Molecular Tracers of Turbulent Shocks in GMCs

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Introduction

Simulations of MHD turbulence in molecular clouds have shown that turbulence dissipates on the order of a crossing time at the driving scale of the turbulence (e.g. Stone et al. 1998; Mac Low 1999). Most simulations use an isothermal equation of state, which does not conserve energy, and dissipate turbulence via numerical and artificial viscosity. We attempt to follow this dissipated turbulent energy by running shock models for densities and velocities applicable to molecular clouds. We compare our CO shock spectra to CO spectra from PDR models and we also compare the turbulent energy dissipation rate to the heating rates of other heating mechanisms acting in molecular clouds.

Conclusions

- The dominant molecular coolant in slow shocks is ^{12}CO. While the shock emission is weaker than the emission from cool gas and the PDR surface layer for low J transitions, the shock emission is much stronger for higher J transitions for our low magnetic field and high velocity models. If the turbulence is driven on scales much smaller than the size of the cloud, the low J shock lines could also be significant.
- 20% to 60% of the turbulent energy dissipated in shocks goes towards compressing the magnetic field.
- If the energy injected into magnetic fields leads to global heating of a molecular cloud, this heating rate could be as large as that from cosmic ray heating, especially for lower density clouds. The increase in the magnetic field strength could also make heating by ambipolar diffusion, and subsequent cooling through radiation, significant.

Shock Models

Following Kaufman & Neufeld (1996), we have run shock models for 2 and 3 km s^{-1} shocks in 1000 cm^{-3} gas, consistent with what would be predicted from Larson's Laws. We have set the magnetic field to follow the relation

$$B = b\sqrt{n(H)/cm^{-3}}\ \mu\text{G}, \qquad (1)$$

and have run models for b = 0.1 and b = 0.3, corresponding to 4 μG and 13 μG field strengths.

We find that ^{12}CO is the dominant radiative coolant with 40% to 80% of the energy being emitted from ^{12}CO in the different models. A significant fraction, between 20% and 60%, of the turbulent energy also goes into compressing the magnetic field in the various models. It is unclear whether this extra magnetic energy would drive more turbulence, dissipate across the entire cloud, and thereby contribute an additional heating mechanism to the cloud, or leak out of the cloud by coupling to the external medium of the cloud.

Turbulent Dissipation Rate

Following the discussion in Basu & Murali (2001), the turbulent energy dissipation rate per volume can be expressed as

$$\Gamma_{turb} = \left(\frac{3}{2}\rho\sigma^2\right)\left(\frac{\sigma}{\kappa L}\right), \qquad (2)$$

where ρ is the mass density, σ is the 1-dimensional velocity dispersion, κ is the ratio between the turbulent dissipation timescale and the crossing time of a cloud, and L is the diameter of the cloud. Using the Larson's law relations presented in Solomon et al. (1987) and a mean mass per particle of 2.77 amu, Equation 2 can be transformed into a total shock luminosity for a cloud:

$$L_{turb} = 5.5\times10^{32}\kappa^{-1}\left(n/1000\ \text{cm}^{-3}\right)^{-5/2}\text{ergs s}^{-1}. \qquad (3)$$

We use Equation 3, with κ = 1 (e.g. Basu & Murali 2001), to scale our shock models to predict the integrated intensity from a cloud with a number density of 1000 cm^{-3}. Figure 1 shows these predictions assuming that all of the turbulent energy is dissipated by shocks. If the strengthened magnetic fields do drive more turbulence, then the strengths of the CO lines from shocks should be increased by up to a factor of two. If turbulence is driven at scales smaller than the cloud length scale, corresponding to κ values less than 1, then these shock predictions presented in Figure 1 would be underestimate by the factor κ^{-1}.

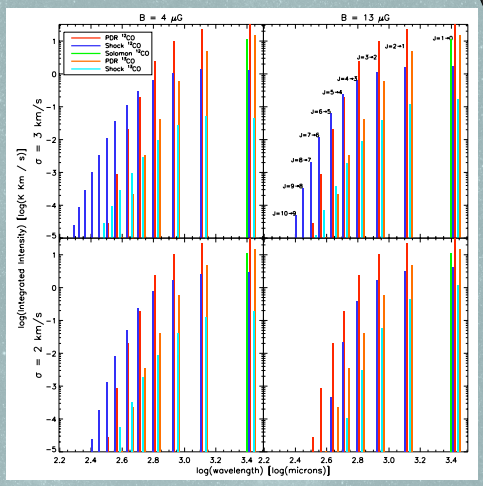


Figure 1: The integrated intensities of various ^{12}CO and ^{13}CO rotational transitions for a cloud with a density of 1000 cm^{-3}. The shock velocity and initial magnetic field strength used for each model are given on the left and top of the grid respectively. The green shows the Solomon et al. (1987) ^{12}CO J = 1 to 0 line strength, the dark blue shows the ^{12}CO shock spectrum, the red shows the ^{12}CO PDR spectrum, the light blue shows the ^{13}CO shock spectrum, and the orange shows the ^{13}CO PDR spectrum. The rotational transition of each ^{12}CO line is labelled in the upper right grid panel. Note how the shock spectrum dominates over the PDR spectrum for high J transitions.

PDR Models

To determine whether the previously calculated ^{12}CO shock emission is significant, we use the Kaufman et al. (1999) PDR models to determine the expected contribution of ^{12}CO emission from not only the cold, well shielded interior of a molecular cloud, but also from the warm outer layers of the cloud. We use a model with an incident interstellar radiation field of 3.0 Habing and a density of 1000 cm^{-3}, and we adjust this plane parallel model to account for spherical geometry. We set the radius of the modeled cloud so that the peak CO column density is 1.2 x 10^{18} cm^{-2}, as would be expected for a cloud compatible with Larson's laws and with a CO abundance of 2 x 10^{-4} (Glover et al. 2010). Figure 1 shows the integrated intensities for this model. Also shown in this figure is the typical observed integrated intensity of the CO J = 1 to 0 line for a cloud with a density of 1000 cm^{-3}, as determined by Solomon et al. (1987).

Heating Rates

Cosmic ray heating is believed to be the dominant heating source in well shielded molecular gas (e.g. Goldsmith 2001). The heating rate due to cosmic rays (Dalgarno 2006; Goldsmith 2001) is usually estimated to be in the range

$$\Gamma_{cr} = 3 \text{ to } 16\times10^{-25}\left(n(H_2)/1000\ \text{cm}^{-3}\right)\text{ ergs s}^{-1}\text{ cm}^{-3}. \qquad (4)$$

If some of the turbulent energy dissipates relatively uniformly across the cloud, then Equation 3 can be rewritten to express this heating rate as

$$\Gamma_{turb} = 5.9\times10^{-25}\left(n/1000\ \text{cm}^{-3}\right)^{0.5}\kappa^{-1}\eta\text{ ergs s}^{-1}\text{ cm}^{-3}, \qquad (5)$$

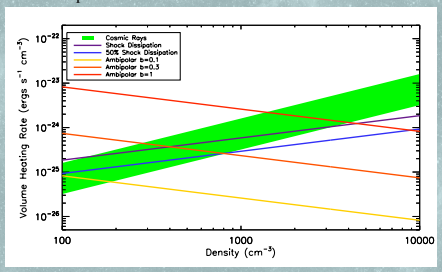
where η is the fraction of the energy dissipated that is not immediately radiated away by line radiation.

Padoan et al. (2000) found that the ambipolar heating rate is

$$\Gamma_{ambi} = 2\times10^{-25}\left(\langle|B|\rangle/10\mu\text{G}\right)^4\left(M_A/5\right)^2\left(\langle n\rangle/1000\ \text{cm}^{-3}\right)^{\frac{3}{2}}\text{ ergs s}^{-1}\text{ cm}^{-3}. \qquad (6)$$

where <|B|> is the mean magnitude of the magnetic field, M_A is the Alfvénic mach number of the turbulence, and <n> is the mean density of the cloud.

Figure 2: The heating rates given by Equations 3, 4, and 5. The green shaded region shows the generally accepted range for the cosmic ray heating rate, the purple line shows the total turbulent energy dissipation rate, the blue line shows 50% of the total turbulent energy dissipation rate, and the red, orange, and yellow lines show the ambipolar diffusion rates for various b values.



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