HOT GAS IN THE DISK, HALO, AND DISK-HALO INTERACTION

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ABSTRACT. The interstellar medium and its hot gas component are very different from common conception.

1. INTRODUCTION

For a wide variety of reasons it has seemed likely that hot gas might be common in the disk of the Galaxy (e.g. Cox and Smith, 1974), possibly in the form of a pervasive "coronal" phase (e.g. McKee and Ostriker, 1977). Similarly, hot gas might be expected in the galactic halo (e.g. Spitzer, 1956), possibly deriving from infall (e.g. Sciama, 1972), from a fountain rising out of the disk (e.g. Shapiro and Field, 1976), or from the blowout of OB association bubbles, or "chimneys" (see review by Tenorio-Tagle and Bodenheimer, 1988; Norman and Ikeuchi, 1989).

This paper presents a critical review of some of the evidence for such hot gas, and the corresponding disk-halo connection mechanisms.

2. THE SOFT X-RAY BACKGROUND

Attempts to understand the soft X-ray background led to early rejection of many source mechanisms, eventually leaving "thermal" emission of a "collisional" plasma at a temperature $T \approx 10^6$ K. (As yet we have no confirming spectra.) Comparison between simple models and the observed surface brightness suggest that a thermal pressure $p/k \approx 10^4$ cm^{-3} K and path ≈ 100 pc are sufficient (see McCammon et al., 1983; McCammon and Sanders 1990 for reviews).

The apparent observation that the Solar System is immersed in a large region of temperature 10^6 K was sufficient to suggest that gas of this temperature could be common is the interstellar medium (ISM) and led to consideration of supernova generation of the hot gas (Cox and Smith, 1974). Since this early work, however, much has been learned about details. These details have rather consistently shown that most of the X-rays observed below 1/4 keV arise in a single Local

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Bubble, nearer than N ~ 10^{19} cm^{-2} of absorbing material. This bubble corresponds to a local hole in the HI distribution and, to everyone's surprise and no one's satisfaction, much of the observed anticorrelation between the X-ray surface brightness and N_{HI} appears to derive not from absorption, but from the scale of the hole being comparable to that of the scale height of the narrow HI components (e.g. Snowden, et al. 1990).

Two points appear worth stressing. The origin of the Local Bubble is not well understood; several options have been discussed (e.g. Cox and Reynolds, 1987), but none are particularly satisfying. More relevant to this discussion, the soft X-ray background does not directly imply that 10^6 K gas is common in the ISM, only that it is present right around us. More particularly, there seem to be a few directions in which absorption is low for quite some distance, without the X-ray surface brightness being large in those directions.

The limit placed on X-ray emission from the galactic halo (or beyond) is rather severe: The total emission measure at 10^6 K is no greater than that in the Local Bubble, which is to say that over the 10 kpc scale of the galactic potential, no more emission is present than in the first ~ 100 pc. The net surface brightness has been estimated at $\lesssim$ 1% of the available supernova power.

The X-ray background is much less stringent in its restrictions on material at lower temperature (e.g. 3×10^5 K) or at higher temperature (e.g. 3×10^6 K). In fact, the slightly higher energy M band (~ 0.5 to 1 keV) is not yet understood. Away from bright features associated with specific bubbles, about half of the M band appears to derive from a combination of extragalactic and stellar sources, while the rest is sufficiently isotropic that it requires extra components from both inside and outside the Galaxy (c.f. McCammon and Sanders, 1990). The emission coefficient in this band would be highest at $T \simeq 3 \times 10^6$ K, but even at that temperature is sufficiently small that very high volume occupation of the plane would be possible at typical pressure estimates. A corresponding peculiarity is that even though dynamically significant amounts of very hot gas are allowed and possibly even suggested by the M band data, both in the disk and in the halo, the total radiated power of this material is again only of order 1% of the available supernova power. If there is widespread material at this temperature, the supernova energy deposited within it almost certainly is thermally conducted to colder regions where it is radiated, probably in the EUV. (Cox, 1986, argued that the alternative of a powerful galactic wind would shorten the cosmic ray escape time too severely.) The necessary conductivity is available, even if saturated, but would have to occur only on large scales; conduction to an embedded cloud population could lower the temperature as much as a factor of ~ 10, bringing on a McKee and Ostriker scenario.

In short, the soft X-ray background indicates that our own environment is 10^6 K gas, but that such gas may be unusual. Much of the medium energy X-ray background is unexplained and could be interpreted as indicating large amounts of 3×10^6 K gas in and around the Galaxy, though not radiating the available power. Models of the ISM with large filling factor of such high temperature gas are so far in very short supply, but would undoubtedly become very common if a spectrum of the low intensity M band were to indicate a diffuse thermal origin. (The only example I know of so far is a picture explored by Sanders, et al., 1983.)

2. X-RAY OBSERVATIONS OF OTHER GALAXIES

The halo of our galaxy is radiating less than about 1% of the available supernova power at temperatures of 1-3 × 10^6 K. Similar limits have been placed on the emission from two edge-on spirals (NGC 3628 and 4244 by Bregman and Glassgold 1982) and the face-on M101 (McCammon and Sanders, 1984). In the latter galaxy, at least, there is no shortage of evidence for supernovae, OB associations, and large holes in the ISM. Evidently such activity at a moderate rate does not lead to a halo or fountain radiating the supernova power at high temperature.

As in the Galaxy, this probably does not rule out the presence of a dynamically significant amount of very hot gas, but requires that energy dissipation occur at lower temperatures.

3. HIGH IONIZATION STAGES IN THE DISK

High ionization stages have been found in UV absorption studies of the ISM. The mean densities have been estimated to be:

$\bar{n}(\mathrm{O\ VI}) \sim 2.8 \times 10^{-8}\ \mathrm{cm}^{-3}$
$\bar{n}(\mathrm{N\ V}) \sim 3 \times 10^{-9}\ \mathrm{cm}^{-3}$
$\bar{n}(\mathrm{C\ IV}) \sim 7 \times 10^{-9}\ \mathrm{cm}^{-3}$
$\bar{n}(\mathrm{Si\ IV}) \sim 2 \times 10^{-9}\ \mathrm{cm}^{-3}$

(Jenkins, 1978 for O VI, Savage and Massa, 1987). These ions are thought to indicate the presence of gas with $T \sim 10^5$ to 3×10^5K rather commonly in the lower disk, although the actual volume filling factor of the required gas is low (~ 1%).

Historically, these ions have been used extensively as evidence for the presence of substantial amounts of hot gas in interstellar space, the ions arising in boundary layers with cooler gas (e.g. McKee and Ostriker, 1977). The fact is that the ions also place constraints on the amount of hot gas present. For example, if the hot gas temperature were typically ~ 3 × 10^5 K occupying most of interstellar space, the implied O VI density contributed by the hot gas itself is one to two orders of magnitude higher than the observations. (This problem disappears at $T \gtrsim 10^6$ K where the oxygen is more highly ionized.) Thus it has long been common practice to suppose that turbulence in the hot gas hides the large intrinsic component of O VI, making the line too broad for the Copernicus satellite to have seen it and leaving only the weak boundary regions visible.

Recently, however, Slavin and Cox (1990) and Cox and Slavin (1990) have proposed an alternate source for these ions. By showing that supernova disruption of the interstellar warm gas was previously overestimated by roughly a factor of 30, they conclude that it is reasonable to investigate the long term evolution of SNR generated bubbles in an environment with typical intercloud density $n \sim 0.2\ \mathrm{cm}^{-3}$. Including a significant nonthermal pressure term, corresponding to $B \approx 5\mu G$, they find remnants disturb the medium very little, creating bubbles of fairly hot gas ($\sim 4 \times 10^5$ K) lasting roughly 5×10^6 years. The collection of these bubbles is found to provide the observed mean densities of O VI, N V, and C IV (and maybe Si IV as well when photoionization is included), while occupying only about 10% of interstellar space.

With this model, the high ions in the disk no longer constitute strong evidence for there being a pervasive distribution of hot gas occupying most of interstellar space. A modest occupation by isolated bubbles is entirely sufficient.

(The reasons for the earlier overestimate of the porosity are that: a high SN rate was assumed, SNR bubble evolution was approximated to be adiabatic between shell formation and pressure equilibration with the surroundings -- a faulty assumption dating back to Cox, 1972 -- and the high interstellar pressure was represented only by its nearly inconsequential thermal component.)

4. HIGH ION STAGES IN THE HALO

Savage and Massa (1987) have estimated the scale height of the high ions to be roughly 3 kpc, a number which depends somewhat on whether the distribution at high z is directly related to the ions found in the plane. There has been some indication, in fact, that the high ion density has a rather sudden increase a few hundred parsecs off the plane. The evidence for the latter is controversial (see Savage, this volume) but it remains distinctly possible that much of the ion content in the plane has a separate origin from that found at high z.

Apart from the M band possibilities, the high ions found both in absorption and emission (again, Savage, this volume for review and references) at high z are the only direct evidence we have that there is high temperature gas in the halo. And once again, the total amount of that observed hot gas is small (Savage quotes a 3% filling factor in the 3 kpc path, for total of 100 pc along an average sight line out of the Galaxy.) Only if there are much larger amounts of much higher temperature gas is this material dynamically interesting.

In contrast to the X-ray results, however, the limited information we presently have on C IV emission (from Martin and Bowyer, 1990) implies that it is possible that this small quantity of fairly hot gas could be radiating at a rate comparable to the SNR input power in the disk. (An alternative not yet fully explored is that a significant amount of the C IV emission derives from the boundary of the Local Bubble or a few SNR bubbles along the line of sight.)

5. IMPLICATIONS OF THE THICK DISK

Evidence reviewed elsewhere (e.g. Boulares and Cox, 1990, Cox and Slavin 1990, Lockman, this volume, Reynolds, this volume) indicates that it is inappropriate to think of the disk of the Galaxy having a scale height of roughly 100 pc, beyond which lies the halo. Instead, measurements of neutral and ionized gas, cosmic rays, and magnetic field all show that the Galaxy has a much thicker disk, reaching to roughly 2 kpc above the plane. Within this thick disk, the dense cloud population is like a condensate, low in the gravitational potential.

By evaluating the weight of the material in the disk, one learns that the midplane pressure has been seriously underestimated. The value implied (Boulares and Cox find $p/k \gtrsim 25{,}000\ \mathrm{cm}^{-3}\ \mathrm{K}$) is roughly consistent with recent upward trends in measurements of the interstellar magnetic field, the cosmic ray pressure, and the dynamical pressure of the warm HI.

This change in perspective has severe consequences for the evolution of large bubbles blown by OB associations. They continue to encounter appreciable matter densities a few hundred parsecs off midplane, and substantial pressures for a much greater distance beyond that. The smaller of these bubbles should be even smaller than previously calculated, while the larger ones will avoid breakout and could grow to larger size holes in the plane. In addition, the shells will be less compressed, owing to the large magnetic pressure, and will rebound sooner to erase the HI evidence for the bubble's having been there. A pioneering numerical model showing some of these effects is presented by Tomisaka in this volume.

Having an ISM disk whose scale height (for the warm components) is greater than the (probable) scale height for diffuse supernova explosions (i.e. those not clustered in OB associations) also alters one's thinking on whether supernova generation of diffuse hot gas can sustain low density channels through the disk to the halo. Hence, both common types of fountain models (general disk source, superbubble blowout source) are made much less likely by the presence of this thick disk.

6. DISCUSSION

It is possible that within the lower disk, hot gas is found primarily in individual bubbles generated by supernovae and in the larger but confined collective bubbles generated by OB associations. Estimates suggest these two types occupy ≈ 10% and ~ 20% respectively of the midplane volume in the Solar neighborhood. That gas alone is sufficient to explain the high ion content of the midplane, and is consistent with the constraints implied by the soft x-ray background.

In this picture it is unlikely that either of the popular types of galactic fountain actually occurs, consistent with the weak halo emission in X-rays. For that reason an alternative source is needed for the high ion stages found in the outer parts and boundary of the thick disk. Two such alternatives that appeal to me rely on local high z energy dissipation in a "chromospheric" layer on the outer boundary of disk (Sciama, 1972; Hartquist 1983). The energy could be carried to that regime by thermal conduction from a much hotter halo, by large amplitude Alfven waves in the warm disk, or possibly even by thermal conduction along hot channels following flux tubes out of the lower disk.

In any case, nothing is so certain as we might like to have believed. The thick disk and its high pressure complicate all fountain/chimney models enormously. There is no airtight evidence for a quasicontinuous distribution of hot gas in the disk. My best guess at present for the high z high stage ions is that they arise from shocks in a region where nonlinear Alfven waves produce highly supersonic motions. Yet, at the same time that I am suggesting that most hot gas evidence can be explained in terms of discrete events rather than global behavior, I have a wary eye on the M band map and the nearly unexplored possibilites of the transmegakelvin regime.

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