GHRS OBSERVATIONS OF THE LOCAL INTERSTELLAR MEDIUM AND THE DEUTERIUM/HYDROGEN RATIO TOWARD CAPELLA

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ABSTRACT

I summarize the analysis of GHRS observations of interstellar D I, H I, Fe II, and Mg II line absorption for the 12.5pc line of sight to Capella. We derive the interstellar gas properties and an atomic deuterium/hydrogen ratio by number of $(D/H)_{\text{LISM}} = 1.65 (+0.07, -0.18) \times 10^{-5}$. This D/H ratio lies near the mean of many earlier but less certain values for the Capella line of sight and toward other stars located as far as 1 kpc from the Sun. We argue that a constant value for $(D/H)_{\text{LISM}}$ in the nearby Galactic disk should be adopted as the best available working hypothesis, but this hypothesis must be tested by future HST observations of Capella at phase 0.75 and of other stars. Galactic evolution calculations indicate that the primordial D/H ratio, $(D/H)_p$, probably lies in the range of $(1.5-3.0) \times (D/H)_{\text{LISM}}$. Standard Big Bang nucleosynthesis models for $(D/H)_p = 2.2-5.2 \times 10^{-5}$ imply that $\Omega_B h^2_{100} = 0.06-0.08$, where $\Omega_B$ is the baryonic density in units of the Einstein-de Sitter closure density, and $h_{100}$ is the Hubble constant in units of 50 km s$^{-1}$ Mpc$^{-1}$. If $H_0 = 80$ km s$^{-1}$ Mpc$^{-1}$ as recent evidence suggests, then $\Omega_B = 0.023-0.031$. Thus the Universe will expand forever, unless nonbaryonic matter greatly exceeds the amount of baryonic matter.

1. GHRS OBSERVATIONS AND ANALYSIS

Linsky and collaborators on the GHRS Team observed Capella with the GHRS on 1991 April 15. These observations are summarized in Table 1; a complete description of the data and their reduction and analysis is given by Linsky et al. (1992). Here I briefly summarize the reduction procedures and concentrate on the cosmological implications of the data. The processing of the spectra employed the 1991 December version of the CALHRS calibration software.

<table>
<thead>
<tr>
<th>Grating</th>
<th>Aperture</th>
<th>Spectral Range</th>
<th>Spectral Resolution $\lambda/\Delta\lambda$</th>
<th>Exposure Time (sec.)</th>
<th>Start Time (UT)</th>
<th>Important Spectral Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA-46</td>
<td>SSA 9</td>
<td>1211–1217Å</td>
<td>84,030</td>
<td>3917</td>
<td>10:04</td>
<td>HI, DI 1216Å</td>
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<tr>
<td>EB-22</td>
<td>SSA 7</td>
<td>2594–2606Å</td>
<td>91,740</td>
<td>707</td>
<td>13:37</td>
<td>FeII 2599Å</td>
</tr>
<tr>
<td>EB-20</td>
<td>SSA 7</td>
<td>2793–2807Å</td>
<td>84,750</td>
<td>707</td>
<td>13:23</td>
<td>MgII 2796, 2803Å</td>
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<tr>
<td>G140L</td>
<td>LSA 5</td>
<td>1161–1449Å</td>
<td>1,000</td>
<td>25.6</td>
<td>07:05</td>
<td>HI, CII, SiIV, etc.</td>
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</tbody>
</table>

1.1 The interstellar lines of Fe II and Mg II

We observed the Fe II and Mg II lines at the same time as the D I and H I lines to take advantage of their smaller thermal broadening. We could then search for multiple velocity components along the short line of sight to Capella and separate the effects of thermal broadening from turbulent broadening. The continuum-normalized line profiles are shown in Figure 1 as plots of normalized flux versus heliocentric velocity. The observed absorption lines, centered near 22 km s$^{-1}$, are symmetrical and show no evidence for multiple component structure.

To determine the column densities and absorption-line centroid velocities, we fitted the normalized absorption lines with Gaussian-broadened absorption lines parameterized by the standard Gaussian velocity spread parameter $b$ (km s$^{-1}$) (see Spitzer 1978). For a combination of thermal line broadening and macroscopic turbulent broadening, $b^2 = (2kT/m) + \xi^2$, where the most probable speed of the turbulent mass motions represented by $\xi$ (km s$^{-1}$) is assumed to be described by a Gaussian function. The results are shown in Figure 1 and are listed in Table 2, where $\lambda_c$ is the observed centroid wavelength, $v_c$ is the velocity

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Figure 1: (top) GHRS spectrum of the Fe II 2599 Å line profile (±1σ error bars), the best fit to the data (solid line), and the best-fit profile before application of the instrumental smearing (dashed line). (middle) Same for the Mg II 2803 Å line. (bottom) Same for the Mg II 2796 Å line.
displacement of \( \lambda \) from the laboratory vacuum wavelength, and \( \tau_0 \) is the line center optical depth of the fitted profile before instrumental blurring. The best fit was taken as that which produced the minimum value of \( \chi^2 \).

**TABLE 2  
INTERSTELLAR LINE PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mg II h</th>
<th>Mg II k</th>
<th>Fe II</th>
<th>D I</th>
<th>H I</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda (\text{Å}) )</td>
<td>2802.9175</td>
<td>2795.7429</td>
<td>2599.5752</td>
<td>1215.4269</td>
<td>1215.756</td>
</tr>
<tr>
<td>( v_c (\text{km s}^{-1}) )</td>
<td>22.75</td>
<td>23.04</td>
<td>20.68</td>
<td>22.04</td>
<td>21.74</td>
</tr>
<tr>
<td>( b (\text{km s}^{-1}) )</td>
<td>2.52</td>
<td>2.64</td>
<td>2.40</td>
<td>7.81</td>
<td>10.91</td>
</tr>
<tr>
<td>( N_L (\text{cm}^{-2}) )</td>
<td>( 6.49 \times 10^{12} )</td>
<td>( 6.44 \times 10^{12} )</td>
<td>( 3.01 \times 10^{12} )</td>
<td>( 2.97 \times 10^{13} )</td>
<td>( 1.80 \times 10^{18} )</td>
</tr>
<tr>
<td>( \tau_0 )</td>
<td>3.30</td>
<td>6.25</td>
<td>1.09</td>
<td>2.85</td>
<td>1.73 \times 10^5</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>2.79</td>
<td>9.18</td>
<td>1.40</td>
<td>0.897</td>
<td>-</td>
</tr>
</tbody>
</table>

1.2 The interstellar lines of D I and H I

The interstellar lines of D I and H I are separated by 0.3307 Å or 81.55 km s\(^{-1}\) (see Fig. 2). The wings of the H I absorption influence the continuum for the D I absorption. Therefore, the two absorptions must be analyzed together. We have adopted the atomic parameters including wavelengths, \( f \) values, and damping constants for H I and D I as tabulated by Morton (1991). The analysis allows for the fact that both D I and H I are each closely spaced doublets with \( \Delta \lambda = 0.0054 \) Å, which corresponds to a velocity spacing of 1.33 km s\(^{-1}\).

Linsky et al. (1992) describe an iterative method for obtaining \( v_{\text{DP}} \), \( b_{\text{HI}} \), \( N_{\text{D}} \), and \( N_{\text{HI}} \). Assuming that the H I has the same velocity as the D I and a Doppler broadening function given by \( b_{\text{HI}} = \sqrt{2} b_{\text{DP}} \), we reconstruct the “H I continuum” by dividing the observed spectrum by \( e^{-[N_{\text{HI}} \sigma_{\text{H}I}] / \zeta} \frac{SF(\Delta \lambda)}{SF(\Delta \lambda)} \). The value of \( N_{\text{HI}} \) is selected to give the best continuum reconstruction, \( \sigma_{\text{H}I} \) is the wavelength-dependent cross section for the H I doublet including natural broadening and Doppler broadening, and \( SF(\Delta \lambda) \) is the instrumental blurring function. What we call here the “H I continuum” is the intrinsic Ly\( \alpha \) emission line profile of Capella before interstellar absorption.

The best fit to the D I absorption line is shown in Figure 3. The GHR S almost completely resolves the D I absorption. Uncertainties in determining the column density of D I will be mostly determined by continuum placement errors associated with the imprecision in determining the value of \( N_{\text{HI}} \). Our fits to the Fe II, Mg II, and D I line profiles lead us to the conclusion that \( T = 7000 \pm 200 \) K and \( \xi = 1.66 \pm 0.03 \) km s\(^{-1}\) for the Capella line of sight.

1.3 The intrinsic Ly\( \alpha \) profile of Capella

We now ask whether this reconstructed profile (see Fig. 4) is consistent with what we know about the Capella system and the formation of the Ly\( \alpha \) emission line in stellar chromospheres. Capella is a spectroscopic binary system consisting of a G8 III star (called the “G star”) and a G0 III star (called the “F star”) in a 104-day period orbit. At the time of the GHR S observations, the phase was 0.26 using the ephemeris cited by Ayres (1984, 1988), and the radial velocity separation of the two stars was 53.6 km s\(^{-1}\) with the F star at negative radial velocity (displaced toward shorter wavelengths) relative to the binary system center of mass. Ayres et al. (1983) and Ayres (1988) have previously found that the F star contributes most of the flux for the chromospheric and transition region lines of the Capella system. The line asymmetry is observed to be the same (red peak brighter than the blue peak) at both quadratures, even though \( v_{\text{star}} - v_{\text{LISM}} \) changes sign from one quadrature to the next. Since the F star dominates the combined profile, we model the F star profile as asymmetric with brighter red peak emission.

We developed a model for the intrinsic Ly\( \alpha \) emission line from the Capella stars using the solar profile as a template. The quiescent Sun profile (taken from Vidal-Madjar 1977) has steep wings and emission features near line center of about equal intensity with a pronounced central reversal about 30% deep and 0.4 Å wide. The rapid rotation of the F star (v sin i = 36 km s\(^{-1}\)) will also partially fill in the self-reversal feature for this star. Working with these constraints, we searched for the intrinsic stellar line profiles that would provide the best fit to the reconstructed GHR S Ly\( \alpha \) line profile, over a range of assumed values for the interstellar hydrogen absorption. Figure 5 shows the computed sum of the intrinsic line profiles for \( N_{\text{HI}} \).
Figure 2: High-dispersion ($\lambda/\Delta\lambda = 84,000$) spectrum of the 1216 Å region obtained with the ECH-A grating. The profile consists of a broad Ly$\alpha$ emission line produced in the chromospheres of both stars and absorption by interstellar hydrogen and deuterium ($\Delta\lambda = -0.3307$ Å relative to hydrogen) along the 12.5 pc line of sight to Capella. In this presentation the residual scattered light in the core of the Ly$\alpha$ line has not been removed.

Figure 3: GHRS spectrum of the D I Ly$\alpha$ line profile ($\pm 1\sigma$ error bars), the best fit to the data (solid line), and the best-fit profile before application of the instrumental smearing (dashed line).
Figure 4: GHRS spectrum of the Lyα line (lower profile) and four reconstructed profiles of the intrinsic Lyα emission line of Capella obtained by dividing the observed profile by $[e^{-\tau_\lambda} \times SF(\Delta \lambda)]$, where $\tau_\lambda$ is the interstellar hydrogen opacity and SF($\Delta \lambda$) is the instrumental spectral spread function. The top four curves, from top to bottom, are for $N_{HI} = 2.20 \times 10^{18}$, $N_{HI} = 2.00 \times 10^{18}$, $N_{HI} = 1.80 \times 10^{18}$ and $N_{HI} = 1.60 \times 10^{18}$ cm$^{-2}$.

= 1.6, 1.8 and 2.0 $\times 10^{18}$ cm$^{-2}$ and our best fit models for the intrinsic profiles of the individual stars. The inferred intrinsic profiles that meet this constraint lie in the range $N_{HI} = (1.7-1.9) \times 10^{18}$ cm$^{-2}$. Thus, under the assumption that the intrinsic stellar profiles can be reasonably approximated by scaled solar profiles, we find an uncertainty of $\pm 0.1 \times 10^{18}$ cm$^{-2}$ in $N_{HI}$, which we characterize as a random error.

Our assumption that the intrinsic Capella Lyα profile is like the quiet Sun, however, could be wrong. It is possible that the intrinsic profile has a flat top (no central reversal) like the Lyα line in solar plages (see Basri et al. 1979), as the Capella F star is active. In this case $N_{HI}$ could be as large as 2.1 $\times 10^{18}$ cm$^{-2}$ and still be consistent with the observed line shape at phase 0.26. Allowing for systematic errors associated with the derivation of $N_{HI}$, we conclude that $N_{HI} = 1.8 \,(+0.3, -0.1) \times 10^{18}$ cm$^{-2}$, which implies that $(D/H)_{LISM} = 1.65 \,(+0.07, -0.18) \times 10^{-5}$.

2. DISCUSSION

2.1 The temperature and flow velocity in the warm LISM

The kinetic temperature, $T = 7000 \pm 200$ K, of the warm neutral gas in the cloud in the direction of Capella is accurately determined from the high-quality D I, Mg II and Fe II line profiles. Previous (21-cm) measures of temperature in the warm, neutral ISM have been reviewed by Kulkarni & Heiles (1987), who cite a rough estimate of $T \sim 8000$ K. The quality of the profile fit in Figure 3 for such a short path through the LISM confirms the theoretical expectation (Spitzer 1978, Ch 2) that a simple Maxwell-Boltzmann velocity distribution function is indeed a valid description for the particle motions in the warm, neutral interstellar medium.

The five interstellar lines observed with the Echelle show a mean heliocentric velocity $v_{LISM} = 22.0 \pm 0.9$ km s$^{-1}$. This may be compared with the value of 20 $\pm 1$ km s$^{-1}$ determined by Ayres (1988) from IUE spectra that were calibrated using the known $\gamma$-velocity of the Capella system (Batten, Fletcher & Mann 1978) and the predicted flow vector along the Capella line of sight of 20.0 km s$^{-1}$ (Crutcher 1982). Thus we
Figure 5: Observed GHRS spectrum (solid line), the intrinsic Lyα emission lines of the Capella F and G stars (dotted lines), and the sum of these intrinsic stellar lines folded through the interstellar medium (dashed line). The top panel is for $N_{HI} = 2.0 \times 10^{18} \text{ cm}^{-2}$, the middle panel is for $N_{HI} = 1.8 \times 10^{18} \text{ cm}^{-2}$, and the lower panel is for $N_{HI} = 1.6 \times 10^{18} \text{ cm}^{-2}$. 
2.2 Does the D/H ratio depend on line of sight in the LISM?

The first analysis of *Copernicus* Lyα spectra for the lines of sight toward α Cen A and Capella (Dupree *et al.* 1977) resulted in D/H ratios that differed by a factor of 16, despite the short distances to these stars. These and subsequent D/H measurements led many authors to conclude that the D/H ratio is far from constant in the LISM. We have come to the opposite conclusion for the following reasons: (1) The previous D/H measurements for the Capella line of sight were based on *Copernicus* and IUE data, which have much lower S/N and spectral resolution. All lie outside the range of the present result. (2) McCullough’s (1992) reanalysis of all the IUE and *Copernicus* observations of interstellar Lyman line absorption toward both cool and hot stars without evidence for variable winds is consistent with the hypothesis that D/H = 1.5 (±0.2) × 10^{-5}.

With GHRS spectra of other nearby late-type stars we should be able to test the interesting hypothesis that there is a constant value of D/H in the LISM. Until such spectra demonstrate otherwise, our working hypothesis is that the D/H ratio is constant in the LISM and in the disk of the Galaxy out to 1 kpc with the same D/H ratio as towards Capella. Comparison of the D/H ratio towards Capella with the results of analyses of *Copernicus* observations of the less saturated interstellar higher Lyman lines towards hot stars (see Figure 6) is consistent with this hypothesis. The disk thus appears to be well mixed, presumably by supernovae explosions and by stellar winds.

2.3 The primordial D/H ratio and the evolution of the Universe

The value of D/H in the local region of our galaxy, (D/H)$_{\text{LISM}}$, should be a hard lower limit to the primordial value, (D/H)$_{\text{p}}$, since deuterium is readily destroyed by nuclear reactions in stars (astration) but is not easily created in stars or in the interstellar medium. Clayton (1985) estimates that (D/H)$_{\text{p}}$ ≥ 3 (D/H)$_{\text{LISM}}$ on the basis of a calculation in which he assumes that the gas in the primitive galaxy had a primordial abundance. He included star formation, astration, the return of deuterium-depleted gas to the interstellar medium as stars die, and the infall of gas with (D/H)$_{\text{p}}$ from the Galactic halo to the disk. The value will be greater than 3 if the infalling material is itself deuterium poor due to astration in Galactic halo stars. The degree to which the infalling gas is depleted in deuterium is uncertain. Delbourez-Salvador, Audouze & Vidal-Madjar (1987) conclude that (D/H)$_{\text{p}}$ could be much larger than 3 times (D/H)$_{\text{LISM}}$. More recently Steigman & Tosi (1992) have made similar calculations resulting in a value for the survival fraction
of deuterium at the present time in the range 1.5–3.0 with the larger value for models with no infalling gas. In what follows we assume this range for the survival fraction, which implies that \((D/H)_p = (2.2-5.2) \times 10^{-5}\).

A good estimate of \((D/H)_p\) is important, because according to Big Bang nucleosynthesis models the light elements were created in the first 1000 seconds of the Universe and they provide one of the very few available constraints on physical conditions at that time. The simplest Big Bang nucleosynthesis models assume that General Relativity is valid at early times, that the Universe is homogeneous and isotropic, and that only presently known forms of matter (baryons and leptons) and radiation were present. The recent nucleosynthesis calculations by Walker et al. (1991) assume only three species of light neutrinos and the recent measured value of 10.27 ± 0.08 minutes for the neutron half life (cf. Byrne et al. 1990).

Comparison of our adopted value of \((D/H)_p = (2.2-5.2) \times 10^{-5}\) with the Walker et al. calculations indicates that \(\eta_{10} = 3.8-6.0\), where \(\eta_{10}\) is \(10^{10}\) times the ratio of nucleons to photons by number. The \(^4\)He abundance varies in the opposite sense to \((D/H)_p\), because with increasing density at the time of nucleosynthesis deuterium will be more completely converted into \(^3\)He and \(^4\)He. Walker et al. find that the best-estimate value of the primordial \(^4\)He/H ratio by mass, \(Y^\text{obs}_p\), places \(\eta_{10}\) in the range 2.8 to 4.0, consistent with the value inferred from our adopted value of \((D/H)_p = (2.2-5.2) \times 10^{-5}\). Pagel (1990) reaches a similar conclusion. This range in \(\eta_{10}\) leads to the important result that \(0.06 \leq \Omega_B A^\text{obs}_B \leq 0.08\), where \(\Omega_B\) is the baryon density in units of the Einstein-de Sitter closure density, and \(A^\text{obs}_B\) is the Hubble constant in units of 50 km s\(^{-1}\) Mpc\(^{-1}\). Should the Hubble constant be about 80 km s\(^{-1}\) Mpc\(^{-1}\), then the deuterium data alone require that \(\Omega_B = 0.023-0.031\).

If only presently known forms of matter exist, the basic assumptions of the Big Bang nucleosynthesis models are valid, and the cosmological constant is zero, then our results require an open Universe. There are, however, both empirical and theoretical arguments that should be considered when discussing the evolution of the Universe. In his recent discussion of the dynamical evidence for dark matter, Tremaine (1992) concludes that approximately 90% of the mass of the Universe is in the form of dark nonbaryonic matter. This matter is located in the extended halos of galaxies, in clusters of galaxies, and perhaps elsewhere. Inflation models predict that the density parameter \(\Omega \approx 1\). On the basis of our data we can say that if the early Universe was homogeneous, then for \(\Omega\) to equal unity the amount of nonbaryonic matter must be 14 times that of ordinary matter for \(h_{50}=1\) or 60 times for \(h_{50}=2\). Whether or not the expansion of the Universe will eventually be stopped thus remains an open question.

3. FUTURE OBSERVATIONS

We have demonstrated that very accurate values of the D/H ratio and interstellar properties can be obtained for the Capella line of sight by analyzing the high-resolution and high signal/noise Ly\(\alpha\) profile obtained with the GHRS Echelle-A grating. Our results are consistent with the hypothesis that the D/H ratio is constant in the Galactic disk out as far as 1 kpc, but clearly this hypothesis should be tested by observing other lines of sight. Also, the uncertainties in \(N_{\text{HI}}\) and \((D/H)_{\text{ISM}}\) for the Capella line of sight could be reduced considerably by observing Capella near phase 0.75. Observations with Echelle-A are not presently feasible, but lower resolution observations with the G-160M grating can accomplish this task with somewhat lower accuracy. We believe that this program should proceed.

This work is supported by NASA Grant S-56500-D to the National Institute of Standards and Technology.

REFERENCES