Molecular Tracers of Turbulent Shocks in GMCs

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Shock Models

Giant molecular clouds (GMCs) contain supersonic turbulence that should decay rapidly due to energy dissipation within shocks (e.g., Stone et al. 1998). In Pon et al. (2012), we run shock models to predict which lines should be the dominant cooling lines in these turbulence induced shocks. These models are based upon the code of Kaufman & Neufeld (1996) and have shock velocities, initial densities, and initial magnetic field strengths ranging from 2 to 3 km s^{-1}, $10^{2.5}$ to 10^5 cm^{-3}, and 3 to 134 μG, respectively. Under the assumption that the turbulent energy of a molecular cloud dissipates on a crossing time, as suggested by numerical simulations, we scale our shock models to predict the total molecular line emission from shocked gas in a molecular cloud.

We find that the majority of the energy dissipated in these shocks is emitted in CO rotational lines.

We compare this shock emission to that from the ambient, unshocked gas in a molecular cloud by comparing our shock models to a Kaufman et al. (1999) photodissociaton region (PDR) model with a density of 1000 cm^{-3} and an interstellar radiation field (ISRF) of 3 Habring. The PDR and shock model predictions are shown in Figure 1.

We find that mid-J CO transitions (J = 5-4 and higher) provide observational tracers of shock excited gas.

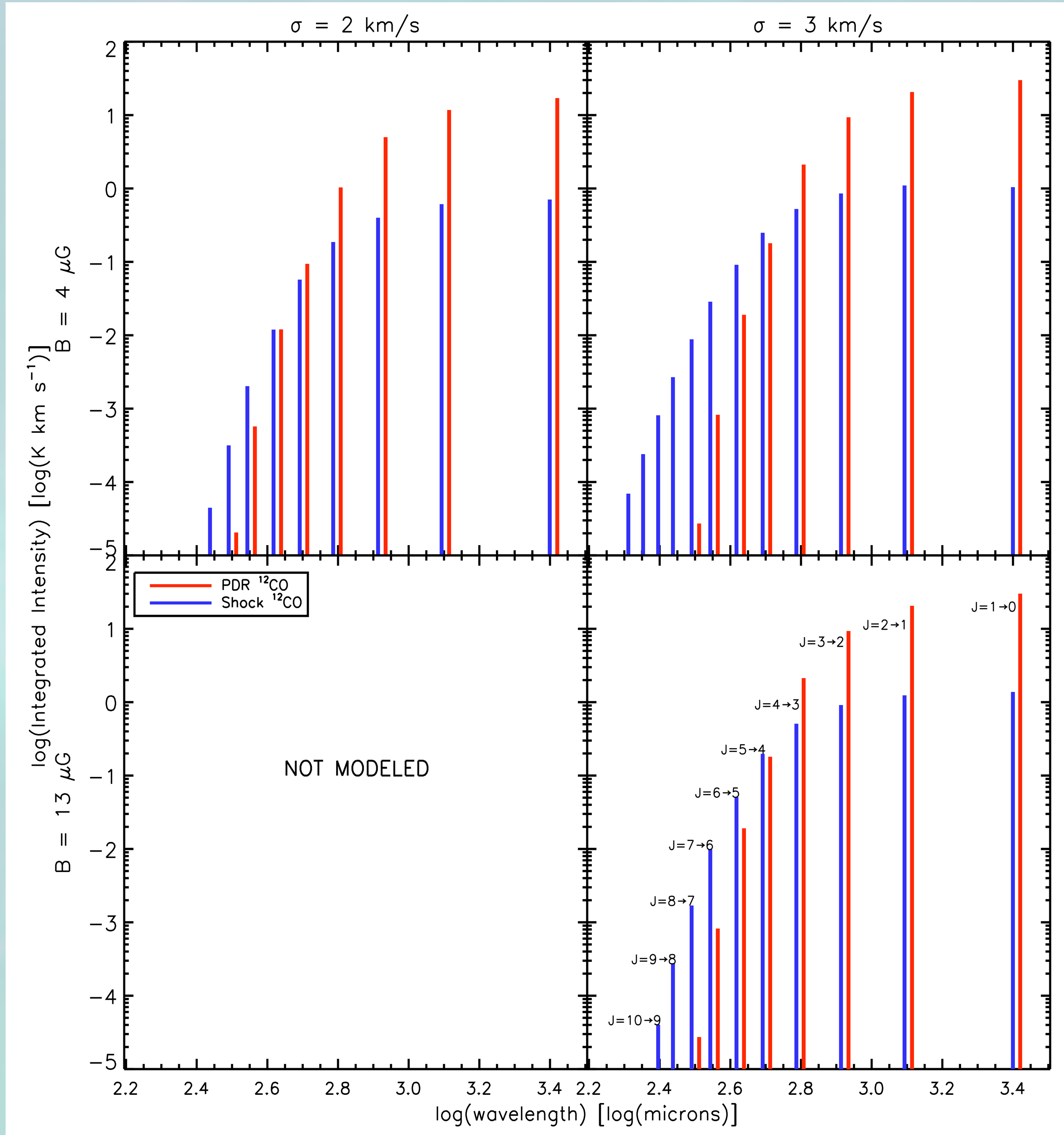


Figure 1: The integrated intensities of various ^{12}CO rotational transitions. The dark blue shows the emission predicted by our shock models with an initial density of 10^3 cm^{-3}, while the red lines show the emission predicted from the PDR model. Note how the shock spectrum dominates over the PDR spectrum for mid to high J transitions.

Perseus B1-East

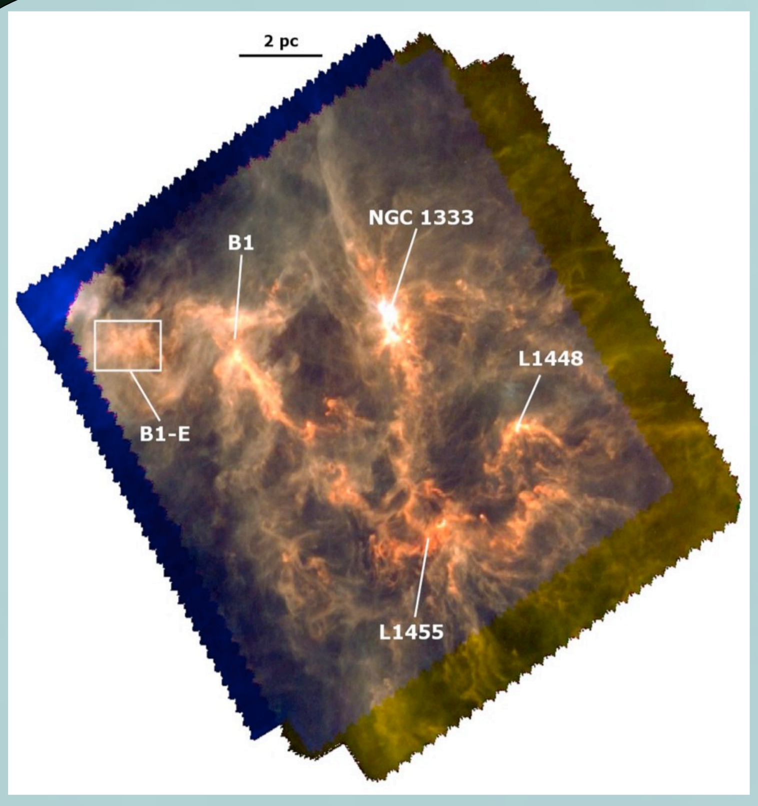
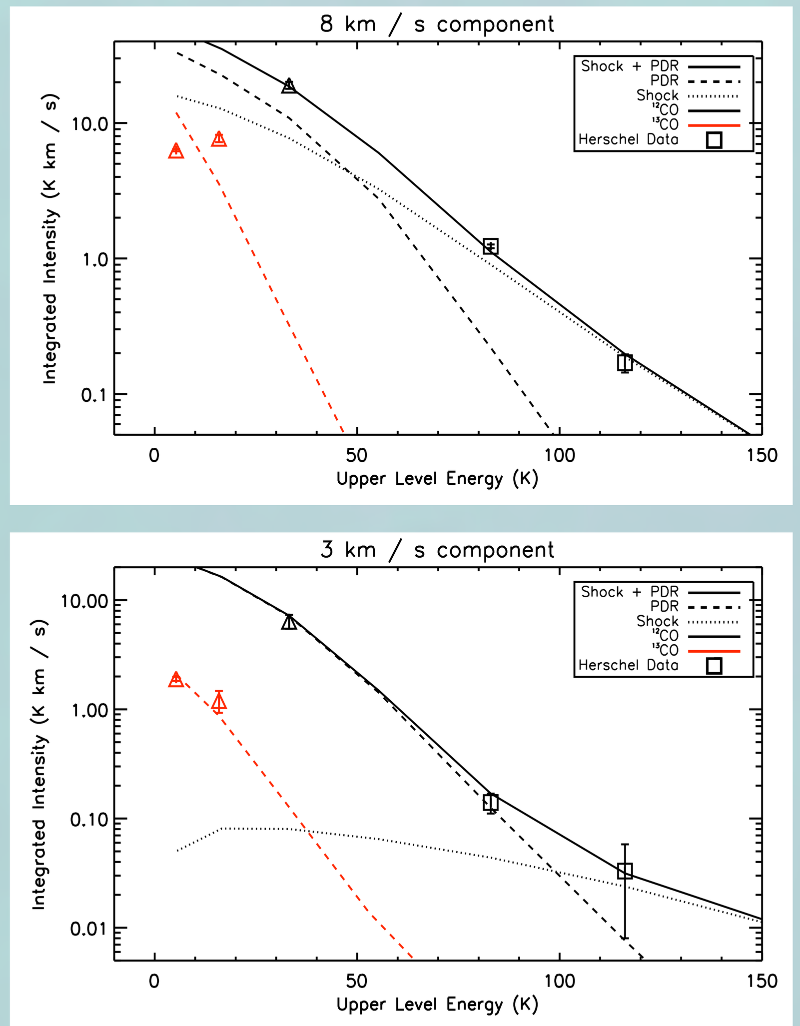


Figure 2: Three colour Herschel image of the southern half of the Perseus molecular cloud showing the location of B1-E, from Sadavoy et al. (2012).

The Perseus B1-East (B1-E) region is located within the nearby Perseus low mass star forming region (as shown in Figure 2) and contains no embedded objects. We have detected the CO J = 5-4 and 6-5 transitions towards B1-E using the Heterodyne Instrument for the Far-Infrared (HIFI) on the Herschel Space Observatory.

We find that the 5-4 and 6-5 lines are too bright, relative to lower J ^{12}CO and ^{13}CO lines, to be explained by a single PDR model. Instead, a hot gas component is also required, consistent with the presence of shock heated gas. Figure 3 shows the spectral line energy distributions (SLEDs) for the 3 km / s and 8 km / s line components detected towards B1-E.

Figure 3: SLEDs for the two velocity components detected towards B1-E. The solid line shows the best fitting model made of two components, a PDR component (dashed line) and a shock component (dotted line). The black points and lines are for ^{12}CO and the red is for ^{13}CO. Our Herschel observations are shown as squares. The ^{12}CO 3-2 and ^{13}CO 2-1 integrated intensities are from Sun et al. (2006) and the ^{13}CO 1-0 integrated intensity is from Ridge et al. (2006). Note how a shock component is required to match the intensities of the higher lines.



Infrared Dark Clouds (IRDCs)

Using HIFI on Herschel, we have mapped the CO J = 8-7, 9-8, and 10-9 transitions around four quiescent cores in dense (10^5 cm^{-3}) infrared dark clouds. Figure 4 shows the integrated intensity of the CO J = 8-7 transition towards three of these IRDC cores. No significant emission was detected towards the fourth core.

The locations with the strongest CO emission have integrated intensities larger than predicted from PDR models and these integrated intensities appear to be consistent with a shock origin, although further analysis of the higher lines needs to be conducted.

It is striking how the CO emission tends to preferentially come from the outskirts of the cores, rather than towards the centers of the cores where the column density is the highest and there are presumably the most shock fronts in the line of sight. The spatial location of the CO emission suggests that this emission may have a non-shock origin, such as coming from gas warmed by H_2 formation due to chemisorption onto dust grains (Röllig et al. 2013), a process not currently included in our PDR models. Our shock models indicate that the CO intensity should be relatively insensitive to moderate CO depletion onto dust grains.

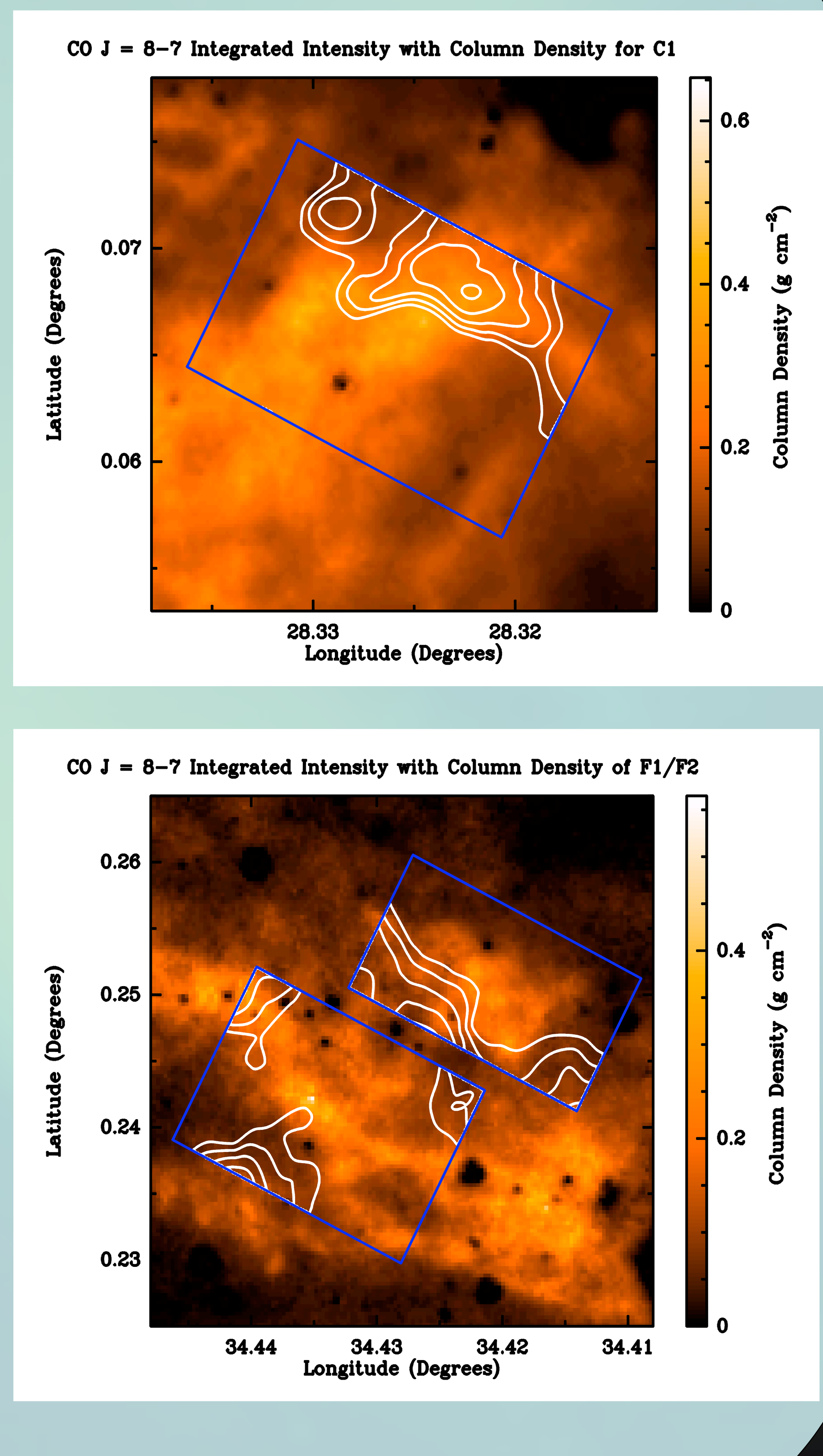


Figure 4: CO J = 8-7 integrated intensities towards three quiescent cores in IRDCs are shown in white. The blue boxes indicate the regions surveyed and the colour scale is the column density from Butler & Tan (2009).

Conclusions

- The dominant molecular coolant in slow shocks is ^{12}CO.
- Mid-J CO transitions (J = 5-4 and higher) should trace shocked gas.
- The CO J = 5-4 and 6-5 lines towards Perseus B1-East are brighter than expected from PDR model fits of lower J lines, thereby indicating a warmer gas component is present, such as shock heated gas.
- The CO J = 8-7 line towards three quiescent cores in IRDCs is brighter, in localized regions, than expected from our PDR models. This emission, however, is preferentially located towards the outskirts of the cores. This excess emission could be from shocks or could be from additional gas heating due to H_2 formation from hydrogen chemisorbed onto dust grains.

References

Butler, M. J. & Tan, J. C. 2009, ApJ, 696, 484
Kaufman, M. J. & Neufeld, D. A. 1996, ApJ, 456, 611
Kaufman, M. J., Wolfire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, ApJ, 527, 795
Pon, A., Johnstone, D., & Kaufman, M. J. 2012, ApJ, 748, 25
Ridge, N. A. et al. 2006, AJ, 131, 2921
Röllig, M., Szczerba, R., Ossenkopf, V., & Glück, C. 2013, A&A, 548, A85
Sadavoy, S. I. et al. 2012, A&A, 540, A10
Stone, J. M., Ostriker, E. C., & Gammie, C. F 1998, ApJ, 508, L99
Sun, K., Kramer, C., Ossenkopf, V., Bensch, F., Stutzki, J., & Miller, M. 2006, A&A, 451, 539