Molecular Hydrogen in the FUSE Translucent Lines of Sight: The Full Sample

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ABSTRACT

We report total abundances and related parameters for the full sample of the FUSE survey of molecular hydrogen in 38 translucent lines of sight. New results are presented for the “second half” of the survey involving 15 lines of sight to supplement data for the first 23 lines of sight already published. We assess the correlations between molecular hydrogen and various extinction parameters in the full sample, which covers a broader range of conditions than the initial sample. In particular, we are now able to confirm that many, but not all, lines of sight with shallow far-UV extinction curves and large values of the total-to-selective extinction ratio, $R_V = A_V/E(B-V)$ — characteristic of larger than average dust grains — are associated with particularly low hydrogen.
molecular fractions ($f_{H_2}$). In the lines of sight with large $R_V$, there is in fact a wide range in molecular fractions, despite the expectation that the larger grains should lead to less H$_2$ formation. However, we see specific evidence that the molecular fractions in this sub-sample are inversely related to the estimated strength of the UV radiation field and thus the latter factor is more important in this regime. We have provided an update to previous values of the gas-to-dust ratio, $N(H_{tot})/E(B-V)$, based on direct measurements of $N$(H$_2$) and $N$(H I). Although our value is nearly identical to that found with Copernicus data, it extends the relationship by a factor of 2 in reddening. Finally, as the new lines of sight generally show low to moderate molecular fractions, we still find little evidence for single monolithic “translucent clouds” with $f_{H_2} \sim 1$.

Subject headings: ISM: abundances — ISM: clouds — ISM: lines and bands — ISM: molecules — ultraviolet: ISM

1. Introduction

Molecular hydrogen is the most abundant molecule in the universe, and a detailed knowledge of H$_2$ is crucial for a full understanding of the physics and chemistry of the interstellar medium. A broad overview of interstellar H$_2$ is provided by Shull & Beckwith (1982), while a recent overview of chemical processes in diffuse and translucent clouds is provided by Snow & McCall (2006).

A major goal of the Far Ultraviolet Spectroscopic Explorer (FUSE) was a survey of molecular hydrogen in 45 lines of sight with an emphasis on interstellar clouds with as much extinction as possible. The extinctions covered the range of the so-called “translucent clouds” with $A_V$ in the range 1–5 mag. Within these limits, lines of sight were chosen from a variety of environments and dust characteristics. The first results from the study were presented by Rachford et al. (2002 [Paper I]).

Paper I contains the details regarding the previous history of H$_2$ observations and the rationale for the FUSE survey. Slightly more than one-half of the planned targets had been observed and analyzed and those lines of sight were detailed. A main finding was that in most cases a line of sight was likely composed of multiple clouds, suggesting a change in terminology to “translucent lines of sight” pending the clear identification of a high-extinction line of sight made up of one highly molecular cloud.

The main purpose of the present paper is to provide the community with the overall H$_2$ results for the full sample, as well as refine and strengthen some of the conclusions of Paper I. The additional lines of sight give us much better coverage of the variety of dust characteristics than the original partial sample and we emphasize those results. Also, we have taken advantage of the publication of the 2MASS All-Sky Survey of Point Sources (Skrustkie et al. 2006) to provide more reliable extinction parameters for the full sample.
The rest of the paper is organized as follows: in § 2 we describe the remaining target for the FUSE translucent H$_2$ survey, along with comments on the stars chosen; in § 3 we give the details of the observations, data reduction, and analysis; in § 4 we discuss the results and their implications; and we summarize the paper in § 5.

2. Target Selection and Stellar Properties

2.1. General Comments on the Sample

Specific information on the selection criteria is given in Paper I, which includes details on the FUSE programs containing the observed stars. In this paper, we report new H$_2$ results for observations towards 15 stars, whose basic parameters are listed in Table 1. In a few cases, the data quality was poor for the new targets, but we were able to obtain reasonable H$_2$ measurements.

While the overall observing program was very successful, for 7 out of the original 45 targets FUSE was unable to adequately observe the target, or not observe it at all, as follows. HD 37021 and HD 37061 are both very bright targets in the Orion molecular cloud and the lines of sight display unusual extinction characteristic of larger than normal dust grains. We had anticipated that the sensitivity of FUSE would decrease to the point where the UV fluxes would be safe, but that did not happen. HD 147889 is in the ρ Oph complex, which also shows unusual extinction in the same sense as the Orion targets. However, a dearth of suitable guide stars in the field prevented this observation from taking place. Fortunately, FUSE was able to observe nearby HD 147888 as noted below. Walker 67 (in open cluster NGC 2264) and HD 166734 are two targets on the high end of the extinction range we wished to cover, but both targets were fainter in the far UV than anticipated and FUSE did not collect enough counts in either observation for an adequate analysis. HD 94414 was also a faint target and had some data quality issues. HD 21483 was also not observed.

2.2. Stellar and Extinction Properties

We have generally applied the techniques of Paper I to determine the relevant extinction parameters for each line of sight, namely the color excess ($E(B-V)$), the total-to-selective extinction ratio ($R_V$), and the total visual extinction ($A_V$). However, in the interim between Paper I and the current paper we have made some improvements. Many of the authors of both papers have been involved in a major project to understand the diffuse interstellar bands (DIBs). Part of this project includes deriving a consistent set of extinction measures for the FUSE translucent lines of sight plus a much larger sample of reddened stars. This project has led to some modifications in the tabulated $V$ magnitudes, spectral types, and extinction values used for our FUSE sample. These modifications result in the best consistency between the translucent sample, our DIB project, and
the papers on chemical depletions in the translucent sample in which the two lead authors of the present paper were involved (Jensen, et al. 2005, 2007). We have thus not only provided extinction parameters for the new targets, but also the revised values for the targets from Paper I, and these values are given in Table 2.

The differences between the new procedure for determining extinction parameters and the original procedures in § 2.2 of Paper I are as follows. First, the values of $E(B-V)$ were homogenized as much as possible, which has led mostly to cosmetic changes from our values in Paper I. Two exceptions are HD 24534 and HD 110432, which are both emission-line stars where some of the observed reddening is likely circumstellar, and the $E(B-V)$ values we quote here are somewhat larger than those given in Paper I. However, these changes do not result in any significant changes in the overall results.

Our primary technique for determining $R_V$ involves fitting a functional form to color excess ratios at optical and IR wavelengths. This is based on the method of Martin & Whittet (1990), which we discuss in detail in Paper I. Subsequent to the completion of Paper I, the full version of the 2MASS All-Sky Survey of Point Sources (Skrutskie et al. 2006) became available which includes very high quality $JHK$ photometry for all of our sources. Thus, we have used these values in our derivation of $R_V$, which has significantly improved the quality, consistency, and completeness of extinction values in our sample. We also used correlations between $R_V$ and the wavelength of maximum polarization ($R_V = 5.6\lambda_{\text{max}}$, with $\lambda$ in $\mu$m; Whittet & van Breda 1978) and the far-UV rise in the extinction curve ($c_2 = -0.824 + 4.717R_V^{-1}$; Fitzpatrick 1999) as ancillary proxies for the photometric values, again as discussed in Paper I.

The listed uncertainties in the extinction parameters in Table 2 are necessarily estimates, but are mostly based on the scatter observed for that particular technique or correlation and the notion that systematic effects are likely important. For the $R_V$ values that did not come from an analysis of the IR photometry, and for the latter values when the fit appeared qualitatively reasonable, we assumed uncertainties of 0.3. In several cases, the IR photometry deviated from the expected relationship and we thus adopted larger error bars. However, in those cases, if at least one of the other two techniques for determining $R_V$ agreed with the IR method, we then adopted the IR value and used smaller error bars. Finally, when we did not have any $R_V$ information (only for HD 186994), we adopted the Galactic average value of 3.1 (Draine 2003). As can be seen in Table 2, in only 3 cases, HD 24534, HD 102065, and HD 186994 did we not use the $R_V$ derived from the IR photometry. HD 24534 is a Be star (as discussed below) for which we could not confirm the photometric value with other methods. The other two stars have $E(B-V) < 0.2$ for which we were concerned about the large relative effect that a small error in the color indices or spectral type will have on the photometric $R_V$. Published values of $R_V$ for HD 102065 are near 4.0 (Boulanger, et al. 1994; Paper I).

It is worth noting that as we pointed out in Paper I, the photometric method is the most direct and the other two methods are basically correlations between another parameter and $R_V$ derived
from IR photometry. Thus, it is not a surprise that there is generally excellent agreement between the three indicators. Of the 22 points with both photometric and polarimetric measurements only 4 disagree by more than 2 $\sigma$, and only an additional 3 disagree by more than 1 $\sigma$. The statistics comparing the photometric and extinction curve values for $R_V$ are nearly identical. One limitation with the polarimetric method is that it is poorly constrained for $R_V \gtrsim 4$ (Whittet & van Breda 1978; Figure 1). In fact, we do not derive $R_V > 3.9$ for any of our targets with this method, even when the other two methods give larger $R_V$. This is one reason we have not attempted to average together values from different methods.

There are two particular problems with the photometric method of determining $R_V$ that we wish to address. First, 7 of the stars in our sample are Be stars and thus have circumstellar material. Processes in this material skew not only the optical photometry via emission lines and continuous free-bound emission, but also optical polarization and IR photometry. The other issue is variability. Not only are Be stars generally variable, but there are other types of variable stars within the O and early B types.

In a similar context to ours, Bowen et al. (2008) discussed these issues as they related to determining extinction parameters for the FUSE survey of O VI in the Galactic disk. These targets generally had $E(B-V) \lesssim 0.4$. One advantage we have in the present survey is that our targets generally have $E(B-V) \gtrsim 0.4$. This is important because the greater the color excess, the smaller the relative error caused by variability, and variability is often small in this stellar temperature range. The Be stars are somewhat more problematic, although again we expect the fractional effects in our extinction parameters will be lessened for the more highly reddened stars, and most of the Be stars have small variability amplitudes (e.g. Hubert & Floquet 1998). Furthermore, issues like these are one reason that we have typically adopted relatively large errors for $R_V$. In fact, all 7 of the Be stars in our sample were flagged as not fitting the Martin & Whittet (1990) relation very well and thus were given particularly large errors, which were only reduced in the adopted $R_V$ if either of the other methods agreed with the photometric value. Still, because these values may be unreliable for Be stars, in some cases we have eliminated these stars when considering a particular correlation.

While preparing our present manuscript, Fitzpatrick & Massa (2005, 2007) published an updated version of their seminal work in parametrizing extinction curves. They slightly modified their parametrization of the UV portion of the extinction curves, and greatly expanded the sample of lines of sight, including a few from our sample which have not previously been analyzed. However, since other authors have published curves in the original 6-parameter scheme (Fitzpatrick & Massa 1986, 1988, 1990), an exclusive use of the new scheme would result in a significant decrease in the fraction of stars available in a self-consistent system. Thus, we have continued to use values based on the older parametrization which are given in Table 3 for our new targets. The key parameter for the present paper is $c_2$, the linear coefficient of the far-UV rise in the curve.

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1In addition to the 5 Be stars in Table 1, HD 24534 and HD 110432 from Paper I are also Be stars.
We note that Fitzpatrick & Massa (2005, 2007) also used 2MASS JHK photometry for the IR portion of the extinction curves, and derived $R_V$ for their sample using a technique similar to ours (Paper I). Indeed, there is an excellent match between our values and theirs, as expected.

2.3. Special line-of-sight characteristics

Many of the lines of sight are of special interest due to their location and/or environment. As in Paper I, we give a brief overview of each line of sight in the following sections, including the mention of particularly relevant values from Tables 1–3.

2.3.1. HD 37903

This star lies within the Orion molecular cloud and illuminates the reflection nebula NGC 2023. UV spectra indicate significant quantities of vibrationally excited H$_2$ along the line of sight (Meyer et al. 2001) and the FUSE spectrum confirms this. Meyer et al. (2001) concluded that the excitation was due to UV fluorescence in a dense area of gas within 1 pc of the star. The line of sight $R_V$ is above average and may be even larger within the dense material local to the star. While the UV extinction curve does not have a particularly unusual shape, it does show smaller than normal extinction at all wavelengths below 2500 Å (Fitzpatrick & Massa 1990).

2.3.2. HD 38087

This star illuminates the reflection nebula IC 435, with estimates that about one-quarter or less of the line-of-sight material is local to the star (Snow & Witt 1989). The line of sight shows far less than normal far-UV extinction as well as a significant shift of the 2175 Å bump to longer wavelengths (Fitzpatrick & Massa 1990). IR photometry indicates an exceptionally large total-to-selective extinction ratio, $R_V = 5.57$, consistent with the small far-UV extinction. Also, Witt, Bohlin, & Stecher (1986) found evidence for scattering associated with the 2175 Å interstellar feature. These data strongly suggest that larger than normal dust grains have developed in this presumably quiescent environment. Enhanced (but uncertain) depletions of manganese and zinc in the line of sight also suggest grain mantle growth (Snow & Witt 1989), while the abundances of oxygen (Jensen, et al. 2005) and nitrogen (Jensen, et al. 2007) are normal.

2.3.3. HD 40893

The extinction curve shows a relatively narrow and somewhat weak 2175 Å bump and slightly enhanced far-UV extinction (Jenniskens & Greenberg 1993). IR photometry also indicates an
abnormally small total-to-selective extinction ratio, $R_V = 2.46$.

2.3.4. *HD 41117, HD 42087, HD 43384*

These stars all lie within the Gem OB1 association and sample a roughly 2.5 × 4.5 degree field in the foreground of this association. Extinction curves are available for the first two stars and are very similar and normal, and the other extinction measures for all three stars are similar and near average. HD 41117 and HD 42087 are Be stars and the uncertainties in the photometric $R_V$ are large, but there is excellent agreement with the other two techniques.

2.3.5. *HD 46056, HD 46202*

These stars lie within a quarter-degree of each other in open cluster NGC 2244 within the Mon OB2 association and the lines of sight show very similar extinction parameters. In both cases, $R_V$ is slightly smaller than average and the amount of far-UV extinction is above average. Also, the 2175 Å bumps are relatively weak and narrow. As will be shown, the H$_2$ parameters are indeed nearly identical.

2.3.6. *HD 53367*

The line of sight to this star shows a relatively large amount of reddening. IR photometry suggests a smaller than normal value of $R_V$, but this is a Be star and the value is very uncertain. There is no published extinction curve or polarization data to verify the value of $R_V$.

2.3.7. *HD 147888*

This star is also known as ρ Oph D and lies within the ρ Oph cloud complex, which is well known for having unusual dust characteristics. All three methods of assessing $R_V$ result in significantly above average values (~4–5) and the extinction curve (Fitzpatrick & Massa 1990) shows a correspondingly small far-UV extinction. This particular line of sight has small reddening relative to other stars in this complex, and when combined with the shallow far-UV extinction curve, it was accessible to *FUSE* even though the star is of relatively late spectral type and thus has a small UV flux.
2.3.8. HD 149404

This star is relatively bright optically and there have been many studies of the material along the line of sight. Despite the significant number of optical and mm-wave observations, a UV extinction curve has not been published for this star. The photometric value of $R_V$ is uncertain as HD 149404 is a Be star. However, polarization data also indicates a normal value of $R_V$.

2.3.9. HD 152236

This star, also known as $\zeta^1$ Sco, is part of the Sco OB1 association. The star is relatively bright given the amount of extinction and thus provides one of several lines of sight with $A_V \approx 2$ that were easy for FUSE to observe. The UV extinction curve is normal. It is a Be star, but polarization and extinction curve data confirm the apparently normal photometric value of $R_V$.

2.3.10. HD 164740

Also known as Herschel 36, this star excites a compact H II region within the Lagoon Nebula (M8, NGC 6523) known as the Hourglass (Thackeray 1950, Wolff 1961). The value of $R_V$ for this line of sight, 5.36, is exceptionally large and a correction for material in the foreground of M8 would give an even larger $R_V$ (Hecht et al. 1982). The unparametrized far-UV extinction curve published by Hecht et al. (1982) is also exceptionally shallow, and the new parametrization by Fitzpatrick & Massa (2007) gives a similar result. That characteristic allowed us to take the first UV spectrum of this interesting line of sight at sufficient resolution and S/N to investigate interstellar abundances despite the large total extinction. This spectrum shows a number of unusual and interesting features which will be covered in a separate paper (B. L. Rachford, in preparation, 2008), but we will give the overall $H_2$ results here.

2.3.11. HD 179406

Also known as 20 Aql, this star shines through apparently typical diffuse cloud material and lies toward the lower end of the amounts of extinction covered in this study. However, given the small extinction, the abundances of carbonaceous molecules are relatively large indicating that this line of sight may sample a core of denser material (Hanson, et al. 1992). Fitzpatrick & Massa (2007) included this target in their updated UV extinction curve parametrization work, which shows a stronger than normal 2175 Å bump, but is otherwise normal.
2.3.12. HD 186994

This star was primarily observed because it is bright and had been previously observed with *Copernicus*. Despite its relatively large distance (∼2500 pc) the quantity of interstellar material along the line of sight is small. Extinction information is limited for this star simply because the small amount of reddening makes it difficult to properly analyze the UV extinction curve or to determine $R_V$. (In fact, this star has been used as a lightly reddened comparison star in extinction studies; e.g., Sasseen et al. 2002.) The H$_2$ column density observed with *Copernicus* was quite small, log N(H$_2$) = 19.59 (Savage et al. 1977) and we confirm this result.

3. Observations and data analysis

Table 4 gives information on our FUSE observations for the new targets. For all targets with multiple integrations, we performed a shift-and-coadd procedure to combine the data for each detector segment, but did not combine data from different segments. Note that in two cases (HD 179406 and HD 186994), we obtained multiple observations of the target. In both cases, this was required due to the brightness of the targets as a precaution against saturation of the detector. A very short preliminary observation was obtained from which the true flux was determined before spending time on the full observation. The preliminary observation represented a non-trivial fraction of the total data, so we included both datasets in the final co-added spectra.

We originally planned to use spectra that were uniformly processed with version 2.4 (or later) of the CALFUSE pipeline, including a revision of the column densities in Paper I that were measured from earlier reductions. However, in comparing results from differing versions of CALFUSE, we have not seen significant differences in the derived column densities, presumably because the extremely broad profiles are not affected by subtle changes in the algorithms. In only a few cases did the differences approach the value of the 1-σ uncertainty. Thus, we have not revised the older values, nor used CALFUSE versions beyond 2.4 for the newer targets.

We used the same measurement techniques described in Paper I and we will only give a very brief overview of those techniques. We fitted H$_2$ line profiles to the Lyman series (4,0), (2,0), and (1,0) ro-vibrational bandheads, including the $J = 0$, 1, and 2 lines. Weaker lines from higher rotational states and other interstellar species were fitted and removed from the broad bandhead profiles. Our profile fits included the effects of overlapping wings from adjacent bandheads as the $J = 0$ and 1 profiles are heavily damped and extremely broad. The $J = 2$ lines from these bandheads are often strong enough to show damping wings as well, and these lines had to be included due to blending with the broad $J = 0$ and 1 profiles.

At most, we obtained 9 independent measurements of the $J = 0$–2 column densities from the combinations of three ro-vibrational bands and one to four detector segments covering each band. Poor data quality, severe stellar interference in a particular H$_2$ band, and/or problems during the
observation itself occasionally led to fewer suitable combinations of bands and detector segments. The differences from one band/segment combination to another were generally considerably larger than the formal fit uncertainties, so we averaged each individual measurement and used the sample standard deviation as our formal uncertainty.

4. Results and Discussion

4.1. Overall comments

Table 5 gives our primary results for the lines of sight. The H$_2$ column densities were measured directly from the spectra as already described. We also include two derived quantities, the hydrogen molecular fraction ($f_{\text{H}_2}$), and the rotational temperature ($T_{01}$) for each line of sight.

The hydrogen molecular fraction is defined in terms of the molecular and atomic hydrogen column densities as

$$f_{\text{H}_2} = \frac{2N(H_2)}{2N(H_2) + N(\text{HI})}.$$  \hspace{1cm} (1)

The rotational temperature (in Kelvin) is determined by applying the Boltzmann equation to the ratio of the column densities in the first two rotational states, yielding

$$\frac{N(1)}{N(0)} = 9e^{-171/T_{01}}.$$  \hspace{1cm} (2)

Solving for the temperature and expressing the column densities as base-10 logarithms gives

$$T_{01} = \frac{74.0}{\log N(0) - \log N(1) + 0.954}.$$  \hspace{1cm} (3)

As in Paper I, we generally interpret the ratio between $N(1)$ (ortho-H$_2$) and $N(0)$ (para-H$_2$) as the kinetic temperature on the assumption that collisions with H$^+$ (and H3$^+$ when enough is present) dominate over other processes in controlling this ratio.

There is evidence that under some circumstances ortho-H$_2$ can be rapidly converted to para-H$_2$ on grains (Le Bourlot 2000). In this case, the $N(1)/N(0)$ ratio becomes lower, yielding a lower rotational temperature. This process appears to be more likely at the low temperatures in the core of a relatively dense and opaque cloud (Shaw et al. 2005). The fact that we seem to be seeing multiple diffuse clouds along the lines of sight (Paper I) suggests that this process may not important for our sample.

Shaw et al. (2005) have modeled the physical conditions in one of our lines of sight from Paper I, HD 185418. Their model includes the Le Bourlot (2000) treatment of the ortho to para conversion
process. Their derived kinetic temperature for the gas was about 25% lower than our derived $T_{01} = 101 \pm 14$ K. This line of sight has the largest $T_{01}$ of our entire sample, and the gas density is relatively low ($n_H = 27$ cm$^{-3}$, but Sonnentrucker et al. 2003 find an even lower value of $n_H = 6.3$ cm$^{-3}$).

Lacking a complete knowledge of whether or not our lines of sight may have non-thermal $N(1)/N(0)$ ratios, we will generally assume that the measured $T_{01}$ values correlate with kinetic temperature in some manner. However, this potential uncertainty should be kept in mind in the interpretation of correlations of $T_{01}$ with other parameters.

Overall, the second half of the sample shows column densities, molecular fractions, and temperatures similar to those in Paper I. The primary difference is the presence of a sample of lines of sight with large extinction, small $N$(H$_2$), and large $R_V$, which we will discuss in detail in § 4.3.

### 4.2. General correlations with reddening

We have updated several correlations with reddening from Paper I using the new data. In Figure 1 we present a plot of the H$_2$ column density versus color excess (unlike Figure 2 in Paper I, we give $N$(H$_2$) on a linear scale). While this plot shows the expected increase in H$_2$ as we look through more material, it also reflects that our targets probe a wide variety of environments in that we usually see a range of column densities at a given color excess.

One particularly important relationship we can investigate with the complete dataset is the gas-to-dust ratio. Using Copernicus data, Bohlin, et al. (1978) found $N$(H$_{tot}$)/$E$(B−V) = 5.8 × 10$^{21}$ atoms cm$^{-2}$ mag$^{-1}$. In Figure 2, we present plots of $N$(H$_{tot}$) versus $E$(B−V). In the upper panel we include the Bohlin et al. Copernicus data and our FUSE data. In the lower panel we only include our FUSE data for lines of sight with direct determinations of $N$(H I) and $N$(H$_2$), and also excluded Be stars as the color excesses might be overstated due to the circumstellar emission. This should give the most homogeneous sub-sample possible that covers a broad range in color excess. When constrained to pass through the origin, our error-weighted best-fit slope is $(5.94 \pm 0.37) \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$, essentially identical to the Copernicus value for less reddened lines of sight. The solid line in both panels is the best fit, and it is worth noting that many of the most discrepant FUSE points in the upper panel are Be stars, which are removed in the bottom panel.

For reference, we have also included an unconstrained fit in these panels which furthermore does not include the low-reddening point at $E$(B−V) = 0.17 (HD 186994). This illustrates the significance of constraining the fit with points at small reddening. Clearly this line is not a good fit to the low-extinction Copernicus points. One possibility is that the high-extinction sample has a different slope than the low-extinction sample. This would represent a difference in the gas-to-dust ratio that might indicate a change in dust properties in the clouds with higher extinction. Such a difference is not clearly seen in our data. The slope of the dashed line is $(4.2 \pm 1.7) \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$, less than the value for the constrained fit, but with large enough uncertainty to be
consistent with the constrained fit.

We performed the same analysis for the total visual extinction, $A_V$, which is simply the product of $E(B-V)$ and $R_V$. Figure 3 shows panels corresponding to the ones shown in Figure 2. Again, we have fitted a line to our “best” sub-sample in the lower panel, which yields $N(H_{tot})/A_V = (2.15 \pm 0.14) \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$. This value is nearly identical to a simple division of $5.94 \times 10^{21}$ by the average $R_V = 2.93$ for this sub-sample; the latter value is slightly less than the galactic average of 3.1 (Draine 2003). Again, excluding HD 186994 and not constraining the fit to pass through the origin gives a slightly smaller slope of $(1.50 \pm 0.43) \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$. Visually, there is a hint of a slope change in the $A_V = 1.5–2.0$ interval in the upper panel, but with so few reliable points with $A_V \geq 2$, such a trend is not clear.

As Figure 4 shows (an update of Figure 5 in Paper I), there appears to be a weak inverse correlation between rotational temperature and reddening. However, it is critical to note that much of this trend disappears if we were to exclude the Copernicus data points with $N(H_2) < 10^{20}$ cm$^{-2}$. In the region of overlap with Copernicus data, the FUSE lines of sight show smaller average temperatures, while the FUSE data for large reddening do not deviate from the similar data for small reddening. The mean $T_{01}$ for our entire FUSE sample is 67 K with a standard deviation of 14 K. This result is similar to other studies, including the $< T_{01} > = 86 \pm 20$ K from the FUSE Galactic disk survey (J. M. Shull et al., in preparation). However, the $T_{01}$ distribution of our sample is not normal, having a general rise in frequency up to around 75–80 K, and just a few stars with temperatures above that; the latter fact can easily be seen in Figure 4.

In principle, the larger color excesses could be associated with denser clouds, which in turn might be expected to show lower temperatures. In Paper I we noted a correlation between the rotational temperature and the fractional abundance of the CN radical, the latter of which is a good density indicator (Federman, et al. 1984). However, as we discussed in Paper I, the lines of sight in the translucent sample seem to mostly be made up of multiple diffuse clouds. Thus, while the slight trend is in the right direction to suggest that we are probing somewhat denser clouds in the FUSE sample, this conclusion is somewhat speculative.

Figure 5 (an update of Figure 7 in Paper I) shows a similar pattern to Figure 1 in that once $H_2$ becomes self-shielded and relatively abundant, the molecular fraction covers nearly the entire possible range at any given reddening. Again, part of this may be a selection effect as the lines of sight were chosen to sample a variety of environments. However, it is notable that even with the additional sample we have not found a line of sight with $f_{H_2} > 0.8$. In fact, as seen in Table 5, the new lines of sight preferentially have relatively small $f_{H_2}$ given the large extinctions.
4.3. The high $R_V$ sample

4.3.1. Significance

An important aspect of the completed translucent sample is that we have determined the molecular hydrogen column densities for several lines of sight with particularly large values of $R_V$ combined with larger $A_V$ and total hydrogen column densities than previous samples. In some cases, these lines of sight show unusually small molecular fractions and are of particular interest because of the relationship between dust parameters and molecular hydrogen formation and destruction.

Snow (1983) first investigated the possibility that $\text{H}_2$ abundances may be inversely correlated with grain size. Larger grains, through the coagulation of small grains, provide less surface area per unit dust mass. With less surface area available, the $\text{H}_2$ formation rate should be diminished. Using the compilation of Copernicus data of Bohlin et al. (1978), Snow demonstrated that the mean molecular fraction in the $\rho$ Oph cloud was a factor of 2.6 less than the rest of the sample.

Cardelli (1988) explored the related issue of the relationship between $\text{H}_2$ abundances and $R_V$. The $\text{H}_2$ abundances again came from Bohlin et al. (1978), while the values of $R_V$ came from an analysis of IR photometry similar to that which we have applied in the present work.

Cardelli’s sample displayed an inverse relationship between the $\text{H}_2$ to $A_V$ ratio and $R_V$, with a weaker, but similar dependence of the hydrogen molecular fraction and $R_V$. When splitting the Copernicus lines of sight at $R_V = 3.5$, the high $R_V$ group had an average molecular fraction of approximately a factor of 2.5 less than the low $R_V$ group. As $R_V$ is thought to be positively correlated with grain size (or grain size distribution) this result provides further support for the role of grain size in regulating the $\text{H}_2$ abundance. Furthermore, the large values of $R_V$ are associated with smaller than normal far-UV extinction, which allows more photodissociating radiation to penetrate the interstellar clouds and provides further reduction in the hydrogen molecular fraction. In fact, it appears that only the lines of sight with the largest $R_V$ have extinction curves that deviate in a consistent manner from average (Fitzpatrick & Massa 2007).

In Paper I, we had minimal coverage of high $R_V$ lines of sight in our FUSE sample, but the newly added targets improve the situation. In Figure 6 we show the relationship between $f_{\text{H}_2}$ and $R_V$ for the FUSE and Copernicus samples. This provides a major update to Figure 8 in Paper I as we have also included the Copernicus sample, using 2MASS photometry to derive the values of $R_V$ as with the FUSE sample.

Interestingly, using the Spearman rank correlation coefficient, at best we only see an anti-correlation between molecular fraction and $R_V$ at about the 1 $\sigma$ level whether or not we restrict the sample to the best determinations of either parameter. A more significant trend (3 $\sigma$) appears when considering the $\text{H}_2$ to $A_V$ ratio versus $R_V$ similar to Cardelli’s result, but as he discussed, this division works best when one can make the assumptions of similar average densities in the various clouds and that most of the extinction occurs in the regions where $\text{H}_2$ is significantly present.
However, it is not clear that this is an appropriate way to look at the FUSE translucent sample. In particular, much of the trend disappears if we exclude lines of sight with $A_V > 2$. As discussed in Paper I, we believe that most of our lines of sight are sampling multiple clouds that may be spread out in space, and thus may have a variety of conditions.

We wish to consider in more detail the lines of sight with $R_V > 4$, which are labeled in Figure 6, split equally between the FUSE and Copernicus samples. We will ignore the Copernicus target HD 10516 ($\phi$ Per) due to the very large uncertainty in $R_V$ and small extinction ($E(B-V) \approx 0.2$ and $A_V \sim 1$). We will thus focus our discussion on the five remaining lines of sight with high $R_V$ and large extinction.

Detailed modeling of an individual line of sight is complex and requires a large amount of data to constrain the model, although this has been done for a few favorable lines of sight from Paper I (Rachford et al. 2001; Sonnentrucker et al. 2003). Barring such an analysis, we can get a sense of the strength of the local UV radiation field using the high $J$ lines of H$_2$, and thus an estimate of the importance of photodissociation. A preliminary analysis of lines from $J = 2$ up to the highest observable levels in a line of sight yields column densities that can be used to estimate the amount of radiative pumping to these levels. This has proven challenging in many of the translucent lines of sight due primarily to data quality and the resulting difficulty in measuring weak lines and properly interpreting saturated lines. This is particularly acute in these heavily reddened lines of sight as in many cases the S/N rapidly decreases with decreasing wavelength. Also, the strengths of other lines are typically larger than in less reddened lines of sight which causes more interference with the high-$J$ lines. However, we have enough information for most of these five lines of sight to use $N(6)$ and $N(7)$ as potential indicators of the strength of the radiation field. These lines are typically weakly saturated and not as difficult to interpret as the stronger lines from lower rotational states, when the data quality permits their detection or the derivation of well constrained upper limits. For reference, the column densities for HD 110432 (Rachford et al. 2001) were $\log N(6) = 14.20 \pm 0.20$ and $\log N(7) = 13.25^{+1.25}_{-1.00}$ for a radiation field that was modeled as twice the strength of the average curve of Draine (1978). Particle density also plays a significant role in controlling H$_2$ excitation, so we should look at the high $J$ column densities as an indicator of the strength of the radiation field, but not as a definitive measurement.

4.3.2. HD 38087

HD 38087 has $f_{H_2}$ greater than half, the largest of the group, but this value is uncertain because we do not have a direct measurement of interstellar N(H I) due to the very late spectral type. Fitzpatrick & Massa (1990) report $\log N$(H I) = 21.48 from Lyman $\alpha$. However, at spectral type B5 V, the interstellar line is strongly contaminated or even dominated by the stellar line (Shull & van Steenberg 1985; Diplas & Savage 1994).

Atomic hydrogen column density is highly correlated with the strength of certain diffuse in-
terstellar bands, including \( \lambda 5780 \) (S. D. Friedman et al. 2008, in preparation; see Herbig 1993 or Welty et al. 2006 for similar correlations), and applying this correlation to HD 38087 gives \( \log N(H I) = 21.08 \), similar to our quoted value and which would only reduce the derived molecular fraction from 0.52 to 0.42. Thus, it seems likely that this line of sight is genuinely rich in molecules.

We have already noted in § 2.3.2 that this line of sight samples a quiescent environment where grain growth might be expected to occur (Snow & Witt 1989). However, only about 25% of the line of sight material is thought to be in the reflection nebula. The extinction curve indicates that the interstellar material should be relatively transparent to photodissociating far-UV radiation – if such radiation exists at the cloud location. HD 38087 itself is of rather late spectral type, so it may not contribute significantly to the far-UV radiation field at the location of the bulk of the line of sight material. However, the \textit{FUSE} spectrum clearly shows \( H_2 \) lines up to the \( J = 7 \) level and we derive a logarithmic column density of about 15.0 in that level, a very large value that implies a significant excitation mechanism.

It is important to note that even a “large” quantity of excited \( H_2 \) corresponds to a very small fraction of the total \( H_2 \) column density. One simply needs a particularly high excitation temperature to produce a relatively “flat” rotational distribution with a high percentage of the \( H_2 \) in the excited states, while keeping the total column density of this material several orders of magnitude below the \( 10^{20-21} \, \text{cm}^{-2} \) totals seen in the translucent lines of sight. It thus may be the case that the excited \( H_2 \) is produced in the reflection nebula, while the bulk of the low-excitation \( H_2 \) is found farther from the star where photodissociation is not as important.

4.3.3. HD 148184

The other line of sight from the high \( R_V \) sample with significant molecular material is HD 148184 (\( \chi \) Oph), with \( f_{H_2} = 0.33 \) (Bohlin et al. 1978). This star is about 5 degrees from the \( \rho \) Oph grouping and samples material from the general Sco-Oph cloud complex. The \textit{Hipparcos} parallax is 6.21 ± 0.23 mas (van Leeuwen 2007), corresponding to a distance of 161 ± 6 pc, which places it near the distant edge of the interstellar material. The star itself has spectral type B2 IVpe and may contribute significant UV radiation to the material in the line of sight, nearly all of which is likely associated with the cloud complex. However, in the overall sense this portion of the complex is not as highly populated by B-type stars as in the immediate \( \rho \) Oph area.

This star was observed with \textit{Copernicus} at high resolution, but with very limited wavelength coverage. Frisch (1980) reported upper limits for two \( J = 6 \) lines, yielding an upper limit of \( \log N(6) < 14.33 \). Thus, there does not appear to be an unusually large source of excitation.

One final important consideration for this star is that it is the only one of the five which is a Be star and thus the caveats given in § 2.2 apply. As the large error bar in Figure 6 implies, we found the color excesses to be a poor fit to the Martin & Whittet (1990) relation. There is no available extinction curve for this star. The wavelength of maximum polarization is 0.55 \( \mu \text{m} \) (Coyne et al.
1974), corresponding to \( R_V = 3.08 \). It is thus possible that this line of sight should not be in the high \( R_V \) group.

### 4.3.4. The \( \rho \) Oph cloud: \( \rho \) Oph A & D

The \( \rho \) Oph cloud has long been known as a location which exhibits large \( R_V \) and larger than normal dust grains (Carrasco, et al. 1973; Whittet 1974). The name \( \rho \) Oph is applied to four stars within a few arcminutes of each other labeled A through D. The A component (HD 147933) is the brightest star in both the visible and UV and was observed by \textit{Copernicus}. The D component (HD 147888) is part of the present \textit{FUSE} sample. Improved \textit{Hipparcos} distances to these stars (van Leeuwen 2007) have been used as part of a study of the distribution of interstellar material in the cloud by Snow et al. (2008). These distances are \( 111_{-10}^{+12} \) pc for \( \rho \) Oph A and \( 125_{-11}^{+14} \) pc for \( \rho \) Oph D. The overall analysis indicates that both stars are in front of the denser material that is sampled by the more distant and more heavily obscured line of sight to HD 147889 that we had hoped to study with \textit{FUSE} as noted in § 2.1.

The uncertainties in the \textit{Copernicus} measurements of \( N(\text{H}_2) \) and \( N(\text{H I}) \) for \( \rho \) Oph A are relatively large, but still strongly indicate a small molecular fraction. Unfortunately, the spectral type of \( \rho \) Oph D (B5 V) is late enough that the interstellar Ly\( \alpha \) line will be severely contaminated by the stellar line, as with HD 38087, thus \( N(\text{H I}) \) is very uncertain. Cartledge et al. (2004) indirectly estimated a value \( \log N(\text{H}_{\text{tot}}) = 21.73 \pm 0.09 \) based on measurements towards nearby \( \rho \) Oph A. For this paper, we have used our preferred method for stars later than spectral type B2, namely, applying the Bohlin et al. (1978) \( N(\text{H}_{\text{tot}})/E(B - V) = 5.8 \times 10^{21} \) atoms cm\(^{-2}\) mag\(^{-1}\) value we discuss in § 4.2. This gives \( \log N(\text{H}_{\text{tot}}) = 21.44 \), much smaller than the value for \( \rho \) Oph A, but in excellent agreement with the correlation between \( N(\text{H I}) \) and the equivalent width of the \( \lambda 5780 \) DIB discussed in § 4.3.2. It should be noted that \( \rho \) Oph A is well known as a line of sight with a larger than normal gas-to-dust ratio (e.g. Bohlin et al. 1978). For that reason, our derived value of \( \log N(\text{H}_{\text{tot}}) \) for \( \rho \) Oph D may also be too low. A larger value of \( N(\text{H}_{\text{tot}}) \) would produce an even smaller molecular fraction than the \( f_{\text{H2}} = 0.21 \) depicted in Figure 6. Thus, it appears that the molecular fractions toward both stars are relatively small given the amount of reddening and extinction.

There are a number of B-type stars in the vicinity and the UV radiation field is thought to be strong in this area despite the lack of O-type stars (e.g., Kulesa et al. 2005). Our preliminary analysis of the high \( J \) lines in the \textit{FUSE} spectrum of \( \rho \) Oph D reveals no conclusive detections beyond \( J = 6 \), from which we derive an uncertain \( \log N(6) = 14.3 \). This is comparable to that found toward HD 110432 (Rachford et al. 2001) which was modeled with a radiation field twice the interstellar average curve of Draine (1978).
4.3.5. Herschel 36

As noted in § 2.3.10, HD 164740, better known as Herschel 36, lies within the Lagoon Nebula (M8) in a region with recent and ongoing star formation. The molecular fraction (0.03) is the smallest known for a line of sight with $E(B-V) > 0.3$. It is believed that some of the intervening material lies close to the star and is thus subject to the very strong far-UV radiation field of the late O-type star. In fact, our FUSE spectrum shows extreme H$_2$ excitation, including numerous lines from vibrationally excited states (B. L. Rachford, in preparation) demonstrating the likelihood of significant H$_2$ lying close to the star and the resultant exposure to a large far-UV flux. Furthermore, the exceptionally small far-UV extinction will allow the radiation from the O-type stars in M8 to influence a greater distance along the line of sight. Thus, while this line of sight samples a complicated environment, it is plausible to assume that the radiation field is contributing to the small line of sight molecular fraction.

4.3.6. Overall properties of this sample

The 5 lines of sight were chosen for having evidence for larger than normal grains, thus providing smaller than normal H$_2$ formation rates per unit dust mass. Also, the far-UV extinction is small which allows greater than normal penetration of the photodissociating radiation. However, there remains a large range in molecular fractions that spans most of the total range we see in the overall translucent sample.

In formation-destruction equilibrium, the hydrogen molecular fraction will be proportional to the factors controlling formation, which are density ($n_H$) and the formation rate coefficient ($R$), and inversely proportional to the far-UV radiation field which controls destruction. For the moment, we will focus on the last point.

There seems to be some evidence that the strength of the local radiation field is responsible for this range, particularly when considering the ρ Oph cloud and Herschel 36. However, the line of sight toward HD 38087 is an exception. As already noted, the distribution of material along this line of sight likely also plays a significant role.

Interestingly, these lines of sight have small H$_2$ rotational temperatures. In Figure 7 (an update of Figure 9 in Paper I) we show the relationship between molecular fraction and rotational temperature. In Paper I, we highlighted the high $f_{H2}$, low $T_{01}$ lines of sight. Much rarer are lines of sight with low $f_{H2}$ and low $T_{01}$. In fact, ρ Oph A and D and Herschel 36 are the only lines of sight in the Copernicus/FUSE sample with $f_{H2} < 0.2$, $T_{01} \leq 60$ K, and $E(B-V) > 0.2$ (or log N(H) > 21.1).

In contrast to the high $R_V$ lines of sight with small molecular fraction and low temperature, there are numerous lines of sight with normal or low values of $R_V$ that have small molecular fractions and higher than normal temperatures, particularly within the Copernicus sample. Gas heating due
to grain electron photoemission (Draine 1978) may contribute to this fact, although there is not a significant overall relationship between $R_V$ and $T_{01}$. The 13 Copernicus lines of sight with $R_V < 4$ and $f_{H_2} < 0.2$ all have $E(B - V) = 0.2$–0.4, and all but one (HD 147165; $T_{01} = 64$ K) have rotational temperatures greater than the average from our FUSE sample of 67 K. Of the 4 FUSE lines of sight with $R_V < 4$ and $f_{H_2} < 0.2$, only one has $T_{01} < 67$ K (HD 152236; $T_{01} = 62$ K). Of these 17 Copernicus and FUSE total lines of sight none have $T_{01}$ as small as $\rho$ Oph A, $\rho$ Oph D, or Herschel 36.

It is clear from Figure 7 that these three lines of sight are part of a small group that stand out from the rest of the sample, going against the generally inverse relationship between molecular fraction and temperature and lying in the bottom left of the figure. We would expect the cold lines of sight to contain denser material and represent the expected environment for the large grains. But, for at least Herschel 36 and $\rho$ Oph D, the material is subject to considerable far-UV radiation, contributing to the small molecular fractions.

In these cases, we may be seeing the effect of a broad distribution of material. Perhaps there is both “cold” diffuse material which contains most of the H$_2$ and is still not dense enough to exhibit a level of self-shielding that would allow a large molecular fraction, yet there is also a relatively small amount of material closer to the hot stars that not only has few molecules, but also considerable H$_2$ excitation. In particular, for Herschel 36 there seems to be a significant velocity difference between the excited material and the “cold” material as indicated by the low-$J$ lines of H$_2$. Thus, the cold material may be significantly in the foreground of Herschel 36.

As previously noted, the radiation field is one of three factors that influence the molecular fraction in the models of Browning et al. (2003), along with formation rate coefficient and density. The models show that for the column densities we are sampling in this paper, there can be degeneracy in the molecular fractions that result from different combinations of the three factors. In particular, a small formation rate coefficient can lower the molecular fraction in a manner similar to an increase in the UV flux.

The total column densities in our sub-sample of 5 high $R_V$ lines of sight cover the range $\log N(\text{H}_\text{tot}) \approx 21.2$–22.0 ($N$ in cm$^{-2}$). In this range, Browning et al. (2003) find that a UV radiation field 50 times the Galactic mean reduces the molecular fraction by $\sim 5$ orders of magnitude at the low end, to factors of $\sim 2$–3 at the high end. A reduction in the formation rate coefficient by a factor of 10 reduces the molecular fraction by $\sim 2$ orders of magnitude at the low end and by a minimal amount at the high end. These two factors in combination were required to match H$_2$ data for the Small and Large Magellanic Clouds at levels of extinction generally below those in our present sample.

The most likely variables that would change the formation rate coefficient are grain size and temperature. Since we have limited this sub-sample to high $R_V$, differences in grain size distribution have presumably been minimized. If the $N(1)/N(0)$ rotational temperature is a meaningful indicator of kinetic temperatures, our sub-sample is more or less isothermal.
Density, the third factor considered in the Browning et al. (2003) models, is generally not as important within our range of column densities for typical Galactic values of radiation field and formation rate coefficient, particularly since the molecular fractions are usually relatively large already. When combined with large radiation field or small formation rate coefficient, density variations can cause a large spread in the resulting small molecular fractions.

In conclusion, given the relatively large column densities in the regime we are probing with our sample, it appears more likely that large variations in radiation field are the dominant cause for the variations in molecular fraction. Formation rate coefficients far below the Galactic average may contribute to smaller molecular fractions in our regime, but it is more certain that some of the clouds we are studying lie very close to major UV sources that dramatically increase the local radiation field.

5. Summary

We have completed the primary molecular hydrogen analysis for the FUSE translucent lines of sight. Total H$_2$ column densities have been measured for a total of 38 lines of sight with $A_V \gtrsim 1$ via profile fitting of transitions from the lowest two vibrational levels which contain $\sim 99\%$ of the material. In addition, we have derived the H$_2$ molecular fractions and rotational temperatures for the lines of sight and considered various correlations between parameters. In particular, using these data we have found that the gas-to-dust ratio ($N$(H$_{\text{tot}}$)/$E$(B − V)) remains identical to that found with Copernicus data out to $E$(B − V) $\approx 1$, a factor of 2 farther than the previous determination.

These lines of sight were chosen to sample a wide variety of environments, including those with unusual dust characteristics, as dust grains are thought to provide the primary environment for H$_2$ formation in these clouds. An important consequence of the updated sample is that we have much better coverage of lines of sight with large total-to-selective extinction ratios ($R_V$) and smaller than normal far-UV extinction. These unusual characteristics are thought to indicate larger than normal dust grains for which the grain area per unit mass will be lower. In the lines of sight with large grains, we still see a large range in molecular fraction and can mostly attribute this to a range in the strength of the local interstellar far-UV radiation field, perhaps enhanced by material being widely distributed along the line of sight and/or by variations in the H$_2$ formation rate coefficient. Overall, we do not see a statistically significant trend of decreasing molecular fraction with increasing $R_V$.

As our new lines of sight all have molecular fractions $f_{H_2} \lesssim 0.5$, our conclusions regarding the presence of truly “translucent clouds” with $f_{H_2}$ near unity are unchanged. Namely, the lines of sight in our survey are primarily sampling multiple clouds without a high-extinction core that is dominated by molecules.

Work is still ongoing to fully utilize the FUSE data for the translucent sample, including a survey of the HD molecule (Snow et al. 2008), and a detailed analysis of the line of sight to Herschel 36 (B. L. Rachford 2008, in preparation).
With the official end of the FUSE mission in 2007, direct far-UV measurements of another significant sample of reddened lines of sight will have to wait until another mission is launched. One of the goals of the planned Hubble Service Mission 4 in late 2008 will be to install the Cosmic Origins Spectrograph (COS) in the Hubble Space Telescope. This instrument is primarily designed to observe UV wavelengths longward of 1150 Å at high sensitivity and similar resolution to that of FUSE. This will provide access to lines from numerous atomic and molecular species in more heavily reddened lines of sight than any previous mission. However, the combination of the HST optics and COS may have enough residual sensitivity at 1108 Å to sample the longest wavelength (0,0) ro-vibrational bandhead of H$_2$. These potential observations of H$_2$ would occur at much lower resolution than FUSE ($R \sim 3000$) and will thus be more difficult to analyze. However, this might provide a significant constraint on molecular fractions for very heavily reddened lines of sight that were not accessible with FUSE, possibly revealing true “translucent clouds” with $f_{H_2} \approx 1$.

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Facilities: FUSE (LWRS, MDRS)

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### Table 1. Target list

| Star | $\ell$ | $b$ | Assoc.   | $V$ | MK type |
|------|-------|-----|----------|-----|---------|
| HD 37903 | 206.85 | -16.54 | Orion   | 7.83 | B1.5 V  |
| HD 38087 | 207.07 | -16.26 | Orion?   | 8.30 | B5 V    |
| HD 40893 | 180.09 | +4.34  |          | 8.90 | B0 IV   |
| HD 41117 | 189.65 | -0.86  | Gem OB1  | 4.63 | B2 Iae  |
| HD 42087 | 187.79 | +1.77  | Gem OB1  | 5.75 | B2.5Ibe |
| HD 43384 | 187.99 | +3.53  | Gem OB1  | 6.25 | B3 Ib   |
| HD 46056 | 206.34 | -2.25  | Mon OB2  | 8.16 | O8 V    |
| HD 46202 | 206.31 | -2.00  | Mon OB2  | 8.19 | O9 V    |
| HD 53367 | 223.71 | -1.90  |          | 6.96 | B0 IVe  |
| HD 147888| 353.65 | +17.71 | Sco-Oph  | 6.74 | B5 V    |
| HD 149404| 340.54 | +3.01  |          | 5.47 | O9 Iae  |
| HD 152236| 343.03 | +0.87  | Sco OB1  | 4.73 | B1 Ia+pe|
| HD 164740| 5.97   | -1.17  | M8       | 10.30| O7.5 V  |
| HD 179406| 28.23  | -8.31  |          | 5.34 | B3 V    |
| HD 186994| 78.62  | +10.86 |          | 7.50 | B0 III  |
Table 2. Extinction parameters for Paper I sample and present sample

\begin{table}[h]
\centering
\begin{tabular}{lcccccccc}
\hline
\textbf{Star} & \textbf{$E(B-V)$} & \textbf{Phot.} & \textbf{Polar.} & \textbf{Ref.} & \textbf{E.C.} & \textbf{Adopted} & \textbf{$A_V$} \\
\hline
\text{BD +31\degree} 643 & 0.85 & 3.13±0.30 & 3.75 & 1 & 3.54 & 3.13±0.30 & 2.66±0.26 \\
\text{HD 24534} & 0.59 & 1.70±1.00 & 3.47 & 2 & & 3.47±0.30 & 2.05±0.18 \\
\text{HD 27778} & 0.37 & 2.72±0.30 & & & & 2.72±0.30 & 1.01±0.11 \\
\text{HD 62542} & 0.35 & 2.83±0.30 & 3.27 & 3 & 2.14 & 2.83±0.30 & 0.99±0.14 \\
\text{HD 73882} & 0.70 & 3.37±0.30 & 3.51 & 3 & 2.93 & 3.37±0.30 & 2.36±0.23 \\
\text{HD 96675} & 0.30 & 3.85±0.30 & 2.80 & 4 & 4.02 & 3.85±0.30 & 1.16±0.15 \\
\text{HD 102065} & 0.17 & & & & & 2.89 & 2.89±0.30 & 0.49±0.10 \\
\text{HD 108927} & 0.22 & 3.14±0.30 & & & & 3.73 & 3.14±0.30 & 0.69±0.11 \\
\text{HD 110432} & 0.51 & 3.95±0.60 & 3.30 & 5 & & 3.95±0.60 & 2.02±0.33 \\
\text{HD 154368} & 0.78 & 3.00±0.30 & & & 3.14 & 3.00±0.30 & 2.34±0.25 \\
\text{HD 167971} & 1.08 & 3.17±1.00 & & & & 3.17±1.00 & 3.42±1.08 \\
\text{HD 168076} & 0.78 & 3.55±0.30 & 3.19 & 6 & 3.62 & 3.55±0.30 & 2.77±0.26 \\
\text{HD 170740} & 0.48 & 2.71±0.30 & 3.08 & 5 & & 2.71±0.30 & 1.30±0.17 \\
\text{HD 185418} & 0.50 & 2.32±0.30 & & & 3.98 & 2.32±0.30 & 1.16±0.17 \\
\text{HD 192639} & 0.66 & 2.84±1.00 & & & & 2.84±1.00 & 1.87±0.67 \\
\text{HD 197512} & 0.32 & 2.35±0.30 & & & 2.56 & 2.35±0.30 & 0.75±0.12 \\
\text{HD 199579} & 0.37 & 2.95±1.00 & & & 2.74 & 2.95±1.00 & 1.09±0.14 \\
\text{HD 203938} & 0.74 & 2.91±0.30 & & & 3.00 & 2.91±0.30 & 2.15±0.24 \\
\text{HD 206267} & 0.53 & 2.67±0.30 & & & & 2.67±0.30 & 1.41±0.18 \\
\text{HD 207198} & 0.62 & 2.42±1.00 & 2.30 & 7 & 2.66 & 2.42±1.00 & 1.50±0.20 \\
\text{HD 207538} & 0.64 & 2.25±0.30 & 2.23 & 3 & & 2.25±0.30 & 1.44±0.20 \\
\text{HD 210121} & 0.40 & 2.08±0.30 & 2.13 & 8 & 2.01 & 2.08±0.30 & 0.83±0.14 \\
\text{HD 210839} & 0.57 & 2.78±0.30 & 2.86 & 9 & & 2.78±0.30 & 1.58±0.19 \\
\text{HD 37903} & 0.35 & 3.67±0.30 & 3.89 & 3 & 3.90 & 3.67±0.30 & 1.28±0.15 \\
\text{HD 38087} & 0.29 & 5.57±0.30 & 3.06 & 3 & 4.48 & 5.57±0.30 & 1.61±0.19 \\
\text{HD 40893} & 0.46 & 2.46±0.30 & & & 3.18 & 2.46±0.30 & 1.13±0.16 \\
\text{HD 41117} & 0.45 & 2.74±1.00 & 3.02 & 5 & 2.89 & 2.74±1.00 & 1.23±0.16 \\
\text{HD 42087} & 0.36 & 3.06±1.00 & 3.08 & 5 & 2.78 & 3.08±1.00 & 1.10±0.14 \\
\text{HD 43384} & 0.58 & 3.06±0.30 & 2.97 & 5 & & 3.06±0.30 & 1.78±0.20 \\
\text{HD 46056} & 0.50 & 2.60±0.30 & & & 2.81 & 2.60±0.30 & 1.30±0.17 \\
\text{HD 46202} & 0.49 & 2.83±0.30 & & & 2.79 & 2.83±0.30 & 1.39±0.17 \\
\text{HD 53367} & 0.74 & 2.38±1.00 & & & 2.38±1.00 & 1.76±0.74 \\
\text{HD 147888} & 0.47 & 4.06±0.30 & 3.82 & 3 & 4.93 & 4.06±0.30 & 1.91±0.19 \\
\text{HD 149404} & 0.68 & 3.28±0.60 & 3.08 & 5 & & 3.28±0.60 & 2.23±0.42 \\
\text{HD 152236} & 0.68 & 3.29±1.00 & 3.25 & 5 & 2.82 & 3.29±1.00 & 2.24±0.23 \\
\text{HD 164740} & 0.87 & 5.36±0.30 & 3.75 & 5 & & 5.36±0.30 & 4.66±0.31 \\
\text{HD 179406} & 0.33 & 2.86±0.30 & 2.86 & 5 & & 2.86±0.30 & 0.94±0.13 \\
\text{HD 186994} & 0.17 & & & & & 3.10±0.30 & 0.53±0.13 \\
\hline
\end{tabular}
\end{table}
Table 2—Continued

| Star | $E(B - V)$ | Phot. | Polar. | Ref | E.C. | Adopted | $A_V$ |
|------|------------|-------|--------|-----|------|---------|-------|

Revised values for Paper I targets are given first, followed by the values for the new targets.

- Derived using 2MASS photometry
- Derived from the wavelength of maximum polarization
- Derived from the linear far-UV rise in the extinction curve based on the $c_2$ parameters given in Table 3.

References. — (1) Andersson & Wannier 2000; (2) Roche et al. 1997; (3) Martin, Clayton, & Wolff 1999; (4) Whittet et al. 1994; (5) Serkowski, Mathewson, Ford 1975; (6) Orsatti, Vega, & Marraco 2000; (7) Anderson et al. 1996; (8) Larson, Whittet, & Hough 1996; (9) McDavid 2000
### Table 3. Extinction curve parameters\(^a\)

| Target     | \(\lambda_0^{-1}\) (\(\mu\text{m}^{-1}\)) | \(\gamma\) (\(\mu\text{m}^{-1}\)) | \(c_1\)  | \(c_2\)  | \(c_3\)  | \(c_4\)  | Ref. |
|------------|-----------------------------------|-----------------------------------|---------|---------|---------|---------|------|
| HD 37903   | 4.615                             | 1.045                             | 0.965   | 0.384   | 3.300   | 0.440   | 1    |
| HD 38087   | 4.563                             | 1.026                             | 1.137   | 0.230   | 4.508   | 0.311   | 1    |
| HD 40893   | 4.591                             | 0.83                              | 0.26    | 0.66    | 3.13    | 0.55    | 2    |
| HD 41117   | 4.621                             | 0.97                              | -0.38   | 0.81    | 3.64    | 0.56    | 2    |
| HD 42087   | 4.636                             | 1.05                              | -1.28   | 0.87    | 4.36    | 0.53    | 2    |
| HD 43384   | 4.611                             | 0.932                             | -0.527  | 0.857   | 3.032   | 0.541   | 1    |
| HD 46056   | 4.599                             | 0.842                             | -0.348  | 0.864   | 2.542   | 0.515   | 1    |
| HD 53367   | 4.587                             | 1.022                             | 1.611   | 0.133   | 3.823   | 0.339   | 1    |
| HD 147888  | 4.587                             | 1.022                             | 1.611   | 0.133   | 3.823   | 0.339   | 1    |
| HD 149404  | 4.622                             | 1.06                              | -0.51   | 0.85    | 3.71    | 0.38    | 2    |
| HD 152236  | 4.622                             | 1.06                              | -0.51   | 0.85    | 3.71    | 0.38    | 2    |
| HD 164740  | 4.622                             | 1.06                              | -0.51   | 0.85    | 3.71    | 0.38    | 2    |
| HD 179406  | 4.622                             | 1.06                              | -0.51   | 0.85    | 3.71    | 0.38    | 2    |
| HD 186994  | 4.622                             | 1.06                              | -0.51   | 0.85    | 3.71    | 0.38    | 2    |

\(^a\)In the parameterization scheme of Fitzpatrick & Massa 1990

References. — (1) Fitzpatrick & Massa 1990; (2) Jenniskens & Greenberg 1993
Table 4. *FUSE* observations

| Target | *FUSE* data ID | Date       | $N_{\text{int}}^a$ | $t_{\text{int}}^b$ | S/N$^c$ |
|--------|----------------|------------|---------------------|---------------------|---------|
| HD 37903 | P1160601      | 2001 Oct 18 | 4                   | 4.0                 | 20.4    |
| HD 38087 | P1160701      | 2001 Oct 18 | 4                   | 4.0                 | 16.2    |
| HD 40893 | P2160101      | 2001 Oct 14 | 3                   | 7.1                 | 12.7    |
| HD 41117 | P2160201      | 2004 Mar 03 | 1                   | 0.1                 | 2.0     |
| HD 42087 | P2160301      | 2001 Oct 15 | 6                   | 2.9                 | 12.1    |
| HD 43384 | P2160401      | 2001 Oct 15 | 6                   | 8.1                 | 1.8     |
| HD 46056 | P2160901      | 2003 Jan 25 | 3                   | 7.1                 | 8.1     |
| HD 46202 | P2161001      | 2001 Oct 16 | 2                   | 5.0                 | 10.0    |
| HD 53367 | P1161101      | 2001 Oct 26 | 7                   | 11.4                | 9.9     |
| HD 147888 | P1161501     | 2003 Aug 21 | 23                  | 12.2                | 12.8    |
| HD 149404 | P1161701     | 2001 Aug 07 | 38                  | 17.9                | 28.9    |
| HD 152236 | P1161801     | 2001 Aug 08 | 4                   | 4.6                 | 6.1     |
| HD 164740 | P1162001     | 2000 Aug 30 | 3                   | 5.9                 | 9.0     |
| HD 179406 | P2160701     | 2001 Apr 27 | 1                   | 0.1                 | 3.7     |
| HD 179406 | P2160702     | 2002 Jun 11 | 3                   | 1.0                 | 14.4    |
| HD 186994 | P2160801     | 2001 Jul 02 | 1                   | 0.1                 | 6.3     |
| HD 186994 | P2160802     | 2001 Sep 07 | 1                   | 0.4                 | 17.2    |

$^a$Number of integrations

$^b$Total integration time

$^c$Average per-pixel S/N for a 1 Å region of the LiF 1A spectrum near 1070 Å, between the Lyman (3,0) and (2,0) bandheads of H$_2$. One resolution element corresponds to about 9 pixels.
| Target   | Bands | Log $N(H_2)$ (N in cm$^{-2}$) | Log $N(0)$ (N in cm$^{-2}$) | Log $N(1)$ (N in cm$^{-2}$) | $T_{01}$ (K) | Log $N(H\text{ I})$ (N in cm$^{-2}$) | Ref   | $f_{H_2}$ |
|----------|-------|-------------------------------|-------------------------------|-------------------------------|-------------|--------------------------------------|-------|-----------|
| HD 37903 | 6     | 20.92±0.06                    | 20.68±0.07                   | 20.54±0.05                   | 68±7        | 21.17±0.10                           | 1     | 0.53±0.09 |
| HD 38087 | 7     | 20.64±0.07                    | 20.39±0.08                   | 20.29±0.05                   | 70±8        | 20.91±0.30                           | 2     | 0.52±0.20 |
| HD 40893 | 9     | 20.58±0.05                    | 20.27±0.05                   | 20.28±0.05                   | 78±8        | 21.50±0.10                           | 3     | 0.19±0.06 |
| HD 41117 | 2     | 20.69±0.10                    | 20.51±0.10                   | 20.22±0.10                   | 59±8        | 21.40±0.15                           | 4     | 0.28±0.13 |
| HD 42087 | 7     | 20.52±0.12                    | 20.31±0.12                   | 20.11±0.12                   | 64±11       | 21.39±0.11                           | 1     | 0.21±0.10 |
| HD 43384 | 2     | 20.87±0.14                    | 20.59±0.10                   | 20.54±0.18                   | 74±16       | 21.27±0.30                           | 5     | 0.44±0.24 |
| HD 46056 | 9     | 20.68±0.06                    | 20.40±0.06                   | 20.35±0.06                   | 74±8        | 21.38±0.14                           | 1     | 0.29±0.09 |
| HD 46202 | 9     | 20.68±0.06                    | 20.38±0.07                   | 20.38±0.07                   | 78±9        | 21.58±0.15                           | 1     | 0.20±0.09 |
| HD 53367 | 9     | 21.04±0.05                    | 20.89±0.04                   | 20.52±0.07                   | 56±4        | 21.32±0.30                           | 2     | 0.51±0.19 |
| HD 147888| 7     | 20.47±0.05                    | 20.39±0.04                   | 19.71±0.10                   | 45±4        | 21.44±0.30                           | 5     | 0.18±0.14 |
| HD 149404| 9     | 20.79±0.04                    | 20.60±0.03                   | 20.34±0.05                   | 61±4        | 21.40±0.15                           | 1     | 0.33±0.09 |
| HD 152236| 1     | 20.73±0.12                    | 20.53±0.12                   | 20.29±0.12                   | 62±10       | 21.77±0.15                           | 1     | 0.15±0.08 |
| HD 164740| 1     | 20.19±0.12                    | 19.92±0.12                   | 19.86±0.12                   | 60±10       | 21.95±0.15                           | 6     | 0.03±0.02 |
| HD 179406| 4     | 20.73±0.07                    | 20.55±0.07                   | 20.26±0.08                   | 59±6        | 21.23±0.15                           | 7     | 0.30±0.12 |
| HD 186994| 9     | 19.59±0.04                    | 19.18±0.06                   | 19.37±0.03                   | 97±10       | 20.90±0.15                           | 8     | 0.09±0.04 |

References. — (1) Diplas & Savage 1994, Lyα; (2) Jensen et al. 2007, $N(\text{H}\text{ I}) = 5.8 \times 10^{21} E(B−V) − 2N(\text{H}_2)$; (3) Jensen et al. 2007, Lyα; (4) Present work, Lyα; (5) Present work, $N(\text{H}\text{ I}) = 5.8 \times 10^{21} E(B−V) − 2N(\text{H}_2)$; (6) Fitzpatrick & Massa 1990, Lyα; (7) Hansen et al. 1992, Lyα; (8) Bohlin et al. 1978, Lyα
Fig. 1.— Molecular hydrogen column density versus color excess. Crosses: FUSE; diamonds: Copernicus. Typical H$_2$ uncertainties for the Copernicus data points ($\sim$25%) are slightly larger than for the FUSE data points.
Fig. 2.— Total hydrogen column density versus color excess. Symbols as in Figure 1. Top panel: All data points. Bottom panel: Only FUSE points with reliable H I and H$_2$ measurements toward non-Be stars. Solid line in both panels is the best fit to the data in the lower panel, constrained to pass through the origin. The dashed line is an unconstrained fit that does not include the point at $E(B-V) = 0.17$ (HD 186994). Typical $N(H_{\text{tot}})$ errors for the Copernicus data points ($\sim30\%$) are slightly larger than for the FUSE data points.
Fig. 3.— Total hydrogen column density versus total visual extinction. Symbols as in Figure 1. Top panel: All data points. Bottom panel: Only FUSE points with reliable H I and H$_2$ measurements toward non-Be stars. The solid line in both panels is the best fit to the data in the lower panel, constrained to pass through the origin. The dashed line is an unconstrained fit that does not include the point at $A_V = 0.53$ (HD 186994). Typical $N(H_{tot})$ errors for the Copernicus data points ($\sim 30\%$) are slightly larger than for the FUSE data points.
Fig. 4.— Rotational temperature versus color excess. Crosses: FUSE; diamonds: Copernicus points with \( N(\text{H}_2) > 10^{20} \text{ cm}^{-2} \); squares: Copernicus points with \( N(\text{H}_2) < 10^{20} \text{ cm}^{-2} \).
Fig. 5.— Molecular fraction versus color excess. Crosses: *FUSE*; diamonds: *Copernicus* points with $N$(H$_2$) > $10^{20}$ cm$^{-2}$; squares: *Copernicus* points with $N$(H$_2$) < $10^{20}$ cm$^{-2}$. Typical $f_{H_2}$ errors for *Copernicus* data points (∼30%) are slightly larger than for the *FUSE* data points. Error bars are not given for *FUSE* values derived without direct measurements of $N$(H I).
Fig. 6.— Molecular fraction versus total-to-selective extinction ratio. Symbols and comments as in Figure 5. To make the plot easier to read, error bars for $R_V$ are only given for the high $R_V$ sample discussed in § 4.3. We also give error bars for $f_{H2}$ for the two Copernicus targets discussed in § 4.3.
Fig. 7.— Molecular fraction versus rotational temperature. Symbols and comments as in Figure 5