

IUE OBSERVATIONS OF THE INTERSTELLAR MEDIUM TOWARD β GEMINORUM

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ABSTRACT

We present a high-dispersion ($\Delta\lambda = 0.1 \text{ \AA}$) IUE spectrum of the hydrogen Ly α emission line of the nearby late-type star β Gem (K0 III, $d = 10.8 \text{ pc}$, $l = 192^\circ$, $b = 23^\circ$), from which we have derived the density, velocity dispersion, and bulk velocity of the interstellar H I in that direction. We find values for these parameters consistent with our previous IUE results toward several other stars in the same general direction, with an upper limit of 0.21 cm^{-3} on the hydrogen density [$N(\text{H I}) \leq 7.3 \times 10^{18} \text{ cm}^{-2}$] at the 90% confidence level and 0.15 cm^{-3} at the 50% confidence level. Although we cannot set formal limits on the velocity dispersion, if we assume an upper limit of $1.6 \times 10^{18} \text{ cm}^{-2}$ on the hydrogen density, as was previously found toward HR 1099, we may place a lower limit of 13 km s^{-1} on the velocity dispersion at the 90% confidence level and 15 km s^{-1} at the 50% level. While interstellar deuterium Ly α is clearly seen in absorption in our line profile, we do not obtain a useful limit on the ratio. The present result is important in confirming the generality of the "emptiness" of the interstellar medium away from the Galactic center.

Subject headings: interstellar: abundances — stars: individual (β Gem) — ultraviolet: spectra

I. INTRODUCTION

It is now generally accepted that the Sun is located inside a warm, low-density ($n_{\text{H I}} \sim 0.1 \text{ cm}^{-3}$, $T \sim 10^4 \text{ K}$) cloud, with a total column density of 10^{19} cm^{-2} toward the Galactic center, dropping to 10^{18} cm^{-2} in most other directions, which is, in turn, embedded in a hot, diffuse ($n_{\text{H I}} \sim 10^{-2}$ to 10^{-3} cm^{-3} , $T \sim 10^6 \text{ K}$) substrate (Bruhweiler 1984). There is a bulk motion of the gas in this cloud with an average incoming velocity of $(l, b, v) = (28^\circ, 10^\circ, 28 \text{ km s}^{-1})$ with respect to the Sun (Crutcher 1982) which may be resolved into several components by high-resolution observations (Lallement, Vidal-Madjar, and Ferlet 1986), possibly indicative of shock fronts passing through the cloud. A comprehensive review of recent theoretical and observational results in the local interstellar medium (LISM) has been given by Bruhweiler and Vidal-Madjar (1987).

In previous papers (Murthy *et al.* 1987 and references therein), we have derived H I densities, velocity dispersions, and bulk velocities toward several nearby late-type stars (which are plotted as a function of galactic longitude and distance in Fig. 1) through observations of interstellar H I Ly α absorption against the chromospheric Ly α emission line of those stars. This is currently the only available method for directly determining the interstellar H I parameters within 50 pc of the Sun. In the present work, we present a high-resolution ($\Delta\lambda = 0.1 \text{ \AA}$) spectrum of the late-type star β Gem, taken through the small aperture of the short-wavelength (SWP) camera on the *International Ultraviolet Explorer* satellite (IUE) on 1986 October 15. From these data, representing 800

minutes of exposure, we have attempted to derive the density ($n_{\text{H I}}$), velocity dispersion ($b_{\text{H I}}$), and bulk velocity ($v_{\text{H I}}$) of the neutral hydrogen along that line of sight. Interstellar D I absorption is observed at its isotopic blueshift of 0.33 \AA relative to the H I line, and we have also placed limits on the cosmologically important D/H ratio ($n_{\text{D I}}/n_{\text{H I}}$).

II. DATA ANALYSIS

The data analysis closely followed the procedure of Murthy *et al.* (1987), and we will give but a brief description here. The first step was to assign errors to each of our data points. These errors were calculated by combining the errors due to camera noise, estimated from a flux-free region near the Ly α line, in quadrature with those due to photon noise, assuming a 12:1 signal-to-noise ratio (Joseph 1985). Three points in the center of the interstellar absorption core were contaminated by geocoronal Ly α emission imaged through the small aperture and were deleted from consideration.

Our observation of β Gem was of sufficient quality that we were able to extract spectra from both the primary (echelle order 113) and the secondary (echelle order 114) orders. The two spectra were co-added, weighting each by the square of the signal-to-noise ratio, and the reduced spectrum is shown as $\pm 1 \sigma$ error bars in Figure 2, with the blank space in the center of the absorption core being due to the elimination of the geocoronal Ly α contaminated points.

The four interstellar parameters of interest ($n_{\text{H I}}$, $b_{\text{H I}}$, $v_{\text{H I}}$, and $n_{\text{D I}}/n_{\text{H I}}$) were searched for by constructing a model profile with eight free parameters—scaling factor (normalization of Gaussian), zero level, FWHM of stellar line, a possible error in the wavelength scale, and the four interstellar parameters men-

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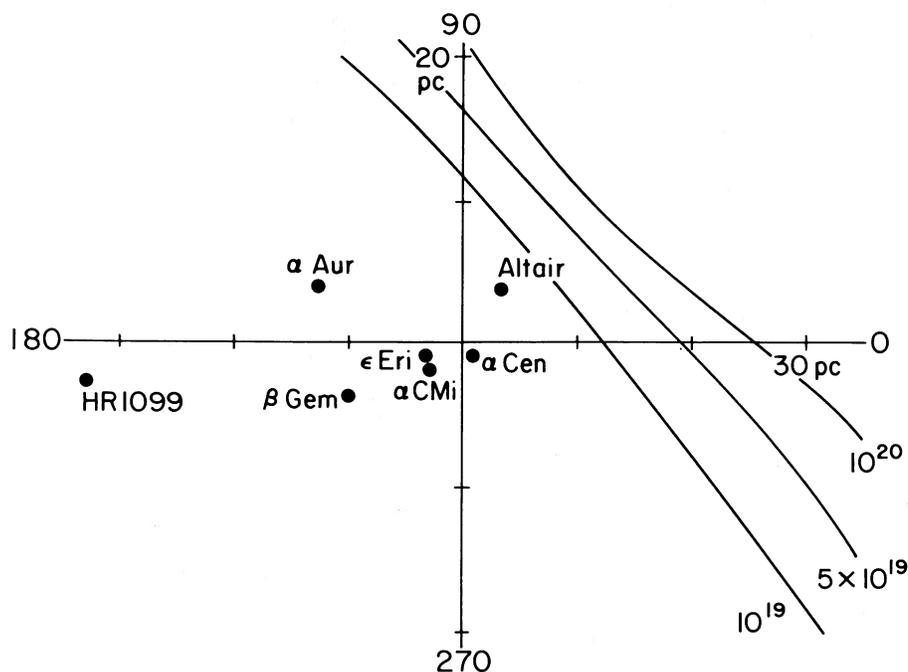


FIG. 1—The positions of all the stars observed in our *IUE* program (including β Gem) are shown as a function of Galactic longitude and distance from the Sun. The estimated hydrogen column density contours for $N(\text{H I}) = 10^{19} \text{ cm}^{-2}$, $5 \times 10^{19} \text{ cm}^{-2}$, and 10^{20} cm^{-2} (Paresce 1984) are also shown.

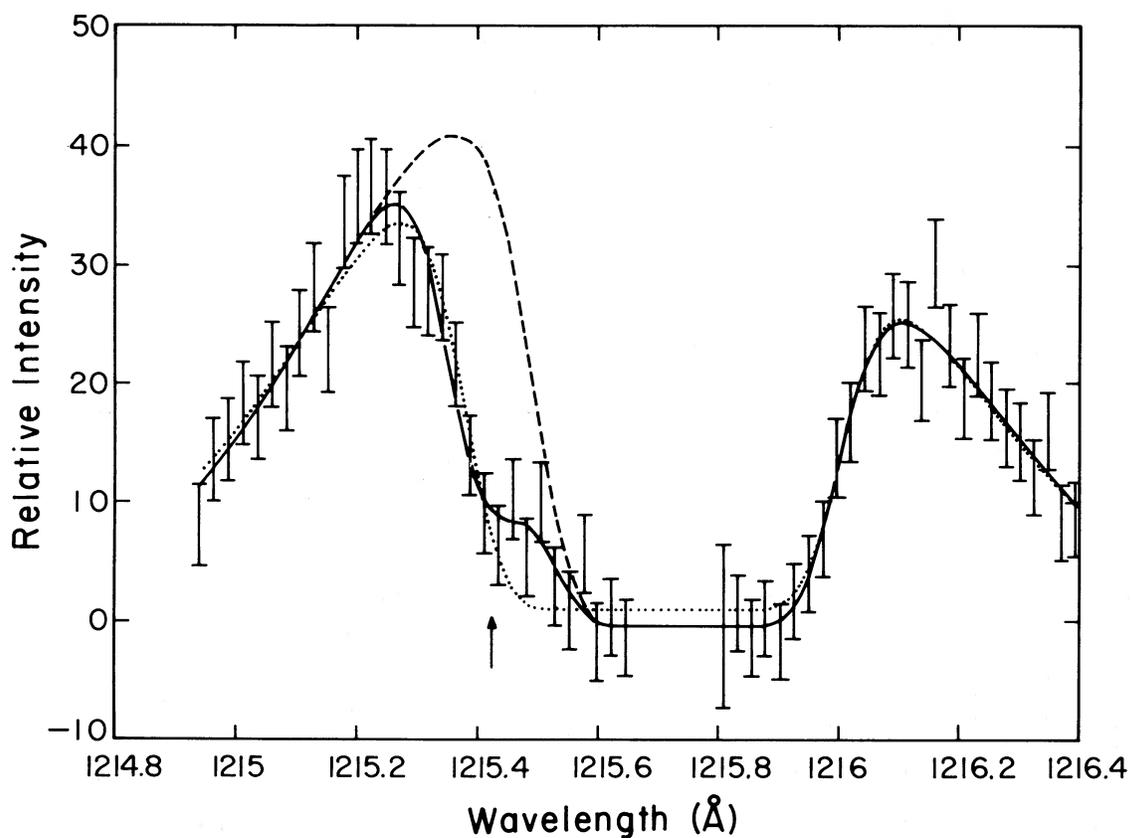


FIG. 2—The reduced spectrum of β Gem is plotted as $\pm 1 \sigma$ error bars. The best-fit model is superposed as a solid line, while the dashed line has the same parameters as the best-fit model, but with the interstellar D I density set to zero. The dotted line is the best-fit model with the interstellar D I density set to zero. The blank space in the center of the interstellar absorption core is due to the removal of geocoronal Ly α emission. The arrow indicates the position of the center of the deuterium line.

tioned above—and by varying the parameters until a minimum χ^2 goodness-of-fit with the data was obtained. The model profile was calculated by multiplying a symmetric Gaussian profile, representing the stellar profile, by Voigt absorption profiles for the interstellar H I and D I absorption, with the above eight free parameters, and finally convolving the resultant with a Gaussian instrumental broadening profile of FWHM 0.1 Å (Evans and Imhoff 1985).

The two most critical assumptions in our modeling procedure are that the stellar line can be model simply by a symmetric Gaussian profile and that there is but a single velocity component along the line of sight to β Gem. Fortunately, the column density of H I along any reasonable line of sight in the LISM is large enough that the interstellar absorption line is saturated over a broad wavelength region, rendering it impossible to observe any structure, such as self-reversal, in the center of the stellar emission line and thus causing the derived interstellar parameters to be relatively insensitive to the assumed stellar profile. This has been borne out by Landsman *et al.* (1986) who obtained consistent values for the interstellar parameters toward each of the stars in the binary system α Cen A (G2 V) and α Cen B (K2 V), despite the very different stellar types. The second assumption is perhaps somewhat less justified as, for example, Ferlet, Lallement, and Vidal-Madjar (1986) detected three velocity components toward Altair which Murthy *et al.* (1987) found to be blended together in H I to give the appearance of a much hotter cloud. However, Murthy *et al.* have provided evidence for the presence of only a single cloud

in the general direction of β Gem and, as will be shown later, the data from β Gem itself favor the single-cloud hypothesis.

III. RESULTS

Our reduced profile of β Gem is plotted as $\pm 1 \sigma$ error bars in Figure 2. The solid line is the figure shows the best-fit model profile ($n_{\text{HI}} = 0.035 \text{ cm}^{-3}$, $b_{\text{HI}} = 18 \text{ km s}^{-1}$, $n_{\text{DI}}/n_{\text{HI}} = 3.7 \times 10^{-5}$). The effects of interstellar D I absorption may be seen from the difference between the solid line and the dashed line, which has the same parameters as the best-fit profile but with $n_{\text{DI}}/n_{\text{HI}}$ set to zero.

As the three parameters n_{HI} , b_{HI} , and $n_{\text{DI}}/n_{\text{HI}}$ are closely correlated, more information may be gained from confidence contours of one parameter against the other (Lampton, Margon, and Bowyer 1976) than from simple error bars and, in Figures 3a, 3b, and 3c, we have plotted 50% (dashed line) and 90% (solid line) confidence contours of, respectively, b_{HI} versus n_{HI} , $n_{\text{DI}}/n_{\text{HI}}$ versus n_{HI} , and b_{HI} versus $n_{\text{DI}}/n_{\text{HI}}$. These contours represent the projection of the multidimensional surface of constant χ^2 (of the appropriate confidence level) onto the plane defined by the two parameters of interest. As an example of the use of these plots, if we fix b_{HI} at 10 km s^{-1} then, from Figure 3a, we can set 50% confidence limits of $0.07\text{--}0.15 \text{ cm}^{-3}$ and 90% confidence limits of $0.06\text{--}0.21 \text{ cm}^{-3}$ on n_{HI} , regardless of the values of the other parameters.

It is apparent from Figure 3 that a very broad range of interstellar parameters is consistent with the data, mainly because the interstellar H I absorption is just leaving the flat

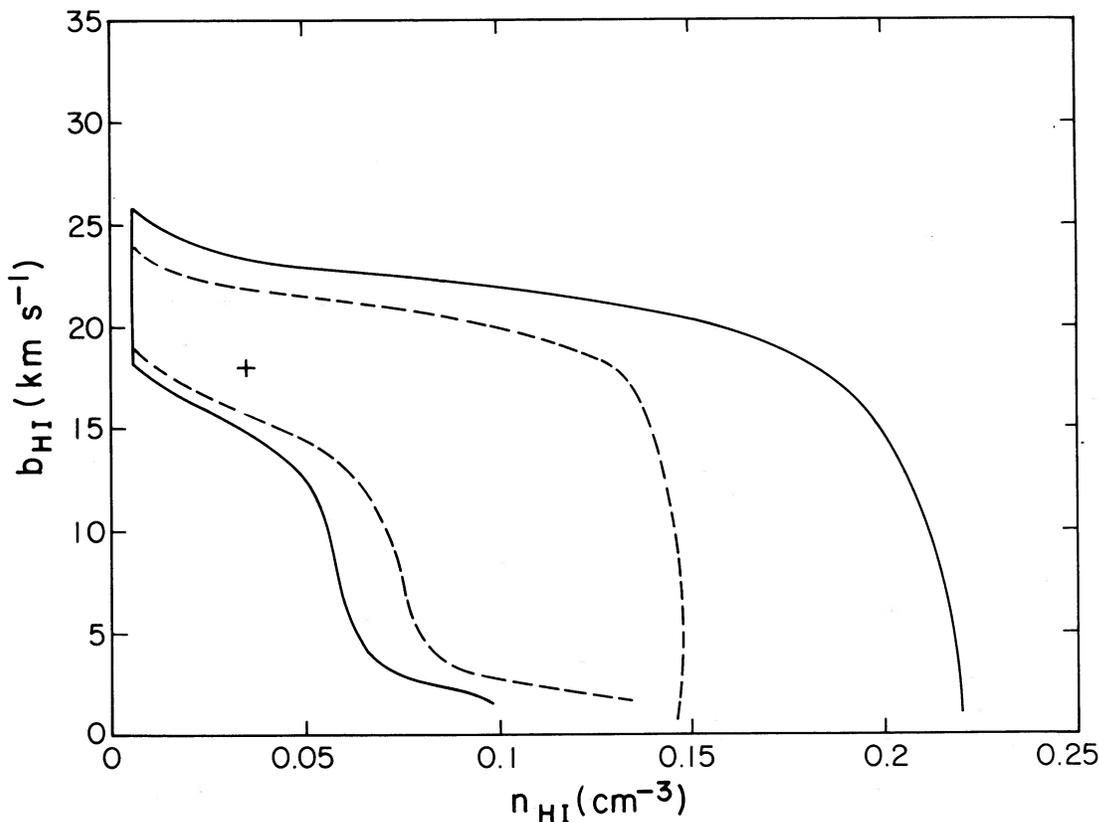


FIG. 3a

FIG. 3.—Contour plots of (a) b_{HI} vs. n_{HI} , (b) $n_{\text{DI}}/n_{\text{HI}}$ versus n_{HI} , and (c) b_{HI} versus $n_{\text{DI}}/n_{\text{HI}}$ are plotted. The solid line represents a 90% confidence contour, while the dashed line represents a 50% confidence contour. The cross in each of the plots indicates the position of the best-fit model plotted in Fig. 2.

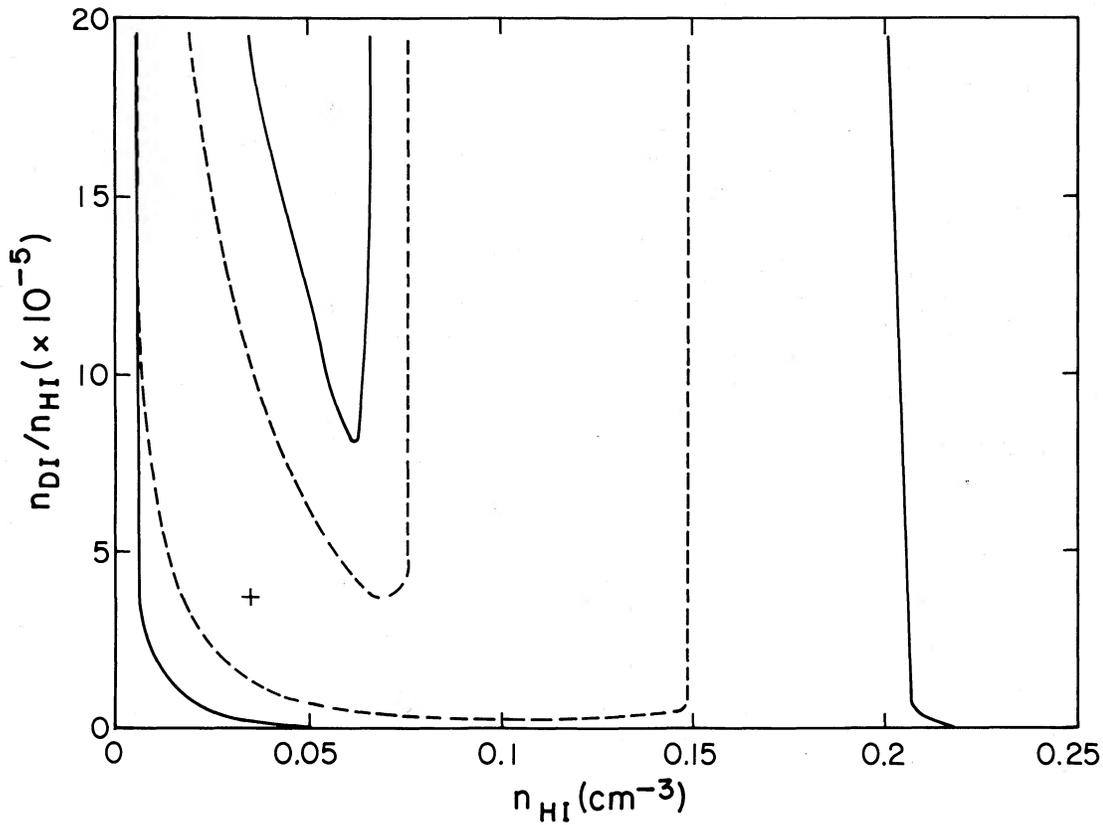


FIG. 3b

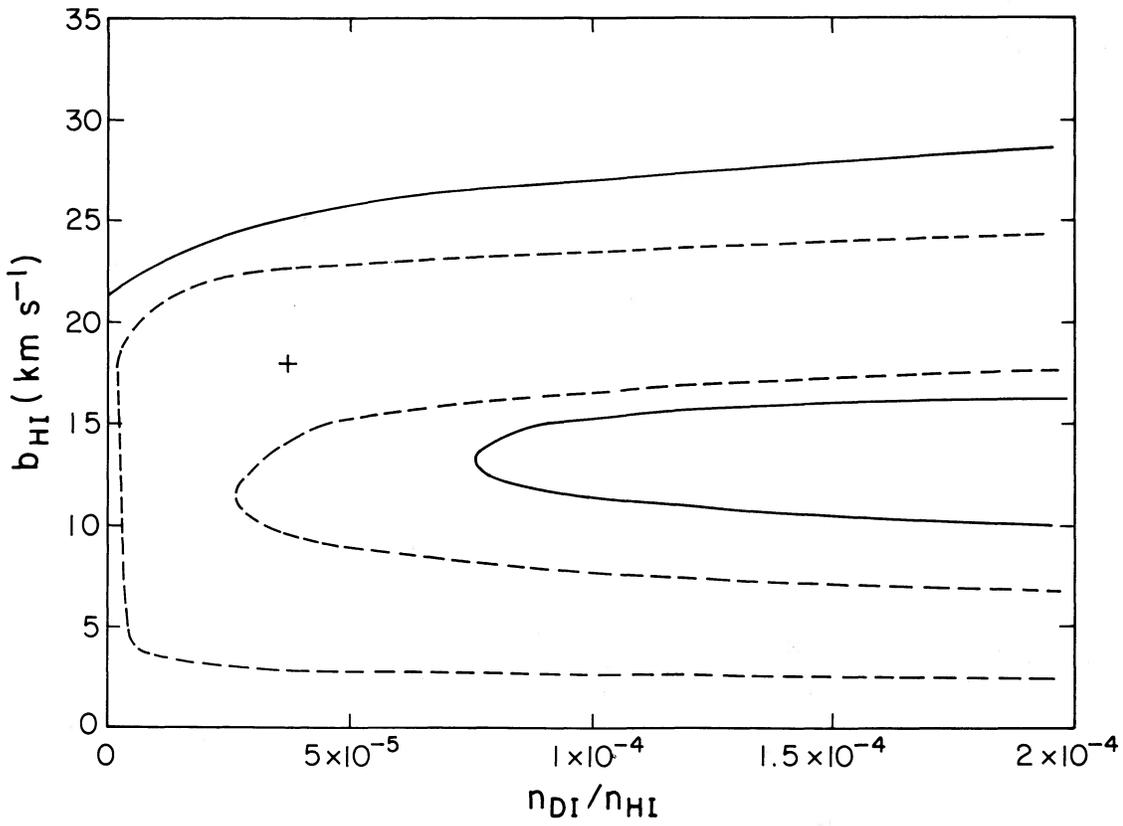


FIG. 3c

TABLE 1
LIMITS ON PARAMETERS

PARAMETER	50%		90%		COMMENTS
	Lower	Upper	Lower	Upper	
n_{HI} (cm^{-3}) .....	...	0.15	...	0.21	$b_{\text{HI}} = 16 \text{ km s}^{-1}$
	0.03	0.14	0.02	0.19	
b_{HI} (km s^{-1})	~ 3	~ 23	...	~ 28	$N(\text{H I}) = 1.6 \times 10^{18} \text{ cm}^{-2}$
	15	22	13	23	
$n_{\text{D I}}/n_{\text{H I}}^{\text{a}}$ .....	...	...	...	...
v_{HI} (km s^{-1})	37	...	...	...

^a Due to the size of the error bars, no formal limits may be set on $n_{\text{D I}}/n_{\text{H I}}$.

part of the curve of growth, and the only useful limits which may be directly placed from the data are a 90% confidence upper limit of 0.21 cm^{-3} [$N(\text{H I}) = 7.0 \times 10^{18} \text{ cm}^{-2}$] and a 50% confidence upper limit of 0.15 cm^{-3} [$N(\text{H I}) = 5.0 \times 10^{18} \text{ cm}^{-2}$] on n_{HI} . The only previous study of the interstellar medium in the line of sight to β Gem was by McClintock *et al.* (1975) who derived similar values for n_{HI} from a poor quality spectrum of β Gem obtained with the low-resolution ($\Delta\lambda = 0.2 \text{ \AA}$) spectrometer aboard the *Copernicus* satellite.

We may place somewhat tighter bounds on the interstellar parameters toward β Gem if we make use of the results of Murthy *et al.* (1987) toward the four stars, ϵ Eri, Procyon, Capella, and HR 1099, which are in the same general direction as β Gem (Fig. 1). The first of these is an upper limit of $\sim 16 \text{ km s}^{-1}$ ($\sim 10^5 \text{ K}$) on the velocity dispersion which allows us, from Figure 3a, to set 90% confidence limits of 0.02 – 0.19 cm^{-3} and 50% confidence limits of 0.03 – 0.14 cm^{-3} on n_{HI} . Conversely, if we assume an upper limit of $1.6 \times 10^{18} \text{ cm}^{-2}$ on the H I column density ($n_{\text{HI}} = 0.048 \text{ cm}^{-3}$), based on the column density toward the more distant star HR 1099 (Murthy *et al.* 1987), we may place a 90% confidence lower limit of 13 km s^{-1} and a 50% confidence lower limit of 15 km s^{-1} on b_{HI} .

Finally, by varying the bulk velocity of H I and looking at the resulting χ^2 , we may place 50% confidence limits of 13 – 37 km s^{-1} on the bulk velocity of the H I towards β Gem (in the heliocentric frame), in complete agreement with the projection of the wind flow vector of Crutcher (1982).

IV. CONCLUSIONS

The interstellar medium in the line of sight to β Gem is consistent with the picture described in the Introduction, with a total column density of $\sim 2 \times 10^{18} \text{ cm}^{-2}$ ($n_{\text{HI}} \sim 0.05 \text{ cm}^{-3}$) and a velocity dispersion of 13 – 16 km s^{-1} and our final parameters are summarized in Table 1. There is no evidence of a multicomponent velocity structure in that direction and, within the broad limits set on the bulk velocity from our data, the flow vector is in agreement with the interstellar wind found by Crutcher (1982). Although we cannot set formal limits on $n_{\text{D I}}/n_{\text{H I}}$, deuterium absorption is clearly seen in our spectrum.

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