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.

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 $B = b_0 (n H_2)/(cm^2/p_c)$, (1)

and have run models for $b_0 = 0.1$ and $b_0 = 0.3$, corresponding to 4 µG and 13 µG field strengths.

We find that 12CO is the dominant radiative coolant with 40% to 80% of the energy being emitted from 12CO in the different models. A significant fraction, between 20% and 50%, 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 bycoupling 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

$$\Gamma_{\text{turb}} = \frac{3}{2} \rho \kappa \sigma \rho \sigma (\kappa_0/\kappa_0^2)$$

where $\rho$ is the mass density, $\sigma$ is the 1-dimensional velocity dispersion, $\kappa$ 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:

$$L_{\text{tot}} = 5.5 \times 10^{18} (\chi / 1000 \text{ cm}^{-1})^2 \text{ergs s}^{-1}.$$ (3)

We use Equation 3, with $\chi = 1$ (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 $\chi$ values less than 1, then these shock predictions presented in Figure 1 would be underestimate by the factor $\chi^2$.

PDR Models

To determine whether the previously calculated 12CO shock emission is significant, we use the Kaufman et al. (1999) PDR models to determine the expected contribution of 12CO 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 $\Phi$ and an incident FUV field of 2 $\Phi$.

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

$$\Gamma_{\text{CR}} = 3 \times 10^{-30} (\rho H_2)/1000 \text{ cm}^{-3} \text{ ergs} \cdot \text{s}^{-1}. \text{(4)}$$

where ($\rho$) is the density of the gas. If some of the turbulent energy dissipates relatively uniformly across the cloud, then Equation 3 can be rewritten to express this heating rate as

$$\Gamma_{\text{turb}} = 5.9 \times 10^{-30} (\rho H_2/1000 \text{ cm}^{-3}) (\chi^2 \eta \kappa_0/\kappa_0^2) \text{ ergs} \cdot \text{s}^{-1}.$$ (5)

where $\kappa_0$ is the mean magnetic field of the turbulent field, $\ell$ is the Alfvén length of the turbulence, and $\chi_0$ is the mean density of the cloud.

Conclusions

• The dominant molecular coolant in slow shocks is 12CO. 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.

References

Dalgarno, A. 2006, Proceedings of the National Academy of Science, 103, 12269

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

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 $\chi$ values.