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# CONSEQUENCES OF A NEW HOT COMPONENT OF THE INTERSTELLAR MEDIUM

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## ABSTRACT

The suggestion that the observed 0.25 keV X-ray background and O VI absorption lines are produced by a new, hot ($T \sim 10^6$ K), diffuse component of the interstellar medium is examined in the context of both a steady-state and a time-dependent model. It is concluded that such a component can explain the two observations only if (1) the pressure of the cooler interstellar medium is $\sim$10 times higher than the previously estimated $p/k \approx 2000\ \mathrm{cm^{-3}\ K}$; (2) a mechanism such as the proposed convective-radiative "galactic fountain" exists to cool the hot gas; and (3) another component is responsible for the presence of O VI at temperatures below $10^6$ K.

*Subject headings:* interstellar: matter — X-rays: general

## I. INTRODUCTION

It has been suggested that the diffuse galactic soft X-ray background at 0.25 keV (SXR) originates in a hot ($T \sim 10^6$ K), low-density gas occupying as much as half of the volume of the galactic disk (Kraushaar 1973; Cox and Smith 1974; Williamson *et al.* 1974; Bunner 1974). Dramatic evidence of the existence of hot galactic gas is presented by the O VI absorption lines observed by *Copernicus* (York 1974; Jenkins and Meloy 1974; Rogerson *et al.* 1973). The proposal has been made that both SXR and O VI are caused by a single hot, diffuse component of the interstellar medium (Cox and Smith 1974; Jenkins and Meloy 1974; Williamson *et al.* 1974; Bunner 1974). We examine the implications of this proposal, within the context of a steady-state model in § II and of a time-dependent model in § III. Our conclusions are summarized in § IV.

## II. STEADY-STATE MODEL

When averaged over many lines of sight, the mean density of O VI is

$$\langle n(\mathrm{O\ VI})\rangle = 1.7 \times 10^{-8}\ \mathrm{cm^{-3}} = A \tag{1}$$

(Jenkins and Meloy 1974). If one adopts an opacity of 5 kpc$^{-1}$ at 44–70 Å wavelengths, the intensity of SXR in the galactic plane implies that

$$\langle n_e^2\rangle \Lambda^* = 7.5 \times 10^{-28}\ \mathrm{ergs\ cm^{-3}\ s^{-1}} = B\,, \tag{2}$$

where $\Lambda^*(T)$ is the emissivity between 44 and 70 Å (Silk 1973).

Let us consider the hot component proposed by Cox and Smith. If it fills a fraction $f$ of the volume of the disk, and has a temperature $T$, then one can compute its electron density $n_e$ and the associated pressure $p = 2n_e kT$ in terms of the steady-state ionized fraction

$$i(T) \equiv n(\mathrm{O\ VI})/n(\mathrm{O}) \tag{3}$$

and emissivity $\Lambda^*(T)$. Equations (1) and (2) imply that

$$n_e = \xi Bi/A\Lambda^* = 3.0 \times 10^{-23} i/\Lambda^*\ \mathrm{cm^{-3}} \tag{4}$$

and

$$f = A^2\Lambda^*/\xi^2 Bi^2 = 8.3 \times 10^{17}\Lambda^*/i^2\,, \tag{5}$$

where $\xi = 6.8 \times 10^{-4}$ is the cosmic abundance of oxygen (Cameron 1973).

Values of $i(T)$ and $\Lambda^*(T)$ have been calculated for a gas in ionization equilibrium by Shapiro and Moore (1976) using the X-ray line data of Tucker and Koren (1971) and the cosmic abundances of Cameron (1973); results are shown in Table 1.

TABLE 1

IONIZATION EQUILIBRIUM VALUES OF O VI IONIZED FRACTION, EMISSIVITY IN THE RANGE 44–70 Å, AND RADIATIVE COOLING TIME*

| $\log T$ (K) | $\dfrac{n(\mathrm{O\ VI})}{n(\mathrm{O})}$ | $\Lambda^* \times 10^{23}$ (ergs cm$^3$ s$^{-1}$) | $t_c n_0 \times 10^{-5}$† (yr cm$^{-3}$) |
|---|---|---|---|
| 6.3 ....... | 0.0018 | 1.5 | 3.9 |
| 6.2 ....... | 0.0030 | 1.7 | 2.6 |
| 6.1 ....... | 0.0042 | 1.8 | 1.8 |
| 6.0 ....... | 0.0062 | 1.4 | 1.4 |
| 5.9 ....... | 0.011 | 0.82 | 1.1 |
| 5.8 ....... | 0.024 | 0.33 | 0.68 |
| 5.7 ....... | 0.058 | 0.088 | 0.46 |
| 5.6 ....... | 0.15 | 0.020 | 0.27 |
| 5.5 ....... | 0.26 | 0.0044 | 0.1 |
| 5.4 ....... | 0.12 | 0.0007 | 0.055 |

* Shapiro and Moore 1976.
† $n_0 \equiv n_{\mathrm{H}} + n_{\mathrm{He}}$.

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Using these values of $i(T)$ and $\Lambda^*(T)$ with equations (4) and (5), we calculated the values of $n_e$, $p$, and $f$ required to satisfy the observations; $p$ is plotted against temperature in Figure 1. There is a sharp peak in $p$ (and $n_e$) which reflects the peak in $i(T)$ at $3 \times 10^5$ K.

For all physically admissible values of $f$ ($<1$), the required pressure exceeds its value at $T = 10^{6.1}$ K, $p/k = 10^{4.2}$ cm$^{-3}$ K. Temperature upper limits for the O VI regions, derived from O VI line widths, indicate that a substantial fraction of the O VI is at $T$ below $10^6$ K (Jenkins and Meloy 1974; York 1974). The required pressure indicated by Figure 1 for a gas at $10^{6.1}$ K is thus a lower limit to the actual required pressures.

Such pressures substantially exceed those in diffuse clouds and in the intercloud medium discussed in the literature. Field (1975) has summarized the observations suggesting that $p/k \approx 10^{3.3}$ cm$^{-3}$ K. If the hot gas is in nearly a steady state, one must assume that it is in pressure equilibrium with the cooler gas. The question therefore arises whether previous estimates of the pressure of cool interstellar gas are in error.

The densities of diffuse clouds are obtained by dividing observed 21 cm column densities by estimated line-of-sight cloud thicknesses, assumed to be comparable to transverse cloud dimensions. In fact, there is evidence that interstellar clouds are sheetlike (McKee and Cowie 1975; Heiles 1974); one can show that the density and hence pressure in clouds can be increased by the required factor of 10 if such sheets are more than an order of magnitude larger in one dimension than the other. In this case, the hydrogen density would approach 300 cm$^{-3}$, and the density of carbon, 0.1 cm$^{-3}$. If carbon is undepleted, free electrons derived from it could then explain the relatively high values of $n_e$ inferred from the ionization equilibrium of calcium and other elements (see Field 1975), rather than such electrons being derived from the cosmic-ray ionization of hydrogen.

In the conventional two-phase model, the wide, low-intensity wings of 21 cm emission lines are interpreted as an intercloud medium with $T \approx 7000$ K and $n \approx 0.3$ cm$^{-3}$. Such an intercloud medium could not be in pressure equilibrium with the hot component under discussion here, because its pressure, $p/k \approx 10^{3.3}$ cm$^{-3}$ K, is an order of magnitude lower than that of the hot component. However, Greisen (1973$a$, $b$) has proposed that the wide emission lines can be explained in another way, as the superposition of emission of larger numbers of small dense clouds moving with high velocity. This model would not require a low-pressure intercloud medium.

If the assumption of a steady state for the hot gas is correct, then some mechanism must cool the hot gas, as it gets reheated every $t_h \sim 10^6$ years by supernova remnant shock waves in the disk (Cox and Smith 1974). For an adopted temperature of $10^6$ K, equations (4) and (5) give $n_e = 0.01$ cm$^{-3}$ and $f = 0.4$. From Table 1, the corresponding radiative cooling time is $t_c \sim 10^7$ years, so that radiative cooling is ineffective

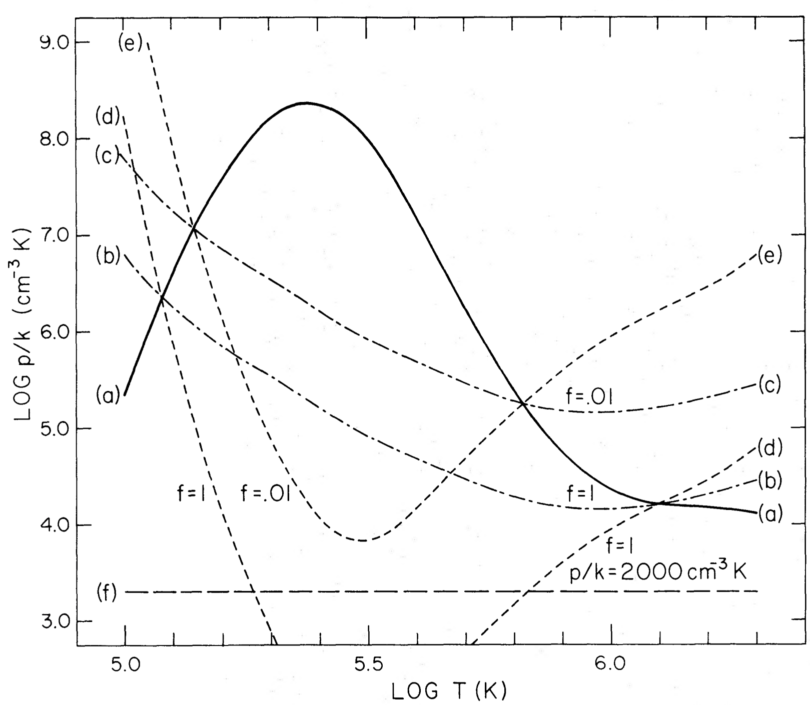


FIG. 1.—($a$) Pressure which satisfies requirement that interstellar gas in ionization equilibrium at temperature $T$ explain both SXR flux and O VI column density. ($b$) Pressure required to produce SXR flux with $f = 1$. ($c$) Same as ($b$), but with $f = 0.01$. ($d$) Pressure required to produce O VI column density with $f = 1$. ($e$) Same as ($d$), but with $f = 0.01$. ($f$) Previously estimated interstellar pressure. Region below either curve ($b$) or ($d$) is unphysical since $f > 1$. Region above ($f$) is overpressured compared to $p/k = 2000$ cm$^{-3}$ K.

in the time between reheating. We have shown elsewhere (Cowie, Shapiro, and Field 1976) that thermal conduction into cool gas is also inadequate to cool the hot gas. This leaves convection.

In the absence of external pressure, the hot gas will stream upward around and through the cool gas in the disk. If the rising gas were not to radiate, it would reach great heights, exerting a pressure on the gas beneath and forming a corona in hydrostatic equilibrium, with a scale height $H = 7500$ pc (Spitzer 1956). In the present case, however, radiation *is* effective, and cool clouds will form at a height $z_c \approx |v_z|t_c$, which, for $|v_z| \leq$ sound speed $c$ $(=170 \text{ km s}^{-1})$, is $\leq 10^3$ pc. Since $z_c \ll H$, the gas streaming will occur at $|v_z| \approx c$, and, thus, $z_c \approx 10^3$ pc. Beyond $z_c$ ballistic motion of the clouds will ensue, gravitation bringing them back to $z_c$ with $v_z \approx -c$. The velocities and heights of this cool gas are reminiscent of high-velocity clouds (HVC), and we tentatively identify them as such.

According to Oort (1970) the mass flux in HVC to both sides of the Galaxy is $\sim 40\ M_\odot\ \text{yr}^{-1}$. As the mass of hot gas in the disk is $\sim 2 \times 10^7\ M_\odot$, an upward flux of hot gas equal to the observed downward flux of HVC will suffice to convect the hot gas out of the disk in $t_h \lesssim 10^6$ years, as required. The mass flux of cool clouds predicted by the steady-state "galactic fountain" described here would be roughly $2\pi R^2 v_z nmf$, where the disk radius $R = 15$ kpc, and $m$, $f$, and $n$ are the mass, filling factor, and density of the streaming gas, respectively. For the parameters adopted here, with $v_z = 170 \text{ km s}^{-1}$, this flux is $\sim 30\ M_\odot\ \text{yr}^{-1}$, in good agreement with observation.

The layer of rising hot gas in this "galactic fountain" is expected to extend to $\sim 10^3$ pc on either side of the plane so that, in the absence of absorption, the SXR intensity at the poles should be 5 times that in the galactic plane (where the observable line of sight is $L = 200$ pc). In fact, H I, and hence absorption, is present, so the intensity should be lower. In units of the intensity in the plane the observed intensity at the North Galactic Pole is $\sim 3$ (Silk 1973) and at the South Galactic Pole is $\sim 1$ (Williamson *et al.* 1974).

## III. TIME-DEPENDENT MODEL

The steady-state model discussed above does not explain the fact that much of the O VI is produced by gas with $T$ below $10^6$ K. Jenkins and Meloy (1974) derived upper limits to $T$ from the widths of the O VI lines. They find that $T < 10^6$ K in $\sim 75$ percent of the cases, $T < 5 \times 10^5$ K in $\sim 30$ percent of the cases, and $T < 2 \times 10^5$ K in $\sim 8$ percent of the cases. (Even the X-ray observations have been interpreted as indicating a range of temperatures below $10^6$ K [Williamson *et al.* 1974].) From Figure 1 one sees that extremely high pressures would be required to account for the O VI and SXR at such temperatures within the context of a steady-state model.

For a gas at the corresponding densities, Table 1 indicates that $t_c$ is no longer large compared to the mean reheating time of $10^6$ years. Moreover, from a different point of view, Table 1 indicates that $t_c < t_h$ for the radiative phase of individual supernova remnants occurring in an ambient intercloud gas of density $n \geq 0.1 \text{ cm}^{-3}$. We therefore undertook calculations of a time-dependent model to determine what effect the radiative cooling of the gas would have on the values of $i(T)$ and $\Lambda^*(T)$, and on the corresponding solution to the O VI–SXR problem.

We calculated $i(T)$ and $\Lambda^*(T)$ in a gas which is allowed to cool radiatively at constant density from $10^6$ K to $10^4$ K. The details will be published elsewhere (Shapiro and Moore 1976). The values of $i(T)$ and $\Lambda^*(T)$ averaged over time were

$$\langle i \rangle = 3.4 \times 10^{-2} \tag{6}$$

and

$$\langle \Lambda^* \rangle = 4.9 \times 10^{-24} \text{ ergs cm}^3 \text{ s}^{-1}\,. \tag{7}$$

From Table 1 we see that both of these values correspond to the same equivalent steady-state temperature, $T \approx 10^{5.8}$ K, the cooling being so rapid below that temperature that the low-temperature phases do not contribute. From equations (4), (5), (6), and (7), we find that the required density is $n_e = 0.2 \text{ cm}^{-3}$, corresponding to an initial pressure of $10^{5.6} \text{ cm}^{-3}$ K and a filling factor $f = 0.004$. We conclude that time-dependent radiative cooling does not vitiate our conclusion that high pressures are required. However, a pressure of $10^{5.6} \text{ cm}^{-3}$ K is too high to be reconciled with an assumption of pressure equilibrium with the cooler gas.

Without pressure balance, such a high-pressure hot gas will expand adiabatically on a time scale short compared to $t_c$. In this case, the cooling is no longer isochoric. If the gas expands adiabatically, it will spend almost no time in the temperature domain in which 0.25 keV X-rays are emitted, compared to the time spent in pressure balance at lower temperatures. Hence, such a gas cannot account for *both* the O VI and SXR. However, it is possible that such a gas could account separately for the narrower O VI lines (and perhaps the X-rays observed at energies below 0.25 keV) while the model described in § II accounts for the SXR and the O VI with $T \gtrsim 10^6$ K.

## IV. CONCLUSION

A steady-state model of the hot component such as that of Cox and Smith (1974) can explain the SXR and hot ($T \gtrsim 10^6$ K) O VI only if the pressure is $\sim 10$ times higher than that previously estimated for the cool components of the interstellar medium. It is possible that the latter has in fact been considerably underestimated. Neither conduction nor radiation in the disk can suitably cool the hot gas, but convection away from the disk followed by radiation may be able to. We therefore tentatively suggest a "galactic fountain" model in which the hot gas rises about 1 kpc before cooling and condensing to form clouds, which fall to the plane at $\sim 100 \text{ km s}^{-1}$. Such a "galactic fountain" may provide an interpretation of high-velocity clouds and of the SXR from the North Galactic Pole.

The steady-state model fails, however, to explain the narrow O VI lines seen in a number of cases. A time-dependent model was calculated as the more appropriate one to account for the narrow lines as well. The pressures required by this model are so large as to make pressure equilibrium with the cooler gas inconceivable. Without pressure equilibrium, such hot gas will expand quickly, cooling adiabatically. Perhaps such a gas can separately explain the O VI observed to be at temperatures below $10^6$ K. No single component of the interstellar gas, however, can simultaneously explain the O VI at all temperatures observed as well as the SXR. It should be noted that Castor, McCray, and Weaver (1975) have proposed a model which explains the O VI observations without reference to the SXR observations. The presence of low-temperature O VI is a natural consequence of this model.

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