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GLOBAL STRUCTURE OF THE MULTIPHASE INTERSTELLAR MEDIUM

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Abstract

Interstellar H I can be described in terms of two phases, cold ($T \sim 10^2$ K) and warm ($T \sim 10^4$ K), that are in approximate pressure equilibrium. Photoelectric heating by FUV radiation absorbed by large molecules and very small grains is the dominant heating mechanism for this gas. The evidence for a pervasive hot phase of the ISM is discussed. Evaporation of embedded clouds dominates the cooling of this gas above about 5×10^5 K, which renders the gas thermally stable. Evaporative cooling augments radiative cooling at EUV wavelengths at the expense of that at X-ray wavelengths; as a result, supernova remnants could produce more warm ionized medium than heretofore estimated. The interstellar magnetic field affects both the filling factor of the hot gas and the pressure balance between the hot gas and the rest of the ISM.

1 Introduction

The interstellar medium (ISM) of the Galaxy is extremely inhomogeneous, with the density, temperature and pressure ranging over many orders of magnitude. However, on theoretical grounds one expects that the pressure should vary less than the density or temperature, since pressure differences tend to smooth out in a dynamical time [64]. Observations of the ISM are consistent with this expectation: regions of very high pressure, such as young supernova remnants and regions of massive star formation, occupy only a very small fraction of the volume; regions of very low pressure are difficult to observe, but they should not be common because they will be crushed by the weight of the overlying ISM. The concept of pressure balance in the ISM was one of the key ideas in the two–phase model of the ISM, which began with early work by Field [25] and Pikel'ner [51] and culminated in the work of Field, Goldsmith and Habing [27], hereafter referred to as FGH. In a two–phase medium, the heating and cooling properties of the gas conspire to enable gas at very different temperatures and densities to coexist at the same pressure. Such a two–phase medium is generally possible only over a limited range of pressure, which enables one to predict the pressure of a two–phase medium theoretically. The two thermally stable phases in the FGH model are the cold ($T \sim 10^2$ K) H I clouds and the warm ($T \sim 10^4$ K) H I intercloud medium.

If the ISM were heated only by cosmic rays, as envisioned by FGH, the ISM would be very quiescent. In fact, as pointed out by Cox & Smith [18], violent heating by supernova remnants (SNRs) creates large volumes of hot gas in the ISM. This insight was instrumental in the development of the three–phase model of the ISM by McKee & Ostriker [45] (hereafter MO). In this model, the cold and warm phases of the ISM are embedded in a pervasive hot medium produced by SNRs. This model can provide only a partial account of the ISM, since it omits the fact that many supernovae originate in OB associations and are therefore clustered together in space and time; it does not include the effects of the interstellar magnetic field; it does not attempt to model the gaseous halo of the Galaxy; and it does not take into account molecular clouds and the star formation occurring therein. Nonetheless, it has been remarkably successful in accounting for a number of the properties of the ISM, including its thermal pressure, the high degree of turbulence, the properties of the warm ionized component of the ISM, and the existence of substantial amounts of hot gas, as seen locally. Recently, Bowyer et al [7] have attacked the model on the basis that it cannot account for the large disparity in the thermal pressure inferred for the local warm and hot components of the ISM. Don Cox and I have been debating the validity of the model for many years, and he expressed his opinions in a *Nature* News and Views article entitled "Crumbling Canons" that commented on the Bowyer et al result [16]. This talk presents my first opportunity to respond, which tempts me to rename my talk "The Three–Phase Model of the ISM: Crumbling Canon or Persistent Paradigm?" Let me begin, however, with a discussion of two–phase models of interstellar H I. A more extensive discussion of multiphase models of the ISM can be found in reference [44].

2 Two–Phase Models of Interstellar H I

A variety of mechanisms has been proposed to heat the ISM: cosmic rays (FGH), X–rays [61], dissipation of magnetic energy through reconnection [54] or wave dissipation [24], and photoelectric heating by starlight on grains [70], [20], [22], [19] (see Table 1). Of these mechanisms, only photoelectric heating is adequate: it taps into the largest energy source in the ISM, starlight. However, photoelectric heating by starlight is intrinsically inefficient, and it is only when very small grains and large molecules (polycyclic aromatic hydrocarbons, or PAHs) are included that this mechanism becomes viable [69],[71].

Table 1. Heating Mechanisms for Interstellar H I

Mechanism	Energy Source	Energy Density	Does it work?
Observed cosmic rays	SN	~ 1 eV cm^{-3}	No: Heating too low
2 MeV (FGH)	SN	0.04 eV cm^{-3}	No: Inadequate range, ζ too high
X-rays	SNRs Gal. XRS	$\sim 10^{-5}$ eV cm^{-3}	No: Heating too low
Magnetic:	Galactic	~ 1 eV cm^{-3}	
reconnection	differential		No: Applies to ionized gas
wave dissipation	rotation		No: Heating too low
Photoelectric heating	Stars	~ 1 eV cm^{-3}	Yes

Mark Wolfire, David Hollenbach, Xander Tielens, Emma Bakes, and I have developed two–phase models for the ISM that incorporate many of the advances that have been made in our understanding since the original work of FGH [71]. The principal advance is the realization of the importance of photoelectric heating on very small grains and large molecules, as just mentioned. We used the detailed results of Bakes & Tielens [1] for photoelectric heating by a Mathis, Rumpl, & Nordsieck [41] distribution of carbon grains extending down to 3 Å; Bakes & Tielens's results imply that grains smaller than 15 Å absorb only about 10% of the FUV flux, but contribute about half the heating. The efficiency of grain heating depends on the charge of the grains, since that affects the energy of the photoelectrons; as a result, ionization of the gas by X–rays and by cosmic rays can increase the photoelectric heating by reducing the grain charge. On the other hand, the recombination of electrons onto the grains results in recombination cooling, and Bakes & Tielens find that this outweighs the photoelectric heating for $T \gtrsim 8000$ K. In our models, we adopted a primary cosmic ray ionization rate of 1.8×10^{-17} s^{-1}, far smaller than that adopted by FGH. This rate is based on an extension of the work of Ip & Axford [34], who determined the steady state cosmic ray spectrum that results from an injection spectrum that is a power law in momentum, as expected for cosmic rays that are accelerated by shocks. We also included X–ray heating based on the X–ray spectrum observed by Garmire et al [29]. We found that photoelectric heating dominates over the entire range of densities we considered, $10^{-2} < n_H < 10^3$ cm^{-3}. The cooling of the warm neutral medium (WNM) is due primarily to Lyα, recombination onto grains, and the fine structure lines of [C II] and [OI]. The cooling of the cold neutral medium (CNM) is due almost entirely to the [C II] fine structure line at 158 μm. The typical pressure in the two–phase equilibrium is predicted to be 2300 cm^{-3} K. At this pressure, the temperature and density of the WNM are $T = 8000$ K and $n = 0.26$ cm^{-3}, whereas that of the CNM are $T = 53$ K and $n = 41$ cm^{-3}.

Table 2. Two–Phase Model for Interstellar H I: Comparison with Observation

	Observation	Standard Model [71]
Pressure (K cm^{-3})	Jenkins et al [36] 4000 (median)	990–3600
Temperature (K)	Kulkarni & Heiles [38]	
CNM	20–250	41–210
WNM	$\sim$ 6000–10000	5500–8700
C II cooling rate $n\Lambda(158\ \mu\mathrm{m})/(10^{-26}$ erg s^{-1} H$^{-1})$		
Disk	Pottasch et al [52]: 10 Gry et al [30]: 3.5	CNM: 6.2 WNM: 0.62
Halo	Bock et al [5]: 2.6 (per H I) Savage et al [59]: 1.4	2.8 (avg. for $b > 45$ deg)
Galactic luminosity ($L_\odot$)	Wright et al [73]: 5×10^7	3.3×10^7

Table 2 compares our standard model with the observations. The theoretical results for the pressure, temperature, and the [C II] λ 158 μm line are all in quite good agreement with the data (note that the model results for [C II] are based on a pressure of 3000 K cm^{-3}). The model is based on the assumption that the gas is in a steady state. This should be a good approximation for the cold gas, but not necessarily for the warm gas, which has a thermal time scale of order 10^6 yr [71]. Given the importance of the [C II] λ 158 μm line to the cooling of the ISM, it is fortunate that there a number of observations of its intensity. We argued that the observations of Pottasch et al [52] were biased toward high values, since they included regions near bright stars, where the photoelectric heating is greater. Some of the lines of sight observed by Gry et al [30] have a significant contribution from the WNM, which may account for the fact that their average cooling rate is less than that we estimate for the CNM. Our estimate for the line intensity in the Galactic halo includes a substantial contribution from the warm ionized medium (WIM). Finally, our estimate for the luminosity of the Galaxy in the [C II] λ 158 μm line is based on two quite uncertain assumptions: (1) that half the H I in the Galaxy is CNM; and (2) that the emissivity of this gas in the [C II] λ 158 μm line is the same as we estimated for the local gas, 6.2×10^{-26} erg s^{-1} H^{-1}. The estimate for the mass of H I in the Galaxy is taken from Henderson et al [32], 4.9×10^9 $M_\odot$ (including 10% He by number and rescaling their results to a Galactocentric distance of 8.5 kpc). We are in the process of making a more accurate theoretical estimate of the Galactic [C II] luminosity, allowing for the variation of the ISM with Galactic radius.

3 The Three–Phase Model of the ISM

3.1 Evidence for hot gas

There is general agreement that there is a hot component of the ISM with a temperature $T \gtrsim 10^{5.5}$ K. What is less certain is whether this hot component is a widespread phase that strongly affects the conditions in the rest of the ISM [45], or whether it is confined to a relatively small fraction of the volume of the ISM, $f_h \lesssim 20\%$ [62].

On purely observational grounds, there are two lines of evidence for hot gas, the soft X–ray background emission and the O VI absorption lines. Indeed, Cox & Smith [18] cited both data in support of their idea that the hot gas could have a significant filling factor. Since then it has become clear that the X-ray emission implies a high filling factor for the hot gas, at least locally. Not only are we embedded in a Local Bubble of hot gas, but we are right next to another hot bubble, the North Polar Spur. Observations of X–ray shadows by ROSAT [11], [63], [74] have shown that this X–ray emitting gas is not confined to the Local Bubble, but they do not as yet allow an inference of its filling factor away from our local vicinity. As for the O VI absorption lines, Jenkins' analysis [35] showed that they are quite common, with a mean free path of only about 165 pc. The three–phase model ascribes the O VI absorption lines to conductive interfaces of interstellar clouds. A very crude estimate of the total amount of O VI was within about a factor 2 of that seen by Jenkins; however, in the model, the O VI is distributed in a larger number of smaller features than found by Jenkins. Shelton & Cox [60] have reanalyzed these data and have concluded that the mean free path to an O VI feature is about 500–1000 pc, substantially greater than estimated by Jenkins. Such a large mean free path is consistent with either a small filling factor of hot bubbles produced by individual SNRs or with a larger filling factor of superbubbles produced by OB associations [60]. The absence of evidence for O VI in conductive interfaces around individual interstellar clouds is as yet unexplained in the three–phase model; whether it is a fatal flaw remains to be seen.

Further supporting observational evidence for the three–phase model comes from studies of the warm interstellar gas that suggest that it is not pervasive, so that very low density gas must have a substantial filling factor. Such very low density gas is either hot now, or was hot recently and has cooled radiatively. The mean density of WNM in the plane from 21 cm observations is $\langle n_H \rangle = 0.17$ cm^{-3} [21]. This agrees quite well with the mean density $\langle n_H \rangle = 0.16$ cm^{-3} found by Bohlin et al [6] in their analysis of UV observations of low–reddening lines of sight with the *Copernicus* satellite. There are fluctuations around this value, however; by focusing on lines of sight with particularly low values of N_H, Cowie & Songaila [14] found that there are regions with $\langle n_H \rangle \simeq 0.1$ cm^{-3} over distances up to 2.5 kpc in length. It is very difficult to argue that this gas has a filling factor close to unity, however: the thermal pressure is only about 1500 K cm^{-3}, substantially less than the median pressure of 3500 K cm^{-3} measured by Jura [37] or 4000 K cm^{-3} measured by Jenkins et al [36]. Models of the WIM that adopt such a low value of the density predict that the mean electron density is about 0.06 cm^{-3} [48], over twice as large as the observed value of 0.025 cm^{-3} [13]. Cox [16] has pointed out that the absorption line observations of Spitzer & Fitzpatrick [66] provide striking evidence for the small filling factor of the warm gas: they show that the each H I component along the line of sight to the halo star HD93521 is partially ionized, with a total column of electrons about equal to that expected for that line of sight from pulsar dispersion measures. However, as shown by Reynolds [56], these electrons must be clumped with a filling factor $\lesssim 0.36$ in order to account for the diffuse Hα emission. The observations of Spitzer & Fitzpatrick [66] thus suggest that the warm medium is strongly clumped, leaving a substantial fraction of the volume of the ISM filled by gas of much lower density.

Additional arguments in favor of a substantial filling factor for hot gas can be brought to bear by considering theory together with observation. In the absence of turbulent motions, the scale height of the ISM would be much smaller than observed [43]. Since the turbulent motions and the hot gas are both produced primarily by SNRs [65], the filling factor of hot gas f_h increases with the proportion of the pressure due to turbulence; McKee [43] estimated $f_h \sim 0.5$ based on an argument of this type. More recently, Bregman et al [9] have modeled the structure seen in 21 cm maps of the Galaxy, and concluded that the filling factor of the H I is only 20–50%. Evidence for a three–phase medium in the halo of the Galaxy has been provided by Wolfire et al [72], who have shown that the observed two–phase high–velocity clouds can be in pressure equilibrium with a hot halo that can account for the non–local part of the soft X–ray background.

Finally, we come to the purely theoretical argument pioneered by Cox & Smith [18]: direct calculation of f_h by determining the size and lifetime of SNRs in the ISM. They argued that f_h could be significant; MO [45] estimated $f_h \simeq 0.6$; and more recently, Slavin & Cox [62] have estimated $f_h \simeq 0.2$. A major factor underlying these different estimates is the effect of the interstellar magnetic field. MO implicitly assumed that the effects of a field on the dynamics of an SNR could be included in the ambient pressure. Slavin & Cox [62] made an allowance for the field by including a pressure proportional to the square of the density; they adopted a field strength of 5 μG, corresponding to a pressure of 7200 K cm^{-3}. However, the observed field is primarily random in orientation, not uniform [31], and the pressure of a random field is only $(1/3)B^2/8\pi$. Using Heiles's [31] values for the uniform and random components of the field strength ($B_u = 2.2$ μG and $B_r = 3.6$ μG, corresponding to a total field strength of 4.2 μG), the average interstellar magnetic pressure is only about 2600 K cm^{-3}, which is less than the median thermal pressure and much less than that assumed by Slavin & Cox. The dynamics of an SNR thus depend on the scale on which the field becomes random: if this scale is large, $\gtrsim 100$ pc, then an expanding SNR would feel a magnetic pressure close to the $B^2/8\pi$ appropriate for a uniform field, whereas if it were smaller, then the magnetic pressure would be substantially reduced. At present, the observational situation is not clear: based on an analysis of the differences in pulsar dispersion measures and rotation measures between nearby pulsars, Ohno & Shibata [50] estimate that the correlation length of the field is in the range 10–100 pc, which allows either possibility.

It is clear that estimating f_h involves a number of approximations, and I am not optimistic that a significantly more accurate value can be derived from pure thought anytime soon. The conclusion from theory is therefore that the filling factor of the hot gas is

$$f_h = 0.4 \pm 0.2. \tag{1}$$

This value agrees with that found by Rosen & Bregman [58] in a large scale simulation of the ISM. When stated this way, it seems as if we have almost determined the value of f_h. Unfortunately, as in the case of the Hubble constant, the exact value matters: if f_h is near the lower end of this range, then the hot gas does not play an important role in the overall dynamics of the ISM, whereas for $f_h \gtrsim 0.5$ it may play a dominant role. We must rely on observation to obtain a more accurate answer.

3.2 Evaporative cooling of the hot gas

A key feature of FGH's two–phase model of the ISM is that each phase is thermally stable: a perturbation in the temperature of either the CNM or the WNM will damp out, so that these phases can remain in equilibrium indefinitely. The hot phase of a three–phase medium (the hot ionized medium, or HIM) has a temperature that is constantly changing due to impulsive heating by SNRs and due to radiative cooling. Nonetheless, the thermal stability of this gas is crucial: if it were unstable, then parts of the hot gas would experience a thermal runaway and heat up to very high temperatures. Gas at temperatures above about 10^5 K is thermally unstable [26], and this would appear to pose a severe problem for the model. However, the hot gas is rendered thermally stable by the evaporation of embedded clouds. This point was made in a qualitative fashion by MO, and placed on a firmer footing by McCray (private communication) and Begelman & McKee [3].

Let $\dot{n}_{ev}$ be the rate at which the mean density of the hot gas is increasing due to evaporation. The specific entropy of the gas, s, drops due both to radiative losses ($-n^2\mathcal{L}$) and to evaporation [3],

$$nT\frac{ds}{dt} = -n^2\mathcal{L} - \frac{5}{2}P\left(\frac{\dot{n}_{ev}}{n}\right). \tag{2}$$

Radiative losses drain energy from the plasma, whereas evaporation shares the energy among more particles. Both effects cool the gas, however. To make this explicit, we write the evaporative loss term as $-n^2\Lambda_{ev}$. Balbus's [2] generalization of Field's criterion for thermal instability follows directly from equation (2) if the perturbation is isobaric: instability occurs if the perturbation in the specific entropy, δs, has the same sign as the perturbation in the RHS of the equation. Since δs is proportional to δT, the criterion for instability is $\partial(\mathrm{RHS})/\partial T > 0$. If the thermal conductivity κ is a power law in temperature, then $\dot{n}_{ev} \propto \kappa$ [15] and $n^2\Lambda_{ev} \propto \kappa/n \propto \kappa T$. For classical conduction, $\kappa \propto T^{5/2}$, so that $-n^2\Lambda_{ev} \propto -T^{7/2}$: the derivative is negative (stable) with a magnitude that increases rapidly with temperature. As a result, any medium in which the cooling is dominated by evaporation, such as the HIM, is thermally stable.

In the three-phase model of the ISM, evaporative cooling dominates until the temperature drops to about 5×10^5 K, the typical temperature of the HIM. To see this, we note that evaporative cooling dominates at high temperatures ($n^2\Lambda_{ev} \propto T^{7/2}$) whereas radiative cooling dominates at lower temperatures ($n^2\mathcal{L} \propto n^2T^{-1/2} \propto P^2T^{-5/2}$). The minimum temperature at which evaporative cooling can dominate is given by balancing the evaporative cooling rate with the SN heating rate, SE, where S is the SN rate per unit volume and $E \simeq 10^{51}$ erg is the average energy of a supernova. Since all this energy must in fact be radiated away, it follows that $n^2\mathcal{L}$ must also equal SE at the typical temperature in the hot gas; as a result, the cooling switches from evaporative to radiative at this typical temperature. With MO's values for the density of clouds and the radius of the clouds in the disk of the Galaxy, balancing evaporative cooling against supernova heating leads to a temperature [44]

$$T \simeq 5 \times 10^5 \left(\frac{S}{10^{-13}\mathrm{pc}^{-3}\ \mathrm{yr}^{-1}}\right)^{2/7} \ \mathrm{K}. \tag{3}$$

This result is quite close to the value for the temperature of the hot medium obtained by MO from more detailed considerations, and it emphasizes the key role of evaporative cooling.

There are several important consequences of this evaporative cooling. First, in the disk of the Galaxy it prevents radiative cooling from setting in until the temperature has dropped below about 10^6 K. This implies that energy injected by supernovae in typical regions of the disk will be radiated in the EUV part of the spectrum, not the X-ray. Evaporative cooling could therefore account for the absence of detectable X-ray emission from edge-on spiral galaxies [8], [42]. Even in the case of NGC 891, which has a relatively luminous Hα halo, the observed X-ray emission accounts for only about 1% of the expected supernova energy injection [10].

A second implication of evaporative cooling is that, because SNRs cool in the EUV, they produce more ionizing radiation—and therefore more WIM—than previously estimated. Reynolds [55] has shown that 4×10^6 ionizing photons cm^{-2} s^{-1} are required to ionize the WIM. He estimated that SNRs could provide only about 1/6 of the required ionizing flux based on Chevalier's [12] estimate that about 1/3 of the energy of an SNR in a homogeneous medium would be emitted as ionizing radiation in the 13.6 eV–60 eV band. However, if the dominant cooling above 5×10^5 K is due to evaporation, the energy going into ionizing photons in this band could easily be doubled. Reynolds adopted a surface density of supernovae based on a Galactic radius of 15 kpc. If instead we adopt a surface density of supernovae based on the recent analysis of OB associations by McKee & Williams [47], the surface density of supernovae goes up by a factor 4/3. Altogether, SNRs could account for about half of the total ionizing flux in the local WIM. When the ionizing luminosity of B stars and white dwarfs, including the nuclei of planetary nebulae, is included, the amount of ionizing radiation needed from O stars is significantly reduced. This is fortunate, since existing models of an O-star produced WIM (e.g., [48]) do not allow for cloud photoevaporation, which tends to confine ionizing photons to the H II regions around the O stars [23].

A necessary condition for evaporative cooling is the presence of embedded clouds. What happens if there are no clouds? In that case, the hot gas will be thermally unstable, as described above, and part of it will heat up to very high temperatures, $T \gtrsim 10^7$ K. Such very hot gas may be subject to conductive cooling at the boundary of the hot cavity, but this will be minimized if the cavity is very large. Natural potential sites of large, hot cavities are in the Galactic bulge, where the gas density drops to a low value [38], and in superbubbles, where cloud photoevaporation by OB stars homogenizes the ISM [46]. Direct evidence for very hot gas in the Galaxy comes from the hard X-rays that are observed from the Galactic ridge and the Galactic bulge, both in the continuum (1.1–18.5 keV) and in the 6.7 keV iron Kα line [75]. Norman & Ikeuchi [49] have previously suggested superbubbles as the origin of the hot gas in the disk, based on models that did not include evaporative or conductive cooling. Further observations of the sources of the diffuse hard X-ray emission in the Galaxy would be valuable.

3.3 The pressure in the local ISM

Consider now the issue raised by Bowyer et al [7]: the pressure in the local hot gas as determined from EUVE, $P/k \simeq 1.9 \times 10^4$ K cm^{-3}, is far greater than the pressure of the warm gas near the Sun as determined from He I 584 Å backscatter measurements [28], which they take to be 730 K cm^{-3}. They conclude that there is no pressure balance between the hot and warm gas in the local ISM, violating one of the key assumptions in the three-phase model.

First of all, this point is not new. MO [45] inferred a pressure for the Local Bubble of 10^4 K cm^{-3} from X-ray data about 20 yr ago, and observations of backscattered Lyα implied a local pressure of order 10^3 K cm^{-3} 10 years ago [4]. Cox & Reynolds [17] commented on the disparity between the pressure of the local hot gas and that in interstellar clouds in their review in 1987. Second, there are questionable aspects in Bowyer et al's analysis: They infer the pressure of the hot gas from the EUV intensity in the direction of an interstellar cloud, but there is no evidence that all the signal from in front of the cloud is interstellar (Lieu, private communication); and, in estimating the pressure of the local warm gas, they did not allow for the ionization of the gas.

Just what is the pressure of the local gas? At the Sun, the best estimate for the neutral density from backscatter observations appears to be $n(\mathrm{H}^0) = 0.135 \pm 0.025$ cm^{-3} [53]. Ionized gas is excluded from the heliosphere, so it is necessary to use a theoretical argument to infer the ionization of the local gas. *If* this gas is in ionization equilibrium, and if ϵ CMa dominates the ionization as suggested by Vallerga & Welsh [68], then the local ionization is $n(\mathrm{H}^+)=0.02$ cm^{-3}. For a temperature of 7000 K [40] the pressure would then be 1350 K cm^{-3}. Vallerga and Welsh show that the ionization varies rapidly with distance as one approaches ϵ CMa, so these conditions may not be typical in the local cloud. Furthermore, the recombination time is about 4 Myr, so the assumption of ionization equilibrium is questionable.

Alternatively, one can estimate the pressure from absorption line observations that average over path lengths to nearby stars. The observations of Mg I and Mg II toward Sirius by Lallement et al [39] imply an ionization $n(\mathrm{H}^+)=0.10$ cm^{-3} after using the value for the Mg II dielectronic recombination rate, $\alpha_d = 1.7 \times 10^{-12}$ cm^3 s^{-1}, recently calculated by Romanik [57]. This approach is subject to the same caveat concerning ionization equilibrium as the above estimate for the ionization, but it has the advantage of leading to a shorter recombination time, $\sim 2 \times 10^5$ yr, which makes the assumption of equilibrium more reasonable. The average density of the local cloud toward Procyon, which is close to Sirius, is $n(\mathrm{H}^0)=0.11$ cm^{-3} [40]. Note that if the warm gas fills only a fraction f of the space between us and Procyon, then the value of $n(\mathrm{H}^0)$ in the warm gas would increase by a factor $1/f$. Together, these results imply that H is about 50% ionized in the local cloud, which is consistent with the upper limit of 75% obtained by Hurwitz & Bowyer [33]. The minimum value of the thermal pressure in the local cloud (corresponding to $f = 1$) is $P/k \simeq 2300$ K cm^{-3}. This latter value is well within the range of interstellar pressures measured by Jenkins et al [36].

In view of the uncertainty in Bowyer et al's determination of the pressure of the local hot gas, we shall use the value determined by X-ray observations, $P_h/k \simeq 10^{4.0}$ K cm^{-3} [45], [17]. With this value for the pressure of the hot gas, the discrepancy between the pressures of the local warm and hot gas is smaller than that inferred by Bowyer et al, but it is substantial nonetheless. The gas pressure in the local cloud appears to be mostly thermal, with no evidence for a shock [40]. The most likely way to achieve dynamical equilibrium with the surrounding hot gas is to have a magnetic field in the local cloud that is substantially larger than that in the hot gas [17], [16]. If the magnetic pressure in the hot gas is small compared to the thermal pressure, then the field strength in the local cloud needed to achieve pressure equilibrium is $B = 5.89(\Delta P/k)^{1/2}$ μG $\simeq 5.3$ μG, where ΔP is the difference in pressure between the hot and warm phases of the local gas. This field is comparable to the value of the interstellar magnetic field estimated by Heiles [31], $B = 4.2\ \mu$G. In other words, the gas in the local cloud is quite similar to that in a typical warm ionized cloud in the three–phase model, although it has a somewhat lower thermal pressure, and the field in the cloud is slightly higher than average.

In achieving this pressure balance, we have assumed that the B field in the hot gas is negligible. This is reasonable if the hot gas was produced by an SNR in a homogeneous medium, since the SNR will reduce the field along with the density as it expands. However, in a cloudy medium, the field is anchored by the embedded clouds, and the expansion of an SNR could even amplify the field by stretching it. Furthermore, in a cloudy medium, hot gas will exist on the same flux tubes as warm and cold gas, and on average one would expect thermal pressure balance among the different phases. We must therefore assume that the local bubble occurred in a relatively homogeneous medium, which is consistent with the lack of cold clouds in a large region of the bubble.

What are the implications of this discussion of the role of magnetic pressure in the local gas for the ISM as a whole? Since large pressure fluctuations are predicted [45] and observed [36] in the ISM, an additional dispersion in the thermal pressure due to the field is relatively unimportant. To have a significant effect on pressure balance in the ISM, the field would have to cause a systematic offset between the thermal pressure of the H I, $P_{\rm HI}$, and that of the hot gas. However, there is as yet no evidence that this is the case; on the contrary, the typical observed value of $P_{\rm HI}$ agrees well with the theoretical value of P_h (the typical observed value of P_h in the ISM is not known). As discussed above, one expects to have thermal pressure balance in a cloudy medium. The applicability of the three–phase model thus depends on the density structure of the gas: if the cold and warm gas is distributed in a large number of clouds, as assumed by MO, then approximate thermal pressure balance among the phases will be maintained (although, as pointed out by Jenkins et al [36], large clouds may not have time to come into pressure equilibrium). Such a distributed population of embedded clouds is also necessary for the evaporative regulation of the hot gas that underlies the three–phase model. Recent observations of cold H I in the local ISM [67] are consistent with this type of cloudy ISM. On the other hand, if the warm and cold gas in the ISM is primarily distributed in very large structures many 10's of pc in size with large voids in between, then magnetic fields could lead to substantial differences between the thermal pressures of the hot phase and the rest of the gas. Further observational study of the structure of the cold and warm phases of the ISM could thus have important implications for our understanding of the hot component.

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