0.5	1000	...

[a] See text.

[b] $M_{\rm total}$ calculated assuming $\dot{M} = 3 \times 10^{-5} M_\odot$ yr^{-1} (Goldreich and Scoville 1976).

[c] $M_{\rm total}$ calculated assuming $\dot{M} = 10^{-5} M_\odot$ yr^{-1}.

objects in question. Column (7) is the upper limit to the mass of hydrogen in the circumstellar envelope based on calculations and assumptions described in the text.

III. DISCUSSION

The primary motivation for the observations was to detect atomic hydrogen flowing away from evolved giants and supergiants, "protoplanetary" nebulae, and bona fide planetary nebulae. Emphasis in the following discussion is therefore on estimating limits to the amount of atomic hydrogen present in the circumstellar environment and the various implications of these limits. In addition, distance limits to planetary nebulae can be investigated by 21 cm wavelength absorption measurements.

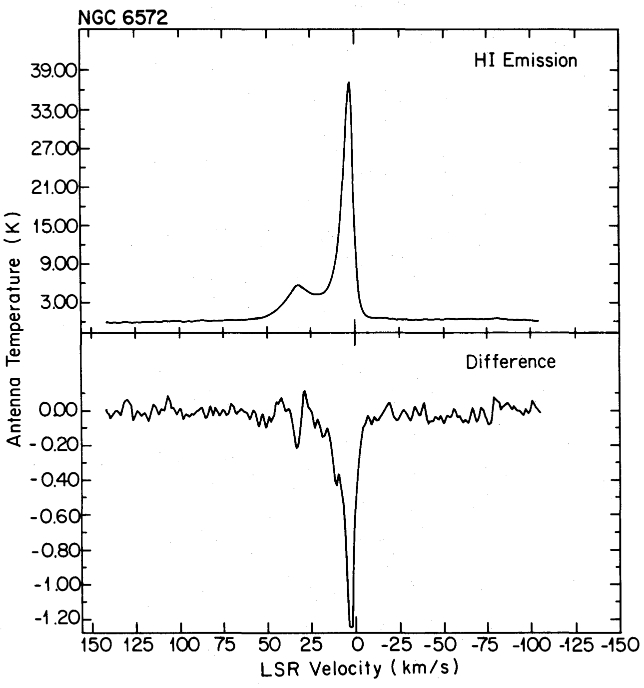

FIG. 1

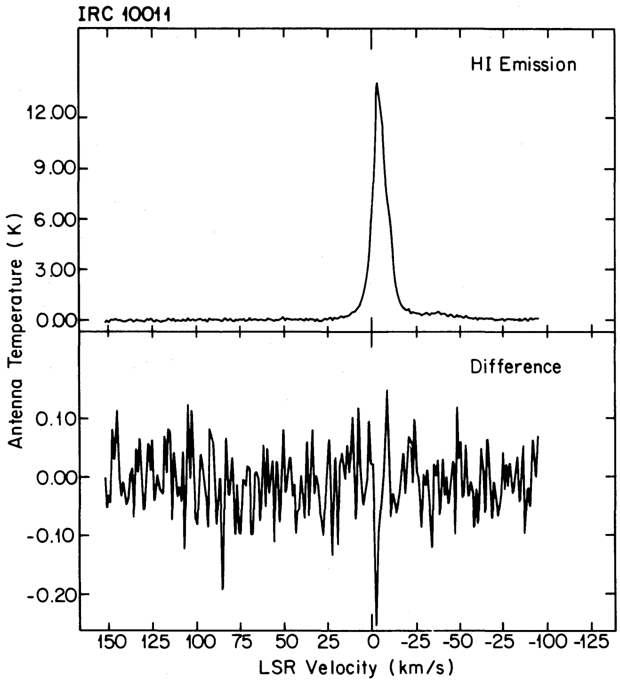

FIG. 2

FIGS. 1, 2, 3.—Neutral hydrogen emission and difference spectra toward NGC 6572, IRC 10011, and IRC 10216. Absorption of the continuum source NGC 6572 by foreground H I is evident in the difference spectrum in Fig. 1.

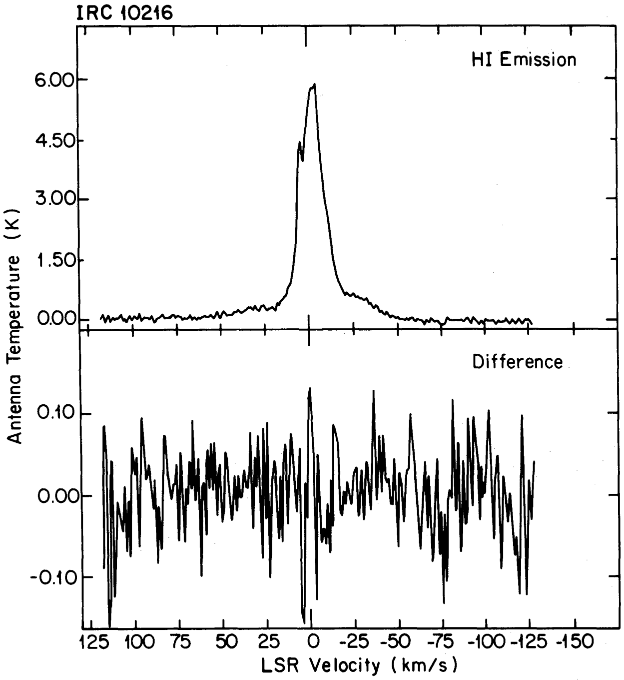

FIG. 3

a) *Ratio of Atomic to Molecular Hydrogen*

In Figure 4 we sketch two possible geometries relevant to our experiment. In both cases we assume that the extent of 21 cm hydrogen emission associated with the "source" (star or planetary nebula) is comparable to the size of the 3′2 Arecibo beam but small with respect to the 3′5 offsets we used for our OFF positions. If, instead, there is a substantial amount of hydrogen associated with the source but in the OFF positions, this introduces a negative spike in the expected source profile at the systemic velocity. (This is because hydrogen far from the star in the plane of the sky is flowing transverse to our line of sight.) We also assume that background and/or foreground 21 cm hydrogen emission is uniform over the region of the ON and OFF positions and that the stellar source is not itself a 21 cm continuum source (this last assumption is relaxed in § III*c* below).

Then, for case 1, where the star is in front of the bulk of the interstellar gas we have:

$$T_{\rm ON} = T_s(1 - e^{-\tau_s}) + e^{-\tau_s}T_i(1 - e^{-\tau_i}) , \qquad (1)$$

$$T_{\rm OFF} = T_i(1 - e^{-\tau_i}) , \qquad (2)$$

$$\Delta T = T_{\rm ON} - T_{\rm OFF}$$

$$= (1 - e^{-\tau_s})[T_s - T_i(1 - e^{-\tau_i})] , \qquad (3)$$

and for case 2, where the star is behind the bulk of the interstellar gas, we have

$$T_{\rm ON} = T_i(1 - e^{-\tau_i}) + e^{-\tau_i}T_s(1 - e^{-\tau_s}) \qquad (4)$$

$$T_{\rm OFF} = T_i(1 - e^{-\tau_i}) \qquad (5)$$

$$\Delta T = T_s e^{-\tau_i}(1 - e^{-\tau_s}). \qquad (6)$$

The various symbols are defined in the caption to Figure 4. Here τ_i and τ_s are functions of frequency. For some of the sources in Table 1, τ_i and $T_i(1 - e^{-\tau_i})$ are small at radial velocities corresponding to the expected circumstellar emission and it need not concern us whether case 1 or case 2 applies. We first discuss these sources.

For IRC +10216, IRC +10011, NML Tau and IRC +30219 over most of the range of circumstellar velocities given in column (4) of Table 1, $T_i(1 - e^{-\tau_i})$ is a few degrees or less. Since, presumably, $T_i \gtrsim 40$ K (Dickey, Salpeter, and Terzian 1978), $\tau_i \ll 1$.

But what of T_s? Following Purcell and Field (1956) we need to know the density (ρ) and the kinetic temperature (T_k) in the circumstellar shell. For constant velocity outflow, $M(r) \propto r$ where $M(r)$ is the mass in the shell between $r_{\rm inner}$ ($\sim$few times $r_{\rm star}$) and r. Therefore, for most shells, for which [H]/[H$_2$] either does not vary significantly with r or increases with r, the bulk of the atomic hydrogen is found at large r and, hence, small T_k. At 21 cm wavelength the half-power diameter of the Arecibo beam in pc at a distance D(pc) from the Earth is $\sim 10^{-3}D$. Therefore, for an assumed distance to IRC +10216 of 200 pc the telescope beam covers the circumstellar shell out to a distance $\sim$0.1 pc from the central star. The model of Kwan and Hill (1977) yields $T_k \sim 10$ K at 10^{17} cm from the star and $\sim$5 K at 4×10^{17} cm. These may be underestimates of the true values of T_k based on recent measurements of Wannier *et al.* (1979). Thus over most, if not all, of the volume of the IRC +10216 envelope covered by the Arecibo beam, $T_k \gtrsim 10$ K. At a distance of 3×10^{17} cm from the central star Kwan and Hill's model yields a particle density $\sim 10^2$ cm^{-3} (again

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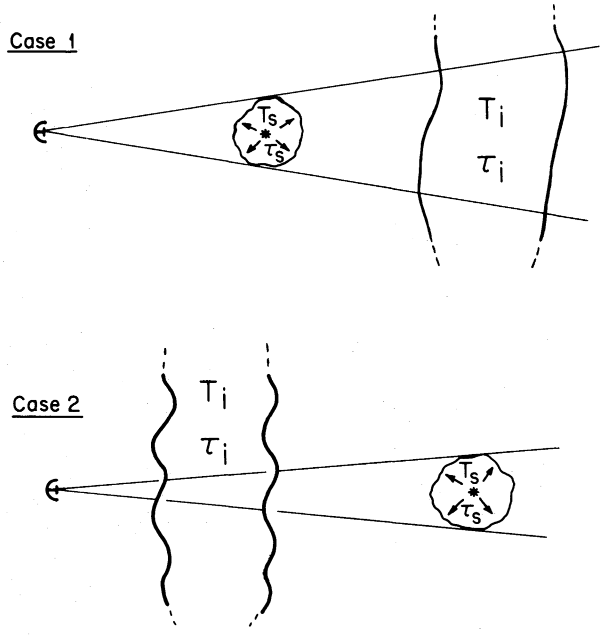

FIG. 4.—Geometry of observer, source (star), and interstellar cloud, where T_s = excitation temperature of the hydrogen in the envelope of the star; T_i = excitation temperature of the hydrogen in the interstellar cloud; τ_s = optical depth of the hydrogen in the envelope of the star; and τ_i = hydrogen optical depth in the interstellar cloud.

the observations of Wannier *et al.* suggest that this may be an underestimate). Our 21 cm wavelength measurements are sensitive to atomic hydrogen densities $\sim 1\%$ of this density (i.e., ~ 1 H atom cm^{-3}). When $n_{\rm H} \gtrsim 0.1$ cm^{-3} and $T_k \sim 10$ K, $T_s = T_k$ (Purcell and Field 1956).

Thus $T_s = T_k \gtrsim 10$ K over most of the volume of the IRC +10216 circumstellar envelope. For somewhat more-distant sources (e.g., IRC +10011 at 500 pc, Hyland *et al.* 1972; NML Tau at 400 pc, Cahn and Wyatt 1978) T_s in the outer portions of the envelope covered by the Arecibo beam may be slightly lower but, probably, $\gtrsim 5$ K. Then the ON source profiles for these three sources suggest that even if case 1 is applicable, we may safely neglect $T_i(1 - e^{-\tau_i})$ with respect to T_s over all or most of the velocity range given in column (4) of Table 1.

We now compute an upper limit to the mass of atomic hydrogen in the Arecibo beam. When $\tau_s \ll 1$ hydrogen column densities (cm^{-2}) are given by

$$n_{\rm H} l = 1.8 \times 10^{18} T_B \Delta V , \qquad (7)$$

where ΔV is in km s^{-1}. With values for T_B and ΔV from columns (4) and (5) of Table 1 we obtain $n_{\rm H} l \lesssim 6 \times 10^{18}$ cm^{-2} for both IRC +10216 and IRC +10011 and $n_{\rm H} l \lesssim 10^{19}$ cm^{-2} for NML Tau. Then the total mass of atomic hydrogen ($M_{\rm H}$) in the beam is

$$M_{\rm H} = \pi r^2 n_{\rm H} l m_{\rm H} , \qquad (8)$$

where $m_{\rm H}$ is the mass of a hydrogen atom. For IRC +10216, $r \sim 3 \times 10^{17}$ cm (at 200 pc); therefore $M_{\rm H} \lesssim 3 \times 10^{30}$ g. From the Kwan and Hill (1977) model, $\dot{M} = 2 \times 10^{-5}\ M_\odot$ yr^{-1} for 6000 years (to go 3×10^{17} cm at 16 km s^{-1}). Then the total mass in the envelope ($M_{\rm total}$) out to 3×10^{17} cm equals 2×10^{32} g; hence for the source IRC +10216, $M_{\rm H}/M_{\rm total} \lesssim 1.5 \times 10^{-2}$. The ratio is smaller if the CO results of Wannier *et al.* (1979) are used to obtain $M_{\rm total}$.

Corresponding ratios for the other sources may be obtained from the limits to T_B given in Table 1, a distance to the source, and a total mass-loss rate. It is interesting to note that, in general, in the case of constant mass outflow ($\rho \propto r^{-2}$), source-filling the telescope beam, and a given upper limit to $n_{\rm H} l$, the derived upper limit to $M_{\rm H}/M_{\rm total}$ is proportional to the distance D to the source. If ρ were proportional to r^{-1}, then there would be no D-dependence, and if ρ = constant then $M_{\rm H}/M_{\rm total} \propto D^{-1}$.

b) Mechanisms for Producing Atomic Hydrogen in Cool Circumstellar Shells

Atomic hydrogen may be present in cool circumstellar shells as a result of various causes. We now discuss four such causes.

1. If the effective temperature of the star is sufficiently high ($\gtrsim 2600$ K according to the models of Vardya 1966) most of the hydrogen will be atomic in regions near the photosphere where chemical equilibrium holds. In the following paragraph we argue that these relative H and H_2 abundances will probably be retained in the lower density circumstellar shells since molecular hydrogen will not be able to form within a time that is less than the expansion time.

Grains in the inner portion of the circumstellar shell, if they exist at all, are too hot to permit hydrogen recombination on their surfaces. In the outer, cooler portions of the shell the rates are too slow with respect to the expansion time scale of the envelope to permit substantial H_2 formation on grains (in general, $t_{\rm formation}/t_{\rm expansion} \propto \rho^{-1/2}$ when $\rho \propto r^{-2}$). Conditions are also probably inappropriate for formation of H_2 via reactions of H and H^-. For example, following Bernat (1977), we assume that the atomic hydrogen and electron densities at the inner radius of the expanding circumstellar shell of α Ori are 3×10^6 cm^{-3} and 800 cm^{-3}, respectively. Then, at a temperature of ~250 K, the characteristic time scale for the reaction $H + e \rightarrow H^- + h\nu$ is $\sim 10^{13}$ s (Clegg 1979). This is very slow with respect to the expansion time scale. Conditions in the region between the photosphere and the expanding shell are not well understood (e.g., Altenhoff, Oster, and Wendker 1979; Boesgaard 1979) but, probably, are also not conducive to the formation of H_2.

We may conclude that in the circumstellar shells of α Tau (K5 III, $T_{\rm eff} \sim 3800$ K) and α Ori (M2 I, $T_{\rm eff} \sim 3500$ K) hydrogen will probably be mainly atomic. The mass-loss rate from α Tau is not expected to be large; we looked at it primarily because it is so close. For a nominal expansion velocity of 10 km s^{-1} our upper limit to T_B translates into a hydrogen column density $\lesssim 10^{19}$ cm^{-2}. Kelch *et al.* (1978) estimate a column density $\lesssim 10^{17}$ cm^{-2} for α Tau, so it is not surprising that we did not detect a hydrogen line.

The case of α Ori is more complicated. Bernat (1977) estimated a hydrogen column density of 1.3×10^{22} cm^{-2} based on lines in the visual part of the spectrum and assuming solar abundance ratios. This column density applies along a line of sight to the star. To compare with our results over a much larger area we use instead Bernat's estimated mass-loss rate for α Ori, 3×10^{-5} $M_\odot$ yr^{-1}. Then, because α Ori is probably ~200 pc from the Earth (Field 1978), the total circumstellar mass in the Arecibo beam is essentially the same as for IRC +10216. Unfortunately, our 21 cm wavelength results for α Ori are badly confused by background hydrogen emission, and the data suggest that the background hydrogen is very clumpy around α Ori. In addition, the background emission is very strong at all velocities characteristic of circumstellar material around α Ori. Therefore, the value of the expression $[T_s - T_i(1 - e^{-\tau_i})]$ is very uncertain; it could be greater than, less than, or approximately equal to zero.

Nonetheless, because of the considerable interest in mass loss from α Ori in addition to our usual four OFF positions, we also obtained ON-OFF measurements for four additional OFF positions offset by ±7′ in R.A. and decl. from the star. The result is as follows: at radial velocities of a few km s^{-1} (near the systemic velocity of α Ori) relative to all OFF positions 3′.5 and 7′ north, east, and west of the star there is always excess emission at the ON position, typically, $T_B \sim 5$ K. But relative to the OFF positions 3′.5 and 7′ south of α Ori the emission at the ON position is ~4 K weaker at velocities near zero km s^{-1}. It is tempting to suppose that this may have something to do with the presence of the long Hα tail that extends southward from α Ori (Morgan, Strömgren, and Johnson 1955). Only additional detailed mapping can establish or deny this possibility.

In any event, because we know neither the sign nor the magnitude of the expression $[T_s - T_i(1 - e^{-\tau_i})]$ when averaged over the telescope beam solid angle it is not possible to draw even a firm upper limit to the atomic hydrogen content in the circumstellar envelope around α Ori. If we assume $T_B = 5$ K, roughly corresponding to the largest deflection from our observations, then our result is just consistent with the mass-loss rate $\sim 3 \times 10^{-5}$ $M_\odot$ yr^{-1} estimated by Bernat (1977).

2. In the atmosphere of late-type Mira variables shocks are believed to be present and probably help to drive mass loss (e.g., Willson and Hill 1979; Wood 1979). Since the Balmer emission lines are a well-known feature in the spectra of these stars, velocity jumps across the shocks apparently are sufficient to dissociate much of the molecular hydrogen. It is difficult to calculate the fraction of hydrogen that remains in the atomic form long after the passage of the shock. Goldreich and Scoville (1976) assumed $n(H) = n(H_2)$ in their model of the circumstellar envelope surrounding an OH/IR star. The present results suggest that, in fact, very little hydrogen survives in the atomic form in the circumstellar envelope. (Nonetheless this has a negligible effect on the Goldreich-Scoville model.)

3. Most red-giant stars are located far from interstellar molecular clouds. Therefore, at large distances from the stars, the expanding circumstellar envelopes will merge with the interstellar gas and most, if not all, of the circumstellar molecules will be photodissociated by the interstellar radiation field. The question is, how much of the H_2 is photodissociated during the period of $\sim 10^4$ years that characterizes the expansion age of the circumstellar material in the Arecibo beam?

IRC + 10216 may serve to illustrate this effect. The expansion age out to 3×10^{17} cm at 16 km s^{-1} is 6000 years. During this time at wavelengths ~1000 Å a typical interstellar photon "flux" of $\sim 2 \times 10^{-8}$ photons cm^{-2} s^{-1} Hz^{-1} (Jura 1974) will have impinged upon the outer edge of the circumstellar cloud. Assuming that the H_2 molecules in the shell absorb *all* such photons that lie between 1108 and 912 Å and that 10% of these absorptions lead to dissociations (Black and Dalgarno 1976), there are 10^6 dissociating photons cm^{-2} s^{-1} entering the circumstellar shell. After 6000 years a mass of 7×10^{29} g of atomic hydrogen will have resulted. This should be regarded as an upper limit since some of the potential dissociating photons that lie far from the center of any of the relevant H_2 Lyman lines will be absorbed by dust grains or another molecule such as CO before they are absorbed by an H_2 molecule. A mass of 7×10^{29} g is less than the observational upper limit for IRC +10216 derived above in § III*a*.

More distant stars will have longer characteristic expansion times to fill the Arecibo beam, but also larger masses of hydrogen to produce a given signal, so the expected 21 cm wavelength intensity due to this effect is beyond our ability to detect.

4. For very young planetary nebulae there is the

additional possibility of photodissociating the molecular cloud with radiation from the central star. CRL 618, which is known to be surrounded by both an H II region and an expanding molecular cloud (Lo and Bechis 1976), appears to be the most promising candidate that we have observed in this program. Presumably, between the H II region and the surrounding molecular cloud there is a shell that is primarily atomic where molecules are dissociated by radiation longward of the Lyman limit. Because the CO emission from the molecular cloud is very strong relative to the total flux from the star (see Fig. 1 in Zuckerman *et al.* 1977) it is likely that a majority of the shell is still molecular. This suggests a mass in the atomic shell $\lesssim 0.1\ M_\odot$ unless CRL 618 is the remnant of a very massive star. The ultraviolet flux from the underlying B0 star (Westbrook *et al.* 1975) should be sufficient to photodissociate this much molecular gas in times $\lesssim 1000$ years.

Unfortunately, owing to the probably large distance (~ 2 kpc) between CRL 618 and the Earth and the strong hydrogen emission in this direction, even 0.1 $M_\odot$ of hydrogen would be very hard to detect unambiguously. The signal from the circumstellar hydrogen is expected to be less than the observed emission peaks, most of which are at velocities that cannot be associated with CRL 618.

c) The Planetary Nebulae

In this program we also observed several prominent planetary nebulae to investigate any neutral hydrogen shells that might surround these objects. We detected galactic H I absorption of the continuum source NGC 6572 at $v_{\rm LSR} \sim 3$ km s^{-1}, and possibly at $v_{\rm LSR} \sim 32$ km s^{-1} (Fig. 1). Distances reported for NGC 6572 range from 670 pc (Acker 1978) to 1910 pc (Higgs 1971). Cudworth (1974), using statistical parallaxes, derived a distance of 904 pc. If the absorption feature at 32 km s^{-1} is real and if the hydrogen responsible for this absorption is at the distance implied by the standard Schmidt rotation curve of the galaxy, then NGC 6572 is at least 2.3 kpc from the Earth. Considering the fairly high galactic latitude ($\sim 11^\circ\!.8$) of NGC 6572, the Schmidt curve may not be relevant.

Following the approach outlined in § III*a* we computed upper limits to the total mass of neutral hydrogen in the envelopes of the observed planetary nebulae. However, expressions (3) and (6) are modified because the planetaries are themselves 21 cm continuum sources. Adopting 21 cm continuum fluxes and sizes from Higgs (1971) and Cahn and Kaler (1971), the 21 cm continuum brightness temperatures T_c for the four planetaries range from ~ 7 to ~ 1100 K. If we assume that the neutral hydrogen in the envelopes is expanding at a rate roughly equal to the expansion rate of the ionized gas, then factors like $\tau_s(v)(T_s - T_c)$ appear in the modified versions of expressions (3) and (6), but only for the blueshifted wing of the line. (The expressions are essentially unchanged for the redshifted wing.) Since T_c may be larger than T_s, the 21 cm hydrogen emission profile may have a "P Cygni" shape.

In the last column of Table 1, we give estimates for the upper limit to the neutral hydrogen mass associated with each of the four planetary nebulae. Here we have assumed that $M_{\rm total} = M_{\rm ionized} + N_{\rm H\,I}$, and $M_{\rm ionized} = 0.2\ M_\odot$. It appears that high- sensitivity 21 cm wavelength interferometric line observations with angular resolutions of $\sim 10''$ are needed to explore more closely the association of H I with the envelopes of planetary nebulae.

IV. SUMMARY

The data in Table 1 indicate that only a small percentage of hydrogen may be in the atomic form in the atmospheres of very cool giant stars that are undergoing extensive mass loss. The same conclusion is suggested for planetary nebulae. For other types of stars the situation is still ambiguous due to intense interstellar hydrogen emission, large distances to the relevant stars, and smaller mass-loss rates. To significantly improve upon the present results will require very sensitive receivers on very large telescopes. Even so, background and foreground hydrogen will still be a problem in many cases.

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