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HYDROMAGNETIC WAVES IN MOLECULAR CLOUDS

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ABSTRACT

We suggest that the observed large widths of CO emission lines may be due to the presence of moderate-amplitude hydromagnetic waves in molecular clouds. For parameters typical of CO emitting regions, this hypothesis is viable if such clouds contain systematic magnetic fields of strength $B_0 \gtrsim 40$ microgauss. The damping rate of the waves is discussed, as is the energy required if the observed line widths are due to hydromagnetic waves. To illustrate how wave energy may be supplied, a simple model is outlined for the emission of magnetoacoustic waves by H II regions embedded in magnetized molecular clouds.

Subject headings: hydromagnetics — line profiles — magnetic fields — molecules, interstellar — star formation — turbulence

I. INTRODUCTION

Recent investigations of the interstellar molecules CO, CS, HCN, and H_2CO have led to extensive discussion of the origin of the observed line widths, which are large compared with values expected from thermal broadening. The two main broadening mechanisms suggested to date are (1) radial motions of the molecular cloud (Liszt *et al.* 1974; Goldreich and Kwan 1974; Scoville and Solomon 1974), and (2) "turbulence" (Morris *et al.* 1974; Zuckerman and Evans 1974). In this *Letter* we point out that a third alternative, hydromagnetic wave motions, may also be worthy of consideration.

The qualitative similarity between line profiles observed in transitions of very different optical depths (e.g., Tucker, Kutner, and Thaddeus 1973) seems difficult to explain by using a simple, homogeneous field of turbulent velocities. Furthermore, a broadening mechanism which relies on hydrodynamic eddy turbulence to produce the line widths is hard to understand in view of the strong dissipation in large-amplitude shock waves, which would occur at the high Mach numbers implied by the line widths. Finally, the lack of observable gradients in the velocity field has been used to exclude large-scale rotation as the source of the line widths in some regions (Liszt *et al.* 1974). These facts have indicated to some investigators that such regions are instead in radial collapse, or possibly expansion.

Radial motion models generally predict a decrease in the observed line widths, as a sufficiently small telescope beam moves from the direction of the cloud center toward the cloud edge. Morris *et al.* (1974) use the lack of such a decrease in line width to rule out radial motions models in one specific molecular cloud region. Furthermore, if the collapse interpretation is applied to *all* molecular hydrogen regions from which CO emission is observed, the predicted rate of star formation may be considerably in excess of the observed value (see Zuckerman and Palmer 1974 for a discussion of this problem). Further problems with the radial motion model have been discussed by Zuckerman and Evans (1974).

Our purpose here is to point out the existence of another class of motions which can exist in molecular clouds if the clouds are threaded by a reasonably intense, reasonably systematic magnetic field. These motions can in principle be either coherent or "turbulent." The presence of a strong magnetic field allows the material to undergo oscillations which, because of magnetic pressure, can be hypersonic yet only weakly dissipative. Because of the organization of the material imposed by the magnetic field, such motions do not involve collisions of independent eddies or "clouds." In § II, we give sufficient conditions for the existence of these hydromagnetic motions, with particular reference to moderate-amplitude hydromagnetic (HM) waves whose wavelengths are substantially less than the size of an individual molecular region. We show that if the line widths are due to these HM motions, energy is damped out quickly enough to require some energy source in the clouds. We discuss several possible sources in § III, devoting particular attention to the interaction of compact H II regions with the magnetized cloud medium.

II. SUFFICIENT CONDITIONS FOR A HYDROMAGNETIC INTERPRETATION OF MOLECULAR LINE WIDTHS

In the presence of a magnetic field, a gaseous medium can sustain hypersonic motion without the formation of strong shocks if two conditions are satisfied: (1) the medium must be well enough ionized for all constituents to be strongly coupled to the magnetic field, and (2) the gas pressure force must be small compared with the magnetic stress, or $\beta \equiv 4\pi p/B_0^2 \ll 1$, where B_0 is the magnetic field and p is the gas pressure. The latter condition is just $V_A^2 \gg C_s^2$: the Alfvén speed must be large compared to the sound speed. Normalized to parameters typical of CO clouds, this gives a lower limit for the magnetic field strength of

$$B_0 > 20\left(\frac{n_{\mathrm{H}_2}}{10^3\ \mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{T}{30^\circ\ \mathrm{K}}\right)^{1/2}\ \mu\mathrm{gauss}\ , \tag{1}$$

which is sufficient to give $\beta < 0.25$ in a CO region.

We shall assume that this magnetic field forms a systematic structure with scale comparable to that of the region in which organized CO emission is observed—for example, the $\sim 1^\circ \times 1^\circ$ Orion molecular region (Phillips *et al.* 1974; Zuckerman and Palmer 1974). The field is unlikely to be very tangled unless the Reynolds stress $\frac{1}{2}\rho V^2$ is large compared with the magnetic stress (Weiss 1966). If the magnetic field were weak in this latter sense, the hypersonic flow would be highly dissipative and hence uninteresting as an alternative explanation of the observed line widths.

We now specialize our considerations to the properties of hydromagnetic waves propagating in the cloud. We assume there are perturbations δB of the magnetic field with scale $\lambda \ll L_c \equiv$ the cloud size. When $\beta \ll 1$, the gas moves in the perturbed magnetic field with a speed $\delta v \approx V_{\mathrm{A}}\ \delta B/B_0$, if $\delta B/B_0 \lesssim 1$. Here $V_{\mathrm{A}} \equiv B_0\ (4\pi\rho)^{-1/2}$ is the Alfvén speed. The above expression for δv becomes exact for $\delta B/B_0 \ll 1$. In calculating the Alfvén speed V_{A}, we shall take the mass density to be the total density $\rho = \rho_{\mathrm{H}_2} + \rho_{\mathrm{He}} + \rho_{\mathrm{ions}}$ of the molecular medium, and we shall assume that the velocity δv is the speed of *both* the ions and the neutrals. Because the magnetic field interacts directly only with the charged component, these assumptions are valid only when the time scales of the magnetic perturbations are long compared with the time scale for momentum transfer between the neutrals and the ions (Kulsrud and Pearce 1969), or

$$\frac{2\pi}{P} \ll 2\nu_{ni} = \left(\frac{2m_i}{m_i + m_n}\right) n_i\langle v_{ni}\sigma_{ni}\rangle$$

$$= 2 \times 10^{-11}\mu_{ni}\left(\frac{x}{10^{-5}}\right)\left(\frac{n_{\mathrm{H}_2}}{10^3\ \mathrm{cm}^{-3}}\right)\left(\frac{\gamma_{ni}}{10^{-9}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)\mathrm{s}^{-1}\ . \tag{2}$$

Here $\mu_{ni} \equiv m_i/(m_i + m_n)$, $x \equiv n_i/n_{\mathrm{H}_2}$ is the ionized fraction (we have used one ion species, for simplicity), and $\gamma_{ni} \equiv \langle|v_n - v_i|\sigma_{ni}\rangle$ is the rate coefficient for ion-neutral collisions when both species have Maxwellian distribution functions at the same temperature T. Observations of H_2CO in absorption probably require $x < 10^{-5}$ (Evans *et al.* 1975), and these authors argue that the same limit applies to H_2CO in emission. Some models for molecule formation in the gas phase of dense H_2 regions imply an ionized fraction substantially below this observational upper limit (Oppenheimer and Dalgarno 1974; Dalgarno, Oppenheimer, and Berry 1973; Herbst and Klemperer 1973). The minimum wavelength for which ions and neutrals are closely coupled together by collisions, corresponding to the minimum allowable period $2\pi/P_{\min} = 2\nu_{ni}$ of equation (2), is $\lambda_{\min} \sim 2.5 \times 10^{-2}$ pc, for the same normalization as in equation (2).

We now wish to interpret the molecular line widths as reflecting gas velocity in low-frequency HM waves of small or moderate amplitude (both shear Alfvén and magnetoacoustic modes). Then the condition $\delta B/B_0 \lesssim 1$ implies

$$B_0 > (4\pi\rho)^{1/2}(\Delta V_{1/2}/2)\ , \quad \text{or}$$

$$B_0 > 40\left(\frac{\Delta V_{1/2}}{4\ \mathrm{km\ s}^{-1}}\right)\left(\frac{n_{\mathrm{H}_2}}{10^3\ \mathrm{cm}^{-3}}\right)^{1/2}\ \mu\mathrm{gauss}\ , \tag{3}$$

where $\Delta V_{1/2}$ is the observed full line width in velocity at half-maximum, if the line is optically thin. We note that in this interpretation, the Reynolds stress $\frac{1}{2}\rho V^2$ is in equipartition with the *perturbed* magnetic stress $\delta B^2/8\pi$, and is in equipartition with the *background* magnetic field only when the amplitude of the oscillation becomes moderate ($\delta B \approx B_0$). Thus if the HM waves satisfy equation (3), it is self-consistent to assume that the background field B_0 is ordered on the scale of the whole molecular cloud.

Expressions (1)–(3) are the basic requirements of this hydromagnetic interpretation of line widths.[1] Equations (1) and (3) give the necessary magnetic fields, while (2) gives the needed range of wave period. The hydromagnetic-wave interpretation is not free of requirements on energy sources, however. The friction between neutrals and ions, which makes the neutral gas respond to the magnetic stress, is dissipative (viscous damping in neutral H_2 is negligible), and results in damping of the wave amplitude and gas velocity by the factor e^{-1} in the time (Kulsrud and Pearce 1969)

$$\tau_D(P) = 1.6 \times 10^5\left(\frac{P}{10^5\ \mathrm{yr}}\right)^2(\mu_{ni})\left(\frac{x}{10^{-5}}\right)\left(\frac{\gamma_{ni}}{10^{-9}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)\left(\frac{n_{\mathrm{H}_2}}{10^3\ \mathrm{cm}^{-3}}\right)\mathrm{years}\ . \tag{4}$$

Only oscillations with periods $P < \tau_D(P)$ are of interest.

We can compare τ_D with the lifetime of a molecular cloud, which must be greater than or equal to its free-fall time. We find that in the absence of energy sources, the wave energy would be damped away on time scales less than the life of a typical CO region, unless the waves correspond to bulk oscillations of substantial parts of the whole

[1] The same types of requirements apply if one wishes to explain the line widths at 21 cm of H I regions as HM oscillations (Field 1970).

cloud ($\lambda \sim L_c$). If the wavelengths are small compared with the cloud size, HM wave energy must therefore be replenished by sources at a rate given by the oscillation energy in waves of period P, divided by $2\tau_D(P)$:

$$\dot{E}_{\rm HM} > \frac{10^{36}}{\mu_{ni}}\left(\frac{M_c}{10^5 M_\odot}\right)\left(\frac{\Delta V_{1/2}}{4\ {\rm km\ s^{-1}}}\right)^2\left(\frac{10^5\ {\rm yr}}{P}\right)\left(\frac{10^{-5}}{x}\right)\left(\frac{10^{-9}\ {\rm cm^3\ s^{-1}}}{\gamma_{ni}}\right)\left(\frac{10^3\ {\rm cm^{-3}}}{n_{\rm H_2}}\right) {\rm ergs\ s^{-1}}\,. \quad (5)$$

The equality sign holds if the waves consist of a *few* coherent modes, all of period P. The inequality sign in (5) applies if the magnetic field perturbations consist of a randomly phased spectrum of coupled waves from a large number of sources.

If resonant coupling between different modes has had sufficient time to act [$\tau_D(P) \gg P(B_0/\delta B)$], energy will be transferred from long wavelengths to shorter scales, thus making the total wave energy damp faster (Kraichnan 1965; Cesarsky 1971). This resonant coupling leads to a turbulent spectrum of HM waves. However, such HM turbulence has little similarity to hydrodynamic eddy turbulence. For parameters typical of CO regions, damping rates are probably large enough to prevent the full development of a turbulent HM spectrum, even when sources for the waves are numerous. Thus the energy requirement shown in equation (5) is probably close to the minimum value.

The energy input in equation (5), which is needed to offset damping of the waves, is small compared with the rate of release of energy from the collapse of $10^5\ M_\odot$ over a distance of 10 pc, and is extremely small compared with the total energy output from infrared sources embedded in extended molecular regions (Wynn-Williams and Becklin 1974). The short damping time for waves with $\lambda \ll L_c$ does require, however, a mechanism for converting some fraction of the output of these or other sources of energy into HM waves.

If sources for HM waves are available having the energy input required by equation (5), the consequent HM wave damping can be significant as a heat source for the molecular hydrogen. For example, if a $10^5\ M_\odot$ cloud radiates as a blackbody in the CO lines, then waves of period $\sim 4 \times 10^6$ years will lead to a heating rate sufficient to maintain the cloud at a temperature of 30°–80° K, for the normalizations of expression (5). If the velocity field in the waves is highly systematic (i.e., a few coherent modes), the CO might radiate in an optically thin manner, in which case waves of period $\sim 10^6$ years would give sufficient heating. In making these estimates, we have assumed a CO region of dimension ~ 8 pc, $n_{\rm H_2} \sim 10^3$ cm^{-3}, and a full line width of 4 km s^{-1}. We have used the CO cooling rate due to Goldsmith (1972).

III. POSSIBLE SOURCES FOR HYDROMAGNETIC OSCILLATIONS IN MOLECULAR CLOUDS

Several possible sources of HM waves may exist in molecular clouds. Suppose that various smaller parts of the cloud are in gravitational collapse, but remain temporarily linked to the rest of the cloud via their magnetic fields. Then their rotation can drive torsional magnetic motions akin to Alfvén waves, as the collapsing prostellar fragments lose angular momentum (Mestel 1965; Gillis, Mestel, and Paris 1974). This kind of source may be of particular importance in true "dark" clouds, where there are no embedded H II regions or infrared sources. If the mass of a rotating subcloud is δM_c, its radius is R_c; and if the magnetic field which connects the subcloud to the surrounding medium is aligned with the rotation axis, then the energy lost in waves is (Gillis *et al.* 1974; Rose 1973)

$$L_{\rm rot} \sim \tfrac{1}{2}\delta M_c V_{\rm rot}^2 V_{\rm A}/R_c = 3 \times 10^{35}\left(\frac{R_c}{0.6\ {\rm pc}}\right)\left(\frac{n_{\rm cloud}}{10^5\ {\rm cm^{-2}}}\right)\left(\frac{10^3\ {\rm cm^{-3}}}{n_{\rm H_2}}\right)^{1/2}\left(\frac{B}{50\ \mu{\rm g}}\right)\left(\frac{V_{\rm rot}}{V_{\rm ff}}\right)^2 {\rm ergs\ s^{-1}}\,. \quad (6)$$

Here $V_{\rm A}$ is the Alfvén velocity in the background medium, $V_{\rm ff}^2 \equiv 2G\delta M_c/R_c$, and we have used a subcloud mass, radius, and density appropriate for the molecular "ridge" seen in the direction of the Kleinmann-Low nebula (Liszt *et al.* 1974).

Another possibility is large-scale, nonradial oscillation of the clouds (Stone 1970; Mouschovias and Shu 1974), particularly since these bulk motions are only weakly damped, and thus can continue to exhibit dynamics left over from the initial cloud-formation process. If there are infrared sources in the molecular cloud (e.g., Carrasco, Strom, and Strom 1973; Grasdalen, Strom, and Strom 1973), their radiation pressure may be able to push on the surrounding magnetic field, because the dust and gas are closely coupled. Finally, the expansion of an H II region against a background magnetic field can drive HM waves, and may be of interest in some circumstances. We discuss this possibility here as an illustrative example.

The picture we have in mind is that a newly formed H II region, if it tries to expand at a velocity comparable to the sound speed into an initially uniform background magnetic field, will be able to compress the field until the magnetic energy $B^2/8\pi$ is large enough to balance the gas pressure of the H II region. But because of the inertia of the ionized gas, the expansion overshoots this equilibrium radius and continues until the magnetic pressure overcomes *both* inertia and the gas pressure. The excess magnetic pressure then forces the H II region inward, until the gas pressure grows large enough to overcome the inward inertia and magnetic pressure, and restarts the expansion. Photoionizing stars within the H II region maintain the region at a constant, essentially uniform temperature. These stars are the energy supply for the magnetic field oscillations, which are radiated away from the bouncing H II region as magnetoacoustic waves. There are several mechanisms which may be able to maintain these oscillations over the whole lifetime of the H II region. However, it is also possible that this behavior is only a transient effect, lasting for the first few bounces of the H II region. In the latter case, an H II region would supply HM waves for a time interval equal to several times the bounce period given in equation (7) below.

Assume that one or more massive stars has formed in the midst of a magnetized cloud, in a region where the magnetic field is at least as large as the value in equation (3). Define a radius R_0 such that the magnetic energy contained in a sphere of volume $(4\pi/3)R_0^3 = V_0$ is equal to the thermal energy in the stars' Strömgren sphere, whose volume is $V_S \equiv (4\pi/3)R_S^3 \approx S_H/\alpha n_H^2$. Here S_H is the number of ionizing photons needed to maintain the ionized hydrogen in the Strömgren region (S_H is less than the total number of ionizing photons emitted from the massive stars if dust is mixed with the ionized hydrogen). The parameter α is the total recombination coefficient for hydrogen with recombination to the ground state neglected, and $n_H = 2Cn_{H_2}$ is the hydrogen density in the H II region. The density enhancement factor C allows for possible increased density in the star-forming region, above and beyond the original density n_{H_2} of the molecular cloud.

Consider a newly formed H II region, which begins to expand outward at the sound speed. The preexisting magnetic field must readjust, even if $V_0/V_S \lesssim 1$, to accommodate the extra pressure of the new ionized region. Because of the inertia of the ionized gas, the expanding zone overshoots the radius where the magnetic pressure can exactly balance the gas pressure of the H II region. Oscillations about the equilibrium radius follow. The period of these small amplitude oscillations can be calculated to be

$$P_0 \approx \frac{2 \times 10^5}{fC^{1/3}} \left(\frac{S_H}{3 \times 10^{49}\ \mathrm{s^{-1}}}\right)^{1/3} \left(\frac{10^3\ \mathrm{cm^{-3}}}{n_{H_2}}\right)^{1/3} \left(\frac{50\ \mu\mathrm{gauss}}{B}\right)^{2/3} \mathrm{years}\,. \tag{7}$$

The factor $f \sim 1$ represents the fact that the oscillation is not uniform. This general picture remains valid even if $V_0/V_S \gtrsim 1$, except that the magnetic field oscillates about the value $B_0[1 + (V_0/V_S)]$ instead of B_0.

The fact that the magnetic field is tied to the rest of the molecular cloud, whose mass is high compared with that of the H II region, is crucial to this model, as is the fact that the time needed to reach the equilibrium configuration is short compared with the lifetime of the exciting stars. By contrast, Lasker's (1966) numerical studies of magnetized H II regions considered conditions such that $V_0/V_S \gg 1$, and the time to oscillate even once was long compared with the stellar lifetimes.

The oscillation energy is radiated in the form of HM waves (specifically magnetoacoustic waves) of wavelength $\sim R_0$, resulting in a power loss from the H II region:

$$\begin{aligned} P_{\mathrm{H\,II}} &= \tfrac{1}{2} M_{\mathrm{H\,II}} (kT_{\mathrm{H\,II}}/m_H)(V_A/R_0) \\ &= \frac{6 \times 10^{33}}{C^{2/3}} \left(\frac{S_H}{3 \times 10^{49}\ \mathrm{s^{-1}}}\right)^{2/3} \left(\frac{T_{\mathrm{H\,II}}}{10^4\ ^\circ\mathrm{K}}\right) \left(\frac{B_0}{50\ \mu\mathrm{gauss}}\right)^{5/3} \left(\frac{10^3\ \mathrm{cm^{-3}}}{n_{H_2}}\right)^{7/6} \mathrm{ergs\ s^{-1}}\,. \end{aligned} \tag{8}$$

Here the Alfvén speed V_A is evaluated in the neutral medium outside the H II region. Because their wavelengths are small compared with the cloud size ($R_0 \ll L_c$), the emitted HM waves are damped in the surrounding molecular cloud at a rate fast enough that strong mode-coupling cannot occur. If a molecular cloud contains an H II region, then the time-average, rms component of the velocity field along the line of sight in its immediate environment is

$$\begin{aligned} \langle \delta V_\parallel \rangle = \frac{1.1}{fC^{2/3}} \left(\frac{x\mu_{ni}}{10^{-5}}\right)^{1/2} \left(\frac{\gamma_{ni}}{10^{-9}\ \mathrm{cm^3\ s^{-1}}}\right)^{1/2} \left(\frac{10^3 M_\odot}{M_{H_2}}\right)^{1/2} \left(\frac{S_H}{3 \times 10^{49}\ \mathrm{s^{-1}}}\right)^{2/3} \left(\frac{T_{\mathrm{H\,II}}}{10^4\ ^\circ\mathrm{K}}\right)^{1/2} \\ \times \left(\frac{B_0}{50\ \mu\mathrm{gauss}}\right)^{1/6} \left(\frac{10^3\ \mathrm{cm^{-3}}}{n_{H_2}}\right)^{5/12} \mathrm{km\ s^{-1}}\,. \end{aligned} \tag{9}$$

Thus H II regions may be sources of systematic, wavelike motion for halos of H_2 and other molecules surrounding the H II region (Wynn-Williams 1971). The relatively low value of $\langle \delta V_\parallel \rangle$ in equation (9) makes it unlikely that this particular source of HM waves could be responsible for the entire velocity dispersion seen in giant molecular regions ($M_{H_2} \sim 10^5\ M_\odot$). If the H_2 is highly inhomogeneous and clumpy, however (Zuckerman and Palmer 1974; Chiao 1974), the total mass in giant regions might be lower, and then HM waves radiated by H II regions could be a source of the relative velocities of different clumps.

IV. DISCUSSION

We emphasize that the hydromagnetic velocity field under consideration here could be either "turbulent" or systematic, depending on the number and character of the sources, and the strength of wave damping in the particular region of interest. Even when a medium is very clumpy, its motions can be wavelike. For example, one might have wavelike oscillations of small clouds strung out along magnetic field lines like beads on a string, with the wavelength much greater than the clump size.

If observational information on the strength and structure of magnetic fields in molecular clouds could be obtained, indicating the presence of large-scale, strong magnetic fields, then more detailed magnetohydrodynamic models and calculations of line profiles would be worthwhile. Therefore we would like to emphasize the importance of obtaining such observations—for example, via the longitudinal Zeeman effect in OH at high enough spatial resolution to avoid confusion by OH masers.[2]

Finally, we point out that while star formation is certainly inhibited in strong magnetic fields, it is likely that the tendency for magnetic fields and gas to overturn in the presence of gravity will allow the formation, in a time moderately longer than the free-fall time, of dense pockets of gas. In these small regions, the breakdown of flux-freezing would allow the final collapse of a fraction of the cloud. Thus one would expect some subregions in a large cloud (e.g., the "ridge" in OMC 1) to have already formed protostars or to be in gravitational collapse at the present time. We view the hydromagnetic waves discussed in this *Letter* as an alternative line-broadening mechanism for those parts of a large molecular cloud which are not in radial collapse.

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[2] Verschuur (1969) has observed magnetic fields of order 50 microgauss in the direction of Orion A in H I. Beichman and Chiasson (1974) have reported milligauss fields in Orion A. They used observations of OH in emission which suffer from possible confusion with OH masers. Dyck *et al.* (1973) and Carrasco *et al.* (1973) report 10 μ and 2–3 μ polarization in front of the Becklin-Neugebauer object and in the ρ Oph cloud complex, respectively, which probably indicate the presence of magnetic fields. But the field strengths inferred are sensitive to unknowns in the grain composition (Jones and Spitzer 1967). Clark and Johnson (1974) interpreted observations of broad lines in SO at the center of Orion A as evidence for Zeeman splitting in a field of $\sim$1 gauss. But such fields, if they are real, almost certainly would be found in regions denser than $n_{H_2} \sim 10^3$ cm^{-3}.

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