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H_2 EMISSION AS A TRACER OF MOLECULAR HYDROGEN: LARGE-SCALE OBSERVATIONS OF ORION

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ABSTRACT

We have detected extremely extended (>1°.5, or 12 pc) near-infrared H_2 line emission from the Orion A molecular cloud. We have mapped emission in the 1.601 μm $v = 6$–4 $Q(1)$ and 2.121 μm $v = 1$–0 $S(1)$ lines of H_2 along a $\sim 2°$ R.A. cut and from a $6' \times 6'$ region near θ^1 Ori C. The surface brightness of the extended H_2 line emission is 10^{-6} to 10^{-5} ergs s^{-1} cm^{-2} sr^{-1}. Based on the distribution and relative strengths of the H_2 lines, we conclude that UV fluorescence is most likely the dominant H_2 emission mechanism in the outer parts of the Orion cloud. Shock-heated gas does not make a major contribution to the H_2 emission in this region. The fluorescent component of the total H_2 $v = 1$–0 $S(1)$ luminosity from Orion is 30–40 $L_\odot$. Molecular hydrogen excited by UV radiation from nearby OB stars contributes 98%–99% of the global H_2 line emission from the Orion molecular cloud, even though this cloud has a powerful shock-excited H_2 source in its core. The ability to detect large-scale H_2 directly opens up new possibilities for the study of molecular clouds.

Subject headings: infrared: ISM: lines and bands — ISM: clouds — ISM: individual (Orion Nebula) — ISM: molecules

1. INTRODUCTION

Most of the gas in giant molecular clouds is H_2. Yet, beyond a few well-defined small regions near sites of star formation or ionization fronts, the only direct detections of the molecular gas are through emission from trace species, most notably the lowest rotational lines of CO. Rovibrational H_2 emission in the near-infrared arises as a result of UV excitation by nearby OB stars and/or as a result of shock heating of the molecular gas and is therefore an excellent tracer of energetic environments (e.g., Shull & Beckwith 1982; Beckwith et al. 1983; Hayashi et al. 1985; Sellgren 1986; Gatley et al. 1987). Outside these energetic regions, the H_2 lines are faint and difficult to detect. Near cloud cores, measurements of the ratios of H_2 lines longward of 2 μm imply that the highest surface brightness H_2 emission is thermally excited in shock-heated gas (e.g., Draine, Roberge, & Dalgarno 1983; McKee, Chernoff, & Hollenbach 1984). On parsec scales, both UV radiation from OB stars and large-scale shock dissipation of the kinetic energy in protostellar winds and molecular outflows may excite H_2, producing emission from the entire cloud. We can distinguish between the possible excitation mechanisms by comparing the strengths of well-chosen H_2 lines.

Using a new instrument optimized for the detection of diffuse, near-infrared line radiation, we have made the first observations of large-scale H_2 emission from the Orion A molecular cloud. Previous maps of lines of trace species toward Orion A have revealed very extended molecular gas. In ^{13}CO, the cloud extends 4° North-South and appears filamentary; the brightest feature is a $\sim 10' \times 80'$ "∫-shaped filament" behind the Orion Nebula (Bally et al. 1987). At the declination of the nebula, bright ($\int T_A{}^*[V]dV > 5$ K km s^{-1}) ^{13}CO emission extends east-west over $\sim 40'$ as well. In ^{12}CO (Maddalena et al. 1986), the cloud is elongated north-south ($\sim 10°$), but is also very extended ($\sim 3°$) east-west. The molecular cloud lies behind the compact H II region M42, which is ionized by the Trapezium cluster stars, in particular θ^1 Ori C, and to a lesser extent θ^2 Ori A. Stacey et al. (1993) have detected [C II] emission over more than 30′ (4 pc) along the H II region/molecular cloud interface. The Orion A cloud also contains at least 12 molecular outflows (Fukui et al. 1993), including the powerful BN-KL outflow source, and is surrounded by a spherically expanding, high-velocity ($v_{LSR} \sim -100$ km s^{-1}) shock triggered by a supernova event $\sim 3 \times 10^5$ yr ago (Cowie, Songaila, & York 1979). This global shock may be influencing the outer regions of the Orion cloud (Bally et al. 1987). A copious supply of UV photons and the presence of possible sources of shock excitation make Orion A a good place to search for widespread H_2 emission.

Ultraviolet excitation (UV fluorescence) populates high vibrational levels of H_2, which are not populated collisionally in shocks. Therefore, H_2 lines from high-v levels ($v > 2$) are the best tracer of fluorescent H_2 emission. Virtually all previous detections of fluorescent H_2 have relied on the strongest H_2 lines between 2 and 2.4 μm ($\Delta v = 1$, $v_{\rm upper} = 1$ or 2), which are often an unreliable diagnostic of fluorescent gas (Sternberg & Dalgarno 1989; Burton, Hollenbach, & Tielens 1990). To have definitive tracers for both thermally and UV-excited H_2, we observed the 2.121 μm $v = 1$–0 $S(1)$ ($E_{\rm upper} = 7 \times 10^3$ K) *and* the 1.601 μm $v = 6$–4 $Q(1)$ ($E_{\rm upper} = 3.1 \times 10^4$ K) lines of H_2. We chose the $v = 6$–4 $Q(1)$ line based on the strength of this high-v level transition, as predicted by Black & van Dishoeck (1987) and Sternberg (1988).

2. OBSERVATIONS

We observed the 1.601 μm $v = 6$–4 $Q(1)$ and the 2.121 μm $v = 1$–0 $S(1)$ H_2 transitions in Orion on the McDonald Observatory 2.7 m and 0.9 m telescopes in 1992 October/December and in 1994 January, respectively, and on the Steward Observatory 1.55 m telescope in 1994 February. We used the University of Texas Near-Infrared Fabry-Perot Spectrometer (Luhman et al. 1994). The instrument beam size is 49″ ($\Omega = 4.4 \times 10^{-8}$ sr), 150″ ($\Omega = 4.2 \times 10^{-7}$ sr), and 65″ ($\Omega = 7.9 \times 10^{-8}$ sr) on the McDonald 2.7 m, 0.9 m, and Steward 1.55 m telescopes, respectively. The spectrometer consists of a solid-nitrogen-cooled InSb photovoltaic detector behind a narrowband (0.5%–1%) filter. The filter serves as an order sorter for an ambient temperature Fabry-Perot interferometer. The system is limited by sky noise due to telluric OH^- line intensity fluctuations at 1.6 μm and by thermal background at 2.1 μm.

We calibrated the wavelength scale using an argon lamp and a helium/neon discharge tube. We observed by scanning the Fabry-Perot across the unresolved H_2 line. The velocity resolution was 91 km s^{-1} at 1.6 μm and 111 km s^{-1} at 2.1 μm. The integrating detector readout electronics allowed us to observe without rapid sky chopping. We removed the background signal by subtracting sky spectra taken 2° west of θ^1 Ori C ($\alpha_{1950} = 5^h32^m49^s.0$, $\delta_{1950} = -05°25'16''$) immediately before or after on-source observations.

We made an E-W strip map at the declination of θ^1 Ori C, acquiring spectra at 2′ to 4′ intervals within 10′ to 20′ of θ^1 Ori C and with increased spacing farther from the star. For the outer portions of the cut, we observed only the $v = 1$–0 $S(1)$ line. We also mapped a ~6′ square region centered on the Trapezium star cluster by raster-scanning the telescope on a 1′ grid. The absolute pointing uncertainty was 5″ and 10″ for the $v = 6$–4 $Q(1)$ and the $v = 1$–0 $S(1)$ data, respectively. The flux calibrator was the B0 Ia star BS 1903, assumed to have H and K band magnitudes $m_H = 2.13$ and $m_K = 2.18$, corresponding to a flux density of 1.5×10^{-21} ergs s^{-1} cm^{-2} Hz^{-1} at 1.60 μm and 9.4×10^{-22} s^{-1} cm^{-2} Hz^{-1} at 2.12 μm. To correct for atmospheric opacity changes, we scaled the data by the line strength toward θ^1 Ori C, which we measured repeatedly. Based on comparisons with other standard stars and on variations in the H_2 line flux toward θ^1 Ori C, we estimate that the absolute flux calibration is accurate to ±15%.

3. RESULTS

Figure 1 shows E-W strip maps of the $v = 6$–4 $Q(1)$ and $v = 1$–0 $S(1)$ lines, as well as the 158 μm [C II] line (Stacey et al. 1993). All H_2 data points are $\geq 3\,\sigma$ detections, except for the $v = 1$–0 $S(1)$ measurements toward 6′ W, 8′ W, 16′ E, and 60′ E (2 σ); 34′ W and 76′ E (<1 σ). The $v = 1$–0 $S(1)$ line strength ([3.03 ± 0.10] $\times 10^{-4}$ ergs s^{-1} cm^{-2} sr^{-1} in a 49″ beam) toward θ^1 Ori C agrees with previous observations smoothed to our spatial resolution (Garden 1986). Figure 1 shows that the H_2 emission is extremely widespread, detectable out to ~1°, or 8 pc ($D = 450$ pc), from θ^1 Ori C. The E-W cut in the $v = 1$–0 $S(1)$ line shows a "plateau" beyond 4′ from θ^1 Ori C that drops off gradually toward the edges of the strip map, similar to the "plateau" seen in the [C II] line.

Figure 2 shows the $v = 6$–4 $Q(1)$ and $v = 1$–0 $S(1)$ maps of the inner 6′ × 6′ of Orion A, along with the [C II] map of Stacey et al. (1993). In Orion, the [C II] line traces hot neutral gas at cloud surfaces illuminated by 11.2–13.6 eV photons. While the $v = 1$–0 $S(1)$ and [C II] line strengths vary by an order of magnitude or more over the mapped region, the $v = 6$–4 $Q(1)$ line only varies by a factor of 2. Observations using small chopper throws (1′–2′) therefore would have suppressed the $v = 6$–4 $Q(1)$ line. Note that the $v = 6$–4 $Q(1)$ and [C II] peaks lie toward the Trapezium cluster, while the $v = 1$–0 $S(1)$ peak lies toward the BN-KL outflow source.

4. DISCUSSION

What produces the large-scale, low surface brightness H_2 emission: UV-excited or shock-heated gas? Several arguments suggest that UV fluorescence excites H_2 in the region beyond 4′ from θ^1 Ori C, which we refer to as the "plateau" or "outer cloud" region. First of all, the observed relative H_2 line strengths ($\bar{I}_{1-0S(1)} = 2.9 \times \bar{I}_{6-4Q(1)}$) for the "outer cloud" agree well with model predictions of fluorescent H_2 emission from photon-dominated regions or PDR's ($I_{1-0S(1)} =$ [2.4–3.2] $\times I_{6-4Q(1)}$; Black & van Dishoeck 1987; Sternberg 1988), implying that UV fluorescence excites H_2 across the face of the extended Orion molecular cloud. Next, the absolute H_2 line emission along the "plateau" compares well with the calculated fluorescent line intensities. The typical $v = 1$–0 $S(1)$ intensity from the "plateau," say ~15′ east of θ^1 Ori C, is

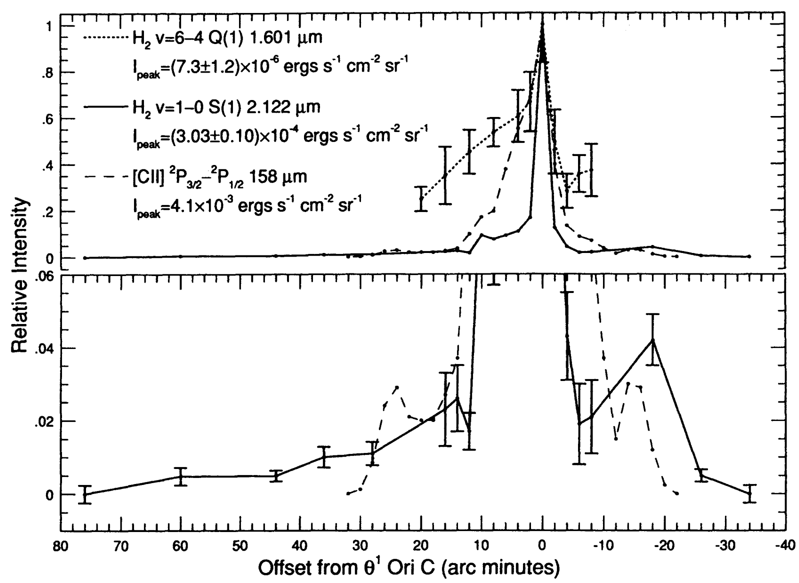

FIG. 1.—*Top*: Right ascension strip map ($\delta_{1950} = -05°25'16''$) across the face of the Orion molecular cloud in the H_2 $v = 6$–4 $Q(1)$ and $v = 1$–0 $S(1)$ lines (49″ beam) along with the 158 μm [C II] line (55″ beam; Stacey et al. 1993). The [C II] cut is offset ~75″ to the north of θ^1 Ori C. We have normalized the line intensities by the peak values shown in the figure and have plotted the $v = 6$–4 $Q(1)$ data with 1 σ error bars. We have not dereddened the H_2 line strengths. *Bottom*: H_2 $v = 1$–0 $S(1)$ and [C II] R.A. cuts plotted on a scale suitable to the low-level emission, along with the 1 σ error bars for the $v = 1$–0 $S(1)$ data points.

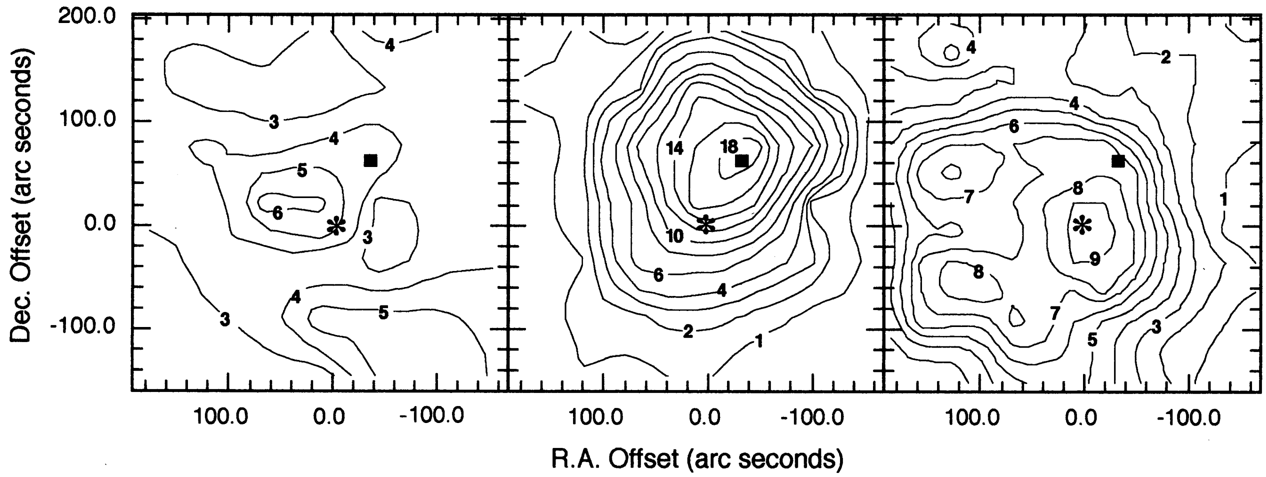

FIG. 2.—*Left*: $v = 6$–4 $Q(1)$ map of the Orion H II region/molecular cloud interface. The peak contour level corresponds to a surface brightness of 6.4×10^{-6} ergs s^{-1} cm^{-2} sr^{-1} in a 65″ beam. The 0, 0 position is at θ^1 Ori C. We have marked θ^1 Ori C and the BN-KL outflow by an asterisk and a square, respectively. *Center*: H_2 $v = 1$–0 $S(1)$ map of the interface region. The contour units are in multiples of the lowest contour level, which corresponds to a surface brightness of 3.53×10^{-5} ergs s^{-1} cm^{-2} sr^{-1} in a 150″ beam. *Right*: 158 μm [C II] map of Stacey et al. 1993 (55″ beam). The contour units are in multiples of the lowest contour level (3.9×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}).

$\sim 7 \times 10^{-6}$ ergs s^{-1} sr^{-1}. Toward this position, the H_2 density n is $\sim 10^3$ cm^{-3} and the incident UV field strength χ is $\sim 10^2$ (Stacey et al. 1993), where χ is unity for Draine's (1978) fit to the average interstellar radiation field. For the same physical conditions, Black & van Dishoeck (1987) and Sternberg (1988) predict $I_{1-0S(1)} = 5.8 \times 10^{-6}$ and 2.4×10^{-6} ergs s^{-1} cm^{-2} sr^{-1}, respectively. Likewise, for the position 1° east of θ^1 Ori C ($n \sim 10^3$ cm^{-3}, $\chi \sim 10$ assuming geometric dilution), the PDR models predict $I_{1-0S(1)} \sim 10^{-6}$ ergs s^{-1} cm^{-2} sr^{-1}, consistent with the observed value of 1.4×10^{-6} ergs s^{-1} cm^{-2} sr^{-1}. The drop ($\sim 5\times$) in $I_{1-0S(1)}$ from 15′ to 1° east of θ^1 Ori C also agrees with Sternberg's (1988) scaling law for fluorescent H_2 emission.

Shock excitation, on the other hand, cannot explain the large-scale H_2 emission. None of the favored shock models for Orion produce significant $v = 6$–4 $Q(1)$ emission (e.g., Chernoff, Hollenbach, & McKee 1982; Brand et al. 1988). They also cannot explain the strong inner ($< \pm 4'$) and diffuse outer envelopes of both the $v = 1$–0 $S(1)$ line and the 158 μm [C II] line, which is produced in PDR's but not in most shock-excited regions (Hollenbach & McKee 1989). Furthermore, the mechanical luminosity from the shock sources available for excitation of H_2 in the "outer cloud" is far less than the observed H_2 luminosity. The known embedded molecular outflows toward the "outer cloud" deposit ~ 2 $L_\odot$ into the Orion A cloud (Fukui et al. 1986, 1993). The mechanical luminosity associated with the high-velocity component of the Orion OB1 association supernova remnant is ~ 0.1 $L_\odot$ over a ~ 3 square degree region of Orion A (Cowie et al. 1979). Over the same area, the measured $v = 1$–0 $S(1)$ luminosity is 34 $L_\odot$, obtained by spatially weighting the points along the "plateau" (excluding the bright inner region) and assuming a circular source as projected on the sky. Even if all of the shock kinetic energy is converted into H_2 emission, neither shock source can account for the observed $v = 1$–0 $S(1)$ luminosity.

Based on the discussion above, we conclude that the H_2 emission from the "plateau" is purely fluorescent. Thus, the value of $L_{1-0S(1)}$ ($=34$ $L_\odot$) derived from the "plateau" emission implies that the total fluorescent H_2 luminosity of Orion is ~ 1900 $L_\odot$, assuming the $v = 1$–0 $S(1)$ line contributes 1.8% of the total H_2 fluorescent emission (Black & van Dishoeck 1987; Sternberg 1988). This luminosity is a lower limit since it applies to the inner 110′, the length of our strip map. We can place a crude upper limit on the fluorescent H_2 luminosity if we assume that the $v = 1$–0 $S(1)$ emission beyond our cut corresponds to our 1 σ detection limit. In this case, the remaining material as defined by the $\sim 3° \times 10°$ CO cloud (Maddalena et al. 1986) can contribute an additional 1600 $L_\odot$, for a total fluorescent H_2 luminosity of 3500 $L_\odot$.

Gautier et al. (1976) and Burton & Puxley (1990) measured a $v = 1$–0 $S(1)$ line luminosity from the Orion/BN-KL shock of ~ 2.5 $L_\odot$, not correcting for extinction. The fraction of the total shocked emission emitted through the $v = 1$–0 $S(1)$ line is $\sim 1/15$ (Burton et al. 1988). Therefore, the emergent H_2 line luminosity from the BN-KL region is ~ 38 $L_\odot$. As mentioned, the remaining molecular outflows contribute at most 2 $L_\odot$ to the total shocked H_2 emission. Thus, the total emergent shocked H_2 luminosity from the whole Orion A cloud is ~ 40 $L_\odot$, which is a mere 1%–2% of the fluorescent contribution.

Toward the "inner" Orion cloud, i.e., $<4'$ from θ^1 Ori C, the faintness of the $v = 6$–4 $Q(1)$ emission compared to $v = 1$–0 $S(1)$ ($I_{6-4Q(1)} = 2.4\% \times I_{1-0S(1)}$ toward θ^1 Ori C) indicates that the H_2 lines arise in a dense PDR ($n \sim 10^5$ cm^{-3}, $\chi \sim$ a few times 10^5) with thermalized emission from UV-pumped H_2. For $n \geq$ a few times 10^4 cm^{-3} and $\chi \geq 10^4$, collisional deexcitation can both depopulate the $v \geq 2$ levels, lowering the contribution of high-v level lines to the total H_2 emission, and thermalize the low-v levels (Sternberg & Dalgarno 1989; Burton et al. 1990). In the "inner" region, UV fluorescence produces high-v H_2 line emission. However, thermal/shock excitation swamps the fluorescent contribution to the $v = 1$–0 $S(1)$ emission toward the Trapezium and BN-KL. The uniformity of the $v = 6$–4 $Q(1)$ emission suggests that toward cloud cores where n and χ are high, the high-v lines of H_2 are suppressed compared to other tracers of UV-illuminated material such as [C II] (see Fig. 2).

5. IMPLICATIONS

The diffuse, large-scale H_2 emission gives us a unique new view of interstellar molecular clouds. Since the diffuse H_2 emission is not thermally excited, we cannot probe the bulk of the molecular gas, but the very different fluorescent excitation mechanism has several key advantages. First of all, fluorescent H_2 emission only traces where UV photons strike *molecular* gas, unlike [C II], which can arise in molecular, atomic, and extended low-density ionized gas (e.g., Stacey et al. 1985; Shibai et al. 1991). We estimate that we can detect H_2 emission from regions with densities and UV illumination as low as $n = 10^2$ cm^{-3} and $\chi = 10$–30. Thus, H_2 can serve as a very useful complement to other large-scale tracers such as [C II] by highlighting cold edges illuminated by modest UV fields. Also, H_2 can trace molecular gas where CO is absent, particularly in low metallicity or low column density clouds (e.g., van Dishoeck & Black 1987; Lada & Blitz 1988). Last, in shock-dominated environments, H_2 is a sensitive probe of diffuse shock emission.

The fact that fluorescence dominates the global H_2 emission in Orion is important for extragalactic studies that compare the H_2 emission from external galaxies with that from Orion (e.g., Fischer et al. 1983, 1987; Kawara, Nishida, & Gregory 1987). Often, these studies assume that the Orion H_2 emission arises in shocked gas. Our H_2 observations show that most of the integrated H_2 emission from Orion and, presumably, from extragalactic giant molecular clouds with nearby OB stars is UV-excited, not shock-heated. Therefore, the inner regions of those galaxies with shock-like spectra cannot be thought of simply as ensembles of OB association/molecular cloud complexes.

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