Molecular Line Emission from Time-Dependent, Multifluid, Magnetohydodynamic Shock Waves

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Abstract

We describe the initial results of a program to model time-dependent, MHD shock waves in protostellar outflows. Our ultimate goal is to provide detailed models of the H_2, CO, and H_2O emission to be observed by SOFIA and Herschel. We show why steady shocks do not exist in outflows younger than ~10^4 yr, i.e., why time dependent models are required for most outflows. We explain why nonsteady shocks invariably consist of J shocks with magnetic precursors, as the interpretation of existing data has suggested. We show that very young J shocks evolve rapidly into a quasi-self similar form. The existence of an approximate similarity solution has important practical applications for detailed numerical models of molecular line emission, a result we intend to explore in the next phase of our program.

1. Motivation

The shock waves driven by protostellar outflows into nearby molecular gas are prodigious sources of near- and far-infrared emission in the rotation-vibration transitions of H_2, CO, H_2O, and other species (e.g., Kaufman & Neufeld 1996). In these environments, where the fractional ionization is low, shocks have a multifluid structure wherein the charged and neutral particles act as separate, interacting fluids (Draine 1980). The velocity and other variables in a multifluid shock may be continuous ("C type") or undergo jumps over length scales comparable to the particle mean free path ("J type"). There have been many attempts to model the molecular line emission from outflows with *steady* J- and C shocks but steady models generally fail to provide unique, acceptable fits (Wilgenbus et al. 2000; Flower et al. 2003). Because the dynamical ages of outflows are typically much less than 10^4 yr, it has been hypothesized that *nonsteady* models are the answer (e.g., Jimenez-Serra 2005, 2008). A small number of *fully* time-dependent calculations on multifluid shocks have been carried out, but only to study the development of instabilities (Mac Low & Smith 1997; Neufeld & Stone 1997; Stone 1997) or evolutionary effects (Smith & Mac Low 1997; Chieze, Pineau des Forets & Flower 1998; Ciolek & Roberge 2002; Lesaffre et al. 2004; Ashmore et al. 2010). In view of the copious spectroscopic data expected from SOFIA and Herschel, time dependent models of molecular emission from multifluid shocks are urgently needed.

2. Formulation

We model the plasma as a fluid of neutral particles plus a second fluid of ions and electrons. We consider perpendicular shocks with fluid motions along the *x* direction and magnetic fields along the *z* direction. The neutral (n) fluid is described by Euler's equations for an ideal gas,

$$\frac{\partial}{\partial t}(\rho_n) + \frac{\partial}{\partial x}(\rho_n v_n) = S_n, \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho_n v_n) + \frac{\partial}{\partial x}(\rho_n v_n^2 + P_n) = F_n, \qquad (2)$$

$$\frac{\partial}{\partial t}\left(\tfrac{1}{2}\rho_n v_n^2 + U_n\right) + \frac{\partial}{\partial x}\left[\left(\tfrac{1}{2}\rho_n v_n^2 + U_n + P_n\right) v_n\right] = G_n + F_n v_n - \tfrac{1}{2} S_n v_n^2 \qquad (3)$$

$$P_n = \frac{\rho_n k T_n}{\mu_n}, \qquad (4)$$

$$U_n = \frac{1}{\gamma - 1} P_n. \qquad (5)$$

where ρ_n, μ_n, v_n, and T_n are the mass density, mean particle mass, fluid velocity, and kinetic temperature of the neutrals, U_n and P_n are the thermal energy density and pressure, respectively, and the source terms S_n, F_n, and G_n are the net rates per volume at which mass, momentum, and thermal energy are added to the neutrals by elastic scattering with the ions, radiative cooling, etc. We calculated these source terms as described in Ciolek & Roberge (2002). In this preliminary study we set γ=5/3, μ_n=2 amu and treat the neutral fluid as H_2, CO, and H_2O with fixed abundances. Chemistry and molecular excitation will be included in later work.

The ion-electron (i) fluid is governed by mass and momentum conservation plus the induction equation:

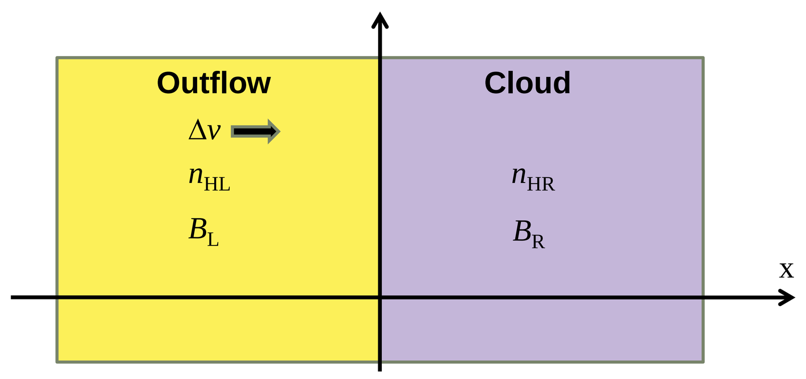
$$\frac{\partial}{\partial t}(\rho_i) + \frac{\partial}{\partial x}(\rho_i v_i) = -S_n, \qquad (6)$$

$$\frac{\partial}{\partial t}(\rho_i v_i) + \frac{\partial}{\partial x}\left(\rho_n v_i^2 + \frac{B^2}{8\pi}\right) = -F_n, \qquad (7)$$

$$\frac{\partial B}{\partial t} + \frac{\partial}{\partial x}(B v_i) = 0. \qquad (8)$$

We omit the energy equations for the ions and electrons because ion/electron thermal pressure is negligible compared to magnetic pressure.

3. Riemann Initial Conditions



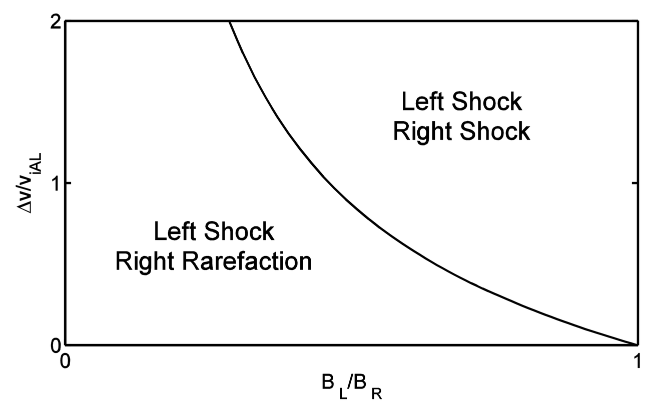
We adopt Riemann initial conditions where the left (L) and right (R) half planes are initially uniform. The material on the left plane ("outflow") has velocity Δ*v* and the right plane ("cloud") is stationary. In this paper we assume for simplicity that the left and right states are otherwise identical initially (n_{HL}=n_{HR}=n_H, B_L=B_R=B). The calculations described here used the numerical values in the table below.

Symbol	Meaning	Value
Δv	Outflow speed	20 km s^{-1}
n_H	No. density, H nuclei	4 x 10^4 cm^{-3}
B	Magnetic field	50 μG
x_i	Fractional ionization	3 x 10^{-8}
μ_i	Mean mass/ion	25 amu
v_{iA}	Ion Alfven speed	894 km s^{-1}
τ_{in}	Ion-neutral drag time	1.1 x 10^{-2} yr
τ_{ni}	Neutral-ion drag time	3.0 x 10^4 yr

The ion Alfven speed is the "signal speed" at which the charged fluid, in the absence of coupling to the neutral fluid, would communicate compressive disturbances. The ion-neutral drag time is the time scale for an ion to be slowed by elastic scattering (friction) with the neutrals; it is also the time scale for the ions to lose their inertia. The neutral-ion drag time is the time for a neutral particle to be slowed by friction; it is also the time scale for the neutral fluid to be accelerated by the ions in a magnetic precursor. This leads to three important conclusions:

- The time to attain steady flow cannot be less than τ_{ni}. The shocks in protostellar outflows are typically not steady.
- If a time-dependent simulation includes ion inertia, the smallness of τ_{in} compared to τ_{ni} makes the problem extremely stiff. This is presumably why most simulations have neglected ion inertia.
- Ion inertia is nevertheless important for a very brief period of ~ τ_{in}. If ion inertia is neglected, one has no assurance that a solution corresponds to the adopted initial conditions.

4. Decoupled Motions (t << τ_{in} ~ 0.01 yr)

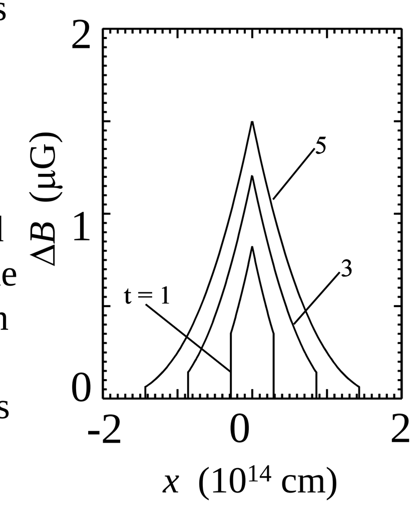


At extremely short times the charged and neutral fluids decouple and the flow is described by two separate Riemann problems. An exact solution for the neutral fluid can be calculated using widely available "Riemann solvers" (e.g., Toro 1999). For the initial conditions studied here, the neutral flow consists of two strong J shocks propagating in opposite directions with speeds of 13.6 km s^{-1} relative to the undisturbed gas. These shocks are adiabatic on this time scale.

We have developed an exact Riemann solution for the charged fluid. For the conditions studied here the solution is two weak shocks with speeds very close to v_{iA}. However it is interesting to note that this example is not a representative case: The solutions depend on the collision speed Δ*v* and the ratio B_L/B_R of the magnetic fields in the two half planes. The figure shows that outflows with Δ*v* < 10^2 km s^{-1} will contain a rarefaction wave unless B_L/B_R is extremely close to unity. Multifluid rarefaction waves should be common in molecular outflows but their spectroscopic signature has never been studied.

5. Formation of Magnetic Precursors (t ~ τ_{in})

The figure on the right shows the earliest stages in the formation of magnetic precursors on the two J shocks in the neutral fluid ("neutral shocks"), where Δ*B*(x) = *B*(*x*,*t*)-*B*(*x*,0). The curves are labeled with time in units of τ_{in}. These structures are damped ion magnetosound waves in the ion-electron fluid. The jumps at the leading and trailing edges are the jump fronts in the two ion-electron shocks, which propagate with speed v_{iA}. The characteristic length scale is

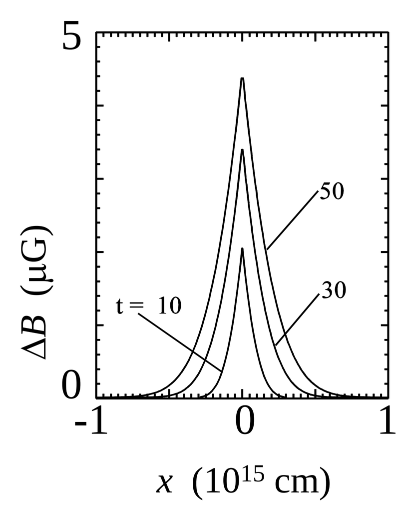


$$L_{iA} = v_{iA}\tau_{in} = 3 \times 10^{13} \text{ cm}$$

Damping by ion-neutral scattering causes the amplitudes of the jumps to decay on a time scale τ_{in}, as shown.

6. Ion Diffusion and Self Similarity (t >> τ_{in})

Here we see the two magnetic precursors at times an order of magnitude larger than in the preceding figure. The jumps in the magnetic precursor have completely decayed. Now the precursors are growing because the neutral shocks (not shown) are driving them. The ions and B field are diffusing Into the upstream gas to the left and right. This is confirmed by close examination of the length scales, which increase as $t^{1/2}$.



The shape of the solution is suggestive of self similar behavior. We have shown that there is an exact similarity solution for the ion-electron fluid in the limit v_s/v_{iA}=0, where v_s is the speed of the shocks in the neutral fluid.

7. Summary

- The time scale for multifluid MHD shocks to attain steady flow is the neutral-ion damping time, τ_{ni}. Since the dynamical ages of protostellar outflows are not much larger than τ_{ni}, time-dependent models are required to model the emission lines of H_2, CO, H_2O and other molecules to be observed by SOFIA and Herschel.
- Before they attain a steady state, multifluid MHD shocks invariably consist of J shocks with magnetic precursors. This is a simple consequence of the fact that the charged fluid has virtually no effect on the neutral fluid at very early times.
- We have studied the evolution of multifluid MHD shocks at very early times in order to understand how the solution at much later (observable) times may depend on the initial conditions. We specifically studied shocks with Riemann-type initial conditions.
- We found an exact Riemann solution for the ion-electron fluid.
- Our Riemann solution shows that multifluid rarefaction waves should be common in shocked molecular gas. The spectroscopic signature of multifluid rarefactions is unknown.
- We showed that the magnetic precursor in a multifluid shock rapidly approaches an "almost" self similar solution. This is significant because a self similar solution has "forgotten" its initial conditions. The implications are (i) that time dependent models of molecular emission lines should not be sensitive to the particulars of the initial conditions; and (ii) that numerical simulations can begin at the self similar phase, where the inertia of charged particles can be neglected.

Acknowledgement

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References

Ashmore, I., Van Loo, S., Caselli, P., Falle, S.A.E.G., & Hartquist, T.W. 2010, A&A, 511, A41.
Chieze J.-P., Pineau des Forets G., Flower D. R., 1998, MNRAS, 295, 672
Ciolek G. E., Roberge W. G., 2002, ApJ, 567, 947
Draine, B.T. 1980, ApJ, 241, 1021
Flower, D.R., Le Bourlot, J., Pineau des Forets, G., & Cabrit, S. 2003, MNRAS, 341, 70
Jimenz-Serra, I., Martin-Pintado, J., Rodriguez-Franco, A., &Martin, S. 2005, ApJ, 627, L121
Jimenez-Serra, I., Caselli, P., Martin-Pintado, J.& Hartquist, T.W. 2008, A&A 482, 549
Kaufman, M.J., & Neufeld, D.A. 1996, ApJ, 456, 611
Lesaffre P., Chieze J.-P., Cabrit S., Pineau des Forets G., 2004, A&A, 427, 147
Mac Low M.-M., Smith M. D., 1997, ApJ, 491, 596
Neufeld D. A., Stone J. M., 1997, ApJ, 487, 283
Smith M. D., Mac Low M.-M., 1997, A&A, 326, 801
Stone J. M., 1997, ApJ, 487, 271
Toro E. F., 1999, Riemann Solvers and Numerical Methods for Fluid Dynamics, 2nd edn. Springer-Verlag, Berlin
Wilgenbus, D., Cabrit, S., Pineau des Forets, G., & Flower, D.R. 2000, A&A, 356, 101