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NEAR-INFRARED H_2 EMISSION AS A PROBE OF THE GLOBAL ENERGETICS AND MORPHOLOGY OF MOLECULAR CLOUDS

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RESUMEN

Presentamos observaciones y resultados que demuestran la utilidad del H_2 como trazador de las propiedades energéticas globales y la morfología del medio interestelar molecular. Con un nuevo espectrómetro optimizado para la detección de líneas en emisión de bajo brillo superficial, podemos trazar directamente el H_2 a lo largo de las superficies externas de las nubes moleculares. Por ejemplo podemos medir la luminosidad de H_2 en gran escala, de las nubes moleculares galácticas gigantes e investigar la contribución relativa de fotones UV y procesos colisionales (choques) en las propiedades energéticas globales. La emisión del H_2 difuso y extendido proporciona un nuevo conocimiento de las nubes moleculares que complementa la de nuestros trazadores convencionales de la morfología molecular en gran escala.

ABSTRACT

We present observations and results which demonstrate the usefulness of H_2 as a new tracer of the global energetics and morphology of the molecular interstellar medium. With a new spectrometer optimized for the detection of low surface brightness line emission, we can directly trace H_2 along the outlying surfaces of molecular clouds. We can measure the large-scale H_2 luminosity of galactic giant molecular clouds, for example, and probe the relative contribution of UV photons and collisional processes (e.g., shocks) to the global energetics. The diffuse, extended H_2 emission provides a new view of molecular clouds to complement our conventional large-scale tracers of cloud morphology.

Key words: **INFRARED: INTERSTELLAR: LINES — ISM: CLOUDS — ISM: INDIVIDUAL OBJECTS: THE ORION NEBULA — ISM: MOLECULES — MOLECULAR PROCESSES**

1. MOTIVATION

Most of the gas in 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 molecular gas are through emission from trace species, most notably the lowest rotational lines of CO. Ro-vibrational H_2 emission in the near-infrared arises as a result of UV excitation (UV fluorescence) 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. We can distinguish between the possible excitation mechanisms by comparing the strengths of well-chosen H_2 lines (e.g., Black & van Dishoeck 1987; Sternberg & Dalgarno 1989).

Outside the energetic cloud cores (> 0.5 pc), the H_2 emission is faint and very difficult to detect, often lying beyond the sensitivity range of existing instruments. As a result, the H_2 emission is unexplored from environments such as the outlying portions of giant molecular clouds, diffuse clouds, and the global interstellar medium of nearby galaxies. To detect and map very low-surface brightness line emission in the near-infrared, we have constructed a new instrument, The University of Texas Near-Infrared Fabry-Perot Spectrometer (UT FPS; Luhman et al. 1995a). With this instrument we can detect previously unseen H_2 emission from large-scale interstellar environments, probing the global energetics and surface morphology.

2. H_2 EMISSION: A TRACER OF THE GLOBAL ENERGETICS OF MOLECULAR CLOUDS

We have detected extremely extended (>1.5°, or 12 pc) near-infrared H_2 line emission from the Orion A molecular cloud (Luhman et al. 1994). We have mapped emission in the 1.601 μm v=6–4 Q(1), 2.121 μm v=1–0 S(1), and 2.247 μm v=2–1 S(1) lines of H_2 along a $\sim$ 2° R.A. cut near θ^1 Ori C. The surface brightness of the extended H_2 emission is 10^{-6}–10^{-5} ergs s^{-1} cm^{-2} sr^{-1}. Based on the distribution and relative strength of the H_2 lines, we conclude that UV fluorescence is 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 UV fluorescent component of the total H_2 v=1–0 S(1) luminosity from Orion is 30–40 L$_\odot$. Molecular hydrogen

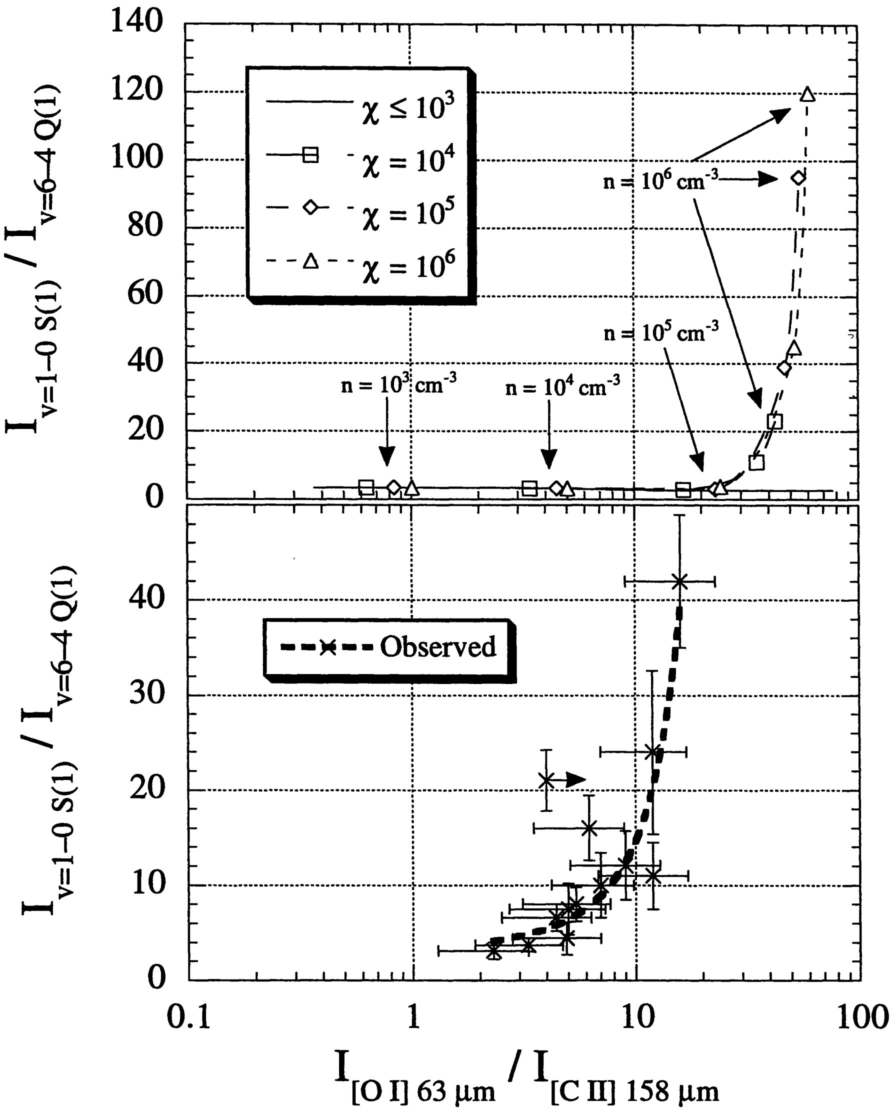

Fig. 1. *(top)* Plots of the H_2 v=1–0 S(1) to v=6–4 Q(1) line ratio versus the [O I] 63 μm to [C II] 158 μm ratio according to the PDR models of A. Sternberg, Tel Aviv University. The strength of the UV field is in multiples of χ, where $\chi = 1$ = average interstellar UV field intensity (Draine 1978). For the data points shown, we label the input density n. *(bottom)* Plot of the observed v=1–0 S(1) / v=6–4 Q(1) versus [O I] 63 μm / [C II] 158 μm. The heavy dashed line depicts an exponential fit to the data points. The "knee" of the exponential fit corresponds to an H_2 critical density of a few times 10^4 cm^{-3}.

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 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 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.

3. H_2 EMISSION FROM DENSE GAS: TESTING THEORETICAL MODELS

We have observed near-infrared H_2 line emission from dense ($n \geq 10^4$ cm^{-3}) photon-dominated regions (PDRs) along the Orion A molecular cloud "ridge" and toward the NGC 2024 H II region in the Orion B molecular cloud (Luhman et al. 1995b). Specifically, we have observed the 1.601 μm v=6–4 Q(1), 2.121 μm v=1–0 S(1), and 2.247 μm v=2–1 S(1) lines of H_2. The observed PDRs reside near one or more OB stars and are exposed to relatively high radiation fields compared to the ambient interstellar field. We combine our H_2 data with observations of the [O I] 63 μm, [O I] 146 μm, and [C II] 158 μm fine-structure lines to make the first cospatial analysis of the PDR line emission from H_2, O^0, and C^+.

Comparing our observations to the predictions of theoretical PDR models, we find that for the range of incident UV field strengths and gas densities that characterize the PDRs, the observed H_2 emission arises, at least in part, from collisional de-excitation of UV-pumped H_2. The theoretical appearance of the H_2 spectrum in this collisionally-quenched regime is not well known, largely due to the highly uncertain critical density n_c at which collisional processes modify the emergent radiative fluorescent spectrum of H_2. We find that the H_2 line ratios depart from their radiative fluorescent values in qualitative agreement with the theoretical models (see Figure 1). However, as shown in Fig. 1, we measure the critical density of H_2 to be a few $\times$ 10^4 cm^{-3}, which is 10 times smaller than the n_c implied by Orion-type PDR models (e.g., Burton, Hollenbach, & Tielens 1990).

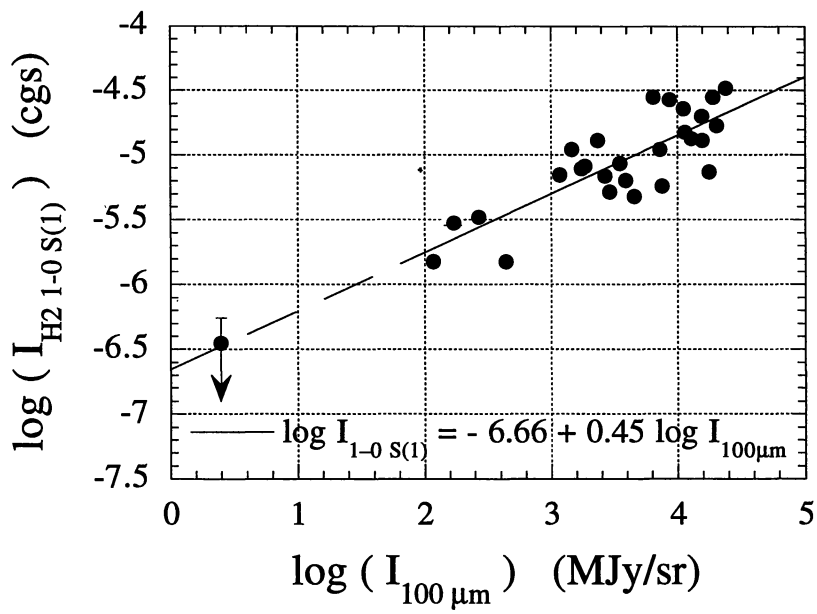

Fig. 2. Log plot of the observed intensity of H_2 v=1–0 S(1) as a function of the *IRAS* 100 μm dust continuum emission. The physical conditions of the observed regions vary from $n \sim 10$–10^2 cm^{-3}, $\chi \sim 1$–10 (lower left-hand corner) to $n \sim 10^4$ cm^{-3}, $\chi \sim 10^3$ (upper right-hand corner). The observed correlation and the slope of the fit shown can be explained solely in terms of the mutual dependence of the H_2 and thermal dust emission on χ, without invoking geometric effects.

4. H_2 EMISSION FROM LOW DENSITY GAS: A NEW TRACER OF THE GLOBAL MORPHOLOGY OF MOLECULAR CLOUDS

We have detected diffuse H_2 emission from low density (10^2–10^4 cm^{-3}) gas exposed to modest UV fields (1–10^2 times the average interstellar radiation field). In this regime, the excitation of H_2 is dominated by UV fluorescence. The observed regions include the outlying portions of the Orion A molecular cloud, the western edge of the NGC 2024/Orion B cloud, and diffuse infrared cirrus clouds. In Figure 2 we plot the observed H_2 v=1–0 S(1) emission from these environments as a function of the *IRAS* 100 μm continuum radiation. The relationship between the H_2 and 100 μm emission implies that, with the UT FPS we can detect H_2 emission from clouds where the infrared flux falls below the sensitivity limit of *IRAS*.

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. The diffuse H_2 emission can trace low density cloud envelopes illuminated by weak UV fields. Therefore, H_2 can serve as a very useful complement to conventional large-scale tracers such as [C II] and CO, which are thermally-excited and are not seen once the gas drops below a certain critical density. Secondly, 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 gas (e.g., Stacey et al. 1985; Shibai et al. 1991). Next, particularly in low metallicity or low column density environments, H_2 can trace molecular gas where CO is absent. Lastly, in shock-dominated environments, H_2 is a sensitive probe of diffuse shock emission.

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