IV - SHOCKS AND INSTABILITIES

MAGNETOHYDRODYNAMIC SHOCK WAVES IN MOLECULAR CLOUDS

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ABSTRACT. The fluid dynamics of MHD shock waves in magnetized molecular gas is reviewed. The different types of shock solutions, and the circumstances under which the different types occur, are delineated. Current theoretical work on C*- and J-type shocks, and on the stability of C-type shocks, is briefly described. Observations of the line emission from MHD shocks in different regions appear to be in conflict with theoretical expectations for single, plane-parallel shocks. Replacement of plane-parallel shocks by bow shocks may help reconcile theory and observation, but it is also possible that the observed shocks may not be "steady", or that theoretical models have omitted some important physics.

1. Introduction

Shock waves are a relatively common phenomenon in molecular clouds, particularly in star-forming regions. A shock wave may be described as a "hydrodynamic surprise" – a pressure-driven disturbance propagating into the ambient medium with a speed v_s larger than the "signal speed" for compressive waves in the unperturbed gas.

The structure of a shock wave depends upon the shock speed v_s and on the properties of the ambient medium. The density $n_{\rm H} \equiv n({\rm H}) + 2n({\rm H_2})$ extends from $n_{\rm H} \approx 10^2\,{\rm cm^{-3}}$ in relatively diffuse regions to $\gtrsim 10^6\,{\rm cm^{-3}}$ in dense cores; the fractional ionization x_e ranges from $\sim 10^{-4}$ in diffuse clouds to $\sim 10^{-8}$ in regions of density $\sim 10^6\,{\rm cm^{-3}}$. Our limited knowledge of magnetic fields in interstellar clouds appears to be roughly consistent with $B_0 \approx b_0(n_{\rm H}/\,{\rm cm^{-3}})^{1/2}\mu{\rm G}$, with $b_0 \approx 1$(see the review by Heiles [1991]).

In the absence of the magnetic field, the molecular gas would be able to transmit ordinary sound waves with a sound speed $c_n \approx 0.49(T_n/40\,{\rm K})^{1/2}\,{\rm km\,s^{-1}}$. However, for $b_0 \approx 1$ the Alfven velocity $v_A = 1.84 b_0\,{\rm km\,s^{-1}}$ is much larger than the sound speed, and the medium is able to transmit compressive waves perpendicular to $\vec{B}_0$ at the "magnetosonic" speed $c_{in} = (v_A^2 + c_n^2)^{1/2} \approx v_A$.

When fluid flows in the ambient cloud have velocities large compared to c_{in}, shock waves

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will occur. In OMC-1, H_2 line emission is observed with line wings extending at least $\pm 100\,\mathrm{km\,s^{-1}}$ from line center (Brand *et al.* 1989*a*; Moorhouse *et al.* 1990), so there is little doubt that strong shock waves must be present. Hypersonic flows are also observed in other star-forming regions.

The present review will touch on some current topics in the fluid dynamics of shock waves in molecular clouds. Shock chemistry, though important, will not be addressed; see the recent review of chemistry in diffuse cloud shocks by Hartquist, Flower, and Pineau des Forets (1990).

2. Fluid Dynamics of MHD Shock Waves

The fluid dynamics of MHD shocks have been recently reviewed (Shull and Draine 1987). It is important to use a two-fluid treatment (Mullan 1971; Draine 1980): the neutral gas (containing most of the inertia) and the magnetized plasma (the bearer of the magnetic stresses) are treated as distinct fluids, with coupling between the two fluids provided explicitly through ion-neutral collisions, ionization, and recombination; a simple derivation of the fluid equations is given by Draine (1986). In a typical quiescent cloud, the coupling between the two fluids is sufficient to ensure that they are essentially comoving. In regions where large gradients are present (e.g., large amplitude, short wavelength disturbances, with shock waves as the extreme case), appreciable "slip" velocities can develop between the neutral and ionized fluids. "Frictional coupling" is provided by ion-neutral collisions, so that slippage produces momentum transfer between the fluids and energy dissipation.

The nature of a steady fluid flow depends critically on the "Mach number" of the flow, where the generalized "Mach number" is defined as the ratio of the flow velocity (in the reference frame where the flow is stationary) to the signal speed for compressive waves. We discuss here the simple case where the preshock magnetic field $\vec{B}_0$ is perpendicular to the shock velocity $\vec{v}_s$; the case of arbitrary orientation of the magnetic field is qualitatively similar (Wardle and Draine 1987). First of all, in order to have a shock we must have $v_s > c_{in}$, where $c_{in} \approx 1.84 b_0\,\mathrm{km\,s^{-1}}$ is the signal speed (in the preshock medium) for long wavelength waves (in which the neutral and ionized fluids move together).

The local signal speed for short wavelength waves in the magnetized plasma is initially $c_i \approx 70 b_0 (x_e/10^{-4})^{-1/2}\,\mathrm{km\,s^{-1}}$, and it increases as the plasma is compressed [here x_e is the fractional ionization and we assume a mean ionic mass of $\sim 10 m_{\mathrm{H}}$]. Therefore for $v_s \lesssim 50\,\mathrm{km\,s^{-1}}$ shock waves in molecular clouds we may safely assume that the flow velocity of the magnetized plasma will everywhere be "subsonic" (in the frame of reference where the shock is stationary). It is a familiar result of steady flow theory that discontinuities in the flow can only occur at a transonic point where the flow makes a transition from supersonic to subsonic. Therefore the flow of the magnetized plasma must be everywhere *continuous.* One way of interpreting this result is that the large signal speed in the magnetized plasma allows it to "communicate" upstream and "inform" the upstream plasma of the approaching compression; the plasma therefore is not "surprised".

3. Types of MHD Shock Waves

3.1. C-TYPE SHOCKS

The local signal speed (for short wavelength waves) in the neutral fluid is just the thermal sound speed $c_n \approx 0.49(T_n/40\,\mathrm{K})^{1/2}\,\mathrm{km\,s^{-1}}$. If the neutral fluid remains cold (either because the shock is extremely weak or because radiative cooling is very effective) then the neutral fluid may remain everywhere supersonic, with no supersonic→subsonic transition and therefore no discontinuity. Such shocks – in which both the ion and neutral flow variables are everywhere continuous – are termed "C-type" (Draine 1980). In C-type shocks the energy dissipation (and entropy generation) is due entirely to the ion-neutral collisions in the region of ion-neutral "slip". Fluid velocities in a C-type shock are illustrated in Fig. 1.

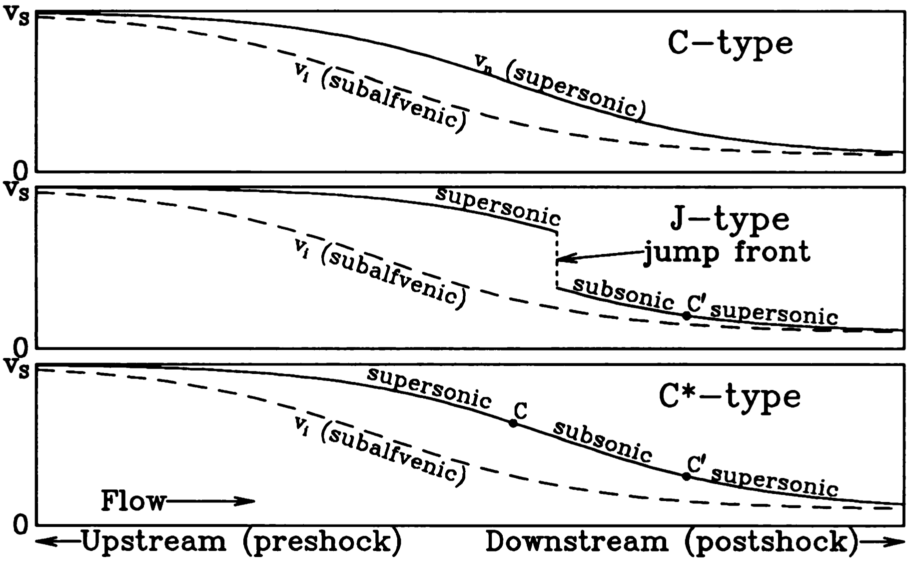

Figure 1. v_n (solid) and v_i (broken) for C-type, C*-type, and J-type shock waves.

3.2. J-TYPE AND C*-TYPE SHOCKS

If cooling is unable to hold down the neutral temperature, then the neutral sound speed will increase as the neutral flow velocity decrease; the Mach number will decrease and a supersonic→subsonic transition may occur in the flow. It turns out there are two very different ways in which this can occur. Under some circumstances the supersonic→subsonic transition takes place at a "viscous subshock", where the neutral fluid undergoes a "jump" effected by ordinary molecular viscosity (just as for classical single fluid shocks): this is termed a "J-type" shock. Fig. 1 shows the velocity structure in a J-type shock; the sonic point (C') at which the neutral gas makes the subsonic→supersonic transition is indicated.

Under other conditions, however, it is possible for the supersonic→subsonic transition to take place *smoothly* as the neutral gas is heated and decelerated (in the "shock frame") by collisions with streaming ions. Such solutions – termed "C*-type" shocks – have been discussed by Chernoff (1987) and Roberge and Draine (1990). The velocity structure in a C*-type shock is shown in Fig. 1, including the two sonic points (C and C')

3.3. SHOCK TRAJECTORIES IN THE PHASE PLANE

Chernoff (1987) invented a "phase plane" analysis which proves very useful in understanding the different shock types. Once the preshock conditions and shock speed are specified, then, to an excellent approximation, the laws of conservation of mass and momentum permit the physical conditions at a given point in a shock to be fully determined by just two flow variables: the neutral and ion flow velocities v_n and v_i. In particular, given these two flow variables, the neutral temperature T_n can be determined. The flow of the fluid through the shock can therefore be represented by a "trajectory" on a "phase plane" with coordinates $q = v_i/v_s$ and $r = v_n/v_s$. The trajectory begins at the point $U = (1,1)$. The local derivative of the trajectory is an explicit function of q and r, which can be written $dr/dq = R(q,r)/(M^2 - 1)$, where $M = v_n/c_n$ is just the neutral Mach number, and R is an explicit function of q and r. Chernoff showed that there were three important lines on this phase plane: the line $q = r$ (the trajectory begins and ends at points U and D on this line); the line $M = 1$ (where dr/dq is singular); and the line where the function $R(q,r) = 0$. These three lines are shown qualitatively in Fig. 2. Simple arguments can be used to show that certain regions bounded by these curves are forbidden: a trajectory which begins at U either cannot enter these regions or, if in the region, cannot reach the downstream solution D. These forbidden regions have been shaded in Figs. 2 – 4. Note in particular the two potential "sonic points" C and C' where the $R = 0$ and $M = 1$ curves intersect. These are the only places where it is possible for continuous trajectories to cross the $M = 1$ or $R = 0$ curves. Note that the region *above* the $M = 1$ line (which includes the initial point U and, we will assume, the downstream point D) is the locus of *super*sonic flow – if the cooling is able to keep the gas cool (and the sound speed low), then the entire trajectory will remain above the $M = 1$ line. Now if a trajectory which begins at $U = (1,1)$ always remains above the $M = 1$ line, then it is everywhere continuous and it must inevitably terminate at the downstream solution D: such a "C-type" trajectory is illustrated in Fig. 2.

If, on the other hand, the neutral temperature rises so that the trajectory beginning at U will intersect the $M = 1$ curve, there are two possibilities. If the trajectory beginning at U collides with the $M = 1$ curve at a point F, as shown in Fig. 3, then it is necessary to abandon this trajectory at some earlier point J, and invoke a "jump" in the neutral flow variables (i.e., change r while $q = constant$, using the Rankine-Hugoniot jump conditions) to a point J' (below the $R = 0$ curve), and begin integrating a new trajectory beginning at J'. The "jump" point J must be chosen so that J' lies on the (unique) trajectory which passes through the sonic point C' – otherwise there is no way to reach the (unique) downstream steady state D. Iterative numerical techniques to accomplish this have been implemented (Roberge and Draine 1990). It is also worth noting that integration of the trajectory in the region below the $M = 1$ line is numerically delicate: small errors grow

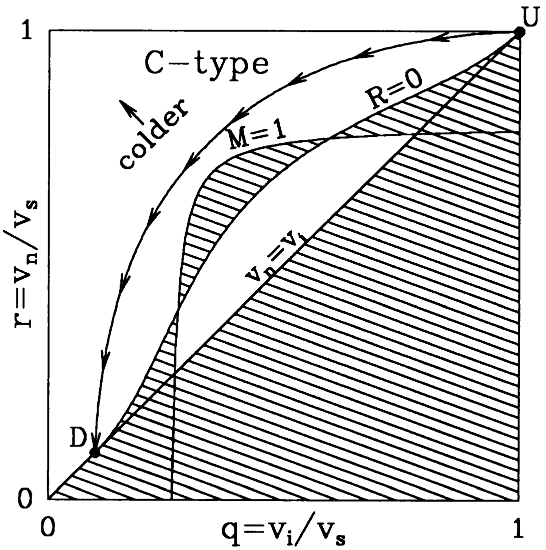

Figure 2. Phase space trajectory for C-type shock. Shaded areas are forbidden.

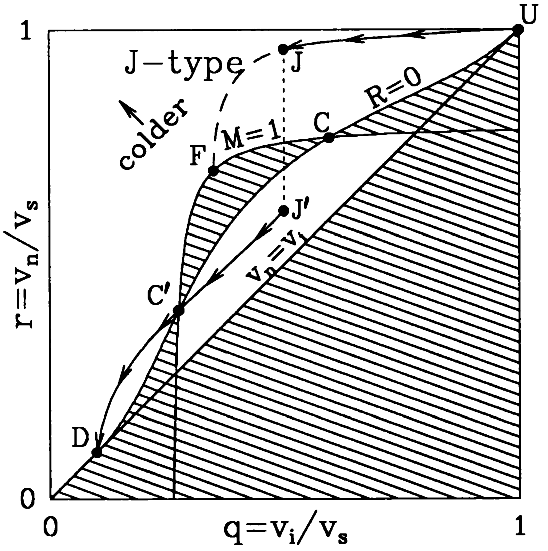

Figure 3. Phase-space trajectory for J-type shock.

exponentially. "Shooting" techniques are therefore employed to successfully integrate the $J' - C'$ portion of the trajectory (Roberge and Draine 1990).

At first sight it might appear that only a fortuitous choice of initial conditions could produce a trajectory beginning at U which reached the sonic point C – it turns out, however, that the sonic point C is an "attractor" in this phase plane: trajectories in the supersonic

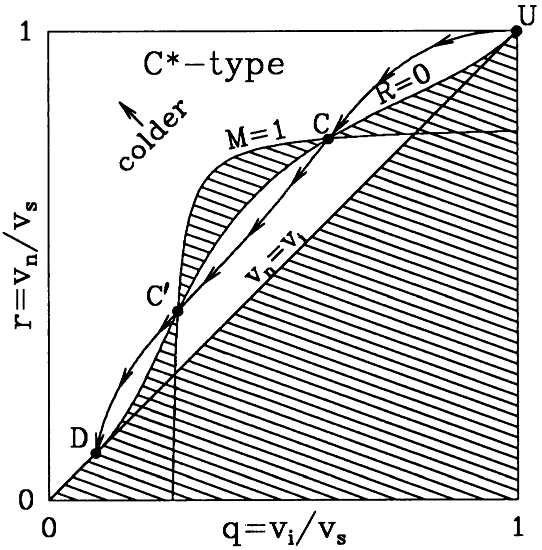

Figure 4. Phase-space trajectory for C*-type shock.

region which come sufficiently close to C will be "sucked" into it, thereby permitting a smooth transition from supersonic to subsonic flow. On the subsonic side of C there are an infinite number of trajectories which originate from C – one chooses the one which reaches the second sonic point C'. Such a solution is referred to as a "C*-type" shock. From the standpoint of the fluid dynamics these solutions are fundamentally different from the C-type shock solutions. However, from the standpoint of the thermal structure in the flow, there is a fundamental similarity in that, just as for C-type shocks, the heating is a smooth, continuous function of space – the "impulsive" heating which is associated with a "jump" is absent – and therefore the cooling processes may be able to keep the temperature from rising to high levels. (Of course, the very fact that the C*-type solutions include a subsonic portion implies that cooling is unable to hold the temperature down to very low values.)

3.4. BREAKDOWN

It is important to recognize that the multifluid character of the flow depends on the weak coupling between the ion and neutral fluids. Appreciable slip velocities can exist over appreciable distances only if the fractional ionization remains low. Furthermore, if the shocks are to account for strong molecular line emission (e.g., in OMC-1) then H_2 must survive in the shock; survival of H_2 in fast shocks requires that the ion density remain low so that molecular line cooling is able to radiate away the heat dissipated in ion-neutral collisions. Therefore, for given preshock conditions (n_H, $\vec{B}_0$, x_e) there is a "breakdown" shock speed above which the shock destroys essentially all of the H_2 (Draine, Roberge, and Dalgarno 1983; Hollenbach, Chernoff, and McKee 1989; Smith and Brand 1990*a*). There are two ways this can happen: (1) High-velocity ion-neutral collisions may increase the ionization, a process which tends to "run away" as the ion density and heating rate increase. (2) Even if the ionization remains approximately constant, if the neutral temperature rises too high the H_2 will be collisionally-dissociated.

It should be noted that even above the "breakdown" velocity there may still be appreciable molecular emission from the "magnetic precursor" at the leading edge of the shock, unless the shock speed is so high that UV radiation from the shocked gas is able to raise the preshock ionization and thereby reduce the extent of this precursor.

4. Instabilities

Nearly all of the theoretical work on MHD shocks in molecular clouds has been restricted to steady, plane-parallel flows; with these assumptions, numerical solutions to the fluid equations can be found. It is, however, crucially important to know whether or not such flows are *stable*.

Wardle (1990*a*, *b*, 1991) has analyzed the stability of steady, plane-parallel, C-type shocks. Wardle pointed out that one could intuitively anticipate the possibility of an instability which would involve the "buckling" of field lines, in a manner reminiscent of (but fundamentally different from) the Parker instability for magnetized gas in a gravitational field.

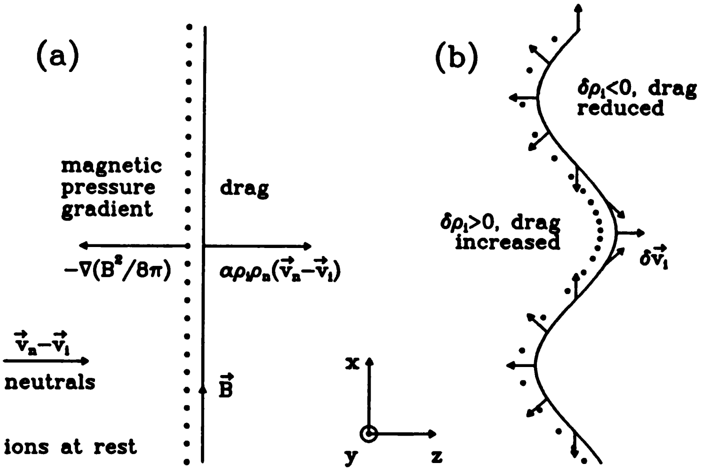

Figure 5. Possible instability mode described in text (from Wardle 1990*a*). The dots represent ions along a magnetic field line. In the unperturbed case (a), the ion density is uniform along a field line. In the perturbed case (b), the ions are driven into the "valleys" by the "neutral wind", resulting in an increase in the local force density which may further deform the magnetic field.

Consider the dynamics of the ionized fluid at a point in the flow, and adopt a reference frame moving with the velocity of the ionized fluid. The plane-parallel, steady solution is illustrated in Fig. 5a, for the special case where the magnetic field $\vec{B}$ is perpendicular to the direction of propagation of the shock. In the adopted reference frame the ions are (locally) stationary, as are the magnetic field lines (frozen into the ionized fluid). Consider the dynamics of the ions: they are subject to a force density $\alpha\rho_n\rho_i(\vec{v}_n - \vec{v}_i)$ due to collisions with the atoms in the "neutral wind" which blows from left to right in Fig. 5a (here α is just a constant proportional to the rate coefficient for ion-neutral scattering), and they are also subject to a force density $-\nabla(B^2/8\pi) = (1/c)\vec{J}\times\vec{B}$. Because the ions have essentially no inertia, these two opposing force densities must almost exactly balance! Note that so long as the field lines remain straight, the force on the ions due to the "neutral wind" is perpendicular to $\vec{B}$.

Now consider what may happen if the magnetic field $\vec{B}$ for some reason has a bend in it, as shown in Fig. 5b. The force due to the neutral wind is still directed from left to right, but at most points this force now has a component parallel to $\vec{B}$, which cannot possibly be balanced by the $\vec{J}\times\vec{B}$ force! This means that the "neutral wind" will tend to drive the ions *along* the field lines, resulting in an increase in ρ_i in the "valleys" defined by $\vec{B}$. This in turn implies that the force density $\alpha\rho_n\rho_i(\vec{v}_n - \vec{v}_i)$ will increase in these valleys, in which case it may now exceed $-\nabla(B^2/8\pi)$, in which case the bends in the field lines will tend to grow! This is the basic mechanism of the Wardle instability, where the "neutral wind" plays the role analogous to that of gravity in the Parker instability.

Wardle has performed a linear stability analysis of the fluid equations for the special case where $\vec{B}\cdot\vec{v}_s = 0$, both for an isothermal equation of state (Wardle 1990*a*) and for realistic radiative cooling (Wardle 1990*b*). The stability analysis has been extended to general case of arbitrary orientation of preshock $\vec{B}$ (Wardle 1991). The stability depends upon a number of parameters, but Wardle's results may be approximately summarized as follows: the stability of C-type shock waves depends primarily on the "Alfven Mach number" $M_A = v_s/v_A$, where $v_A = 1.84b_0\,\mathrm{km\,s^{-1}}$ is the Alfven speed in the ambient gas. Wardle found C-type shocks to be stable when $M_A \lesssim 5$, and unstable for $M_A \gtrsim 5$. This implies that MHD shocks will only be stable for $v_s \lesssim 9b_0\,\mathrm{km\,s^{-1}}$! Steady, plane parallel multifluid MHD shock models are therefore of questionable validity for $v_s \gtrsim 10b_0\,\mathrm{km\,s^{-1}}$.

Wardle's investigation was limited to a linear stability analysis; the nonlinear development of the instability remains unknown. In particular, it is not clear whether the instability will grow to a large amplitude or whether nonlinear terms may limit the growth of the instability before it becomes large. It seems likely that the Wardle instability mechanism (based upon the delicate balance of momentum transfer from the "neutral wind" against the gradient of magnetic pressure) will also apply in J-type and C*-type shocks, but this has not yet been demonstrated. These are important topics for future investigation.

It therefore appears that plane-parallel steady models of MHD shocks may be regarded as accurate approximations for C-type shocks in uniform media only for $v_s \lesssim 10b_0\,\mathrm{km\,s^{-1}}$. For higher shock speeds, we can at present only hope that the plane-parallel, steady shock models provide a good estimate for the average emission from and chemistry in the shock; if, however, the instability grows to large amplitudes this will not be the case.

5. Puzzles

5.1. H_2 Line Emission from OMC-1

Powerful line emission is observed from H_2 and high$-J$ CO in the BNKL region of OMC-1. In an attempt to explain this emission, two different groups (Draine and Roberge 1982; Chernoff, Hollenbach and McKee 1982) proposed C-type shock models. The models attempted to account for all of the observed emission using a single shock (approximated as spherically-symmetric). The C-type shock models were reasonably successful at accounting for the observations, and it appeared at the time that the shock models – while clearly an oversimplification in aspects such as spherical symmetry – were probably a good first approximation.

The C-type models did not, of course, provide a perfect fit to observed line ratios; as additional emission lines were observed, and the reddening by dust was more accurately determined, it became clear that the C-type models predicted insufficient emission in both the lowest excitation [$v = 0 \rightarrow 0S(2)$] and highest excitation [e.g., $v = 0 \rightarrow 0S(17)$ and $v = 4 \rightarrow 3S(3)$] transitions of H_2 (Brand *et al.* 1988).

In an attempt to understand the observed emission line ratios, Brand *et al.* (1988) proposed a very simple model: a *nonmagnetic* single-fluid radiative shock wave, in which dissociation of and emission from H_2 dominate the cooling. The Brand *et al.* model provides a good fit to the observed H_2 line ratios, and further predicts that the line ratios should be quite insensitive to the shock speed for v_s in the range $10 - 25\,\mathrm{km\,s^{-1}}$.

The Brand *et al.* model ostensibly has no "adjustable parameters", and yet achieves impressive agreement with the observations of H_2 emission, whereas the complex C-type models, with a number of adjustable parameters, failed. This is even more remarkable when one considers the fact that we have fundamental theoretical reasons for rejecting the Brand *et al.* model: (1) The Brand *et al.* model assumes H_2 to be the only coolant, whereas all theoretical studies of the chemistry in such shocks conclude that a large fraction of the O is converted to OH and H_2O, which, at the densities $n_H \gtrsim 10^6\,\mathrm{cm^{-3}}$ in question, should dominate the cooling. (2) In order to obtain the observed H_2 line intensities, high preshock densities ($n_H \gtrsim 10^6\,\mathrm{cm^{-3}}$) must be assumed; the resulting densities ($n_H \gtrsim 5 \times 10^6\,\mathrm{cm^{-3}}$) in the shock-heated gas are so high that excessive amounts of emission from very high rotational levels ($J \gtrsim 35$) of CO would be produced, in conflict with observations. Note that good agreement with the observed CO emission spectrum is obtained in the C shock models of Chernoff, Hollenbach, and McKee (1982), where the density in the emitting region is only $n_H \approx 5 \times 10^5\,\mathrm{cm^{-3}}$. (3) We have independent reasons for believing that dynamically-important magnetic fields must be present in molecular clouds; if our estimates of Alfven velocities $v_A \approx 2\,\mathrm{km\,s^{-1}}$ are even approximately correct, then the magnetic fields *must* have an important effect on the fluid dynamics, and multifluid flow models must be used.

5.2. H_2 Line Ratios in OMC-1 and Other Objects

The emission spectrum computed for C-type shock models (Draine and Roberge 1982;

Chernoff, Hollenbach, and McKee 1982; Draine, Roberge and Dalgarno 1983) was a sensitive function of the shock parameters: shock speed v_s, preshock density $n_{\rm H}$, magnetic field B_0, and fractional ionization x_e. Since it seemed certain that physical conditions (particularly the density $n_{\rm H}$ and the orientation of local $\vec{B}$ relative to $\vec{v}_s$) would vary from point-to-point along the shock front, it is fair to say that one of the firm predictions of the C-type shock models was that the actual H_2 line ratios would be found to vary with position in OMC-1.

Brand *et al.* (1989*b*) cleverly chose to study the $v = 1 \rightarrow 0O(7)$ and $v = 0 \rightarrow 0S(13)$ transitions – two lines with nearly identical wavelengths (3.807 and 3.847 μm, respectively, so that differential extinction may be neglected) but originating from levels with energies differing by $\Delta E/k = 9093\,{\rm K}$. The intensity ratio for this line pair would be expected to be a quite sensitive function of shock parameters for C-type shock models: the levels in question have sufficiently high energies that the emission from a C-type shock would be dominated by the region of peak temperature, and the peak temperature varies as the shock parameters are varied. Brand *et al.* mapped the line ratio over a significant area in OMC-1. Amazingly, the line *ratio* remained *constant* to within obserational uncertainties, even as the line *intensities* varied by an order of magnitude from one position to another! Such a result is very difficult to understand if the emission originates in a plane-parallel C-type shock. The observed line ratio is, however, close to that "predicted" by the nonmagnetic shock models (Brand *et al.* 1988), but this appears to be fortuitous since, as discussed above, there are strong reasons for believing such nonmagnetic shock models to be inapplicable.

To further complicate the observational constraints, Burton *et al.* (1989) measured the $1 \rightarrow 0O(7)/0 \rightarrow 0S(13)$ line ratio in CRL618, HH7, and two positions in IC443. Even though the line ratio was found to be constant within OMC-1, it *does* vary from object to object, although only by a factor of ~ 2 among the objects and positions observed.

6. Discussion and Future Directions

What are these observations telling us? It seems clear that simple, planar C-type shock models are not consistent with the observations, but it is not entirely clear how the models need to be changed.

There seem to be two distinct avenues to explore. Smith, Brand, and Moorhouse (1990) argue that the observed H_2 line intensities from OMC-1 and IC443 (the two best-studied outflows) can be understood in terms of *bow shocks* in which the shock transition at a given point on the bow shock is computed as for a planar multifluid C-type shock, but with the emission from a single bow shock structure involving a sum over shock parameters. For high-velocity bow flows the inner portions of the bow shock are dissociative; the bulk of the H_2 line emission comes from the outer portions of the bow shock where the component of the bow velocity *normal* to the shock surface is below the "breakdown" velocity. Using approximate treatments of the shock structure, Smith *et al.* show that good agreement with observations can be obtained. Recent H_2 line images of OMC-1 (Bally 1990; Beichman 1990) are indeed suggestive of "interstellar bullets", in which case this bow shock interpretation may indeed be called for. However, Smith and Brand (1990*b*) concluded that the H_2 line *profiles* in OMC-1 were *not* consistent with the predictions of their bow shock model.

It should further be noted that a C-shock in OMC-1 will have a hot transition zone of thickness $\sim 10^{15}$cm (Draine and Roberge 1982) – corresponding to $0.13''$ at the 500 pc distance of Orion. The "bow shock" modelling of Smith *et al.* presumes the radius of the "bullet", and hence the radius of curvature of the shock, to be large compared to this shock thickness. We would therefore expect observations with a small aperture (say $\sim 1''$) to sample only a portion of the bow shock structure, in which case line ratios such as $I[0-0S(13)]/I[1-0O(7)]$ would be expected to vary with position. The observational study by Brand *et al.* (1989*b*) employed a $5''$ aperture; future observations with a smaller aperture will be of value to test the "bow shock" interpretation.

It is important to keep in mind that the existing multifluid shock calculations make a number of approximations, some of which are of questionable validity. Perhaps the flows are unstable, and perhaps somehow the nonlinear development of the instabilities can account for the observed line ratios in a "natural" way. The existing shock models have used a highly simplified and approximate treatment of the grain dynamics; perhaps a more refined and exact treatment of the grain dynamics will lead to a more satisfactory H_2 emission spectrum. Perhaps we are overlooking some other important physical or chemical processes. Only further theoretical investigation will tell!

Acknowledgements

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