Annu. Rev. Astron. Astrophys. 2005. 43:337–85
doi: 10.1146/annurev.astro.43.072103.150615

First published online as a Review in Advance on June 14, 2005

THE THREE-PHASE INTERSTELLAR MEDIUM REVISITED

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Key Words dust, galaxies, interstellar medium, Milky Way, supernova remnants, X rays

■ **Abstract** The interstellar medium in the vicinity of the Sun is arranged in large-scale structures of bubble walls, sheets, and filaments of warm gas, within which close to the midplane there are subsheets and filaments of cold dense material; the whole occupies roughly half the available volume and extends with decreasing mean density to at least a kiloparsec off the plane. The remainder of the volume is in bubble interiors, cavities, and tunnels of much lower density, with some but not all of those lower density regions hot enough to be observable via their X-ray emission. This entire system is pervaded by a rather strong and irregular magnetic field and cosmic rays, the pressures of which are confined by the weight of the interstellar gas, particularly that far from the plane where gravity is strong. Observations suggest that the cosmic rays and magnetic field have an even more extended vertical distribution than the warm gas, requiring either the weight of additional coronal material or magnetic tension to confine it to the disk. Adjusting one's perception of this medium to embrace the known aspects is difficult. After this adjustment, there are many problems to solve and prejudices to overcome—the weak role of thermal instability, the suppression of certain gravitational instabilities, the problem of determining the state in the low-density regions, the twin difficulties of not having too much OVI (O^{+5}) and getting enough diffuse 3/4 keV X-ray emission, the possible importance of large old-barrel–shaped supernova remnants in clarifying matters, the possible role of dust evolution in adjusting the heating to make clouds stable, the factors influencing the magnitudes of the interstellar pressure and scale height—things that global models of the medium might examine to clarify some of these matters; attention to these details and more constitute the challenge of this subject.

1. OVERVIEW

The interstellar medium (ISM) is a fascinating place to spend one's life. There is ample beauty in the images, abundant challenge in the observations, good company in the fellow travelers, and a high sense of importance attached to the work as a foundation for understanding how galaxies work, along with the ways they may have influenced one another and the intergalactic medium. There is also sufficient uncertainty about what is happening that it presents a huge canvas for the joyous exercise of imagination.

The field spans such a wide range of areas, however, that it has become difficult to form a cohesive overview within which to imagine the activities at smaller scales. In addition, there has been a considerable inertia against the clearing away of the less useful aspects of earlier conceptions. A good big picture has been hard to come by.

For those working in this field, the twin purposes of this review are to highlight the difficulties with most of the common conceptions of the ISM and to propose changes that could better guide our understanding. The reader from outside this discipline will find descriptive material about what the ISM is like (and not), a peek into some of the complexities and controversies, and a proposed view of the medium's structure that will better inform their qualitative impressions of what can and does happen there.

In its hurry to provide ways to think about the subject, the review may seem dismissive or ignorant of the work of others. One may wish to turn to other comprehensive presentations for a more balanced survey. Those of McKee (1995) and Ferrière (2001) recommend themselves. The proceedings of a conference in Granada on the workings of the Galaxy (Alfaro, Perez & Franco 2004) and of one held at Arecibo in the late summer of 2004, celebrating the 65th birthday of Carl Heiles, also promise to be very valuable resources.

1.1. Background on Two-Phase and Three-Phase Categorizations of the ISM

The ISM has a wide span of densities and temperatures; ranges of these are often designated as components, or phases. In the three-phase version, those phases usually include the following: the dense cold gas (the cold HI, or diffuse clouds), with densities above about 10 cm^{-3} and temperatures below 100 K; the warm component with densities in the range 0.1 to 1 cm^{-3} and temperatures of several thousand Kelvins (the warm intercloud medium, some of which is ionized); and the hot low-density component with temperatures in excess of 10^5 K and densities below about 0.01 cm^{-3} (the hot, or coronal, component).

There is also a colder denser component, the dark clouds, which may sometimes be thought of as a short-term product of the activities of the ISM leading to star formation, or as occupying so little volume that it can be neglected in considering the diffuse ISM characteristics. Or it may be included as a fourth phase.

In early work, the likely importance of the hot component was not fully recognized and models were made of the two-phase ISM, consisting of the cold clouds and warm intercloud medium. Modern versions of these are still important for understanding the segregation of material into those two components, while the warm intercloud medium is further riddled with even lower density spaces, the third phase.

Certain ranges of density and temperature are not included in the above census. The gap between the cold and warm components has to do with the balance between heating and cooling mechanisms and the role of thermal instability in excluding the unstable range. (This presumption is currently under revision, as discussed in Section 4.2.) The temperature range between 10^4 and 10^5 K is generally excluded because the cooling rate would be very high at the pressure of the ISM, and one supposes that it would cool to join the warm component. An alternative excuse for these segregations is observational; components we can see are identified.

1.2. Outline and Summary

Section 2 is a review of the average vertical structure of the medium, neglecting the hot component, with the usual results. The disk is thicker than we used to think and significantly higher in pressure. A large fraction of the pressure is nonthermal. The midplane values of the weight-per-unit area and the sum of observed pressure components agree, which is a major improvement over matters some years ago. The vertical extent inferred from the synchrotron emission is significantly greater than that found from the distribution of material providing the weight. Ways of reconciling this discrepancy are discussed.

Section 3 explores a very simple model of the effects of supernovae (SN) occurring within that averaged medium, in particular finding the average X-ray emissivity of their remnants (SNRs), the porosity they might provide, and their contribution to the mean density of OVI. We discover that the supernovae could cause appreciable disruption and that the average X-ray emissivity and OVI density are in rough agreement with the observations.

Section 4 reviews the nature of models attempting to understand the segregation of HI into cold cloud and warm intercloud components, and summarizes the current status of this two-phase modeling. Several of its less well-known aspects are discussed, the surprises provocatively highlighted in Section 4.3. It also provides a rough estimate of the filling factors of the HI and warm HII (H^+) components. The sum of these is less than one, leaving a wide-open space for something else, something with low density and possibly hot.

Section 5 introduces larger scale inhomogeneity. It first reminds us of the likely arm/interarm contrast, discussing both density and pressure. It then reviews observations of extremely low-density regions, cavities that are associated with nearby superbubbles, and cavities and tunnels that are not. The current status of understanding of the local hot gas, the Local Bubble, is outlined. Two other regions are also discussed that could be large-scale old supernova remnants that have evolved in very-low-density environments. Apparently, large-scale low-density regions are common in interstellar space, but they are not always hot or dense enough to be seen in X-ray emission. Section 5 closes with a short discussion of the distribution of higher density material in the ISM, in large structures of warm gas within which the smaller, denser cold structures are apparently enveloped.

By this point, we are well into the notion of there being a Three-Phase Medium, with dense cold cloud material, diffuse warm intercloud material (some of which is ionized), and large regions of relative emptiness, some of which are hot. Section 6 discusses limits on the amounts of higher temperature gas set by two observations, the mean density of OVI in the disk, and the apparent surface brightness of the disk in $\sim 3/4$ keV X rays. A recent example of a global magnetohydrodynamic (MHD) model of the ISM is then explored for its ability to satisfy these observations. The idea, in part, is to coax creators of such models to evaluate their results in these terms.

Section 7 presents the simple analytical ideas leading to the notion that the ISM has a thermostat problem. At the fiducial pressure of hot gas established previously, there is a critical density and temperature at which the ISM can just radiate the energy input from supernovae. At higher densities, it easily copes with the power input, whereas at lower densities it cannot. Yet large-scale regions of such lower densities may well be common in interstellar space. The scheme introduced by the three-phase ISM model of McKee & Ostriker (1977) to circumvent this problem is reviewed. (A subsection discusses the strengths and weaknesses of their model as a whole.) Other notions that have attempted to resolve this problem are reviewed briefly, and then an idea that embraces the problem rather than solving it is suggested as an alternative. The idea is that there are regions of interstellar space so low in density that the energies of supernovae occurring within them cannot be thermalized. The section goes on to imagine how supernovae within them might evolve, and to mention peculiarities of observed remnants that may be telling us the answer. The importance of stochasticity in the heating is then presented to show the relationship between the critical density for cooling and the porosity of the medium. It also highlights the way in which the McKee & Ostriker model led to a dynamical understanding of the magnitude of the interstellar pressure, an insight I am reluctant to abandon but cannot quite see how to generalize.

Section 8 reviews various popular conceptions of the interstellar medium, with several intents. Some reasonably common conceptions are totally at odds with current knowledge and can be eliminated. Others can be considerably constrained. Some are not commonly held, but are possible.

In Section 9, I advocate one conception in particular, that the pervasive, thick, erratic magnetic field essentially weaves the ISM into a sort of tenuous 3D elastic polymer with highly variable amounts of mass interspersed from place to place. The magnetic influence is high enough to be important in the quiescent regions, but not so high that it substantially interferes with major dynamical events. It is not a perfect conception, but serves to provide some new ways of thinking about things.

Section 10 then concerns itself with merging the observationally based view of the ISM as riddled with cavities and tunnels with the just-presented notion that the field is an interwoven structure. It clarifies that low-density regions can be cold if they are not too large. It similarly asks whether the tunnels might develop in such a way that they have normal-strength magnetic fields within them, so they are not always obliged to be supported by thermal pressure. There is also a small amount of conjecture on other interesting consequences these observed low-density regions might have.

Section 11 discusses several faces of the all-important question of why the interstellar medium has the pressure that it does. The question is talked around, but left unanswered.

I would like to have closed with a concise summary, with definite conclusions about the way things are, but cannot. I have given you reasons to abandon archaic ideas that hinder progress in this business. I have sketched a global view of how things are arranged, and the nature of the influence of the magnetic field. I have provided some ideas about problems, and some thoughts on their possible solutions. That is all. The understanding of the field is incomplete and evolving, somewhat in need of clever ideas of what to look for to test various possibilities, and waiting for a grand synthesizer who can weave the whole melange into a comprehensive picture of what is going on. The way things are looking, the grand synthesizer may someday be a machine, guided by someone with a profound ability to approximate subgrid behaviors.

2. SCHEMATIC DISTRIBUTION OF INTERSTELLAR COMPONENTS PERPENDICULAR TO THE GALACTIC PLANE

This section presents estimates of the vertical distributions of the various interstellar components (exclusive of the hot gas), specifically in the Solar Neighborhood, the gravity they experience, the pressure required to support their weight, the thermal pressure due to those components, and the residual nonthermal pressure required.

Except as noted, all estimates in this article of the distributions of interstellar densities, supernova rates, etc., with distance from the midplane, z, are those adopted in the excellent review by Ferrière (2001); no further reference is made here to the invaluable original sources of this information. The true distributions are uncertain but these are a good fiducial set on which to center our discussion.

2.1. Gaseous Components

I will refer to the six highest density components as molecular, cold HI, warm HIa, warm HIb, HII regions, and diffuse HII. The adopted distributions of the mean densities (H nuclei per cm^{-3}) in the Solar Neighborhood are:

$$\text{molecular: } 0.58\ \exp[-(z/81\,\mathrm{pc})^2]$$

$$\text{cold HI: } 0.57 * 0.7\ \exp[-(z/127\,\mathrm{pc})^2]$$

$$\text{warm HIa: } 0.57 * 0.18\ \exp[-(z/318\,\mathrm{pc})^2]$$

$$\text{warm HIb: } 0.57 * 0.11\ \exp(-|z|/403\,\mathrm{pc})$$

$$\text{HII Regions: } 0.015\ \exp(-|z|/70\,\mathrm{pc})$$

$$\text{diffuse HII: } 0.025\ \exp(-|z|/1000\,\mathrm{pc}).$$

I have changed the scale height of the diffuse HII from 900 to 1000 pc, Ron Reynolds's currently preferred number. I have also been somewhat cavalier about separating the cold and warm HI using the scale height component fit. One could do better using estimates of their individual scale heights to partition the HI more carefully. The mass density, including helium, is 1.4 hydrogen masses per hydrogen nucleus.

Figure 1 shows the total density distribution from the above components, and that excluding the molecular and cold HI. The latter is a first attempt to categorize the diffuse interstellar density, separating off material in dense regions occupying little of the volume.

2.2. Vertical Gravity

The vertical gravity at the Solar circle of Dehnen & Binney (1998) Galactic Model 2 (DB2) was decomposed into its components, and the interstellar component, which in their model had a scale height of only 40 pc, was replaced by the integrated effect of the ISM distribution adopted above. The result was not strikingly dissimilar

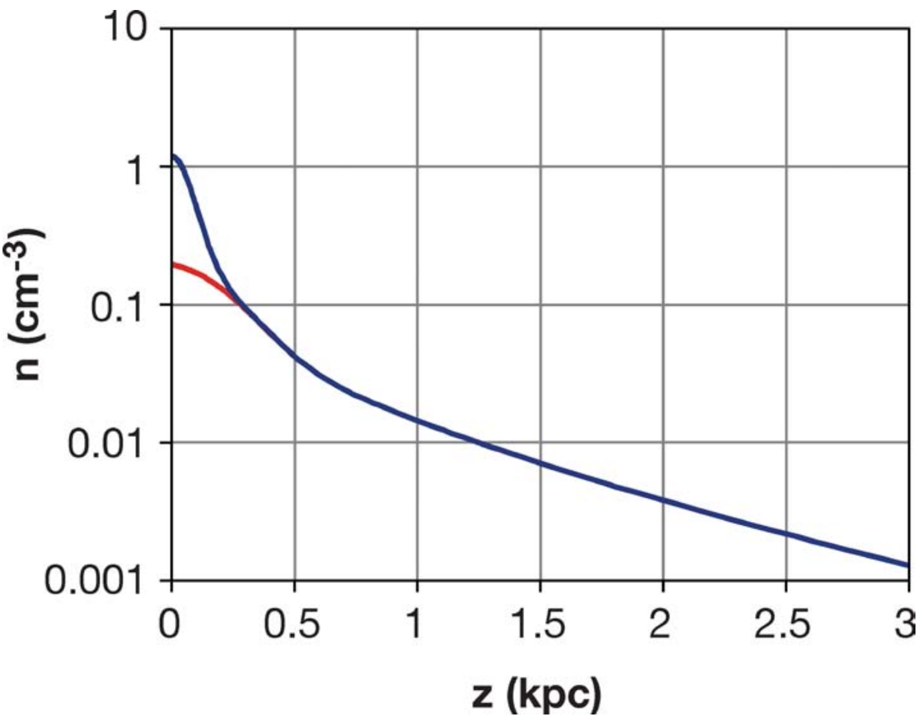


Figure 1 The distribution of interstellar hydrogen density above the Galactic Plane. The total is shown in *blue*, the warm diffuse component in *red*.

except close to the plane where the initial slope was reduced. A simple fit that agrees to better than 2% between z of 0 and 10 kpc is

$$|g| = 10^{-9}\,\mathrm{cm\ s^{-2}}\,\{4.2[1 - \exp(-|z|/165\ \mathrm{pc})] + 4.1|z|/2\ \mathrm{kpc}\}$$

$$\cdot (1 - |z|/27\ \mathrm{kpc})/[1 + (z/6\ \mathrm{kpc})^2]^{1/2}.$$

The first term on the first line represents the contributions of the ISM and disk stars, the second term is due to halo material, and the factors on the second line represent an accurate fit to the shaping apparently provided by the nonplanar geometry in the DB2 model.

2.3. Interstellar Weight and the Vertical Distribution of Pressure

Given the vertical density and gravity distributions, it is straightforward to calculate the weight of interstellar material above z, and thereby obtain an estimate of the vertical distribution of total pressure, p. Badhwar & Stephens (1977) made the initial bold steps in this direction, obtaining pressure values that were shocking at the time, but are now close to plausible after the revolution they precipitated. The self-consistent pressure distribution for the conditions above is shown as the upper curve in Figure 2, assuming zero pressure at $z = 10$ kpc. The midplane value is 3.0×10^{-12} dyn cm^{-2}, or $p/k_B = 22{,}000$ cm^{-3} K, where k_B is Boltzmann's Constant.

2.4. The Thermal and Nonthermal Pressure Components

Through the use of conventional values of the temperatures of the included interstellar components, their contributions to the spatially averaged thermal pressure can be estimated. The specific choices made here are 15 K for molecular gas, 80 K for cold HI, 5000 K for warm HIa, 8000 K for warm HIb, 7500 K for HII regions, and 9000 K for diffuse HII. As shown in Figure 2, the average thermal component is only 10% of the total in the midplane, and that percentage decreases outward. Note that this does not include thermal pressure of a high-temperature component that we have not yet discussed.

In a study of this type, Boulares & Cox (1990) found that it was reasonable to suppose that there is rough equipartition between the nonthermal pressure forms; that assumption is now adopted as a hypothesis. As a result, the magnetic, cosmic ray, and dynamical pressures are each taken as one third of the nonthermal pressure of Figure 2, 0.92×10^{-12} dyn cm^{-2} in the midplane. (Part of that dynamical pressure might be thermal pressure in the so-far ignored hot component.) For comparison, Ferrière quotes midplane values of 10^{-12} and 1.28×10^{-12} dyn cm^{-2} for magnetic field and cosmic rays, respectively. Assuming that the magnetic field is predominantly parallel to the plane allows calculation of the field strength versus z, as shown as the lower line in Figure 3. The midplane value is about 4.8 μG,

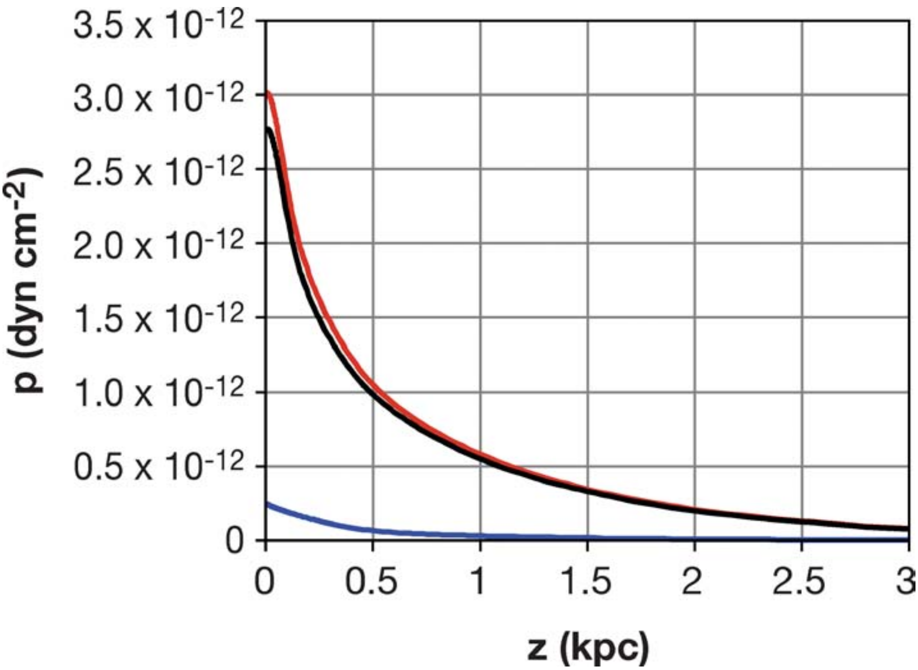


Figure 2 Comparison of the total (*red*) and volume average thermal (*blue*) pressure distributions, and their difference (*black*) interpreted as the nonthermal pressure. In this case, the total is taken from the weight distribution of the ISM. The thermal pressure neglects any contribution from the hot component.

similar to current estimates of its strength (5 to 6 μG). The rms vertical velocity of the gas flows required to produce the dynamical pressure are moderate and of the order expected, rising from 6 km s^{-1} in the midplane. By the assumption of equipartition, they are close to the Alfven speed at all heights.

The mean density sampled by cosmic rays is quoted as 0.24 cm^{-3} by Ferrière from measurements by Simpson & Garcia-Muñoz (1988) of the relative abundances of a radioactive isotope versus stable ones produced in the cosmic rays by spallation. By assuming that the local density of cosmic rays is proportional to the time they spend at a given height, and that they are equally likely to return to the Solar location from any height, the mean density sampled becomes just $\int n\, p_{CR}\, dz / \int p_{CR}\, dz$. For the above distributions of (total) density and nonthermal pressure the result is 0.19 cm^{-3}, very similar to the measurement. If the particles diffuse outward, the mean density sampled by those that are found near the Sun would be somewhat higher. If the cosmic ray distribution is thicker, as found below, the value would be lower.

The next comparison exposes a difficulty. The observed synchrotron emission of the Galaxy has been modeled, including its distribution above the plane in the solar

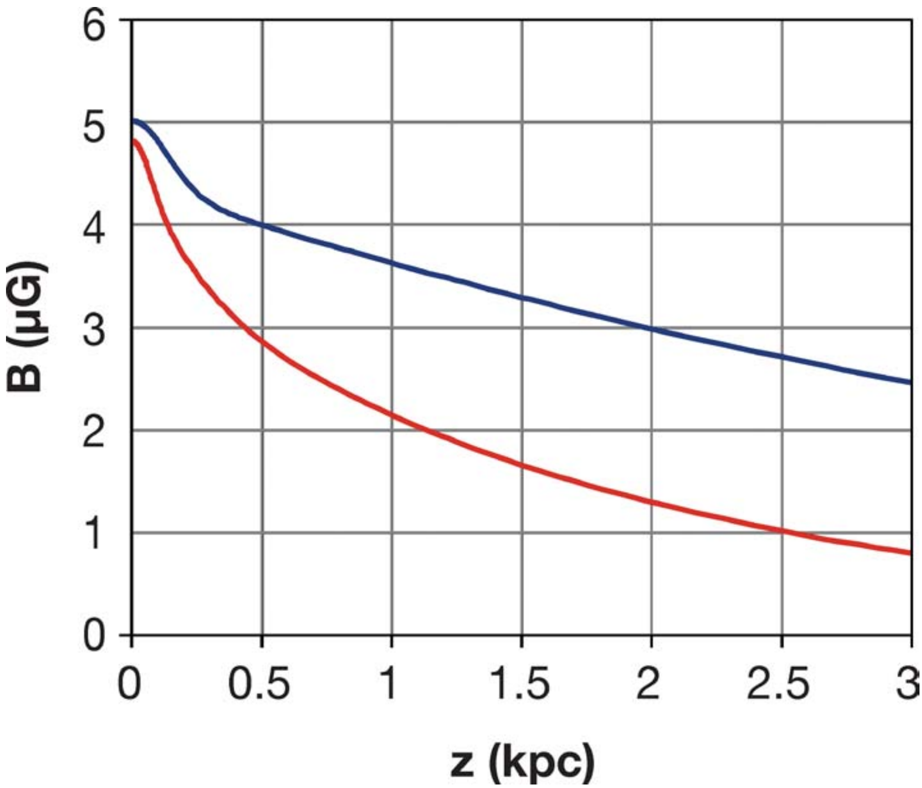


Figure 3 The vertical distribution of magnetic field strength. The *red curve* follows from assuming that one third of the nonthermal pressure of Figure 2 is magnetic, with the field parallel to the plane. The *blue curve* arises from the vertical distribution of the synchrotron emissivity, which implies that the rms field drops much more slowly with height.

neighborhood. By assuming that the responsible cosmic ray electrons and magnetic field pressure track one another and the total nonthermal pressure p_{NT}, Ferrière shows that the emissivity distribution behaves approximately as ${p_{NT}}^{(1/0.53)}$. Thus, the synchrotron distribution offers an independent test of the vertical structure of the nonthermal pressure. With Ferrière's midplane values of magnetic and cosmic ray pressures and her quoted vertical distribution for the synchrotron emissivity, one obtains an estimate for the sum of these two pressures, which is compared to that found above in Figure 4. The figure also shows their difference. The difference in the midplane could easily be due to the uncertainties; but what is certainly true is that if the synchrotron emissivity distribution is correct, the magnetic fields and cosmic rays drop off much more gradually with height than found in our simple model. Returning to Figure 3, for example, the synchrotron-implied rms magnetic field is shown as the *upper line*. It remains above 3 μG out to z $=$ 2 kpc! If anyone

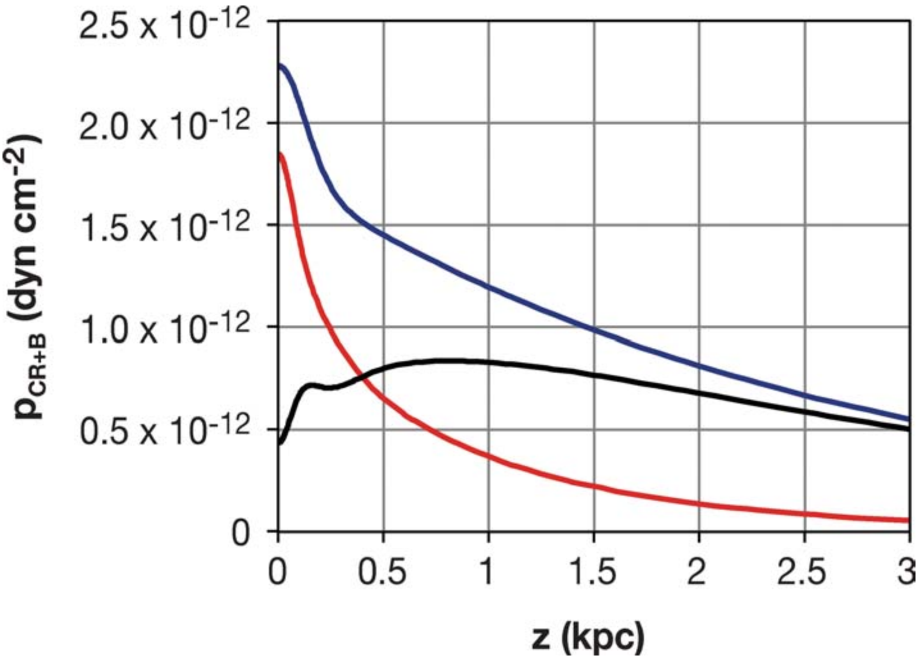


Figure 4 Comparison between the cosmic ray plus magnetic pressure estimated from the distribution of ISM weight (*red*) and that implied by the model adopted by Ferrière for the vertical distribution of the synchrotron emissivity (*blue*). The substantial difference is shown in *black*.

is left who is inclined to believe that the galactic distributions of interstellar matter and pressure resemble that of a phonograph record, it is time to adjust that view to the extreme thickness of these distributions.

The synchrotron emissivity implies that the cosmic rays and magnetic field persist to greater heights than would be inferred from the weight distribution of the interstellar matter considered so far. Facing this dilemma, Boulares & Cox (1990) showed that the high z nonthermal pressures could be coupled to lower z weight via magnetic tension, something like a suspension bridge. They proposed that the effective vertical magnetic pressure was $(B^2 - 2B_z^2)/8\pi$. With this explanation, the *upper* of the two curves in Figure 3 represents the rms B, whereas the *lower* represents the horizontal average of $(B^2 - 2B_z^2)^{1/2}$. It would require a substantial vertical component as one moves away from the plane.

An alternative, proposed by both Badhwar & Stephens (1977) and Bloemen (1987), is to assume an additional very-thick-density component whose weight is sufficient to provide the additional pressure at high z. I will refer to this possibility as a coronal component. By assuming that the true pressure of cosmic rays and magnetic field is that advocated by Ferrière, I find that a component with density

(0.007 cm^{-3}) exp(–|z|/4 kpc) brings our pressure distributions into reasonable agreement.

So far, I have neglected the potential thermal pressure of this coronal material. The calculations can be redone with any other assumption about this term. If it supplies the kinetic pressure component at z $\sim$ 1 to 3 kpc (by hypothesis one third of the pressure not provided by the thermal pressures of the denser components), its temperature would be on order 3×10^5 K. If the temperature were about three times that, the material would be self supporting and not useful in solving the synchrotron emissivity distribution problem. In other words, it must not be too hot or it is not useful in this context. One must also take care that it does not excessively produce X rays. If the temperature actually were 3×10^5 K, OVI would be close to its peak concentration, about 0.25 of total oxygen. With an oxygen abundance of 5.6×10^{-4} relative to hydrogen (Esteban et al. 2004, 2005), the total column density of OVI would be about 10^{16} cm^{-2}, roughly two orders of magnitude more than is observed looking out of the galactic plane as we shall see below. If this coronal material were neutral, the column density of hydrogen would be about 10^{20} cm^{-2}, making it comparable to that in the denser components. If it were photoionized and at T $\sim 10^4$ K, its emission measure looking out from the plane would be about 0.1 cm^{-6} pc, comfortably smaller than that of the Reynolds Layer (the thick HII mentioned previously), but its column density of electrons would be comparable (compare 0.007 times 4 kpc with 0.025 times 1 kpc). A modern plot of $N_e \sin(b)$ versus z for high z pulsars (where N_e is the column density of electrons) would be expected to test the existence of this coronal layer. I doubt it is there in this quantity. Interstellar material is surely present far from the plane of the Galaxy, but the quantity and properties of that material are heavily constrained by observations.

3. SUPERNOVAE IN A HOMOGENEOUS MEDIUM

This Section ignores nearly all inhomogeneity of the medium, asking how individual supernovae might evolve in it and what the observable consequences might be. It is a rough way to estimate the disruption they might cause, as well as the overall contributions to some observables that that fraction of the supernovae that avoid low-density regions might make.

3.1. The Vertical Distribution of Supernova Rates

The supernova rate distributions adopted by Ferrière (2001) for the Solar Neighborhood are, for Type I SNe (actually Ia),

$$S_I \approx [7.3\ \mathrm{kpc}^{-3}\ \mathrm{Myr}^{-1}]\ \exp(-|z|/325\ \mathrm{pc})$$

and for Type II (actually Ib, Ic, and II),

$$S_{II} = [50\,\mathrm{kpc}^{-3}\,\mathrm{Myr}^{-1}] * \{0.79 * \exp[-(z/212\,\mathrm{pc})^2] + 0.21 * \exp[-(z/636\,\mathrm{pc})^2]\}.$$

The latter was chosen to follow one of the models of pulsar birth sites of Narayan & Ostriker (1990). The term exp(–|z|/325 pc) in S_I was chosen to represent the vertical distribution of stars.

Ferrière further estimates that roughly 60% of the Type II SNe occur in groups, and that the range of group sizes is 4 to ~7000 SNe with an average of 30. These groups are in the familiar association of OB stars, and lead to the growth of superbubbles, which evolve differently in volume occupation, pressure, and temperature from the remnants of the same number of supernovae occurring independently. As I am not comfortable with my understanding of that evolution, I will largely neglect superbubbles in the discussion below. That is not to say that they are unimportant, but that their actual effects on the observations I will discuss are difficult to estimate. So, the mindset is something like: This is what individual SNRs would likely do, at least approximately, and the presence of correlations in their occurrences will change things, downward by factors of less than two or upward by an unknown amount.

3.2. A Simple Model of SNRs at High Temperature

As long as neither radiative cooling nor external pressure has yet become important, a reasonable idea of the evolution and surface brightness of an SNR of explosion energy E_0 evolving in uniform density $\rho_0 = mn_0$ can be derived from the Sedov self-similar solution. The radius, expansion speed, post–shock temperatures, etc. are $R = [2.025\ E_0\ t^2/\rho_0]^{1/5}$, $v = dR/dt$, $T = (3/16)\ m\ v^2/(\chi k_B)$, $\chi = (n + n_e)/n$, and $m = \rho/n$, while the luminosity is approximately $2.3\ Vn_0^2\ L(T)$ where V is the volume. A reasonable fit to the nonequilibrium cooling coefficient is $L(T) \approx \alpha\ T^{-1/2}$, where $\alpha \approx 10^{-19}$ erg cm^3 s^{-1} K$^{1/2}$ (the Kahn approximation; for more detailed accounts see Cox & Anderson 1982 for its usefulness and Smith et al. 1996 for its accuracy). The "2.3" in the luminosity derives from the average compression of the material. (Note: $n = n_H + n_{He} = 1.1\ n_H$, except in Sections 2 & 4 where $n = n_H$.)

Two further pieces of information are useful when considering X-ray emission, first that the average surface brightness is the luminosity divided by πR^2. This is often estimated in terms of the average "emission measure" $\int n_e^2\ dl$, which for this simple remnant model is $EM \sim 2.3\ (4/3)\ n_0^2\ R$. The second item is that Snowden et al. (1997) provide the count rate per emission measure in various ROSAT bands. From their figure 9, for example, a RS plasma model at 10^6 K with no intervening absorbing material and an emission measure of 1 cm^{-6} pc is expected to provide roughly 1.5×10^5 [10^{-6} counts s^{-1} arcmin^{-2}] in the R12 (= R1 + R2) energy band. This response function depends on the atomic physics and abundances used. Once again, I will simply adopt the curves of Snowden et al. (1997) as a fiducial set, with concerns about details beyond the present scope.

Because I am first concentrating on the potential X-ray emission by remnants, it is useful to describe their properties as a function of the post–shock temperature, T_6, in units of 10^6 K. Using E_{51} as the explosion energy in units of 10^{51} ergs, from above one can derive the following:

$$R \approx 19.3 \text{ pc } [E_{51}/(n_0 T_6)]^{1/3},$$

$$t \approx 28{,}000 \text{ years } (E_{51}/n_0)^{1/3}/T_6^{5/6},$$

$$\Delta E_{rad}/E \approx 0.064\ (E_{51}\ n_0^2)^{1/3}/T_6^{7/3} \text{ (fraction of energy radiated above } T_6\text{), and}$$

$$EM \approx\ 59 \text{ cm}^{-6} \text{ pc } n_0^{5/3}\left(E_{51}/T_6\right)^{1/3}.$$

If the rate of supernova occurrences per unit volume, S, is expressed in units of SN $(\text{kpc})^{-3}$ $(\text{Myr})^{-1}$, the fractional volume occupation of remnants hotter than T_6 is given by

$$f \approx 3.83 \times 10^{-7}\ S\ (E_{51}/n_0)^{4/3}/T_6^{11/6}.$$

In what follows, I shall assume that all supernovae occur with 10^{51} ergs, and lose little of this (to cosmic ray acceleration, for example) prior to entering the adiabatic phase. (This is probably an upper limit.) The total SN power density at midplane is then 6.15×10^{-26} erg cm^{-3} s^{-1}, and the total power per unit area (for both sides of the disk) is 1.05×10^{-4} erg cm^{-2} s^{-1}.

3.3. The Average Interstellar X-Ray Emissivity from Supernova Remnants

Using these distributions and the result above for the fraction of energy radiated at temperatures T_6 and above, one can calculate the local volume average emissivity of the population of supernova remnants, assuming that at each height, z, all of the remnants (ignoring clustering) evolve in the average density. Given the extreme inhomogeneity of the ISM, this is a peculiar thing to do, but it provides a sense of the orders of magnitudes anticipated for various quantities and their variation with z. For $T_6 = 1$, this was done for two cases, supernovae evolving in the total average density, and instead evolving only in the average of the intercloud or "diffuse" component. At higher temperatures, the results must be scaled by $T_6^{-7/3}$. For the two cases, the midplane emissivities are 4.4×10^{-27} and 1.4×10^{-27} erg cm^{-3} s^{-1}, while the total vertically integrated efficiency for radiation of SN power above 10^6 K is 3.2% for interaction with the full average density and 1.6% for interaction with the diffuse gas only. We recover the usual result that SNRs in uniform density radiate very little of their energies in X rays; most of their emission comes later at lower temperatures, in the EUV (hard ultraviolet).

The radii of the remnants at 10^6 K are moderate in the midplane (18 to 33 pc) but increase to 48 pc at $z = 400$ pc and 78 pc by $z = 1$ kpc. The fraction of the volume occupied by remnants with $T_6 > 1$ is very small; even if they interact only with the diffuse gas it is only about 2×10^{-4} for $|z| < 1$ kpc. The chance of encountering a hot remnant on any given line of sight is extremely small.

Suppose, however, that one overall effect of interstellar inhomogeneity is to further homogenize the X-ray emission of the Galaxy, without substantially altering its average rate. One then expects the ROSAT R12 band, sensitive to gas at roughly 10^6 K, to be responding to a surface brightness, from data given above, of about 2% of half of 1.05×10^{-4} erg cm^{-2} s^{-1}, looking out of the plane of the Galaxy. Using the previously mentioned Kahn approximation to the cooling coefficient, the corresponding emission measure is 3.4×10^{-3} cm^{-6} pc. The remarkable coincidence is that this is roughly the value ascribed to the Local Bubble to produce the diffuse 1/4 keV X-ray background.

We can similarly estimate the M band or R45 count rate, sensitive to ~3/4 keV X rays. By converting the $\Delta E/E$ formula to a probability distribution function in $\langle n_e^2 \rangle$ with T, and invoking the ROSAT sensitivity to gas between 2.5×10^6 and 6.3×10^6 K, my estimate of the midplane R45 count rate achieved in 1 kpc (approximately one optical depth) is $200 n_0^{2/3}$ [10^{-6} counts s^{-1} $arcmin^{-2}$]. For the total and diffuse midplane densities, this ranges from 220 down to 66 in these units. Again we have an amazing coincidence that these estimates bracket the observed diffuse count rate of roughly 120 in R45 in the midplane. It appears that the diffuse component X rays we observe are comparable to those expected from the Galactic population of individual SNRs, but somehow homogenized. Without that homogenization, the emission would be confined to small bright remnants. Some of it, of course, is.

3.4. Porosity and OVI

The notion of supernova-generated porosity of the ISM was introduced by Cox & Smith (1974). The basic idea is that if one calculates how remnants would evolve independently of one another, and from that the total volume fraction of the ISM the population of remnants would occupy, then one has a measure of the likelihood that remnants will or will not evolve independently. That volume-fraction-assuming-independence is called the porosity, q. If q is much less than 1, it is safe to assume that remnant interactions are rare and that the remnants do indeed occupy a volume fraction q of the medium. If q is not small, it is less clear what happens. Remnant interactions are important. Some supernovae would occur in very-low-density regions already evacuated by previous remnants, or would occur in a denser region but break into a low density one during their evolution. The medium evolves toward some new configuration in which low-density and high-temperature regions are common. The critical porosity for this change in configuration of the medium has not yet been established and probably will depend sensitively on the details one assumes about the medium and remnant evolution at the outset. Smith (1977) presented an attempt to find this critical porosity, with the result that, if it existed, it was larger than supposed by Cox & Smith (1974). The result is derived from a specific and complex view of how remnants interact with one another and their environment.

McKee & Ostriker (1977) presented an estimate of q for the ISM and found that it was very large, demanding restructuring be present. Slavin & Cox (1993) concluded that the McKee & Ostriker estimate was too large, for several reasons, and that the porosity of the medium outside superbubbles could well be small. Subsequent efforts have been made to calculate the porosity due to superbubbles separately from that of the medium outside (see Ferrière 2001). We now evaluate the porosity anticipated in our homogeneous medium model.

If the volume of the low-density cavity of a remnant is V(t), and the rate of SNe per unit volume is S, then the porosity defined above is

$$q = S \int V(t)\, dt,$$

where the integral is over the entire lifetime of the remnant cavity. Various attempts to estimate the V(t) function from analytical considerations have not been very successful, but one set of hydrodynamic calculations was made by Slavin & Cox (1992, 1993) to learn how remnants might evolve at late stages. Their work made specific approximations to the role of magnetic pressure in the ISM and thermal conduction within the hot gas, approximations that might not satisfy all tastes, but which are clearly described and reasonably motivated. They fit their results for varying density, explosion energy, and external pressure with the expression

$$q = 0.176\ S_{-13}\ E_{51}^{1.17} n_0^{-0.61}\ (10^{-4}\ p/k_B)^{-1.06},$$

where S_{-13} is the SN rate in units of $10^{-13}\ pc^{-3}\ yr^{-1}$. (Ferrière's total midplane rate, including clustered SNe, of 57.3 corresponds to $S_{-13} = 0.573$.) In this equation, p is the external pressure within which the remnants are evolving. It is reasonable to assume this is roughly half the total pressure, taking old remnants to be largely transparent to cosmic rays and neglecting some of the dynamical pressure of the medium as well. Using our results for the distributions of SNe, density, and pressure (specifically that of Figure 2), again with $E_{51} = 1$, we arrive at the porosity versus height curves shown in Figure 5, the *lower curve* for all SNRs evolving in the full density, the *upper* for all SNRs evolving in the diffuse mean density.

The two porosity curves differ by a factor of 3 in the midplane, but converge at higher z where the cloud component is largely absent. The values are substantial, ~0.25 from $z = 250$ to 700 pc, particularly in light of the Cox & Smith (1974) suggestion that above a rather modest porosity there might be a tendency for the SNe to occur within existing low-density cavities and promote the growth of a pervasive phase of hot gas, their tunnel network (but see also Smith 1977). (The reason that high porosity is consistent with the very-low-filling factors for hot remnants in Section 3.3 is that most of $\int V\, dt$ comes from the late stages of evolution, during further expansion after cooling has occurred, and when the SNR bubble is collapsing.)

Porosity, though useful as a theoretical tool, is not an observable phenomenon. On the other hand, the mean density of an ion, O^{+5}, present during the late evolution of remnants, is observed, and can be used as a direct test of whether this porosity calculation has any validity. We shall see that, in fact, the OVI density and distribution calculated next are very much in line with the observations.

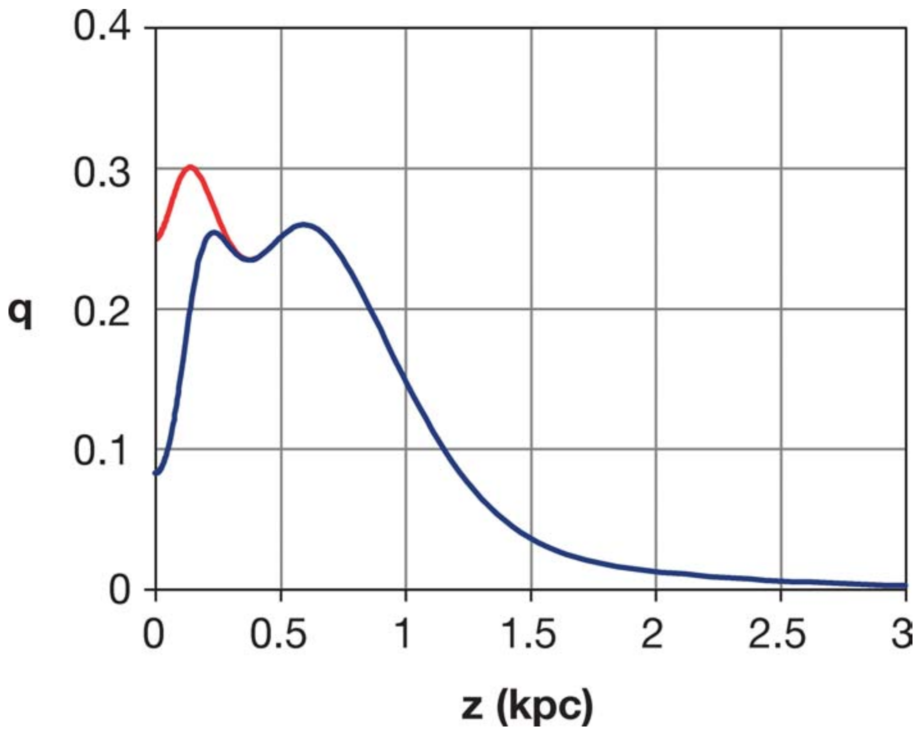


Figure 5 The distribution of SNR-induced porosity, assuming that all SNe occur in the total average density (*blue*) or diffuse density (*red*).

In the same set of calculations, Slavin & Cox (1993) also fit their results for the OVI dosage of their remnant evolutions, where dosage is defined as $D = \int N(OVI)\,dt$ and N(OVI) is the number of O^{+5} ions in the remnant as a function of time. Their fit was

$$D_{OVI} = 8.13 \times 10^{60}\ E_{51}^{1.11} n_0^{-0.76}\ (10^{-4}\ p/k_B)^{-0.16}\ \text{ion years}.$$

The corresponding mean density of OVI ions is $3.4 \times 10^{-69}\ S_{-13}\ D_{OVI}$. Shelton (1999) considered three remnant evolutions at densities substantially lower than those sampled by Slavin & Cox. Using the parameters of Shelton's remnants, it is found that the Slavin & Cox formula underestimated her OVI dosages by factors ranging from 1.34 to 1.5. The agreement is thus well within the range of uncertainty of the many parameters employed in making these estimates.

Once again using our vertical structure, this mean OVI density calculated versus z from the above formula is shown in Figure 6. The midplane range for the two assumed densities is 1.4×10^{-8} to 5.4×10^{-8} ion cm^{-3}. The column densities perpendicular to the plane are 0.82×10^{14} to 1.0×10^{14} cm^{-2}, per side.

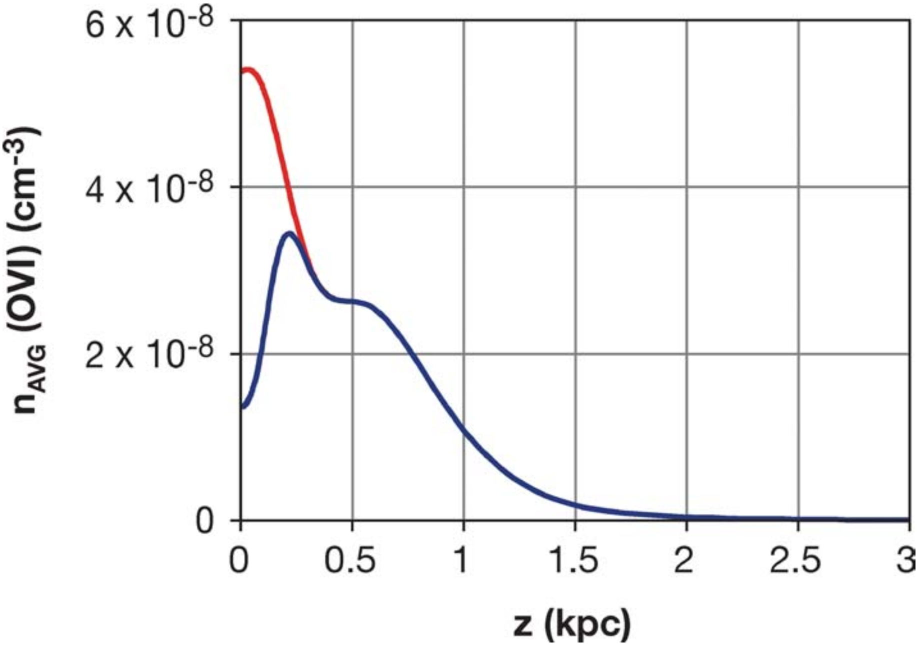


Figure 6 The distribution of average interstellar density of OVI, assuming that all SNe occur in the total average density (*blue*) or diffuse density (*red*). The observed midplane value is about 1.7×10^{-8} cm^{-3}.

The observed average midplane density of OVI is approximately 1.7×10^{-8} cm^{-3} (Bowen et al. 2005), very similar to the above value from all SNe interacting with the total density. A similar number would be found by taking only the SNe outside groups and using the diffuse ISM density. Attempts to measure the column density perpendicular to the plane have been made by Savage et al. (2003), who find the OVI to be very patchy with values ranging from 0.6×10^{14} to 3×10^{14} cm^{-2}; the larger values are prevalent in the north. The southern and northern median values are 1.1×10^{14} and 1.8×10^{14} cm^{-2}. The values of our model above lie at the low end of the observed range, and do very well at reproducing the median in the south. Patchiness and edge brightening of the OVI-bearing volumes can lead to individual sight lines with column densities well above the mean. On the whole, the model predictions are very close, certainly within the uncertainties of the calculation. Reference to the *lower curve* of Figure 6 suggests that estimating a scale height for this material could be misleading. The modeled mean density rises considerably away from the plane before it drops again. One might describe the thickness of the layer as about 1 kpc rather than the 2 kpc obtained by dividing the vertical column by the midplane density.

As will become apparent later, the problem with OVI is not how to get as much as is seen, the problem is always how to keep from getting too much. The simple model presented above shows that just about the right amount would derive from Slavin Bubbles, the old cooling cavities of SNRs evolving in the warm intercloud environment. As we examine the ISM and discover its large volumes of much lower density, it becomes unclear how to avoid having much larger quantities of OVI.

4. THE TWO-PHASE MEDIUM REVISITED

4.1. Basics

The fundamental purpose of the modern two-phase calculations is to explore the segregation of the bulk of the interstellar material into cold and warm components. Its methods are to assume a density, calculate the ionization and electron density at that density, along with the charge state of the PAHs (poly aromatic hydrocarbon molecules), and find the self-consistent thermal balance between the photoelectric (and other sources of) heating and radiative cooling. The result is an equilibrium T(n). From that, one calculates the thermal pressure function $p_{Th}(n)$. The details are sensitive to a variety of input parameters. The typical result is a sinuous curve for which there is a range of p_{Th} over which the density is triple-valued at constant pressure. With that curve in hand, one examines it for the possibility of having clouds and intercloud gas at the same thermal pressure with a thermally unstable regime between them, the phase segregation.

There is not a universal $p_{Th}(n)$ curve; the heating rate varies with galactic location and time (e.g., Parravano, Hollenbach & McKee 2003), and with the opacity between the gas parcel of interest and the sources of radiation providing the ionization and heating. In what follows, a representative example for the Solar Neighborhood is taken from Wolfire et al. (2003). It is shown, somewhat decorated with auxiliary information, in Figure 7.

The *lower curve*, shown in three colored segments, is the original; the *upper* (*dotted aqua*) *curve* shows the approximate effect of having a heating rate about 10 times higher. Also shown are the approximate weight per unit area of the interstellar medium (*dashed black*), the probable typical magnetic pressure close to the galactic plane (*dashed orange*), and a region bordered by a rectangle to be discussed later.

The $p_{Th}(n)$ curve has several familiar features, described in the classic paper on this subject by Field, Goldsmith & Habing (1969). These include separate branches for warm intercloud (*red*) and cold cloud (*green*) components, a maximum intercloud thermal pressure (4400 cm^{-3} K for the curve shown), a minimum cloud thermal pressure (1700 cm^{-3} K for this example), and a range of density (0.8 to 7 cm^{-3}), or more fundamentally temperature (roughly 270 to 5500 K), between these two (*blue*) that is regarded as forbidden in equilibrium because at constant thermal pressure it is thermally unstable. In the unstable region, gas slightly above the curve is too hot for its density and cools. But at constant thermal

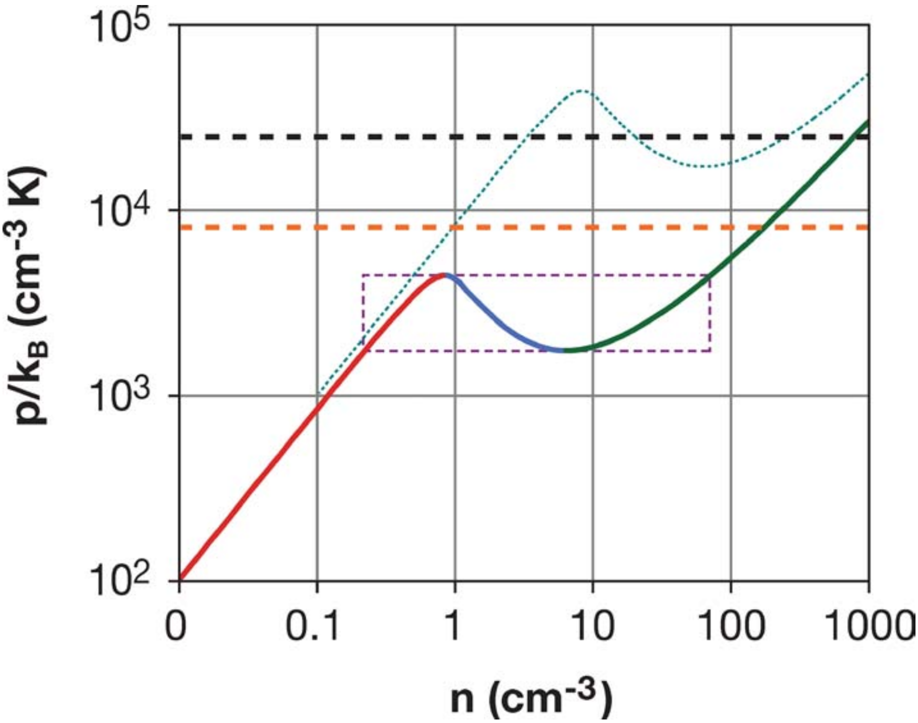


Figure 7 The Two-Phase Medium thermal pressure versus density curve is shown in the *red-blue-green curve*. The *red* segment is the thermally stable warm component, the *green* the corresponding stable cold component, and the *blue* the thermally unstable regime. The *black dashed line* is the total midplane pressure, the *orange dashed line* represents the magnetic pressure, the *dashed aqua line* shows how the p(n) curve shifts when the heating rate is raised considerably, and the *dashed purple rectangle* outlines the regime of essentially zero bulk modulus.

pressure, cooling moves it to the right, to higher density, taking it further from the curve and making it cool faster, until it reaches the stable cloud branch. Similarly, gas slightly below the curve has excess heating and at constant thermal pressure moves horizontally to the left until it joins the stable intercloud component.

4.2. Less Familiar Aspects of the $p_{Th}(n)$ Diagram

For the standard curve, the mean midplane interstellar density in the Solar Neighborhood (slightly over 1 cm^{-3}) is in the unstable regime. This appears to guarantee that both the cloud and intercloud branches will be populated.

A significant portion of the cold-cloud branch lies below the total midplane pressure (the weight per unit area of the ISM), and even below the mean magnetic pressure that is about a third of the total. This appears to allow the cold-cloud population a comfortable existence. The total pressure is more than enough to hold them together, and whatever thermal pressure they lack can be augmented by sufficient internal magnetic pressure.

Note however that with the higher heating rate sketched, both of the above conditions would change. The current mean density would then be well into the intercloud branch, while even the minimum allowed thermal pressure of a cold cloud would be close to the total available pressure and well above the thermal pressure that any abutting intercloud gas (at the mean density or lower) might have. This combination assures that clouds would be very difficult to form or sustain, while the medium could rest quite comfortably in a fully warm component.

With no cold HI component, it might be very difficult to make molecular clouds; if so, the star formation rate would decline with time. As the photoelectric heating relies predominantly on radiation from the younger stars, heating would also decline until clouds were once again stable. (This is a situation that Antonio Parravano has been exploring since at least 1987.) Thus, the ability of dense clouds to exist at thermal pressures available in the medium appears to set an upper limit on the mean star formation rate. This is a complicated subject dependent on grain and PAH properties, on the local ionizing radiation field, on the scale height of the warm component (as it basically provides the weight determining the midplane pressure), and even on the absolute and relative gas-phase abundances of carbon and oxygen. But properly understanding it might lead to a prescription for a self-consistent star formation rate, given the total pressure (which likely also depends on that star formation rate).

One of the most interesting features of $p_{Th}(n)$ is that over a density range of a factor of 350, from 0.2 to 70 cm^{-3}, the thermal pressure variation is less than a factor of three. In Figure 7, this region is shown enclosed by a *dashed purple rectangle*. It is a regime in which the thermal pressure offers essentially zero bulk modulus. This means that if, for some reason, the ISM had a totally random distribution of densities within this range, the corresponding distribution of thermal pressures would be observationally indistinguishable from one in which thermal pressure had an active role in arranging things, except there would be no range of forbidden densities. Most of the remaining points have to do with how this might be related to the actual interstellar situation.

A reasonable first order approximation to interstellar conditions (near the plane) is to think of the sum of thermal and magnetic pressure being constant at roughly half the total pressure. This assumes that the cosmic ray component is uniform and that the dynamical component is roughly so as well. For the Solar Neighborhood, that sum should be on the order 1.5×10^{-12} dyn cm^{-2} or 11,000 cm^{-3} K. (This is not a firm number; I have elsewhere quoted it as 20,000 cm^{-3} K only a few years ago. The observations underlying it have uncertainties, and the role of the dynamic pressure component is situation-dependent.) This number then provides an upper limit on the thermal pressure. In regions that are quiescent, in pressure equilibrium with their surroundings, but in which abundant thermal energy has caused enough expansion that the magnetic field pressure is substantially reduced from normal, this pressure would be almost entirely thermal. The expected range of thermal pressures in the quiescent cloud component of the ISM should then lie between the minimum cloud pressure, 1700 cm^{-3} K, and the upper limit, 11,000 cm^{-3} K. This is comfortingly similar to the range of most observations reported by Jenkins & Tripp (2001). At the low-density end of the diagram, however, the allowed range of thermal pressures is much broader, from zero to the upper limit.

The previous two paragraphs have suggested that the small variation in thermal pressure between regions of differing density can be compensated by slight changes in the somewhat stronger magnetic field pressure. This is true when establishing pressure uniformity across the magnetic field lines, but equilibrium parallel to the field cannot be established in this way. So, one might still imagine that thermal pressure has a role in arranging things parallel to the field and will lead to cloud–intercloud segregation and the disappearance of material from the thermally unstable regime. The fundamental flaw in this idea is not recognizing the importance of the extreme density difference between the cloud and intercloud components. The differential is two to three orders of magnitude. If thermal pressure is to move material from intercloud to cloud component, parallel to the field, then to build a cloud of 1 pc extent, it must collect intercloud material from several hundred parsecs. Even at a relative velocity of 10 pc/Myr, the approximate sound speed in the warm component, this requires several tens of Myr, a long time to imagine interstellar quiescence is appropriate. The converse process, in which a cloud expands into a low-pressure region to fill it with intercloud material, takes even longer at the lower sound speed of the cloud. It appears to me, and several others who have begun modeling gas in transition (e.g., Vazquez-Semadeni et al. 2003), that dynamics is all-important in deciding what densities will be where; thermal instability has a decidedly secondary role. At the high densities of cold clouds, the temperature and ionization adjust rapidly to the equilibrium, producing results consistent with the $p_{Th}(n)$ equilibrium, but at lower densities the temperature and ionization can take a long time to adjust, and between the high- and low-density components, adjustment to uniform thermal pressure takes much longer yet.

4.3. Surprises of Two-Phase Modeling

A number of dramatic consequences follow from the above discussion. They include the following:

(1) Thermal pressure in diffuse HI in the Galaxy has little dynamical effect. In quiescent regions, it is usually several times smaller than the magnetic pressure, so thermally driven flows, to the extent they exist, will tend to be along the field, one dimensional. In addition, these 1D transitions between components take longer than the timescale for the external alterations of their environment.

(2) Zero thermal pressure is allowed at low densities. Such regions occupied by their full complement of cosmic rays and magnetic field require no additional thermal pressure.

(3) Over a very wide range of HI densities, the limited range of the equilibrium thermal pressures makes thermal pressure look important even when it is not.

(4) In quiescent regions, the value of the magnetic field should vary little with density—a little low where thermal pressure is high, a little high where thermal pressure is low.

(5) The forbidden range of n,T is probably common, present in the slow transition between stable components, or just put there by dynamical events.

(6) If cold clouds must exist for star formation to occur, then photoelectric heating provides a feedback loop for setting an upper limit to it for a given pressure.

4.4. Filling Factors of the Denser Components

From the thermal pressure curve, along with the mean thermal pressures found in clouds, it has become customary to assume that the equilibrium thermal pressure of HI is about 3000 cm^{-3} K. I adopt 2800 cm^{-3} K. From Figure 7, the cloud and intercloud components then have densities and temperatures of 30 cm^{-3}, 93 K, and 0.36 cm^{-3}, 7800 K, respectively. I will make these choices, with one exception. I regard the density of 1 cm^{-3} to be more likely for a significant fraction of the component I have referred to as warm HIa, because in experiments with the transition between clouds and intercloud components, it seems to be true that material often spends a great deal of time in the vicinity of the density at which the intercloud pressure is maximum. I will therefore assume 30 cm^{-3} for the local density of clouds, 0.36 cm^{-3} and 1 cm^{-3} each for half of component HIa, and 0.36 cm^{-3} for all of component HIb. I will neglect the filling factors of the molecular and classical HII regions, which are very dense or contain little material, respectively. I will further assume that the diffuse HII gas is the ionized part of HIb and that the material has expanded slightly laterally, with $B \propto n$, as the temperature increases to 9000 K and the number of thermal particles doubles in the ionization. Constant thermal plus magnetic pressure then results in a density of 0.3 cm^{-3} for the diffuse HII. That is, the thermal pressure in the ionized gas is somewhat higher, and the magnetic field somewhat lower, than in the warm HI with this assumption. It is a rough estimate, but embodies the basic idea.

From the mean densities in the midplane given earlier, the filling factors (with considerable uncertainty) are then 0.013 for cold HI, 0.194 for warm HIa, 0.174 for warm HIb, and 0.083 for diffuse HII. The grand total is roughly 46%. The implication is that something like half the volume of interstellar space might have much lower densities than that in the components above. As it is almost certainly ionized, that component's mean density must be less than something like

0.02 cm^{-3} in order not to contribute substantially to the electron density measured via pulsar dispersions. The only clear alternative is that the warm components fill nearly all of the space, with a lower density than estimated above, about 0.2 cm^{-3}, and this is inconsistent with the inhomogeneity described in the following section.

5. LARGE-SCALE INHOMOGENEITY

Segregation of the matter into cold and warm components is not the only source of inhomogeneity in the ISM. In this section we consider the arm/interarm contrast, the observations indicating that there are large cavities and tunnels of very low density in the ISM and the observed distribution of the denser matter.

5.1. Spiral Arm Contrast

The interstellar medium is expected to have a certain amount of large-scale inhomogeneity just from dynamical events. Consider first the anticipated contrast between arm and interarm regions. In a recent single-phase MHD model of Galactic ISM dynamics, for example, Gomez & Cox (2004) found column-density contrasts of about a factor of three. My impression is that in the Milky Way the denser components probably do have contrasts between three and five, but that the contrast is likely much less for the more diffuse components.

I bring this up because our fiducial calculation of the weight of the ISM used estimates of the mean densities of the various components, with different sampled regions contributing to the estimates for different components. In addition, if all components had contrasts of three, one might suppose that there would be similar differences in the arm and interarm pressures. One of the tests made by Gomez & Cox dealt with this question, comparing the ISM weight and midplane pressure around the Solar circle in their model (see their figure 12). The averages of the two were equal, but the weight per unit area was about a factor of four higher in the arms than interarm regions (higher column density and thicker distributions). But, the midplane pressure variation was closer to a factor of two, with twice the spatial frequency, having peaks in both arms and interarm regions. The principal cause for this difference was vertical dynamics, i.e., the bouncing of high z material. The bottom line to this diversion is that the pressure we previously calculated likely has significant variations about it associated with the arm/interarm contrast, perhaps with about a factor of two in range. Students of radio continuum emission could probably offer a better estimate.

5.2. Cavities

Another large-scale dynamical activity is the formation of superbubbles by the winds and supernovae of OB associations. Several of these are known nearby, including the Orion-Eridanus and Loop I superbubbles. It has been estimated that the diffuse interiors of the collection of these bubbles occupy something like

20% of the volume in the midplane (Heiles 1990, Ferrière 1998). In each case, the remainder of the OB stars responsible for the bubbles is plainly seen. But, there is another considerable cavity for which there is no clear association of young stars, the Local Cavity surrounding the Solar location, to which we now turn.

The most recent report of a very ambitious effort to map the density distribution in the Solar vicinity is provided by Lallement et al. (2003). Column densities in NaI are reported for about 1000 stars, and from them, maps of the spatial distributions of column density and density of cold gas within the nearest few hundred parsecs of the Sun are derived. There is a very-low-density region around the Sun, with the nearest high-density gas about 55 to 60 pc away in the first quadrant. In other directions, the dense "wall" of the Local Cavity is much farther away. The cavity is essentially open at high positive and negative latitudes, with tunnel like extensions in the disk in a variety of directions, some seeming to connect our cavity with others nearby. The authors' view is that other nearby cavities are younger higher pressure regions that are forcing the walls toward us, squeezing our older lower pressure cavity. Perhaps their future studies of the motions of the intervening material will confirm this squeezing. In any case, there is a very large irregular hole in the distribution of gas near the Sun, a hole that appears to have narrower connections to more distant voids and that extends well out of the plane.

Lallement et al. show an inner contour that they say corresponds to a column density of 2×10^{19} cm^{-2} of hydrogen. In a distance of 60 pc, the mean sightline density is 0.1 cm^{-3}. But the mean densities to individual closer stars are often much lower, such that the column density of the contour is acquired only as the wall is approached. On the other hand, their method is sensitive only to cold dense gas, and could miss the warmer low-density material. Such material is, in fact, found in the spectra of stars close to the Sun, the Local Fluff, but it appears to have a low filling factor in the cavity as a whole.

Much of the 1/4 keV soft X-ray background appears to derive from within roughly one million Kelvin gas occupying at least part of the Local Cavity. This hot region is generally referred to as the Local Bubble, or Local Hot Bubble. What I think I know about this can be found in Cox & Reynolds (1987), Cox (1998, part of a whole conference volume on the subject; 2004), Cox & Helenius (2003), and Florinski et al. (2004). I will just mention some recent developments. Further discussion and references appear also in Lallement et al. (2003).

In brief, the 1/4 keV soft X-ray background is now known to have three source components: heliospheric emission from charge exchange of highly ionized Solar wind particles with interstellar neutrals penetrating into the Solar System, thermal emission from the Local Hot Bubble, and additional thermal emission from more distant hot gas regions within the thick interstellar disk. The origin of the Local Cavity has been speculated upon, but is unclear. The true story of the Local Bubble emission will remain uncertain until we have spectral resolution that tells us precisely what stages of ionization of what elements are responsible for the X-ray emission and we can separate the heliospheric contribution spectrally. The Local Fluff has interesting stories to tell, but is not yet fully understood. Among other things, it has a pressure problem. The measured thermal pressure in the Local Fluff is only about one fifth of that inferred for the hot gas surrounding it. If the difference is made up by magnetic field, models imply that, contrary to fact, the termination shock of the Solar wind should already have been encountered by Voyager I, unless the field is locally parallel to the relative motion of the Sun and Local Cloud (Florinski et al. 2004).

5.3. Two Other Examples of Non-OB Association Cavities, and Two More Tunnels

There are two other rather large regions observed to be emitting 1/4 keV X rays but which, like the Local Bubble, are not superbubbles. One of these is the MonoGem Ring, the other the higher latitude Draco enhancement. The MonoGem Ring is a round feature 25° in diameter, centered at $l = 203°$, $b = +12°$. Its brightness in the ROSAT R12 band is about 420 (10^{-6} counts s^{-1} $armin^{-2}$) after correction for moderate intervening absorption. Using the previously mentioned 1.5×10^5 conversion from EM to R12 units at 10^6 K, one arrives at the implied emission measure of 2.8×10^{-3} cm^{-6} pc. Using our Sedov SNR model, one arrives at the anticipated EM of 59 $n_0^{5/3}$ for $E_{51} = T_6 = 1$. The required value of n_0 is then 2.55×10^{-3} cm^{-3}. With that same model, the radius and age are 141 pc and 2×10^5 yrs. With a post–shock temperature of 10^6 K, assumed above and implied by the X-ray emission, the post–shock pressure would be $4n_0\chi k_B T_s \sim 3 \times 10^{-12}$ dyn cm^{-2}, high enough that further expansion would be expected if the cavity is large enough. The angular diameter implies a distance of about 640 pc. The object has been modeled more carefully by Plucinsky et al. (1996) with similar conclusions for $E_{51} = 1$. Lower energies would place the object closer, making it smaller, younger, and evolving in slightly higher density (see their table 7). Stating that another way, if this object is a few hundred parsecs distant, it is a couple of hundred parsecs across, contains of order one supernova worth of thermal energy, and has an average density between about 3×10^{-3} and 5×10^{-3} cm^{-3}. It is therefore in an exceedingly large cavity with a very low density, a cavity not associated with a superbubble.

The Draco enhancement in the 1/4 keV background is a bright region with a diameter of roughly 15° centered at about $l = 95°$, $b = +38°$. It is shadowed by much of the HI along the line of sight, but its surface-brightness contribution has been separated from the Local Bubble emission by Snowden et al. (1998), and corrected for the absorption. Its R12 brightness before absorption is about 2600 (10^{-6} counts s^{-1} $armin^{-2}$), implying an emission measure of 0.017 cm^{-6} pc. Following the above procedure with the simple Sedov model, again assuming $E_{51} = T_6 = 1$, we are led to $n_0 = 7.5 \times 10^{-3}$ cm^{-3}, R = 98.5 pc, age = 1.43×10^5 years, distance = 750 pc, z = 460 pc. In this case, the post–shock pressure is about 9×10^{-12} dyn cm^{-2} so that the shock is still strong. It is a quite reasonable candidate for being a supernova remnant fairly high up in the thick galactic disk. Shelton (1999) has provided detailed models for such objects.

One might wonder about the likelihood of supernova remnants as young as this at high latitude. But, integrating Ferrière's SN distribution in a cone about the zenith with opening angle θ, we come to the total SN rate on one side of the plane of 5.8 $\tan^2(\theta)$ Myr^{-1}, most of them between 500 and 1500 pc off the plane. As the Draco enhancement is at $\theta \sim 52^\circ$, we expect 1.4 remnants at this latitude or higher with ages of 1.43×10^5 years or lower. So, what we see, one, is plausible. The more surprising part is that the size is again large and the mean density once again quite low. From Figure 1, we find that the mean density 500 pc off the plane should be about 0.04 cm^{-3} and that it does not drop to 7.5×10^{-3} cm^{-3} until z $\sim$ 1500 pc.

An important point is that the density in these two regions, like that in the Local Cavity, was low prior to the assumed supernova explosion that brought them up to 10^6 K. The temperature must also have been low, or we would not need the supernovae to heat them.

One last thing. Plucinsky et al. (1996) discuss the observed column densities toward stars in the direction of the MonoGem Ring. In their table 4, several stars with quoted distances of 700 to 2300 pc have total column densities in the range 1.1×10^{20} to 2.3×10^{20} cm^{-2}. A column of 10^{20} cm^{-2} in 1000 pc has a mean density of only about 0.03 cm^{-3}. It is an example of those directions for which, over vast distances, very-low-density lines of sight are found, as discussed by Lallement et al. (2003). Another was recently rediscovered by Madsen & Reynolds (2005) toward the inner Galaxy, a 6 kpc line of sight toward Scutum with a mean density of about 0.16 cm^{-3}. This mean is not so extraordinarily low, but is likely made up of stretches with much lower density between those with more normal values (and which show up as velocity peaks in the HI profile). This case is exceptional in its great length.

In summary, there are very large regions of interstellar space with very low density, many of which are not in currently active superbubbles, and some of which are apparently not hot (so that they can be reheated by supernovae to appear as bright regions in the soft X-ray sky). Others could be too hot and diffuse to make their presence known via X-ray emission.

5.4. How is the Matter Arranged?

We have so far considered only the photographic negative view of the structure of the ISM, where material is not. There are a few things to say about how material is arranged where it is found, the photographic positive of the picture. My opinion is that the best idea of this is found by actually looking at pictures. Examine the 21-cm survey pictures, IRAS pictures, Hα pictures, and optical continuum pictures. What do you see? The distribution appears to be dominated by many large-scale structures. There are loops, filaments, and shells galore, as well as some concentration into the arm structures, though it is sometimes difficult to discern.

There is also some information about the relative locations and geometries of the various components. Heiles & Troland (2003) reviewed the HI information. I think a fair summary is that warm low-density HI is arranged in large sheets, with some considerable thickness. Within these sheets, there is filamentary structure, and denser cold subsheets and filaments, the cold cloud material of low volume filling factor. With increasing distance from the plane, the relative proportions shift, with the cold component less prevalent. This is mirrored in the differences in the scale heights of the two introduced at the beginning. At very high $|z|$, the cold component tends to peter out, but in the inner Galaxy, at least, Lockman (2002) finds there are small fragmentary bits of warm HI, some of which have cold cores. What about the molecular clouds and their complexes? I do not pretend to know anything about these, but my impression is that, except near the Galactic Center, they are found only in regions where there is a large amount of HI in the neighborhood. Various excuses are given for this—shielding from the UV, gravitational binding, compression in the spiral arms, etc. An outsider gets the impression that they are just another natural form of condensation that occurs when a lot of material gets close together. There is heated discussion about how long they exist and how long it takes them to form stars.

6. LIMITS ON 3×10^5 AND 3×10^7 K GAS IN THE ISM

6.1. The OVI Constraint on 3×10^5 K Gas

The average midplane density of O^{+5} is about 1.7×10^{-8} cm^{-3} (Bowen et al. 2005). The abundance of oxygen relative to hydrogen is $A_O = 5.6 \times 10^{-4}$ (Esteban et al. 2004, 2005). In collisional equilibrium, the peak of the fraction of oxygen that is in O^{+5} is about 0.25, at a temperature of about 3×10^5 K. If the thermal pressure in gas of this temperature is half the midplane value, 1.5×10^{-12} dyn cm^{-2}, as advocated previously for quiescent hot regions, then the local density of O^{+5} is about 2.2×10^{-6} cm^{-3}. The average density is exceeded unless the filling factor of this material is less than about 0.8%. If one third of the oxygen is locked up in dust grains, this rises to 1.2%.

This is a very small filling fraction. Its calculation depended on the atomic rates, the assumption of collisional equilibrium, the choice of pressure for the gas, and lesser details like the gas phase oxygen abundance. Gas at 3×10^5 K may be cooling rapidly and not be isobaric with the hotter regions near it. That could raise its allowed filling factor inversely with its lower pressure. The fact that in cooling regions OVI lags behind equilibrium, due mainly to the slow recombination of OVII, is something that might depress the OVI by about a factor of two at the peak, but then additional OVI is found at lower temperatures. The fountain flow models of Edgar & Chevalier (1986) calculated several cases that illuminate these last two points. The isobaric flows, or any flow that began as isobaric and then turned isochoric at a temperature less than 10^5 K, had essentially the same amount of OVI as that calculated for a collisional equilibrium case. A fully isochoric flow had nearly twice the OVI of the others, probably because the reduced density slowed the cooling, enhancing the time spent near the OVI peak. It does not appear that simple nonequilibrium situations will heavily reduce the constraint. Perhaps turbulent mixing would (Section 6.3).

Let us now generalize this calculation to one in which there is a distribution of temperatures, or more particularly, a distribution of volume fraction, f, with temperature given by a probability density function (pdf) of the form df/d log T. We then have

$$dn_{avg}(OVI)/d\log T = A_O\ c_{VI}(T)\ n_H(T)\ df/d\log T,$$

where $c_{VI}(T)$ is the fractional concentration of OVI to total oxygen, and n(T) is the density at T. A very good fit to the equilibrium concentration, somewhat dependent on the choice of ionization and recombination rates used (from log T = 5 to 7, outside of which OVI is negligible), is

$$c_{VI}(T) = [T/(3 \times 10^5\ K)]^9 * \{1 + 6.5 * \exp[-18 * (\log T - 6.37)^2]\}/D,$$

where

$$D = \{1 + 2.8 * [T/(3 \times 10^5 K)]^{13}\} * \{1 + [(1.58 \times 10^5\ K)/T]^{13}\}.$$

Assuming the pdf is of the form (with s the fractional slope per decade)

$$df/d\log T = [df/d\log T]_{5.5} * [1 + s * (\log T - 5.5)],$$

that $c_{VI}(T)$ is approximately that in collisional equilibrium, and that the gas is roughly isobaric at thermal pressure p, the numerical integral for n(OVI) is (for s = –1 to 1)

$$n_{avg}(OVI) = [df/d\log T]_{5.5} * [p/(1.5 \times 10^{-12}\ dyn\ cm^{-2})] * (5.19 \times 10^{-7} - s * 6.5 \times 10^{-9})\ cm^{-3}.$$

The effect of adding a slope to the pdf is minor. The observed average density of OVI requires

$$[df/d\log T]_{5.5} * [p/(1.5 \times 10^{-12}\ dyn\ cm^{-2})] = 0.033.$$

The first factor on the left is the value of the pdf at log T = 5.5. By comparing this to the first calculation of the filling factor of 3×10^5 K gas, we learn that OVI samples an effective range in log T of 0.25. At the fiducial pressure, gas with log T distributed between about 5.4 and 5.6 occupies less than 0.8% of the volume. Even at a thermal pressure 10 times lower, this gas can occupy only 8% of the volume. This constraint basically invalidates any model that has large volumes of gas including this temperature range.

6.2. A Frequently Overlooked X-Ray Constraint on 3×10^7 K Gas

In Wisconsin we refer to the brightness of the 3/4 keV band X rays in the galactic midplane as the M band problem. (The sensitivity function of the Wisconsin rocket payloads to X rays at about this energy is called the M band. The corresponding ROSAT range is termed the R45 band.) The problem is that at high latitude, away from Loop I and other prominent sources, the 3/4 keV band is very smooth, mostly due to extragalactic emission, much of which has by now been resolved or extrapolated from resolved point sources. In the Galactic plane, with a density of about 1 cm^{-3}, the mean free path for absorption of these X rays is about 1 kpc. Although this is about 10 times further than we can see in the 1/4 keV band, the low-latitude Galactic disk is still optically thick to the extragalactic radiation. Nevertheless, the emission is found to extend fairly smoothly through the midplane, requiring a galactic source that just compensates for the absorption of the extragalactic flux. It must have the right emissivity to do this in 1 kpc and perhaps the right scale height, so that there is neither a dip nor rise approaching the plane from above. Hence, the M band "problem."

This problem was studied early on by Nousek et al. (1982), who came to favor a model with extragalactic, local, and thick disk components. The apparent temperature of the thick-disk emission was about 3×10^6 K. This disk, if hot gas, had a vertically integrated emission measure of 4×10^{-3} cm^{-6} pc. They concluded that if it were due to hot gas with a scale height of 1 kpc, the rms midplane density of this gas would be about 2×10^{-3} cm^{-3}. Filling the full volume, its p/k_B would be about 10^4 cm^{-3} K. They pointed out, however, that Rosner et al. (1981) had found that some significant fraction, perhaps 10–30%, might be due to dM stars. This problem was further explored by Sanders et al. (1983), who found that with the thick disk, the emission might still show a dip in the midplane unless there were an additional component closer to the plane, which they suggested might be a population of something like Local Bubbles. In fact, the much higher spatial resolution map of the ROSAT R45 band does show a dip in the midplane in directions where there is a larger than normal amount of absorbing gas within 1 kpc. But in wide swaths of longitude, the emission is smooth across the plane with an R45 count rate of about 120 (10^{-6} counts s^{-1} $arcmin^{-2}$).

Let us now repeat the process of calculating what would be seen from a pdf containing the temperature range 2.5×10^6 to 6.3×10^6 K over which the ROSAT bands 4 and 5 are sensitive. From Snowden et al. (1997), the conversion from EM to ROSAT surface brightness units in this range is 7000 T_6. Outside of this temperature range the sensitivity drops rapidly. Referring to the count rate as C (10^{-6} counts s^{-1} $arcmin^{-2}$) and assuming a mean free path of 1000 pc, we have

$$dC/d\log T = 7 \times 10^6\ T_6\ n(T)^2\ df/d\log T.$$

This time taking

$$df/d\log T = [df/d\log T]_{6.5} * [1 + s * (\log T - 6.5)],$$

along with constant thermal pressure, we arrive at the numerical integral (only over the range above)

$$C = [df/d\log T]_{6.5} * [p/(1.5 \times 10^{-12}\ \text{dyn cm}^{-2})]^2 * (25 + 1.4\,s).$$

The slope of the pdf again has little effect. For comparison, with a single temperature of 3.16×10^6 K,

$$C = [f]_{6.5} * [p/(1.5 \times 10^{-12}\ \text{dyn cm}^{-2})]^2 * 59,$$

indicating that the integral samples a range of about 0.4 in log T, as expected.

We now have a new M band problem. At the fiducial pressure, neither of these expressions leads to the observed count rate of 120, even with the hot gas occupying the whole plane ($[f]_{6.5} = 1$ or $[df/d\log T]_{6.5} = 2.5$ over the 0.4 span of log T). In either case, the count rate is only 50. Assuming, however, that the true contribution of hot gas to the count rate is only 120δ, because some may derive from stars or other complications, we learn that the diffuse 3/4 keV emission requires

$$[df/d\log T]_{6.5} * [p/(1.5 \times 10^{-12}\ \text{dyn cm}^{-2})]^2 = 4.8\delta.$$

This is an enormously powerful constraint unless δ is small ($\lesssim$0.5). If δ is not small, this requires that the hot gas responsible for this X-ray emission be in regions with significantly higher pressure than the fiducial value. At their elevated pressure, they are likely expanding. The smoothness of the emission along the galactic plane also seems to require that such gas be found commonly on a path of 1 kpc. Candidates for this emission include the population of youngish expanding superbubbles, or a population of supernova remnants evolving in low-density regions, but probably not quiescent hot gas filling a network of tunnels.

There are two caveats. A modest fraction of this radiation derives just from the recombination of O^{+7} and O^{+8} ionized by supernova remnants when they are young. From the Sedov model, one easily calculates that each supernova will heat approximately 300 E_{51} solar masses of gas to 3×10^6 K or higher, fully ionizing the oxygen within it. Assuming that one K shell X ray is emitted each from O^{+8} and O^{+7} as they eventually recombine (or charge exchange with H or He), Ferrière's supernova rate would generate 2×10^{-20} photons cm^{-3} s^{-1} in the galactic plane. The integrated rate looking out of the plane would be about 1.5 photons cm^{-2} s^{-1} sr^{-1}, whereas that in a path of 1 kpc in the plane is about 4 times higher. The effective area of ROSAT at this energy leads to an estimate of roughly 24 (10^{-6} counts s^{-1} arcmin^{-2}) in the plane, 20% of the observed rate. For those remnants that evolve in relatively high density, this recombination radiation is only a minor contribution to their M band emission, but at very low densities it is relatively more important. A minor contribution also likely arises from charge exchange of solar wind ions with neutrals in the Solar System. The good news is that X-ray detectors finally exist that will be able to discern emission from these various mechanisms spectrally (though the theoretical predictions for charge exchange spectral details are somewhat unclear).

6.3. Comparison with a Global Model

There are various sorts of Global ISM models, but here I refer to MHD calculations attempting to include a lot of physics and model the dynamics of a fairly good-sized piece of the Galaxy. They include magnetic field, a sensible amount of interstellar material, vertical gravity, shear due to differential rotation, heating and cooling prescriptions, star formation prescriptions, supernova occurrences, etc. An example is that of Korpi et al. (1999) in which a large bubble grows in a very inhomogeneous environment, extends vertically, has mass pushed into it by supernovae at higher z, and appears to cope with the input power. Thermal conduction was included, though I am uncertain with regard to its magnitude. It appears that the pressure in the ambient medium is somewhat lower than the roughly 3×10^{-12} dyn cm^{-2} we find from either the weight of the ISM or the sum of pressures in the midplane, and the thickness of the pressurized layer was thinner than inferred from the synchrotron emissivity, but still it is an excellent view of what a superbubble and the surrounding medium might be like.

The Korpi et al. model provides pdfs for density, temperature, and pressure at three epochs. The model pdfs for temperature are remarkably flat, with a modest dip around 10^5 K. Taking one as representative and assuming the various components have the same thermal pressure ($p/k = 11{,}000$ cm^{-3} K, rather than the lower pressure of the actual model), one can confirm that the medium, on average, radiates the supernova power. Its emission is concentrated in the temperature decade around 10^5 K. Higher temperature gas occupies much of the volume, therefore absorbing much of the SN power, but radiates poorly. There is roughly a factor of 7 too much OVI and a factor of 15 too little 3/4 keV emission.

The OVI problem would be alleviated if gas near 3×10^5 K had a preferentially low pressure, and the cooling of the hot gas and the M band problem would be improved if the gas near 3×10^6 K had a preferentially high pressure. Whether this is the case in global models of this sort can easily be explored by their creators, via bivariate pdfs or direct calculation of the mean n(OVI) and R45 count rate per kpc. The required information to do that is all in the above presentation. It would be nice if the models also included a realistic magnetic field strength and vertical distribution of its pressure. (Some representation of the cosmic ray pressure will also be needed to get the vertical distribution to come out right.)

Is there another way to solve the OVI problem? Turbulent mixing has the nice feature that parcels on opposite sides of the OVI temperature peak can be suddenly mixed to some intermediate temperature. The initial ionization is also mixed, but includes no OVI. If the mixed temperature is below $10^{5.2}$ K or the cooling to that temperature is very rapid, the only OVI will be that from recombination of the

O^{+6} that was initially in the hotter component. Given the high density and rapid cooling, those ions will recombine more rapidly and have less OVI overall than if the hotter gas had slowly cooled without the mixing (Slavin, Shull & Begelman 1993). Maybe something entirely different is at work, the above mentioned increase of pressure with temperature or something, that the makers of such models could identify to clarify the situation. In the absence of a suppression agent for OVI, the bottom line is that models with pdfs similar to that of Korpi et al. would have significantly too much OVI.

It is not clear to me how, in the model, the high T gas rids itself of its energy. A higher pressure would help by increasing the radiation. In fact, the M band problem seems to require that some of the hot gas is overpressured and therefore not only radiating more but expanding, heating the surroundings with shocks, or losing energy by doing work on expanding shells. Other possibilities include turbulent mixing of hot and cooler gas, growth of the hot regions to higher z, or even perhaps some numerical diffusion.

It would also be useful to know more about the details of how global models, particularly those with significant magnetic fields, structure the low-density parts of the medium. Do they tend to produce something like low-density cavities and tunnels through the medium? If tunnels, do they tend to follow the magnetic field? Is the field typically fairly strong or weak within them, and are they sometimes rather cold, waiting for SN reheating? One could, for example, isolate regions with densities below 0.01 and examine their restricted pdf for temperature and for the ratio of thermal-to-magnetic pressure. One could produce images of those regions that are both low in density and not hot, and others of those that are low in density but also hot. A slice through the volume showing the local magnetic field directions within the low-density regions could be very interesting. We could get a better idea of how current modeling efforts create structures in the medium, low-density structures of various types, as opposed to the high-density ones that are becoming familiar.

7. THE THERMOSTAT PROBLEM

7.1. The Uniform Heating Version

Using the Kahn cooling coefficient, $L = 1 \times 10^{-19}\,T^{-1/2}$ cgs, the emissivity of gas at temperature T and pressure p is

$$\varepsilon = Ln^2 = 2.7 \times 10^{-27}\ \mathrm{erg\ cm^{-3}\ s^{-1}}[p/(1.5 \times 10^{-12}\ \mathrm{dyn\ cm^{-2}})]^2/T_6^{5/2}.$$

This is to be compared with our estimate of the average supernova power density, 6.15×10^{-26} erg cm^{-3} s^{-1}. The ratio is $[p/(1.5 \times 10^{-12}\ \mathrm{dyn\ cm^{-2}})]^2 (0.29/T_6)^{5/2}$. At the fiducial pressure, gas below about 3×10^5 K radiates copiously, whereas above that temperature it does not. This introduces a thermostat problem when much of interstellar space has very low density, as is apparently observed. If the regions have densities lower than about 0.02 cm^{-3}, the heating by supernovae to temperatures above 3×10^5 K cannot be balanced by radiative cooling. The regions are then expected to expand and experience more heating, with less ability to radiate and so on. A thermal runaway is anticipated.

This problem was recognized and, in the ISM model of McKee & Ostriker (1977), the disaster was averted by having thermal evaporation of clouds within remnants raise their densities above that of the initial low intercloud value, allowing radiative dissipation to succeed. When a denser shell of this cooled material forms and encounters clouds further out, the shell material is redeposited on those clouds, returning the medium to the assumed initial state.

7.2. Parenthetical Comments on the McKee & Ostriker Model

I am a great admirer of the McKee & Ostriker model of the ISM, but not a believer in the direct applicability of its results to the ISM. It was a bold first step to consider the inhomogeneity of the medium and the way SNRs might interact with it. It included a lot of physics and astrophysics, dealt with the thermostat problem, gave a dynamical reason (discussed below) for the value of the interstellar pressure, as well as its possible variations, and managed to radiate the supernova power within the Galactic disk. It was a masterful piece of work.

What are its failings? First and foremost, the type of inhomogeneity considered—that there was a random distribution of small clouds to be evaporated—is qualitatively different from the sort of inhomogeneity we actually see: large cavities, long tunnels, and large structures of material. A counter argument to that is that there are the Local Fluff cloudlets within the Local Bubble. My second complaint is that these remnants interacted only with the thermal pressure they encountered. The authors may actually have reasons for believing that somehow the interstellar magnetic field is incorporated by the expansion, perhaps via the cloud evaporation, but I am inclined to take the opposite view, that the remnants have to push against the field pressure to accomplish their expansion, as in the Slavin & Cox modeling. That field pressure is very large and substantially alters the remnant evolution. Thirdly, for many years, I was disinclined to believe that when denser features are overrun by a shock in the low-density surroundings, they could be evaporated into it. I imagined the relative motion would set up a cometary magnetic field structure around the cloud across which thermal conduction could not easily occur. McKee has countered this with various ideas about hydrodynamic stripping to provide the mass exchange. A stronger counter argument for me, however, is that which Blair Savage shared with me recently, that the Far Ultraviolet Spectroscopic Explorer, FUSE has finally seen OVI associated with the Local Fluff, as though evaporation or some sort of mass loss to the hot gas is occurring. It can't be very fast, or the clouds would be gone already, but it seems to happen. On the other hand, if the mass accumulation is not via something like classical conduction, it will not have the same hot gas temperature dependence, and it is no longer clear that the thermostat will work as advertised. For me, a fourth major problem with the model is that it has a large fraction of the volume filled with gas containing OVI. The authors advertise their cloud evaporation as the source of the observed OVI, but calculate an additional mean density for their general hot component of 9×10^{-8} cm^{-3}, several times higher than the observed amount. They believed that the high velocity width of this component might make it difficult for Copernicus to observe. I believe that FUSE has not yet found it either. One can wonder how their gas, with a significant fraction of the volume, something like 40%, filled with gas with temperatures between 3.4×10^5 and 4.4×10^5 K, would not have a vastly larger amount of OVI, given the analyses above. The answer is twofold: in their model the thermal pressure of this gas is very low ($p/k_B \sim 1200$ to 5000 cm^{-3} K) compared to the fiducial value of 11,000; and the temperature is just high enough to be past the peak of the OVI fractional abundance. Their hot gas temperature distribution truncates at 3.4×10^5 K! A fifth problem is the enormous size of their supernova remnants when they finally manage to cool. The radii are something like 182 pc. This makes them larger than the scales of the gross inhomogeneity of the medium, so that interaction with the existing sheets, walls, and such of the medium is unavoidable. They might occur, to some extent, in the cavities and tunnels of the ISM, but cannot grow to this final size without noticing the large-scale structure.

So, for me, the bottom line is that the ideas are useful, the geometry is wrong, and the details trouble me, particularly when the high density of OVI seems unavoidable (because the temperatures found are essentially those required to accomplish the cooling). Nevertheless, it was a good first crack, as Chris likes to say, and can help guide future efforts. In addition, some aspects may continue to be useful.

7.3. Other Ideas for Solving the Thermostat Problem

How is this thermal runaway avoided in the large cavities and tunnels of low density that are apparently present in the ISM? Other ideas that have been proposed include expansion of the hot regions to much larger volumes above the SN source region, with cooling occurring in the flow (a Galactic Fountain, Shapiro & Field 1976); the filling of the halo of the Galaxy with such material until it is dense enough to radiate the SN power input (an extension of the model of Spitzer 1956); the flow of the hot material out of the Galaxy in a wind; or other mechanisms such as turbulent mixing or photoevaporative flows, possibly in conjunction with thermal conduction, that drive denser material into the hot gas and raise its ability to radiate. In a few tens of Myr, small cavities could even refill by ambipolar diffusion of neutrals out of the abutting HI regions.

Hot haloes of galaxies, including the Milky Way, do not radiate a substantial fraction of the supernova power at the temperatures needed for filling the halo. A Galactic wind may be occurring, but I do not believe that it carries off a significant fraction of the supernova power from the Solar Neighborhood because it would carry off a similar power in the pervading cosmic rays, or even more if they are able to diffuse more rapidly in the low-density channels. The cosmic rays do not leave that quickly. Galactic fountains are tricky, with several incarnations. They were first taken seriously before the great thickness of the interstellar gas disk was recognized. When it was discovered that Galaxies do not radiate much of their supernova power in X rays, the temperatures of the fountains became constrained to lie below 10^6 K, and the extent of the fountains then was less than the disk thickness. Most of them became confined superbubbles. I have no ready argument against turbulent mixing or other mass loading scenarios, except that when they are incorporated into global models, we need to see how the energy is shared, that it is not via numerical diffusion, and how the OVI constraint is avoided.

7.4. Embracing Thermal Runaway

Another possibility is that thermal runaway is not avoided. Low-density regions are continuously heated, and grow along the magnetic field directions, until their densities become so low that there is nothing left for a supernova to heat. Thereafter, the SN ejecta more or less freely expand until they impact the cavity or tunnel walls, depositing their energies and momenta in much denser gas.

I imagine from the observed low-density passageways that tunnels might have diameters on the order of 20 pc. This contrasts with Smith (1977) in which they were contorted to rather smaller scales, which also might be occurring as part of the competition between their creation and destruction. The mass within a sphere of radius 10 pc is 125 n_0 Solar masses. As a result, even a Type Ia supernova could not thermalize its energy in a region of this scale with a density below 8×10^{-3} cm^{-3}. As a first guess, then, I imagine this is the tunnel density below which the thermal runaway fails, and which might therefore be the sort of density actually found within them. Perhaps it is a coincidence that the densities inferred for the MonoGem Ring and for the Draco enhancement are of a similar magnitude. In those cases, however, the low-density regions had radii exceeding 100 pc, and therefore more than sufficient mass to thermalize the ejecta.

If these tunnels existed with such low densities, it would considerably alter the morphology of the remnants of supernovae occurring within them. In fact, there is a class of remnants with the barrel-like appearance one might expect in this case (e.g., Kesteven & Caswell 1987; Bisnovatyi-Kogan, Lozinskaya & Silich 1990; Gaensler et al. 1998). The possibility that the older ones among them have occurred in low-density channels has been suggested by some of their observers. A good project might be to see relatively how many there are. The anticipated statistics might be a little tricky, however, because they reach a large size, that of the tunnel, very quickly. Also, this study must be restricted to the subset of barrel remnants old and large enough to be interacting with the ISM's structure, as opposed to their preSN winds. Models of such remnants would also be useful, indicating how quickly they become radiative, the effect of the decrease of internal pressure after the impact, and how quickly they fade from view in X rays and optical emission. In such modeling, I would assume the tunnel walls to have the density found earlier for intercloud material, about 0.3 cm^{-3}, except in modeling remnants for which the preshock density is obviously higher. Other remnants also have peculiar morphologies, suggesting they have evolved in regions of intersecting bubbles and/or at the ends of long narrow tunnels. One last example: apparently the outer shock of the Crab Nebula has not yet been found. It seems to be expanding in a low-density cavity.

Can such a scenario provide the solution to the M band problem? I don't know, maybe. It could be a way to make the collective X-ray emission of remnants more amorphous, smoothing its distribution on the sky. If it happens, the task likely falls to as yet unidentified remnants, those too diffuse to have been found as individuals.

7.5. Enter Stochasticity

The previous discussion did not deal with the subject of stochasticity. Paralleling another of the great insights introduced by McKee & Ostriker (1977), we can examine the likelihood that, in a quasi-uniform medium, an evolving remnant experiences another supernova explosion before it manages to cool, and how that is related to whether it is close to overlapping with its neighbors at the time it cools.

By returning to the Sedov SNR model of Section 3.2 and simply defining the cooling epoch to be when $\Delta E_{rad}/E = 1$, we can find the parameters of a remnant at that time, as a function of the density in which it is evolving, in particular, the cooling time, t_c, and the remnant volume at that time, V_c. To see whether that evolution is disturbed by another explosion, we can compare t_c with the mean time between SN occurrences in the volume V_c, $t_{rep} = 1/(SV_c)$.

For the estimate of the filling factor of remnants at that time, we use the porosity for isolated remnants in the adiabatic phase evaluated at t_c. For $R \propto t^{2/5}$, as in Section 3.2, $q = S \int V\,dt = (5/11)\,SVt$.

With these two, the ratio of cooling to SN occurrence timescales (in V_c) can be written as $\Gamma = t_c/t_{rep} = (SV_c t_c) = (11q_c/5)$. For very small Γ, not only do the remnants occupy little of the volume (by the time they have cooled), they also are very unlikely to have another explosion within V_c before they enter the cooling epoch. For $\Gamma \sim 1$ remnants do not evolve independently. Much of their history occurs after cooling, and the chance that it is disturbed by another explosion is quite large. Situations with $\Gamma > 1$ are those in which the medium experiences a continuum of SN heating that must be dealt with collectively, as in the earlier discussion. Writing the cooling epoch characteristics (and the associated initial density) as functions of Γ, we have

$$n_0 = (0.01\,\mathrm{cm}^{-3})\,E_{51}^{15/26}\Gamma^{-7/13},$$

$$T_c = (0.8 \times 10^5\,\mathrm{K})\,E_{51}^{4/13}\Gamma^{-2/13},$$

$$p_{sc} = (1 \times 10^{-12}\,\mathrm{dyn\,cm}^{-2})\,E_{51}^{23/26}\Gamma^{-9/13},$$

$$R_c = (200\,\mathrm{pc})\,E_{51}^{1/26}\Gamma^{3/13},$$

$$t_c = (1\,\mathrm{Myr})\,E_{51}^{-3/26}\Gamma^{4/13},$$

where the numerical values all assumed Ferrière's diffuse SN rate, 40% of the Type II occurrences and all of the Type Is, for a total of 27.3 SNe $\mathrm{kpc}^{-3}\,\mathrm{Myr}^{-1}$ in the midplane. This is to concentrate on the effects of the SNe and the ISM outside superbubbles. As Γ is proportional to S, the equations can be generalized to other assumed rates simply by dividing each Γ by the rate relative to that used here. The numerical values given above differ from those in McKee & Ostriker (1977) owing to several differences in the details of the calculations, but the qualitative features are similar and well illustrated by the equations above.

Small Γ thus requires high n_0 and leads to higher temperature, higher post–shock pressure, and smaller younger remnants at cooling. Once again, the critical density for remnants being able to radiate the SN power is on the order of 10^{-2} cm^{-3} (in this case at $\Gamma = 1$).

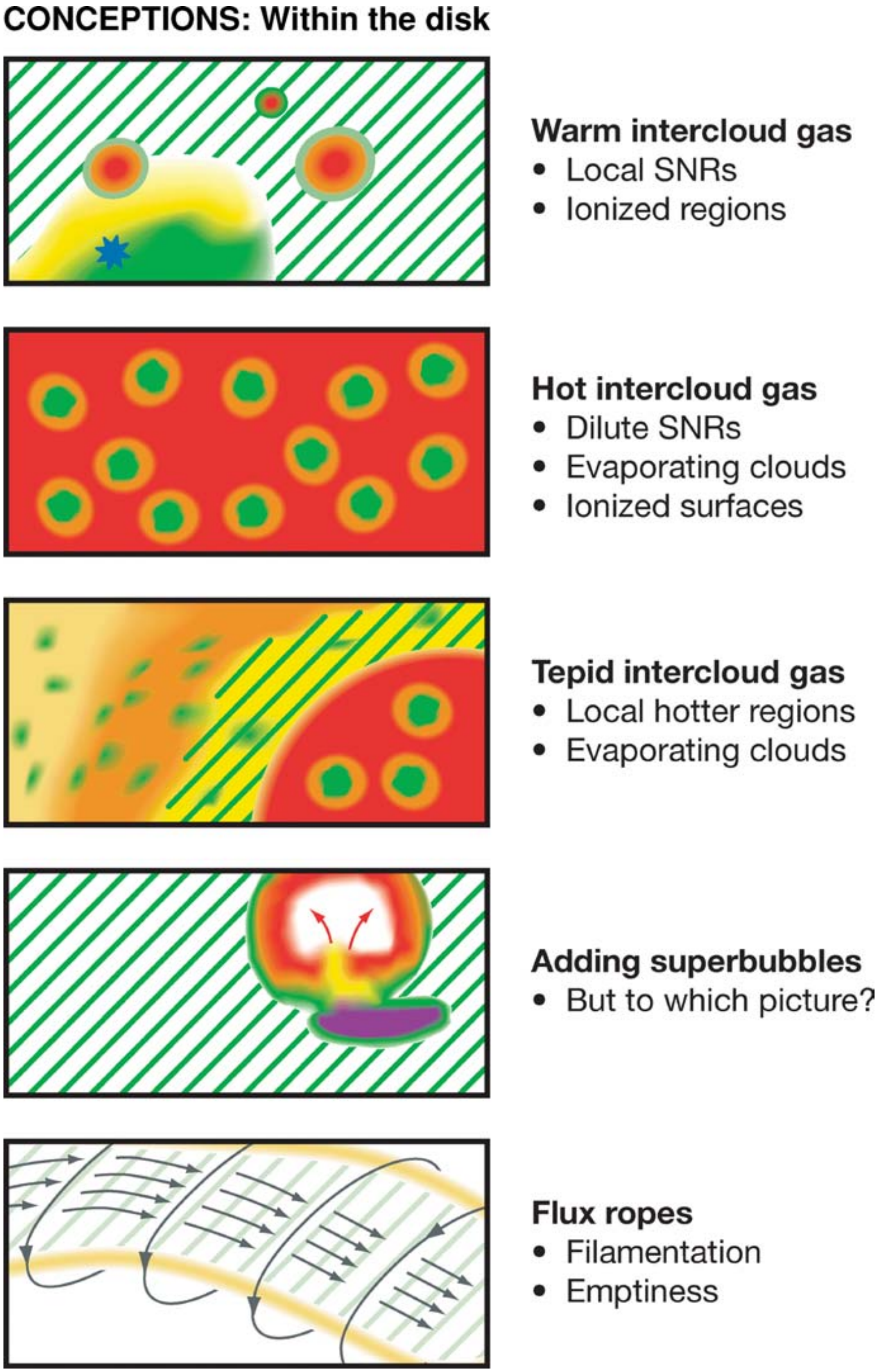
Two new insights are provided by this analysis in conjunction with the previous one. First is that large Γ not only signals that SN heating is continuous, it further shows that that continuous heating is not something the medium can radiate without raising the pressure first. The radiation is either in individual remnants, or it is inadequate at the dynamical pressure. The second insight has to do with the critical case of $\Gamma \sim 1$, showing us the characteristics of the remnants that would be required. They would be very large, take a long time to evolve, and have post–shock pressures as they approach cooling that are comparable to the actual pressure observed in the ISM.

The last point above is one of the most remarkable feats of the McKee & Ostriker model. It gave us hope that we might be able to understand why the ISM has the pressure it has, namely that it is the pressure within the collection of SNRs as they overlap with one another. It is determined by the SN occurrence rate, remnant dynamics, and the cooling function. Having said that this model seems to have little to do with the actual ISM, I have to admit that I am reluctant to abandon this great possibility. It is another place in which I hope that inhomogeneity might somehow provide an effective homogenization, leading us back to a dynamical understanding of the ISM pressure.

8. CONCEPTIONS OF THE ISM

Figures 8, 9, and 10 show sketches of various conceptions of the ISM that I think might be prevalent, or at least have been in the past twenty years or so. In each figure the regions shown in *orange* are those containing OVI. The *red* component is hotter and emits X rays. The *solid green* regions are cold HI clouds, the *solid purple* the even colder and denser star-forming clouds, the *hatched green* is the warm HI, and *hatched green over yellow* is the diffuse HII.

The *upper panels* of Figure 8 show three common conceptions about how these elements might be arranged near the galactic plane. The *top panel* assumed that the disrupting influence of supernovae was small, that they are isolated events occurring, usually, in the warm intercloud gas. This was essentially the Slavin & Cox (1993) picture, viewed with skepticism by L. Spitzer (private communication), who could not believe that its intercloud component could maintain the required homogeneity. Apparently, he was right. The *second panel* has a very low intercloud density, kept hot by supernova explosions, and a population of clouds within it

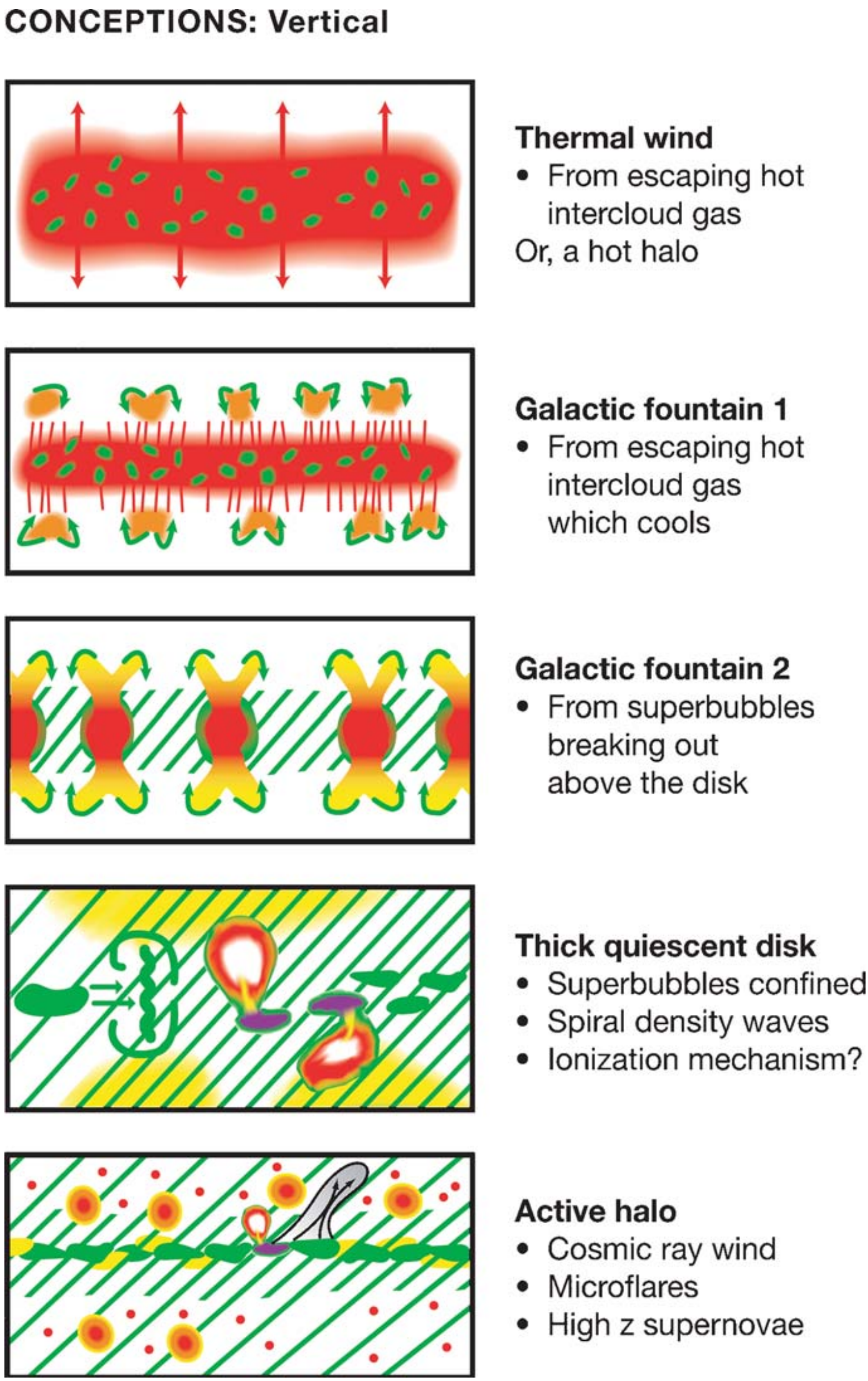

CONCEPTIONS: Within the disk
Warm intercloud gas
• Local SNRs
• Ionized regions
Hot intercloud gas
• Dilute SNRs
• Evaporating clouds
• Ionized surfaces
Tepid intercloud gas
• Local hotter regions
• Evaporating clouds
Adding superbubbles
• But to which picture?
Flux ropes
• Filamentation
• Emptiness

containing the warm and cold HI. Because the intercloud density is low, it is subject to thermal runaway, as discussed previously. The *third panel* is similar and different. It is an attempt to illustrate the McKee & Ostriker picture, in which hot remnants are transient events in a low-density medium, but manage to radiate before overlapping. They evaporate clouds within them and return the mass to clouds further out later on. It has large volumes of OVI-bearing gas in order to deal with the energy radiatively. The *fourth panel* introduces superbubbles, but asks what the medium is like in which they grow. The *fifth panel* expresses my sentiment that magnetic flux ropes might be common in the interstellar medium, maybe in the Pleiades, for example, and that empty regions are possible.

Figure 9 tries to extend these conceptions vertically, first with a hot gas-driven wind, followed by two versions of Galactic fountains, then remembers that the Galactic disk is, in fact, an order of magnitude thicker than previously realized, and ponders the activities within it. This, together with the final part showing the possibilities of activity in the outer parts of that thick disk (often referred to as the halo), come closest among these to showing what I think is possible, given the observations. It does not clarify the way in which supernova energy is dissipated, requiring either that the warm gas has a lower density than we previously estimated, so that its filling factor is large, or that something else like a tunnel network or mass loading solves the thermostat problem.

Finally, Figure 10 tries to imagine the larger picture. As I have said before, the hot halo and/or wind seem to be severely constrained by observations. One or the other may be present, but not such that it disposes of a significant fraction of the supernova power from the Solar Neighborhood. The *second panel* showing the fountain is likely out as well, principally because the disk is too thick for most OB associations to drive bubbles to such a size that they can break out in the way envisioned. The *third and fourth panels* include features that I think are likely; disturbances are largely confined to the disk unless they are the rare events that could create plumes reaching through the disk. I think a wind from the inner region of the Galaxy is possible and even likely, but have not yet been able to model one that reproduces the X rays discussed by Almy et al. (2000). Then there is the possibility of activities within the halo, and the question of the Galactic environment.

Figure 8 Various conceptions of the interstellar medium within the disk. In this figure, *purple* indicates dark molecular clouds; *solid green*—cold HI clouds; *hatched green*—warm HI; *hatched green on yellow background*—diffuse warm HII; *orange*—hotter gas bearing OVI; *red*—material hot enough to emit X rays; and (in this figure only) *black lines with arrowheads*—the magnetic field. A blue star in the *top panel* is shown contributing to the ionization of the diffuse gas in its vicinity. The *top three panels* are common (mis)conceptions whose difficulties are discussed in the text. The *bottom two panels* show features that need to be added. None show the correct nature of the inhomogeneity.


CONCEPTIONS: Vertical
Thermal wind
• From escaping hot intercloud gas
Or, a hot halo
Galactic fountain 1
• From escaping hot intercloud gas which cools
Galactic fountain 2
• From superbubbles breaking out above the disk
Thick quiescent disk
• Superbubbles confined
• Spiral density waves
• Ionization mechanism?
Active halo
• Cosmic ray wind
• Microflares
• High z supernovae

9. A NEW CONCEPTION: THE POLYMERIC CHARACTER OF THE ISM

What are the apparent facts regarding the Galactic interstellar magnetic field? It has such a large magnitude that its pressure exceeds the thermal pressure in all diffuse interstellar components, except those involved in dynamical events of considerable strength or that were created by such events and left hot. The field distribution is thick and largely erratic. Its rms value, about 5 μG in the plane, is several times larger than its uniform component. It seems to have a much thicker distribution than that of the gas, whose weight confines it to the Galaxy. The field lines are known to wander, meaning that any individual field line that might be part of a flux bundle in one region finds itself, after some distance, associated with an entirely different group of field lines. It is as though the flux bundles unravel and re-form with different allegiances.

And what is implied by those facts? On the whole, the field distribution vaguely resembles felt, or perhaps more accurately, an interwoven polymer. But, it is an elastic medium as well, with a pressure approximately inversely proportional to the square of its vertical extent. On its own, it would expand out of the Galaxy. But here and there within that structure, there is mass attached, mass that experiences the gravitational pull of the galactic plane. We have seen that all of the weight of the material is needed to provide the midplane pressure, that is, to confine the field and the associated cosmic rays. And most of that weight is provided by the low-density material far from the plane where the gravity is large. If it were not there, the field and cosmic rays could not be confined to the disk.

Material far off the plane is not, for example, on some ballistic orbit having been expelled from the disk to be eventually returned to the midplane. It is up there close to equilibrium, hanging on the elastic matrix. If it is moving, which it often is, it likely isn't going far, but rather oscillating on the elastic support. (There is at least one exception to this, a large region above the Solar Neighborhood, the

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Figure 9 Various conceptions of the interstellar medium within about 300 hundred parsecs of the midplane. In this figure, *purple* indicates dark molecular clouds; *solid green*—cold HI clouds; *hatched green*—warm HI; *hatched green on yellow background*—diffuse warm HII; *orange*—hotter gas bearing OVI; and *red*—material hot enough to emit X rays. The *green arrows* in the *fourth panel* indicate material flowing into a spiral arm and encountering a combination shock and hydrualic jump (shown as a *vertical squiggly green line* with arcs enclosing it at high |z|). The *red dots* in the *bottom panel* represent microflares, releases of magnetic energy via localized reconnection events; whereas the *gray region* is a column of escaping cosmic rays and the associated distortions of the magnetic field. Difficulties with the *top three panels* are discussed in the text, and the *bottom two panels*, though they contain greater realism, do not correctly represent the large-scale inhomogeneity within the disk.

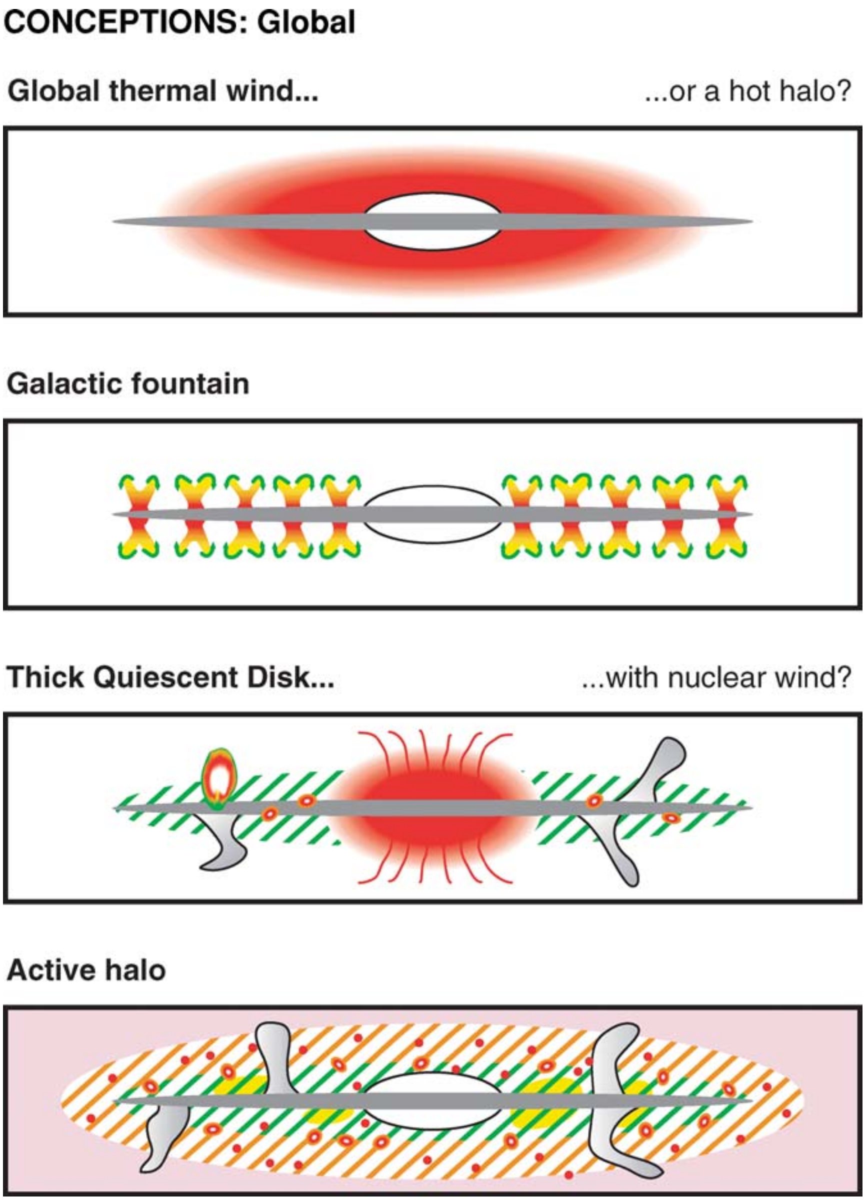

Figure 10 Various conceptions of the larger scale structure of the Galactic atmosphere. In this figure, *hatched green* indicates warm HI; *hatched green on yellow background*—diffuse warm HII; *orange*—hotter gas bearing OVI; *red*—material hot enough to emit X rays; *gray*—plumes of escaping cosmic rays; and *red dots*—microflares. Problems with the *top two panels* are discussed in the text. The *lower two panels* contain some elements of potentially greater realism.

IV Arch, that is high up and moving rapidly down. It should crash into the disk in about 10 Myr. A model of its impact could be quite interesting. Because the magnetic energy is elastic, there is a possibility even in this case that part of it will bounce.)

Ignoring the IV Arch, try to envision this medium in quiescence, with a very irregular loading of mass on it. In places it will sag, with positive upward curvature. In lightly loaded regions, the curvature will be in the opposite direction. It experiences tensile as well as compressional forces. If, as suggested by the earlier data review, there are regions above which the mass density is low but the magnetic structure continues to even greater heights, the confinement of the field and cosmic rays depends entirely on tension from the weight distributed below.

Now, try to envision this polymer in a differentially rotating Milky Way. The relative motion of the interconnected radial zones requires "creep" or its exaggerated form, "slip." These terms describe the plastic deformation and flow of a material under stress. Even crystalline solids have creep and slip. I think that in our case, these must arise either from some sort of forced reconnection (Lazarian & Vishniac 1999; Lazarian, Vishniac & Cho 2004), which allows layers to slip relative to one another, or turbulence-enhanced ambipolar diffusion (Zweibel 2002, Heitsch et al. 2004), which constantly re-forms the alliances of flux tubes. The efforts of solid-state physicists suggest that in order for the slip to occur at rates far higher than naively expected, the action concentrates in small regions at any given moment, as is embodied in the papers just referenced.

How is this view different from common conceptions? For those who think of the field as a secondary player, courteously getting out of the way when clouds, shells, infalling material, and plumes of hot gas wish to pass, it should provide motivation for rethinking this mindset. Buoyant bubbles of hot gas, for example, cannot simply rise out of the Galaxy. They are every bit as confined as the cosmic rays. For those who already recognize the significance of the field, but are hidebound in thinking of it as basically parallel to the plane and azimuthal, it challenges their notions that large-scale flux tubes can interchange, allowing those that have more mass to sag through the collection of those that are more buoyant, as in the Parker-like gravitational interchange instability. Such action takes place only as fast as the creep allows. Above some coherence scale, perhaps a few parsecs, perhaps a highly variable length, the medium is viewed as interwoven. It collectively sags when it has mass in it, the latter supported by the resulting compression and tension.

Suppose the field were not as I have described, instead being largely coherent with Parker instability and interchange motions common. Add to the actions of those instabilities the effects of massive vertical stirring in spiral arm disturbances, the actions of SNRs and superbubbles in the inhomogeneous environment, and the effects of a substantial pressure of cosmic rays that are working their way out of the Galaxy. Ask yourself what such a medium would be like after a few billion years. Unless reconnection is extremely fast, those actions would likely lead to just the sort of interweaving described above. Long-term coherence and the presence of all that activity are incompatible.

For those who cannot see the effects of the magnetic field the way they are so clearly present above the surface of the Sun, it is important to recognize the difference in regime. Above the Sun, the fields are very much in control of the dynamics in the low-density material. In the interstellar medium, the strength is not such that the large events are driven by the field. Those events that occur are impeded and moderated by the field, which itself is somehow brought into approximate equipartition with the mean kinetic pressure of the medium, not the extraordinary values of active supernova remnants or superbubbles. Looking further down into the Sun, where the density is much higher, the field there is driven about by the dynamics and likely has a similar equipartition. Conversely, well above the plane of the Galaxy, the field may have a more imposing role.

10. CAVITIES AND TUNNELS IN A POLYMERIC ISM

Suppose that the view above, of the medium being pervaded by an important elastic component, is approximately correct at some modest level of accuracy. We then see within it large cavities and tunnels. Some of those features are easily understood as examples of ongoing energetic disturbances, the elastic medium simply being highly distorted by the events. Some seem to have less clear origins. What can we imagine might be their states and origins?

First, despite my having led us to believe that low-density regions will invariably be hot because they cannot radiate the mean supernova power, there is a fallacy in that argument for smaller cavities. They are able to rid themselves of most of their thermal energy by expanding into ever increasing ambient density in the cavity walls, where the energy can be radiated. It falls to thermal conduction to cool the interiors on a similar timescale. The MonoGem Ring (and the Local Bubble) are marginally able to do this if their cavities are not much larger than their present hot volumes, while the Draco hot spot is better able because of its higher density and the lower supernova rate far off the Galactic plane.

Small cavities have time to cool between explosions. This is even truer of tunnel structures. The timescale for SN recurrence in a stretch of tunnel is very long if the tunnel diameter is much less than 100 pc. For smaller tunnels, a large fraction of the energy of a supernova occurring in a tunnel is quickly deposited in the material in the tunnel walls where, one hopes, it radiates enough at 3×10^6 K to solve the M band problem and evolves through 3×10^5 K so rapidly that there is little OVI. The tunnels themselves either radiate a much smaller fraction of the energy, or simply don't, because they are so diffuse that their radiation is negligible. In the latter case, we might well imagine that the tunnels occasionally have some slight excess pressure leading them to grow along the direction of the ambient field. In the end, they could be very pervasive, hot or not, with their pressures dominated by the magnetic field and cosmic rays. They could be a fine example of the case in which the thermal pressure is even more negligible than usual. Those that are hot, on the other hand, could have enough thermal pressure to make the field weak. This might apply, in particular, to those that are large or recently reheated.

The existence of such a tunnel network with fields within it could change our view of some other things as well, offering channels for the wider dispersion of some of the mass returned from dying stars, for cosmic ray propagation, possibly even trapping some of the SN ejecta as a very-low-energy cosmic ray component, along the lines of Field, Goldsmith & Habing (1969).

I have been thinking about the ISM for too long, and been fooled too often by its many coincidences, to take the description just above as a likely correct view of the way things are. My purpose is to try to synthesize the apparent facts into a scenario that includes them all as well as I can, and to try to get others either to dispute the facts as we seem to know them, or not to ignore those that are inconvenient.

11. WHY DOES THE ISM HAVE THE PRESSURE AND VERTICAL DISTRIBUTION THAT IT DOES?

The short and truthful answer to the above question is I do not know. The purpose of the question is to point out that the reader doesn't either, and to provoke the reader to figure it out so we will all know, someday.

We can talk about the pieces, however. The ISM has the pressure it does, in the midplane, because some of the material is distributed above the plane where gravity is strong. Its weight provides the pressure. Consider the Earth. Remove the atmosphere. Neglecting the action of dissolved air, the top several centimeters of ocean water will evaporate. That new atmosphere provides the vapor pressure at the ocean surface, restoring the equilibrium between evaporation and condensation. Is this what is happening in the ISM? Is there just enough warm intercloud gas to provide the pressure to make the cold dense clouds stable? This was a component of the original Field, Goldsmith & Habing 1969 discussion of the two-component medium. Above some height the pressure was too low to have clouds. But I am puzzled by the fact that the amount of material needed to provide the pressure is a significant fraction of the total ISM. The cold clouds are not like the ocean, a huge reservoir of material, only a small fraction of which is needed for the confining atmosphere. There are comparable amounts of material in all components. I feel that the relative amounts are adjusted, not by pressure but by something else—time or geometry, for example. Furthermore, the pressure provided also depends on the scale height of the warm material, which we now understand is not a reflection of its temperature. It is as though the pressure determines the scale height rather than the other way around.

On the other side, we find that the magnetic field and cosmic rays are the major components of the observed pressure. I have made facile excuses for this for many years, that the field arises through some sort of dynamo action that saturates when the field is strong enough to impede the mass motions driving the dynamo. That would put the dynamic pressure into the control seat. The cosmic rays are accelerated and accumulate until their pressure is high enough that they, in turn, strain the confining field to create escape routes, bringing equipartition there too. But these can also be argued in reverse. The dynamical motions in the ISM may not have a lot of dissipation until they accumulate to Alfvenic levels, after which there is likely enough creation of compressive waves that will lead to damping. Another reverse approach is to assume that the dynamo continues actively creating field, which in turn expands to maintain the pressure provided by the ISM weight, with excess flux constantly leaving the Galaxy, unable to be held in by the interstellar weight. Somehow, I think the mysteries of equipartition and relative scale heights hide among these ramblings, but do not explain why the pressure has the value it does.

What do I mean by relative scale heights? My impression from the talk by Ralf-Juergen Dettmar at the 2004 Heiles meeting is that observations of edge on galaxies show that in regions for which the star formation rate is higher, the thickness of all high z components is higher also. That includes the warm ionized gas, X-ray emission, dust, and synchrotron emission. The whole works more or less scales up together.

The discussion of stochasticity led to an estimate of the interstellar pressure that supernova remnants would have as they overlapped in a low-density medium just capable of radiating their power. It was a great achievement of McKee & Ostriker to identify this as the potential reason for the pressure having the value it does. Whether something similar is possible in the tunnel-riddled inhomogeneous medium is not clear. One can hope. A mechanism for making the effective density comes out right, and avoiding the OVI problem is still needed. Maybe it is just a matter of getting the cooling to occur, given the star formation rate, but then what sets the star formation rate?

Another clue lies in the earlier discussion of the two-phase medium. Evaluation of the pressure equilibrium at a fixed level of FUV heating, with fixed gas-phase abundances of carbon, oxygen, and PAHs, leads to a curve with pressures like those observed (after perhaps a bit of adjustment of something called $\phi_{\rm PAH}$ and other uncertainties). But changes, in any of those parameters, alters the curve, and substantial changes can alter one's impression of what is possible. The case of an altered heating rate was discussed. The situation with which we find ourselves comfortable has a mean interstellar density in the forbidden regime, which I said made it likely that both cloud and intercloud components are populated. In addition, the allowed cloud pressures included a significant range below the total interstellar pressure. I offered a feedback mechanism via the star formation rate that would try to bring this about. That is, it would act to make cold clouds possible by altering the heating rate. But, is there also some insistence that the mean density lie in the forbidden regime? What if the heating rate, etc., were exactly the same but the mean density only 0.2 cm^{-3}, something that would obtain if all the cold material were suddenly removed? It wouldn't change the ISM weight much, as that depends mainly on the warm components. Is there a mechanism other than the decline of the star formation rate that would make clouds reappear? If there were, the mass in the warm component would decline and presumably the interstellar pressure would decline, but the thermal-pressure curve would remain unchanged. It isn't clear that clouds would form, just that their allowed range of thermal pressures would be narrowed by the drop in total pressure.

Perhaps, it is related to the observed fact that the characteristics of dust are different in warm diffuse gas than they are in cold dense gas (Cox 1990). The diffuse gas has, on average, lower depletions onto dust, with a different distribution of grain sizes than cold clouds. There may also be a radically different abundance of PAHs. (An excellent review of dust properties will be in the conference proceedings of the 2004 Heiles meeting, the paper given by François Boulanger.) The proposed idea is that in cold dense quiescent regions, the grain population builds up a fragile component. When that material is returned from the molecular component to the warm diffuse component, it initially has that same grain population; but in the more hostile environment of the latter, the more fragile parts of the grain distribution are gradually destroyed. The destruction involves, at first, the disruption of coagulated grains and an increased population of small grains. Thereafter, the small grains are gradually returned to the gas phase. The longer the gas stays in that component, the fewer PAHs and small grains it has (so goes the idea). The photoelectric heating depends on that fragile grain component, and declines with time. A new cold region can form when this material is compressed by an interstellar event only if the photoelectric heating is low enough so that the cloud comes to a pressure lower than the total pressure of the ISM. Hence, just letting the intercloud material sit for a longer time in an active environment also lowers the heating rate (besides any reduction due to the reduced star formation rate), making cold gas once more a viable entity. Note that this is an idea, not a model, and maybe even an idea that is backwards from what actually happens to dust and PAHs. But, it offers a scheme by which the ISM can adjust its heating rate to move its mean density into the regime allowing both cold clouds and warm intercloud gas. The result would be what we see.

12. OTHER MATTERS

I created many outlines for this article, and have many pages of rough notes about what I imagined it should contain. Once I got to writing, many things fell away as the aspects I thought I might actually illuminate took over. The two subjects about which I feel worst for neglecting are the insights available from the LMC observations, and what X-ray and OVI characteristics should be expected from superbubbles. In the end I decided you'd be better off just reading what You-Hua Chu has to say on the subjects in the review she is preparing for her section of the Heiles meeting. Then there are the fascinating Zweibel (2004) questions. Have a look at them.

ACKNOWLEDGMENTS

This effort was supported in part by NASA Grant NAG5-12,128 to the University of Wisconsin-Madison. I would also like to acknowledge the gracious hospitality of the Instituto de Astronomía de la UNAM in both Mexico City and Ensenada during the early period of trying to write this document. Help with portions and drafts of the manuscript was provided by Ron Reynolds, Katia Ferrière, Ellen Zweibel, Bob Benjamin, Dan McCammon, Blair Savage, Wilt Sanders, Mike Winokur, Bruce Balick, Ewine von Dishoek, and Chris McKee, none of whom are responsible for the content or style, but all of whom made it a little better than it otherwise would have been. I am also very grateful to Doug Beckner and Roselyn Lowe-Webb at the Annual Reviews, Doug for his remarkable work (and patience) in the preparation of the figures and Roselyn for her careful and understanding editing.

The *Annual Review of Astronomy and Astrophysics* is online at http://astro.annualreviews.org

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Annual Review of Astronomy and Astrophysics
Volume 43, 2005

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