THE STRUCTURE OF THE NEUTRAL INTERSTELLAR MEDIUM: A THEORY OF INTERSTELLAR TURBULENCE

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Abstract. We present a model for the development of density structure in the neutral interstellar medium. In this model, bulk kinetic energy is injected mainly at small scales, by jets and expanding nebulae generated by young and/or massive stars. Subsequently, this bulk kinetic energy propagates to, and is dissipated on, larger scales.

This is in contrast to standard (incompressible) Kolmogorov turbulence, where kinetic energy is injected at larger scales, then propagates to, and is dissipated on, smaller scales. The sense in which the Second Law of Thermodynamics drives the propagation of turbulent energy is reversed in the interstellar medium because virialized self-gravitating gas clumps and ensembles of clumps (clouds) have negative effective specific heat.

The model is able to explain Larson's relations (between the mass, size, and velocity-dispersion of molecular clouds and clumps; Larson 1981), the maximum masses of giant molecular cloud complexes, the velocity dispersions observed (at low resolution) in face-on spirals like the Milky Way, and the apparent scaling of the interstellar magnetic field with density.

1. Injection of turbulent energy into the interstellar medium by stars, and the generation of small-scale density structure by fragmentation of shells and layers

We assume that stars - in particular young and/or massive stars associated with jets, outflows and overpressured nebulae (HII regions, stellar wind bubbles, and supernova remnants) - are the main sources of bulk kinetic energy for the neutral gas in the interstellar medium. When a shell of dense gas is swept up by an expanding nebula, it eventually fragments

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gravitationally into clumps. Theoretical analysis (Whitworth et al. 1994) shows that, irrespective of local details, (i) the column-density of hydrogen nuclei (in all forms) through the shell at this stage is always close to the canonical value $N \sim 6 \times 10^{21} cm^{-2}$ (corresponding to a visual optical depth $\tau_V \sim 3$), and (ii) the masses of the clumps depend strongly only on the effective sound speed a_{eff}, *viz.* $M \propto a_{eff}^{\alpha}$ where $\alpha \sim 3.5 - 3.8$. Since we expect $a_{eff} \sim 0.2 - 2.0\, kms^{-1}$, clumps are created with a range of masses $5 - 5000 M_\odot$, but all having approximately the same column-density. If clumps formed in this way can virialize without significant dissipation, they will subscribe to Larson's relations in the form

$$R \sim 0.07\, pc\, (M/M_\odot)^{\beta} \qquad \beta \simeq 0.5 \tag{1}$$

$$\Delta v \sim 0.24\, kms^{-1}\, (M/M_\odot)^{\gamma} \qquad \gamma \simeq 0.25 \tag{2}$$

where R is the radius of a clump, and Δv is the velocity dispersion within a clump.

Moreover, if two such clumps collide supersonically and the resulting radiative shock produces a dense layer which has smaller internal velocity dispersion than the two original clumps, the layer will fragment gravitationally thereby generating even smaller clumps. These clumps will at their inception also have the canonical surface density; and if they virialize without too much dissipation, they will also subscribe to Larson's relations.

We conclude that the interaction between stars and the interstellar medium can inject turbulent energy into the interstellar medium and deliver density structure obeying Larson's relations, on small-to-medium scales, $< 10^4 M_\odot$, provided virialization occurs without too much dissipation. We now argue that this turbulent energy and density structure should evolve mainly by propagating to larger scales.

2. The consequences of the 2nd Law of Thermodynamics for the propagation and amplification of turbulent energy in an ensemble of self-gravitating gas clumps

Since the effective temperature of an ensemble of clumps (as determined by their mean random kinetic energy) greatly exceeds the effective temperature of the ambient radiation field (as determined by the mean density of electromagnetic radiation), the 2nd Law of Thermodynamics requires the ensemble of clumps to evolve in the sense which entails a net loss of heat to the ambient radiation field, *i.e.* radiative cooling. We demonstrate below that this requirement promotes an evolution in which small clumps more often amalgamate to form larger ones than *vice versa.*

To be specific, consider a virialized clump of mass M and radius R. Its self-gravitational potential energy is $-\zeta_1 GM^2/R$, (where ζ_1 is a factor of order unity which depends on the detailed density profile of the clump). Since the clump is virialized, its net energy is half this.

Now suppose that we have a virialized ensemble of such clumps with filling factor f_{vol}, and consider the energy budget of two nearest-neighbor clumps. The bulk kinetic energy of the pair (relative to their mutual center of mass) is $f_{vol}^{(1-\beta)/(1-3\beta)} GM^2/2R$. Their mutual gravitational potential energy is $-(3f_{vol}/4\pi)^{1/3}\zeta_2(f_{vol})GM^2/R$, (where $\zeta_2(f_{vol})$ is a function which accounts for tidal interaction between the clumps and approaches unity for small values of f_{vol}.

Finally suppose that these two clumps amalgamate to form a single clump having mass $2M$, radius $2^\beta R$, and net energy $-\zeta_1 2^{1-\beta} GM^2/R$. The net energy which must be radiated away is then

$$Q = \left[\zeta_1 \left(2^{(1-\beta)} - 1 + \frac{1}{2} f_{vol}^{(1-\beta)/(1-3\beta)}\right) - \left(\frac{3f_{vol}}{4\pi}\right)^{1/3} \zeta_2(f_{vol})\right] \left[\frac{GM^2}{R}\right] \tag{3}$$

Amalgamation will be the dominant sense of evolution, provided $Q > 0$, *i.e.* provided β is small (clump radius does not increase too rapidly with increasing mass) and f_{vol} is small (nearest-neighbor clumps are well separated). Observations indicate that $\delta \sim 0.5$ and that $f_{vol} \sim 0.1$; setting $\zeta_1 = \zeta_2 = 1$, these values give $Q \sim 5.13(GM^2/R)$, implying that amalgamation is thermodynamically favored over fragmentation. If we neglect the bulk kinetic energy term completely (on the assumption that the velocities of nearest neighbors are perfectly correlated), we still obtain $Q \sim 0.13(GM^2/R)$, and so amalgamation is still the thermodynamically preferred sense of evolution. Even with perfectly correlated velocities, the combinations of β and f_{vol} which must be invoked to make Q negative are untenable.

Additionally, since $dln[\Delta v]/dln[M] > 0$, amalgamation amplifies the turbulent energy. We refer to this as gravitational amplification. In other words, gravitational energy is being released both to compensate the dissipative losses going into radiation, and to increase the turbulent kinetic energy.

Basically, the negative specific heat of a virialized system means that loss of heat entails an increase in both the internal random (*i.e.* turbulent) kinetic energy and the binding energy (*i.e.* the modulus of the self-gravitational potential energy). The observed low filling factor for clumps and the observed relatively slow decline in mean clump-density with increasing clump-mass then necessitate that the turbulent energy injected into the interstellar medium on relatively small scales propagates to larger scales by amalgamation and in so doing is amplified by gravity. This is in direct contrast to the theory of gravitational virialization proposed by Scalo & Pumphrey (1982), where clumps break up into smaller clumps.

3. Cosmic opacity and the elastic limit of interstellar gas

The lack of low-energy resonance transitions in the two most abundant atomic species in the Universe (H & He) means that the coupling between diffuse gas and radiation at low temperatures $T < T_R \sim 10^4 K$ is much weaker than at higher temperatures. At higher densities, hydrogen is mainly molecular, but even then the coupling is much weaker below $T_R \sim 3000K$ than above. In effect, the opacity of the interstellar medium, and hence its ability to cool radiatively, increase rather abruptly as the temperature rises above T_R. The upshot is that high-velocity shocks ($v > v_R \sim 10\,kms^{-1}$) which raise the temperature of the gas above T_R will be significantly more dissipative than slower shocks. In other words v_R corresponds to an abrupt decrease in the elasticity of the interstellar medium.

[In passing, we note that this same fundamental microphysical property of cosmic matter can be held responsible for a great diversity of universal phenomena, including the origin of the cosmic microwave background and the closeness of its spectrum to that of a blackbody, thermostatic control of primordial gas in galaxy and cluster formation (Hoyle 1955), the Hayashi limit of stellar surface temperatures (Hayashi 1961), and the distribution of binary star periods (Whitworth 1994).]

4. Dissipation of turbulent energy in an ensemble of self-gravitating gas clumps, the maximum mass for giant molecular cloud complexes, and the HI velocity dispersions in face-on spiral galaxies.

The abrupt decrease in the elasticity of the interstellar medium for shock speeds exceeding v_R suggests that there is a large range of values for the rate of injection of turbulent energy into the interstellar medium over which the turbulent energy is amplified gravitationally to, but not beyond, speeds of order v_R. Substituting $\Delta v \sim v_R$ in Eqs. (2) and (1), we obtain a maximum mass $M_{max} \sim 3 \times 10^6 M_\odot$, and a maximum radius $R_{max} \sim 100\,pc$, which agree well with the values for the largest giant molecular cloud complexes observed in the Milky Way. The inference is that in these extreme complexes gravitational amplification of turbulent energy terminates because the shock velocities start to exceed v_R, and therefore become more dissipative. Presumably complexes which attempt to evolve beyond this limit undergo a disruptive episode of violent self-propagating star formation, thereby returning the residual interstellar matter to the low end of the clump mass-spectrum.

For the same reason, isolated face-on spiral galaxies observed in HI or CO, at sufficiently low resolution to sample a macroscopic portion of their interstellar media, should have velocity dispersions of order v_R at all radii. Figure 10 in Shostak & van der Kruit (1984) and Figure 10 in van der Kruit & Shostak (1984) present observations of the galaxies NGC 628 and NGC 1058 which clearly support this suggestion.

5. Shock dissipation as the the process limiting turbulent amplification of the interstellar magnetic field, and the apparent scaling of the field with density

We assume that interstellar and circumstellar magnetic fields are generated and sustained by turbulent dynamos, and that when the process operates efficiently the field is amplified to equipartition with the turbulence, so that the Alfvén speed $v_A = (4\pi\rho)^{-1/2}B$ (where the symbols have their usual identities) is comparable with the turbulent speed. As long as the process injecting turbulent energy has a coherence time-scale much longer than the ion-neutral coupling time-scale, dissipation of turbulence will be dominated by radiative shocks, and for a wide range of injection rates will set in at shock speeds of order v_R. Consequently, the largest magnetic fields observed in interstellar and circumstellar gas are likely to have $v_A \sim v_R$ or equivalently

$$B_{||} \sim (64\pi k T_R \rho / 9 < m >)^{1/2} \sim C(n/cm^{-3})^{1/2} \tag{4}$$

where $B_{||}$ is the line-of-sight component of the magnetic field, and n is the number-density of hydrogen nuclei in all forms.

Figure 1 reproduces the observational results of Fiebig & Gusten (1989), along with Eq. (4). For predominantly atomic gas, at low densities $n < 10^3 cm^{-3}$, with $T_R \sim 10^4 K$ and $< m >\sim 2.1 \times 10^{-24} g$, we have $C \sim 5.5$ microgauss. For predominantly molecular gas, at high densities $n > 10^3 cm^{-3}$, with $T_R \sim 3000K$ and $< m >\sim 3.5 \times 10^{-24} g$, we have $C \sim 2.5$ microgauss. We see that the theoretical relationship provides a tight upper limit to the observational points.

We emphasize that the gas in which turbulent dynamo amplification of the magnetic field occurs does not have to be self-gravitating, and indeed in the circumstellar OH and H_2O maser sources contributing to Figure 1 it is most unlikely to be. Observations pertaining to self-gravitating gas are confined to the density range $10^2 - 10^4\, cm^{-3}$, where the scaling relation is not well defined. Therefore it is important to stress that we have not in this section invoked virialization.

Also, the observations may well select only the largest fields, because these are the most easily detected. In this case the inference is that these are the only places where the injection of turbulent energy has been sufficiently vigorous to reach speeds of order v_R.

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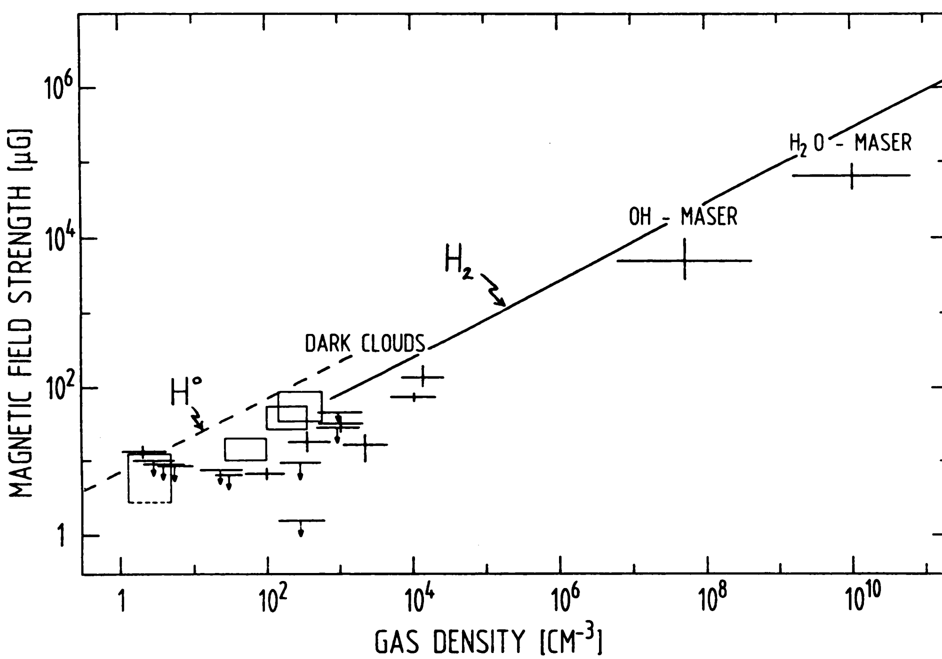

Figure 1. The variation of magnetic field strength with density, from Fiebig & Güsten (1989). The lines are the upper limits predicted by Eq. [4]. See text for details.