OVERVIEW OF THE INTERSTELLAR MEDIUM: SUPERNOVA RELATED ISSUES

Donald P. Cox
Department of Physics
University of Wisconsin-Madison

Abstract: Establishing that the interstellar pressure is higher than usually realized and that the magnetic component is probably dominant, I propose a drastic revision for our understanding of the interstellar landscape.

I have spent much of the past year thinking about and collaborating on a review paper (with Ron Reynolds) on the Local Interstellar Medium (LISM) (1). Since I have come to regard the LISM as an anomalous region, atypical of the interstellar medium at large (ISM), this activity has done little to prepare me for giving this talk. Fortunately, other recent reviews (2,3,4,5) have satisfied me that a general presentation of the diverse properties of the ISM would be superfluous. At this time an honorable man would probably return to his seat. What I plan instead is to discuss a wide range of ISM issues relevant to both the nature of the medium and the interaction of supernovae with it.

In order to make a detailed predictive model of the evolution and appearance of a remnant, one needs to know a great deal about its interstellar environment. Roughly speaking, the requirements are the spatial distributions of material (including density, temperature, elemental abundances, dust grains, and ionization stages) as well as those of the magnetic field, nonthermal particles, background sources of ionization, and mass motions.

Super Bubbles, Etc.: As you know, many of the relevant environmental parameters can be seriously perturbed by the presence of a massive presupernova star, or worse, by an association of such stars, some of which exploded in the medium prior to t=0 for the supernova remnant about to be modeled.

I have no intention of amusing you with my ignorance of the physics of sequential supernovae and the possibilities of generating superbubbles and worms thereby. Superbubbles and worms, like the LISM, fall in the category of anomalous regions. A paper (6) by Tenorio-Tagle, Bodenheimer, and Rozyczka that I recently refereed, however, added an interesting twist to this subject, showing that shell formation could be Rayleigh-Taylor unstable when driven by sequential explosions.

The Cygnus Loop Environment: Not surprisingly, the way one actually learns the sort of detailed ISM information needed for remnant modeling is by observing remnants. For example, studies (7) of the Cygnus Loop have indicated that there are at least four density regimes with which it is currently interacting. Away from regions of bright optical emission, the shock speed is thought to be about 400 km s^{-1}, into an effective density $n_0 \sim 0.16$ cm^{-3} (8,9), generating diffuse x-ray emitting gas with $T \simeq 2.4 \times 10^6$ K. In many places around the circumference, however, the Hα signature of "non-radiative" shocks is evident in deep exposures (10,11,12,13). In some of these areas, at least, the shock velocity is more like 150 to 200 km s^{-1}, into $n_0 \sim 1$ cm^{-3}. Interestingly enough, this preshock gas must be neutral in order to generate the Hα signature. With a recombination timescale of about 10^5 years, this places an interesting lower limit on the time since the explosion, or an upper limit on the combined ionizing UV of the preexplosion and exploding star.

In regions of the bright optical emission of radiative shocks, the UV and optical spectra suggest shock velocities in the neighborhood of 100 km s^{-1} and preshock densities $n_0 \sim 8$ cm^{-3} (7). Abundances seem normal, but with evidence of depletion of Si and Fe relative to other elements. The weak 2 photon continuum shows that this higher density medium has been preionized by the recent UV emission of the shock itself.

Finally, there are a few small dense knots of material (e.g. Miller position 2, XA of Hester and Cox (14,7)).

Some years ago when it was first realized that the Cygnus Loop had the gross properties of shocks with speeds of both 100 and 400 km s^{-1}, it was suggested (15) that one should envision a "blast wave" traveling in a low density (0.16 cm^{-3} for example) within which there are clouds (8 cm^{-3} for example). The high pressure behind the blast wave was imagined to drive the slower radiative shock waves into the clouds. In a sense, this is the picture I just described. But I want to encourage a bit of caution. The cloudlet/intercloud blast wave picture was originally directed toward understanding how the x-rays can be brightest in precisely those areas where the radiative shock waves are found. The cloudlet scale was presumed infinitesimal ($\lesssim 3 \times 10^{-3}$ pc) and their numbers huge so that seemingly smooth continuous filaments could be regarded as loci of the radiative shocks of a population of recently encountered cloudlets.

I wish to state categorically that this microcloudlet picture has absolutely nothing to do with the reality of the Cygnus Loop (14). The X-rays are bright in the regions of radiative shock waves because these regions are large and recently encountered. The reflected shock front in the lower density material just interior is sufficient for the observed x-ray production. A cloud/intercloud picture is appropriate only on much larger scales.

My overall impression is that the density varies between the "0.16 cm^{-3}" and "1 cm^{-3}" values on fairly large scales, since it is possible to follow the "non-radiative" structures for very large distances along the Loop perimeter (16). Perhaps the preshock density of these is frequently close to the lower value above, with the higher value more characteristic of the brighter areas chosen for detailed study. The "8 cm^{-3}" density regions, however, are found in several discrete patches over the surface of the Loop (in my thesis I estimated they covered 12% of the surface) with scales of 10 to 20 pc. Within these large structures, the density is > 10 cm^{-3} in a few dense knots but is more typically in the range $\lesssim$ 5 to 10 cm^{-3}. Gradual density variations of factor of 2 are found along the 0.3 pc length of one filament near the smaller Miller 2 knot (7). This gradient may have caused much of the apparent rotation of the filament from tangential alignment. In most regions away from knots, the density gradients are probably smaller. Much of the caustic surface structure of the filament pattern would follow from much smaller density variations (17).

We shall shortly find that the ISM should have a gap in its density distribution, between roughly 0.5 cm^{-3} and 15 cm^{-3}, hence disallowing the densities which are so common in the large clouds around the Cygnus Loop. This density gap, however, is appropriate for optically thin material bathed in a full complement of starlight. Since the regions around the Loop show noticeable obscuration of background stars, perhaps the heating rate and equilibrium densities are lower. In any case, either by the action of the precursor star or by chance, the Cygnus Loop environment too appears to be in the noticeably atypical category.

As a small aside, I would like to point out that all of the above analyses have ignored the possible role of strong cosmic ray acceleration by the shock fronts. One of my students, Ahmed Boulares, is currently of the opinion that starting from the observed post shock temperatures and densities and using reasonable values for the preshock B and p_{CR}, that much the same observational picture could derive from shocks of 3 times higher velocity, putting 90% of their energy into cosmic rays. The Loop age is thereby reduced by a factor of 3 and its energy increased by a factor of 10. An indication of the possible dominance of non-thermal pressure in the Spur filament was recently found observationally. Although these inferences may sound outlandish, we will have to continue to be careful with the foundations of our house of cards.

The Interstellar Pressure and Its Scale Height: The interstellar pressure can be estimated from the vertical distributions of density and gravity (4,18,19). The resulting weight of the interstellar material significantly exceeds estimates made of the midplane pressure by other means (19,1). The size of this discrepancy has increased as we have gained appreciation of the magnitude of the densities of HI and H^+ at high z.

As a rough approximation, material distributed exponentially with scale height z_i and midplane density ρ_{0i} in the galactic gravity of the solar neighborhood contributes a midplane pressure

$$\Delta p_i \simeq \rho_{0i} z_i (10^{-8}\ \mathrm{cm/s^2})/(1+500\mathrm{pc}/z_i)$$

or

$$\Delta p_i/k \simeq 8500\ \mathrm{cm^{-3}\ K}\{\sigma_i(M_\odot/\mathrm{pc}^2)\}/(1+500\mathrm{pc}/z_i)$$

where $\sigma_i=2\rho_{0i}z_i$ is the full disk surface density of the component. With $\sigma_i \sim 2M_\odot \mathrm{pc}^{-2}$ each for HI with $z_i \sim 400$ pc and H^+ with $z_i \gtrsim 1000$ pc (2,3), the combined p/k contribution is at least $1.9 \times 10^4\ \mathrm{cm^{-3}}$ K. The cold HI (and associated warm HI) closer to the plane contribute much less pressure per gram because of their reduced weight at lower z. In addition, that contribution is to first order balanced by the velocity dispersion and can be disregarded in our quest for the magnitude of the general diffuse interstellar pressure (19). Subtracting 3000 $\mathrm{cm^{-3}}$ K cosmic ray pressure from the above estimate we have the contemporary estimate of the combined thermal, magnetic and wave (or turbulence) pressures in the diffuse interstellar material at z=0:

$$p/k|_{1987} \simeq 16{,}000\ \mathrm{cm^{-3}\ K}.$$

This neglects a potentially significant contribution from halo material (4,18). Even so, it is a factor of four higher than many typical estimates of the thermal component. In those regions for which the thermal and wave component sums to 6000 $\mathrm{cm^{-3}}$K, the residual magnetic field must have a value of 5 μG. This is probably more typical of the interstellar field than the roughly factor of 2 lower value commonly estimated from various measurements (20,4).

As an aside, the thermal pressure within the hot gas of the Local Bubble is probably more nearly $10^4\ \mathrm{cm^{-3}}$ K, consistent with a reduced B field in the very low density cavity (1,19). The fact that at higher interstellar densities there is virtually no dependence of B on density (20) is a direct consequence of the dominant contribution of the magnetic field to the overall pressure.

Pressure scale height information has been somewhat confusing. Certainly the observed mass scale heights indicate the scale of significant pressure gradients, namely 400 pc to 1 kpc. The latter is said to be a lower limit to the electron scale height and since the corresponding ions seem now to provide the largest weight contribution, the pressure gradient may extend significantly beyond 1 kpc. Information from γ-rays indicates that cosmic rays have a thicker distribution than the interstellar material of the lower disk (4). The ^{10}Be studies have suggested that cosmic rays sample a mean density of only 0.1 cm^{-3} (21), implying a probable scale height somewhat in excess of 1 kpc. The ratio of pole brightness to plane emissivity in nonthermal radio at 10 MHz corresponds roughly to an emission path of 1.4 kpc (4,22). Since that emissivity derives from a product of magnetic field and energetic electron density, its distribution may drop off slightly faster than B^2 or the cosmic ray pressure. Collectively these evidences seem to push for effective scale heights for cosmic ray and magnetic pressures of about 2 kpc. The H^+ scale height may be similar.

The confusing part is that we have effectively assumed that the nonthermal pressures are the major form of support for the material, yet unless the distributions are pushed somewhat beyond reasonability, it appears that a significant portion of the weight to be supported is lower (e.g., around $z \sim 400$ pc) than much of the gradient in the nonthermal pressure (e.g., $z \sim 1$ to 2 kpc).

One way around this difficulty has been to introduce a halo component to the density distribution (4,18). At low z the thermal pressure gradient in the halo component helps to support the H I distribution while at high z the weight of the halo material helps hold down the magnetic field and cosmic rays. For best results, halos with pressure minima around 1 to 3 kpc have been invoked.

It seems to me that the high z distribution of electrons and ions probably extends to the low density halo of the coronal ion (23) population. I have no problem with the idea that material may be present at high z. This does, however, increase the midplane pressure. In theory this can be compensated by the separate inclusion of the pressure of a hot interstellar component of significant filling factor in the plane. This is just a bit tricky however. The rms value of B must be kept high (~ 5 μG) while the thermal pressure in low density regions is very significantly enhanced. This can be done in a steady state fashion only by having B within the H I even higher (say 7 μG) with a lower value in the very hot low density material. This pushes a bit beyond credence for my taste.

A simple alternative is that we have been fooled into the use of a laminar B field. By consideration of magnetic tension it is straightforward to tie high z fields and cosmic rays to the weight of lower lying material. A direct consequence is that field lines will have upward curvature below 400 pc and downward curvature above 1 kpc. This picture has been present for some time, but I and others have occasionally forgotten its significance. High z B field is "anchored" by lower z weight. It is the natural picture espoused by students of the instability of the laminar configuration (See ref 4 for a survey of some of the literature on the Parker instability).

We can illustrate the mechanism of tension while at the same time deriving an interesting limit on its effectiveness. Consider the configuration in figure 1 with a flux tube of cross sectional area A, length L, interior mass density ρ, in gravity g.

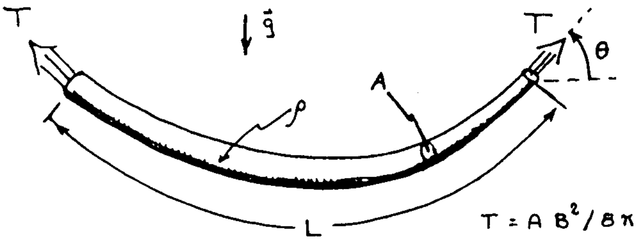

Figure 1. Geometry of a tension supported cloud.

The force balance requires $\rho A L g = 2AB^2 \sin\theta/8\pi$. Since the dominant pressure form is magnetic, the tube cross section is nearly constant and B is essentially the ambient field strength. As a consequence, there is an upper limit to the magnitude of g (and hence the height z) to which a tube of given ρL can be supported:

$$g_{max} = \frac{2}{\rho L} \cdot \frac{B^2}{8\pi} \simeq \frac{p}{(\rho L)} \cdot$$

For $z \lesssim 200$ pc, we have $p \sim 2 \times 10^{-12}$ dyn cm^{-2} and $g \simeq 2 \times 10^{-9}$ cm s^{-2} (z/100 pc). In this range, the absolute maximum ($\sin\theta = 1$) height of suspension is

$$\frac{z}{100\ \text{pc}}\Big|_{\max} = \frac{160\ \text{pc cm}^{-3}}{L\ n} .$$

Stable configurations will likely avoid heights greater than about half the maximum ($\sin\theta \sim 1/2$). As a consequence, the denser diffuse clouds (say $n \sim 40\ \text{cm}^{-3}$ and $L \sim 2$ pc) should never be supported above 200 pc and rarely above 100 pc. Flux tubes with this mass density on them but greater linear extent (e.g., 20 pc) should in equilibrium be found only very near the plane. Conversely, low density (e.g., $0.16\ \text{cm}^{-3}$) flux tubes shorter than 100 pc can be tension supported at any height.

There are two further interesting relationships following directly from this result. One is that for a spherical cloud, the maximum downward force on the field is essentially $A\ B^2/8\pi$ and hence the maximum downward force of a cloud population is $(\Sigma\ A)\ B^2/8\pi$.* As a result, the maximum downward force per unit area is roughly the "sky coverage factor" of the clouds times the pressure.

For stringy clouds, the maximum downward force is further reduced by the aspect ratio. On the whole, the observed cloud population is not likely to anchor more than roughly one fourth of the total pressure. The remainder must be provided by the diffuse intercloud material.

The second aspect involves consideration of the net effective vertical magnetic pressure as a function of z, including both the non verticality of the "pressure" perpendicular to B and the tension along B. The result is that

$$p_B^{(eff)} = \left\langle \frac{B^2}{8\pi} (\cos^2\theta - \sin^2\theta) \right\rangle = \frac{1}{8\pi} \langle B^2(z) - 2\ B_z^2(z) \rangle$$

Here $B_z = B \sin\theta$ is the vertical component of B, asymptotically zero at $z = 0$ and z large. The resulting possible effective magnetic pressure distributions are shown schematically in Figure 2, for three levels of tension induced distortion of the field. Clearly the introduction of magnetic tension through a vertical component of B provides the same sort of effect achieved in the halo models. There is possibility of a strong gradient in the effective pressure close to

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* I thank Charlie Goebel for a useful discussion leading to this point.

the plane, while having a much weaker gradient in B^2 and the cosmic ray density, allowing their large scale heights.

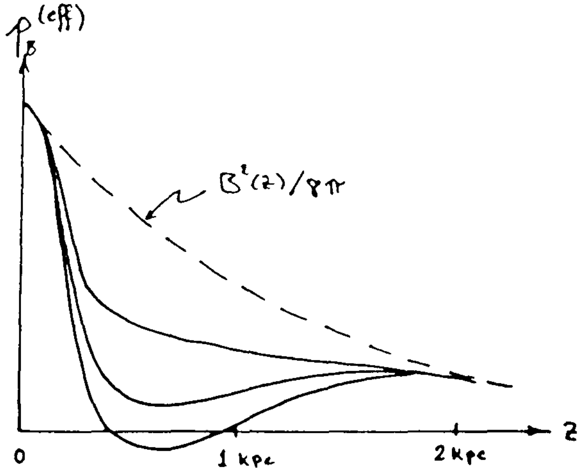

Figure 2. Effective magnetic pressure distributions.

We will return to further discussion of the interstellar pressure, but for the moment we have the result that the nominal interstellar pressure exclusive of cosmic rays is 16,000 cm^{-3} K, much of which is magnetic, and that a comparable pressure extends to high z (scale height 1 to 2 kpc). This then is the typical pressure with which isolated supernova remnants must contend. (In the absence of appreciable magnetic tension, the midplane pressure is probably even higher, but I then have trouble understanding the low measured values of B.)

Further Aspects of Cold HI Regions: Statistics of H I column density measurement indicate that the number of clouds with column density $> 10^{20}$ N cm^{-2} is 5.7 $N^{-0.8}$ per kiloparsec, for $0.32 < N < 2.2$ (2,3). A remarkably similar result in both slope and normalization was found by Hobbs using K I absorption lines (24). His quoted range of validity is $1.7 < N < 17$, consistent with the bias of the K I line toward high H I column densities. The T-τ relation, as discussed by Kulkarni and Heiles, augmented with the assumption that thermal pressures have nT ~ 3000 cm^{-3} K nominally implies cloud temperature, line of sight depth, and local density given by

$$T \sim 96 \text{ K } N^{-2/3}$$

$$L \sim 1 \text{ pc } N^{1/3}$$

$$n_{H\ I} \sim 31 \text{ cm}^{-3}\ N^{2/3}$$

although there is great scatter in the relation and much of it may be due to complications of radiative transfer in inhomogeneous clouds rather than systematic parameter variation between clouds (Kulkarni, private communication). With these results, however, one concludes that the space filling factor of all clouds in this range is

$$f = 0.02\ (nT/3000 \text{ cm}^{-3} \text{ K}).$$

If these clouds were spheres, then $L = 4\ r/3$, the number of clouds of radius exceeding r is

$$\#\ (> r) = 5.5 \times 10^{-4} \text{ pc}^{-3}\ (1 \text{ pc}/r)^{4.4}$$

for $r > 0.53$ pc, at which point $\# = 9 \times 10^{-3}$ pc^{-3}. Hence a remnant the size of the Cygnus Loop (R~ 20 pc) could be expected to have about 300 such clouds of radius 0.5 to 1 pc and typical separation of 4.8 pc - or one fourth the Loop radius. Quite clearly a filling factor of only 0.02 is not equivalent to implying that large remnants will not have a significant cloud presence.

On the other hand, I can think of no reason whatever to suppose that clouds should be spheres, while many processes lead reasonably to linear or planar structures. We could, for example consider 10 pc square cloud sheets of effective depth 1 pc, equivalent to roughly 100 of the spherical clouds. We would then find the Loop interacting with only a few such cloud sheets, roughly as observed. Furthermore, as Kulkarni has shown (private communication), the cloud number per column density interval is consistent with all clouds being sheet like, with the same normal column density, viewed at random angles.

Pressure measurements in the cold H I clouds, as summarized by Kulkarni and Heiles (2,3) seem to reinforce the notion that the usual thermal pressure is of order 3000 cm^{-3} K, but with factor of 3 variations possible in either direction. Even with a fairly nonviolent ISM, such thermal pressure variations are possible because of the dominance of the magnetic contribution. In a truly static case, however, such variation would not be present at a given z because the absence of magnetic force along B leads to the usual hydrostatic conditions involving only the thermal pressure. My sense is that the interstellar dynamical timescale is too short for us to have to worry about pressure equilibration along flux tubes, except over short distances.

An interesting aspect of the diffuse clouds is that cold H I ($40\ \mathrm{K} \lesssim T \lesssim 100\ \mathrm{K}$) seems to be closely associated with warm H I ($100\ \mathrm{K} \lesssim T \lesssim 400\ \mathrm{K}$). It has been suggested that the latter envelops the former, as though there were a core mantle relationship, perhaps due to the attrition of some heating mechanism important on the outside. Let us, however, consider the simple heating - cooling balance for optically thin clouds heated by "starlight" at a rate $C_\star$ per atom. A region with density n is heated per unit volume at a rate $C_\star$ n and cooled at a rate L(C II,T)n^2. Hence the density temperature relationship in equilibrium is

$$n\ (T) = C_\star\ /\ L\ (T)$$

$$nT = C_\star\ T\ /\ L\ (T)$$

from which we can construct the nT versus n relationship shown in Figure 3. (The values of $C_\star$ and L(T) were inferred from reference 2 and 3 but the magnitude of $C_\star$ was slightly reduced to make the pressure minimum consistent with other measures.) A secondary segment of the graph indicating the warm neutral medium with T ~ 8000 K is sketched in as well.

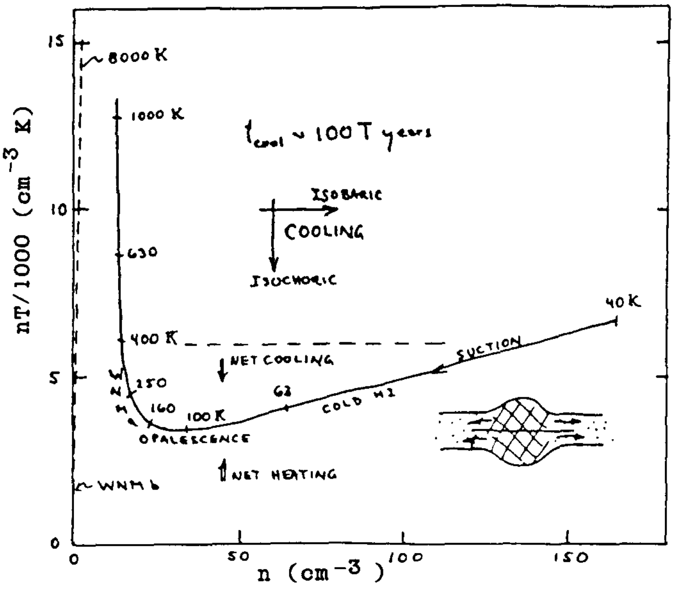

Figure 3. Phase diagram for equilibrium between starlight and C^+ cooling.

So far this figure seems to provide us with a mild variant of the phase diagram upon which the Field, Goldsmith, and Habing ISM model (25) was based. In their view, at high z the total pressure was lower than the lowest cloud pressure, allowing only the intercloud component. But at lower z the overlying material weight was great enough to allow both clouds and intercloud gas as stable phases. If the scale heights were fixed in such a way that the pressure was provided mainly by the weight of the intercloud component, then the total pressure at midplane (or actually at cloud top) would hover closely around the minimum pressure allowing clouds, independent of the total H I surface density. The intercloud surface density would (for the same g, etc) always would be just the constant amount needed to stabilize most of the mass in clouds.

The above description makes a lovely picture but doesn't apply directly to our system where the pressure is largely magnetic and heating and cooling occur mainly at constant density rather than constant pressure. For isochoric cooling, material at too high (or low) nT for given n cools (heats) and moves downward (upward) to the equilibrium line. This differs drastically from isobaric cooling where the motion is left-right, and the warm leg of equilibria (100 K $\lesssim$ T < 1000 K shown) unstable. In our case such equilibria are in fact stable, although they occur over a very narrow density range (and fairly rapidly varying thermal pressure above ~ 400 K). The total temperature range with nT $\lesssim 10^4$ cm^{-3}K is ~ 34 to 700 K, although stability is greater lower in the pressure well where 45 K $\lesssim$ T $\lesssim$ 400 K. Within this range there is still a slow instability due to the thermal pressure gradients along field lines. At the two extremes the thermal pressure is high and the field is bloated. In each case the system wants to move toward relaxation by adjusting the density to settle into the thermal pressure minimum. Since this minimum is broad and shallow, ranging say from (n ~ 25 cm^{-3},T ~ 160 K) to (n ~ 50 cm^{-3}, T ~ 80 K), the fluid has zero bulk modulus (the pressure is independent of density over times larger than the thermal time ~ 100 T years). As a result it is similar to a fluid such as CO_2 at its critical point. Such fluids exhibit critical point opalescence, a notion which may have some interstellar relevance.

In any case, I have hoped to show in this section that cold H I is perfectly capable of being in close association with warm H I ($\lesssim$ 400 K say) with exactly the same heating rate per atom; that in a magnetically dominated system, clouds seek (via suction) the local pressure minimum; and that as a consequence, thermal pressures significantly lower than the total pressure are the expected norm. Notice, however, that the "warm neutral medium" component associated with cold material in this way (WNMa) should not have a density lower than about 15 cm^{-3} (in an optically thin environment, subject to details of the heating rate). As a consequence it cannot contribute appreciably to filling the intercloud spaces. In addition, there is no advantage to any sort of core halo or onion-like structure for clouds.

Volume Filling Versus the Porosity Imperative: A recurrent topic in ISM discussions involves the fraction of the interstellar volume occupied by warm HI (or H^+) versus a very hot (or coronal) phase. In 1977 we were impressively convinced by McKee and Ostriker (26) that Coxswain's Myth[*] (27) had underestimated the interstellar porosity. The then popular supernova rate acting on the then popular intercloud medium (0.1 cm^{-3}) would cause total disruption into a mix of hot gas and cold dense sheets within one generation (about 2 x 10^6 years).

Yet it is ever more likely that an 8000 K diffuse HI component of mean density 0.1 cm^{-3} is an observational reality, along with an ionized one of average density about 0.03 cm^{-3} (2,3). By comparing the dispersion and emission measures of the latter, the volume filling factor of warm H^+ is estimated to be about 0.11, making the local density about 0.25 cm^{-3} and p/k ~ 4000 cm^{-3} K (28). If the neutral HI has similar thermal pressure and temperature (as various indicators suggest) its local density should be 0.5 cm^{-3} and its filling factor about 0.2. Including the small contributions of the denser phases, we are lead to believe that the total noncoronal filling factor is about 0.35. Some pundits may be uncomfortable with a value this high, others quite satisfied with the 0.65 left for the hot component.

Certainly however, the arguments above are not airtight. In some scenarios the HI is more likely to have the same density as the H^+ rather than the same pressure (3). That could raise the noncoronal occupation to 0.55. If a larger fraction of the warm HI is in the diffuse form (WNMb, 8000 K) versus cloud form (WNMa, 100-400 K), or if observational uncertainties are included, I would guess that nearly 100% occupation is possible.

One stumbling block to accepting a high spatial filling factor is that it requires a rather low intercloud thermal pressure. Full occupation would probably need p/k ~ 1500 to 2000 cm^{-3} K. Actually, the diffuse HI could typically have a thermal pressure this low. The

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$p/k \sim 10^3$ cm^{-3} K, a value consistent with full occupation of space by the warm HI intercloud component. Of course we cannot presently deny the existense of large discrete regions of hot material - the Local Bubble, Loop I, etc., but their general volume fraction may be small.

The theoretical reason that $p/k \lesssim 3000$ cm^{-3} K is perfectly acceptable for the intercloud component is that the ISM does not in fact have thermal pressure balance between phases. The cold and lukewarm HI is caught in the local pressure minimum of the phase diagram of figure 3, but the intercloud phase is not. Its stable equilibria probably include much lower pressures. Given the suction mechanism described earlier, we even expect the phase to tend toward low p, except that the dynamical and thermal timescales are both of order 10^6 years and the above tendency is frequently disrupted.

We are still faced with the porosity imperative of McKee and Ostriker (26). Supernovae would seem to disrupt the system totally on a short timescale. A careful review of the argument leading to this conclusion, however, shows that it is incorrect (29). Let me summarize. The early evolution of a remnant of energy 10^{51} E_{51}ergs in a medium of density n_0 is evaluated for the radius, mass M_c, and shell velocity v_c at the cooling epoch. Assuming negligible ambient pressure, the expanding shell is followed thereafter until the remnants overlap with their neighbors. From that, the characteristic pressure at the time of overlap is evaluated and found to be

$$p_{ov} \sim \frac{M_c v_c}{8\pi R_g^2 \tau_{sn}} \sim 10^{-12} \text{ dyn cm}^{-2}\, E_{51}\, (E_{51}\, n_0^2)^{-1/14}$$

where the numerical value assumes τ_{sn} = 30 years in a galactic disk of radius, R_g = 15 kpc. Characteristic values of the radius, velocity, and time at overlap are 104 pc, 13 km s^{-1}, and 2 x 10^6 years in the simplest model with E_{51} = 0.5 and n_0 = 0.1 cm^{-3}. We thus refind the McKee and Ostriker result that the volume occupation is of order 1 when the shell dynamical pressure is comparable to the general pressure of the ISM.

Have we thus found that the SN would immediately generate a foam of holes and shells, meaning that we calculated the SN evolution in a medium unlike the one left by SNe? Well, no we don't. We must reevaluate the mental image. These very large remnants are not sweeping the ICM into thin dense shells. Owing to magnetic field and cosmic ray pressure, the compression possible even in a radiative shock of this strength is at most a factor of 2. The kinetic energy of the shell and the energy radiated are both very small compared to the energy in the compressed field and compressed or accelerated cosmic rays: The late expansion is very nearly adiabatic, and a comparatively weak disturbance.

Rather than a foam of thin dense shells surrounding large volumes of hot gas, we find large radii volumes of slightly compressed and slightly accelerated material with bubbles of hot material buried deep inside. The medium is certainly no longer homogeneous, but a dominant fraction of the volume contains material with a density not very different from that assumed initially. Rather than saying that the remnants have destroyed the initial condition, it is more accurate to say that they have rearranged it slightly. High volume occupation by weak remnants does not imply high porosity.

The medium in which supernovae evolve would seem to be one in which there are density variations of roughly a factor of 2 about 0.15 cm^{-3} over scales of order 40 pc or so, with those components in motion at characteristic speeds $\lesssim$ 15 km s^{-1}. In addition there are included bubbles of gas at coronal temperatures created by the intense heating of material close to the explosion sites.

Although I am convinced from the above that supernovae would not immediately sweep the interstellar medium into a cloud/coronal configuration, I can't prove that some sort of cloud/coronal state would not persist if formed, or even that a diffuse warm intercloud state is stable against gradual accumulation of long lived hot bubbles as originally advocated by Barry and me (27). One's understanding of stability depends very much on assumptions about how supernova remnants "acquire" interstellar matter. Do remnants propagate primarily in a coronal component but augment its density by thermal evaporation or hydrodynamical stripping? Or does the pressure wave simply interact with all material it engulfs, everywhere heating but at any moment to very different temperatures? My prejudice has leaned to the latter picture for many years, and at times I have been able to describe a feedback mechanism that guaranteed a noncoronal filling factor of about 50%. In its absence the remnant would be unable to acquire sufficient mass for radiation of its energy. The medium goes thermally unstable, starting a strong wind. The pressure drops, destabilizing the clouds and voila, the warm intercloud component seizes the space. Something like that.

Hot bubbles, generated by supernovae in a warm intercloud ISM dominated by magnetic pressure, seem to provide a very good model for the origin of the OVI measurements (29). The bubbles are essentially in pressure equilibrium with the surroundings, cooling mainly by thermal conduction to their surfaces where the energy is radiated. The OVI is found mainly in these boundary layers, condensation rather than evaporative boundaries. The mean interstellar OVI density is, like the supernova contribution to the pressure, directly proportional to the supernova power. The observed mean density is consistent with the observed pressure, both consistent with the estimated supernova power. The typical OVI feature column density, mean free path, low speed, and narrow width are all compatible with observations.

We have seen that the largest reasonable scale for an individual remnant is about 100 pc. (For various reasons, McKee and Ostriker found a somewhat larger value, about 180 pc.) For years this lead me to view the system as two dimensional, remnants occurring at some rate per unit area, essentially in the plane, and then expanding until they broke out above the HI layer, dumping their hot interiors at the base of the corona, thereby causing a galactic fountain. Since it has become clear that the dominant volume filling HI phase extends 400 pc or more above the plane, and possibly that the relevant scale height for Type I SNe does also (5), the above picture cannot be correct. In my view now, the "base of the corona" is at z ~ 2 kpc. Remnants occur in an essentially three dimensional space through which there may be an appreciable transport of energy to the corona. Individual remnants do not expand to the point that they deposit their hot interior material directly into a fountain or other coronal form.

System Configuration: I would like one day to be able to say that I understand how a certain total gas surface density σ_g when placed in a stellar disk $\sigma_\star$, scale height $h_\star$, will distribute itself among the various phases, and in space. The fact that I cannot now do that makes its discussion all the more important. As a consequence, let us consider some plausible attributes of the interstellar system.

As we have seen, supernovae cause the interstellar system to have at least a certain total pressure, which in some simple models is proportional to the supernova power per unit area of the disk. Let us assume that this is the dominant contribution to the total pressure requirement, that the supernova rate is proportional to the stellar density, and the scale height of this total pressure is thus approximately that of the stars, $h_\star$.

The thermal pressure of clouds is the minimum pressure of the nT versus n diagram (always near T ~ 100 K) and is directly proportional to the heating rate per atom. Given that the latter is proportional to the density of starlight, the ratio of thermal pressure in clouds to total pressure provided by remnants is independent of the stellar density. It is a mass function parameter. We have also seen that a cloud population with small sky coverage factor is incapable of confining the pressure provided by the remnants. The job thus falls to an intercloud component.

Presumably there is some organization to the mass motions in the disk, leading to a dynamo generating the magnetic field. The action saturates when the field strength is sufficiently large that it interferes with the mass motions (the crank on the dynamo becomes stiff). Cosmic ray acceleration also consumes SN power at a relatively constant rate, the density building up until it can distort the magnetic field, allowing escape at a rate equal to production (30). (These are the equipartition excuses that I've found most reassuring over the years e.g. ref. 31).

The intercloud component is not constrained to have the same thermal pressure as the clouds. It is furthermore not easily disrupted into a coronal/cloud configuration because the supernovae are perturbations on an environment they have themselves created. As individuals of large scale, they necessarily constitute rather weak disturbances in a highly elastic medium. The intercloud component can apparently be supported by the B field to high z, and as a consequence we expect its scale height to be a significant fraction of that of the pressure (h_* in the current discussion.) As a result, the intercloud weight which balances the supernova induced pressure requires an intercloud surface density σ_{IC} which is independent of the density and scale height of the stars. (Both the pressure and the effective gravity have been made proportional to σ_* by our prior assumptions, leaving σ_{IC} independent of it). In addition, the signal velocity in the intercloud medium $v_{IC} \propto \sqrt{p/\rho}$ is some constant fraction of the stellar dispersion velocity.

In this simplistic picture, we have in essence supposed that clouds, intercloud gas, interstellar pressure, the supernova rate density, and stars have the same relative z distributions, so long as stars dominate the mass density. The total and thermal pressures depend on supernovae and starlight, respectively, such that their ratio is mass function rather than density dependent. Finally, the surface density of intercloud gas needed to confine the interstellar constituents to the disk is nearly constant.

If pushed to the extreme, I would say that flaring of the galactic HI disk at large radii probably follows from breakdown of the assumption that stars dominate gravity. In addition, the HI hole at small r may follow from there having been too little gas there to provide even the intercloud component, in which case the system is probably unstable to wind evacuation. But enough of this speculation. It's time to return to survey the carnage and construction in our recent path.

Summary: The total interstellar pressure at midplane can be read directly from the weight of the ISM. The resulting value is roughly a factor 4 higher than estimates of the diffuse cloud thermal pressure, and is consistent with $B_{rms} \simeq 5\mu G$, largely independent of density.

Nonthermal indicators suggest a pressure scale height of 1 to 2 kpc, while much of the mass is located below 400 pc. This is interstellar pressure. (Cloud support tends to be largely dynamic rather than hydrostatic.)

Cloud and intercloud components are not constrained to have similar thermal pressures. Interphase pressure equilibrium is dominated by the magnetic field. Clouds are suctioned to the local minimum of the p, n diagram, with a broad temperature range around 100 K. The actual value of that pressure is proportional to the heating rate, presumably to the local starlight density. The thermal timescale is roughly 100 T years at 10^{-25} erg s^{-1} per atom. The minimum density of warm HI associated with clouds appears theoretically to be about 15 cm^{-3}. (The Cygnus Loop's involvement with such a component, however, seems to show material down to at least 5 cm^{-3} in the cloud regions, and even lower density in the surroundings. The lower density material should be overheated and in transit to the intercloud component.)

The intercloud HI (at 8000 K) is not subject to the cloud pressure minimum. Its particular distribution is dominated by dynamics. It probably has a filling factor ≥ 0.3 (with the H^+) and could approach 0.8. The low local densities needed for the high filling factor are seen in the VLISM and the preshock density of the intercloud component of the Cygnus Loop as well as other locations.

Supernova disruption of the intercloud medium is much less severe than previous estimates have suggested; the medium is highly elastic to the disturbances. Modest scale bubbles of hot gas are necessarily created by remnants, and their late evolution easily accounts for the interstellar OVI observations. Some large regions of hot gas exist (Local Bubble, Loop I, etc.); but it is not clear whether SN bubbles will collect to generate a hot interstellar phase. There is no clear observational need for such a phase, but if it exists, it occupies less than 0.65 of the volume and comingles with a very smoothly distributed intercloud component.

Our understanding of the control mechanisms for pressure, phase segregation, equipartition, and scale heights is exceedingly limited. Simple considerations suggest that scales should all be proportional to the SN source distribution, that the ratio of cloud thermal pressure to supernova dominated total pressure should be fixed by the population rather than density of stars, and that the total intercloud component surface density should be fairly constant.

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