I - LARGE SCALE STRUCTURE

CHARACTERISTICS OF THE DIFFUSE INTERSTELLAR MEDIUM

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ABSTRACT. There have been several recent changes in perspective on the diffuse interstellar environment, including recognition of a thick disk of warm gas, cosmic rays, and magnetic field. In addition, evidence for a pervasive hot phase driven by supernova disruption has weakened to the point that a quasihomogeneous warm intercloud gas may occupy most of the interstellar volume at midplane, with individual bubbles created by supernovae and OB associations occupying perhaps 10 and 20 per cent respectively. The bubble population is sufficient to explain the high stage ions (O VI, N V, C IV, perhaps Si IV) found in the disk, though possibly not those found at higher z. The estimated midplane pressure has increased, leaving the thermal pressure inside clouds almost negligible. The reduced porosity of the medium, its greater thickness, and its larger pressure all act to suppress fountain activity, either arising from the disk generally, or from the blowout of superbubbles. Finally, there appears to be a peculiar coincidence between the cloud heating mechanism and the activity determining the interstellar pressure.

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1. INTRODUCTION

I would like to draw the attention of students of the denser parts of the interstellar medium (ISM) to changes that have taken place in the picture of the surrounding medium. I expect that those changes will affect how one describes the formation of molecular clouds, as well as the boundary conditions relevant to their stability.

Perhaps the most significant results in this context are: that the total midplane pressure corresponds roughly to $p/k \approx 25{,}000$ cm^{-3} K, with roughly 1/3 each in cosmic ray, magnetic, and kinetic forms; and that the most probable density in the ISM could well be that in warm gas (WIM or WNM), about 0.2 cm^{-3}.

2. THE THICK DISK

Evidence for a thick disk extending to $|z| \sim 2$ kpc is found in radio synchrotron studies, dispersion and rotation measures to pulsars (and rotation measures of extragalactic objects), measures of cosmic ray pathlength and trapping timescale, observations of HI and Ti II which traces HI, observations of H^+ and Al III which traces H^+ (c.f., Boulares and Cox, 1990). The weight of the large amount of low density HI and H^+ high off the plane is substantial, causing the increase in the estimated midplane pressure to the value quoted above, even in the presence of lowered estimates for the gravitational acceleration.

This increase in pressure is in line with recent reevaluations of the magnetic field strength, cosmic ray pressure, and kinetic pressure associated with the broad wings of the 21 cm line. The dominance of magnetic over thermal pressure (perhaps 8000 cm^{-3} K magnetic versus 3000 cm^{-3} K thermal in clouds) is also consistent with the nearly density independent magnitude of B. These points are discussed further in, for example, Cox (1988, 1989, 1990a, 1990b), Spitzer (1990), Boulares and Cox (1990), and Cox and Slavin (1990), with references to the large body of relevant observational work.

3. THE PROBABLE DEMISE OF THE INTERCONNECTED HOT PHASE

Several lines of evidence once led us to think that a relatively large fraction of the interstellar volume was occupied by very low density gas ($n \lesssim 10^{-2}$ cm^{-3}) at high temperature ($T \gtrsim 3 \times 10^5$ K). None of these, however, has proven to be a certain indicator of such gas. The soft X-ray background appears to arise from a single Local Bubble of 10^6 K gas surrounding the Sun. There are other such bubbles, generally too large to be created by individual supernovae and normally associated with OB associations. The origin of the Local Bubble remains mysterious, but its identification and bounded character remove its interior conditions from being an example of interstellar material everywhere. This is discussed further in Cox and Reynolds (1987), Snowdon et al. (1990), Cox and Slavin (1990).

A rather convincing argument for the widespread presence of hot gas in the ISM was made by McKee and Ostriker (1977). They demonstrated that at the anticipated rate, supernovae (SNe) would violently disrupt a warm intercloud medium into a froth of hot gas and dense included bits of shells, or clouds. Because the warm intercloud gas, with typical density ~ 0.2 cm^{-3}, had been the only candidate other than hot gas for filling the volume, it appeared certain that only hot gas was actually left as a possibility.

This argument has been critically reviewed by Cox and Slavin (1990). They find that a combination of factors (lower SN rate, improved remnant model, higher interstellar pressure) lowers the estimated porosity generated by SNe in the intercloud medium by at least a factor of 30 from the previous results. The best current estimate appears to be $q \sim 0.1$.

As a consequence we can no longer be certain that supernovae are capable of the disruption that would guarantee the existence of a pervasive hot phase. Their influence appears instead to be the production of individual localized bubbles of hot gas occupying about 10% of the interstellar volume.

This re-analysis made use of a new model for SNR evolution by Slavin and Cox (1990). The model included significant magnetic pressure and followed the remnant evolution until its hot bubble completely disappeared. With an explosion energy of 5×10^{50} ergs, an ambient density of 0.2 cm^{-3}, and a magnetic field of 5 μG, the bubble achieved a maximum radius of 56 pc and disappeared after 5.5×10^{6} years.

Furthermore, the evolution-averaged contents of the ions O VI, N V, and C IV in the bubble had the correct ratios and magnitudes to indicate that the observed average interstellar densities of these ions would be just those expected from the population of bubbles. Thus the other chief indicator of interstellar hot gas, the high stage ions, is better understood as being due to individual SNR bubbles than from any previous description.

4. THE PROBABLE DEMISE OF GALACTIC FOUNTAINS

Without a hot phase pervading the ISM, models with galactic fountains that rise diffusely out of the general disk have no source term (except for a few SNe at very high z).

With a thick disk including warm interstellar gas (with scale height of perhaps 500 pc), as well as the pressure of cosmic rays and magnetic field (with even greater scale height and continued existence to at least 2 kpc), the breakout of OB association driven bubbles from the disk of the Galaxy is made much more difficult. Models of fountains using such breakouts as their source function will now find that far fewer, if any, of the Galactic OB associations will be sufficiently vigorous to serve that function. Small bubbles should be smaller than previously estimated, large ones avoiding breakout will grow even larger in the plane. The magnetic pressure will make the shells thicker, and cause them to rebound more quickly to eliminate both bubble and shell.

5. OTHER DYNAMICAL ASPECTS OF THE THICK DISK

I think there are several other dynamical features that will be interesting to explore, but are now only vague thoughts. One is connected to the fact that the Alfven speed is roughly 30 km s^{-1} at midplane and probably increases with z to perhaps 50 km s^{-1} at 1 kpc.

My suspicion is that waves generated by SN, OB associations, molecular cloud motions, and density waves will increase in energy density until saturated (i.e. $\delta B/B \sim 1$). Then nonlinear effects provide dissipation. If this is true at all z, it implies $\rho v^2 \sim B^2/8\pi$ and a rough equipartition between diffuse gas kinetic pressure and the field pressure. It also implies that at high z there will be dissipative shocks produced with characteristic velocities of order 50 km s^{-1}, possibly even higher at higher z. These high velocity components are a potential source of high stage ions far off the plane, though one would tend to expect highly variable amounts of the very highest stage ions, O VI and N V relative to the lower stages like C IV and Si IV in individual features.

In addition, the outer layers of the disk should be very prone to large excursions from equilibrium, like the upper end of an exponential atmosphere. In situations with large relative velocities between interarm and arm material, hydraulic jumps could be an interesting aspect of spiral structure.

6. THE DIFFUSE CLOUD COINCIDENCE

Diffuse clouds, or at least their denser parts, occupy no more than a few percent of the interstellar volume at midplane, and only a rather small fraction of one percent of the total thick disk. I think of them as a condensate in the more diffuse environment, low in the gravitational potential.

One tends to think of diffuse clouds gathering up material and magnetic flux from the intercloud phase as they are formed, and therefore having higher magnetic field as well as higher density. Except for transients during formation, however, that is impossible. The clouds have no surrounding pressure capable of keeping their magnetic field elevated. Even ram pressure cannot be very significant for a population whose dispersion velocity is significantly lower than the Alfven speed in the surrounding gas. Thus it cannot be too surprising that the magnetic fields in diffuse clouds are no larger than those in the surroundings. The field pressure is too large for it to be otherwise.

As a consequence, the diffuse cloud phase equilibrium should not be thought of as taking place at a constant thermal pressure imposed by the surroundings, except on perhaps irrelevantly long time scales.

On short timescales, I think this means that any thermal pressure is allowed within the clouds, so long as it is not so large as to blow them apart, i.e., it should not exceed the roughly 8000 cm^{-3} K available from the external field pressure. It also means that higher thermal pressure should be accompanied by lower field pressure inside the clouds.

So the minimum requirement for the existence of diffuse clouds is that they not be heated so much that their minimum thermal pressures exceed the available magnetic pressure. As it happens, this requirement is met only marginally (see Cox 1988 for diagram and discussion), suggesting that there is probably some link between these two pressures, though in existing models, there isn't.

There are at least two possible forms for such a link.

The first, which was explored somewhat by Field, Goldsmith, and Habing (1969), works in analogy with a fluid in a closed container, or the Earth's ocean and atmosphere. If there is too little fluid in the vapor phase to provide the needed pressure to confine the liquid, then more of the liquid will vaporize. The equilibrium vapor pressure is approached automatically. In this picture, the clouds accept only excess material from the environment above that needed to establish the pressure needed to confine them. Since we usually think of the heating and cooling mechanisms of diffuse clouds being tied to the stellar radiation field, the elemental abundances, and the grain population, we find ourselves looking for mechanisms by which the clouds can decide on the value of the surrounding pressure, particularly the contribution of the magnetic field.

In the opposite perspective, one can inquire instead about what mechanisms operate directly to set the intercloud pressure. The value must equal the weight of the intercloud gas, thus the total intercloud column density and scale height are involved. Certainly the approach above acts directly on the column density, but another factor decides the scale height, and thus the average gravity experienced by the gas.

If one supposed that supernova stirring somehow creates the motions required to establish the magnetic field, that cosmic rays and wave fields equilibrate with that, then the supernovae could be the active agent deciding on the scale height, establishing the pressure versus column density relationship, completing a picture which involves supernovae plus cloud heating and cooling to set the equilibrium.

This has got to be too simplistic. There will almost certainly be a model like this that works, but it cannot be complete. It relies on a coincidence. When all is said and done, out of all the orders of magnitude available, the required scale height for the gas turns out to be very similar to that of the stars themselves.

Another way of viewing this coincidence is to assume at the outset that the scale height of the diffuse gas will be comparable to that of the stirring agent, the diffusely located supernovae. Then the explosions are not needed to specify the pressure/column density relationship, but the picture doesn't work unless the supernovae can stir the system to run the dynamo.

In short, either the cloud heating or supernova rate is accidentally just right, or one of them is controlled in some way by the other.

I have given some thought to how such control might come about. My favorite idea at the moment (c.f. Cox 1990a) is that dust grains are expelled from dense clouds into the intercloud medium with properties that will not allow that material to condense immediately into clouds. But grain processing in that environment eventually leads the grains to photoelectrically absorb less of the starlight, until finally they have the right properties to allow stable clouds to condense. It may not be the right idea, but I am told at least (Savage, private communication) that there is observational evidence that the UV extinction of dust is larger in low density regions.

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