SPATIAL VARIABILITY IN THE RATIO OF INTERSTELLAR ATOMIC DEUTERIUM TO HYDROGEN. II. OBSERVATIONS TOWARD $\gamma^2$ VELORUM AND $\zeta$ PUPPIUS BY THE INTERSTELLAR MEDIUM ABSORPTION PROFILE SPECTROGRAPH

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ABSTRACT

High-resolution far-ultraviolet spectra of the early-type stars $\gamma^2$ Vel and $\zeta$ Pup were obtained to measure the interstellar deuterium abundances in these directions. The observations were made with the Interstellar Medium Absorption Profile Spectrograph (IMAPS) during the ORFEUS-SPAS II mission in 1996. IMAPS spectra cover the wavelength range 930–1150 Å with $\Delta \lambda / \lambda \sim 80,000$. The interstellar D I features are resolved and cleanly separated from interstellar H I in the Ly$\delta$ and Ly$\epsilon$ profiles of both sight lines and also in the Ly$\gamma$ profile of $\zeta$ Pup. The D I profiles were modeled using a velocity template derived from several N I lines in the IMAPS spectra recorded at higher signal-to-noise ratio. To find the best D I column density, we minimized $\chi^2$ for model D I profiles that included not only the N(D I) as a free parameter, but also the effects of several potential sources of systematic error, which were allowed to vary as free parameters. H I column densities were measured by analyzing Ly$\alpha$ absorption profiles in a large number of IUE high-dispersion spectra for each of these stars and applying this same $\chi^2$-minimization technique. Ultimately we found that $D/H = 2.18^{+0.31}_{-0.36} \times 10^{-5}$ for $\gamma^2$ Vel and $1.42^{+0.25}_{-0.23} \times 10^{-5}$ for $\zeta$ Pup, values that contrast markedly with $D/H$ derived in Paper I for $\delta$ Ori A (the stated errors are 90% confidence limits). Evidently, the atomic D/H ratio in the ISM, averaged over path lengths of 250–500 pc, exhibits significant spatial variability. Furthermore, the observed spatial variations in D/H do not appear to be anticorrelated with N/H, one measure of heavy-element abundances. We briefly discuss some hypotheses to explain the D/H spatial variability. Within the framework of standard big bang nucleosynthesis, the large value of D/H found toward $\gamma^2$ Vel is equivalent to a cosmic baryon density of $\Omega_b h^2 = 0.023 \pm 0.002$, which we regard as an upper limit since there is no correction for the destruction of deuterium in stars.

Subject headings: cosmology: observations — ISM: abundances — ISM: evolution — stars: individual ($\gamma^2$ Velorum, $\zeta$ Puppis) — ultraviolet: ISM

1. INTRODUCTION

The abundance ratio of atomic deuterium to hydrogen (D/H) in interstellar gas is widely regarded as an important tracer of Galactic chemical evolution (Audouze & Tinsley 1974; Boesgaard & Steigman 1985; Tosi et al. 1998) and a key discriminant of the cosmic baryon-to-photon ratio ($\eta$) in big bang nucleosynthesis (BBN; Walker et al. 1991). A standard interpretation is that D should not be produced in significant quantities in astrophysical sites other than the big bang (Epstein, Latimer, & Schramm 1976). The generally accepted viewpoint is that while D is produced primordially, its destruction takes place when some of the gas is cycled through stars. The uncertainties surrounding this process represent a stumbling block in arriving at the primordial value. For this reason, a measurement of D/H is often regarded as a lower limit to the primordial ratio, and this may be translated into an upper limit to $\eta$ (for BBN, larger D/H implies lower $\eta$).

Rogerson & York (1973) made the first measurement of the atomic D/H abundance ratio in the interstellar medium (ISM) on the line of sight toward $\beta$ Cen. Measurements with the Copernicus satellite toward an additional 14 stars (100 pc < $d$ < 500 pc) found that D/H values cluster around $1.5 \times 10^{-5}$, but with a dispersion that, in some cases, seemed to exceed the stated uncertainties (see review by Vidal-Madjar & Gyr 1984). While a simple interpretation of the Copernicus data suggested that the D/H measurements revealed spatial variations, the reality of these differences has been difficult to substantiate because of concerns stemming from the somewhat inadequate resolution of Copernicus (15 km s$^{-1}$ FWHM) for this purpose.

Using the Goddard High Resolution Spectrograph (GIRS) and Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST), several measurements of D/H in the local interstellar medium (LISM; $d < 100$ pc) have been made with observations of Ly$\alpha$ (see Lemoine et al. 1999 for a review). Linsky et al. (1993, 1995) found $D/H = 1.60^{+0.14}_{-0.19} \times 10^{-5}$ toward Capella. Vidal-Madjar et al. (1998) reported evidence for a factor of ~2 difference in D/H between two components on the line of sight toward the white dwarf G191-B2B ($d = 75$ pc). Sahu et al. (1999) reevaluated the GHRIS data as well as new STIS echelle spectra of G191-B2 and concluded that, as a result of improved instrumental characterization (echelle scattered light correction near Ly$\alpha$), D/H values in both com-

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components appeared to be consistent with the usual LISM value. Questions remain, however. For example, Howk & Sembach (2000) found a different STIS echelle scattered light correction, one that agrees with the GHRS Ly α profile (Vidal-Madjar 2000). The resolution of the conflicting conclusions about the G191-B2B sight line may be provided by observations of higher Lyman series lines (Ly β and Ly y) by the Far Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000).

The Interstellar Medium Absorption Profile Spectrograph (IMAPS) provides a new window to study deuterium in the galaxy by virtue of its wavelength coverage and very high spectral resolution ($\lambda/\Delta \lambda \sim 80,000$), which alleviate many of the previous obstacles to accurate D/H measurements. Prior to the IMAPS deuterium studies, D/H measurements in our Galaxy after the Copernicus mission have been confined to the local ISM, since the saturated core of H I Ly α envelops the D I Ly α feature for $N(\text{H}I) \gtrsim 1 \times 10^{19}$ cm$^{-2}$ and higher Lyman lines lie beyond the reach of HST. The goal of the IMAPS deuterium program is to obtain high-precision measurements of D/H on sight lines toward bright OB stars beyond the LISM. In the first paper of this series, Jenkins et al. (1999a, hereafter Paper I) measured the D/H abundance ratio toward δ Ori A using IMAPS spectra. They found $D/H = 0.74^{+0.19}_{-0.13} \times 10^{-5}$, a value that is much lower than that found in the LISM. Paper I also showed that the low abundance of D toward δ Ori A is not accompanied by an overabundance of N and O relative to H, as would be expected if the gas had been more thoroughly cycled through stellar interiors. We note that two other deuterium measurements using the Tübêlchen echelle spectrograph (resolution $\lambda/\Delta \lambda \sim 10,000$) on the OREUS-SPAS II mission have been recently reported: Götz et al. (1998) found $D/H = 0.8^{+0.4}_{-0.4} \times 10^{-5}$ toward BD +28 4211, an O-type subdwarf $\sim 100$ pc away, and Bluhm et al. (1999) measured $D/H = 1.2^{+0.4}_{-0.4} \times 10^{-5}$ toward BD +39 3226, an sdO star located $\sim 270$ pc from the Sun.

In this paper we analyzed the lines of sight toward two well-known hot stars, γ² Velorum (HD 68273) and ζ Puppis (HD 66811). They are among the brightest stars in the sky at 1000 Å, well studied by Copernicus, have H I column densities $\lesssim 10^{20}$ cm$^{-2}$, and hence are prime D/H targets for IMAPS. These stars were observed under an OREUS-SPAS II Guest Investigator program.

The sight lines to γ² Vel and ζ Pup have been studied extensively (γ² Vel: Morton & Bhavsar 1979; Sahu 1992; Fitzpatrick & Spitzer 1994; ζ Pup: Morton & Dinerstein 1976; Morton 1978), including D/H measurements with observations from the Copernicus satellite. York & Regerson (1976) found $D/H = 2.0_{-0.6}^{+1.4} \times 10^{-5}$ toward γ² Vel. Vidal-Madjar et al. (1977) studied the sight line toward ζ Pup and found that solutions consistent with the data permit a wide range of D/H values ($1.7 \times 10^{-5} \lesssim D/H \lesssim 2.5 \times 10^{-4}$). γ² Vel and ζ Pup are the most luminous stars in the Vel-Puppis region. Their role in powering the Gum Nebula and their relationship to the Vela OB2 association, Vela supernova remnants, and various structures in the ISM in Vela-Puppis have been analyzed by Sahu (1992). Table 1 summarizes some basic properties of the two stars. The distances listed were derived from HIPPARCOS data by Schaefer, Schmutz, & Grenon (1997), placing γ² Vel significantly closer than earlier estimates.

γ² Vel is the closest (and brightest) Wolf-Rayet star, and consequently it has been studied intensively for more than a century (van der Hucht et al. 1981). Nevertheless, because of the complexity of the stellar system, its fundamental stellar parameters have been continuously debated and revised (as recently as 1997 when several papers were published, e.g., Schaefer et al. 1997; Schmutz et al. 1997). γ² Vel is a double-lined spectroscopic binary star composed of a W-R star (WC8) and a late O star (O8 III) of comparable brightness.

The high velocity resolution provided by IMAPS opens the way for more accurate line profile measurements in the far-ultraviolet spectra of bright stars. Our observations of γ² Vel and ζ Pup described in § 2 build on our earlier results for δ Ori A described in Paper I. We follow with discussions of how we derived D/H column densities (§ 3), H I column densities (§ 4), and values for D/H and N/H (§ 5). The paper concludes with a discussion in § 6 of the possible implications of the differences in D/H for the three stars covered in this paper and Paper I.

### Table 1

**Stellar Data**

| Name     | HD      | $l$ (deg) | $b$ (deg) | Spectral Type | $V_\text{r}$ (mag) | $v \sin i$ (km s$^{-1}$) | $\Delta v_{\text{lar}}$ (km s$^{-1}$) | $d$ (pc) |
|----------|---------|-----------|-----------|---------------|---------------------|----------------------------|----------------------------------|---------|
| ζ Pup    | 66811   | 253.98    | -4.71     | O4 Iaf        | 2.25                | 211                      | -18.04                          | 429.11  |
| γ² Vel   | 68273   | 262.81    | -7.70     | WC8 + O8     | 1.76                | ...                      | -17.48                          | 258.41  |

*a* $v_{\text{lar}} = v_{\text{helio}} + \Delta v_{\text{lar}}$

*b* Schaefer et al. (1997).
than the target, an echelle grating with a 63° blaze angle, and a parabolic cross disperser. The spectral format is imaged on a solid KBr photocathode, whose electrons are magnetically focused on a windowless, back-illuminated CCD with a 320 x 256 pixel format. The nominal wavelength range of 930–1150 Å is obtained in four selectable tilts that span the free spectral range of the echelle grating. The gratings were coated with LiF over aluminum, providing excellent throughput longward of 1000 Å. Although the reflectivity of LiF drops substantially shortward of 1000 Å, IMAPS achieved a useful throughput even in the 930–980 Å region. The spectral resolution in IMAPS spectra obtained during the 1996 flight was approximately λ/Δλ ~ 80,000, or ≤4 km s⁻¹. The telluric O I lines (e.g., ~950.112 near Lyδ; see Fig. 1) have FWHM ~ 5 km s⁻¹, but these lines are probably partly resolved in IMAPS spectra (see Jenkins et al. 1999b).

γ² Vel and ζ Pup were chosen for this IMAPS Guest Investigator program because they were available in 1996 November, have a flux near Lyδ > 10⁻⁹ ergs cm⁻² s⁻¹ Å⁻¹, have v sin i ≥ 100 km s⁻¹, and N(H I) ≤ 10²⁰ cm⁻².

γ² Vel was observed by IMAPS on 1996 November 27 14:34–15:11 and 16:00–16:47 UT for a total of 4224 s. ζ Pup was observed on 1996 November 26 18:44–19:23 and 20:16–20:57 UT also for a total of 4224 s. The exposure time at each echelle grating position ranged from 817.6 to 1226.4 s. These exposure times were chosen to obtain spectra with good signal-to-noise ratios (S/Ns) near the cores of the D I Lyδ (949.485 Å) and Lyε (937.548 Å) lines. Typically, we found S/N = 10–15 in the local continuum near the Lyδ and Lyε interstellar features.

3. COLUMN DENSITY OF ATOMIC DEUTERIUM

3.1. General Considerations

The data reduction and analysis of the γ² Vel and ζ Pup spectra and the determination of the D I column densities were identical to those described in Paper I for the line of sight toward δ Ori A. IMAPS spectra were analyzed to determine the total N(D i) (§§ 3.3 and 3.4). A large number of International Ultraviolet Explorer (IUE) high-resolution Lyz spectra were obtained from the National Space Science Data Center archive to determine the total H I column density [N(H i)] in § 4. We note that, given that N(H i) ~ 10¹⁵ cm⁻² on these sight lines and that D/H ~ 10⁻⁵, the gas that gives rise to the H I Lyz damping wings is the same gas responsible for the D I Lyδ and Lyε features.

In § 3.2 we show that N i is a good tracer of H i and D i on these sight lines. The line-of-sight column density per unit velocity [N_a(v); see Paper I] for N i, defined by a range of N i lines recorded in the IMAPS spectra, provided a velocity template for modeling the D i profiles. The high S/N for the N i lines helped to constrain the model profiles that gave an acceptable fit to the lower S/N D i lines. This can prevent noise in the D i profiles from giving arbitrarily large or small N(D i) at specific velocities. We did not decompose the velocity profiles of N i or D i into separate (blended) Gaussian components—the D/H ratios determined here were based on total column densities for each sight line.

Using the method outlined in Paper I, we corrected for the effects of the weak lines Fe II 2937.652 and H₂ Lyman 14–0 P(2) 2949.351. The Fe II line is located at +51 km s⁻¹ in γ² Vel and at +53 km s⁻¹ in ζ Pup on the heliocentric velocity scale whose zero point is the laboratory wavelength of D I Lyδ (see Figs. 1 and 2). The H₂ line is located at +10 km s⁻¹ in γ² Vel and at +12 km s⁻¹ in ζ Pup on the D I Lyδ heliocentric velocity scale. The strength and shape of

![Fig. 1](image-url) Line profiles of Lyδ and Lyε from IMAPS spectra for γ² Vel. The zero point of the velocity scale is computed with respect to the laboratory wavelengths of the D I lines. The narrow width of the O I lines (e.g., ~950.112 near Lyδ; see Figs. 1 and 2). The line is located at ~1000 Å in γ² Vel and at ~1000 Å in ζ Pup on the heliocentric velocity scale whose zero point is the laboratory wavelength of D I Lyδ (949.485 Å) and Lyε (937.548 Å) lines. Typically, we found S/N = 10–15 in the local continuum near the Lyδ and Lyε interstellar features.

![Fig. 2](image-url) Line profiles of Lyγ, Lyδ, and Lyε from IMAPS spectra for ζ Pup. The zero point of the velocity scale is computed with respect to the laboratory wavelengths of the D I lines.
these features were computed from other transitions of the same species recorded at longer wavelengths (and higher S/N) in the IMAPS spectra of $\gamma^2$ Vel and $\zeta$ Pup. The computed central residual intensities of these features are nearly identical for the two stars: $0.66$ for Fe II $\lambda937.6$ and $0.95$ for H$_2$ $\lambda949.3$. The other potentially contaminating lines noted in Table I of Paper I can safely be ignored.

The possible contamination of the Ly$\delta$ order by scattered light from an adjacent order that contains the strong $\lambda$ line is minimal. (The grid collimator rejects light coming from more than about a factor of 10 fainter than the adjacent order that contains the strong line.) The $\chi^2$ analysis found that any residual contamination of the spectrum in the vicinity of Ly$\delta$ by the pattern of saturated N I features was $<1\%$ of the continuum in both $\gamma^2$ Vel and $\zeta$ Pup. Amplitudes for this correction larger than $\sim1\%$ caused unacceptably bad deviations in the bottom of the H I Ly$\delta$ profile. Given the general noise characteristics of the Ly$\delta$ profiles, this is a negligible effect.

For the case of $\gamma^2$ Vel, there is another potential contamination source. A companion star, $\gamma^1$ Vel, is located 42$^\circ$ to the southwest of $\gamma^2$ Vel. Its light should be accepted along with that from $\gamma^2$ Vel, since IMAPS is an objective grating spectrograph without an entrance slit to reject unwanted sources. (The grid collimator rejects light coming from more than 1$^\circ$ from the axis, however.) $\gamma^1$ Vel is 2.5 mag fainter than $\gamma^2$ Vel in V and has a spectral classification of B1 IV (Hoffleit & Jaschek 1982). Even though $\gamma^1$ Vel is cooler than $\gamma^2$ Vel, its flux is not diminished much below the peak of the Planck distribution at our wavelengths of interest, so we expect its intensity at a given wavelength to be not more than about a factor of 10 fainter than $\gamma^2$ Vel. Fortunately, when the observations were taken the roll angle of the spacecraft about the optical axis of IMAPS (governed by the position of the Sun in the sky) was such that the faint light from $\gamma^1$ Vel was displaced along the cross-dispersion direction toward the long-wavelength part of the format. As a consequence, any spectral segment in the spectrum of $\gamma^2$ Vel had light superposed on it from shorter wavelengths in $\gamma^1$ Vel (the separation was slightly less than the distance between three echelle orders). The rapid decline in the sensitivity of IMAPS toward shorter wavelengths thus amplified the factor of 10 disparity in relative fluxes at any given position on the format. Therefore, the contamination of the $\gamma^2$ Vel spectrum by light from $\gamma^1$ Vel is negligible. As a final note, on visual inspection we are unable to see any ghostlike spectrum of $\gamma^1$ Vel on top of the spectrum of $\gamma^2$ Vel.

The Lyman line profiles for $\gamma^2$ Vel and $\zeta$ Pup are shown in Figures 1 and 2. These profiles have been corrected for Fe II and H$_2$ line absorption, as described above. The background levels near the D I lines were determined from the broad, saturated cores of the adjacent H I profiles. As explained in Paper I, we compared resolution-degraded forms of the IMAPS profiles with those recorded by Copernicus to test the proposition that the cores of the H I lines indeed represented the zero-intensity levels in the vicinity of the adjacent D I features. This was done to check that we were not being misled by an effect from possible strong, broad wings extending away from the main peak in the instrumental profile of IMAPS. We concluded that indeed the cores of the H I profiles provided very good estimates of the zero levels in the vicinity of the D I lines.

The best answers for N(D i) and the deviations permitted by the data were evaluated by minimizing $\chi^2$ (see Lampton, Margon, & Bowyer 1976 and Bevington & Robinson 1992 for details) when all of our unknown parameters were allowed to vary. The 10 free parameters for $\gamma^2$ Vel are (1) N(D i), (2) the gas temperature T, (3)–(8) the continuum slopes, y-intercepts, and background levels for Ly$\delta$ and Ly$e$, (9) a shift in the velocity zero point between the D i lines and the N i template, and (10) a coefficient for scaling the N i contamination signal in Ly$\delta$ (see § 3.2 in Paper I). The gas temperature is an important parameter because the D I line can be broadened significantly compared to the N i template by thermal motions; see § 4.1 in Paper I for details. There are three additional free parameters for $\zeta$ Pup because of the addition of Ly$\gamma$ to the analysis. Note that the linear continuum fitting (with specific velocity limits as given in §§ 3.3 and 3.4) is an integral part of the $\chi^2$ evaluation; i.e., the deviations of the continuum levels are considered, in addition to the behavior inside the D I profiles. The same holds for the zero level as defined by the bottom of the adjacent H I profile. We used Powell’s method (Press et al. 1992, p. 406) to find the minimum $\chi^2$. We then set confidence limits by increasing (or decreasing) N(D i) and T with the other parameters freely varying until $\chi^2$ increased by the appropriate amount for the confidence limit of interest with two useful parameters, N(D i) and T. We also used different initial values to establish that the minimum $\chi^2$ is unique.

3.2. Velocity Profile Templates

In Paper I we discussed the benefits of obtaining a velocity profile based on high-quality data for N I and O I, two species that are not significantly depleted in the ISM and that have very similar ionization balances to those of D I and H I (Ferlet 1981; York et al. 1983). This profile information is helpful in constraining the variety of possible interpretations that would produce acceptable fits with the D profiles. For N I, we used IMAPS spectra of the 10 lines in the multiplets at 952.4, 953.8, 954.1 and 1134.7 Å. For all of the N I lines except those in the 952.4 Å multiplet, the background level was easily defined because the stronger lines were saturated. Of course, these lines were useful for defining the behavior of the gas only at velocities somewhat removed from the line core. Since the lines in the multiplet at 952.4 Å were not saturated, we had to determine the background level by a different method. For both $\gamma^2$ Vel and $\zeta$ Pup, there are U1 scans of this weak multiplet available in the archive of spectra recorded by the Copernicus satellite (Rogerson et al. 1973). After comparing our IMAPS spectrum degraded to the resolution of Copernicus with the actual Copernicus scans, we determined the adjustments to the background levels that were needed for the IMAPS spectra of this N I multiplet. The backgrounds caused by grating scatter in the Copernicus spectra were taken from the observed count rates in the bottoms of the hydrogen Ly$\gamma$ and Ly$\delta$ lines, and these levels were subtracted off before the comparison was made.

As was done for our analysis in Paper I, we adopted a method developed by Jenkins & Peimbert (1997) to create a composite profile for the column density of N I as a function of velocity from the 10 lines in the four multiplets, with the weak lines in each case defining the main part of the profile.

One of the lines in the 1134.7 Å multiplet, the line at 1134.165 Å, had to be omitted from consideration for $\zeta$ Pup because it was too close to the edge of the image format.
and the strong lines outlining the exact shape of the profile's wings, well away from the saturated part of the line. For places where there was overlap in the useful portions of the lines, there was satisfactory agreement. The \( f \)-values of Goldbach et al. (1992) were adopted for our analysis.

Figure 3 shows the \( N_d(a) \) profiles derived for \( \text{N}\,\text{I} \) toward \( \gamma^2 \,\text{Vel} \) and \( \zeta \,\text{Pup} \). In Paper I we showed that the profiles are unlikely to be contaminated by additional contributions from telluric absorption. \( N(\text{N}\,\text{I}) \) is \( \sim 1\% \) of \( N(\text{O}\,\text{I}) \) in the Earth's atmosphere at the altitude of IMAPS (\( \sim 305 \) km) during the ORFEUS-SPAS II mission. Even for our strongest \( \text{N}\,\text{I} \) transition used to derive the far wings of \( N_d(a) \) for \( \text{N}\,\text{I} \) (\( \lambda 1134.98 \)), the telluric absorption should be only one-third as strong as the \( \text{O}\,\text{I} \) \( \lambda 950.112 \) feature present in Figures 1 and 2, and at a heliocentric velocity of \( +12.6 \) km s\(^{-1} \) it would be buried in the saturated portion of the profile. Consequently, telluric \( \text{N}\,\text{I} \) has a negligible effect on the interstellar \( \text{N}\,\text{I} \) profiles.

\( \text{O}\,\text{I} \) is the best tracer of \( \text{H}\,\text{I} \) in the ISM since the ionization potential of \( \text{O}\,\text{I} \) (13.56 eV) is nearly identical to that of \( \text{H}\,\text{I} \). The ionization potential of \( \text{N}\,\text{I} \) (14.53 eV) is only slightly greater than that of \( \text{H}\,\text{I} \). Furthermore, both \( \text{O} \) and \( \text{N} \) are coupled to \( \text{H} \) by resonant charge exchange reactions. As discussed by Sofia & Jenkins (1998) and Jenkins et al. (2000), \( \text{N}\,\text{I} \) closely follows \( \text{O}\,\text{I} \) and \( \text{H}\,\text{I} \) unless \( n_\text{e} \gg n_\text{H} \).

In the IMAPS wavelength band there is no suitable set of \( \text{O}\,\text{I} \) transitions to completely define a velocity profile template. The available \( \text{O}\,\text{I} \) lines are highly saturated or are not detectable, either because they are buried in the core of a Lyman series line or because they are too weak. In Paper I we made use of an archival HST spectrum of the very weak interstellar system transition of \( \text{O}\,\text{I} \) at 1355.6 Å for \( \delta \) Ori A. There is no such spectrum available for \( \zeta \,\text{Pup} \), and the measurement of this line in the spectrum of \( \gamma^2 \,\text{Vel} \) taken by Fitzpatrick & Spitzer (1994) is too noisy to adequately define the shape of the \( \text{O}\,\text{I} \) profile. Therefore, we were forced to use the next best option, \( \text{N}\,\text{I} \), to define the velocity profile template.

Although we do not have a complete \( N_d(a) \) profile for \( \text{O}\,\text{I} \), we tested the assumption that \( \text{N}\,\text{I} \) traces \( \text{H}\,\text{I} \) by comparing selected portions of the \( \text{O}\,\text{I} \) \( N_d(a) \) profile derived from available line profiles in \( \gamma^2 \,\text{Vel} \). First, we computed \( N_d(a) \) from the wings of \( \text{O}\,\text{I} \) \( \lambda 1039.230 \). Second, we used the GHRS spectrum of \( \text{O}\,\text{I} \) \( \lambda 1355.6 \) (Fitzpatrick & Spitzer 1994) to define \( N_d(a) \) in the core of the line. The computed \( N_d(a) \) was scaled by the difference in the \( \text{N} \) and \( \text{O} \) solar abundances (\( \sim 0.90 \) dex; Anders & Grevesse 1989). The results, shown in Figure 3, demonstrate that the wings and core of \( N_d(a) \) for \( \text{N}\,\text{I} \) and \( \text{O}\,\text{I} \) are in excellent agreement. Consequently, we have high confidence that the \( N_d(a) \) profile for \( \text{N}\,\text{I} \) provides an accurate model for the velocity distribution of \( \text{H}\,\text{I} \).

3.3. \( \gamma^2 \,\text{Velorum} \)

The continuum near the \( Ly\delta \) line shown in Figure 1 was determined in the velocity range (\( -40, -10 \)) km s\(^{-1} \) on the blue side of the \( \text{D}\,\text{I} \) line and (\( +170, +205 \)) km s\(^{-1} \) on the red side. For \( Ly\epsilon \), the continuum limits were (\( -14, +8 \)) km s\(^{-1} \) and (\( +170, +210 \)) km s\(^{-1} \). The background level was determined from the core of the two \( \text{H}\,\text{I} \) lines in the velocity range (\( +60, +140 \)) km s\(^{-1} \). The \( \text{D}\,\text{I} \) profiles were fitted in the velocity range (\( -10, +39 \)) km s\(^{-1} \) for \( Ly\delta \) and (\( +8, +39 \)) km s\(^{-1} \) for \( Ly\epsilon \). With a spacing of independent velocity samples of 1.25 km s\(^{-1} \), this resulted in 276 degrees of freedom in the \( \chi^2 \) analysis to fit the 10 free parameters described in §3.1.

By adjusting our estimate for the noise, which was known to only limited accuracy beforehand, we achieved a minimum value for \( \chi^2 \) equal to 247.0 at a column density of \( 1.12 \times 10^{15} \) cm\(^{-2} \). For 276 degrees of freedom, there was a 90% chance that we would have found this value of \( \chi^2 \) or greater. With this 90% confidence level, we arrived at a conservatively high estimate for the noise. It then followed that this noise level, which is perhaps higher than the real noise, gave a conservatively large confidence interval for \( N(\text{D}\,\text{I}) \), as determined by how rapidly the values of \( \chi^2 \) deviated from the minimum value. With the noise level having been set in the manner just described, we explored for 90% and 99% confidence limits for \( N(\text{D}\,\text{I}) \) (i.e., 1.65 \( \sigma \) and 2.58 \( \sigma \) deviations), which correspond to \( \chi^2(\text{min}) + 4.6 \) and \( \chi^2(\text{min}) + 9.2 \), respectively. Table 2 lists \( N(\text{D}\,\text{I}) \) and \( T \) for the best value and these limits. The \( \pm 90\% \) confidence limits on the model \( \text{D}\,\text{I} \) profiles (cross-hatched regions) for \( Ly\delta \) and \( Ly\epsilon \) are compared with the observed deuterium profiles in Figure 4.

In Figure 4 we also show with a dashed line the expected shape and depth of the \( \text{D}\,\text{I} \) profile for \( N(\text{D}\,\text{I}) = 7.7 \times 10^{14} \)
TABLE 2

Limits for \(N(D\text{ i})\) toward \(\gamma\) Vel

| Significance | \(N(D\text{ i})\) \((\times 10^{15}\ \text{cm}^{-2})\) | \(T\) \((\text{K})\) | \(\chi^2\) |
|-------------|---------------------------------|--------|--------|
| Minimum \(N(D\text{ i})\) at the 99% confidence limit | 0.96 6630 255.6 |
| Minimum \(N(D\text{ i})\) at the 90% confidence limit | 1.00 6530 251.6 |
| Best \(N(D\text{ i})\) | 1.12 6070 247.0 |
| Maximum \(N(D\text{ i})\) at the 90% confidence limit | 1.27 5280 251.7 |
| Maximum \(N(D\text{ i})\) at the 99% confidence limit | 1.34 4870 256.1 |

This corresponds to a D/H ratio of \(1.5 \times 10^{-5}\), assuming the \(H\) \(I\) column density derived below in § 4. For this case, \(\chi^2 - \chi^2\)\(\text{(min)}\) = 52.4, which is clearly an unacceptable fit. The dot-dashed line in Figure 4 corresponds to the \(D\) \(\text{i}\) profile for \(N(D\text{ i}) = 3.8 \times 10^{14}\ \text{cm}^{-2}\), the \(D\) \(\text{i}\) column density necessary to achieve \(D/H = 0.74 \times 10^{-5}\), the value found toward \(\delta\) Ori A in Paper I. A similar demonstration for the measurement of \(N(H\) \(I\)) is given in § 5.

3.4. \(\zeta\) Puppis

The measurement of \(N(D\text{ i})\) toward \(\zeta\) Pup used the same methodology described in the previous section with the following modifications. In addition to \(Ly\delta\) and \(Ly\epsilon\) we were

![Graph showing observed and model line profiles of D i Ly\delta and Ly\epsilon for \(\gamma\) Vel](image1)

![Graph showing observed and model line profiles of D i Ly\gamma, Ly\delta, and Ly\epsilon for \(\zeta\) Pup](image2)

TABLE 3

Limits for \(N(D\text{ i})\) toward \(\zeta\) Pup

| Significance | \(N(D\text{ i})\) \((\times 10^{15}\ \text{cm}^{-2})\) | \(T\) \((\text{K})\) | \(\chi^2\) |
|-------------|---------------------------------|--------|--------|
| Minimum \(N(D\text{ i})\) at the 99% confidence limit | 1.07 10600 397.7 |
| Minimum \(N(D\text{ i})\) at the 90% confidence limit | 1.13 10400 393.1 |
| Best \(N(D\text{ i})\) | 1.30 9550 388.5 |
| Maximum \(N(D\text{ i})\) at the 90% confidence limit | 1.49 8500 393.1 |
| Maximum \(N(D\text{ i})\) at the 99% confidence limit | 1.58 7900 397.7 |
able to include the D I profile of Lyγ in the χ² analysis. The blue and red regions for the linear continuum fits were (−40, −10) and (+170, +190) km s⁻¹ for Lyγ, (−39, −10) and (+157, +190) km s⁻¹ for Lyδ, and (−4, +3) and (+180, +220) km s⁻¹ for Lyε. The background levels were determined from the saturated cores of the H I lines over these velocity limits: (+55, +130) for Lyγ and Lyδ and (+65, +115) for Lyε. The model D I profiles were fitted over the range (−5, +40) km s⁻¹ for Lyγ, (0, +40) km s⁻¹ for Lyδ, and (+3, +37) km s⁻¹ for Lyε. This resulted in 426 degrees of freedom to simultaneously fit the 13 free parameters described in § 3.1. The minimum χ² is 388.5 and corresponds to the most probable value of N(D I) for ζ Pup, namely, 1.30 × 10¹⁵ cm⁻². The results of the χ² analysis are summarized in Table 3, including the 90% and 99% confidence limits. The same conservative treatment of the noise described for γ² Vel was followed for ζ Pup. Figure 5 shows the observed D I Lyman line profiles and the range in the best-fit model profiles and continua fits allowed by the 90% confidence limits.

4. COLUMN DENSITY OF ATOMIC HYDROGEN

4.1. Analysis Methodology

The primary objective of this IMAPS program is to determine D/H ratios of sufficient accuracy to test for spatial inhomogeneities. To achieve this goal, we must strive for a precision in N(H I) that is as good as (or preferably better than) that of the deuterium measurement. We must also understand the magnitude and nature of the uncertainties in N(H I) and N(D I) so that we can realistically assess the uncertainty in D/H for comparison with other measurements in the ISM. For these reasons, we decided to conduct our own investigation of the H I column densities toward γ² Vel and ζ Pup, even though a number of measurements of N(H I) toward these stars are already available in the literature (e.g., Jenkins 1971; York & Rogerson 1976; Vidal-Madjar et al. 1977; Bohlin, Savage, & Drake 1978; Shull & Van Steenberg 1985; Díplas & Savage 1994).

We described our method for determining N(H I) in Paper I; here we provide a summary. In §§ 4.2 and 4.3 we discuss details particular to the ζ Pup and γ² Vel sight lines and present the results. We used the Lyα line to determine the total N(H I). Since H I Lyα and Lyδ are on the flat part of the curve of growth, high-velocity gas could influence their profiles. Lyα is immune from this potential problem. Because of the great breadth of the Lorentzian wings (±1000 km s⁻¹; see the velocity scale in Fig. 9), Lyα absorption due to any high-velocity interstellar gas (±100 km s⁻¹) that may be present is confined to the saturated core of the profile. In principle, some high-velocity H I, which is too widely dispersed in velocity to show up in the D I profiles, could contribute to the Lyα damping wings. However, this gas is not detected in the strong lines N I λ1134.98 and O I λ1303.23 observed with IMAPS. It is clear that such high-velocity gas, if present, would have a lower column density and a negligible effect on the Lyα damping wings. Since the Lyα line is not covered by IMAPS and was not observed by the HST spectrographs and the available Copernicus Lyα scans suffer from several problems (see Paper I), we analyzed high-dispersion IUE observations of Lyα to determine N(H I). Furthermore, these stars were observed many times with IUE over the course of many years, and this offers an opportunity to evaluate potential sources of systematic error. For example, γ² Vel is a spectroscopic binary, and the large IUE database allowed a search for systematic changes in the derived N(H I) as a function of orbital phase.

After screening and retrieving the IUE data of interest and correcting for interorder scattered light (see Paper I), we used an approach first used by Jenkins (1971) to constrain the H I column density; i.e., we determined the N(H I) that provides the best fit to the Lyα profile with the optical depth τ at a given wavelength λ calculated from the expression

$$\tau(\lambda) = N(H I) \sigma(\lambda) = 4.26 \times 10^{-20} N(H I) (\lambda - \lambda_0)^{-2}$$

(1)

where \(\lambda_0\) is the Lyα line center at the velocity centroid of the hydrogen (note that the useful portion of the Lyα profile is entirely due to the Lorentzian wings and the effects of instrumental and Doppler broadening can be neglected). As was done for D I, we also determined the important free parameters that can be adjusted to fit the H I Lyα absorption profile; then we found the set of parameters that minimized \(\chi^2\) using Powell’s method. We set confidence limits on the H I column as described in § 3.1 with only one parameter of interest, N(H I). The other (uninteresting) free parameters we selected for fitting the H I profile were three coefficients that specify a second-order polynomial fit to the continuum, and an additive correction to the flux zero point. The continuum was fitted to the spectrum in several windows covering the range 1185–1276 Å. Despite our use of the Bianchi & Bohlin (1984) correction for interorder scattered light, in many cases inspection of the flat-bottomed, saturated portion of the Lyα profile showed that the zero-intensity level was not quite correct. A zero-point shift in the flux scale, one of the terms for evaluating \(\chi^2\), was determined from a region within the saturated core. For both stars, the zero point of the Lyα wavelength scale was set by placing the N I λ1200 multiplet in agreement with the IMAPS N I profiles. The Lyα profile was then fitted only to the red wing because of the presence of strong stellar features superposed on the blue wing. However, the uncontaminated portion of the blue wing of Lyα was checked for consistency with the fit to the red wing and found to be in good agreement.

4.2. ζ Puppis

In Paper I, considerable attention was paid to the spectroscopic binary nature of δ Ori A and whether or not this could cause systematic errors in N(H I). A similar analysis of γ² Vel is presented in § 4.3. The determination of N(H I) toward ζ Pup was less complex than the other stars observed by IMAPS to study D/H. As far as is known, ζ Pup is not a spectroscopic binary star. It is an O4 supergiant, so the stellar H I Lyα absorption line makes a negligible contribution to the H I absorption profile. The star is

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8 The Copernicus studies of D/H on the γ² Vel and ζ Pup sight lines used the much weaker damping wings of Lyβ or Lyγ to determine N(H I).
possibly a nonradial pulsator with very weakly variable stellar absorption lines with a period of 8.5 hr (Reid & Howarth 1996), and the variability of the stellar wind P Cygni profiles is well known and studied (e.g., Prinja et al. 1992; Howarth, Prinja, & Massa 1995) and shows significant power at 19.2 hr and 5.2 day periods. Both of these sources of spectral variations are expected to have little impact on the interstellar $H_I$ column density derived from $Ly_\alpha$, but this can be checked given the large number of observations and good temporal sampling.

There are more than 200 high-dispersion observations of $\zeta$ Pup in the IUE archive, primarily because the star was selected for intensive IUE observing programs to study stellar wind variability in massive stars. We concentrated on the spectra obtained in three specific multiday observing runs in 1986, 1989, and 1995. In 1995 $\zeta$ Pup was observed continuously for 16 days (dubbed the "MEGA" campaign; Massa et al. 1995). We omitted three observations from these observing sessions because the archival data were corrupted or unavailable. This left 189 observations for measurement of $N(H_I)$. All of the observations were obtained with the IUE large aperture, and the signal-to-noise ratios are comparable; the $\zeta$ Pup data set is more uniform than the IUE $Ly_\alpha$ data used for measuring $N(H_I)$ toward $\delta$ Ori A and $\gamma^2$ Vel.

The $N(H_I)$ values derived from each individual observation are plotted in Figure 6, along with the $1\sigma$ uncertainties, versus the observation date. Table 4 summarizes the mean $H_I$ column density $\langle N(H_I) \rangle$ and the root mean square (rms) dispersion $\sigma$ obtained from the 1986, 1989, and 1995 data sets analyzed separately, and $\langle N(H_I) \rangle$ for each data set is indicated with a heavy dashed line in Figure 6. We also list in Table 4 the formal error in the mean $\epsilon = \sigma / (N)^{1/2}$ (here $N$ is the number of measurements) and the reduced $\chi^2$ for the three data sets.

In Paper I we discussed the potential sources of systematic error in the derivation of $N(H_I)$ from IUE spectra, and we suggested that the real uncertainty in the mean is likely to be greater than the formal estimate. The very large $Ly_\alpha$ data set for $\zeta$ Pup shown in Figure 6 appears to confirm that this is indeed the case for this star. From this figure one can see that the column densities derived from the 1995 data are systematically lower than the column densities derived from the 1989 observing run. The mean of the 1995 data set is lower than the mean of the 1989 data by $0.54 \times 10^{19}$ cm$^{-2}$ (0.0256 dex), and this difference is substantially greater than the formal error estimates ($\epsilon$).

This systematic error could be the result of secular changes in the stellar mass loss or circumstellar environment, a previously unrecognized stellar variability with a long period, or instrumental effects. Or perhaps some aspect of the interstellar sight line changed during this period. Since the IMAPS observations for $N(D_I)$ were made almost two years after the MEGA campaign, it is possible that a similar systematic error is present in any IUE estimate of $N(H_I)$ that we choose for comparison with the IMAPS $N(D_I)$. The exact magnitude of this systematic uncertainty is difficult to estimate, but we find that $N(H_I)$ obtained from additional large-aperture spectra of $\zeta$ Pup taken at other epochs are in good agreement with the estimates in Table 4.

![Fig. 6.—$H_I$ column densities toward $\zeta$ Pup derived from the 189 high-dispersion IUE observations obtained in 1986, 1989, and 1995 plotted vs. the observation date. Each measurement is shown with $\pm 1\sigma$ error bars. All observations were obtained with the large aperture and have comparable signal-to-noise ratios. Each data set is separated by a vertical dotted line (i.e., there is a break in the x-axis at each vertical dotted line), and the mean $H_I$ column densities derived from the three data sets are indicated with heavy dashed lines. There appears to be a systematic difference between the column densities derived from the 1995 data and the earlier observations.](image-url)
This indicates that the systematic error is not much larger than 0.0256 dex. For example, large-aperture observations taken in 1988 May, 1989 December, and 1991 March, combined with the three \langle N(H i) \rangle values for the three data sets in Table 4, yield a mean \langle N(H i) \rangle = 9.34 \pm 0.67 \times 10^{19} \text{ cm}^{-2}. We conclude that 0.0256 dex is a conservative estimate of the 1 \sigma uncertainty in \langle N(H i) \rangle. We therefore adopt the unweighted mean of the three \langle N(H i) \rangle values in Table 4 as the best estimate of \langle N(H i) \rangle toward \zeta Pup and 0.0256 dex as its 1 \sigma uncertainty: \langle N(H i) \rangle = 9.18 \pm 0.54 \times 10^{19} \text{ cm}^{-2}. We elected to use a mean of the \langle N(H i) \rangle values in Table 4 instead of a straight mean of all of the individual measurements shown in Figure 6 because the latter would give excessive weight to the 1995 data set because of the much larger number of measurements obtained during that observing campaign.

4.3. $\gamma^2$ Velorum

As noted in § 1, $\gamma^2$ Vel is a complex stellar system with a strongly variable UV stellar spectrum. Figure 7 shows two examples of the high-dispersion IUE spectra of $\gamma^2$ Vel that we have used to derive \langle N(H i) \rangle. These examples were selected to illustrate the variability of the P Cygni emission lines in the vicinity of Lyα, which are weakest at orbital phase \sim 0.5. Figure 7 also shows the complex and variable stellar absorption superposed on much of the blue wing of the interstellar Lyα profile. This variability was a source of concern for this paper. Can we derive reliable H i column densities despite the complex spectral changes occurring in this star? Because of the stellar absorption, the blue wing of Lyα was not useful for constraining \langle N(H i) \rangle. Fortunately, the red wing of Lyα was clean and stable as a function of orbital phase. This can be seen by comparing Figures 7a and 7b. In this paper, we used only the red wing for fitting the Lyα profile, and the resultant fits generally look quite good (see Figs. 7 and 9).

We examined \langle N(H i) \rangle as a function of orbital phase of the spectroscopic binary to check for systematic errors in the derived interstellar H i column density due to the complicated variability of the stellar spectrum. There are considerable discrepancies in the orbital elements published by various groups (Stickland \& Lloyd 1990; Schmutz et al. 1997, and references therein). We adopt the orbital elements derived by Schmutz et al. (1997), who find a period of 78.53 \pm 0.01 days with velocity semiampitudes of $K_{WR} = 122 \pm 2 \text{ km s}^{-1}$ and $K_O = 38.4 \pm 2 \text{ km s}^{-1}$. In addition to the usual intrinsic variability of W-R stars, it is believed that the $\gamma^2$ Vel spectrum may also change as a result of periodic absorption of the O star component by the W-R wind (Stickland \& Lloyd 1990).

After screening the IUE high-dispersion observations of $\gamma^2$ Vel, we were left with 42 spectra, 34 small-aperture observations obtained early in the IUE mission and eight later observations obtained with the large aperture. In Figure 8 we plot the H i column densities derived from all of the observations as a function of the phase of the spectroscopic binary, and Table 5 summarizes the \langle N(H i) \rangle, \sigma, and \epsilon derived from the large-aperture data only, the small-aperture data only, and all of the data combined. While one might argue that a trend is apparent in Figure 8 with a minimum in the derived \langle N(H i) \rangle values at orbital phase \sim 0.5, this is a marginal result at best, and we do not believe that it should be taken too seriously. On the contrary, the

![Fig. 7.—Samples of the IUE observations of $\gamma^2$ Vel used to derive the interstellar \langle N(H i) \rangle: (a) SWP6175, spectroscopic binary phase = 0.33, and (b) SWP4719, phase = 0.48 (phases were calculated using the period and $T_0$ from Schmutz et al. 1997). These spectra have been smoothed with a 5 pixel boxcar for display purposes only; the unsmoothed data were used to constrain \langle N(H i) \rangle as described in the text. The best-fitting H i profiles (dotted lines) and continua (dashed lines) are overplotted on the data. Note the dramatic variability of the P Cygni profiles. Note also the presence of complicated absorption structure, which makes the blue wing of the Lyα profile difficult to use for constraining \langle N(H i) \rangle. Both of these observations were obtained with the small IUE aperture.](image-url)
we found that (the errors are 90% D/H abundance ratio for derived in the previous sections, we determined the atomic D/H ratio implies that even larger values could exist in the Galaxy (confidence limits). This result is a large departure from the true uncertainty in are in good agreement, we adopted the results from the respectively adopt 0.0256 dex as the 1p uncertainty in the mean H column densities derived from the 42 IUE observations of Vel, plotted vs. phase of the spectroscopic binary. Each column density is plotted with ± 1 σ error bars. Data obtained with the large aperture are indicated with open circles, while small-aperture results are shown with filled circles.

5. DEUTERIUM AND NITROGEN ABUNDANCE RATIOS

5.1. D/H

Combining the results for D and H I column densities derived in the previous sections, we determined the atomic D/H abundance ratio for γ2 Vel and ζ Pup. Toward γ2 Vel we found that D/H = 2.18 ± 0.36 × 10^{-5} (the errors are 90% confidence limits). This result is a large departure from the value of D/H usually attributed as “typical” in the ISM of the Galaxy (~1.5 × 10^{-5}). A large value for the average D/H ratio implies that even larger values could exist in individual components if other components have lower D/H values closer to the LISM ratio. Although the previous D/H measurement for γ2 Vel ( = 2.0 ± 0.15 × 10^{-5}; York & Rogerson 1976) appears to be in close agreement with the IMAPS result, we consider this to be coincidental in view of the magnitude of the uncertainties in the Copernicus measurement.

For ζ Pup we find N(D I) = 1.30 ± 0.30 × 10^{-15} cm^{-2}, a value slightly below the lower limit derived from Copernicus spectra by Vidal-Madjar et al. (1977). They found that a large range in N(D I) (1.5–20. × 10^{-15} cm^{-2}) was possible for this sight line because of its complexity and a lack of adequate constraints. Since the value of N(H I) derived by Vidal-Madjar et al. (1977) for ζ Pup is consistent with ours, their large range in D/H must be a result of the N(D I) uncertainty. Much more is known now about the complexity of this sight line than at the time of the Copernicus study (e.g., Welty, Morton, & Hobbs 1996). More importantly, the IMAPS spectra have sufficient spectral resolution that the structure of the ζ Pup sight line in neutral hydrogen can be defined by the N_d(α) profile for N I and used to constrain the determination of N(D I). Thus, with higher spectral resolution and better knowledge of the velocity structure along the sight line, a more accurate value of N(D I) and D/H is derived. We find D/H = 1.42 ± 0.25 × 10^{-5}. The N(D I), N(H I), and D/H results for the three stars studied by IMAPS are summarized in Table 6, where all errors are presented as 90% confidence limits.

We now address a critical question, namely, is there sufficient uncertainty in the N(H I) and N(D I) measurements to reconcile the γ2 Vel D/H abundance ratio with the general result observed in the local ISM or with the D/H derived in Paper I for the sight line to δ Ori A? Figure 9a shows with

![Figure 8](https://example.com/fig8.png)

**TABLE 6**

| Quantity | γ2 Vel | ζ Pup | δ Ori A |
|----------|--------|-------|---------|
| N(D I) (10^{-15} cm^{-2}) | 1.12 ± 0.15 | 1.30 ± 0.19 | 1.16 ± 0.29 |
| N(H I) (10^{-15} cm^{-2}) | 4.10 ± 0.34 | 7.62 ± 0.84 | 6.19 ± 0.51 |
| N(D/H) (10^{-5}) | 2.18 ± 0.36 | 1.42 ± 0.23 | 0.74 ± 0.08 |
| N(H I) (10^{-15}) | 7.99 ± 1.02 | 8.30 ± 1.22 | 3.97 ± 0.51 |

* All errors presented in this table are 90% confidence limits (1.65 σ).

**TABLE 5**

| Data Set | Number Spectra | <N(H I)> (cm^{-2}) | σb (cm^{-2}) | ε (cm^{-2}) | χ^2_d |
|----------|----------------|-------------------|--------------|-------------|--------|
| Large aperture | 8 | 5.35 ± 10^{-19} | 0.51 ± 10^{-19} | 0.18 ± 10^{-19} | 1.15 |
| Small aperture | 34 | 5.10 ± 10^{-19} | 0.48 ± 10^{-19} | 0.08 ± 10^{-19} | 1.71 |
| All data | 42 | 5.13 ± 10^{-19} | 0.49 ± 10^{-19} | 0.08 ± 10^{-19} | 1.62 |

* All N(H I) measurements were derived from IUE high-dispersion spectra. This table shows the mean H I column density, <N(H I)>, derived from the large IUE aperture data only, the small-aperture data only, and all of the data combined.

b σ = rms dispersion [both σ and <N(H I)> were weighted inversely by the variances of the individual N(H I) measurements].

c ε = error in the mean = σ/(number measurements)^0.5.

d Reduced χ^2 = χ^2/(degrees of freedom), where χ^2 = ∑(N_i[H I] - <N(H I)>)/σ(N[H I])^2.
Fig. 9.—Expanded plots of the H I Lyα profile in γ² Vel shown in Fig. 7b (SWP4719), again smoothed with a 5 pixel boxcar for display purposes only. The best-fitting profile and its corresponding continuum are indicated with solid lines. The broader damping profiles outside the best fit show the appearance of mild variations in the profile when N(H i) is forced to take on a value so that (a) D/H = 1.5 × 10⁻⁵ as generally observed in the local ISM, given the values of N(D i) in Table 3 [the dotted line assumes the most probable N(D i), while the dashed lines use the 90% confidence limits on N(D i)], and (b) D/H = 0.74 × 10⁻⁵ as observed toward δ Ori A in Paper I. Note that the region between 1207 and 1210 Å is sometimes affected by F Cygni emission (which happens to be weak in this observation, see Fig. 7).

5.2. Nitrogen Abundances

The N i column density N(N i) was computed by integrating the column density profiles shown in Figure 3. The N(N i) results for the three targets are listed in Table 6. This table also contains the resulting N/H and D/N abundance ratios. We examined the potential error in N(N i) by examining the errors in the portions of the various N i profiles used to construct N_v(λ). The 1 σ uncertainty in N(N i) for γ² Vel and δ Ori A is conservatively estimated to be 5% since the N i profiles were all of high quality. There may be some question about the structure in the core of N_v(λ) for δ Ori. The uncertainty in N(N i) for γ² Pup was estimated by supposing that the spike in N_v(λ) at v ~ 19 km s⁻¹ is due largely to noise fluctuations in the core of N i λ952.5, the weakest N i line we detect on this sight line. If we truncate the N_v(λ) profile at the level of the secondary maximum at v ~ 24 km s⁻¹ [N_v(λ) = 5.6 × 10⁻¹⁴ cm⁻² (km s⁻¹)⁻¹], we find that the area of the spike is 3.6 × 10⁻¹⁴ cm⁻², or 4.7% of the total. We then suppose that the total uncertainty in N(N i) for γ² Pup is √2 times this, or 1 σ = 5.1 × 10⁻¹⁴ cm⁻², to allow for the possibility that there may be other such fluctuations.

6. DISCUSSION

There are two principal conclusions of the IMAPS D/H program. First, the atomic D/H ratio in the ISM, averaged over path lengths of 250–500 pc, exhibits significant spatial variability. Differences in the atomic D/H ratio on long path lengths in the ISM have been suspected for many years (Vidal-Madjar et al. 1978; Vidal-Madjar & Gry 1984), but not until now have data of sufficient quality been available to evaluate and reduce statistical and systematic errors to levels where these differences are unequivocal. Second, we find no support for the simple picture that variations in D/H anticorrelate with those of N/H, i.e., one measure of how much the gas has been processed through stellar interiors. Figure 10 shows the relationship between D/H and N/H for the three sight lines studied by IMAPS plus the white dwarf G191—B2B (Vidal-Madjar et al. 1998; Sahu et al. 1999). We point out that some elements are systematically removed from the gas phase as they are incorporated into interstellar dust (Savage & Sembach 1996), but the abundance of N does not seem to be appreciably altered by this effect (Meyer, Cardelli, & Sofia 1997).

Beyond the effects from depletions onto dust, spatial variations in interstellar gas abundances can arise as a

![Graph](https://via.placeholder.com/150)
natural consequence of Galactic chemical evolution and the changing influences of different stellar populations. The lack of an anticorrelation between N/H and D/H depicted in Figure 10 indicates that the variability of D/H is not just a consequence of different mixing ratios of material with differing levels of stellar processing, as we might anticipate, for instance, from the variable addition of metal-poor, infalling gas from the Galactic halo (Meyer et al. 1994). We may need to go further and draw a distinction between contributions from stars that simply destroy deuterium and those that both destroy deuterium and enrich the medium with additional nitrogen. That is, we could envision some stars cycling material only through their shallow layers that are only hot enough to burn deuterium, while others eject material from much deeper layers where the synthesis of heavier elements has taken place. This additional level of complexity could explain the behavior that we observed.

Global models of Galactic chemical evolution (Audouze & Tinsley 1974; Tosi 1988a, 1988b; Dearborn, Steigman, & Tosi 1996; Scully et al. 1996; Tosi et al. 1998) describe the destruction of D during stellar formation, evolution, and eventual mass loss. These models predict variations in D/H, N, and O abundances that are manifested as abundance gradients on a scale of \( \gtrsim 1 \) kpc. However, the predicted trends in Galactic abundances may not accurately represent what is observable in the diffuse ISM. Tenorio-Tagle (1996) showed that the chemical enrichment of the diffuse ISM by OB associations, including supernovae from massive stars, is a slow process. Following a supernova explosion, chemically enriched ejecta remain clumpy and not well mixed with the diffuse ISM they encounter until they are incorporated into new star-forming regions. This is a result of very long timescales for diffusion between different parcels of gas in the warm (10^4 K) and cold (10^2 K) phases of the ISM.

The diffusion timescale for enriched gas to thoroughly mix with the warm diffuse ISM can be very long (\( t_d \gtrsim 10^{10} \) yr; Tenorio-Tagle 1996). On the spatial scale sampled by the IMAPS observations, different sight lines may encounter regions with very different dynamical and chemical histories. Differential Galactic rotation and random cloud motions are expected to stir the diffuse ISM and chemically enriched parcels of gas, but these parcels retain their distinct chemical properties until they are disrupted through photoevaporation, most likely by the formation of new massive stars. Tenorio-Tagle finds that diffusion is efficient only for the hot phase of the ISM (\( t_d \gtrsim 10^6 \) yr), which accounts for a very small fraction of the total diffuse ISM. Only after the enriched gas and diffuse gas are highly ionized would the chemically enriched gas from the earlier generation of stars quickly diffuse into the ambient ISM. Thus, the timescale for mixing interstellar gases with different processing histories can be much longer than the chemical evolution timescale. However, it is possible that interstellar turbulence and its secondary phenomena may accelerate the mixing rate. Since the distribution of star-forming regions (OB associations) shows large inhomogeneities on scales \( \lesssim 1 \) kpc, their corresponding chemical enrichment of the ISM may be expected to be nonuniform as well. This is perhaps revealed indirectly by variations in H II region abundances (Peimbert 1999) and solar-type stars at similar Galactocentric radii (Edvardsson et al. 1993).

Several processes unrelated to stellar nucleosynthesis may, under the right circumstances, alter the atomic D/H ratio of some parcels of interstellar gas (see Lemoine et al. 1999 for a review). D may be incorporated into HD (Watson 1973), but the fraction of molecular gas on our sight lines is very low (see Paper I). Differential radiation pressure on D and H (Vidal-Madjar et al. 1978; Bruston et al. 1981) may lead to a separation of D in some clouds near strong radiation fields. Adsorption of D onto dust grains (Jura 1982) may deplete D from the gas phase. Bauschlicher (1998) found that reactions of H and D with polycyclic aromatic hydrocarbon (PAH) cations might systematically provide some D enrichment in PAHs. A very different perspective has been offered by Mullan & Linsky (1999), who suggested that significant quantities of D may be formed in stellar flares from M dwarf stars and ejected into interstellar space. Some or all of these processes could be at work in the diffuse ISM and alter the atomic D/H ratio on individual sight lines, independent of the degree of chemical enrichment from stellar evolution. However, they have not yet been demonstrated to be quantitatively significant. Observational and theoretical tests of the efficiency and applicability of these processes are needed to better understand the mechanisms affecting the D/H ratio in the diffuse ISM.

While the D/H ratios derived from IMAPS spectra are in the general range expected from Galactic chemical evolution models, a factor of 3 variation in the mean D/H ratio on path lengths of several hundred parsecs is unexpected. The apparent lack of an anticorrelation of the D/H abundance ratio with the metallicity of the gas and its variability on smaller than expected scales suggests that other processes in the Galaxy may be masking more general chemical evolution trends. This may pose a problem for deriving a "primordial" D/H by extrapolating back from D/H measurements in the Milky Way to extragalactic absorbers at higher and higher redshifts, or even for evaluating "primordial" D/H directly from high-redshift observations, until we understand the reasons for these differences. The spatial variations found in this study underline the importance of high-quality D/H determinations. D/H measurements in more distant regions of the Galaxy are needed to determine whether the properties of the gas within 500 pc of the Sun are representative of the Galactic disk. Observations with the FUSE satellite should probe such more distant environments and hopefully answer some of these questions.

The value of D/H for \( \gamma^2 \) Vel is larger than that usually considered typical for the Milky Way. This robust result establishes a new lower limit to the primordial D/H ratio. Within the framework of standard big bang nucleosynthesis (Walker et al. 1991), the large value of D/H found toward \( \gamma^2 \) Vel is equivalent to a cosmic baryon density of \( \Omega_b h^2 = 0.023 \pm 0.002 \). This error simply reflects the uncertainty in the D/H ratio toward \( \gamma^2 \) Vel reported in this paper. We regard this value of \( \Omega_b h^2 \) as an upper limit since no correction has been applied for the destruction of deuterium in stars. This upper limit on \( \Omega_b h^2 \) is consistent with the preferred values of \( \Omega_b h^2 \) derived from recent analyses of the BOOMERANG and MAXIMA cosmic microwave background measurements (e.g., Lange et al. 2000; Tegmark & Zaldarriaga 2000; Hu et al. 2000). However, any lowering of this upper limit on \( \Omega_b h^2 \) to correct for astrophase will lead to a marginal disagreement with simple inflation models (see Fig. 4 in Tegmark & Zaldarriaga 2000) and requires adjustments of other cosmological parameters. Alternatively, the \( \Omega_b h^2 \) upper limit from D/H may be taken as a prior assumption for the constraint of other cosmological param-
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