Proceedings ASA, 1994, **11** (1) 58–60

Magnetic Fields and Shocks in Molecular Clouds

S. E. Byleveld, D. B. Melrose and H. Pongracic
Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006

Abstract: We discuss the expected properties of shocks in molecular clouds when the effect of a magnetic field is included. The results suggest that shocks should have magnetic precursors, and may be C-shocks rather than J-shocks, but the observations are not obviously consistent with this prediction. The effect of these shock properties on cloud collisions triggering star formation is discussed.

1. Introduction

Molecular clouds are observed to be sites of star formation. The material within these clouds is disordered, in supersonic motion (Falgarone and Philips 1991), and partially ionised. Within molecular clouds, one possible 'trigger' of star formation is the compression of cloud material by shock waves. These produce regions of high density which may collapse to form protostars, and eventually stars themselves. Shock waves may arise from the collision of two or more molecular clouds, supernovae explosions or expanding HII regions. Recently, Chapman *et al.* (1992) reported the results of simulations of shock compression initiated by the first of these mechanisms. In these simulations, collisions between molecular clouds result in the formation of regions of very high density that are identified with protostars. An equation of state which allows radiative cooling of the shocked material was incorporated in the model.

Here we discuss the possible effects of including magnetic fields in these simulations. Although magnetic fields are observed in star forming regions (e.g. Garcia-Baretto *et al.* 1988), little is known of their influence on the physics of star formation. Since shock waves are of intrinsic importance to this model, our investigation of magnetic fields is focused on their effects on shock waves. Draine (1980) showed the structure of a shock wave to be very sensitive to the strength of the ambient magnetic field. We apply Draine's theory using the physical conditions thought to exist within molecular clouds and hence determine the relevant structure of shock waves likely to be involved in star formation. The magnetohydrodynamic fast mode wave is discussed here since it is the relevant mode of propagation of pressure fluctuations in magnetised plasmas. Since the fast mode speed depends on the Alfvén speed, the properties of the fast mode wave are related to those of Alfvén waves. We follow the treatment of Alfvén waves given by Kulsrud and Pearce (1969) in discussing the propagation of these waves in the interstellar plasma.

2. Waves in Partially Ionised Plasmas

Molecular clouds are composed of partially ionised plasmas, and as such the nature of waves in these clouds depends on the properties of the partially ionised medium itself. Under certain conditions, fast and Alfvén waves propagate only in the ionised component and under other conditions they propagate in the medium as a whole. The latter case applies if there is a sufficiently high collisional frequency between the neutral and ionised components. Then the collisions bind together the ionised and neutral components so that pressure and magnetic field fluctuations are felt by the neutral component as well as by the ionised component. If collisions are too infrequent, then these fluctuations are felt only by the ionised component and the neutral component decouples from the wave motion. The 'collisions' that are important include charge exchange in which an atom or molecule becomes ionised and an ion becomes neutralised.

These waves can only influence the structure of a shock wave if their wavelength is comparable to the thickness of the shock itself. For example, consider a hypothetical shock with thickness d. A spatial Fourier transform of the shock contains Fourier components with wavenumbers $k \leq 2\pi/d$. In the presence of a magnetic field these components tend to propagate away as fast mode waves with wavelengths $\lambda = 2\pi/k \gtrsim d$. If these waves propagate faster than the shock, the shock would be dispersed, implying that the hypothetical shock does not exist. By comparing wavelengths with shock thickness, we can determine whether the MHD waves propagate predominantly in the ion component of the medium or in the medium as a whole. Kulsrud and Pearce (1969) treated Alfvén waves in a partially ionised medium. They showed that Alfvén waves are weakly damped, both at very low frequencies (where neutral particles are dragged along with the ions), and also at high frequencies (where the waves propagate only in the ionised component). These weakly damped regimes correspond to wavelengths

$$\lambda > \lambda_{in} = \frac{\pi V_A}{\nu_0 \sqrt{\epsilon}}, \tag{1}$$

$$\lambda < \lambda_i = \frac{4\pi V_A}{\nu_0}, \tag{2}$$

respectively, where $V_A = B/(\mu_0 \rho_i)^{\frac{1}{2}}$ is the Alfvén speed in the ionised component, B is the magnetic field, ρ_i is the density of the ions, ν_0 is the collision frequency between ions and neutral particles, and

ϵ is the ratio of the densities of the ions to neutral particles in the medium.

Possible parameters for the conditions within a molecular cloud are: $\rho_i = 1{\cdot}7 \times 10^{-23}\,\mathrm{kg\,m^{-3}}$, $\epsilon = 10^{-4}$ and $\nu_0 = 10^{-7}\,\mathrm{s^{-1}}$, in which case (1) gives

$$\lambda_{in} = 0{\cdot}2\left(\frac{B}{1\,\mathrm{nT}}\right)\mathrm{pc} \qquad (3)$$

for the minimum wavelength of Alfvén waves in the neutral component and (2) gives

$$\lambda_i = 0{\cdot}9 \times 10^{-2}\left(\frac{B}{1\,\mathrm{nT}}\right)\mathrm{pc} \qquad (4)$$

for the maximum wavelength of Alfvén waves propagating in the ionised component. In a molecular cloud the magnetic field has a value of $B \approx 1\,\mathrm{nT}$ (e.g. Elitzur 1992). This implies a range of wavelengths from $\lambda_i \approx 10^{-2}\,\mathrm{pc}$ to $\lambda_{in} \approx 10^{-1}\,\mathrm{pc}$ where there are no weakly damped Alfvén waves. We wish to compare the values for the limiting wavelengths (3) and (4) to the thickness of a shock wave propagating in molecular clouds. The thickness of a shock wave is of order one collisional mean free path. The dominant collisions in this medium are between hydrogen molecules. The cross section for these collisions is $\sigma \approx 10^{-20}\,\mathrm{m^2}$ and we take the number density of hydrogen molecules to be $n = 10^8\,\mathrm{m^{-3}}$ (Lang 1974). Thus the shock thickness d can be approximated by

$$d \approx (\sigma n)^{-1} \approx 10^{12}\,\mathrm{m} = 3 \times 10^{-4}\,\mathrm{pc}\,.$$

We conclude that only wavelengths of Alfvén waves propagating in the ionised component are relevant on the length scale of the shock.

3. Magnetic Fields and Shock Waves

Shock waves can exhibit different structures when propagating in a partially ionised gas, depending on the strength of the magnetic field that permeates the medium (Draine 1980). When a weak magnetic field is present, the shock structure is that of a J-type shock. In a J-type shock the hydrodynamic variables undergo a discontinuous jump at the shock front, and fast mode waves are ineffective in dispersing the shock structure. If the magnetic field is sufficiently strong, the shock is preceeded by a 'magnetic precursor' in the ionised component which heats and compresses the medium ahead of the J-type shock front. The magnetic precursor may be attributed to fast mode waves propagating ahead of the shock and communicating the approaching shock to the upstream plasma. For an even stronger magnetic field it is possible that no J-type shock occurs, but rather, the hydrodynamic variables of both the ion and neutral particles undergo a continuous change. This is referred to as a C-type shock.

A magnetic precursor can only occur when the signal speed in the charged component of the gas is greater than the shock speed. Following the treatment of this problem by Draine (1980), we take the magnetic field to be perpendicular to the direction of propagation of the shock. Thus we require a wave mode that can interact with ion density and travel perpendicular to the magnetic field. The fast magnetosonic mode is the relevant mode. Thus, a magnetic precursor occurs when the fast mode speed, v_f, is greater than the shock speed, v_s. This relation can be used to calculate the threshold magnetic field for which a magnetic precursor occurs, given the Mach number of the shock. The fast mode speed can be expressed as

$$v_f = (V_A^2 + c_s^2)^{\frac{1}{2}}\,, \qquad (5)$$

where V_A is the relevant Alfvén speed and c_s is the sound speed of the medium.

Using the expression for the Alfvén speed propagating only in the ion component, and ignoring an unimportant relativistic correction included by Draine (1980), equation (5) takes the following form:

$$v_f = \left(\frac{B^2}{\mu_0\rho_i} + \frac{5(n_i+n_e)kT}{3(\rho_i+\rho_e)}\right)^{\frac{1}{2}}\,, \qquad (6)$$

where T is the temperature of the medium, n and ρ are the number and mass densities respectively with the subscripts i and e indicating whether the quantity is for ions or electrons. The shock speed is expressed in terms of the sonic Mach number M of a shock and the sound speed c_s as:

$$v_s = Mc_s\,. \qquad (7)$$

A critical magnetic field is defined by the requirement $v_f = v_s$. The critical magnetic field is defined for a given value of M by equating (7) and (6) and solving for B. We take $T = 50\,\mathrm{K}$ as a typical temperature and the number densities $n_i = n_e = 10^4\,\mathrm{m^{-3}}$ for the conditions in a molecular cloud. For a shock with $M = 4$ the critical magnetic field for the existence of a magnetic precursor is $B = 0{\cdot}8 \times 10^{-2}\,\mathrm{nT}$. For a very strong shock with $M = 20$ the field required is $0{\cdot}5 \times 10^{-1}\,\mathrm{nT}$. Given a magnetic field in a molecular cloud of $B \approx 1\,\mathrm{nT}$, we can conclude that all shocks should exhibit magnetic precursors.

Finally, it remains for us to determine if C-type shocks are likely to occur in this medium. For an adiabatic shock, it is possible to find the critical magnetic field analytically using the method due to Chernoff (1987). Chernoff exploited the condition that the fluid in a standard C-type shock remains everywhere supersonic to calculate the conditions required for such a shock to form. The neutral-Alfvén Mach number is defined as

$$M_{nA} = \left(\mu_0 \rho_n v_s^2 / B^2\right)^{\frac{1}{2}} , \qquad (8)$$

where ρ_n is the density of the neutral component. If $M_{nA} < 2{\cdot}76$ it is possible to find a solution which continuously connects the hydrodynamic variables in the upstream and downstream media. This constraint on M_{nA} makes it is possible to determine the critical magnetic field required for a C-type shock to exist for a given sonic Mach number. This is calculated by substituting the expression for the shock speed (7) in equation (8) using a given value of ρ_n (which may be calculated using the values of ρ_i and ϵ given in the previous section). As for the previous consideration of J-type shocks with magnetic precursors, we consider shocks with sonic Mach numbers of 4 and 20. These values result in critical magnetic fields of $0{\cdot}8$ and 4 nT respectively. Since magnetic fields of $B \approx 1$ nT exist in molecular clouds, it is expected that C-type shocks occur for shock speeds with sonic Mach numbers $\lesssim 4$.

4. Discussion

Numerical simulations of star formation provide the primary motivation for this consideration of magnetic fields in molecular clouds. However, to apply these results to the simulations, and hence make predictions, it is necessary to relate the assumption of an adiabatic equation of state to the cooling equation of state invoked in the numerical models. Here a simple argument is presented which takes radiative cooling into account.

By its very nature, a cooling equation of state must result in a lower ambient temperature in the medium. This, in turn, causes the sound speed to decrease. It is the fast mode waves, with speed $v_f = \sqrt{(B^2/\mu_0\rho_i) + c_s^2}$, which allow magnetic precursors to occur in the ionised component of the medium. The decreased sound speed thus enhances the relative importance of the magnetic field. Since the requirement for the existence of a magnetic precursor is that $v_f > v_s$, where $v_s = Mc_s$ is the speed of the shock, this implies that for a lower sound speed, the critical magnetic field is lower. Hence the values of $B_{\rm crit}$ calculated in the previous section for an adiabatic equation of state serve only as upper limits for a cooling equation of state. However, since we have concluded that the magnetic field in a molecular cloud is strong enough for magnetic precursors and C-type shocks to exist in the absence of cooling, it remains sufficiently strong to ensure their existence when cooling is included.

The numerical model under discussion (e.g. Chapman *et al.* 1992) relies on shock compression of the material. We argue that the structure of shock waves in molecular clouds may be continuous rather than discontinuous. A C-type shock allows the propagation of energy ahead of the shock. Because of this, we might anticipate that shock compression is effective in forming the regions of high density required for the onset of star formation, even when the magnetic field is included in the simulation.

The increase of energy ahead of the shock front in the case of a continuous shock might suggest that the compression of material in this region is more difficult to achieve. Thus we expect that, if C-type shocks dominate in molecular clouds, collisions between these clouds would cause shocks to form as in previous simulations. However, the compression of material by these shocks would be less efficient than compression by J-type shocks. Thus we predict that the formation of high density compression regions necessary for star formation is more difficult to achieve when the magnetic field is taken into consideration in the simulations.

Despite the theoretical predictions of the possible existence of C-type shocks in molecular clouds, it has been pointed out that this prediction does not seem to be supported by observations (M. Burton, private communication). This may indicate a possible deficiency in the theory, which we have yet to explore. It may be that the Mach numbers are sufficiently high that the shock speed exceeds v_f, in which case a J-type shock rather than a C-type shock occurs.

5. Conclusion

The likely forms of shock waves propagating within a molecular cloud that possesses a magnetic field of $\approx$1 nT are (a) J-type shocks in the neutral component with magnetic precursors in the ionised component or possibly (b) C-type shocks. Further treatment of the properties of shocks in molecular clouds is needed, with an appropriate cooling equation of state.

Chapman, S. J., Pongracic, H., Disney, M. J., Nelson, A. H., Turner, J. A. and Whitworth, A. P., 1992, *Nature*, **359**, 207.
Chernoff, D. F., 1987, *Astrophys. J.*, **312**, 143.
Draine, B. T., 1980, *Astrophys. J.*, **241**, 1021.
Elitzur, M., 1992, *Astronomical Masers*, Kluwer, Dordrecht.
Falgarone, E. and Philips, T. G., 1991, *Astrophys. J.*, **359**, 344.
Garcia-Baretto, J. A., Burke, B. F., Reid, M. J., Moran, M. J., Haschick, A. D. and Schilizzi, R. T., 1988, *Astrophys J.*, **326**, 954.
Kulsrud, R. and Pearce, W. P., 1969, *Astrophys. J.*, **156**, 445.
Lang, K.R., 1974, *Astrophysical Formulae*, Springer, Berlin.

Manuscript received 5 October 1993,
accepted 1 January 1994