STRUCTURE OF THE DIFFUSE INTERSTELLAR MEDIUM

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ABSTRACT

The interstellar medium has a thick disk structure ($|z| \lesssim 1500$ pc, the ECL or extracloud layer) with a thin zone of cloud contamination at $|z| \lesssim 100$ pc. The properties of all components other than clouds (e.g. cosmic rays, magnetic field, extracloud matter, pressure) drop slowly with $|z|$ across the thick distribution, giving this layer a very important influence in the evolution of superbubbles. It seems likely to quench blowout or breakout and virtually all fountain activity. The weight of this layer stabilizes the clouds at low z; its high pressure and low density provide a cushion for impacts of infalling clouds.

The intercloud (or more properly "extracloud") medium is stable against supernova disruption because of the incompressibility and elasticity contributed by its magnetic field. Coronal ions in the galactic disk probably derive in large part from quiescent bubbles of hot gas generated by Type I supernovae. Most of the diffuse ionization close to the midplane is probably caused by O star radiation leaking out of the HII regions, but Type I supernovae could maintain enough partial ionization in the bulk of the extracloud medium to contribute significantly to $\bar{n}_e$. At high z, the increasing degree of ionization is almost certainly due to cones of ionizing radiation emerging from OB associations. The pattern is like sunlight rays through a partially cloudy sky, the neutrals lying in shadows of low z dense material, and between cones.

Above the extracloud layer, there could be a hot, interesting, dynamic corona, and between the two a vigorous transition layer or chromosphere. If so, their study (except for the high z high ions, high velocity clouds, and upper limits to the x-ray emission) lies almost entirely in the future.

I have tried to highlight what I regard as key unsolved problems in this field, should the reader wish to be helpful.

I. To Guido's Health, Happiness, and Continued Good Science.

When I asked among my friends in Wisconsin for stories I could tell on Guido, Dan McCammon told me he was a good guy to go drinking with, Art Code had promised his stories to Don Osterbrock, Ron Reynolds gave me a paper to take to Guido and asked me to bring careful notes on his talk, and Chris Anderson told me there were

https://doi.org/10.1017/S0252921100024313 Published online by Cambridge University Press

no stories that my tender ears would be prepared to hear, but anyway to take Guido his fond greetings. It's a sorry lot altogether and quite the pity. I'd hoped to begin my talk, in this last session of the meeting, with a bit of humor.

In any case, Guido, Salud!

II. Conclusions

Carl Heiles set a good precedent, starting with the conclusions.

The picture which I have been exploring is orthogonal to that of most modelers of galactic fountains, winds, disk-halo interactions, high velocity clouds, superbubbles, and interstellar media dominated by supernovae.

It tends to ignore OB associations, stellar winds, and Type II supernovae, imagining them to be locally contained inflamations in an otherwise fairly docile environment. (At high latitude, the neglect of OB associations' ionizing flux has been an error on my part.)

It ignores interstellar clouds of all types, noticing that even in the midplane their volume occupation is negligible, that their weight contributes only a little to the vertical confinement of the magnetic field, and that (except under the most extreme circumstances) their magnetic field configurations probably adjust to shield them from appreciable interaction with their environment.

In this view, Type I supernovae are an important source of disturbance. But, when the ambient magnetic field is considered, it is quite likely that the medium behaves elastically to first order (Cox 1986, 1988; Cox and Slavin 1989). An old remnant probably consists of a moderate sized hot bubble within a much larger region of shocked but only very slightly compressed material. The latter "shell" of the remnant is indistinguishable from the surroundings, its inner edge rebounds to fill the bubble in a few million years. These conclusions need confirmation via 2D magnetohydrodynamic calculations so that the complex behavior of oblique shocks can be secured. (See Cox, 1988; Spitzer 1989.)

There are several important consequences of such an evolution for isolated remnants.

(1) Viability of Warm Intercloud Medium. The supernovae do not disrupt the intercloud medium into a froth of hot gas and dense shells or clouds -- a warm intercloud medium of density 0.1 to 0.2 cm^{-3} is possible owing to the lack of compressibility of $B^2/8\pi$.

(2) Coronal Ions. Preliminary calculations of the ion content of the quiescent hot bubbles show that their population can provide the observed interstellar mean densities of O VI, N V, C IV, and Si IV (Cox and Slavin, 1989). (Although much work remains to be done on this topic, the picture is already at least as successful as any other for providing these ions.)

(3) SN Energy Dispersal. This evolution drastically alters one's perception of the ultimate distribution of the supernova energy. After the onset of the radiative phase, much of the energy is stored in magnetic field compression, rather than being radiated in EUV. At later times it is recovered, driving the re-expansion of the shell material. The energy is ultimately dissipated over a very large volume in quite weak shocks. The prime functions of such shocks may be: (A) the partial ionization of hydrogen along with an appreciable production of Lyman α by collisional excitation*, and, (B) occasional reheating of the intercloud gas to roughly 10^4 K, from which it cools only very slowly.

(4) Survivability of Interstellar Dust. The significant change in the character of these shocks compared to the highly compressive radiative shocks of earlier models may result in much lower dust destruction rates.

(5) The Cowie and York Test. One must similarly reevaluate the expected frequency of radiative shock signatures, before the significance of the Cowie and York (1978) limit is known.

In this picture, the intercloud medium, the high z medium and the interarm medium are all the same thing, with parameters varying gradually with increasing height above the plane, z.

A three layer description seems to be useful for the diffuse galactic environment.

1. The Cloud Zone. At the galactic midplane is the cloud contaminated zone, a thin disk with $|z| \lesssim 100$ pc. The dominant interstellar beasts of this neighborhood include dark clouds, diffuse clouds, lower density cloud envelopes, the intercloud medium (in neutral and ionized forms), hot bubbles, cosmic rays, and a strong magnetic field (with a significant component parallel to the disk). There are also the superactive subzones around sites of present and former OB associations, considered extensively by other speakers at this conference.

Characteristic densities, temperatures, pressures, filling factors, and power requirements associated with thin disk components are shown in Table 1. The notes mention some of the major issues. I differ from most other authors, in discarding the assumption of thermal pressure balance between components (noting that $B^2/8\pi$ is large enough to make up any discrepancies), and thus in my conclusion that the neutral intercloud medium occupies a large fraction of the total volume. As mentioned previously, the magnetic field stabilizes this phase against disruption by supernovae.

There are three aspects of the thin disk parameters about which I remain uneasy: (A) I don't believe we have yet located the cosmic ray acceleration sites; (B) the maintenance of widespread ionization in the intercloud medium requires more power than any source other than O stars can comfortably provide, but O stars should

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*John Mathis points out that this could depend somewhat sensitively on the extent of preshock ionization.

Table 1

Midplane Characteristics of the Interstellar Medium[a]

		Power	Pressure	Density	Temperature	Volume
		(vol. avgd.) $[10^{-26} \mathrm{erg\ cm^{-3}\ s^{-1}}]$	(p/k) $[\mathrm{cm^{-3}\ K}]$ (thermal)	(local) $[\mathrm{cm^{-3}}]$	[K]	[%]
Clouds	dark	?	moderate	large	15	small
	diffuse	10[b]	3000	40	80	$\lesssim 2$
	envelopes	$\lesssim 1$	3000	$\lesssim 8$	400	$\lesssim 10$
Intercloud	neutral	$\lesssim 1$	1000[c]	0.2	5000	$\gtrsim 60$[c]
	ionized	7[d]	3000	0.2	8000	15
Type I SNR	bubbles	(at 10^6 years)	1000	0.003	3×10^5	12
	power	2[e]	(S ~ 4×10^{-14} $\mathrm{pc^{-3}\ yr^{-1}}$ at 5×10^{50} ergs)			
Ionizing UV	O stars	110	from Abbott, 1982			
	B stars	2.2				
	Other	0.3	From Panagia and Terzian, 1984			
			(non thermal)			
Cosmic Rays		1[e]	6000			
Magnetic Field		small[g]	6000-10,000[h]			

Notes:

[a]These are best guess schematic results. Power neglects dust absorption of light and production of FIR.

[b]10^{-25} egs/atom-sec to balance gas cooling

[c]Low thermal pressure of neutral intercloud medium is commonly used as evidence that the local density is higher and filling factor lower, leaving room for a hot component, but see h below.

[d]Power to keep the diffuse ionized gas ionized is very large. (See Reynolds, 1984)

[e]The cosmic ray power requirement is a significant fraction of the Type I SN output. (Both are assumed to have 300 pc scale ht. in this chart.)

[f]The large UV power from O stars does not leak well into the intercloud component far from OB associations if the neutral hydrogen is randomly distributed.

[g]The field replacement timescale from windup or radial inflow is long. SN driven dynamo could be significant.

[h]Large magnetic pressure makes medium difficult to compress, the compression is elastic, thermal pressure balance is not enforced between components except over timescales much longer than those of major disturbances.

have difficulty delivering their photons where needed (but see section IV); and (C) the diffuse cloud heating mechanism seems accidently to result in minimum cloud thermal pressures of an allowed magnitude, somewhat below the weight of the interstellar medium (but see discussion of FGH model below).

2. The Extracloud Layer. Surrounding the cloud-contaminated zone is a much thicker disk, having $|z| \lesssim 1500$ pc. I have come to regard this zone with great respect; it is not the location of just a few trace amounts of this and that, of no particular consequence. Rather it is a zone in which the magnetic field is only slightly less than that at midplane; it is the trapping volume for the cosmic rays; it is home to a distribution of gas whose heating and ionization require an extraordinary amount of power and whose weight defines the midplane pressure. It is the atmosphere, the overburden, the thermostat, the buffer for the interstellar system, dictating the conditions within the cloud environment at low z.

The thick distribution of cosmic rays and magnetic field is displayed by the galactic synchrotron emission, the low mean density within the cosmic ray trapping volume, and the galactic contribution to Faraday rotation of extragalactic sources (see references in Boulares and Cox, 1989). The γ-ray emission of the Galaxy also contains hints of it (Bloemen, private communication). These components drop slowly, to $|z| \sim 1500$ pc, from their midplane values. The presence of "intercloud" material at high z has shown up in 21 cm studies (e.g. Lockman, Hobbs, and Shull, 1986), in studies of trace ions such as Ti II (Edgar and Savage, 1989, and references therein), and in the distribution of pulsar dispersion measures (Reynolds, 1989a). The neutral component of the intercloud medium, the Lockman Layer, has a midplane mean density $\bar{n}_{HI}(0) \sim 0.1$ cm^{-3} and scale height of roughly 400 to 500 pc. The ionized component, the Reynolds Layer, has a midplane mean density $\bar{n}_e(0) \approx 0.025$ cm^{-3} and scale height of about 1500 pc. The masses in the two are comparable, and similar to that of the clouds. Because they are at high z, their weight exceeds that of the clouds.

Considering the Lockman and Reynolds Layers as the neutral and ionized portions of the same material distribution, Ron Reynolds and I would like to propose subsuming both, along with the "intercloud medium", the "interarm medium", the magnetic field, and the cosmic rays into one general term, the "extracloud layer", ECL*. Then ECM (extracloud matter, medium, or material) is appropriate to refer to the material itself. The material in the Lockman and Reynolds layers can then be NECM and IECM, or one can continue to use the WNM and WIM designations.

There are several outstanding problems regarding the thick disk. These include (A) determination of the high z supernova rate, (B) understanding cosmic ray transport and escape, (C) determination of the magnetic field configuration, (D)

*"Extra" connotes outside of, as well as above. "Layer" calls to mind the overall distribution in a thick disk; in addition, Reynolds points out that it was the term used by Hoyle and Ellis (1963) when they originally proposed the existence of what I now call the Reynolds Layer.

measuring the degree of intermixture of the neutral and ionized components, (E) determining the origin of the ionization (which as in the midplane, requires an extraordinarily large amount of power--see Reynolds, 1984, 1989b), (F) understanding the binding of the large field energy to the Galaxy and the associated hydrostatics of the extracloud layer, and (G) understanding the layer's effect on the formation of superbubbles, chimneys, and fountains. Models of the latter which do not include the interaction with 10^{-12} dyn cm^{-2} of nonthermal pressure over kpc scales, as well as with the material in the ECL, cannot hope to be realistic. The ECL, for example, could make possible the growth of superbubbles to much larger dimensions in the plane than previous calculations have found, while quenching blowout and fountain activity.

Of possibly more than historical interest, the marriage of zones 1 and 2 into a comprehensive ISM picture was an essential feature of the Field, Goldsmith, and Habing (1969, FGH) model. The view was rather like the atmosphere-ocean phase equilibrium. Without the overburden of an atmosphere, the ocean would evaporate explosively until the atmospheric pressure exceeded the vapor pressure of the water, suppressing boiling. In the FGH picture, there was just enough intercloud material for its weight to provide the critical pressure required for the existence of clouds in the vicinity of the galactic midplane.

In my view, (Cox, 1988) the clouds have a powerful heating mechanism (possibly photoelectric ejection off grains by starlight) which provides them with a certain equilibrium temperature (and therefore pressure) at each density. That pressure has a very flat minimum around $p/k \sim 3000$ cm^{-3} K. This value is higher than what I regard as typical of the thermal pressure in the extracloud medium ($p/k \sim 1000$ to 3000 cm^{-3} K from Table 1), but is considerably lower than the weight of the ECM ($p/k \sim 2$ to 3×10^4 cm^{-3} K), much of which is borne by the cosmic rays and magnetic field. Thus it is possible yet that the system forces material into the extracloud component until there is sufficient weight to confine the clouds, using the magnetic pressure as the intermediary. Clouds would then be possible in regions of slightly lower than typical field or higher than typical external thermal pressure.

There are at least two bugs in this prescription. One is that the cloud and extracloud components have very similar amounts of mass (in contrast to the ocean and atmosphere). This is a very awkward situation for the clouds, having used up a substantial amount of their material to stabilize themselves. A second peculiarity is that there are other models of the ISM in which supernova explosions define the background pressure dynamically (McKee and Ostriker, 1977; Cox, 1981). One necessarily wonders at the coincidence of the results from two apparently independent mechanisms.

3. The Galactic Corona. Beyond the thick disk there may well be a qualitatively different environment, the galactic corona. In this region I imagine that the density is extremely low, the temperature is possibly very high ($\sim 2 \times 10^6$ K), the galactic material and cosmic rays outflowing, and extragalactic material infalling. Almost every aspect of this region is unknown or known poorly

and represents an outstanding problem. An important constraint on its state distribution is that the X-ray emission is very weak.

Between the thick ECL and the galactic corona there could also be a very interesting transition layer, something like the galactic chromosphere suggested by Sciama (1972), in which downward energy flow lights up the higher density gas. This boundary could be very irregular; in a conversation, Laura Danly and I imagined it might provide an excess population of high ions between $|z| = 1$ and 2 kpc. An important energy source for the ECL might be the stoppage of infalling clouds. For the very high velocity clouds, high temperatures (and their tell-tale but unobserved X-rays) might be avoided if the HVC motions had low Alfven Mach number in a high B low n environment above 1.5 kpc. (At 1 kpc with $B \sim 2\ \mu G$ and $n \sim 0.01\ cm^{-3}$, the Alfven speed is about 40 km s^{-1}. Continuation of B to much lower densities in the corona would probably be required for this to work.)

III. The Problems of Hydrostatics in the ECL

Two recent papers, at least, have discussed the hydrostatics of the thick extracloud layer (Bloemen, 1987; Boulares and Cox 1989), addressing the same difficulty with different methods. For some time the essential problem had been thought to be that, although the tracers of the nonthermal components all point to a thick layer, the weight of the known material was concentrated at lower z. Under the normal assumption that weight is what restrains the field and cosmic rays from free escape, one concluded that the pressure gradient is concentrated lower than the pressure itself. The pressure almost surely decreases somewhat at moderate z, by an amount needed to support the material, but what then holds down the field and cosmic rays at greater heights? What does their residual pressure gradient do?

In the context of the 1D analysis, four solutions to this problem seemed to be possible.

(1) A possibility explored by Badhwar and Stevens (1977) and Bloemen (1987) is that there is unseen low density material at high z, too cold to be supported by its thermal pressure gradient.

(2) A second but perhaps unlikely possibility is that the Galaxy is surrounded by a significant external pressure.

(3) Hydrostatics may be the wrong picture. Perhaps the gradient in the nonthermal pressure at high z accelerates a wind from the Galaxy, somewhat as described here by Heinz Volk.

(4) A solution proposed by Cox (1988) and explored in greater detail by Boulares and Cox (1989) is that magnetic tension is important. At high z the net magnetic force could even be downward, restraining the cosmic rays, coupling them to the anchoring weight below by tension in the field. This configuration works wonderfully for suspension bridges.

Solution (4) has the advantage that it seems to be a natural consequence of instabilities in the system (e.g. Mouschovias, 1974). It is also consistent with data on rotation measures of extragalactic objects (Simard-Normandin and Kronberg 1980). The idea has been criticized on the grounds that the particles and fields may not actually be bound, but I regard this as a subtle point. Tension can restrain expansion; it does so in the field around a straight current-carrying wire. The wire itself experiences a net inward force. Similarly, the magnetic force on a current carrying loop is toward the plane of the loop (attempting to squash the wire--parallel currents attract) but radially outward (attempting to stretch the wire into a larger loop). It is quite possible that the galactic field on the larger scale is restrained in part by the radial gravitational force on interstellar material.

An additional sobering truth is that the configuration we observe should have questionable stability. The cosmic rays do, after all, escape. Very likely some of the field does also. I regard the suggestion by Kraushaar (1963) that the field is strained to near breaking by the cosmic ray pressure as almost certainly correct. As such, I don't think it surprising that we cannot easily demonstrate that the configuration is stable.

But recently there has been a shift in the nature of the hydrostatics problem. The Reynolds layer is intermixed rather well with the cosmic rays and magnetic field to high z and has sufficient weight to provide their restraint, making solution (1) above potentially adequate within the uncertainties, at least to $z \sim 1$ kpc. But when looked at in detail, the layer's weight is so great for the commonly assumed gravity distributions that the total ISM weight exceeds any current estimate of total midplane pressure. Cox and Snowden (1986) and Cox (1988) used this as further evidence for an rms midplane magnetic field of 5μG. Spitzer (1989, private communication) and Boulares and Cox (1989) find typical required fields even larger. Spitzer has remarked that the ECM may have a dispersion velocity at high z of 30 km s^{-1}, aiding its support, but this does not help the difficulty with the midplane pressure unless, perhaps, the high velocity dispersion extends down to $z = 0$. Boulares and Cox favored the use of a weaker gravity (less weight yields lower midplane pressure), consistent with the observed galactic matter distribution (no dark matter) as proposed recently by Bienaymé, Robin, and Crézé (1987). But there is yet considerable room for debate and need for observational clarification.

IV. The Ionization Power Problem

For some time Ron Reynolds has been emphasizing the importance of the diffuse ionization problem. As shown in Table 1, only O stars among the known sources have sufficient power to provide the observed diffuse Hα. (Adding Type II makes SN a marginal contender as well.) But ionization exists far from O stars and it has been difficult to see how the ionizing photons can find clear paths over great distances.

(Note, for example, that in the McKee and Ostriker, 1977, model, the mean free path between cloud envelope intersections was only 12 pc.) The WNM or neutral extracloud medium gets in the way. (But see Harrington and Bregman, 1986)

In preparation for this meeting I tried to solve the problem using Type I supernovae and their new late time evolution that can pump a substantial fraction of their energy, perhaps as much as 1/3, into ionization. Cox and Slavin (1989) found that supernovae with energies of 5×10^{50} ergs need a rate $S \sim 4 \times 10^{-14}$ pc^{-3} yr^{-1} to explain the high ions (O VI, N V, C IV, Si IV) in the galactic plane as arising from their bubbles. That result is tentative and could be low by as much as a factor of 2. Taking the larger rate, 1/3 of the total energy, and assuming 30 eV is expended per ionization, the average ionization power would be 1.4×10^{-26} erg cm^{-3} s^{-1}, the ionization rate 3×10^{-16} cm^{-3} s^{-1}, the sustainable mean square density 10^{-3} cm^{-6} (at 8000 K) and the rms electron density 0.03 cm^{-3}. I was encouraged by the fact that the rms density is comparable to the observed mean density $\bar{n}_e$ (z = 0) = 0.025 cm^{-3} (see references in Reynolds 1989a). The supernovae could provide the diffuse electrons seen via pulsar dispersion measures, but that uniform distribution would miss providing the Hα by a factor of 7.

I next wondered whether the supernovae might at least provide the bulk of the ionization found at high z, the distribution being (Reynolds, 1989a) $\bar{n}_e (z) = 0.025\, e^{-z/1500\ pc}$ cm^{-3}. I decided first to compare the supernova ionization rate possible in a 1 cm^2 column toward the pole. Following Heiles (1987) I took the Type I scale height to be 300 pc, yielding a maximum achievable emission measure of (10^{-3} cm^{-6}) (300 pc) = 0.3 cm^{-6} pc. This is again a factor of about 7 lower than the characteristic emission measure "toward the pole" as inferred by Reynolds (1984). I moaned about this fact at the meeting, causing Guido to respond that he had observed emission measures as low as 0.5 cm^{-6} pc. Something was clearly wrong with my simplistic view of the Hα background.

Since the meeting I have discussed Guido's remark and several other aspects of the diffuse Hα background with Ron Reynolds. The results of those discussions will require a paper all their own (Cox and Reynolds, in preparation). The tentative conclusions are as follows:

(A) The distribution of electrons <u>in the galactic midplane</u> (not counting those in bonafide HII regions) requires at least 3 components for even a rudimentary description:

1. A dense component ($n_e \sim 1$ cm^{-3}) occupying very little of the interstellar volume, contributes modestly to $\bar{n}_e$ and appreciably to $\overline{n_e^2}$;

2. A fully ionized portion of the ECM ($n_e \sim 0.2$ cm^{-3}) occupying a few percent of the volume, provides roughly half of both $\bar{n}_e$ and $\overline{n_e^2}$.

3. Partial ionization in the rest of the ECM ($n \sim 0.2$ cm^{-3}, $n_e \sim 0.01$ cm^{-3}) occupying 75% of interstellar space, provides about a third of $\bar{n}_e$ but very little of $\overline{n_e^2}$.

(B) Type I supernovae are capable of providing the partial ionization in the mostly neutral regions of the ECM as well as making a modest contribution to the fully

https://doi.org/10.1017/S0252921100024313 Published online by Cambridge University Press

ionized ECM; but most of the fully ionized material (in the ECM and dense regions) is due to O star radiation.

(C) Although the Type I supernovae are plausibly capable of providing an emission measure contribution of 0.3 cm^{-6} pc toward the pole, their probable contribution is less than that unless the supernova rate has been underestimated.

(D) OB associations are fully capable of drilling high latitude ionized rays through the neutrals in the ECM except where their radiation is significantly shadowed by denser foreground clouds (the resulting rays resembling the pattern of sunlight through partial cloud cover). As in the paper presented at this meeting by José Franco, the ionized zone is in a cone above the association. The overlapping of those cones at z ~ 1 kpc results in a nearly fully ionized ECM above that point.

(E) Lower latitude HI in the ECM survives because of shadowing by clouds (in shells?) and self shadowing, resulting in the finite opening angles of the associations' ionization beams. Due to shifting source and cloud patterns with time, as well as Type I supernovae, the neutral regions have a modest partial ionization, contributing significantly to $\bar{n}_e$.

(F) The low emission measures at high latitude (typically 1 cm^{-6} pc at $|b| > 50°$ but as low as half that in some directions, compared to the expected 2.3 cm^{-6} pc found by Reynolds (1984) from a best fit, assuming a csc $|b|$ dependence, to the b variation at $|b| \lesssim 50°$) result from our not being located directly below the illumination cone of an OB association.

In short, the Reynolds Layer receives most of its ionization from direct rays from OB associations. The neutrals lie between the rays in shadows of clouds, are in no way randomly distributed or intermixed, and do not get in the way of the ionizing photons. (When they do, they are rapidly ionized.)

V. Summary

(A) The things we know are not well known, at least not to me.
(B) The thick extracloud layer changes everything.
(C) Shadows of vapor, as usual, are important in the interstellar medium.
(D) There is much interesting work left to do.

This research was supported, in part, by the National Science Foundation under grant number AST-8643609 and by the National Aeronautic and Space Administration under grant number NAG5-629.

As usual, the reader should be aware that I consistently overstate my certainty in interpretations, in order to present as clear a picture as possible.

I would like to acknowledge useful conversations with Ron Reynolds, Jon Slavin, Ahmed Boulares, Guido Münch, Pepe Franco, Dick Edgar, Laura Danly, Charlie Goebel, Hans Bloemen, John Mathis, Blair Savage, and Lyman Spitzer. I am particularly grateful to Ron for patiently teaching me about the diffuse Hα and for a critical reading of the manuscript, and to Lyman for his constructive criticism regarding the hydrostatic problem.

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Discussion:

VÖLK (Comment): Assuming strong, large scale B-fields up to high $|Z|$, then these force free fields should behave similar to the solar case, random fluid motions resulting from stellar mass loss moving the feet of the field lines around. As argued by Parker, this should lead to magnetic field dissipation and corresponding gas heating. Indeed the high $|Z|$ highly ionized species like CIV, NV, etc., which have been discussed by K. de Boer and L. Danly at this meeting might very well be produced by this nonthermal heat source.