21-CM PROBES OF REDSHIFTED CLOUDS

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21 cm studies, carried out with the 305 m telescope at Arecibo, of absorption-line clouds in QSOs have resulted in the following discoveries: (a) A search for 21 cm absorption in redshift systems selected for exhibiting Mg II/Fe II absorption in radio-bright QSOs resulted in the detection of a $z \approx 0.4$ 21 cm line in PKS 1229-02; (b) the detection of 21 cm absorption at $z \approx 1.8$ in MC3 1331+170; and (c) the discovery of 21 cm emission from regions ~100 kpc distant from the ScI galaxy NGC 628, that occurred during a search for outlying H I in a complete sample of spiral galaxies.

A. INTRODUCTION

I shall discuss results of recent experiments carried out during the past year whose objective was to understand the nature of absorption-line clouds in QSOs. I shall also discuss some theoretical work that has grown out of these studies. Because a detailed version of an identical paper will be published elsewhere (Wolfe 1980), I shall summarize the results very briefly.

B. DETECTION OF 21 CM ABSORPTION IN 1331+170

The very strong L_α absorption feature at $z \approx 1.8$ in 1331+170 (Carswell et al. 1975) makes this redshift system a prime candidate for 21 cm absorption. A large H I column density, $N(\text{H I}) \sim 10^{21}$ cm^{-2}, is indicated because the rest-frame equivalent width of L_α, $W_\lambda \sim 20$ Å, is much larger than equivalent widths of the heavy-element lines identified with the two redshift systems comprising this absorption complex; and this is the case if L_α is on the damping portion of the curve-of-growth. Recent spectral scans of the L_α absorption trough (Hegge,

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Liebert, and Strittmatter 1979) show that most of the absorption arises in system A (z_A = 1.7763) rather than in system B (z_B = 1.7851).

M. M. Davis and I recently detected a 21 cm absorption line in system A (Wolfe and Davis 1979). This weak absorption feature has an optical depth $\tau(21) = 0.02$ and the line profile can be fit by a Gaussian function with velocity dispersion $\sigma = 8.5$ km s^{-1}. The detection of 21 cm absorption and L_α absorption in the same material allows a determination of the hydrogen spin temperature T_s in a high-z object for the first time (Wolfe 1979). We find that $T_s < 980$ K: the upper limit accounts for the possibility that the absorbing cloud doesn't cover the entire radio source. When combined with the upper limits on collisional de-excitation set by the absence of C II λ 1335.7 absorption from the J = 7/2 fine-structure level, this limit on T_s requires that system A be further than d $\approx$ few kpc from 1331 + 170; otherwise 21 cm continuum excitations would raise T_s above 980 K. This limit would rule out radiative ejection at the implied velocity of $u \approx 0.1$ c from this z = 2.08 QSO.

System A could be closer to 1331 + 170 provided that another source of hyperfine excitation dominates the 21 cm continuum. L_α pumping of the ground hyperfine levels via 2p excitations is an interesting possibility since atomic recoil causes $T_s \rightarrow T_k$, where T_k is the local kinetic temperature (Field 1959): T_k is expected to be less than 980 K in the H I region that gives rise to 21 cm absorption. Furthermore, recombination L_α produced through photoionization by the QSO Lyman continuum results in a pumping rate that is many orders of magnitude larger than the excitation rate due to 21 cm radiation emitted by 1331 + 170. The problem is that L_α is produced in the H II region that faces the QSO, while 21 cm absorption arises in the outward facing H I region which has an optical depth in L_α of $\tau(L_\alpha) \sim 10^8$. Thus it is not clear whether L_α remains strong enough to cause pumping after propagating into this extremely opaque medium.

J. J. Urbaniak and I (Urbaniak and Wolfe 1979) have studied the transfer of L_α that arises in the H II region and propagates across an ionization front into the H I region. The important parameters in this problem are v, the relative velocity between H II and H I regions, and σ and N(H I) of the H I region. For all plausible values of v, that is $0 < |v| < 250$ km s^{-1}, we find that L_α pumping dominates the 21 cm continuum. Solutions with larger values of $|v|$ cause larger pumping rates since larger amounts of radiation penetrate and emerge from the H I region. In all cases the emergent radiation displays a double-hump spectrum that is symmetric about the line center, with peak-to-peak separation $\Delta\lambda \sim 8$ Å. Such a feature would be detectable if

$|v| > 100$ km s^{-1}, and if the fraction of the sky subtended by system A at the QSO is given by $\Omega/4\pi > 2 \times 10^{-4}$. Recently Hegge, Liebert, and Strittmatter (1979) detected a narrow ($\Delta v < 350$ km s^{-1}) feature centered at $\lambda = (1 + z_A)(1215.7$ Å). Its central location indicates that this feature does not arise according to the above scenario which predicts a negligible fraction of emergent radiation at the line center. The redshift, velocity width, and luminosity ($\sim 10^{43}$ ergs s^{-1}) are more easily understood if this feature originates in a galactic nucleus with redshift z_A. In these respects it resembles the star-like emission object associated with the 21 cm absorber in AO 0235+164 (Smith, Burbidge, and Junkkarinen 1977). Further observations are needed in order to confirm this very interesting discovery.

C. A SEARCH FOR 21 CM ABSORPTION IN Mg II/Fe II ABSORPTION SYSTEMS

At redshifts $z < 1.8$ where L_α is inaccessible the leading candidates for 21 cm absorption are redshift systems with Mg II ($\lambda\lambda$ 2796, 2803) and Fe II ($\lambda\lambda$ 2344→ 2600) absorption. These clouds are promising because Mg II and Fe II lines are present in previously detected 21 cm systems (cf. Wolfe 1979), and because these ionic stages dominate in galactic H I regions. However, the presence of strong Mg II absorption need not indicate 21 cm absorption. The reason is that low-resolution optical scanning devices preferentially detect saturated lines produced by highly turbulent material, whereas the high resolution of radio spectrometers selects material of low velocity dispersion and high column density. Therefore we need to find redshift systems in which highly opaque clouds of low velocity dispersion lurk in the midst of rapidly moving clouds of considerably lower optical depth.

F. H. Briggs and I have searched for 21 cm absorption in 16 redshift systems that are in front of 14 QSOs. The results of our observations are mainly negative: 15 out of the 16 redshift systems in the survey have no radio absorption lines. Our subsequent data analysis was motivated by two questions: (1) are Mg II systems with detectable 21 cm absorption optically distinct from the others? , and (2) why are most Mg II systems transparent to 21 cm radiation?

To answer the first question Briggs and I compared $\tau(21)$ with W_λ (Mg II λ 2796) for redshift systems in which Mg II equivalent widths are available. A plot, which includes data from previously detected 21 cm systems, shows no obvious correlation (see Wolfe 1979). Moreover, $\tau(21)$ is not correlated with DR, the Mg II doublet ratio. In fact the largest DR (= 1.54) is found in the $z = 0.395$ absorption system in PKS 1229-02 for which we have a 21 cm detection. This would be surprising if the same gas produced both Mg II and 21 cm absorption since the indicated Mg II optical depth, τ(Mg II) $\sim$ 1, corresponds to $\tau(21) \ll 1$ unless the metal abundances are unacceptably low. But it is clear that the two types of lines form in different gas. A curve-of-growth analysis of the Mg II lines indicates $\sigma \approx 100$ km s^{-1}, while the 21 cm absorber has $\sigma = 4.8$ km s^{-1}. This supports the turbulent/opaque model for Mg II/21 cm systems, as suggested above.

The absence of 21 cm absorption in most Mg II systems can be explained in a number of ways. First, let us assume that Mg^+ is associated with regions in which H is mostly neutral. If $Mg^+/H^o = X(Mg)_\odot$, our null detections require that $T_s > 30$ K (recall that $\tau(21) \propto N(H\ I)/(\Delta v\ T_s)$). This is not a prohibitive restriction for clouds ejected from QSOs, nor for clouds in intervening galaxies. However, we would not expect gas in galactic disks nor in galactic halos to have solar abundances of Mg, so these limits on T_s probably do not pertain to intervening galaxies. Indeed, if Mg^+/H^o assumes the "Copernicus" abundance, then $T_s > 500$ K in many cases. Since spin temperatures this large are rarely observed in the galactic plane, one would consign the Mg II regions to galactic halos, a site previously suggested by Bahcall and Spitzer (1969). Perhaps the simplest explanation for the absence of 21 cm absorption is that the Mg II-producing region is associated with H that is mostly ionized. But the similar kinematics of the 21 cm and optical absorption profiles in the 21 cm absorber in AO 0235+164 (Wolfe et al. 1978) suggests that the "turbulent" Mg II clouds contain H that is mostly neutral.

From a statistical point of view, the incidence of 21 cm absorption in Mg II redshift systems is compatible with the intervening galaxy hypothesis. In a recent study of a complete sample of QSOs Weymann et al. (1979) find that the incidence of Mg II absorption is about 13 times that expected if Mg II lines form in galactic disks that extend to one Holmberg radius. Therefore galactic Mg II-filled halos with radius $R \sim 3.5\ R_{H_o}$ ($\simeq$ 70 kpc) are required by the intervening galaxy model. Since 21 cm absorption occurs in $\sim$ 10% of the Mg II systems (including the 21 cm absorber in AO 0235+164), galactic disks with $R \sim 1\ R_{H_o}$ are adequate to explain the 21 cm data.

D. A SEARCH FOR OUTLYING H I IN A COMPLETE SAMPLE OF GALAXIES

If the Mg II lines are produced by 70 kpc halos, then galaxies should be surrounded by large halos of hydrogen. Since there is a good chance that Mg^+ is associated with hydrogen that is mostly neutral, one would expect 21 cm emission from the outskirts of a significant fraction of spiral galaxies. To test this hypothesis F. H. Briggs, N. Krumm, E. E. Salpeter and I began a systematic search for 21 cm emission from the outlying regions of a complete sample of spiral galaxies. The idea is to search for 21 cm emission from selected areas around each galaxy. By placing the narrow (4' diameter) beam of the Arecibo 21 cm antenna at two opposite points located at $R \sim 3 R_{H_o}$ along the major and minor axes, one effectively probes the gaseous cross-section required to produce the Mg II lines. We integrated for an hour at each point so that our 3-σ upper limits on N(H I) would place meaningful upper limits on W_λ (Mg II).

Our sample consists of 27 galaxies that (a) are outside the local group, (b) are later than SO, (c) have optical major-axis diameters greater than 7', and (d) are in the Arecibo Dec. range. So far we have investigated 13 galaxies at beam locations comprising $\sim 1/3$ of the total sample. Our results, while obviously not complete, are still interesting enough to report on (see Briggs et al. 1979). Of the 33 beam locations already investigated 70% are null detections, 21% are marginally significant (i.e., signals that exceed the 3-σ noise limit but are confused by side lobe contributions from the main galaxy), and only 9% showed clear evidence for 21 cm emission. We note that isolated galaxies and galaxies with companions obey the same statistics.

The absence of H I halos at a sensitivity level of N(H I) $< (2 \rightarrow 3) \times 10^{18}$ cm^{-2} for bandwidths $\Delta v \simeq 16$ km s^{-1} is a new result with interesting implications. By adopting a velocity dispersion σ for gas at a given beam location and a ratio Mg^+/H^o we can calculate W_λ (λ 2803) from upper limits on N(H I) that are appropriately smoothed. We may then compare the resultant W_λ vs σ curves with the range of these parameters inferred for QSO absorption-line clouds: the statistics of Weymann et al. (1979) are based on systems with $W_\lambda \geq 0.5$ Å, and $\sigma = 100$ km s^{-1} is a conservative upper limit for Mg II systems (Briggs and Wolfe, 1979). We find that gas in beam locations with null or marginal detections cannot produce observable Mg II lines unless $Mg^+/H^o > 0.3\ X(Mg)_\odot$. Thus halo gas with population II abundances, $X(Mg) \approx 0.04\ X(Mg)_\odot$ (Searle and Zinn 1978), or with interstellar abundances, $X(Mg) \approx 0.03\ X(Mg)_\odot$ (Spitzer 1978), cannot produce observable Mg II lines, if the Mg^+ is associated with H I regions. We emphasize that this conclusion is valid even if the Mg^+ is associated with ionized material. Ionization equilibrium arguments (Briggs and Wolfe 1979) show that in this case Mg^+/H^o cannot exceed a conservative upper limit of ≈ 4 X(Mg), so that N(Mg^+) is less than 1/2 of the required value for population II abundances. Consequently, intervening galactic halos like those in our sample will not give rise to observable Mg II absorption lines unless gaseous material with population I metal abundances is present.

The discrepancy between the required Mg II cross-section of intervening galaxies and the average cross-section, $\langle A \rangle$, implied by our survey can be stated in the following manner: The frequency of detecting 21 cm emission at our beam locations indicates that $1.8 < \langle A \rangle / A_{H_o} < 5.0$, where A_{H_o} $(= \pi R_{H_o}^2/2)$ is the average cross-section of a Holmberg disk. We are not certain whether a null detection at a radius R means that H I is confined to R_{H_o}, or whether it extends to just within 1 beamwidth of R, and this accounts for the range in $\langle A \rangle$. In any case the value of $\langle A \rangle$ required by Weymann et al. (1979) is $\langle A \rangle = 13\, A_{H_o}$, so there is a factor of ~ 4 discrepancy.

The only "isolated" galaxy to exhibit 21 cm emission at $R > R_{H_o}$ is NGC 628. The emission coincides with four beam locations surrounding the S-W extension of the outer major axis (p.a. = 80°), which are ~ 100 kpc from the nucleus. Briggs (1980) has recently mapped the entire galaxy and finds H I in every quadrant at $R \sim 3.5\, R_{H_o}$, with a pronounced asymmetry toward the S-W. Because the galaxies nearest to NGC 628 are two dwarfs displaced by $\sim$ 350 kpc on the sky, it is improbable that tidal interactions are the cause of the outlying H I. Rather it appears to be primordial in origin. On the other hand it is difficult to see how a primordial asymmetry could survive the effects of differential rotation which would smear it out in 1 or 2 rotation periods of $\sim 10^9$ y.

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DISCUSSION

G. Burbidge: Would you agree that there is really very little evidence for extended halos containing metals in galaxies?

Wolfe: I would agree that we haven't found any evidence. But the point I was trying to make was that the upper limits we have set to 21-cm emission from the outskirts of galaxies do not rule out MgII absorption at the required level if the Mg/H abundance is population I; this is true if the gas is neutral, and virtually true if it is ionized. Whether population I gas exists in halo regions is a separate question. We know that the stellar content of the halo has low population II abundances. One possibility is a galactic wind. But whether cool regions can persist in a necessarily hot ($T \sim 10^6$ K) wind, out to $R \sim 100$ kpc is problematic.

Spinrad: Your results imply the absence of MgII-producing regions in galactic halos. Yet Boksenberg and Sargent find CaII absorption in the QSO/galaxy pair 3C 232/HGC 3067 where the QSO lies outside the optical image of the galaxy. How can these results be reconciled?

Wolfe: Yes, there is a paradox if the radial distance, R, of the absorbing gas from the nucleus of NGC 3067 is greater than 3 x R_{HO} (R_{HO} = Holmberg radius). But all we know is the impact parameter to 3C 232 which equals 1 R_{HO}. But the 90 km s^{-1} width of the CII lines rules this out. So it is possible that the reason why the absorbing gas in this galaxy is above our upper limit on column density is that it is at a radius smaller than that of our survey points.

Wehinger: Have you looked for 21-cm absorption in Seyfert and/or N galaxies?

Wolfe: No.

D. Roberts: I'd like to report another negative result in the search for 21-cm absorption associated with MgII optical absorption. Bennett, Lawrence, and Burke, at MIT, have used the NRAO 300-foot telescope to observe the double quasar 0957+561 at the optical redshift of 1.3914. A total of 2 hours integration yields a limit of 0.02 K, where the total source temperature is 2 K. However, most of the flux at 594 MHz comes from the extended ratio source associated with the north component, and as a result the optical depth limit is only $\tau_{21\ cm} \lesssim 0.2$ (assuming that the absorbing cloud completely covers both of the compact sources).

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