FUSE OBSERVATIONS OF DIFFUSE INTERSTELLAR MOLECULAR HYDROGEN

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Abstract

We describe a moderate-resolution FUSE mini-survey of H$_2$ in the Milky Way and Magellanic Clouds, using four hot stars and four AGN as background sources. FUSE spectra of nearly every stellar and extragalactic source exhibit numerous absorption lines from the H$_2$ Lyman and Werner bands between 912 and 1120 Å. One extragalactic sightline (PKS 2155-304) with low N(H I) shows no detectable H$_2$, and could be the “Lockman Hole of molecular gas”, of importance for QSO absorption-line studies. We measure H$_2$ column densities in low rotational states ($J = 0$ and 1) to derive rotational and/or kinetic temperatures of diffuse interstellar gas. The higher-$J$ abundances can constrain models of the UV radiation fields and gas densities. In three optically thick clouds toward extragalactic sources, we find $n_H \approx 30 – 50$ cm$^{-3}$ and cloud thicknesses $\sim 2 – 3$ pc. The rotational temperatures for H$_2$ at high Galactic latitude, $(T_{\mathrm{TH}}) = 107 \pm 17$ K (seven sightlines) and $120 \pm 13$ K (three optically thick clouds), are higher than those in the Copernicus sample composed primarily of targets in the disk. We find no evidence for differences in the abundance or state of excitation of H$_2$ between sight lines in the Galaxy and those in the SMC and LMC. In the future, we will probe the distribution and physical parameters of diffuse molecular gas in the disk and halo and in the lower-metallicity environs of the LMC and SMC.

Subject headings: ISM: clouds, molecules — ultraviolet: ISM — galaxies: individual (LMC, SMC)

1. INTRODUCTION

As the most abundant molecule in the Universe, molecular hydrogen (H$_2$) comprises the bulk of the mass of dense interstellar molecular clouds and is the main ingredient of star formation (Shull & Beckwith 1982). The first steps of star formation assemble dense interstellar clouds from diffuse gas, but the formation mechanism for giant molecular clouds from diffuse diffuse gas is still unknown. Little is known about the distribution of diffuse H$_2$ in the interstellar medium (ISM) of our Galaxy, and major uncertainties remain about its formation, destruction, and recycling into dense clouds and stars. H$_2$ also plays a central role in our understanding of interstellar chemistry.

Here, we describe early results on H$_2$ in the Milky Way and the Magellanic Clouds obtained with the NASA Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. The FUSE mission and the capabilities of its spectrograph are described by Moos et al. (2000) and Sahnow et al. (2000). Over its mission lifetime, FUSE will probe hundreds of sight lines through the Galactic disk and halo. We expect a large fraction of these sight lines to exhibit absorption from the Lyman and Werner rotational-vibrational bands of H$_2$, some 400 absorption lines between 912 and 1120 Å, arising from rotational levels $J = 0 – 7$ in the ground vibrational state. With FUSE, our team will map the distribution of H$_2$ in the diffuse ISM, measure its abundance, state of excitation, and rates of formation and destruction. In § 2 we summarize our initial observations and describe our analysis methods. In § 3 we describe results from 8 targets. In § 4 we summarize our results and discuss future directions of FUSE H$_2$ research.

2. OBSERVATIONS AND ANALYSIS

Our FUSE observations were obtained from 1999 September to 1999 November during the commissioning phase of satellite operations. A summary of the observations appears in Table 1. The resolution of the spectrograph across the band was R $\approx$ 12,000 for all observations, based on studies of sharp interstellar lines of H$_2$, Ar I, and Fe II. The data were prepared for analysis by the FUSE data pipeline as described in Moos et al. (2000). Once the two-dimensional spectra were extracted to one dimension, a wavelength solution was applied and the oversampled data were smoothed by a 15-pixel running boxcar to 30 km s$^{-1}$ resolution.

In typical interstellar conditions, excited H$_2$ quickly decays to the ground vibrational state of the ground electronic state (Black & Dalgarno 1973). Observations of H$_2$ with the Copernicus satellite occasionally detected rotational lines up to $J = 7$, and we search for $J \leq 10$. How-

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ever, lines above $J = 4$ are difficult to detect in diffuse interstellar clouds, with our typical $4\sigma$ limiting equivalent width of 30–40 mA and the corresponding column density limit of $N(\text{H}_2) \simeq 10^{14}$ cm$^{-2}$. We use all available $\text{H}_2$ lines, except where they are blended with other interstellar absorption or airglow lines. Typically we neglect the Lyman (6-0) band, which is lost in interstellar Ly$\beta$, and the Lyman (5-0) band, which is coincident with resonance absorption lines C II A1036.34 and C II* A1037.02 and with O I A1039.64 airglow.

We illustrate our data in Figure 1, which displays the FUSE spectrum of ESO 141-G55, a Seyfert 1 galaxy at Galactic latitude $b = -26.71^\circ$. We detect one $\text{H}_2$ Galactic component with $N(\text{H}_2) = 2 \times 10^{19}$ cm$^{-2}$. This spectrum is typical of our FUSE data both in data quality and the abundance of $\text{H}_2$ lines.

We employ a complement of techniques to analyze $\text{H}_2$ absorption. The final products are column densities in rotational levels, $N(J)$, from which we can infer the gas density, UV radiation field, and $\text{H}_2$ formation and destruction rates. For high column density absorbers with damping wings in the R(0) and R(1) lines, we fit the line profiles to derive $N(0)$ and $N(1)$ and use a curve of growth to derive column densities for $J \geq 2$. For absorbers with $N(\text{H}_2) \lesssim 10^{19}$ cm$^{-2}$, we measure equivalent widths of all $\text{H}_2$ lines and produce a curve of growth to infer a doppler $b$-parameter and $N(J)$ – see Fig. 2. We produce initial estimates of the column densities and excitation temperatures by fitting all lines simultaneously with parameters $N(\text{H}_2)$, $b$, and $T$, assuming a Boltzmann distribution at thermal rotational temperature $T_{\text{rot}}$ for $J = 0, 1$ and an excitation temperature $T_{\text{ex}}$ for $J \geq 2$.

The Copernicus $\text{H}_2$ survey (Spitzer & Jenkins 1975; Savage et al. 1977) showed that the molecular fraction, $f_{\text{H}_2} = 2N(\text{H}_2)/[N(\text{H} I) + 2N(\text{H}_2)]$, is correlated with $E(B-V)$ and with total H column density. They found that $f_{\text{H}_2}$ undergoes a transition from low values ($< 0.01$) to high values ($> 0.01$) at $E(B-V) \approx 0.08$. Other Copernicus studies indicate that the populations in $J = 0, 1$ and $J \geq 2$ cannot always be described by a single excitation temperature (Spitzer, Cochran, & Hirshfeld 1974). $T_{\text{ex}}$ is generally higher than $T_{\text{rot}}$ and reflects the fluorescent pumping of the rotational levels by incident UV radiation (Jura 1975a,b). The ratio, $N(1)/N(0)$, is usually set by collisional mixing of the ortho- and para-$\text{H}_2$ states (Shull & Beckwith 1982), but these rotational levels may not yet have reached equilibrium in lower density clouds.

3. RESULTS FOR INDIVIDUAL SIGHT LINES
3.1. Magellanic Cloud Targets

We report observations of one star in the LMC and three stars in the SMC. In the cases of AV 232 and HD 5980, we detect $\text{H}_2$ in both the Galaxy and the SMC (at +119 km s$^{-1}$ and +124 km s$^{-1}$; see Table 2). Our survey contains two Magellanic Cloud targets with no detected $\text{H}_2$ at LMC or SMC velocities. Sk -67 111 (LMC) and Sk 108 (SMC) show Galactic $\text{H}_2$ absorption near $v_{\text{LSR}} \approx 0$ but have no detected $\text{H}_2$ at the MC velocities. Our limiting equivalent width of 60 mA ($4\sigma$) in the Sk -67 111 spectrum sets limits $N(0) < 2.2 \times 10^{14}$ cm$^{-2}$ and $N(1) < 3.2 \times 10^{14}$ cm$^{-2}$ from the (7-0) R(0) and R(1) lines. For Sk 108, the limit of 30 mA yields $N(0) < 1.1 \times 10^{14}$ cm$^{-2}$ and $N(1) \lesssim 1.6 \times 10^{14}$ cm$^{-2}$. The absence of $\text{H}_2$ in these sight lines may be due to low $\text{H}_2$ columns, to intense UV radiation fields that destroy $\text{H}_2$, or to reduced rates of $\text{H}_2$ formation on grain surfaces in warm low-metallicity gas. Abundances for such gas are given by Welse et al. (1999).

The SMC stars HD 5980 and AV 232 are separated by 75$^\circ$ on the sky. Thus, these sight lines may probe the same interstellar clouds in the Galaxy and SMC. With similar column densities and rotational temperatures, the Galactic components appear to arise in the same gas. However, the AV 232 SMC component exhibits a high rotational temperature $T_{\text{rot}} = 300 \pm 60$ K and a higher excitation temperature $T_{\text{ex}} = 520 \pm 90$ K, compared with $T_{\text{rot}} = 98 \pm 13$ K and $T_{\text{ex}} = 300 \pm 60$ K for the HD 5980 absorber. The level populations likely arise from differing excitation rates in separate clouds, $\sim 20$ pc apart at the SMC.

The only detections of Magellanic Cloud $\text{H}_2$ absorption prior to FUSE were observations with ORFEUS (Richter et al. 1998; de Boer et al. 1998), at low signal to noise but comparable ($R \approx 10^4$) resolution. With a longer mission lifetime and higher effective area, FUSE offers significant improvement for H$_2$ studies. For example, with higher S/N, we do not confirm the claimed ORFEUS detections of $\text{H}_2$ ($J = 5, 6, 7$) at +160 km s$^{-1}$ toward HD 5980 (Richter et al. 1998). Our observations of H$_2$ column densities in the +120 km s$^{-1}$ component differ considerably, owing to a better curve of growth (Fig. 2) with $b = 10$ km s$^{-1}$ compared to $b = 6$ km s$^{-1}$ with ORFEUS. Based on 28 FUSE lines ($J = 0 - 3$) compared to 8 ORFEUS lines, we derive log $N(0) = 15.10$ (compared to 16.57) and log $N(1) = 15.30$ (compared to 15.90). Within error bars, both studies agree on $N(2)$ and $N(3)$. Our data yield $T_{\text{rot}} = 98 \pm 13$ K for the SMC gas.

3.2. Extragalactic Targets

Our four extragalactic targets at Galactic latitude $|b| > 25^\circ$ probe a large volume of the Galaxy and its halo and allow us to measure the abundance and physical properties of molecular gas outside the disk for the first time. The Copernicus disk result, $\langle T_{\text{rot}} \rangle = 77 \pm 17$ K (Savage et al. 1977), was drawn from 61 stars with $|b| \leq 65^\circ$. From seven FUSE sightlines, we derive $\langle T_{\text{rot}} \rangle = 107 \pm 17$ K. In the three optically thick extragalactic sightlines, $\langle T_{\text{rot}} \rangle = 120 \pm 13$ K. These results may indicate a higher level of rotational excitation in the upper disk and low halo, which could arise from more intense UV pumping or photodissociative heating from grains in the infrared cirrus. However, these interpretations are still speculative, since the the $J = 0.1$ levels may not be in equilibrium with the kinetic temperature as a result of UV radiative pumping.

In general, the $\text{H}_2$ rotational populations can be modeled (Jura 1975a,b) to provide physical diagnostics of $\text{H}_2$-bearing clouds, such as $n_H$, $T_{\text{rot}}$, thermal pressure, and UV radiation field. We also derive internally consistent values of $N(\text{H}_2)$ and $T_{\text{ex}}$ for these clouds, which could indicate the presence of warm $\text{H}_2$-bearing gas in the lower Galactic halo. For the three AGN sightlines with detectable $\text{H}_2$, we find $n_H = 50$, 50, and 36 cm$^{-3}$ for Mrk 876, ESO 141-G55, and PG 0804+761 respectively, which yields cloud thicknesses of 1.9, 2.4, and 3.3 pc. The line of sight to ESO 141-G55 intersects a region of enhanced IRAS 100 $\mu$m emission (Sembach, Savage, & Hurwitz 1999). The other extragalactic sightlines lie behind high-velocity cloud Complex
C (Mrk 876) and weak infrared cirrus (PG 0804+761). Our H$_2$ results suggest that these clouds are also compressed.

4. SUMMARY AND FUTURE DIRECTIONS

The major results of these early FUSE observations are: (1) the ubiquity of H$_2$ in nearly all sightlines; (2) the generally warmer rotational temperatures, $T_{\text{rot}}$, toward high-latitude gas; and (3) the presence of one low-H$_2$ extragalactic sightline (PKS 2155-304). We have not detected H$_2$ in the high velocity clouds (HVCs) toward Mrk 876 or PKS 2155-304, although we intend to continue our HVC searches toward other targets. The HD molecule was not detected in any diffuse cloud, but results from a complementary program (Snow et al. 2000; Ferlet et al. 2000) detect H$_2$ and HD toward the reddened star HD 73882. Detections of H$_2$ in other FUSE sight lines are analyzed by Friedman et al. (2000), Mallouris et al. (2000), and Oegerle et al. (2000).

The lack of detectable H$_2$ toward PKS 2155-304 is quite interesting, in contrast to the general presence of H$_2$ at high Galactic latitudes. Extragalactic sight lines with low H$_2$ are valuable for studies of QSO absorption lines (Shull et al. 2000; Sembach et al. 2000), since H$_2$ line blanketing can add confusion to line identifications (Fig. 1). The observed low N(H$_2$) may reflect the intrinsic patchiness of the ISM, but can also be influenced by H$_2$ formation/destruction in regions of high UV radiation fields and low hydrogen column density. PKS 2155-304 has the lowest column density, log N(H I) $\approx$ 20.15, of any of our targets. The Sk 108 sight line shows no H$_2$ at SMC velocities, and the Sk -67 111 sight line shows no H$_2$ at LMC velocities. Although H$_2$ formation may not reach equilibrium with UV destruction in these diffuse clouds, the H$_2$ formation rate could depend on the metallicity through the content of dust grains, whose surfaces catalyze H$_2$ formation. In the Galactic halo, some clouds may be exposed to strong UV dissociating radiation from OB associations in the disk. With more sight lines, we should be able to correlate regions lacking H$_2$ with regions of low N(H I) and low metallicity (LMC, SMC). Close sight lines such as those to HD 5980 and AV 232 present an opportunity to probe the size of diffuse H$_2$-bearing interstellar clouds.

The primary product of future FUSE diffuse H$_2$ studies will be a map of the distribution of diffuse clouds in the disk and halo of the Milky Way, using a large sample of sight lines toward Galactic and extragalactic targets. Multiple sight lines to the Magellanic Clouds will permit the study of CO/H$_2$ and possibly HD/H$_2$ in lower-metallicity environs, including high-velocity clouds in the Galactic halo and Magellanic Stream (Gibson et al. 2000). Observations of multiply-intersected absorbers and H$_2$ associated with infrared cirrus and high velocity clouds can constrain the size of these diffuse interstellar clouds.

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Table 1
FUSE H$_2$ MINI-SURVEY TARGET LIST

| Target     | Channels | $t_{\text{exp}}$ (N) | S/N |
|------------|----------|----------------------|-----|
| Mrk 876    | L1 L2 S1 | 45.9 (10)            | 15  |
| ESO 141-G55| L1 L2 S2 | 35.8 (20)            | 15  |
| PG 0804+761| L1 L2 S1 | 39.6 (12)            | 15  |
| Sk -67 111 (LMC) | L1 | 13.8 (7) | 15 |
| AV 232 (SMC) | L1 | 10.3 (5) | 12 |
| HD 5980 (SMC) | L1 | 3.2 (8) | 15 |
| PKS 2155-304 | L1 L2 S2 | 37.1 (22) | 20 |

1 Detectors LiF (L1 and L2 channels) and SiC (S1 and S2 channels) have wavelength ranges described by Moos et al. (2000).

2 Exposure time and number (N) of sub-exposures.

3 Signal-to-noise ratio per smoothed (30 km s$^{-1}$) bin between 1040–1050 Å.

Table 2
FUSE H$_2$ MINI-SURVEY RESULTS

| Name (Type) | $l$ ($^\circ$) | $b$ ($^\circ$) | $v_{\text{LSR}}$ (km s$^{-1}$) | N(H$_2$) (cm$^{-2}$) | N(H I) (cm$^{-2}$) | $f_{\text{H}_2}$ | $T_{\text{01}}$ (K) | $T_{\text{ex}}$ (K) | $b_{\text{dopp}}$ (km s$^{-1}$) |
|-------------|----------------|---------------|-------------------------------|----------------------|-------------------|-----------------|-----------------|-----------------|------------------|
| Magellanic Cloud Sight Lines |
| Sk -67 111 (LMC, O7) | 277.75 | -32.97 | 0 | $2.3 \times 10^{15}$ | $6.2 \times 10^{20}$ | $7.4 \times 10^{-6}$ | 122 | 300 | 8 |
| AV 232 (SMC, O9) | 302.06 | -44.94 | 0 | $1.6 \times 10^{16}$ | $3.6 \times 10^{20}$ | $8.9 \times 10^{-5}$ | 86 | 195 | 5 |
| HD 5980 (SMC, WR) | 302.07 | -44.95 | 0 | $9.8 \times 10^{15}$ | $3.6 \times 10^{20}$ | $5.4 \times 10^{-5}$ | 98 | 195 | 5 |
| Sk 108 (SMC, WR) | 301.63 | -44.99 | 0 | $1.1 \times 10^{16}$ | $3.4 \times 10^{20}$ | $6.5 \times 10^{-5}$ | 85 | 180 | 7 |
| Extragalactic Sight Lines |
| Mrk 876 (Seyf1) | 98.27 | 40.38 | 0 | $2.3 \times 10^{18}$ | $2.7 \times 10^{20}$ | $1.7 \times 10^{-2}$ | 135 | 200 | 5 |
| ESO 141-G55 (Seyf1) | 338.18 | -26.71 | 0 | $1.9 \times 10^{19}$ | $3.5 \times 10^{20}$ | $9.3 \times 10^{-3}$ | 113 | 540 | 10 |
| PG 0804+761 (QSO) | 138.28 | 31.03 | 0 | $6.1 \times 10^{18}$ | $3.5 \times 10^{20}$ | $3.4 \times 10^{-2}$ | 113 | 180 | 8 |
| PKS 2155-304 (BL Lac) | 17.73 | -52.27 | 0 | $<2.7 \times 10^{14}$ | $1.4 \times 10^{20}$ | $<6.6 \times 10^{-6}$ | 8 |

1 Columns: Target name (type); Galactic coordinates ($l$, $b$); H$_2$ absorber velocity in LSR (Galactic H$_2$ is assumed to lie at 0 km s$^{-1}$ in LSR); column densities of H$_2$ (typically ±0.2 dex from FUSE) and H I (21 cm emission, Dickey & Lockman 1990; Lockman, Murphy, & Sembach, in preparation; Savage & deBoer 1981; Sembach, Savage, & Hurwitz 1999); molecular fraction, $f_{\text{H}_2} = 2N(\text{H}_2)/[N(\text{H I}) + 2N(\text{H}_2)]$; rotational temperature $T_{01}$ (typically ±15 K) from $J = 0$ and 1; excitation temperature $T_{\text{ex}}$ (typically ±75 K) from $J \geq 2$; and doppler parameter (typically ±2 km s$^{-1}$) from H$_2$ curve of growth.
Fig. 1.— FUSE spectrum of ESO 141-G55. Bright airglow lines have been truncated. This spectrum has a resolution of $R \approx 12,000$ and $S/N \approx 15$ per smoothed (30 km s$^{-1}$) bin (1040–1050 Å) and $S/N \approx 25$ at 1070 Å. Lower (red) and upper (blue) ticks mark the detected Lyman and Werner lines of H$_2$, respectively. The interstellar and intergalactic lines are analyzed further by Sembach et al. (2000) and Shull et al. (2000).

Fig. 2.— (Left) Composite curve of growth for 28 H$_2$ lines ($J = 0, 1, 2, 3$) in the SMC (+120 km s$^{-1}$) component toward HD 5980 with best-fit doppler parameter, $b = 10$ km s$^{-1}$, and column densities, N(J). (Right) Same 28 FUSE lines but with the higher ORFEUS column densities (Richter et al. 1998, who used $b = 6$ km s$^{-1}$).