69. JWST Observations of Localized Heating of the Quiescent ISM and what PRIMA can Contribute to Understanding Turbulence

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One of the many aspects of interstellar medium (ISM) physics that has remained elusive is turbulence. A significant fraction of the ISM energy resides in the chaotic (turbulent), superthermal motions of the gas, which play a key role in supporting molecular clouds against gravitational collapse and thus have a major influence on the rate of star formation. We have used JWST/MIRI to observe two regions in the boundary of Taurus in the 17.04 µm S(1) transition of ortho H_2, and very clearly detected small-scale structure on scales 1″–2.5″ (140–350 au), limited in part by signal to noise ratio considerations. The column density in the J = 3 level is typically 2e17 cm^{-2}. This is reasonably well-determined, but the total H_2 column density uncertainty is large because the 28 µm S(0) line, the lowest transition of para H_2, could not be observed with JWST/MIRI. While the angular resolution of PRIMA, 7.6″ at 28 µm, is significantly lower than that of JWST/MIRI, having data on the relatively low-lying S(0) transition ($\Delta E/k$ = 845 K) would be extremely valuable. The intensity measured can be compared with that integrated over an appropriate portion of a mosaic observed with JWST, giving a much better handle on the H_2 level populations. This is critical for modeling collisional excitation, constraining the density and temperature of the excited H_2, whether produced by turbulent dissipation or by some other mechanism such as shocks. The predicted 28 µm PRIMA flux is 4e-19 Wm^{-2}, for which we can obtain a 5σ low-resolution spectral measurement in 0.22 hr, and a 120″x120″ map in 18 hr. We propose a ∼270 hr program to survey excited H_2 emission from ten quiescent regions of the ISM in different environments to assess how common localized heating is, and where it occurs.

Science Justification

Introduction

One of the many aspects of interstellar medium (ISM) physics that has remained elusive is turbulence. Turbulence in the ISM is universal (Heyer & Brunt 2004), and a significant fraction of the ISM energy resides in the chaotic (turbulent), superthermal motions of the gas, which play a key role in supporting molecular clouds against gravitational collapse and thus have a major influence on the rate of star formation (Falceta-Gonçalves et al. 2014; Hennebelle & Falgarone 2012). It is generally felt that turbulent energy is input on large scales, by galactic differential rotation, shocks, and cloud-cloud collisions (Klessen & Hennebelle 2010). Local processes such as stellar winds and radiation can locally increase turbulence but have major effect only on relatively small fraction of the ISM. Most theoretical models have turbulent energy cascading from the large injection scale to smaller scales until the lower end of the inertial range is reached and dissipation becomes important. The scale on which dissipation occurs depends on many factors including the viscosity of the ISM gas and the magnetic field. Within the range of field strengths that plausibly permeate the ISM, the latter can affect the shocks, especially the heating of the postshock gas (LeSaffre et al. 2013). At small scales, $\leqq$ 1e15 cm, we can have shocks generated (LeSaffre et al. 2013), or MHD vortices formed, both resulting in local heating of the gas in these so-called Turbulent Dissipation Regions, or TDRs (Falgarone, Pineau des Forêts, & Roueff 1995; Joulain et al. 1998). The presence of locally heated regions with temperatures $\sim$ 1000 K is demanded by the presence of certain molecules, notably CH+, which have large barriers to their formation, but are widely distributed in the diffuse ISM that otherwise has temperature no higher than 100 K (Falgarone et al. 2005; Moseley et al. 2021).

The gas in TDRs includes molecular hydrogen (H_2), with a small fraction of atomic hydrogen depending on the density and environment of the region in question. The warm H_2 molecules can be observed through rovibrational transitions at infrared and far-infrared wavelengths. Emission from 3 rotational transitions of H_2 was observed from multiple regions around the boundary of the Taurus molecular cloud using Spitzer by Goldsmith et al. (2010). The temperature was found to be greater than 250 K from comparison of different line intensities. For sensitivity reasons, the extraction aperture used for the Spitzer data was 10.7″ x 108″, vastly larger than the expected size of TDRs. Falgarone et al. (2005) also observed H_2 emission from regions where UV and formation pumping should not be dominant.

To study small-scale heating on a more relevant scale, we employed JWST/MIRI medium resolution spectrometer (MRS), having 0.67″ angular resolution and spectral resolution R = 2500. We obtained 4 x 4 mosaics of the 17.04 µm S(1) H_2 line in two regions in the boundary of the Taurus molecular cloud, which after cropping of bad edge pixels covered an area 12.4″ x 13.2″. The lines are not resolved by MIRI/MRS, but the line flux is spread over channels surrounding and including that corresponding to the nominal wavelength. Summing over 5 channels including the line yields mean intensities of 19.6 and 11.6 MJy sr-1 for the "peak" and "edge" regions, respectively, while the rms of the background was 1.1 MJy sr^{-1}. We thus had highly significant detections in most pixels (Goldsmith et al. 2025).

Fig. 1 shows the intensity of the S(1) line, the lowest rotational transition of ortho-H_2, in the edge region. Significant small-scale structure with scale 1.0″ to 2.5″, corresponding to 140 to 250 pc is clearly visible. A characteristic intensity of 10 MJy sr^{-1} corresponds to a H_2 column density in the J = 3 state (the upper level of the S(1) transition) of 1.6e17 cm^{-2}. The total column density of H_2 depends on the temperature and density, which is where PRIMA observations are valuable. A value of the column density that yields a reasonable geometry and is consistent with other requirements on physical conditions is $N(H_2)$ = 8e17 cm^{-2}.

PRIMA can observe the lowest rotational transition of para H_2, the S(0) line at 28.22 µm. This line has a significantly lower A-coefficient as well as lower energy (hf/k = 510 K) compared to the S(1) line of ortho H_2 (hf/k = 845 K). The ratio of the two lines can thus be used to constrain the density and temperature, although the ortho to para ratio (OPR) is an additional uncertainty. Different lines of evidence suggest that while the OPR can plausibly lie between 1 and 3, it is likely not far from 1. For fixed OPR, the S(0)/S(1) ratio increases at lower densities and at lower temperatures so that measurement of the ratio of the two lines can determine or at least constrain n(H_2) and T. For accurate comparison, the JWST data will have to be convolved to the angular resolution of PRIMA.

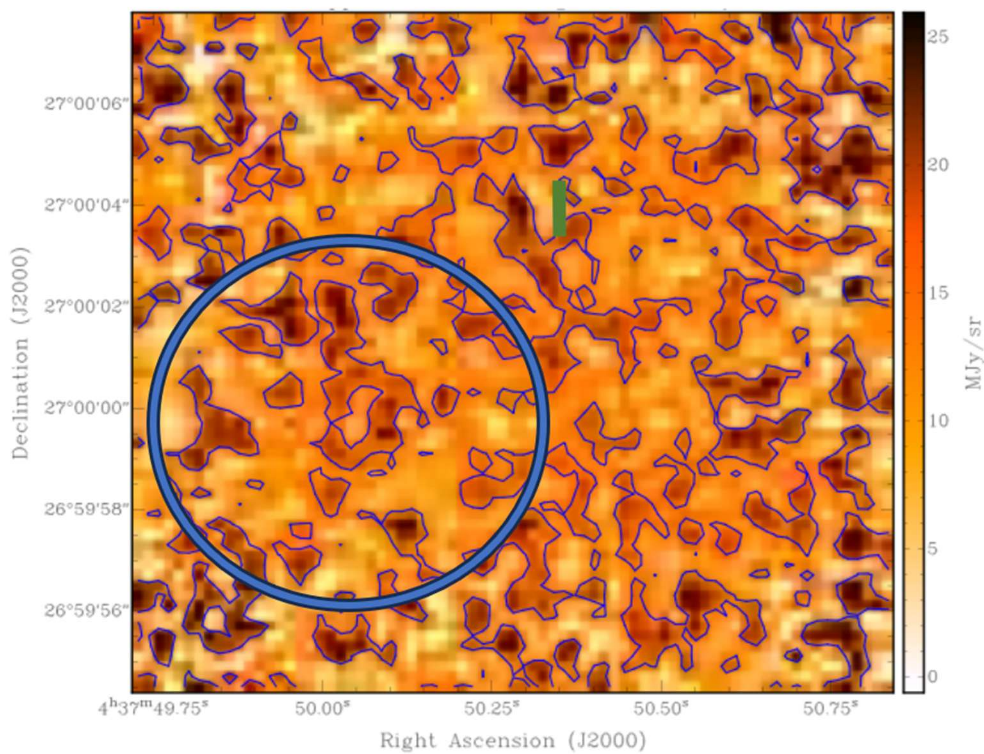

Fig. 1. Image of 17.04 µm H_2 S(1) emission from the edge region in the Taurus molecular cloud boundary obtained with MIRI/MRS instrument on JWST. The angular resolution of JWST at 17.04 µm wavelength is 0.67", corresponding to 94 au at the distance of Taurus. The green bar denotes a size of 1" corresponding to 140 au at the distance of Taurus. The blue circle denotes the 7.6" PRIMA beam at the 28.2 µm wavelength of the S(0) transition of H_2. Adapted from Goldsmith et al. (2015).

The S(0) line has the advantage that, as shown in Fig. 2, its intensity is relatively independent of n(H_2) and T over the range that likely characterizes the heated condensations observed with JWST. It thus can deliver alone a reasonable estimate of N(H_2) in the J = 2 level and so can be used for larger-scale studies of the heated material. Spitzer observations suggested that this was present in regions surrounding the Taurus molecular cloud, and other observations have detected H_2 rotational emission from lines of sight not associated with massive young stars or other obvious heated sources that would produce PDR regions and thus large quantities of hot H_2. However, we have little information on the extent and occurrence of this phenomenon, and modest-sized maps with PRIMA are a very promising way to determine these parameters.

A very large sample would clearly be desirable, but a reasonable start would be to observe 10 regions. These would be in the boundaries of molecular clouds, mostly sources with very limited star formation to avoid contamination by PDR emission. Regions with measured UV energy density would be favored, but if this information really is not available, it could possibly be obtained independently. Spitzer observations (Goldsmith et al. 2010) indicated that the rotationally excited H_2 emission weakened as one looked directly to the interiors of molecular clouds. This suggests that the turbulent dissipation and heating is restricted to the boundary layers of clouds. An important task is thus to study how the excited H_2 emission depends on position. This requires mapping the equivalent of 5 - 120″ x 120″ regions at different positions in the boundary region of the molecular cloud. A total of 15 - 120″ x 120″ region maps is requested.

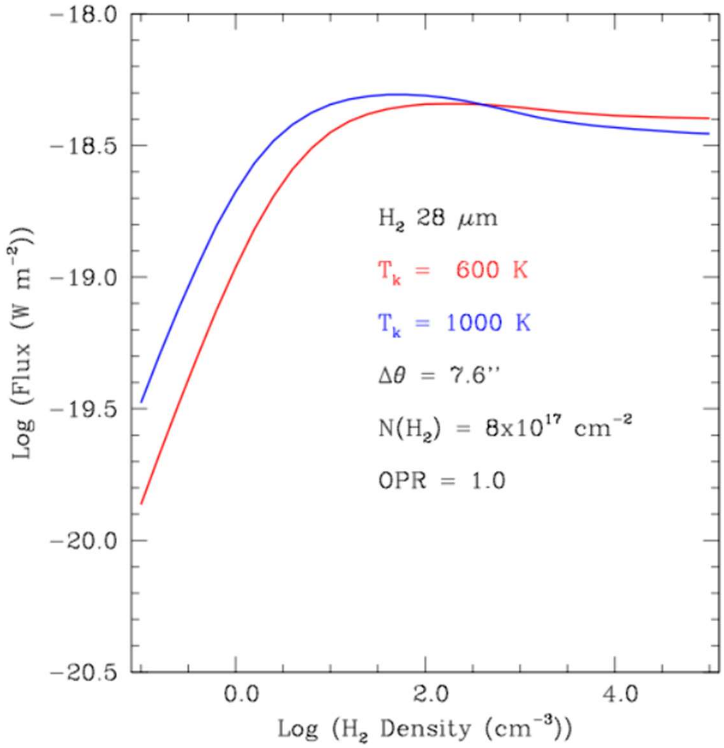

Fig. 2. H_2 S(0) 28 μm flux expected based on JWST measurements of emission from small-scale heated structures shown in Fig. 1.

Instruments and Modes Used

120″x120″ FIRESS low resolution maps at 28 μm, one for each of 15 target regions.

Approximate Integration Time

- Based on the ETC, a 5σ measurement of estimated 4e-19 Wm^{-2} flux with PRIMA requires 0.22 hr integration time for a single pointing. A 120″ x 120″ map with ∼250 spaxels requires 18 hr. To obtain a reasonable sample of regions in different environments, we propose to make 15 such maps. The total integration time will thus be ∼270 hr.

Special Capabilities Needed

None

Synergies with Other Facilities

JWST and ALMA

Description of Observations

We have observed two regions in the boundary of the Taurus molecular clouds with JWST/MIRI and obtained impressive images of H_2 17.04 µm emission, which includes small-scale structures of 1–2.5″ size. The characteristic intensity of these condensations is 10 MJy sr^{-1}. The density and temperature of these regions is uncertain but based on our best estimates of Tk = 600–100 K and $n(H_2)$ = 200 – 400 cm^{-3}, as shown in Fig. 2 we predict a 28 µm flux close to 4e-19 W m^{-2} for PRIMA low resolution spectroscopy. An important aspect of PRIMA observations is that, along with the larger beam size, much more extended maps can be made than are possible with JWST.

Based on the ETC, a 120″ x 120″ region can be mapped to the required 5σ sensitivity of 4e-19 W m^{-2} in 18 hr. The total time required for 15 such maps is thus 270 hr.

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