TURBULENT AMPLIFICATION OF INTERSTELLAR MAGNETIC FIELDS

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ABSTRACT. We show that the radiative cooling properties of the interstellar gas lead naturally to a scaling law for the magnetic field of the form $B \propto n^{1/2}$, *if* the magnetic field is amplified by a vigorous injection of turbulent energy due to expanding HII regions, stellar winds, supernova explosions, stellar jets, *etc.*

1. How is the interstellar magnetic field amplified?

In regions of the interstellar medium which are supersonically turbulent, the magnetic field is amplified until there is approximate equipartition of energy between the turbulence and the magnetic field. The more vigorous the input of turbulent energy, the stronger is the resulting magnetic field.

2. How is amplification limited?

This amplification process is limited by dissipation of the turbulence, either by ion-neutral friction or by radiation from shocks. As long as the processes injecting turbulent energy into the interstellar medium are coherent over time-scales longer than the ion-neutral coupling time-scale, radiation from shocks dominates the dissipation.

Once the field has been amplified to equipartition with the turbulence, disturbances propagate through the medium at speeds

$$v \sim v_A = (4\pi\rho)^{-1/2} B \qquad (1)$$

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where v_A is the Alfvén speed. v_A will therefore be the typical speed of dissipative shocks.

Because the radiative cooling efficiency of the interstellar gas increases steeply by several orders of magnitude above a critical temperature $T_C \sim$ 3000–10000K, shocks with speeds

$$v > v_C \geq (16kT_C/3\overline{m})^{1/2} \tag{2}$$

(where $\overline{m}$ is the mean gas particle mass) are much more dissipative than those at lower speeds.

Turbulent amplification of the magnetic field is therefore relatively efficient as long as $v_A < v_C$, but much less efficient once $v_A > v_C$. Over a wide range of turbulent energy input rates the magnetic field will be amplified until v_A approaches v_C. The corresponding limit on the component of the magnetic field along the line of sight is

$$B_{||} \sim (64\pi kT_C\rho/9\overline{m})^{1/2} \sim C\left(n/\mathrm{cm}^{-3}\right)^{1/2} \tag{3}$$

Here $n = \rho/(2.4 \times 10^{-24}\mathrm{gm})$ is the number density of hydrogen nuclei in all forms in a gas with population I composition.

For predominantly atomic gas with $\overline{m} \sim 2.1 \times 10^{-24}$gm and $T_C \sim 10^4$K (due to the onset of bound-bound and bound-free cooling by H^o), $C_{H^o} \sim 5.8\mu G$. For predominantly molecular gas with $\overline{m} \sim 3.5 \times 10^{-24}$gm and $T_C \sim 3000$K (due to the onset of dissociative cooling by H_2), $C_{H_2} \sim 2.5\mu G$.

3. Comparison with observations

In the Figure, equation (3) is compared with observation. The solid diagonal line represents equation (3) with $C = C_{H_2}$ as appropriate for predominantly molecular gas; whilst the broken diagonal line represents equation (3) with $C = C_{H^o}$ as appropriate for predominantly atomic gas. The rest of the Figure is copied from Fiebig and Güsten (1989) — their Figure 4 — and displays the run of magnetic field strength (parallel to the line of sight) with density. There is a remarkably tight correlation, in the sense that observed values of $B_{||}$ are concentrated just below the limit given by equation (3). This correlation provides strong support for the role of supersonic turbulence in amplifying the interstellar magnetic field.

The fact that very few values of $B_{||}$ are measured well below the limit may be a selection effect, in the sense that larger magnetic fields are more readily detected. This is certainly the case for the H_2O maser observations of high density gas, as emphasized by Fiebig and Güsten (1989). However, it may also be an indication of how vigorously and frequently turbulent energy is injected into the interstellar medium on the scales observed.

4. Discussion

We note that the mechanism discussed here to explain the observed correlation of magnetic field and density is unrelated to that discussed by Mouschovias (1987). Mouschovias' discussion entails the gas being in gravitationally bound, magnetically supported configurations. As stressed by Fiebig and Güsten, these conditions do not obtain in the high density H_2O maser sources. They do not necessarily obtain in the lower density sources either.

These H_2O masers are believed to arise in strong MHD shocks (Kylafis and Norman 1987), which are precisely the conditions produced by vigorously stimulated turbulence.

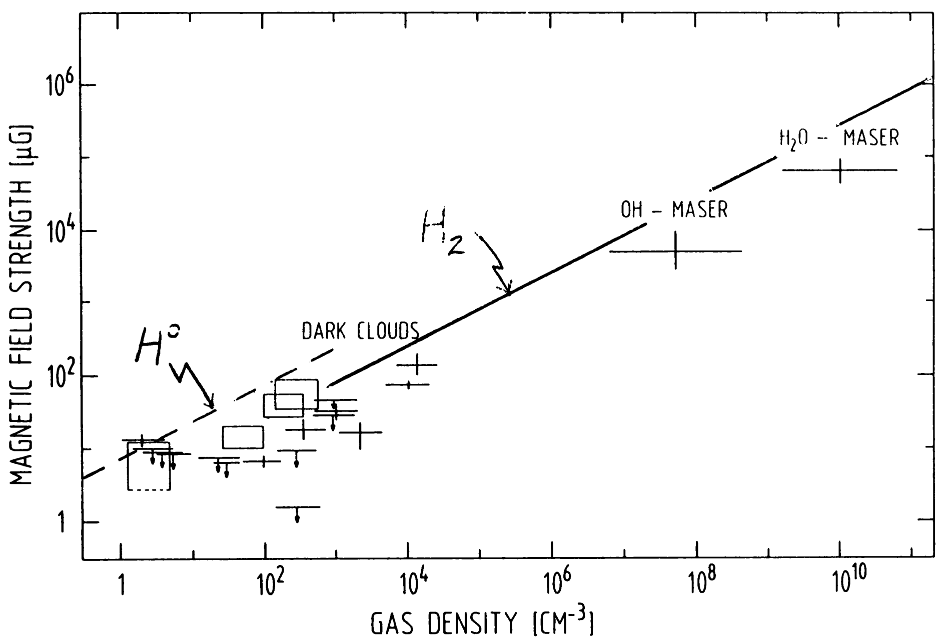

Figure. The variation of $B_{||}$ with n. The diagonal lines represent equation (3) for predominantly molecular gas (full line) and predominantly atomic gas (broken line). The rest of the figure is copied from Fiebig and Güsten (1989) and represents a variety of observational estimates of $B_{||}$ and n.

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5. Conclusions

We conclude that the observed correlation of magnetic field strength and density may be evidence for a high level of interstellar turbulence in the regions observed; and for a high efficiency of magnetic field amplification resulting therefrom.

References

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