HYDROGEN COLUMN DENSITY EVALUATIONS TOWARD CAPELLA: CONSEQUENCES ON THE INTERSTELLAR DEUTERIUM ABUNDANCE

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ABSTRACT

The deuterium abundance evaluation in the direction of Capella has for a long time been used as a reference for the local interstellar medium (ISM) within our Galaxy. We show here that broad and weak H\textsc{i} components could be present on the Capella line of sight, leading to a large new additional systematic uncertainty on the N(H\textsc{i}) evaluation. We find the D/H ratio toward Capella to be equal to 1.67(±0.3) × 10^{-5} with almost identical χ^2 for all the fits (this range includes only the systematic error; the 2 σ statistical one is almost negligible in comparison). We conclude that D/H evaluations over H\textsc{i} column densities below 10^{19} cm^{-2} (even perhaps below 10^{20} cm^{-2} if demonstrated by additional observations) may present larger uncertainties than previously anticipated. We mention that the D/O ratio might be a better tracer for D\textsc{i} variations in the ISM as recently measured by the Far Ultraviolet Spectroscopic Explorer.

Subject headings: cosmology: observations — Galaxy: abundances — ISM: abundances — stars: individual (Capella) — ultraviolet: ISM

1. INTRODUCTION

Deuterium is understood to be produced in significant amounts only during primordial big bang nucleosynthesis and thoroughly destroyed in stellar interiors. Deuterium is thus a key element in cosmology and in galactic chemical evolution (see, e.g., Audouze & Tinsley 1976). Indeed, its primordial abundance is the best tracer of the baryonic density parameter of the universe Ω_\text{b}, and the decrease of its abundance during the galactic evolution should trace the amount of star formation (among other astrophysical interests).

In the Galactic interstellar medium (ISM), D/H measurements made toward hot stars have suggested variations: ISM absorption profile spectrograph observations toward δ Ori led to a low value (Jenkins et al. 1999), confirming the previous analysis by Laurent, Vidal-Madjar, & York (1979) from Copernicus observations, while toward γ Vel they led to a high value (Sonneborn et al. 2000). This seems to indicate that in the ISM, within a few hundred parsecs, D/H may vary by more than a factor of ∼3.

In the nearby ISM, the case of G191-B2B was studied in detail (see the most recent analysis by Lemoine et al. 2002) and the evaluation toward Capella (Linsky et al. 1995) taken as a reference. Their comparison provided, for a while, a possible case for D/H variations within the local ISM.

Concerning G191-B2B, Lemoine et al. (2002) have shown that the total N_{mol}(H\textsc{i}) column density evaluation was greatly perturbed by the possible addition of two broad and weak H\textsc{i} components. Such components, able to mimic the shape of the Lyα damping wings, can induce an important decrease of the evaluated N_{mol}(H\textsc{i}). To illustrate this point, the error bar estimation on N_{mol}(H\textsc{i}) from all previously published studies considered as the extremes of a 2 σ limit was of the order of 0.07 dex, while including the Lemoine et al. (2002) analysis enlarged the error bar to about 0.37 dex. This huge change has, of course, a considerable impact on any D/H evaluation.

This raises two crucial questions. First, is that situation typical of G191-B2B alone and possibly due to an unexpected shape of the core of the stellar Lyα profile improperly described by the theoretical models? Second, if weak H\textsc{i} features are present in the ISM, to what extent are evaluations toward other targets affected?

2. SUMMARY OF THE G191-B2B CASE

From the combination of Space Telescope Imaging Spectrograph (on board the Hubble Space Telescope [HST]) echelle observations and Far Ultraviolet Spectroscopic Explorer (FUSE) ones (Moos et al. 2000), Lemoine et al. (2002) have found through an iterative fitting process (with the OWENS.F fitting program developed by M. Lemoine and the French FUSE team) that three interstellar absorption components are present along the line of sight and that two additional broad and weak H\textsc{i} components could be added, detected only over the Lyα line (negligible over the Lyβ line) but important enough to strongly perturb the total H\textsc{i} column density evaluation.

Within the local ISM, it has been shown that such additional H\textsc{i} absorptions are often present; they have been interpreted either as cloud interfaces with the hot gas within the local ISM (Bertin et al. 1995) or as “hydrogen walls,” a signature of the shock interaction between the solar wind (or stellar wind) and the surrounding ISM (Linsky 1998). This latter heliospheric absorption has been modeled by Wood, Muller, & Zank (2000), and a prediction has been derived in the direction of G191-B2B (see Fig. 9 of Lemoine et al. 2002). Most of the predicted absorption is expected in the saturated core of the observed interstellar line, but some weak absorption (~5% of the continuum) might extend over several tenths of an angstrom on the red side of the line, owing to the neutral hydrogen atoms seen behind the shock in the downwind direction where G191-B2B is located. It was found that the combination of two broad and weak H\textsc{i} components can easily reproduce the model prediction. If this effect is real, besides the three interstellar absorptions, a fourth component representing the bulk of the predicted absorption and a fifth one for the broad and shallow extended red wing are needed. This is exactly what Lemoine et al. (2002) have found.

In the course of determining the minimum number of components (each defined by its H\textsc{i} column density N, its velocity v, its temperature T, and turbulence broadening ξ) needed to fit the data, Lemoine et al. (2002) completed the F-test, which...
uses the Fisher-Snedecor law describing the probability distribution of the $\chi^2$ ratio. What is tested is the probability that the decrease of $\chi^2$ with additional components is not simply due to the increase of free parameters. The result gives a probability $\leq10^{-4}$ and $\sim5 \times 10^{-3}$ that a fourth and a fifth H\textsc{i} component are, respectively, not required by the data. These low probabilities of nonoccurrence strongly suggest that Lemoine et al. (2002) have indeed detected the heliospheric absorption downwind in the direction of G191-B2B.

Note, however, that this heliospheric complex absorption profile is simulated by two components whose physical meaning in terms of hydrogen content and/or temperature is not clear. Furthermore, the photospheric Ly$\alpha$ stellar core is difficult to evaluate (see the discussion in, e.g., Lemoine et al. 2002) and is slightly redshifted relative to the ISM absorptions; this result may very well be simply related to the use of a white dwarf as background target star. The detailed analysis of the Capella line of sight could directly test the heliospheric hypothesis.

3. THE CASE OF CAPPELLA

If the two additional components present along the G191-B2B line of sight are, as a matter of fact, due to a heliospheric phenomenon, it is an extremely local signature (within a few hundred astronomical units, compared to the few tens of parsecs lines-of-sight lengths), which should be also present along the Capella sight line, both stars being separated by only 7$''$ on the sky, and similar in shape to the structure predicted and observed in the direction of G191-B2B. If that description is correct, we are expecting an extra absorption reasonably represented by two additional components, a main one mostly lost within the ISM absorption core and a weak one extending over several tenths of an angstrom on the red side of the line, again due to the neutral hydrogen atoms seen behind the shock in the downwind direction where both G191-B2B and Capella are located.

Recently, Young et al. (2002) analyzed new observations obtained at Ly$\beta$, Ly$\gamma$, and the whole Lyman series with FUSE. The precise Ly$\alpha$ stellar profile compatible with all Lyman lines and with the data sets obtained at different phases of the Capella binary system (see also Linsky et al. 1995) was reevaluated (B. E. Wood 2001, private communication) and is used here as a reference profile, $S_\alpha$.

We thus revisited the fits completed over the Ly$\alpha$ line as observed toward Capella with the best available data set, i.e., the one obtained with the Goddard High Resolution Spectrograph (GHRS; on board HST). The study by Linsky et al. (1995), essentially confirmed by Vidal-Madjar et al. (1998), shows that only one interstellar component (the Local Interstellar Cloud [LIC], also seen toward G191-B2B) is needed on that line of sight. This very simple structure strengthens the Capella case as the simplest one where D/H can be very well evaluated. However, Vidal-Madjar et al. (1998) have already noted that an additional weak and broad H\textsc{i} component was required to better reproduce the profile; this was the first indication of the presence of a heliospheric absorption toward Capella. In fact, we were able to show that, as in the case of G191-B2B, the addition of one or two weak and broad H\textsc{i} components (together with the very weak geocoronal component present at a known velocity but not shown in Fig. 1 for clarity) improves the $\chi^2$. More precisely, we fitted the GHRS data assuming that the stellar continuum was $S_\alpha$. Adding successively to the fit one then two free H\textsc{i} components (the added H\textsc{i} components have only three free parameters: velocity $v$, column density $N$, and width $\tau$, since the thermal $T$ or turbulent broadening $\xi$ act in an undifferentiated manner when only one species is observed), we obtained the following values of $\chi^2$/degrees of freedom (dof): for only the LIC component and the geocorona, 844.89/716; for one additional component, 831.17/713; for two additional components, 822.68/710. The $F$-test probabilities that these two additional components are not required by the data are, respectively, $8.5 \times 10^{-3}$ and $6.3 \times 10^{-2}$. The first one is clearly needed here [its correlated parameter ranges according to different possible solutions similar in terms of $\chi^2$ are $12\leq v$ (km s$^{-1}$)$\leq 22$, $1.4 \times 10^{14} \leq N$ (cm$^{-2}$) $\leq 4.4 \times 10^{15}$, and $10,000 \leq T$ (K) $\leq 32,000$], but unlike in the case of G191-B2B, the second one corresponding to the weaker and broader one [parameter ranges are $24\leq v$ (km s$^{-1}$) $\leq 60$, $3.6 \times 10^{12} \leq N$ (cm$^{-2}$) $\leq 8.5 \times 10^{13}$, and $120,000 \leq T$ (K) $\leq 300,000$] is less strongly needed. These ranges are certainly compatible with the corresponding estimated values in the direction of G191-B2B (see Fig. 10 of Lemoine et al. 2002).

To search for the possible impact of the choice of the continuum on the evaluation of $N$(H\textsc{i}), we fixed this value and looked for the best-fit solutions while the stellar continuum we used, $S_\alpha$, was allowed for some variations by multiplying it by a low-order polynomial (eighth-order) whose coefficients were free to vary along with all component parameters. Results are
shown in Figure 1. Slight changes of the continuum shape by no more than ±10% lead to nearly identical χ²-values, with N(H i) varying from 2.0 × 10¹⁸ cm⁻² to 1.4 × 10¹⁹ cm⁻², which corresponds to a change in D/H from 1.37 × 10⁻⁴ to 1.96 × 10⁻⁴. This is clearly a larger range (∼±0.3 × 10⁻³) than the one previously claimed (≤±0.2 × 10⁻³; Linsky et al. 1995).

The situation could be even worse, since we do not know how far the Capella continuum could be away from δp. The question is thus to evaluate if the Capella Lyα stellar continuum shape is estimated to better than ±10% or not. It is true that having a binary system can help constrain the continuum shape as Linsky et al. (1995) did, but their whole approach requires that the Lyα stellar profiles of both G1 III and G8 III stars are invariant with phase and time. In fact, from the study of 120 IUE echelle spectra, Ayres et al. (1993) have shown on one hand that the line fluxes were surprisingly stable but on the other hand that whichever way they process the data, obvious variations were seen. These seem to be related to variations of the blue peak of the G1 III dominant stellar Lyα line. They found that in the 1981–1986 interval, the line shape at phase 0.25 of the system was quite stable and similar to the one recorded with the GHRs in 1991 (at a ±10% level). Earlier spectra taken in 1980 or later ones observed after 1986 look quite different. This very careful study shows that with the IUE sensitivity level of ±5%, variations are clearly detected. Since Linsky et al. (1995) used GHRs observations at two different phases of the system (0.26 and 0.80) taken, respectively, in 1991 April and 1993 September, i.e., two and a half years apart, it is difficult to ascertain that the Lyα profile evaluated for each stellar component is well controlled. Because of the very careful analysis made by Linsky et al. (1995), it may be possible that the stellar Lyα profiles are relatively well evaluated but certainly not at a level better than ±10%, as previously mentioned.

Thus, a heliospheric absorption is also detected on the Capella sight line; furthermore, even in such a simple ISM configuration (a unique component), it appears impossible to tightly constrain the total H i column density in that direction.

4. DISCUSSION

We have shown that, for two lines of sight, N(\(H^1\)) cannot be evaluated with a high accuracy. Column densities on both sight lines are very similar, of the order of a few times 10ⁱ⁸ cm⁻². For lower column densities, the situation should be worse since then the possible absorption signature of the weak components is becoming relatively more and more important and the Lyα line is getting closer to the flat part of the curve of growth where column densities are indeed difficult to evaluate.

Note, however, that the HST/Echelle Extreme Ultraviolet Explorer (EUV) comparison completed by Linsky et al. (2000) shows that often N(\(H^1\)) values derived from the GHRs and EUVE data (not sensitive to weak H i) are in good agreement, implying that heliospheric absorption (or other hot components) do not necessarily ruin Lyα analyses in a dramatic way. But clearly, counterexamples leave that question open owing to possible systematics related to the evaluation of total H i below the Lyman limit in the EUVE domain.

On the contrary, one could guess that for larger column densities the situation should improve since the Lyα damping wings are becoming broader and the signature of the weak features may disappear in the line core. Just above 10ⁱ⁹ cm⁻², the reliability of the D/H values is greatly enhanced if the studied gas is demonstrably warm (6000 K; for a thorough discussion see York 2001); as one goes above 10²⁰ cm⁻², credibility increases unless either cold gas components are hidden in the warm D i but still affect the H i damping wings or weak H i features at high velocity are present.

The unknown referee further stressed this point through an impressive report. He mentioned that at N(\(H^1\)) = 2.0 × 10²⁰ cm⁻², the half-intensity point of pure damping Lyα and Lyβ profiles, located, respectively, at velocity shifts of 274 and 55 km s⁻¹, should be the place where a putative high-velocity feature could have a strong perturbing influence on the damping profile. However, only very few high-velocity ISM components were detected above 120 km s⁻¹. This could lead to the inverse impression that for larger column densities, the estimation through the Lyβ line should be more questionable than the one made at Lyα. As a matter of fact, in both the γ Cas and ζ Pup lines of sight, the H i column density was discrepant when derived through the Lyα or the Lyβ line (see below). However, in both cases the Lyβ estimations of N(\(H^1\)) are smaller, in contradiction with the formerly suggested cause since the most perturbed evaluation by additional absorptions should lead instead to larger column densities.

High-velocity ISM components essentially observed below 120 km s⁻¹ were only searched for through other lines and species than H i at Lyα the strongest transition of the most abundant element. For instance, Cowie et al. (1979) reported Lyβ and Ly ε H i ISM absorptions up to about 105 km s⁻¹ for ζ Ori. From their study, the referee evaluated that a shock at 274 km s⁻¹ should produce either a very broad (∼175 km s⁻¹) and undetectable (maximum depth of 5.9 × 10⁻³) postshock absorption signature or should originate in a region far downstream from the front where the gas has cooled and compressed enough to allow recombination of the H atoms, i.e., a shock from a supernova explosion entering the radiative phase. In this second case, however, he estimated from Cowie & York (1978) and Spitzer (1978, p. 318) that such signatures should occur only very near a known supernova event, i.e., within about 30–60 pc for standard ISM and supernova values. Thus, that looks unlikely too.

On the other hand, high-velocity gas could be generated by the target stars. While Gry, Lamers, & Vidal-Madjar (1984) seem to detect most of the activity at velocities below 100 km s⁻¹, they nevertheless identified a transient component at −150 km s⁻¹ toward γ² Vel through Lyβ and another one at −220 km s⁻¹ toward ζ Ori, through Lyε. Note also that this survey was completed over a limited spectral domain scanned with the Copernicus instrument and not at Lyα, i.e., with a relatively limited sensitivity.

One might argue that there are some risks that stellar ejecta could influence the Lyα measurements; but the observers have a good defense: multiple observations at very different epochs. This strategy was invoked by Jenkins et al. (1999) and Sonneborn et al. (2000) in their studies of D/H toward δ Ori, ζ Pup, and γ² Vel. Their findings are thus pretty convincing in this regard.

All the above stated arguments should mitigate our concern that small amounts of H i at high velocities are a likely source of confusion for the flanks of the damping profiles for N(\(H^1\)) of the order of or greater than 2.0 × 10¹⁹ cm⁻².

One, however, should recall the two lines of sight for which the H i column density was discrepant when derived through the Lyα or the Lyβ line:

1. \(γ^2\) Cas: Bohlin, Savage, & Drake (1978), from Lyα only (Copernicus), derived N(\(H^1\)) = 1.45(±0.29) × 10²⁰ cm⁻².
H I and deuterium (Burles 2001), while those for which oxygen measurements are well understood.

Finally, we note also that a similar systematic effect has been pointed out by Pettini & Bowen (2001) for the evaluation of D/H in quasar absorption-line systems. Again, as in our study, the systems presenting the highest values of N(H i) are derived from the damping wings of the Lyα line, which also includes all H i in close proximity of the hydrogen at the line center of deuterium (Burles 2001), while those for which N(H i) is evaluated from the discontinuity at the Lyman limit present smaller column densities and larger D/H evaluations. Clearly, many more lines of sight should be analyzed to resolve this issue.

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REFERENCES

Audouze, J., & Tinsley, B. M. 1976, ARA&A, 14, 43
Ayres, T. R., Brown, A., Gayley, K. G., & Linsky, J. L. 1993, ApJ, 402, 710
Bégin, P., Vidal-Madjar, A., Lallement, R., Ferlet, R., & Lemoine, M. 1995, A&A, 302, 889
Bohlin, R. C. 1975, ApJ, 200, 402
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Burles, S. 2001, in XVIIth IAP Conf., Gaseous Matter in Galaxies and Intergalactic Space, ed. R. Ferlet, M. Lemoine, J.-M. Desert, & B. Raban (Paris: Frontier Group), 367
Cowie, L., & York, D. G. 1978, ApJ, 223, 876
Cowie, L., et al. 1979, ApJ, 229, L81
Diplas, A., & Savage, B. D. 1994, ApJS, 93, 211
Ferlet, R., York, D. G., Vidal-Madjar, A., & Laurent, C. 1980, ApJ, 242, 576
Gry, C., Lamers, H. J. G. L. M., & Vidal-Madjar, A. 1984, A&A, 137, 29
Hébrard, G., et al. 2002a, Planet. Space Sci., in press
Jenkins, E. B., Tripp, T. M., Wóźniak, P. R., Sofia, U. J., & Sonneborn, G. 1999, ApJ, 520, 182
Laurent, C., Vidal-Madjar, A., & York, D. G. 1979, ApJ, 229, 923
Lemoine, M., et al. 2002, ApJS, 140, 67
Linsky, J. L. 1998, Space Sci. Rev., 84, 285
Linsky, J. L., Diplas, A., Wood, B. E., Brown, A., Ayres, T. R., & Savage, B. D. 1995, ApJ, 451, 335
Linsky, J. L., Redfield, S., Wood, B. E., & Piskunov, N. 2000, ApJ, 528, 756
Meyer, D. M., Jura, M., & Cardelli, J. A. 1998, ApJ, 493, 222
Moos, H. W., et al. 2000, ApJ, 538, L1
———. 2002, ApJS, 140, 3
Pettini, M., & Bowen, D. V. 2001, ApJ, 560, 41
Sonneborn, G., Tripp, T. M., Ferlet, R., Jenkins, E. B., Sofia, U. J., Vidal-Madjar, A., & Wóźniak, P. R. 2000, ApJ, 545, 277
Spitzer, L. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)
Timmes, F. X., Truran, J. W., Lauroesch, J. T., & York, D. G. 1997, ApJ, 476, 464
Vidal-Madjar, A., et al. 1977, ApJ, 211, 91
———. 1998, A&A, 338, 694
Wood, B. E., Muller, H.-R., & Zank, G. P. 2000, ApJ, 542, 493
York, D. G. 2001, in XVIIth IAP Conf., Gaseous Matter in Galaxies and Intergalactic Space, ed. R. Ferlet, M. Lemoine, J.-M. Desert, & B. Raban (Paris: Frontier Group), 69
Young, P. R., Dupree, A. K., Wood, B. E., Redfield, S., Linsky, J. F., Ake, T. B., & Moos, H. W. 2002, ApJ, submitted