MOLECULAR HYDROGEN IN ORION AS OBSERVED BY THE FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER

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Received 2005 March 4; accepted 2005 July 15; published 2005 August 4

ABSTRACT

Diffuse far-ultraviolet stellar emission scattered by dust grains has been observed in a region near the Orion Nebula. In addition to the scattered stellar continuum, emission and absorption features produced by molecular hydrogen have been identified. In this Letter, we present an analysis of this absorption and fluorescent emission from molecular hydrogen in Orion. We model the spectra obtained with the Far Ultraviolet Spectroscopic Explorer using optical depth templates and a fluorescent-emission code. These results are surprising because previous studies have found little ultraviolet absorption from H₂ in this region, and the emission is coming from a seemingly empty part of the nebula. We find that the emission fills in the observed absorption lines where the two overlap. These data support the claim that fluorescent excitation by ultraviolet photons is the primary mechanism producing the near-infrared emission spectrum observed in the outer regions of the Orion Nebula.

Subject headings: ISM: individual (M42) — ISM: molecules — reflection nebulae — ultraviolet: ISM

Online material: color figure

1. INTRODUCTION

The Orion Nebula (M42) is among the most well studied objects in the sky. Its proximity to the Sun, combined with a bright photodissociation region (PDR) and a giant molecular cloud, makes it an ideal region to study a range of astrophysical processes. Molecular hydrogen (H₂) should account for the majority of the molecular mass in this region. Observations of emission and absorption features of this molecule provide useful diagnostics of the physical conditions in PDRs and molecular clouds (Burton et al. 1989; Luhman et al. 1994; Rachford et al. 2002; Kristensen et al. 2003; France et al. 2005). Previous observations of H₂ emission in Orion have been limited to the weak quadrupole rovibrational transitions arising in the near- and mid-infrared (see references above, as well as Habart et al. 2004). In this Letter, we present an analysis of the first far-ultraviolet fluorescent emission spectra of the electronic transitions of H₂ in Orion, obtained by the Far Ultraviolet Spectroscopic Explorer (FUSE). These spectra have been presented by Murthy et al. (2005), in work focusing on the dust-scattering properties of the region. The spectra show a dust-scattered continuum, on which absorption and emission features of H₂ are identified.

Molecular hydrogen can be excited into upper rovibrational levels via fluorescent excitation by ultraviolet photons, non-thermal electrons, and collisionally (thermally), by shocks. In a gas-rich region that contains outflows from young stars and an intense ultraviolet radiation field produced by O and B stars, it seems likely that multiple processes are at work. Near-IR observations of H₂ in Orion have been used to distinguish which of these excitation mechanisms are consistent with the observed emission (Luhman et al. 1994; Kristensen et al. 2003). These FUSE observations do not rule out the possibility of a contribution from shocks; however, they provide solid evidence for UV fluorescence in Orion.

In § 2, we present the FUSE data obtained during a serendipitous pointing equilibration observation (see Murthy et al. [2005] for a comprehensive description of the observations). Murthy et al. (2005) find that the dust-scattered light is dominated by the intense radiation field of θ¹ Ori C (HD 37022, O6 V; Maíz-Apellániz et al. 2004), despite the small angular separation of the observed field from HD 36981 (B5 V). Given its intense far-UV output, θ¹ Ori C is likely to be the dominant source of excitation for the H₂ emission observed in Orion. A model of the H₂ fluorescence, using the unattenuated continuum of θ¹ Ori C as the excitation source, is described in § 3; that model is compared with the observations in § 4. These observations provide evidence that UV excitation gives rise to the observed near-IR emission lines in the Orion Nebula region, in agreement with the findings of Luhman et al. (1994).

2. FUSE OBSERVATIONS AND ANALYSIS

The diffuse region of the Orion Nebula located at R.A. = 05°35′12″.43, decl. = −05°11′35″.3 (J2000) was observed by FUSE for 16.7 ks in time-tagged (TTAG) mode on 2001 November 26 as part of the S405 channel realignment program, described by Murthy & Sahnow (2004) and Murthy et al. (2005). Nebular spectra were acquired across the FUSE bandpass (905–1187 Å) in the (30′′ × 30′′) LWRS aperture (Fig. 1). Descriptions of the FUSE instrument and on-orbit performance characteristics can be found in Moos et al. (2000) and Sahnow et al. (2000). The spectra were obtained from the Multimission Archive at STScI (MAST) and were analyzed with the original CalFUSE calibration (ver. 1.8.7). The calibrated data files for each orbit were then co-added using IDL software, and the individual channels were combined using a cross-correlation algorithm. The exact pointing was determined by comparing Fine Error Sensor (FES) images with images generated by sky-simulator software.

We present the S4054601 spectra at wavelengths longer than Lyβ (Fig. 2), where the bulk of the far-UV emission from H₂ resides. In addition to the numerous absorption lines coming from molecular hydrogen discussed below, we see the scattered photospheric lines from C III λ977 and λ1176, P v λλ1118, 1128, and Si iv λλ1122, 1128, as well as interstellar absorption from C III λλ1036 and N i λλ1135. These features are identified in Figure 2. The fact that P v λλ1118 was seen in the spectrum is probably the most conclusive argument for θ¹ Ori C (as opposed to HD 36981) illuminating this region of Orion. Atomic hydrogen lines are highly contaminated by the interstellar medium, and Pellerin et al. (2002) find that P v is not
present in stars of spectral type later than B2 V. Finally, we find an unidentified absorption feature at 1031.4 Å that we tentatively assign to blueshifted O VI. Blueshifted O VI absorption is seen in many stars of this spectral type (Pellerin et al. 2002); however, we cannot conclusively identify it, as the 1038 Å component of the doublet falls in a region dominated by H_2 and C II absorption.

3. MODELING MOLECULAR HYDROGEN IN ORION

The ultraviolet absorption and emission features of H_2 observed in Orion are seen imposed on the dust-scattered continuum of θ^1 Ori C (Murthy et al. 2005). A model of the nebular dust-scattering continuum is beyond the scope of this work, but we set the baseline for the molecular hydrogen by fitting the continuum with a double power law of the form

\[ S(\lambda) = \left( \frac{\lambda}{\lambda_0} \right)^\alpha - C \left( \frac{\lambda - \lambda_0}{\lambda_0} \right)^\beta \]

Scaled to the data. This simple empirical expression, with \( \lambda_0 \) of 1187 Å, yields \( \alpha = 0.1, \beta = 2.0, \) and \( C = 5.0. \) An H_2 absorption spectrum was calculated using the “H2ools” optical depth templates (McCandliss 2003). As the Doppler \( b \) value is uncertain, we have adopted 2 km s\(^{-1}\) for this diffuse region, consistent with \( b \)-values observed along the line of sight to other stars in this region of Orion (Spitzer et al. 1974; Jenkins & Peimbert 1997). With that assumption, we used the templates to fit the 4–0 band \( (\lambda \approx 1050 \text{ Å}) \) and find a total \( N(\text{H}_2) = 4.7 \times 10^{19} \text{ cm}^{-2}. \) Absorption out of the ground electro-vibrational state for the first six rotational states was considered, but most
of the absorption lines comes from \( j = 0 \) and \( j = 1 \). Because the absorption lines are partially filled in by the fluorescent emission (see below), the true \( N(\text{H}_2) \) for this line of sight is most likely greater than \( 4.7 \times 10^{21} \, \text{cm}^{-2} \). This level of \( \text{H}_2 \) absorption is surprising, as studies of stars in this region find a very low molecular fraction in the intervening gas (Abel et al. 2004 and references therein).

We fit the emission spectrum of \( \text{H}_2 \) seen in these \textit{FUSE} data using the hydrogen fluorescence model described in France et al. (2005). Using parameters for the Orion region found in the literature for \( N(\text{H}_2) \) and temperature, this fluorescent-emission model assumes a ground electronic state population and then uses photoexcitation cross sections and an incident radiation field to calculate the rovibrational levels of the upper electronic states (predominantly \( B^1\Sigma_u^+ \) and \( C^3\Pi_u \)). The molecules then return to the ground electronic state following the appropriate selection rules and branching ratios, producing the observed UV emission lines and leaving the molecules in excited ro-vibrational levels. Kristensen et al. (2003) imaged regions of the Orion Nebula in the near-IR rovibrational lines of \( \text{H}_2 \) to determine the excitation temperature. They found a clear delineation between hot and cold zones, requiring more than one temperature component to produce a reasonable fit to the observations. We therefore adopted the rotational temperature of 390 K from Habart et al. (2004) as the cool (thermal) component and a vibrational temperature of 2500 K as representative of the hot (shocked or nonthermal) component (France et al. 2005). An \( N(\text{H}_2) = 1 \times 10^{21} \, \text{cm}^{-2} \) (Habart et al. 2004) was used with a \( b \)-value of 2 km s\(^{-1}\). Each of these parameters affects the resultant model spectrum differently. The model spectra change very little with \( b \) for values of a few kilometers per second. Varying the column density changes the total emitted power, higher column density giving more output photons, but self-absorption begins to suppress discrete lines at columns greater than \( \sim 5 \times 10^{21} \, \text{cm}^{-2} \). Temperature controls both the shape and scale of the model spectra, with more levels of the ground electronic state populated at higher temperatures.

Radiation from \( \theta^1 \) Ori C dominates the ambient field in this part of Orion (Murthy et al. 2005). It is most likely responsible for pumping the observed fluorescence and should thus be used as the input field for modeling the \( \text{H}_2 \) emission. This is complicated by two factors: (1) a well flux-calibrated far-UV spectrum of \( \theta^1 \) Ori C does not exist, and (2) the majority of the absorption seen on the HD 37022 line of sight is thought to be located in intervening clouds (Bautista et al. 1995; Murthy et al. 2005). A spectrum of \( \theta^1 \) Ori C as observed from Earth will not be representative of that seen by the molecules in Orion. In an attempt to overcome these concerns, we chose a lightly reddened SMC star of similar spectral type (AV 243; O6 V, \( E_{B-V} = 0.09 \)) from the \textit{FUSE} Magellanic Cloud atlas by Danforth et al. (2002; see also Walborn et al. 2002). A simple correction for the differences between Milky Way and SMC dust was made using the computed extinction curves from Weinberger & Draine (2001), assuming the reddening of \( \theta^1 \) Ori C at the \textit{FUSE} pointing is similar to what is observed along the HD 36981 sight line (\( E_{B-V} = 0.04 \)). We assumed that the reddening on the AV 243 line of sight was due to equal contributions from Milky Way (\( R_V = 5.5 \)) and SMC dust. An \textit{International Ultraviolet Explorer} (IUE) spectrum of \( \theta^1 \) Ori C (SWP01394, also obtained from MAST; Bohlin & Savage 1981) was used to cross-calibrate the surrogate \textit{FUSE} spectrum in the overlap region between 1150 and 1187 Å. Primary uncertainties in this approach are a lack of knowledge about the attenuation between the star and the nebula, the actual contribution from SMC and Milky Way dust, and possible calibration problems with the \textit{IUE} spectrum (Massa & Fitzpatrick 2000). Using this incident radiation field and the parameters described above, we constructed the fluorescence spectrum (convolved with a 0.5 Å box kernel) for comparison with the data.

### 4. Discussion

The nebular spectra and the model described above are shown in Figure 2. The model finds satisfactory qualitative agreement with the relative line strengths seen in the \textit{FUSE} spectra between Ly\(\beta\) and the end of the bandpass. We find effects similar to those seen in far-UV spectra of the emission/reflection nebula IC 63, namely, that the observed \( \text{H}_2 \) emission lines are seen to be broader than what is expected from the instrumental profile for these filled-aperture observations (France et al. 2005). A study of the possible mechanisms that would produce this broadening is under way. The two major discrepancies that we find between the data and the relative strengths predicted by the model are in the region between 1040 and 1050 Å, and the band of lines centered on 1161 Å. The 1040–1050 Å region may be contaminated by broad wind emission from O\,vi, as \( \theta^1 \) Ori C also shows an “excess” in this range (Murthy et al. 2005), but the exact cause is uncertain. The 1161 Å band seems to be sitting on a “shelf” that is not predicted by the model. One hypothesis that we explored was the possibility of hot \( \text{H}_2 \) (\( T \geq 2500 \, \text{K} \)) being fluoresced by nebular Ly\(\alpha\), as is seen in the far-UV spectra of pre–main-sequence stars (Wilkinson et al. 2002) and accreting binary systems (Wood & Karovska 2004). In order to test this theory, we added a linear continuum that extended the excitation spectrum to 1300 Å and a Gaussian emission line at Ly\(\alpha\). This additional excitation out of excited states of \( \text{H}_2 \) does not resolve our problem with the 1161 Å band. We find that as the 1161 Å band begins to fill in, numerous other lines are predicted that we do not observe in the \textit{FUSE} spectra. The most likely conclusion is that our model is lacking some physical mechanism that gives rise to these features.

The model does not agree with the observed absolute flux. We find that in order to correctly predict the observed absolute flux, our model output needs to be scaled up by a factor of 2. We attribute this to three possible causes: (1) an uncertainty in the degree of \( \text{H}_2 \) clumping in this region, (2) an uncertainty of the true strength of the exciting radiation field, and (3) the (unknown) mechanism that causes discrepancies at 1045 and 1161 Å. Dust and molecular hydrogen are known to be found in clumpy or filamentary structures in regions where hot stars interact with their surroundings (O’Dell 2000; Kristensen et al. 2003; France et al. 2004); however, we find this explanation unlikely. Creating similar models at higher column densities shows that while the overall emitted power increases with column, the majority of this extra emission is located outside the \textit{FUSE} bandpass (\( \lambda \geq 1200 \, \text{Å} \)). The second possibility is that our input excitation field does not accurately represent the local absolute radiation field. We feel confident that the spectral characteristics of the input spectrum are good based on the relative agreement with the \( \text{H}_2 \) emission spectrum, but we are less confident in the absolute scale. Changes in our reddening assumptions, absolute calibration of the \textit{IUE} spectrum we used (Massa & Fitzpatrick 2000), and uncertainties in the nebular distance or geometry can easily explain the scaling required. Finally, further modeling efforts are underway to resolve the problems described above.

The molecular hydrogen absorption lines present in the spectra also show an interesting behavior. One would expect, based on the decreasing oscillator strengths (McCandliss 2003), that...
the lines would be shallower during the progression to smaller vibrational transitions (4–0 to 0–0, shown in Fig. 2). We find that the absorption profiles are of almost identical depth in each of the bands. We attribute this to a filling effect by the emission from H₂ where the emitting and absorbing transitions overlap. There are a greater number of emitting transitions overlapping with the absorption lines at shorter wavelengths, so fitting the absorption lines at the 4–0 band leads to an underprediction of the strength of the lines in the longer wavelength bands of molecular hydrogen. This finding leads us to stress that meaningful column densities cannot be determined without correcting for the emission lines and properly addressing the dust scattering to set the continuum level.

There has been uncertainty in the degree to which shocks or ultraviolet photoexcitation leads to the observed near-IR lines of molecular hydrogen seen in Orion (Burton et al. 1989; Luhman et al. 1994; Kristensen et al. 2003). These FUSE data rule out models that consider only shocks as the mechanism producing the near-IR emission. Shocks cannot populate the excited electronic states of molecular hydrogen that give rise to the emission lines seen (Shull & Beckwith 1982). Hydrogen molecules will be dissociated by collisions at temperatures greater than roughly 4000 K; thus, they would be destroyed before reaching temperatures sufficient to begin populating the first excited electronic state, B¹Σ⁺ (E ≈ 11 eV). These data cannot exclude shocks making a contribution to the near-IR H₂ emission (Kristensen et al. 2003), but ultraviolet excitation clearly contributes to the rovibrationally excited population of hydrogen molecules in the Orion Nebula.

We would like to acknowledge Jayant Murthy and Dave Sahnow for alerting us to the existence of these FUSE data and for helpful discussions. We thank Paul Feldman for his insights on molecular hydrogen, and Alex Fullerton for enjoyable discussion about the ultraviolet spectra of hot stars. This Letter has been greatly improved by the comments of an anonymous referee. Observations were obtained by the NASA-CNES-CSA FUSE mission, operated by Johns Hopkins University.

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