

## ORFEUS OBSERVATIONS OF ULTRAVIOLET EXCITED HIGH-J MOLECULAR HYDROGEN

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### ABSTRACT

We present measurements of diffuse interstellar H<sub>2</sub> absorption lines in the continuum spectra of 10 early-type stars. The data were observed with the Berkeley Extreme and Far-Ultraviolet Spectrometer (BEFS) of the ORFEUS telescope on board the *ORFEUS-SPAS I* and *II* space-shuttle missions in 1993 and 1996, respectively. The spectra extend from the interstellar cutoff at 912 Å to about 1200 Å with a resolution of  $\sim 3000$  and statistical signal-to-noise ratios between 10 and 65. Adopting Doppler broadening velocities from high-resolution optical observations, we obtain the H<sub>2</sub> column densities of rotational levels  $J'' = 0$  through 5 for each line of sight. The kinetic temperatures derived from  $J'' = 0$  and 1 states show a small variation around the mean value of 80 K, except for the component toward HD 219188, which has a temperature of 211 K. Based on a synthetic interstellar cloud model described in our previous work, we derive the incident UV intensity  $I_{UV}$  and the hydrogen density  $n_H$  of the observed components to be  $-0.4 \leq \log I_{UV} \leq 2.2$  and  $6.3 \leq n_H \leq 2500 \text{ cm}^{-3}$ , respectively.

*Key words* : ISM: H<sub>2</sub> — ISM: molecular clouds — ultraviolet: FUV

### I. INTRODUCTION

The hydrogen molecule (H<sub>2</sub>) plays a central role in a variety of processes that significantly influence the chemical and physical state of the interstellar medium (ISM). From the *Copernicus* satellite (Savage et al. 1977) to the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) (Shull et al. 2000), many systematic measurements of H<sub>2</sub> absorption in the far-ultraviolet (FUV) have derived  $N(J)$ , the column density of H<sub>2</sub> in the rotational level  $J$  of the ground vibrational and electronic state, to obtain physical conditions of the diffuse and translucent molecular clouds in the ISM (see references in Lee, Pak, Dixon, & van Dishoeck 2007, hereafter Paper I). Recently, detailed H<sub>2</sub> models have been used to obtain constraints on otherwise unobservable parameters of the molecular clouds by reproducing the observed  $N(J)$  terms (Browning et al. 2003; Paper I). For example, in Paper I we found that  $N(4)/N(0)$  is proportional to the incident UV intensity  $I_{UV}$  and the H<sub>2</sub> molecular fraction  $f$  is simply related to the ratio of  $I_{UV}$  and the hydrogen density  $n_H$ , providing a new method to derive  $I_{UV}$  and  $n_H$  from the observational parameters  $N(4)/N(0)$  and  $f$ .

In this paper, we present results from the molecular-hydrogen survey conducted by the Berkeley Extreme and Far-Ultraviolet Spectrometer (BEFS) on the ORFEUS telescope. Since the BEFS has moderate spectral resolution, we have used high-resolution optical measurements to select 10 target stars with a single absorption component for our study. From the column densities of each rotational level  $N(J)$ , we derive the total hydrogen column density  $N(\text{H}_2)$ , the cloud mean temperature  $T_{01}$ , and the excitation temperature  $T_{\text{ex}}$ . We use the relation between  $N(4)/N(0)$  and  $f$  to derive  $I_{UV}$  and  $n_H$  for each line of sight as described in Paper I. Combining our data with new observational results from *FUSE* (Gillmon et al. 2006), we explore the relation between  $n_H$  and  $N(\text{H}_2)$  in interstellar molecular clouds.

### II. OBSERVATIONS AND ANALYSIS

The BEFS flew on board the *ORFEUS-SPAS I* and *II* Space Shuttle missions in 1993 and 1996, respectively. Its performance on the first mission is described by Hurwitz & Bowyer (1995) and on the second by Hurwitz et al. (1998). Its spectral resolution at FUV wavelengths is  $\sim 95 \text{ km s}^{-1}$  FWHM ( $\sim 0.33 \text{ \AA}$ ) for point sources. Its effective area peaked at about  $4 \text{ cm}^2$

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TABLE 1  
TARGET SUMMARY

| Star      | $l$    | $b$    | Sp. Type | $E(B - V)$ | $\log N(\text{HI}) [\text{cm}^{-2}]$ | $d$ [pc] | References*      |
|-----------|--------|--------|----------|------------|--------------------------------------|----------|------------------|
| HD 36402  | 277.77 | -33.04 | OB+WC5   | 0.11       | 20.72                                | 52500    | SB81, W95, SDS93 |
| HD 94473  | 272.83 | +29.17 | B3.0 IV  | 0.14       | 20.89                                | 278      | HIP, P92, P93    |
| HD 97991  | 262.34 | +51.73 | B2.0 V   | 0.01       | 20.64                                | 824      | A83, DS94, A83   |
| HD 149881 | 31.38  | +36.23 | B0.5 III | 0.07       | 20.62                                | 2139     | DS94, SF95, S98  |
| HD 156110 | 70.99  | +35.71 | B3 Vn    | 0.03       | 20.66                                | 567      | F94              |
| HD 167756 | 351.47 | -12.30 | B0.5 Ia  | 0.10       | 20.81                                | 4000     | DS94, H97, KBK98 |
| HD 203664 | 61.93  | -27.46 | B0.5 V   | 0.03       | 20.54                                | 3200     | F94, SM87        |
| HD 214080 | 44.80  | -56.92 | B1.0 Ib  | 0.05       | 20.61                                | 3381     | DS94, H97, SDS93 |
| HD 219188 | 83.03  | -50.17 | B0.5 III | 0.08       | 20.75                                | 2379     | F94, KDM82       |
| HD 220582 | 99.41  | -33.38 | B6 IV,V  | 0.07       | 20.5                                 | 292      | HIP, O87, S66    |

\*References. – A83: Albert 1983; DS94: Diplas & Savage 1994a; F94: Fruscione et al. 1994; H97: Howarth et al. 1997; HIP: ESA 1997; O87: Oja 1987; S74: Sharpless 1974; SF95: Spitzer & Fitzpatrick 1995; S66: Slettebak 1966; KDM82: Keenan et al. 1982; SM87: Savage & Massa 1987; P92: Penprase 1992; SB81: Savage & de Boer 1981; W95: Walborn et al. 1995; SDS93: Sembach et al. 1993; S98: Sembach (private communication); P93: Penprase 1993; W97: Welsh et al. 1997; KBK98: Kennedy et al. 1998

TABLE 2  
OBSERVATION AND ANALYSIS SUMMARY

| Star      | Mission | Time <sup>a</sup> [s] | S/N <sup>b</sup> | Region Fit [ $\text{\AA}$ ] | $\langle v \rangle^c [\text{km s}^{-1}]$ | $b^c [\text{km s}^{-1}]$ | Continuum <sup>d</sup> |
|-----------|---------|-----------------------|------------------|-----------------------------|--|--------------------------|------------------------|
| HD 36402  | I       | 1306                  | 16.6             | 1045–1058                   | +11.0 (SDS 93)                           | 3 (SDS 93)               | HD 37018               |
| HD 94473  | II      | 288                   | 21.2             | 1088–1102                   | -3.4 (P93)                               | 2 (P93)                  | HD 155763              |
| HD 97991  | II      | 500                   | 39.3             | 1088–1101.5                 | -5.7 (A83)                               | 4 (A83)                  | HD 37018               |
| HD 149881 | I       | 1560                  | 52.3             | 1045–1060                   | +1.1 (S98)                               | 2 (S98)                  | HD 122451              |
| HD 156110 | I       | 840                   | 48.3             | 1045–1060                   | -1.7 (D00)                               | 3 (D00)                  | HD 158408              |
| HD 167756 | I       | 866                   | 51.0             | 1045–1060                   | +3.5 (KBK98)                             | 3 (KBK98)                | HD 38771               |
| HD 203664 | II      | 652                   | 40.9             | 1088–1102                   | +1.8 (D00)                               | 4 (D00)                  | HD 122451              |
| HD 214080 | I       | 1550                  | 61.1             | 1045–1060                   | -5.4 (SDS93)                             | 2 (SDS93)                | HD 91316               |
| HD 219188 | II      | 186                   | 25.6             | 1088–1102                   | -3.7 (D00)                               | 6 (D00)                  | HD 36486               |
| HD 220582 | II      | 1083                  | 28.5             | 1088–1102                   | -8.8 (D00)                               | 4 (D00)                  | HD 155763              |

<sup>a</sup>Total integration time.

<sup>b</sup>Statistical signal-to-noise ratio in a 0.25  $\text{\AA}$  bin, averaged over the region fit.

<sup>c</sup>Obtained from Na I optical observations. See references.

<sup>d</sup>*Copernicus* continuum stars (Snow & Jenkins 1977).

\*References. – A83: Albert 1983; P93: Penprase 1993; SDS93: Sembach et al. 1993; S98: Sembach (private communication); KBK98: Kennedy et al. 1998; D00: Dixon (private communication)

for the first mission and about  $9 \text{ cm}^2$  for the second. From the 54 early-type target stars in the Galactic disk and halo and 3 stars in the Magellanic Clouds observed by the BEFS, we have chosen 10 program stars (Table 1) with only a single major velocity component in the high-resolution optical measurements, to avoid line blending. If there are multiple components toward a star, we include it in our sample if the column density of the principal component is more than 3 times the sum of the other components.  $N(\text{HI})$  is important to derive the molecular fraction  $f$ . We referred the  $N(\text{HI})$  values obtained from the 21 cm radio observations (see the references in Table 1).

Table 2 shows the observation log and the summary of results. We use the optical Na I absorption features to obtain the Doppler parameters of the principal absorption components, because the Na I lines trace the diffuse, cloudy component of the ISM (Sembach & Danks 1994). Observed Doppler parameters in Table 2, rounded to the nearest  $b$  value in our model grid, range from 2 to 6  $\text{km s}^{-1}$ , consistent with values found by other authors who use Na I lines to estimate Doppler parameters (e.g., Sonnentrucker et al. 2003). To estimate the stellar continuum, we use reference spectra selected from the *Copernicus* Spectral Atlas (Snow & Jenkins 1977). Reference spectra, listed in Table 2, are selected for their similarity to the observed stars in spectral classification. Priority is given to the shape of the stellar continuum, and we seek the best match among the reference stars of similar spectral type. Because the total  $\text{H}_2$  column density  $N(\text{H}_2)$  in each reference spectrum is less than the uncertainty in either the  $J'' = 0$  or  $J'' = 1$  column of the corresponding program star, we do not attempt to correct for  $\text{H}_2$  absorption in the reference spectrum. The atlas spectra have  $0.2 \text{ \AA}$  resolution, close to that of our data.

We begin our analysis by generating a set of synthetic  $\text{H}_2$  absorption-line models, using an ISM line-fitting package written by M. Hurwitz and V. Saba. Given the column density and Doppler broadening parameter, the program computes a Voigt profile for each absorption feature and outputs a spectrum of  $\tau$  versus wavelength at a resolution equal to the pixel size ( $0.0142 \text{ \AA}$ ) of the BEFS spectra (which are oversampled). The high resolution is necessary because the  $\text{H}_2$  absorption lines are intrinsically quite narrow. For each  $\text{H}_2$  rotational level ( $J'' = 1\text{--}5$ ), we produce a set of absorption-line spectra with the given Doppler parameters.

The models are fitted to the data using the non-linear curve-fitting program SPECFIT (Kriss 1994) to perform a  $\chi^2$  minimization. For stars observed on the 1993 *ORFEUS-SPAS I* flight, we fit the spectral region between 1045 and 1060  $\text{\AA}$ , which contains most of the  $v = 0 \rightarrow 4$  vibrational band of the Lyman series, as this region is least complicated by stellar photospheric absorption or overlapping Werner bands of interstellar  $\text{H}_2$ . Unfortunately, the brightest stars observed on the 1996 flight exhibit detector artifacts in

this part of the spectrum (Hurwitz et al. 1998), so we use the 1088–1102  $\text{\AA}$  region, which contains the  $v = 0 \rightarrow 1$  Lyman series vibrational band, for all but the faintest *ORFEUS-SPAS II* stars. The exact region fitted for each of our program stars is listed in Table 2. For all stars, only the  $J'' = 0$  to 5 rotational features are considered. Photoabsorption to levels with  $J'' > 6$  immediately cascade to the  $J'' = 5$  or  $J'' = 6$  level for ortho and para  $\text{H}_2$ , respectively (Jura 1974), and  $J'' = 6$  lines are rarely observed. We model each  $\text{H}_2$  rotational level independently, using the value of the Doppler parameter  $b$  from Table 2. The radial velocities of each rotational level are tied together, but the entire absorption-line complex is allowed to shift in velocity space to account for wavelength offsets and redshifts.

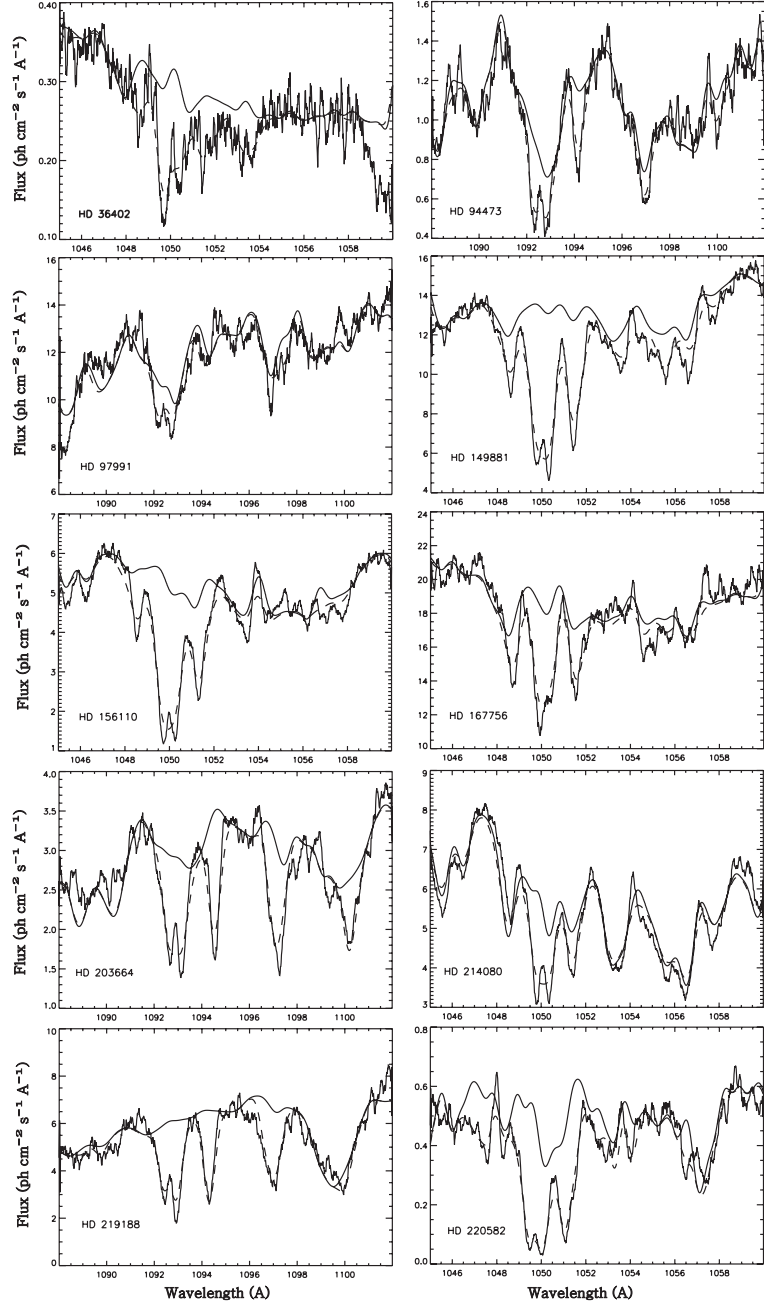
We first fit the  $J'' = 0$  and 1 lines, then add the higher-level lines, as they often lie in the wings of the lower- $J''$  features. Two interstellar features that fall in the 1045–1060  $\text{\AA}$  region, Ar I at 1048.22  $\text{\AA}$  and Fe II at 1055.26  $\text{\AA}$ , and one in the 1088–1102 region, Fe II at 1096.88  $\text{\AA}$ , are also included in the model. A band of Cr III absorption features near 1100  $\text{\AA}$  (Rogerson & Ewell 1985) complicates the fit to the P(3) and R(4) lines at 1099.8 and 1100.2  $\text{\AA}$ , respectively, but other nearby  $J'' = 3$  and 4 features allow us to constrain the column densities of these rotational levels. The only free parameters in the fit are the continuum placement (normalization and “tilt”), the scaling of the absorption-line column densities, and a constant shift in the wavelength scale of the absorption-line system. We adjust the model to fit the data as well as possible by hand, then invoke the automated  $\chi^2$ -minimization algorithm to fine-tune the fit.

Figure 1 shows the spectra of our target stars (thick solid lines), which were background-subtracted, scaled to correct for detector dead-time effects, and wavelength- and flux-calibrated as described by Hurwitz et al. (1998), the continuum spectra (thin solid lines) and our fitting results (dashed lines). Error bars are assigned to the data assuming Gaussian statistics. Hurwitz et al. (1998) find that, at the nominal instrument resolution of  $0.33 \text{ \AA}$ , noise from detector artifacts is about 6.4% of the measured signal, so we sum in quadrature the random-error spectrum with a scaled (by 0.05) signal spectrum, representing this component of the systematic error. The flux calibration is based on in-flight observations of hot white dwarfs and is thought to be uncertain to less than 10 % (Dixon et al. 1998).

### III. RESULTS AND DISCUSSION

#### (a) $\text{H}_2$ Column Densities

Column densities for each rotational level are presented in Table 3. The  $1\text{-}\sigma$  error bars are calculated by SPECFIT and represent only statistical uncertainties. Systematic errors, including line blending, both within the  $\text{H}_2$  absorption bands and with nearby interstellar



**Fig. 1.**— The BEFS spectra of 10 targets, binned by 9 pixels are plotted in thick solid lines. Scaled continuum spectra and the fitting results are overlotted as solid and dashed lines, respectively.

atomic lines, errors in our cloud models, and (most important) errors in our adopted stellar continua, are likely to dominate the statistical uncertainties. Because it is difficult to quantify these effects, we estimate the systematic errors from our experience working with the data. We find that, even in complicated situations, small changes in our model parameters yield changes of 30 % or less in the derived column densities for  $J'' = 0$  and 1, and of a factor of two or less for the higher ro-

tational levels, corresponding to uncertainties of  $\sim 0.1$  dex for  $J'' = 0, 1$  and 0.3 dex for  $J'' > 2$ . Total column densities range from  $\log N(\text{H}_2) = 17.16$  to 19.63 [ $\text{cm}^{-2}$ ], indicating that these sight lines probe diffuse interstellar clouds.

### (b) Temperatures

The mean cloud kinetic temperature  $T_{01}$  for each line of sight is derived from the column densities  $N(0)$

TABLE 3  
 MOLECULAR HYDROGEN ROTATIONAL COLUMN DENSITIES

| Star      | $\log N(0)$         | $\log N(1)$         | $\log N(2)$         | $\log N(3)$         | $\log N(4)$         | $\log N(5)$         | $\log N(\text{H}_2)$ |
|-----------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------------|
| HD 36402  | 18.51<br>$\pm 0.02$ | 18.10<br>$\pm 0.04$ | 15.93<br>$\pm 0.15$ | 13.59<br>$\pm 0.37$ | 13.66<br>$\pm 1.04$ | 14.73<br>$\pm 0.15$ | 18.65<br>$\pm 0.02$  |
| HD 94473  | 18.61<br>$\pm 0.02$ | 18.46<br>$\pm 0.04$ | 15.18<br>$\pm 0.17$ | 17.07<br>$\pm 0.28$ | 15.15<br>$\pm 0.22$ | 14.44<br>$\pm 0.53$ | 18.85<br>$\pm 0.02$  |
| HD 97991  | 17.50<br>$\pm 0.14$ | 16.47<br>$\pm 0.27$ | 14.62<br>$\pm 0.11$ | 14.05<br>$\pm 1.92$ | 14.09<br>$\pm 0.44$ | 13.30<br>$\pm 1.44$ | 17.54<br>$\pm 0.13$  |
| HD 149881 | 18.55<br>$\pm 0.00$ | 18.75<br>$\pm 0.00$ | 15.78<br>$\pm 0.01$ | 15.44<br>$\pm 0.01$ | 14.46<br>$\pm 0.01$ | 14.43<br>$\pm 0.01$ | 18.96<br>$\pm 0.00$  |
| HD 156110 | 18.91<br>$\pm 0.00$ | 18.79<br>$\pm 0.00$ | 15.23<br>$\pm 0.00$ | 15.08<br>$\pm 0.00$ | 14.24<br>$\pm 0.00$ | 14.18<br>$\pm 0.01$ | 19.16<br>$\pm 0.00$  |
| HD 167756 | 17.06<br>$\pm 0.00$ | 16.41<br>$\pm 0.00$ | 15.56<br>$\pm 0.00$ | 15.35<br>$\pm 0.00$ | 14.30<br>$\pm 0.00$ | 14.94<br>$\pm 0.00$ | 17.16<br>$\pm 0.00$  |
| HD 203664 | 18.29<br>$\pm 0.05$ | 18.31<br>$\pm 0.05$ | 16.31<br>$\pm 0.07$ | 18.03<br>$\pm 0.25$ | 14.08<br>$\pm 0.80$ | 12.36<br>$\pm 1.56$ | 18.71<br>$\pm 0.06$  |
| HD 214080 | 18.19<br>$\pm 0.02$ | 17.91<br>$\pm 0.04$ | 14.34<br>$\pm 0.18$ | 16.23<br>$\pm 0.15$ | 14.17<br>$\pm 0.18$ | 14.15<br>$\pm 0.19$ | 18.38<br>$\pm 0.02$  |
| HD 219188 | 18.38<br>$\pm 0.07$ | 18.99<br>$\pm 0.03$ | 16.36<br>$\pm 0.12$ | 16.36<br>$\pm 0.10$ | 15.14<br>$\pm 0.15$ | 15.03<br>$\pm 0.15$ | 19.09<br>$\pm 0.03$  |
| HD 220582 | 19.25<br>$\pm 0.04$ | 19.31<br>$\pm 0.02$ | 18.43<br>$\pm 0.07$ | 18.14<br>$\pm 0.11$ | 15.41<br>$\pm 0.14$ | 13.64<br>$\pm 2.45$ | 19.63<br>$\pm 0.02$  |

\*Units are  $\text{cm}^{-2}$ . Quoted errors are statistical uncertainties returned by SPECFIT.

and  $N(1)$  using the relation

$$\frac{N(1)}{N(0)} = \frac{g_1}{g_0} \exp\left(\frac{-E_{01}}{kT_{01}}\right) = 9 \exp\left(\frac{-170 \text{ K}}{T_{01}}\right), \quad (1)$$

where  $g_0$  and  $g_1$  are the statistical weights of  $J'' = 0$  and  $J'' = 1$ , respectively (Shull & Beckwith 1982). Table 4 shows that the derived temperatures range from 37 K for HD 97991 to 211 K for HD 219188 and average  $T_{01} = 80 \pm 11$  (rms) K, in agreement with the *Copernicus* result of  $T_{01} = 77 \pm 17$  K (Savage et al. 1977). Gillmon et al. (2006) also obtained  $\langle T_{01} \rangle = 124 \pm 8$ , suggesting that the average kinetic temperature of the high-latitude clouds is somewhat higher than that in the Galactic disk, although the range of  $T_{01}$  is about the same as ours.

The excitation temperature  $T_{\text{ex}}$  is derived in Table 4 in the same way, with  $J'' = 2$  and  $J'' = 3$  levels. We have used  $g_J = g_S(2J + 1)$  to get  $g_2$  and  $g_3$ . Here, the spin factor  $g_S$  equals 1 or 3 for para- or ortho- $\text{H}_2$ , respectively. The band energy factor  $E_{23}$   $\text{k}^{-1}$  is 1162 K.  $T_{\text{ex}}$  values range from 423 to 810 K, with a mean of  $603 \pm 54$  (rms) K. This value is slightly higher than that ( $505 \pm 28$  K) found in the high-latitude *FUSE* survey (Gillmon et al. 2006), and twice that of the *FUSE* disk survey (Shull et al. 2005). Considering that most our sight lines probe the Galactic halo – only HD 167756 has a Galactic latitude  $|b| < 20^\circ$  – it is reasonable that our mean value of  $T_{\text{ex}}$  is similar to the *FUSE* high-

latitude survey result.

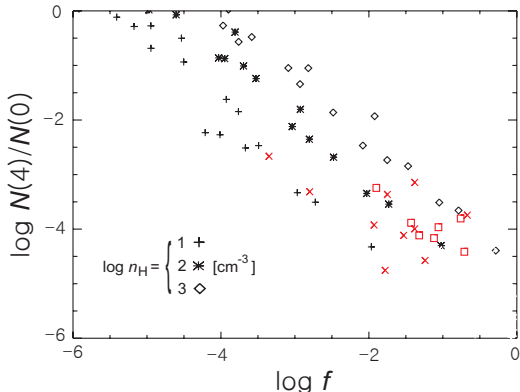
### (c) The Hydrogen Density and The Incident UV Intensity

In Paper I, we used synthetic interstellar cloud models to investigate the formation and destruction of high- $J$  molecular hydrogen in photo-dissociation regions. We found that  $N(4)/N(0)$  is proportional to the incident UV intensity  $I_{\text{UV}}$  and that the  $\text{H}_2$  molecular fraction  $f$  is simply related to the ratio of  $I_{\text{UV}}$  and the hydrogen density  $n_{\text{H}}$ , providing a new method to derive  $I_{\text{UV}}$  and  $n_{\text{H}}$  from the observational parameters  $N(4)/N(0)$  and  $f$ , for an assumed  $\text{H}_2$  formation rate  $R$ . Note that the  $\text{H}_2$  formation rate  $R$  can be written in its simplest form as

$$R = 3 \times 10^{-18} T^{1/2} y_f, \quad (2)$$

where  $y_f$  is the formation rate coefficient, and  $I_{\text{UV}}$  is the enhancement factor compared with the mean interstellar value adopted by Draine (1978), i.e.,  $\phi(\lambda = 1000 \text{ \AA}) = 4.5 \times 10^{-8} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$  when  $I_{\text{UV}} = 1$ .

Figure 2 shows the model calculation results for  $\log N(4)/N(0)$  vs.  $\log f$  for three values of  $n_{\text{H}}$  (black plus:  $10 \text{ cm}^{-3}$ , black asterisk:  $100 \text{ cm}^{-3}$ , and black diamond signs:  $1000 \text{ cm}^{-3}$ ) using  $T = 100 \text{ K}$ ,  $I_{\text{UV}} = 0.1\text{--}1000$ , and  $\log N(\text{H}_2) = 14\text{--}19 [\text{cm}^{-2}]$ . Here, we assume the

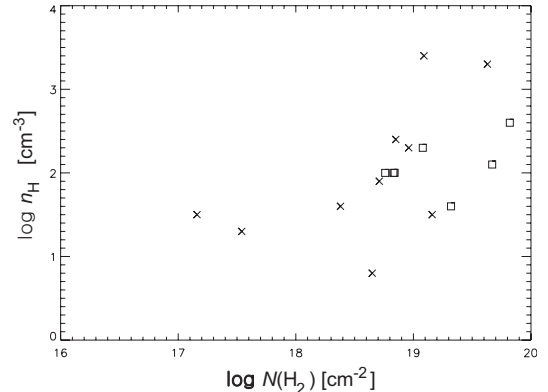


**Fig. 2.**— Model calculation results (see Paper I) of  $\log N(4)/N(0)$  vs.  $\log f$  for three values of  $n_{\text{H}}$  (black plus:  $10 \text{ cm}^{-3}$ , black asterisk:  $100 \text{ cm}^{-3}$ , and black diamond signs:  $1000 \text{ cm}^{-3}$ ) using  $T = 100 \text{ K}$ ,  $y_f = 1$ ,  $I_{\text{UV}} = 0.1\text{--}1000$ , and  $\log N(\text{H}_2) = 14\text{--}19 \text{ cm}^{-2}$ . The BEFS and *FUSE* (Gillmon et al. 2006) observational results from Table 2 are overplotted as red X and red square signs, respectively.

$\text{H}_2$  formation rate  $R$  to be  $3 \times 10^{-16}$ , which is about 10 times the average interstellar value (see details in the Paper I). The BEFS results shown in Table 4 are plotted as red cross signs and the *FUSE* high-latitude survey results observed by Gillmon et al. (2006) are plotted as red squares in Fig. 2. Note that only 7 of the 45 targets in Gillmon et al. (2006) have measured  $N(4)$  column densities. The models reproduce the observational results quite well.

Using these models, we have derived  $I_{\text{UV}}$  and  $n_{\text{H}}$  for our targets and the *FUSE* targets plotted in Fig. 2. As shown in Table 5, the derived incident UV intensity  $I_{\text{UV}}$  ranges from 0.4 (HD 36402) to 158 (HD 219188) times the average interstellar value. It is interesting to note that most sight lines have higher UV intensities than the average value near the Sun. The hydrogen density  $n_{\text{H}}$  for most sight lines in Table 5 is  $\sim 100 \text{ cm}^{-3}$ .

Note that the smallest value is  $6.3 \text{ cm}^{-3}$  toward HD 36402 and the largest is  $2.5 \times 10^3 \text{ cm}^{-3}$  toward HD 219188. HD 36402 is an LMC star that has been observed many times because of its interesting high-velocity absorption components around  $+150 \text{ km s}^{-1}$  (Savage & de Boer 1981; Wakker 2001). In this study, we find that, beside the  $11 \text{ km s}^{-1}$  component, there is another low-velocity component at  $0 \text{ km s}^{-1}$  toward HD 36402, which is a low-density gas with a low incident UV intensity. In contrast, the low-velocity ( $-3.7 \text{ km s}^{-1}$ ) component in the spectrum of HD 219188 represents an active ( $T_{01} = 211 \text{ K}$ ,  $T_{\text{ex}} = 810 \text{ K}$ ), dense ( $n_{\text{H}} = 2.5 \times 10^3 \text{ cm}^{-3}$ ) region. Based on the correlation between the infrared brightness and the measured  $21 \text{ cm H I}$  emission data presented in Desert, Bazell, & Boulanger (1988), Ryu et al. (2000) indicated that the line of sight toward HD 219188 is lo-



**Fig. 3.**— We have plotted  $\log N(\text{H}_2)$  vs.  $\log n_{\text{H}}$  for the BEFS (cross symbols) and the *FUSE* (square symbols) results from Table 3 and 5 to see the relation between the hydrogen density and the  $\text{H}_2$  column density. Only clouds with  $\log N(\text{H}_2) > 18.7 [\text{cm}^{-2}]$  have  $n_{\text{H}} > 100 \text{ cm}^{-3}$ .

cated at the "outskirts" of the high-latitude cirrus dust clouds, which is consistent with our dense hydrogen density. There is no direct evidence of the active environment for the LV component toward HD 219188, but for reference, Welty (2007) analyzed a weak and peculiar intermediate-velocity (IV) component at  $-38 \text{ km s}^{-1}$ , which has a time-variable column density.

Finally, we represent the relation between the hydrogen density and the  $\text{H}_2$  column density in Figure 3. The BEFS and the *FUSE* data are plotted as cross and square symbols, respectively. Only clouds with  $\log N(\text{H}_2) > 18.7 [\text{cm}^{-2}]$  have  $n_{\text{H}} > 100 \text{ cm}^{-3}$ . This means that a minimum hydrogen density is needed to form a translucent molecular cloud, consistent with the results of Spitzer & Jenkins (1975; see their Fig. 4). We do not compare  $n_{\text{H}}$  with the total hydrogen density  $N(\text{H})$ , because the neutral hydrogen column density  $N(\text{H I})$  includes all the hydrogen atoms along the line of sight.

#### IV. SUMMARY

We present an analysis of 10 interstellar  $\text{H}_2$  absorption components observed by the BEFS during the ORFEUS-SPAS I (1995) and II (1996) missions. From the measured  $\text{H}_2$  column densities of each rotational level  $N(J)$ , we derive total hydrogen column densities  $17.16 \leq \log N(\text{H}_2) \leq 19.16 [\text{cm}^{-2}]$ , mean cloud temperatures  $37 \text{ K} \leq T_{01} \leq 211 \text{ K}$ , and excitation temperatures  $423 \text{ K} \leq T_{\text{ex}} \leq 810 \text{ K}$ . Using the relation between  $N(4)/N(0)$  and  $f$ , we derive  $I_{\text{UV}}$  and  $n_{\text{H}}$  not only for our targets, but also for 7 high-latitude *FUSE* targets. We find that  $I_{\text{UV}}$  ranges from 0.4 to 158 and  $n_{\text{H}}$  ranges from  $6.3$  to  $2.5 \times 10^3 \text{ cm}^{-3}$  for our targets. The relation between  $n_{\text{H}}$  and  $N(\text{H}_2)$  confirms that our results are self-consistent: only clouds with  $\log N(\text{H}_2) > 18.7 [\text{cm}^{-2}]$  have  $n_{\text{H}} > 100 \text{ cm}^{-3}$ , which means that a mini-

TABLE 4  
 PHYSICAL PARAMETERS<sup>a</sup>

| Star                      | $T_{01}$ [K]       | $T_{ex}$ [K]  | $\log f^b$       | $\log N(4)/N(0)$ |
|---------------------------|--------------------|---------------|------------------|------------------|
| HD 36402                  | $54 \pm 4$         | $524 \pm 31$  | $-1.78 \pm 0.07$ | $-4.85 \pm 1.04$ |
| HD 94473                  | $67 \pm 4$         | $688 \pm 28$  | $-1.75 \pm 0.07$ | $-3.46 \pm 0.22$ |
| HD 97991                  | $37 \pm 8$         | $423 \pm 90$  | $-2.80 \pm 0.16$ | $-3.41 \pm 0.37$ |
| HD 149881                 | $97 \pm 5$         | $524 \pm 29$  | $-1.38 \pm 0.06$ | $-4.09 \pm 0.01$ |
| HD 156110                 | $69 \pm 4$         | $653 \pm 39$  | $-1.24 \pm 0.04$ | $-4.67 \pm 0.01$ |
| HD 167756                 | $46 \pm 3$         | $605 \pm 47$  | $-3.35 \pm 0.05$ | $-2.76 \pm 0.02$ |
| HD 203664                 | $79 \pm 6$         | $559 \pm 83$  | $-1.53 \pm 0.08$ | $-4.21 \pm 0.85$ |
| HD 214080                 | $59 \pm 4$         | $688 \pm 32$  | $-1.93 \pm 0.07$ | $-4.02 \pm 0.20$ |
| HD 219188                 | $211 \pm 14$       | $810 \pm 136$ | $-1.38 \pm 0.09$ | $-3.24 \pm 0.21$ |
| HD 220582                 | $82 \pm 5$         | $553 \pm 54$  | $-0.67 \pm 0.06$ | $-3.84 \pm 0.18$ |
| ESO 141-G55 <sup>c</sup>  | $144^{+184}_{-47}$ | $406 \pm 317$ | -1.12            | -4.26            |
| HS 0624+6907 <sup>c</sup> | $100^{+34}_{-18}$  | $498 \pm 34$  | -0.76            | -3.90            |
| Mrk 116 <sup>c</sup>      | $71^{+16}_{-12}$   | $437 \pm 82$  | -1.06            | -4.06            |
| Mrk 335 <sup>c</sup>      | $92^{+27}_{-14}$   | $434 \pm 56$  | -1.32            | -4.21            |
| Mrk 1095 <sup>c</sup>     | $121^{+107}_{-39}$ | $501 \pm 129$ | -1.90            | -3.34            |
| NGC 7469 <sup>c</sup>     | $71^{+16}_{-11}$   | $389 \pm 35$  | -0.71            | -4.51            |
| VII Zw 118 <sup>c</sup>   | $108^{+48}_{-24}$  | $552 \pm 80$  | -1.43            | -3.98            |

<sup>a</sup> Quoted errors are calculated from the uncertainties shown in Table 3.

$$^b f = \frac{2N(\text{H}_2)}{[N(\text{HI})+2N(\text{H}_2)]}.$$

<sup>c</sup> High-latitude *FUSE* data from Gillmon et al. (2006)

mum hydrogen density is required to form a translucent molecular cloud.

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TABLE 5  
DERIVED PHYSICAL PARAMETERS

| Object                    | ( $\log n_{\text{H}}/I_{\text{UV}}$ ) | $\log I_{\text{UV}}$ | $\log n_{\text{H}} [\text{cm}^{-3}]$ |
|---------------------------|---------------------------------------|----------------------|--------------------------------------|
| HD 36402                  | 1.2                                   | -0.4                 | 0.8                                  |
| HD 94473                  | 0.9                                   | 1.5                  | 2.4                                  |
| HD 97991                  | 0.8                                   | 0.5                  | 1.3                                  |
| HD 149881                 | 1.3                                   | 1.0                  | 2.3                                  |
| HD 156110                 | 1.3                                   | 0.2                  | 1.5                                  |
| HD 167756                 | 0.5                                   | 1.0                  | 1.5                                  |
| HD 203664                 | 1.5                                   | 0.4                  | 1.9                                  |
| HD 214080                 | 1.0                                   | 0.6                  | 1.6                                  |
| HD 219188                 | 1.2                                   | 2.2                  | 3.4                                  |
| HD 220582                 | 1.7                                   | 1.6                  | 3.3                                  |
| ESO 141-G55 <sup>a</sup>  | 1.2                                   | 0.4                  | 1.6                                  |
| HS 0624+6907 <sup>a</sup> | 1.6                                   | 1.0                  | 2.6                                  |
| Mrk 116 <sup>a</sup>      | 1.6                                   | 0.7                  | 2.3                                  |
| Mrk 335 <sup>a</sup>      | 1.6                                   | 0.4                  | 2.0                                  |
| Mrk 1095 <sup>a</sup>     | 0.6                                   | 1.4                  | 2.0                                  |
| NGC 7469 <sup>a</sup>     | 0.6                                   | 2.1                  |                                      |
| VII Zw 118 <sup>a</sup>   | 1.5                                   | 0.5                  | 2.0                                  |

<sup>a</sup>High-latitude *FUSE* targets (Gillmon et al. 2006).

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