H$_2$ EXCITATION ON THE SIGHTLINES TO $\delta$ SCORPII AND $\zeta$ OPHIUCI: FIRST RESULTS FROM THE SUB-ORBITAL LOCAL INTERSTELLAR CLOUD EXPERIMENT

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ABSTRACT

We present the first science results from the Sub-orbital Local Interstellar Cloud Experiment (SLICE): moderate resolution 1020–1070 Å spectroscopy of four sightlines through the local interstellar medium. High signal-to-noise (S/N) spectra of $\eta$ Uma, $\alpha$ Vir, $\delta$ Sco, and $\zeta$ Oph were obtained during a 2013 April 21 rocket flight. The SLICE observations constrain the density, molecular photoexcitation rates, and physical conditions present in the interstellar material toward $\delta$ Sco and $\zeta$ Oph. Our spectra indicate a factor of two lower total N(H$_2$) than previously reported for $\delta$ Sco, which we attribute to higher S/N and better scattered light control in the new SLICE observations. We find N(H$_2$) = $1.5 \times 10^{19}$ cm$^{-2}$ on the $\delta$ Sco sightline, with kinetic and excitation temperatures of 67 and 529 K, respectively, and a cloud density of $n_H$ = 56 cm$^{-3}$. Our observations of the bulk of the molecular sightlines toward $\zeta$ Oph are consistent with previous measurements (N(H$_2$) $\approx 3 \times 10^{20}$ cm$^{-2}$ at $T_{\text{rot}}$(H$_2$) = 66 K and $T_{\text{exc}}$ = 350 K). However, we detect significantly more rotationally excited H$_2$ toward $\zeta$ Oph than previously observed. We infer a cloud density in the rotationally excited component of $n_H$ $\approx 7600$ cm$^{-3}$ and suggest that the increased column densities of excited H$_2$ are a result of the ongoing interaction between $\zeta$ Oph and its environment; also manifest as the prominent mid-IR bowshock observed by WISE and the presence of vibrationally excited H$_2$ molecules observed by the Hubble Space Telescope.

Key words: Instrumentation: spectrographs – ISM: molecules – stars: individual ($\eta$ Uma (HD 120315), $\alpha$ Vir (HD 116658), $\delta$ Sco (HD 143275), $\zeta$ Oph (HD 149757))

Online-only material: color figures

1. INTRODUCTION

Molecular hydrogen (H$_2$) is ubiquitous in space, comprising the majority of the mass of the interstellar medium (ISM), protostellar/protoplanetary disks, and giant planets. The characteristics of the molecular phases of diffuse and translucent interstellar clouds have largely been determined by far-UV observations of H$_2$ absorption lines on the sightlines to hot background stars. The Lyman and Werner band systems (observed primarily at 912–1120 Å) have been widely studied by sounding rockets (Carruthers 1970; Jenkins et al. 1989; France et al. 2004), Copernicus (Spitzer et al. 1974; Savage et al. 1977), the shuttle-borne IMAPS, HUT, and ORFEUS instruments (Jenkins & Peimbert 1997; Bowers et al. 1995; Lee et al. 2002), and most recently the Far-Ultraviolet Spectroscopic Explorer (FUSE; Rachford et al. 2002, 2009; Burgh et al. 2007). Since the first high-resolution studies with Copernicus in the 1970s, it has been known that many interstellar sightlines display a multi-component H$_2$ population structure (Spitzer & Cochran 1973). The lowest rotational levels ($J'' = 0$ and 1) are collisionally populated and representative of the kinetic temperature of the cloud, while the intermediate rotational levels (J$''$ $\approx 2$–7) follow a higher temperature, possibly non-thermal distribution. The H$_2$ population structure is a powerful diagnostic for understanding the physical conditions of an interstellar cloud, providing constraints on the local UV radiation field, the density, and rate of H$_2$ formation on grains.

Despite the extensive study of the characteristics of interstellar H$_2$, there is still considerable uncertainty about the physical mechanism responsible for the intermediate-$J$ excitation observed in molecular clouds. The canonical view for the excitation of the J$''$ = 2–7 levels is that UV photons, either from the UV-luminous target star or an enhancement in the local interstellar radiation field, fluently excite these states and they are observed in absorption owing to the very long radiative decay times from these levels (Spitzer & Zweibel 1974; van Dishoeck & Black 1986; Browning et al. 2003). Excess energy associated with H$_2$ formation has also been discussed by several authors as the source of the intermediate-$J$ population (Jura 1974; Lacour et al. 2005). There is growing evidence that fluorescent excitation and grain formation energy alone may be insufficient to reproduce the large column densities observed in these levels (Gry et al. 2002; Sonnentrucker et al. 2003). Interestingly, deep Spitzer Infrared Spectrograph observations (Ingalls et al. 2011) of pure rotational emission ($\Delta J = 4 \rightarrow 2$, $\Delta J = 3 \rightarrow 1$, and $\Delta J = 2 \rightarrow 0$) have also found that UV-pumping cannot reproduce the observed column densities of the J$''$ = 2–4 levels. These authors have argued that collisional processes such as the recent passage of a supernova blast wave or the dissipation of interstellar turbulence is the more likely mechanism by which these states are populated.

The nearest O and B stars have not been observed by modern UV space instruments employing low-scatter gratings, large instrumental bandpasses (for optimal continuum normalization), and large-format low-background detectors. The stringent bright-object limits of FUSE prevented the observation of most OB-stars in the local interstellar medium (LISM; d $\lesssim$ 200 pc). The advantages of studying H$_2$ excitation in the LISM include (1) the line-of-sight velocity structure is simple; there is typically only one molecular cloud between the edge of the
local bubble the target star, (2) the average interstellar radiation field is relatively well-constrained in the LISM, and (3) kinematic structures in the LISM can be spatially resolved, allowing one to identify potential interactions between hot stars and the ambient ISM. Most observations of H$_2$ in the LISM date from Copernicus, which recorded spectra in roughly 1 Å scans with large and variable backgrounds from charged particles and scattered light. In order to obtain simultaneous observations of multiple-H$_2$ absorption lines and high-fidelity continuum normalization for LISM targets, we have developed and launched the Sub-orbital Local Interstellar Cloud Experiment (SLICE).

In this Letter, we present the first flight results from SLICE: new measurements and upper limits on H$_2$ column densities for four hot stars at $d \approx 150$ pc ($\eta$ Uma, $\alpha$ Vir, $\delta$ Sco, and $\xi$ Oph) and new determinations of the H$_2$ populations on the sightlines to $\delta$ Sco and $\xi$ Oph.

2. SLICE INSTRUMENT AND OBSERVATIONS

SLICE is a rocket-borne instrument consisting of a far-UV optimized telescope, a spectograph, and an electronics package that interfaces with a NASA telemetry system to downlink the spectroscopic data in real-time (Figure 1). The telescope is a 20 cm primary diameter Cassegrain. The telescope and spectrograph are matched systems at $f/7$. The aluminum telescope and gratings employ LiF-overcoatings to maximize sensitivity in the 1020–1070 Å SLICE bandpass. Stellar spectra are focused onto a spectrograph entrance slit cut into a mirrored slit-jaw, which is imaged by an aspect camera to assist in target acquisition during the flight. The dispersing instrument is a modified Rowland circle spectrograph, which feeds a "chevron/c-stack" microchannel plate intensified photon-counting detector. The SLICE payload achieves a detector resolution-limited resolving power of $R = 5300$ ($\Delta \lambda = 0.2$ Å, $\Delta v \sim 60$ km s$^{-1}$) across the bandpass, with a total system effective area, $A_{\text{eff}} \approx 2$ cm$^2$.

SLICE was launched aboard a Terrier-Black Brant IX sounding rocket from White Sands Missile Range at 02:00 MDT on 2013 April 21 as part of NASA mission 36.271 UG. The detector acquired data for $\approx 400$ s during the flight, with acquisitions divided into "on-target" times when the stars were in the spectrograph aperture and the pointing was stable. This resulted in exposure times of $T_{\text{exp}}^{i} = 4.5$ s, 30 s, 4.5 s, and 12 0 s for $i = \eta$ Uma, $\alpha$ Vir, $\delta$ Sco, and $\xi$ Oph, respectively (see Table 1). SLICE achieved signal-to-noise ratios (S/Ns) of $> 30$ pixel$^{-1}$ on the first three targets and S/N $\approx 12$ pixel$^{-1}$ over the middle of the SLICE bandpass (1045–1060 Å) on $\xi$ Oph. The SLICE wavelength solution was established pre- and post-flight using collisionally excited H$_2$ emission spectra as a reference. The wavelength solution has an accuracy of approximately 2 pixels across the bandpass ($\approx 0.1$ Å), and a zero-point offset was applied to each target to account for the exact location of the star in the spectrograph aperture. The data were downlinked through the telemetry system as an $[x, y, t]$ photon list.

3. ANALYSIS

3.1. Spectral Extraction and Flux Calibration

An $[x, y, t]$ photon list for each star was created by isolating the "on-target" times $\Delta t = T_{\text{exp}}^{i} + T_{\text{exp}}^{\text{off}}$, where $T_{\text{exp}}^{i}$ is the start time for each integration. Each $[x, y, t]$ photon list was collapsed over the cross-dispersion astigmatic height ($\approx 3.5$ mm) and divided by $T_{\text{exp}}^{i}$ to produce one-dimensional stellar spectra in units of (counts s$^{-1}$). We combined our highest S/N observation with stellar models to create a flux calibration curve for the SLICE instrument. We modeled the IUE spectra of $\alpha$ Vir, $\xi$ Sco, and the nearest B-star models (Lanz & Hubeny 2007), finding good agreement with the observed 1150–1250 Å data for a model with $T_{\text{eff}} = 24,000$ K, log($g$) = 3.33, Z = 0.5 $Z_{\odot}$, and $v_{\text{micro}} = 2$ km s$^{-1}$, scaled to an 1150 Å flux, $F(1150) = 8.3 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. A spline function was fitted to the ratio of stellar model-to-SLICE observations for 15 points relatively unobscured by strong stellar or interstellar absorption lines, creating a smooth flux calibration curve from 1020–1070 Å, in units of (erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$/counts s$^{-1}$). The flux-calibrated spectra of $\eta$ Uma, $\alpha$ Vir, $\delta$ Sco, and $\xi$ Oph are shown in Figure 2.

3.2. H$_2$ Profile Fitting and Excitation Diagrams

Column densities. The two primary means of determining column densities for individual H$_2$ rotational levels from absorption line spectroscopy are curve-of-growth fitting and profile fitting. While in principle we have coverage of most of four ($v' = 0$) Lyman bands ($v'' = 6, 5, 4, 3$; with $R(0)$ wavelengths 1024.37 Å, 1036.54 Å, 1049.37 Å, and 1062.88 Å, respectively) that should permit a robust curve-of-growth analysis, $v'' = 6$ is contaminated with stellar+interstellar H$_2$ Ly$\beta$, $v' = 5$ is contaminated with interstellar C II $\lambda 1933$, $3.5$ mm) and divided $T_{\text{exp}}^{i}$ to produce one-dimensional stellar spectra in units of (counts s$^{-1}$). We combined our highest S/N observation with stellar models to create a flux calibration curve for the SLICE instrument. We modeled the IUE spectra of $\alpha$ Vir, $\xi$ Sco, and the nearest B-star models (Lanz & Hubeny 2007), finding good agreement with the observed 1150–1250 Å data for a model with $T_{\text{eff}} = 24,000$ K, log($g$) = 3.33, Z = 0.5 $Z_{\odot}$, and $v_{\text{micro}} = 2$ km s$^{-1}$, scaled to an 1150 Å flux, $F(1150) = 8.3 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. A spline function was fitted to the ratio of stellar model-to-SLICE observations for 15 points relatively unobscured by strong stellar or interstellar absorption lines, creating a smooth flux calibration curve from 1020–1070 Å, in units of (erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$/counts s$^{-1}$). The flux-calibrated spectra of $\eta$ Uma, $\alpha$ Vir, $\delta$ Sco, and $\xi$ Oph are shown in Figure 2.

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Figure 2. Flux calibrated 1020–1070 Å spectra of the SLICE targets. Representative error bars are shown in red and prominent stellar and interstellar lines are labeled. (A color version of this figure is available in the online journal.)

Table 1
SLICE Targets and Results

| Target | Sp Type | d (pc) | T_{exp} (s) | \log_{10} N(H_1)^a | \log_{10} N(H_2) | T(H_2) (K) |
|--------|---------|--------|-------------|---------------------|-----------------|------------|
| η Uma  | B3 V    | 32     | 45          | 20.51 ± 0.11        | <14.86          | ···        |
| α Vir  | B1 III  | 77     | 30          | <19.66              | <14.67          | ···        |
| δ Sco  | B0 IV   | 151    | 45          | 21.04 ± 0.08        | 19.17 ± 0.06    | T_{01} = 67 ± 1 |
|        |         |        |             |                     |                 | T_{exc} = 529 ± 99 |
| ζ Oph  | O9 V    | 112    | 120         | 20.69 ± 0.10        | 20.50 ± 0.12    | T_{01} = 66 ± 3 |
|        |         |        |             |                     |                 | T_{exc} = 350 ± 75 |

δ Sco^b
N(J'' = 0) = 18.93 ± 0.01
N(J'' = 1) = 18.79 ± 0.01
N(J'' = 2) = 16.09 ± 0.05
N(J'' = 3) = 17.20 ± 0.06
N(J'' = 4) = 14.65 ± 0.10
N(J'' = 5) = 14.25 ± 0.14
N(J'' = 6) = 13.33 ± 1.41
N(J'' = 7) <14.51
ζ Oph^b
N(J'' = 0) = 20.26 ± 0.03
N(J'' = 1) = 20.10 ± 0.02
N(J'' = 2) = 18.88 ± 0.04
N(J'' = 3) = 17.47 ± 0.12
N(J'' = 4) = 16.82 ± 0.62
N(J'' = 5) = 15.69 ± 0.25
N(J'' = 6) = 14.08 ± 0.27

Notes.
^a Derived from Lyα measurements (Diplas & Savage 1994), stellar Lyα contaminates N(H_1) measurement for η Uma and α Vir.

^b Errors on individual H_2 rotational levels do not take into account continuum placement uncertainty (see the text).

(McCandliss 2003) and the MPFIT least-squares minimization routines in IDL (Markwardt 2009). Our method takes the theoretical line shape of each H_2 rotational level for a given column density (N(H_2[J'' = J, J']) ≡ N(J'')) and Doppler b-value, convolves the synthetic spectrum with the line-spread-function of the SLICE instrument and simultaneously varies all parameters until a best-fit value is found. A single molecular component is known to dominate each sightline (Spitzer et al. 1974; Morton 1975), thus a single component was employed for our fitting. For computational simplicity, we restrict our fits to a single b-value for all of the H_2. To constrain the b-value, we ran H_2 model fits over a portion of the (4–0) band that restricted the fits to
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**4. DISCUSSION**

4.1. Comparison with Previous Observations

The H$_2$ properties derived from the SLICE observations are in rough agreement (factor of two) with most previous observations of the molecular sightlines toward δ Sco and ζ Oph; however, there are some notable differences.

**δ Sco.** The total H$_2$ column density derived from SLICE is approximately a factor of two lower than obtained from Copernicus and previous suborbital observations (Savage et al. 1977; Snow et al. 1988), while the cloud kinetic temperatures ($T_{01}$) and Doppler $b$-values are comparable. Conversely, we find a roughly factor of two to three larger $J'' \geq 4$ excitation temperature (529 K) for the δ Sco sightline than found by either Spitzer et al. (1974; 318 K) or Snow et al. (1988; 210 K). The largest sources of uncertainty for the measurement of H$_2$ column densities are the continuum normalization and the S/N of the data. The Copernicus measurements were made from narrow-bandpass spectral scans that compromise a robust continuum determination, and the sounding rocket data presented by Snow et al. were of low S/N and affected by a poorly characterized source of instrumental scattered light, which made continuum placement challenging. Therefore, we believe the H$_2$ excitation results derived from the SLICE data are more accurate.

**ζ Oph.** We found a somewhat (∼30%) lower $N$(H$_2$) than Copernicus (Spitzer & Cochran 1973; Savage et al. 1977), although this may be attributable to line-blending between the Ari 1.1048 line and the heavily damped (4–0) $R$(0) line in the lower resolution SLICE data. As a check, we isolated the fits to the (3–0) $R$(0), $R$(1), and $P$(1) lines (recall that stellar
and interstellar spectral contamination prevents measurement of the entire (3–0) Lyman band. The (3–0) $J'' = 0$ and 1 fits found column densities approximately 30% larger than the Copernicus value. Therefore, the average SLICE N(H$_2$) is consistent with the average Copernicus result. We find a nearly identical excitation temperature ($T_{\text{exc}} = 324$ versus 350 K), although the SLICE observations yield $N(J'')$ values 0.3–1.0 dex higher for $J'' = 2–6$. This result is surprising given that we find a nearly identical $b$-value for these lines ($b = 3.8$ versus 4 km s$^{-1}$). We tested this directly by comparing the $J'' = 2–4$ equivalent widths measured from the SLICE data with those given in Spitzer et al. (1974). We find equivalent widths $\sim$15%–25% larger in the SLICE data, which is approximately the expected increase in equivalent width (4%–37%) resulting from the larger SLICE column densities. Therefore, we conclude that the enhanced columns of rotationally excited H$_2$ are a physical effect.

### 4.2. Physical Cloud Conditions

Combining the $N(J''')$ measurements derived from the SLICE observations with a plane-parallel interstellar cloud model, we are able to estimate the physical properties of the clouds on the $\delta$ Sco and $\zeta$ Oph sightlines. Under the assumption of constant density, the product of the H$_2$ formation rate on grains ($R_{\text{form}}$) and the total particle density ($n_{\text{H}}$), $R_{\text{form}}n_{\text{H}}$, can be related to the ratio of H$_2$ column density in the $J'' = 4$ level to the atomic hydrogen column density (Jura 1975a), and can be rewritten as

$$R_{\text{form}}n_{\text{H}} = \frac{N(H_2[v'' = 0, J'' = 4])}{N(H_1)} \frac{A_{4\rightarrow 2}}{(0.19 + 3.8p_{2,0})},$$

where $p_{2,0}$ is the radiative redistribution probability calculated by Jura (1975b), $A_{4\rightarrow 2}$ is the radiative transition probabilities for the mid-IR rotational $\Delta J = 4 \rightarrow 2$ emission line (Wolniwicz et al. 1998), and $N(H_1)$ is the interstellar neutral hydrogen column density taken from direct Ly$\alpha$ measurements (Diplas & Savage 1994). A similar equation can be constructed for $J'' = 5$. Under the assumption that the $J'' = 4$ and 5 levels are predominantly populated by a combination of grain formation and radiative pumping (an assumption that is in question; Section 1), we find that the average $R_{\text{form}}n_{\text{H}}$ for $\delta$ Sco and $\zeta$ Oph are $1.7 \times 10^{-15}$ s$^{-1}$ and $2.3 \times 10^{-13}$ s$^{-1}$, respectively.

The product of the H$_2$ formation rate and the cloud density can be used to calculate the total photoabsorption rate ($\beta$) into the Lyman and Werner bands of H$_2$, which sets the balance for the excitation and dissociation of molecules in these clouds. We find $\beta(J'' = 0) = 4.9 \times 10^{-13}$ cm$^3$ s$^{-1}$ and $4.1 \times 10^{-12}$ cm$^3$ s$^{-1}$ for $\delta$ Sco and $\zeta$ Oph. These values are 2–3 orders of magnitude lower than the canonical H$_2$ photoabsorption rate in the diffuse ISM, $\beta_a \approx 5 \times 10^{-10}$ cm$^3$ s$^{-1}$ (Jura 1974), demonstrating that both of these clouds are heavily self-shielded, as expected given the damped $J'' = 0$ and 1 absorption profiles for these sightlines.

Given the typical interstellar H$_2$ formation rate, $R_{\text{form}} \approx 3 \times 10^{-17}$ cm$^3$ s$^{-1}$ (Jura 1975b; Gry et al. 2002), the average H$_2$ cloud density on the $\delta$ Sco sightline is $n_{\text{H}_2} = 56 \text{ cm}^{-3}$. As noted by Snow (1983), the molecular formation rate in the $\rho$ Oph cloud on the $\delta$ Sco sightline may be lower than the typical ISM by factors of 2–3, therefore the $\delta$ Sco cloud density may be as high as 100–150 cm$^{-3}$ if this is the case.

The density in the highly UV-irradiated portion of the $\zeta$ Oph sightline is $n_{\text{H}_2} \approx 7600 \text{ cm}^{-3}$, roughly consistent with previous estimates of the exterior region of the $\zeta$ Oph molecular absorber based on other spectral diagnostics (Black & Dalgarno 1973; Morton 1975; Wright & Morton 1979), and higher than the bulk of the cooler molecular material on the sightline. The combination of high density and high photoabsorption rate ($\beta_{\text{Oph}} \sim 10 \times \beta_{\text{Sco}}$) suggests that a compressed portion of the interstellar cloud lies in close proximity to a strong source of far-UV irradiation (presumably $\zeta$ Oph itself). The increase in $N(J'' = 2–6)$ suggests spatial structure in the interface region on the scale of $\sim$130 AU (1” at the distance of $\zeta$ Oph, the angular displacement in the 40 yr since the Copernicus measurements). Evidence for the $\zeta$ Oph interaction scenario has been clearly demonstrated byWISE observations of a mid-IR bright bowshock in the direction of the space velocity of $\zeta$ Oph (Peri et al. 2012).

The situation is reminiscent of the mid-IR bowshock observed around the runaway O9 V star HD 34078 (France et al. 2007). FUSE observations of HD 34078 have shown the presence of vibrationally excited H$_2$ absorption arising from the compressed and strongly irradiated material swept up in the interaction between the star and the ambient ISM ($n_{\text{H}_2} \approx 10^4 \text{ cm}^{-3}$, Boissé et al. 2005). $\zeta$ Oph is one of only a handful of other stars known to display vibrationally excited H$_2$ in its spectrum (Federman et al. 1995), lending further support to the interaction scenario. We predict that future high-resolution ($R > 10^4$) far-UV (1000–1600 Å) spectroscopy of the $\zeta$ Oph sightline will be able to isolate the velocity signature of this high-density, high-excitation molecular component.

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