The Light Elements and Their Evolution
IAU Symposium, Vol. 198, 2000
L. da Silva, M. Spite, J. R. de Medeiros, eds.

Deuterium Observations in our Galaxy - View A

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Abstract. Accurate measurements of the D/H ratio in our Galaxy provide critical tests of Galactic chemical evolution and constrain the primordial value of D/H. Very high quality ultraviolet spectra from the GHRS and STIS instruments on HST have been analyzed for lines of sight toward both early and late-type stars and hot white dwarfs. We will summarize the results that are being obtained for D/H along sightlines through the Local Interstellar Cloud (LIC) and other nearby warm clouds. All sightlines through the LIC are consistent with $D/H = (1.53 \pm 0.18) \times 10^{-5}$. Whether or not significantly different values of D/H are present in other clouds within 100 pc of the Sun is not yet settled, but there is evidence that D/H is significantly lower in Orion (500 pc). We will describe the likely sources of systematic errors in determining D/H that must be understood and quanitified when analyzing such ultraviolet spectra.

1. Introduction

Accurate measurements of the ratio by number of deuterium to hydrogen (hereafter called D/H) in different environments are critically needed to address two fundamental problems in astrophysics. First, measurements of D/H in environments where there has been very little processing of gas through stars and the metal abundance is small is essential to infer the primordial D/H ratio that determines the baryonic density of the universe. Second, measurements of the D/H ratio in interstellar gas located throughout the Galactic disk and halo will allow us to track the end result of chemical evolution resulting from nuclear burning of D inside stars (astration), transfer of D-depleted gas into the ISM, formation of new generations of stars from this D-depleted interstellar gas, mixing of the gas with other environments in the ISM, and infusion of gas with presumably primordial D/H from the halo. This complex set of processes is modelled by Galactic chemical evolution codes (e.g., Tosi *et al.* 1998). Accurate D/H measurements can test the predictions of these codes and thereby provide insight into the rates for these processes over the lifetime of the Galaxy.

Lemoine *et al.* (1999) have written an excellent review of D/H measurements in quasar spectra, the ISM, and the solar system (reflecting the D/H ratio in the protosolar nebula). Although the D/H ratio can be inferred from radio frequency hyperfine transitions and from deuterated molecules, the most accurate method today is to measure the interstellar column densities of the H and D Lyman lines seen in absorption against the spectra of normal stars and hot white dwarfs. In the last few years measurements of D/H along many lines of sight have been

https://doi.org/10.1017/S0074180900166525 Published online by Cambridge University Press

determined from the analysis of high resolution spectra from the GHRS and STIS instruments on HST, but the IMAPS experiment on the Astro-Spas platform has also provided data for D/H measurements. We will summarize all of these results below. Careful analysis of the excellent quality spectra now available has led to a better appreciation of the systematic errors that likely are more important than the published random errors and, if not included in the analysis, could lead to factor of 2 or larger underestimates in D/H. For this reason we start with a discussion of systematic and other errors.

2. Systematic and Other Measurement Errors

Since the D/H ratio in the ISM is roughly 1.5×10^{-5}, detection of a D Lyman line requires that the H Lyman line be very optically thick. This simple fact can lead to large systematic errors in the D/H ratios derived by fitting Lyman line spectra unless one includes in the analysis all sources of H absorption. The magnitude of this problem was not appreciated until recently. Observations of the higher Lyman lines with FUSE and IMAPS will lessen the impact of this large ratio of the D and H opacities as one can compare D absorption in a more opaque Lyman line with H absorption in a less opaque higher Lyman line. Even so, the problems described here will still be important and must be addressed in order to obtain credible values for the D/H ratio.

Horizon: Since the D line is located at –81 km s^{-1} relative to the H line, saturated H Lyman line absorption can cover up the D line creating a visibility horizon. For Lyman-α the horizon sets in at about $\log N_{\rm HI} = 18.8$, while for Lyman-γ it begins at about 20.0. The presence of a horizon is important because the large H column densities to hot stars prevent visibility of the D Lyman-α line and often the Lyman-β line, but the sensitivity of the FUSE spectrograph is a factor of 3 or smaller at the higher Lyman lines compared to Lyman-β and much lower than the sensitivity of the HST spectrographs to Lyman-α.

Confusion: Only a few lines of sight to nearby stars appear to have only one velocity component at a resolution of 2.6–3.6 km s^{-1} (GHRS and STIS). Even the short lines of sight to Sirius (2.63 pc, Hébrard *et al.* 1999) and 61 Cyg A (3.48 pc, Wood & Linsky 1998) often show two or more velocity components, and lines of sight to more distant targets can be even more complex. Higher resolution studies of interstellar Na I absorption led Welty, Morton, & Hobbs (1996) to estimate that only 10% of the interstellar velocity components are resolved for unsaturated lines at a resolution of 3.6 km s^{-1}. This result may overestimate the number of velocity components expected for the H and D lines since neutral H and D are present in warm clouds whereas Na I is also formed in cold clouds. Unresolved velocity components can lead to errors in derived H column densities and thus D/H, since $N_{\rm HI}$ is often derived from the shape of the H absorption just outside of the saturated line core where all of the velocity components contribute and the opacity is a nonlinear function of $N_{\rm HI}$ and the broadening parameter b.

Since the H and D lines are broad, closely spaced velocity components identified in the heavier (and thus narrower) metal lines cannot be separated in the H and D lines. The abundance ratio of H to a metal depends on the relative ionization of H and the metal and the depletion of metal atoms onto grains.

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Both of these effects are likely different in each cloud, making it difficult to infer H and D column densities by extrapolating from the metal lines. The best metal lines to use as surrogates for H are N and O because they have nearly the same ionization potential as H, but the uncertain depletion of N and O implies an uncertain distribution in the H column densities in the different clouds. A second problem is uniqueness. In a multicomponent fit, one generally cannot solve for $N_{\rm HI}$ and b, and D/H, for each of several clouds along a line of sight from the analysis of only a few line profiles without making some assumptions, such as assuming common b or D/H values in all clouds, or that the distribution of $N_{\rm HI}$ among the several clouds is the same as is seen in the metal lines. It is difficult to assess the systematic errors than result from such assumptions.

Uncertain background: Absorption by interstellar H and D is measured against the stellar emission or absorption line that serves as the background "continuum." For late-type stars this "continuum" is the chromospheric Lyman emission line, whereas for hot stars, including white dwarfs, the "continuum" is the photospheric absorption line. Unless the star has an extremely high radial velocity, the stellar line is not separable from the interstellar absorption feature and must be estimated or computed. On the other hand, for large column desities ($\log N_{\rm HI} > 20.0$), for example the line of sight to δ Ori A analyzed by Jenkins *et al.* (1999), the interstellar Lyman-α line is so broad that the shape of the background stellar absorption line is irrelevant.

For late-type stars, one approach is to scale the solar Lyman-α line in width depending on the stellar luminosity. This scaling, which is analogous to the Wilson-Bappu effect for the Ca II H and K lines (cf. Linsky 1999), appears to work for late-type dwarfs but not for luminous stars with massive winds, which have P-Cygni emission lines with blue-shifted absorption. An alternative approach is to assume that the stellar Lyman-α line has the same shape (on a velocity scale) as the Mg II k line. This should be valid at least for late-type dwarfs as both lines are optically thick and are formed in about the same layers in a chromosphere. Also, these two lines have the same shape in the solar spectrum. When there is a significant radial velocity separation (> 40 km s^{-1}) between the star and the ISM absorption, it is possible to reconstruct the stellar emission line empirically. Wood, Alexander, & Linsky (1996) developed a technique that assumes that the far wings of the stellar emission line are symmetric about the photospheric radial velocity, although this assumption is probably only valid for solar-like main sequence stars. This technique has recently been applied to the analysis of the line of sight to 36 Oph A. Another very powerful technique is to analyze spectra of RS CVn systems obtained at opposite orbital velocity quadratures. When applied to Capella, for which the component stars have a maximum radial velocity separation of 53 km s^{-1}, and HR 1099, for which the radial velocity separation is 111 km s^{-1}, Linsky *et al.* (1995) and Piskunov *et al.* (1997) could reconstruct the emission line profiles for each component star in the system and thereby obtain very accurate values of D/H.

When analyzing hot star spectra, one must assume a shape for the photospheric Lyman-α absorption line. For hot main sequence stars, the stellar absorption line may be asymmetric due to absorption from a wind. For hot white dwarfs like Sirius B, it is important to compute the Lyman-α line profile using a non-LTE model with accurately determined $T_{\rm eff}$ and $\log g$ (e.g., Hébrard *et al.* 1999). Uncertainties in the photospheric line profile, especially near zero flux where the scattered light correction is important, can lead to errors in the derived D/H ratio.

Scattered light: A little known fact concerning the GHRS instrument is that the echelle grating could not be built to specifications. Instead an off-the-shelf echelle grating with greater scattered light was substituted at the last minute. Unfortunately, the Digicon detector had tall pixels (in the direction perpendicular to the echelle dispersion) and could not sample the spectral shape of the scattered light with high precision. By contrast, the STIS echelle gratings have lower amounts of scattered light that can be measured accurately by the two-dimensional MAMA detector with small pixels. Sahu *et al.* (1999) showed a comparison of the Lyman-α spectra of the hot white dwarf G191-B2B obtained with the echelle gratings on GHRS and STIS. The profiles differ in the core of the D line, which led Sahu *et al.* to conclude that the D/H ratio in the non-LIC cloud toward the star is consistent with the LIC value, whereas Vidal-Madjar *et al.* (1998) had concluded from the GHRS data alone that the D/H ratio in the non-LIC components are significantly lower than in the LIC. The conclusion to this controversy may require additional analysis and new observations, but the important point is that accurate D/H ratios require spectra with an accurate correction for scattered light.

Heliospheric hydrogen absorption: In their analysis of the lines of sight to α Cen A and α Cen B, Linsky & Wood (1996) found two problems: (a) the central velocity of the H absorption is redshifted by $+3.2$ km s^{-1} relative to the velocity of the D, Mg II, and Fe II lines; (b) the broadening of H is larger than expected from the T and turbulent velocity values derived from the other lines. These difficulties imply the existence of extra H absorption on the red side of the interstellar absorption feature. Older *Copernicus* spectra also suggested a redshift of H relative to D in α Cen data and several explanations were proposed (cf. Lemoine *et al.* 1999). The GHRS spectra confirmed the missing H opacity and provided important clues as to its properties. A two-component fit to the α Cen Lyman-α line profiles showed that the extra H has a temperature of about 27,000 K and a redshift of at least 2 km s^{-1} relative to the main interstellar absorber.

The H responsible for this absorption is believed to be located near the heliopause where the inflowing partially ionized interstellar gas interacts with the outflowing ionized solar wind by charge exchange reactions of the protons and hydrogen atoms (cf. review by Zank 1999). Named the "hydrogen wall" by Baranov and Malama (1995), the computed pileup of decelerated and heated neutral H in the wall has properties consistent with those inferred from the additional H opacity toward α Cen. Even though $N_{\rm HI}$ in the H wall is only 10^{-3} that of the interstellar gas, the wall provides measurable absorption on the red side of the interstellar line because the H gas is redshifted, hot, and optically thick. Recent calculations by Müller, Zank, & Lipatov (1999) show that the H wall absorption is redshifted (relative to the interstellar flow) in all directions, because downstream the solar wind accelerates the heliospheric H. Heliospheric absorption has been detected toward α Cen, 36 Oph A (Wood, Linsky, & Zank 1999), and probably also Sirius (Izmodenov, Lallement, & Malama 1999).

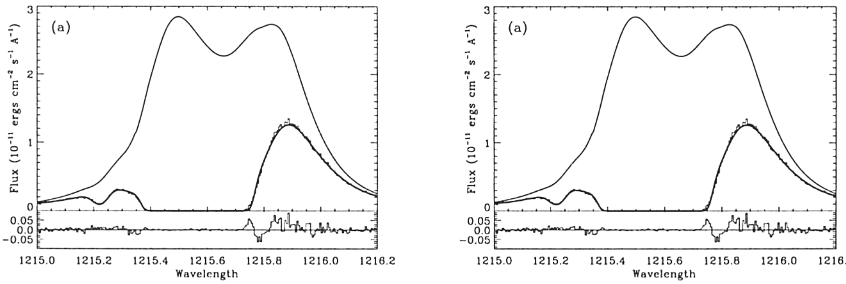

Figure 1. (a) Fitting of the observed Lyman-α line toward 36 Oph A (histogram) with only interstellar absorption. (b) Fitting with three components (interstellar, heliosphere, and astrosphere). The dotted line indicates absorption due only to the ISM, the dashed line is absorption due to the heliosphere, and the dot-dashed line is absorption due to the astrosphere. The thick solid line is the combined absorption of all three components. From Wood *et al.* (1999).

Astrospheric hydrogen absorption: Wood *et al.* (1996) noticed that H absorption is blueshifted relative to D in the spectrum of ϵ Ind. They interpreted this as absorption in the H wall around the target star. At least 9 stars (see Tables 1 and 2) now have identified astrospheric absorption, although many of these detections must be considered to be tentative. The combination of heliospheric absorption on the red side and astrospheric absorption on the blue side of the interstellar absorption means that model fits to the Lyman line that ignore this excess absorption will overestimate $\log N_{\rm HI}$, and thus underestimate D/H. For the nearby stars α Cen, 36 Oph A, and Sirius, fitting the Lyman-α line without absorption in the heliosphere and astrosphere underestimates D/H by about a factor of 2. Figure 1 shows a comparison of the fits of the Lyman-α line toward 36 Oph A, which is located only 12° from the direction of inflowing LIC gas, with only interstellar absorption ($\log N_{\rm HI} = 18.18$) and with all three components ($\log N_{\rm HI} = 17.85$ in the ISM). Since the analysis of the Lyman-α lines toward many nearby stars have not included heliospheric and astrospheric absorption, more refined analyses could potentially lead to an upward revision of some of the reported D/H values.

3. Summary of D/H Measurements

3.1. D/H in the LIC

Table 1 summarizes the published D/H measurements toward nearby stars for which the interstellar gas has a velocity consistent with the LIC velocity vector (Lallement & Bertin 1992). In those cases where the authors derived a D/H ratio by assuming a value for $N_{\rm HI}$, we cite their conclusions that the data are consistent ("con") with a given value of D/H. Figure 2 shows a plot of the D/H measurements with respect to the distance of the background star and the Galactic longitude. There is no trend with either variable, and we conclude that

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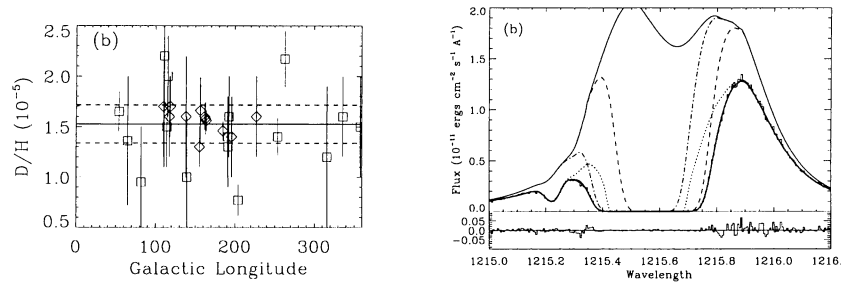

Figure 2. (a) D/H values from Tables 1 and 2 plotted vs. distance to the target star. Diamonds show the LIC values and boxes show the non-LIC values. The horizontal solid line is the weghted mean value of D/H for the LIC measurements and the dashed lines are $\pm 2\sigma$ about the mean value. (b) Similar to (a), but D/H values are plotted versus Galactic longitude.

D/H $= (1.53 \pm 0.18) \times 10^{-5}$ for gas in the LIC, based on the weighted mean and 2σ dispersion of the measurements in Table 1.

The largest potential source of systematic error in the LIC value of D/H is probably heliospheric and/or astrospheric absorption that has not been taken into account in the analyses of many of the target stars. In the analysis of data for 9 of the lines of sight through the LIC, hydrogen absorption in the heliosphere and/or astrosphere was included in the analysis. This is indicated by the symbols A and H in the Helio/Astro column of the tables. For the other lines of sight no inclusion of either absorber was attempted, as these data did not clearly show the presence of non-LISM H absorption, although heliospheric/astrospheric absorption might conceivably be present. The effect of not including heliospheric and astrospheric absorption is to ascribe all of the hydrogen absorption to the LIC and thereby potentially overestimate $N_{\rm HI}$ and underestimate D/H. Calculations of the heliospheric and astrospheric absorption for the lines of sight to Sirius (Izmodenov, Lallement, & Malama 1999) and α Cen A (Gayley *et al.* 1997) indicate that the changes in the derived D/H values could be significant. A reanalysis of many of these data sets is underway by Wood, Müller, & Zank (2000), which should better quantify this source of systematic error. The results summarized in Table 1 suggest, however, that the increase in the mean value of D/H in the LIC that will come from this reanalysis may not be very large, as the D/H values for those lines of sight analyzed including heliospheric and/or astrospheric absorption are not significantly larger than for the lines of sight analyzed without the corrections.

3.2. D/H in other clouds within 500 pc

Two fundamental issues in the study of Galactic chemical evolution are the distance scale over which significant variations in D/H occur and the chemical history of the environments in which different values of D/H are measured. While the value of D/H in the LIC may now be accurately measured and can serve as a reference by which D/H values in different environments can be com-

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Table 1. Summary of D/H Measurements in the LIC

Star	d (pc)	l (°)	b (°)	Instrument	Helio/ Astro	D/H (10^{-5})	Ref.
Sirius A	2.63	227	–09	GHRS/M	H,A	con. with 1.6	L
Sirius A,B	2.63	227	–09	GHRS/M		1.6 ± 0.4	H
ϵ Eri	3.22	196	–48	GHRS/E	A	1.4 ± 0.4	F
61 Cyg A	3.48	082	–06	GHRS/E	A	con. with 1.5	G
Procyon	3.50	214	+13	GHRS/M		con. with 1.6	B
40 Eri A	5.04	201	–38	GHRS/E	A	con. with 1.5	G
Capella	12.9	163	+05	GHRS/E		1.47–1.72	A
Capella	12.9	163	+05	GHRS/M		1.41–1.74	B
Capella	12.9	163	+05	GHRS/E	A	1.56 ± 0.1	I
β Cas	16.7	118	–03	GHRS/M		1.6 ± 0.4	D
β Cas	16.7	118	–03	GHRS/E		1.7 ± 0.3	F
α Tri	19.7	139	–31	GHRS/E		1.6 ± 0.6	F
λ And	25.8	110	–15	GHRS/E	A	1.7 ± 0.5	C
HR 1099	29.0	185	–42	GHRS/E		1.46 ± 0.09	D
G191-B2B	68.8	156	+07	GHRS/E		1.1–1.5	E
G191-B2B	68.8	156	+07	GHRS/E		con. with 1.6	I
G191-B2B	68.8	156	+07	STIS/H		1.33–1.99	J
ϵ CMa	187.	240	–11	GHRS/M		con. with 1.6	K

References: A: Linsky *et al.* (1993); B: Linsky *et al.* (1995); C: Wood, Alexander, & Linsky (1996); D: Piskunov *et al.* (1997); E: Lemoine *et al.* (1996); F: Dring *et al.* (1997); G: Wood & Linsky (1998); H: Hébrard *et al.* (1999); I: Vidal-Madjar *et al.* (1998); J: Sahu *et al.* (1999); K: Gry *et al.* (1995); L: Izmodenov *et al.* (1999).

pared, the LIC value of D/H may or may not be representative of D/H in the disk at the galactocentric distance of the Sun. Future observations, especially with the FUSE spacecraft, are needed to settle this question.

Table 2 summarizes the published D/H measurements for interstellar gas with line of sight velocities different from the LIC velocity vector. The first five stars in the table show absorption at velocities corresponding to the velocity vector of the G cloud (Lallement & Bertin 1992). This cloud, centered in roughly the Galactic center direction, begins very close to the Sun in the direction toward α Cen and 36 Oph, because no LIC absorption is detected along these lines of sight. We include ϵ Ind in this group even though its velocity is the same as the predictions of both the LIC and G vectors, because the LIC model proposed by Redfield & Linsky (2000) predicts very little LIC absorption for this line of sight. Dring *et al.* (1997) proposed that the main absorption feature toward β Gem (22.0 ± 1.8 km s^{-1}) and σ Gem (21.5 ± 1.8) km s^{-1}) are consistent with the projected LIC velocity (19.6 km s^{-1}), but we find that the projected G cloud velocity (21.2 km s^{-1}) is a better match to the data. The present data indicate that D/H for the G cloud is consistent with the LIC value.

Three other clouds can be identified by their respective absorption velocities. The North Galactic Pole (NGP) cloud is seen toward HZ 43 and 31 Com. The South Galactic Pole (SGP) cloud is seen toward β Cet. A third cloud identified by its radial velocity of about +33 km s^{-1} is seen toward β Gem and σ Gem. The D/H ratios for these three clouds, all located within about 30 pc of the Sun, appear to be consistent with the LIC value.

Table 2 includes another 4 stars (Sirius, 61 Cyg A, α Tri, and G191-B2B) located within 100 pc of the Sun for which there are interstellar velocity components different from the LIC, G, NGP, SGP, and +33 clouds. Observations of other lines of sight are needed to determine the size and locations of the clouds responsible for the observed absorption components. Hébrard *et al.* (1999) argue that the +11.7 km s^{-1} absorption component toward Sirius A and B has a D/H ratio that is barely consistent with the LIC value but is more likely much smaller. However, their analysis does not include heliospheric or astrospheric absorption, which Izmodenov *et al.* (1999) argue are important and must increase the interstellar D/H ratio. We await a reanalysis of this line of sight before concluding that the D/H ratio is low in this cloud. The line of sight to the hot white dwarf G191-B2B has been studied by Vidal-Madjar *et al.* (1998) using GHRS spectra and by Sahu *et al.* (1999) using STIS spectra. These analyses arrive at very different conclusions concerning the D/H ratio in non-LIC clouds detected along this line of sight: Vidal-Madjar *et al.* concluded that two clouds are present (+8.2 and +13.2 km s^{-1}) with average D/H $\sim 0.9 \times 10^{-5}$, while Sahu *et al.* concluded that there is only one cloud at +8.6 km s^{-1} with D/H consistent with the LIC value. Sahu *et al.* argued that scattered light in the GHRS echelle spectra is responsible for the very different conclusions. Given this disagreement and no inclusion of heliospheric and astrospheric absorption in either analysis, we believe that it is premature to conclude that D/H has a lower value in these clouds.

The last four lines of sight listed in Table 2 are for stars located beyond 100 pc from the Sun. The observations of the higher Lyman lines were obtained with the high resolution IMAPS spectrograph ($\lambda/\Delta\lambda = 75,000$) or the lower resolution ORFEUS spectrograph ($\lambda/\Delta\lambda = 10,000$). For γ^2 Vel, δ Ori A, and ζ Pup, the D column densities were obtained by fitting the higher Lyman lines, but the H column densities were obtained by fitting IUE spectra of the Lyman-α line. The very broad interstellar absorption in the Lyman-α line means that H absorption in the heliosphere and astrosphere occur where the interstellar absorption is saturated and thus do not need to be included. For these lines of sight there may be several clouds responsible for the absorption, in which case the derived D/H value would represent an average through these different clouds.

The most interesting of these lines of sight is toward δ Ori A, for which Jenkins *et al.* (1999) find that D/H lies in the range (0.61–0.93) $\times 10^{-5}$ in what appears to be a single absorbing cloud. We believe that this is the most reliable measurement so far of a D/H ratio in the Galactic disk that is significantly different from the LIC value. If analysis of other lines of sight in star forming regions in Orion confirm this result, then Galactic chemical evolution models are faced with an interesting test. These models (e.g., Tosi *et al.* 1998) typically show an inverse correlation of D/H with metal abundance as chemical evolution in stars inevitably proceeds in this direction. Jenkins *et al.* (1999), however, find no overabundance of metals in the δ Ori A line of sight, but rather a low abundance of N and a marginally low abundance of O. Since Orion is not a region of enhanced metal abundance, why is D/H so low?

Table 2. Summary of D/H Measurements within 500 pc

Star	d (pc)	l (°)	b (°)	Instrument	Helio/ Astro	Cloud	D/H (10^{-5})	Ref.
α Cen A,B	1.35	316	−01	GHRS/E	H,A	G	1.2 ± 0.7	A
ϵ Ind	3.63	336	−48	GHRS/E	A	G?	1.6 ± 0.4	B
36 Oph A	5.46	358	+07	STIS/H	H,A	G	1.5 ± 0.5	F
β Gem	10.3	192	+23	GHRS/E		G?	1.4 ± 0.4	D
σ Gem	37.5	191	+23	GHRS/E		G?	1.4 ± 0.4	D
HZ 43	32.0	054	+84	GHRS/E		NGP	1.65 ± 0.2	G
31 Com	94.2	115	+89	GHRS/M		NGP	1.5 ± 0.4	C
31 Com	94.2	115	+89	GHRS/E		NGP	2.0 ± 0.4	D
β Cet	29.4	111	−81	GHRS/M		SGP	2.2 ± 1.1	C
β Gem	10.3	192	+23	GHRS/E		+33.2	1.6 ± 0.4	D
σ Gem	37.5	191	+23	GHRS/E		+32.0	1.3 ± 0.4	D
Sirius A	2.63	227	−09	GHRS/M	H,A	+11.7	con. 1.6	O
Sirius A, B	2.63	227	−09	GHRS/M		+11.7	≤ 1.6	H
61 Cyg A	3.48	082	−06	GHRS/E	A	−9.0	con. 1.5	E
α Tri	19.7	139	−31	GHRS/E		+13.1	1.0 ± 0.6	D
G191-B2B	68.8	156	+07	GHRS/E		+8.2	≈ 0.9	K
G191-B2B	68.8	156	+07	STIS/H		+8.6	> 1.26	L
G191-B2B	68.8	156	+07	GHRS/E		+13.2	≈ 0.9	K
BD+28°4211	104.	082	−19	ORFEUS		−4	0.4–1.5	N
γ^2 Vel	260.	263	−08	IMAPS			1.89–2.44	J
BD+39°3226	270.	065	+29	ORFEUS		−24	0.72–1.99	M
δ Ori A	400.	204	−18	IMAPS		+25	0.61–0.93	I
ζ Pup	430.	254	−05	IMAPS			1.21–1.59	J

References: A: Linsky & Wood (1996); B: Wood, Alexander, & Linsky (1996); C: Piskunov *et al.* (1997); D: Dring *et al.* (1997); E: Wood & Linsky (1998); F: Wood, Linsky, & Zank (1999); G: Landsman *et al.* (1999); H: Hébrard et al (1999); I: Jenkins *et al.* (1999); J: Sonneborn *et al.* (1999); K: Vidal-Madjar *et al.* (1998); L: Sahu *et al.* (1999); M: Bluhm *et al.* (1999); N: Gölz *et al.* (1998); O: Izmodenov *et al.* (1999).

Acknowledgments. This work is supported by NASA grant S-56500-D to the University of Colorado and NIST.

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