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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

HOT GAS AND THE GASEOUS STRUCTURE OF THE GALAXY

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RESUMEN

Se presenta una revisión sobre el estado actual del conocimiento del gas caliente en la Galaxia y sus implicaciones en la distribución general del resto de las componentes gaseosas. Todavía hay mucho que hacer y para que haya avances significativos, se requieren las herramientas y mejoras descritas en esta conferencia.

ABSTRACT

A parochial review is presented concerning the status of our understanding of hot gas regions in the Galaxy and their implications for the overall distributions of the Galaxy's gaseous components. We have a long way to go, and for significant progress need the kind of tool improvements highlighted by this conference.

Key Words: **GALAXIES: ISM — HYDRODYNAMICS — SUPERNOVA REMNANTS — X-RAYS: GALAXIES — X-RAYS: ISM**

1. OBSERVED REGIONS OF HOT GAS

In our Galaxy, there are several distinct known interstellar components which are hot (and dense) enough to emit observable X-rays, making them known to us. They are:

the Galactic bulge
superbubbles
the Galactic ridge
the MonoGem ring
an M band source in the Galactic plane.
supernova remnants
the Local Bubble
stellar wind bubbles
halo emission

Although the purported topic of this paper is the role of hot gas in the general structure of the interstellar medium, what I propose as the sobering theme is that it is essential to understand these components individually, getting the physics and geometry right, before those insights can be incorporated into the larger picture. As a result, I will be devoting most of the discussion to what I regard as important recent progress in understanding some of these components.

2. MESSAGES, OLD AND NEW

The conclusions of this review may as well be placed first, where they can be appreciated. Some of those in the list below are ones I have been harping on for quite some time, others are fairly recent results, and the last two are just some bits of good news. The first three are important, and when intuition that disregards them is brought into play, it leads to gross misconceptions and error.

1) The Galactic disk is thick, extending to at least 1 kpc from the plane in magnetic field, cosmic rays, and gas. It is almost certain that the nonthermal pressure component drops off less rapidly than the density, increasing the effective signal speed with height, possibly requiring magnetic tension to hold things together (e.g., Boulares & Cox 1990). Among the things strongly affected by this realization are the shapes, sizes, and lifetimes of superbubbles, the nature of the spiral arm shock (Martos & Cox 1998; Martos et al. this volume), and the speeds of clouds falling toward the Galactic plane (Benjamin & Danly 1997).

2) All models of large hot gas structures must consider magnetic fields and thermal conduction (or other processes for redistribution of entropy) in order to obtain meaningful results. They affect the structure, appearance, and lifetime of the regions. Without their inclusion we incorrectly interpret what we see at the time of observation, and significantly err in our conclusions about later evolution and impact.

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3) Thermal pressure in the interstellar medium, except in hot bubbles, is generally negligible. This fact drastically affects any qualitative understanding of phase segregation in the interstellar medium. As an extreme example, there could conceivably be regions in which the thermal pressure component is effectively absent. It requires only a slight enhancement of the magnetic pressure, presumably combined with the usual cosmic ray pressure. We are accustomed to thinking that there are several gaseous regimes, the molecular clouds, the cold neutral gas, the warm neutral and warm ionized components, and the hot phase, and that together they fill the space. This thinking is frequently pushed into the assertion that whatever space is not filled by the cold and warm components must be occupied by hot gas. I believe it was Spitzer who in 1956 introduced us to this logic, finding clouds far off the Galactic plane and imagining they required external thermal pressure of a very low density (and therefore hot) component to confine them. Having it hot also gave it a sufficiently large scale height that he could believe it would be found there. And yet we often find almost vacant lines of sight along which there does not appear to be an excess amount of X-ray emission. Unmeasurably low densities are not uncommon; the brunt of this message is that they need not be accompanied by exceedingly high temperatures.

4) For the regions that are observed at high temperature, the cooler and more diffuse ones are sorely in need of high quality soft X-ray spectra and reliable diagnostics for their interpretation. This is particularly true of the soft X-ray background where they are needed even to disentangle the spatial distributions of the various contributors to the spectra.

5) And now I have some good news for those interested in making MHD models of violent regions for which it is important to have a reasonable approximation to the cooling rate coefficient. Brad Benson, working with me on his senior thesis, has found that a very simple approximation can work very well. The cooling function depends on both the temperature and the distribution of ionization. By calculating a full manifold of nonequilibrium histories, and subsequently expressing the trace element cooling coefficient, $L(T, Z)$, as a function of the temperature and mean ionic charge, Z, we also find $dZ/dt = nD(T, Z)$, the time evolution of the mean charge with the same form. From it, the mean charge and temperature can be followed in an MHD code with the addition of only one differential equation. Testing this over a wide range of alternative evolutions, we find that the error in the approximation is always within the uncertainty of the true cooling coefficient whenever cooling is important. A user requires only tables of the two functions $L(T, Z)$ and $D(T, Z)$. We suggest that the ionization and cooling due to hydrogen and helium be followed separately, however, requiring three more differential equations.

6) It was shown long ago that the cooling due to infrared emission by dust, following heating by collisions, could be much larger than equilibrium gas phase cooling. A simple method for including dust cooling and evaporation was presented by Smith, Krzewina, & Cox (1996). They conclude, however, that the inclusion of dust in codes will usually have little overall effect on the thermal and dynamical history of the gas. At temperatures above about 4×10^5 K, where dust cooling is significant, dust sputtering is also rapid. The dust cooling tends to be dwarfed by the nonequilibrium gas phase cooling during the brief ion flash. Little energy is emitted by the gas during this brief episode, after which the smaller grains responsible for the dust cooling have been sputtered away, and the cooling remains dominated by the gas, at essentially the same rate it would have had if dust had not been included. The main effect that dust does have is confined to gas which is never heated to such high temperatures. The dust cooling is still not important, but the reduction of the gas phase abundances reduces their cooling, an effect which can be modeled by using depleted abundances in the calculation (if the higher temperatures are uncommon).

3. DISCUSSIONS OF SOME INDIVIDUAL REGIONS

3.1. *The Galactic Bulge*

Several authors have examined the distribution of diffuse 3/4 keV band X-rays toward the Galactic center and concluded that there is a significant component from the Galactic bulge region. A simple model was constructed by Almy et al. (2000) in which the gas was assumed to be isentropic, filling the gravitational potential. For a given potential, there were only two parameters, the central temperature which controlled both the spectrum and the spatial extent, and the central density which controlled the surface brightness. The model which, when corrected for absorption along the line of sight, best fit the *ROSAT* data had a central temperature of 8.2×10^6 K and a central density of 0.011 cm^{-3}. Both drop rather sharply to about half these values 1 kpc from the Galactic center, and more gradually beyond that, to roughly 1.5×10^6 K and 8.4×10^{-4} cm^{-3} in the solar neighborhood. For those parts of the model hotter than 10^6 K, the X-ray emission in the 0.5–2 keV range is 1.2×10^{39} ergs s^{-1} while the total luminosity is roughly 8.9×10^{39} ergs s^{-1}. The cooling timescale was estimated to be 3×10^8 years.

A detailed model, which assumes the sources of mass and energy to be the bulge stars and which resupplies the energy by advective transport and/or thermal conduction, has not yet been made. Once such models exist and sufficiently high spectral resolution observations are available, the models can be tested and selected with diagnostics on the emission lines of hydrogen- and helium-like stages of oxygen. These will vary according to the degree of ionization disequilibrium and thus offer a measure of the flow speed.

The results could have enormous impact on our understanding of the ISM. The successful model may include a wind from the Galaxy, or a cooling outflow that generates clouds falling back on the plane. It could provide an extreme layer of shear between the outflow and the upper layers of the Galactic disk, with the potential for mixing, magnetic field amplification, and high energy cosmic ray acceleration. No matter how it works out, a gaseous bulge centered component consistent with the *ROSAT* 3/4 keV observations is almost surely going to change our picture of the gaseous structure of the Galaxy in dramatic ways.

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3.2. *A Supernova Remnant*

W44 is a very curious supernova remnant that has recently been modeled in considerable detail in a pair of papers by Cox et al. (1999) and Shelton et al. (1999). The observational material available was very extensive including radio continuum maps and spectral index studies, OH maser locations, 21-cm maps versus velocity, optical pictures in Hα and [S II], the former calibrated in brightness, infrared studies including the brightness distribution of the 63μ line of [O I], the X-ray emission distribution and coarse spectral information from *ROSAT*, and the identification of an approximately 20,000 year old pulsar within the remnant. The long-standing puzzle of this remnant is that its X-ray emission is decidedly thermal, but is peculiarly distributed, being brightest near the center and showing no hint of brightening near the outer edge, in a shell, as is more typical for thermal emission from remnants.

As this conference is centered on codes, models, and observations, and I have already mentioned the observations, I will highlight the various tools which were brought to bear on this problem. There were several analytical approximations, for the cooling of a remnant in a uniform medium, for the evolution and cooling of a remnant in a density gradient, for the effect of thermal conduction on the central density and temperature of a remnant, and for the production of radio continuum and gamma rays by cosmic rays and magnetic field in material that is compressed by a radiative shock wave, assuming only betatron acceleration (the van der Laan effect). The first three were used for parameter estimation, while the remainder provided the anticipated radio continuum and gamma ray surface brightnesses (given the structures found from the hydrocodes discussed next). Two hydrocodes were employed with an additional nonthermal pressure term representing the zeroth order effects of the magnetic field. Both included thermal conduction at the classical unquenched rate. (The analytical approximation for the internal conditions indicated that nearly this value was needed to achieve the observed central density and temperature.) A one dimensional code was used in conjunction with a plasma code to provide the nonequilibrium X-ray spectral characteristics. A two dimensional code was used to obtain the structure, with parameters chosen from the analytical analyses, because the asymmetries of the remnant suggested that it had formed a radiative shell on one end but not the other. The geometry was chosen to put the dense end on the far side in the north-east, where the radio continuum showed that shell formation was most mature, and to put the observable 21-cm emission from the dense post-radiative shell in recession as observed. The age was taken to be that of the pulsar.

The net result of this modeling was that it produced a remnant that would look very much like W44, without appealing to collisions of the shock with dense clouds or evaporating clouds in the center. The 21-cm emission was accurately reproduced as was the distribution of radio continuum, both arising from the cooled dense expanding half-shell. The X-ray spectrum was a good match. The X-rays were centrally brightened and dropped monotonically in all directions. Even on the low density end where the shell was not yet formed, the temperature was sufficiently low that there was no X-ray production anywhere near the edge. The optical and infrared emission were in agreement with radiative shock models when projection effects were taken into

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account properly.

There were only three failings. The radio continuum and gamma ray emissions were each about a factor of 4 lower than observed. These could be attributed to a higher preshock concentration of cosmic rays than has been inferred for the ISM on average, but might also be a consequence of acceleration within the remnant beyond the passive view of the van der Laan model. The only other failure was that the X-ray emission distribution was very flat within the center of the remnant, not rising to a lumpy cusp as the observations seem to. A variety of complications to the basic picture was suggested involving, for example, heavy element contamination by the ejecta in the center to create the cusp.

In addition to the extreme success and the modest failures, there was an interesting surprise, available directly from the data. The OH masers, whose inferred magnetic field strengths were in agreement with those anticipated in the dense shell, appeared to be found always just outside of radio continuum filaments, which themselves trace tangencies of the dense shell with the line of sight. It appeared that the masers are found on the outer surface of the dense shell, just interior to the radiative cooling region. Radiative shock models in molecular gas in fact show a local maximum in the OH density at just this location, but have not so far been explored for a pumping mechanism (which might depend on the nonequilibrium in the formation process).

An interesting result of this model is that the characteristics of the shell formation process versus time can be examined versus position in the vicinity of the equator of this remnant. There is in fact a hint of a local enhancement of the Hα brightness in the equatorial belt.

But the most important results are that this fairly young remnant cannot be modeled accurately without the inclusion of its magnetic field, the ambient cosmic ray population, and thermal conduction, and that more precise modeling yet should include cosmic ray acceleration by the shock (setting limits on the allowed rate, at least), the presupernova distribution of circumstellar material, and the contamination of the elemental distribution by the ejecta.

If you would like one single thing to carry away from this, consider yourself informed that the severe central cavity found in the Sedov approximation is a fictitious consequence of the assumption of strict adiabaticity. It does not exist in real remnants. And that the amount of entropy redistribution required for this remnant is that provided by unquenched thermal conduction.

3.3. *Accidental Bubbles*

As pointed out by Cox & Smith (1974, Barham Smith, that is), supernovae will occasionally occur within the remnants of earlier supernovae. The result is a larger, longer-lived bubble. This process can repeat, yielding less common but even larger accidental structures. Cox & Smith concerned themselves with the possibility that supernovae occurring near remnants could create merged remnants, and with sufficient frequency, long chains of stable interconnected remnants, a hot phase of the interstellar medium. Since that time it has been recognized that a large proportion of supernovae occur in OB associations, building individual collective remnants, superbubbles. This seriously reduced the likelihood of the growth of chains, and subsequent calculations by Slavin & Cox (1993), based on hydrocode models for the complete evolution of SNRs in the intercloud medium including the effects of magnetic pressure, found quite low porosity. Even with low porosity, however, there must occasionally be accidental occurrences of multi-SNRs.

Smith & Cox (2000, Randall Smith this time) have explored the characteristics of these accidentals as a potential model for the Local Bubble, a hypothetical entity surrounding the solar location purported to be responsible for the observed local contribution to the diffuse soft X-ray background.

The tools brought to this problem were a one dimensional hydrocode, a plasma evolution and emission code, and various analytic scaling laws that allowed us to generalize the results of the several runs made to a broader class of cases. The hydrocode included a magnetic pressure term and thermal conduction with an adjustable coefficient.

As a reminder, Slavin's modeling of a remnant occurring in the warm intercloud medium provided an entirely new picture of what very old remnants would be like. The dense surrounding shell produced when one is young totally rebounds to the ambient density as it ages and as the pressure returns to ambient. All that is left is the naked hot bubble surrounded by a region which is indistinguishable from the original intercloud component. In time, the bubble cools off and collapses, taking several million years to do so. It is within these hot naked “Slavin Bubbles” that accidental supernovae will occasionally occur. A supernova will reheat the

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bubble, but owing to the bubble's already large size will not contribute a sufficiently large pressure to reform a dense shell. The bubble remains as a largely thermal entity, expanding to an even larger size, slightly beyond pressure equilibration, stagnating, and over a long time cooling and recollapsing.

In modeling multi-SNRs, there are many parameters: the explosion energies, the initial ambient density and pressure, the time between the first and subsequent explosions, the number of explosions, and the level of thermal conductivity. Smith & Cox (2000) considered various combinations of these paramenters for two and three explosions. The parameter on which I would like to concentrate here is the thermal conductivity. The others have somewhat obvious consequences—more explosions or higher energy explosions yield larger bubbles, higher ambient pressure yields smaller bubbles and shorter lives, bubble growth is optimized (we think) when subsequent explosions occur in remnants at their largest sizes. But what about thermal conduction?

When the thermal conductivity is small, there is a very hot central region within the bubble, and a low central density. The temperature distribution, owing to what little conductivity there is, is very flat with a sharp downturn near the outer edge. Because of the low density and high temperature, the bubbles emit little radiation and as a result live a long time, collapsing very slowly after reaching maximum size. Conversely, with higher conductivity there is a much lower central temperature, a higher central density, still with flat profiles until near the edge, and the remnants radiate much more prodigiously, cooling and collapsing more rapidly.

In applying this model to the Local Bubble, several observational constraints were imposed. It was required that the model produce a bubble with a radius of order 100 pc, emitting the correct soft X-ray background, in brightness and in the relative amounts observed in three bands (the Wisconsin B and C bands and an upper limit to the $ROSAT\,M$ band). It was obliged to have an ambient pressure no higher than that found by Boulares & Cox (1990) for the total pressure in the local Galactic midplane, exclusive of cosmic rays. In addition, it was required that the total column density of O^{+5} not exceed the value inferred for the local component by Shelton & Cox (1994). And finally, several measurements had indicated that the gas phase iron abundance in the material emitting the soft X-ray background was depleted by roughly an order of magnitude at least. This imposed two conditions, one that the X-ray modeling be done with the iron abundance reduced, and second that dust destruction within the bubble not have been so complete that all the iron would have been returned to the gas phase.

Earlier modeling by Edgar & Cox (1993) of single explosions of arbitrary energy had shown that this set of constraints was very difficult to accommodate. With the scaling laws, however, Smith & Cox could explore a wide parameter space, with the result that it was possible, just barely, to satisfy the requirements. A reasonable Local Bubble model could be made. It was large enough, the required external pressure equaled the actual pressure in the ISM, and the external density was that commonly attributed to the intercloud component. It turned out that the reduced iron abundance was useful, reducing the lower energy bands preferentially, allowing a lower central temperature in matching the band ratios, and therefore allowing a higher density (at given pressure) and brighter soft X-ray emission without violating the M band constraint. The predicted O^{+5} column density was actually that found by Shelton & Cox (1994) for the local component toward stars just outside the Local Bubble, with a consistent width and the low centroid velocity required. Everything fit.

But the success of that fit depended on having the right amount of thermal conductivity. As discussed above, too low a conductivity would produce too hot a bubble with far too little X-ray emission. Only a narrow range of conductivity, 0.5 to 1 times the unquenched classical value, was acceptable.

There are many possible reactions to this news, among them: "Hooray!" or "This amount of conductivity is impossible!" or "The multi-SNR occurrence rate is so small that this is irrelevant!" Smith & Cox discuss the occurrence rate. It is small. If it were not, the Galaxy would be filled with such things (they give a rough estimate of the filling factor as 3%). Such things should exist; it's just unlikely that we would find ourselves within one.

On the other hand, we do find ourselves within a region of hot gas with the same characteristics as one. And the characteristics of such a region depend strongly on the degree of thermal conduction present during its formation. If the heating source were impulsive, the conduction would be needed to reduce the central entropy and, therefore, temperature to the value observed.

Let me state that another way. Knie et al. (1998) have found an excess of ^{60}Fe in a deep ocean ferromanganese crust which they interpret as deriving from deposition of supernova-produced ^{60}Fe on Earth within the last few million years, concluding that the supernova would have to have been roughly 30 pc from Earth about 5 Myr ago. If that supernova occurred within something like the Local Bubble environment, possibly a little

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smaller, denser, and cooler, it would leave the Local Bubble today with the characteristics it has only if the amount of thermal conduction present were comparable to the unquenched classical rate, just the sort of rate also required to give W44 its observed central X-ray emission, for exactly the same reason.

There is again a small curiosity with potentially large consequences. Models run by Smith & Cox (2000) that included dust destruction explicitly, showed that after two or three explosions, half to three quarters of the silicate dust by mass should have been destroyed. As the iron seems still to be at least 90% depleted, this is further evidence that interstellar iron is found preferentially in its own population of very durable dust particles rather than being primarily intermixed with the silicates.

It has been suggested that such iron grains may form in the supernovae that produce the iron in the first place. In fact, Knie et al. imply that it is the formation of dust within the supernova ejecta itself that may allow the ^{60}Fe from their postulated recent explosion to reach the Earth. It has to have penetrated the hot gas of the Local Bubble, the wispy material in the Local Fluff, and the solar wind.

From there things get a bit sticky. The hot gas in the Local Bubble has a total mass of roughly 100 solar masses. It could easily show abundance anomalies, enrichment from the explosions. Instead, for iron at least, it shows an apparent depletion. That depletion, however, is a relative one because the predicted brightness of the spectral contribution of iron is calculated relative to the emission in the *C* band, which itself arises from intermediate mass elements such as magnesium, silicon, and sulfur, whose abundances could also have been altered. And the anticipated abundance pattern depends on which elements were where in the ejecta, how much of each condenses into dust, how that dust and residual gas phase material interpenetrate and mix with the surroundings, and how much of that dust is subsequently sputtered. We have to be careful in mixing pictures of supernova enrichment of isotopes on Earth and supernova reheating of the Local Bubble. They interact in a complex way that, as usual, I believe will not be disentangled except by definitive measurements. And one of the measurements that is still sorely lacking is a sufficiently high resolution spectrum of the soft X-ray background so that we can see precisely what stages of ionization of what elements are producing it and under what conditions.

I am also still bothered by the fact that the cosmic ray population within the Local Bubble, measured at Earth, is so similar to that inferred for the Galaxy as a whole (e.g., Clayton, Cox, & Michel 1986). With a local recent supernova, I thought it would be different.

3.4. *Superbubbles*

I haven't worked on models of superbubbles, but I have several favorites in the sky. One is the Orion-Eridanus superbubble that stretches out and down from Barnard's Loop and mushrooms from there to fill a vast region below the Galactic plane, powered by the Orion OB association. A second is the bubble around the Sco-Cen association, outlined by radio continuum Loop I. Two others were discovered by making careful H I observations in the vicinity of "worms" which were found to be tangencies to the shell at low latitude. One reaches up in a cone from an active region of the Galactic plane, continues to great height, and is apparently closed at the top. The second is a 400 pc diameter structure whose lower boundary is already some distance off the Galactic plane.

The Orion-Eridanus bubble shows X-ray emission from its interior. The Sco-Cen bubble does also, but it is patchy, apparently not filling the bubble but being bright on some parts of the periphery, notably on the North Polar Spur. The other two may show X-rays. They certainly confirm that the thick disk is a real phenomenon.

What's the point? Well, Katia Ferrière, in a series of papers, (1998, and references therein) has taken it upon herself to calculate the porosity of the interstellar medium due to superbubbles, as a function of Galactocentric radius, and of distance off the plane. This is an enormous undertaking, requiring knowledge of the ambient density and pressure distribution, a census of the OB associations from which a spatial distribution versus number and power can be constructed, a model for the growth of the superbubbles that are created by those associations, especially for their shapes as they grow vertically, and a set of rules for how those bubbles lose volume as they die. And the principal conclusion I take from her results is that the critical feature on which the porosity depends is how the bubbles die. As with Slavin's work on supernovae (this volume, and references therein), most of the volume occupation is due to very old dying bubbles. Her specific results are that the porosity is less than or about 20% in the midplane at the solar circle, in agreement with observational estimates, and decreases with distance from the plane and increasing Galactocentric radius. But at a somewhat smaller

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Galactocentric radius (6.2 to 7.2 kpc) she finds layers about 260 pc above and below the plane, where the bubbles grow very large and die slowly, that are totally occupied by coronal gas.

There are many issues. It may not matter but Ferrière refers to the voids within the bubbles as containing "hot" gas even as they die. Does it matter? Do they stay hot? How does the cooling time within the hot gas seen in superbubbles compare with the time she concludes is required for them to disappear? How rapidly do they die? How rapidly do MHD model bubbles with thermal conduction in their interiors die compared to her estimates? Do the shells reexpand as they did for Slavin's supernovae, leaving only naked bubbles, hot or cold? Are there denser inclusions within the bubbles whose activities need to be taken into account? Just as it took a long time to appreciate the physics involved in the death of supernova remnants (and the story may not be complete yet) I expect it will be quite some time before we know whether Katia got this right the first time.

I certainly don't claim to know the answers; I just wanted to let you know that the gauntlet has been thrown down in this arena and there is a lot of good work needing to be done, either to confirm or refute her conclusions. At the very least, we should not ignore them.

How do superbubbles die? And how is that death rate affected by the other superbubble remnants in the same neighborhood?

3.5. *The Thick Disk and Halo*

The high angular resolution of *ROSAT* made some substantial changes to our knowledge of the spatial distribution of hot gas contributing to the soft X-ray background (Snowden et al. 1998, and references therein). Some things did not change, however. There are localized bright regions associated with specific nearby entities, the Orion-Eridanus Bubble, the Sco-Cen Bubble, the MonoGem Ring, and the nearby bright supernova remnants. The changes were in the distribution of material that had previously been inferred to be local, and ascribed to a hot Local Bubble.

The changes came about via shadowing experiments, in which detailed anticorrelations were found between dense structures, seen in 21-cm studies and with *IRAS*, and the surface brightness of the $\sim$1/4 keV X-rays. By searching for absorption components in optical spectra of projected stars versus stellar distance, it was found that some of the X-ray shadowing structures were several hundred parsecs away. The shadows however, were not black. By careful analysis, the X-ray emission could be separated into foreground and background. The foreground was found to vary fairly smoothly with direction and could still be ascribed to a local component, one which was not appreciably different in structure from the former picture, just a little dimmer at high latitude and not quite so lumpy. The background, however, was found to be very patchy or irregularly distributed at high latitude, patches which in some cases were at least several hundred parsecs away. Assuming that this emission arises beyond the bulk of the interstellar material, not just beyond the clouds used to isolate it, it was found that the emission measure in some directions was considerably greater than that of the Local Bubble. Absorption by the intervening material was said to be responsible for the fact that the observed count rate attributed to the distant component was generally only a modest fraction of the total count rate in any given direction.

It is this distant shadowed emission that tends to be referred to as the hot halo component, though from my earlier remarks you might guess that I prefer to think of its location probably being within the thick disk. It is in any case real, fairly distant, probably not a contiguous extension of the local component, and very perplexing.

The Wisconsin rocket program found that the very soft *Be* band with a very high absorption cross section had a surface brightness that closely tracked that of the somewhat harder *B* band (Juda et al. 1991). With more scatter, the *B* band tracked the harder yet *C* band emission (when identifiable nearby emission regions were avoided). The *Be* band source had to be local while the more penetrating *C* band could easily have been contaminated by more distant emission. In fact, complete sky maps of the C/B ratio quite clearly showed features associated with nearby emission regions such as the Orion-Eridanus bubble, the North Polar Spur, and the MonoGem Ring. With the *ROSAT* decomposition of the high latitude R1 and R2 band emission (comparable to the *C* band) into local and "halo" components, one would expect the larger halo emission regions also to be identifiable in the C/B ratio maps. A detailed analysis comparing the anticipated *Be*, *B*, and *C* band rates with the *ROSAT* observations would test whether the distant component lies beyond all of the interstellar matter in its direction, or whether it too has little intervening material in some directions.

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In short, it would improve our knowledge of the relative positioning of the X-ray emitting and potentially absorbing material.

A brief summary of the characteristics of the soft ($\sim 1/4$ keV) "halo" emission includes:

it is very nonuniform, and generally brighter in the north than the south
it has a temperature similar to that of the local emission
at least parts of it are fairly distant (≥ 200 pc)
it is not obviously beyond the bulk of the ISM
if it is beyond that, it is intrinsically very bright in some directions

It is possible that someone involved in the shadowing experiments already knows whether most of the ISM is in front of the distant hot gas, but no one I have asked so far seems to know (though most feel that someone should know. Perhaps this paragraph will provoke the chain of events to locate that someone.) How far up is the bulk of the observed interstellar material at high latitude, principally the low velocity component?

There is an extensive list of possible sources of patchy halo emission:

1) It is possible that the Sco-Cen superbubble also mushrooms at high z, extending over the top of the local component.
2) It could be due in part to emission from the population of high z supernova remnants, a subject explored by Robin Shelton (this volume, and references therein).
3) It could arise in a hot layer just beyond a chromospheric transition at the outer boundary of the warm disk, potentially heated by a variety of processes including wave action from the disk, reconnection, or even conduction from above if there is a hot, bulge-driven region above that.
4) If the bulge driven region is subject to thermal instability and forms cooling clouds, the radiation from those forming clouds could contribute.
5) As once suggested by John Raymond, it could be the Galactic analog of solar microflares.
6) It could be hot gas that has burbled up from the disk.

Item 6 begs for elaboration. One way, possibly the most likely, that this burbling might take place is the generalization of item 1, that the population of neighboring superbubbles extending out of the plane as in the Ferrière (1998) picture provides the high z distribution of hot gas. In this scenario, we are at least certain that the hot gas exists to do the burbling, and we are similarly certain that some extension to high z actually occurs. The only other source I can imagine for the burbling is in the accidentals, places like the solar vicinity which appear not to be part of OB association bubbles (though if you ask Priscilla Frisch, even that's in some dispute), but are sufficiently low in density that they can be reheated and enlarged by the occurrence of random supernovae within them. If such regions grow sufficiently large, their probability of repeated recharging is not small and they might in time grow to considerable heights above the plane. Or perhaps burbling is the wrong idea. Harold Weaver used to say that the whole solar neighborhood was violently disturbed by a huge event something like 20 Myr ago, if I remember correctly. I can't recall his reasons, but I would imagine that he might have expected that a large region of low density would be a natural corollary. In that case, the "Local Bubble" and "halo" gas might well be contiguous, part of the same large and severely distorted cavity, perhaps reheated in places by the accidental supernovae occurring within it.

4. HOT GAS AND STRUCTURAL MATTERS

So, with this survey of regions of hot gas and the physics involved in some of them, what can we now say about the spatial distributions of material in various states in the Galaxy? The states include H_2 clouds, cold H I, warm H I (some of which is likely associated with the cold H I "clouds" and some of which is likely diffuse), localized H II regions, diffuse warm H II gas (some of which is likely on some of the boundaries of the H I structures and some of which is likely truly diffuse), hot gas, and (maybe) vacuum (except for nonthermal components).

We can pretend we know roughly how the material we see in the cooler components is distributed, but we have to be careful even about that. Models for the heating/cooling balance in the H I regions generally conclude that there are two "phases", one at say 80 K with a density of say 30 cm^{-3}, and one with a temperature about 100 times higher and density 100 times lower, interpreted as the cold and warm H I components. Material with densities between these two is found to be thermally unstable and should not exist except as a transient. Such logic leads us to believe that if the average density in the cold H I is, say, 0.7 cm^{-3} then the cold H I

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

cannot occupy more than about 2 or 3% of the volume. Faced with that logic, how do we deal with the fact that on the periphery of the Cygnus Loop the preshock density varies between about 1 and 15 cm^{-3}? Or that for W44, it ranges from 3 to 10 cm^{-3}? Perhaps you know other regions where the measured density falls in the forbidden regime, regions not in the neighborhood of supernova remnants.

Taking that discrepancy as real, I rationalize it as a confusion over the idea that phases should have about the same pressures. The above logic is based on assuming they have the same thermal pressures. But the magnetic field pressure is several times larger, and can accommodate the full range of thermal pressures found for the intermediate densities with only slight expansion or contraction. If the analysis were redone isochorically rather than at constant thermal pressure, there is no forbidden density regime. But the equilibrium thermal pressures vary by perhaps a factor of 10, about the maximum range that can be accommodated by the magnetic field, and about the range, as I recall, found when measuring thermal pressures in clouds.

Whether you like that reasoning or not, it is quite likely that densities between 0.3 and 30 cm^{-3} are not that uncommon in the ISM, and even lower densities are perfectly acceptable, their thermal pressures just being more insignificant. And that means that we don't have a very good idea of the filling factors of the cold and warm H I components. (Our information is somewhat better for the warm ionized component, neglecting the fact that it probably arises also in a wide range of densities from cloud boundaries to the most diffuse intercloud gas. By measuring both the pulsar dispersions and the diffuse Hα, we sample both the mean density and the mean square density.)

What about hot regions, then? Well, there we know the ones we see. There seems to be an extensive bulge component that may or may not extend to overlie our part of the Galactic disk, that may or may not be a source of cooling clouds falling onto the Galactic plane, that may or may not provide an upper boundary condition on the outer disk. There is a Galactic ridge which I do not understand, very thin and hot, in the inner Galaxy. Then there are the superbubbles, the active ones of which are hot inside and are seen in X-rays. Some of them extend to great distances off the Galactic plane, others like the Sco-Cen bubble are not known to but might anyway. Their older counterparts could fill a significant fraction of some parts of the Galaxy, but may or may not be hot inside. There are supernova remnants, one of which suggests that we quit leaving themal conduction out of our models. There is the Local Bubble, or at least the local hot gas responsible for much of the soft X-ray background, that looks for all the world like a low density region which was reheated by a random supernova a few million years ago, and subsequently adjusted its properties via thermal conduction. And finally there is the halo emission, which has a variety of potential sources, my current favorite being nearby superbubbles peeking over the top of the local cavity.

Is there also something one might wish to call a pervasive phase of the hot ISM, not attributable to individual local events, something like the local hot gas but filling much of the low z disk? Or is it more prevalent in the thick disk, say between 200 and 1000 pc off the midplane? Or is such gas more common in the halo of the outer disk 1 to 5 kpc from the midplane? My answer to all these questions is maybe, but then again maybe not. If so, it's not much like any existing model except for perhaps that of Ferrière (1998). There are, however, very strong constraints on the possibilities that should be considered by anyone proposing such a phase. Be extremely careful with O VI. Unless *FUSE* substantially alters the picture, the tiny amount of O VI found in the Galactic midplane is very difficult to accommodate. Supernova remnants and superbubbles can easily provide it. It is a strong constraint on the mass transfer rate between cold and hot components and the pressure at which that occurs. There is also a constraint from M band, which can be seen to some distance if the gas is a little hotter than the Local Bubble. My recollection is that filling the Galactic plane with gas at 3 million Kelvins and standard interstellar pressure would provide about what is needed to keep the plane from showing up in absorption in this band (another puzzle). It might be just the collective emission from distant superbubbles, but then again it might not. In any case, gas hotter than that would radiate too little to be noticed and could be present in large quantities, so long as it does not thermally evaporate clouds at anywhere near the Cowie and McKee rate (violating the O VI constraint). My transparency also mentions an "incompleteness" constraint, but I can't now remember what that was about.

What about vacuum? Are there also large regions of negligible density that are not known to be hot? Well, there is the "region of bizarre emptiness" in the general direction of βCMa where the material census seems to come up short and yet the X-ray emission is not unusually high. There is the region around the Crab Nebula where the outer part of the ejecta has probably traveled about 10 pc and found nothing to run into yet. There are high latitude stellar absorption line studies for which the inferred column densities and local densities suggest that the observed material occupies only a minute fraction of the line of sight, leaving over a kiloparsec of apparent emptiness. In studies of shells and bubbles of other galaxies, the emptinesses are frequently not X-ray emissive. It appears that emptiness is not a possibility to discard lightly, even though it is very difficult to discern from very hot and diffuse.

One last thing. Dinshaw Balsara was at the meeting and spoke to me on several occasions after my talk, attempting to educate me with regard to turbulence, a word which I use as little as possible. He referred me to the talk by Vishniac (this volume) on fast recombination in turbulent plasmas, pointing out that when turbulence enhances one transport coefficient, it enhances them all. He said that I should not be embarrassed by finding that thermal conduction was large, that it too would likely take place at much more rapid rates than simple arguments on cross field quenching might suggest. I asked him about the temperature dependence—the classical rate having a coefficient proportional to $T^{5/2}$. I understood his response to mean that this temperature dependence, deriving from the mean free path of Coulomb collisions, would no longer be appropriate, being replaced in some sense by an effective mean free path introduced by the turbulence. Perhaps I have that wrong, but I will anyway confess that the results for both W44 and the Local Bubble modeling depend on having this strongly variable coefficient, at least when saturation is negligible. Ultimately, it is the parameter that determines how much mass the internal energy is shared with before cooling beats conduction at the outer, denser, cooler edge.

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