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HIGHLY IONIZED ATOMS IN COOLING GAS

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ABSTRACT

We have calculated the ionization of low density gas cooling from a high temperature, ($\gtrsim 10^6$ K). The evolution during the cooling is assumed to be isochoric, isobaric, or a combination of these cases. The calculations are used to predict the column densities and ultraviolet line luminosities of highly ionized atoms in cooling gas. In a model for cooling of a hot Galactic corona, it is shown that the observed value of N(N V) can be produced in the cooling gas, while the predicted value of N(Si IV) falls short of the observed value by a factor of about 5. The same model predicts fluxes of ultraviolet emission lines that are a factor of 10 lower than the claimed detections of Feldman, Brune, and Henry. Predictions are made for ultraviolet lines in cooling flows in early-type galaxies and clusters of galaxies. It is shown that the column densities of interest vary over a fairly narrow range, while the emission line luminosities are simply proportional to the mass inflow rate.

IONIZED GASES
GAS IONIZATION
" COOLING
LINE SPECTRA
GALACTIC EVOLUTION
ULTRAVIOLET SPECTRA

ISOCHORIC PROCESSES
ISOBARS (PRESSURE)
STELLAR CORONA
S " LUMINOSITY
GAS DENSITY
GALAXIES

I. INTRODUCTION

In the past 15 years, it has become clear that hot gas ($T \gtrsim 10^6$ K) is a significant component of the volume of the universe, including the space within and between galaxies. In many cases, cooling of the gas is expected; these cases include gas in the galactic halo (Shapiro and Field 1976; Chevalier and Oegerle 1979), in spiral galaxies, in early-type galaxies (Forman, Jones, and Tucker 1985), and in clusters of galaxies (Fabian, Nulsen, and Canizares 1984). When the gas cools through the temperature range of about $3 \times 10^4 - 3 \times 10^5$ K, ions are present which can give strong ultraviolet lines (Savage 1984). Since the gas cools relatively rapidly through this temperature regime, thermal equilibrium is unlikely so that time-dependent ionization must be taken into account in making predictions for the ultraviolet lines.

In this paper, we present calculations of the column densities of ions and line emissivities from cooling gas. The calculations treat the isochoric (constant density), isobaric (constant pressure), and intermediate cases. The results are compared with observations of galactic gas and predictions are made for cooling gas in galaxies and clusters of galaxies.

II. CALCULATIONS

We find the column densities of various observable ions in cooling gas. We assume that the cooling is steady and can be characterized by a cooling column density of H atoms per unit time, $\dot{N}_H$, and an initial H density, n_o. We also assume that the cooling process is isobaric, isochoric, or is initially isobaric with a transition to isochoric. This should cover the likely range of pressure evolution, unless there is strong evolution due to hydrodynamic flow. We assume that heat conduction can be neglected. Under these assumptions, the column density of an ion Z^i of element Z produced between temperatures T_{min} and T_{max} is

$$N_{Z^i} = k \frac{\dot{N}_H}{n_o} \left(\frac{n_Z}{n_H}\right) \int_{T_{min}}^{T_{max}} \left(\frac{3}{2} + s\right) \frac{\chi}{\chi_e} \frac{f_i \, dT}{(n/n_o)\Lambda} \tag{1}$$

where k is the Boltzmann constant, n_Z/n_H is the abundance of the element relative to hydrogen, s is 1 for isobaric and 0 for isochoric evolution, χ is the number of particles per H atom, χ_e is the number of electrons per H atom, $f_i = n_{Z^i}/n_Z$, n is the H density in the evolving gas, and Λ is the radiative cooling function, such that $\Lambda \, n_H n_e$ is the energy loss rate per unit volume. The solution of equation (1), especially through Λ and f_i, requires the calculation of the ionization of a number of elements in a cooling gas. A separate calculation for each type of pressure/density evolution is required. Kafatos (1973) and Shapiro and Moore (1976) have performed such calculations for an isochorically cooling gas. The calculations here are similar except we use a variety of pressure evolutions and use the atomic data of Raymond and Smith (1977), updated by Raymond and Smith (1984). The elements included are H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni, with abundances from Allen (1973). The results for isochoric cooling beginning at a temperature of 10^6 K were compared to those of Shapiro and Moore (1976). The cooling function Λ was similar in the two cases. The major differences occurred in the ionized fractions at low temperatures ($T \lesssim 3 \times 10^4$ K). These differences are probably due to differences in the input atomic physics. In our calculation, the isobaric function $\Lambda(T)$ was found to be close to the isochoric function.

The ions of interest here have non-negligible values of f_i in the temperature range 10^4 - 10^6 K. We found that a cooling gas with $T \gtrsim 10^6$ K initially remains in approximate ionization equilibrium until the temperature drops to about 10^6 K. We also found that the time to reach ionization equilibrium at $T \gtrsim 10^6$ K for an initially underionized gas is shorter than the cooling time of the hot gas. Our calculations therefore have $T_{max} = 10^6$ K and $T_{min} = 10^4$ K, and assume equilibrium ionization at T_{max}. The initial density is not important for the ionization calculations because two body processes dominate both the ionization and recombination in the regime of interest so that the density scales out of the problem. The remaining parameter in equation (1) is $(\dot{N}_H/n_o)$. Column densities of selected ions are given in Table 1 for $\dot{N}_H/n_o = 10^7$ cm s^{-1}. The results can be scaled to other values for this quantity. The ions have been chosen because they have strong ultraviolet resonance lines (e.g. Savage 1984). They are C IV $\lambda\lambda$1550.8, 1548.2; Si IV $\lambda\lambda$1402.8, 1393.8; N V $\lambda\lambda$1242.8, 1238.8; S IV λ1062.7; O VI $\lambda\lambda$1037.6, 1031.9; and S VI $\lambda\lambda$944.5, 933.4. The quantity T_{tr} is the temperature at which a transition is made from isobaric ($T > T_{tr}$) to isochoric ($T < T_{tr}$) evolution. The last line in Table 1 gives column densities that would be obtained using ionization equilibrium values for f_i and Λ, and assuming isobaric evolution.

The column densities for higher ion stages (O VI and N V among those quoted here) depend to some extent on the choice of T_{max}. In these cases f_i is small but not negligible at 10^6 K, so that changing T_{max} to a value $\gtrsim 3 \times 10^6$ K (where the f_i are negligible) can increase the column densities by factors of 2.2 (for O VI) and 1.6 (for N V).

The time-dependent case leads to the persistence of highly ionized species to lower temperatures than would be expected from equilibrium calculations. This is particularly true of Li-like species (e.g. C IV, N V, and O VI) as the He-like ion stages recombine especially slowly. It can also be seen that the isobaric case gives lower column densities than the isochoric case. This is related to the property that $n \propto 1/T$ during isobaric evolution, which increases the (n/n_o) factor in equation (1). This effect is largest for ions formed at low temperatures. It can be seen from Table 1 that the differences are larger for the lower ionization stages.

The choices of the parameter T_{tr} correspond to a selection of physical distance scales. If a region which has diameter D at $T = 10^6$ K is cooling from high temperatures, it will remain roughly isobaric until the cooling time becomes shorter than the sound crossing time. The transition temperature T_{tr} is the temperature at which this equality holds. For $T_{tr} = 4.7 \times 10^5$ K, we find that $D \sim 2.8\ n_{o-3}^{-1}$ kpc, while for $T_{tr} = 2.2 \times 10^5$ K, the appropriate value is $D \sim 200\ n_{o-3}^{-1}$ pc. where n_{o-3} represents the initial H density in units of 10^{-3} cm^{-3}. The distance scale D varies quickly with the transition temperature, $[D \propto T_{tr}^{13/6}/\Lambda(T)]$ so transition temperatures of a few $\times 10^5$ K will be appropriate for many distance scales in an astrophysical context. For larger cooling regions, pure isochoric flow will be applicable, while for smaller ones, pure isobaric cooling will apply.

In a similar way, we can calculate the strengths of emission lines that should be seen from these cooling plasmas. We find

$$L_{line} = k \frac{\dot{M}}{\mu m_H} \left(\frac{n_Z}{n_H}\right) \int_{T_{min}}^{T_{max}} \left(\frac{3}{2} + s\right) \chi \frac{f_i j_{line} dT}{\Lambda} \qquad (2)$$

where j_{line} is the line emissivity (in erg cm^{-3} s^{-1}), and L_{line} the emission line luminosity (in units of erg s^{-1}). Table 2 lists luminosities from various strong ultraviolet lines which we have calculated for both the isochoric and isobaric cases. Since these in general vary by less than a factor of two, the intermediate cases are not shown in the table. The values are normalized to $\dot{M}$ = 1 $M_{\odot}$ yr^{-1} and T_{min} and T_{max} are 10^4 K and 10^6 K, respectively.

III. APPLICATIONS

i) The Galaxy

Chevalier and Oegerle (1979) considered a model for the Galactic corona in which approximately 4 $M_{\odot}$ yr^{-1} is circulated on each side of the galactic plane and the typical H density is 10^{-3} cm^{-3}. Another estimate of $\dot{M}$ can be obtained by assuming that supernova remnants evolve as adiabatic blast waves in a uniform medium. Then

$$\dot{M} = 23 \left(\frac{\tau}{40\ yr}\right)^{-1} \left(\frac{E}{10^{51}\ erg}\right) \left(\frac{T_1}{10^6\ K}\right)^{-1} M_{\odot}\ yr^{-1} \qquad (3)$$

is the rate at which mass is heated above temperature T_1, where τ is the time between supernovae and E is the energy per supernova. If the supernova energy is eventually radiated, this gives an estimate of the mass cooling rate.

If we take $\dot{M}$ = 4 $M_{\odot}$ yr^{-1} on one side of the plane, $n_o = 10^{-3}$ cm^{-3} and the area of the Galaxy to be πR^2 with R = 15 kpc, then $\dot{N}_H/n_o \sim 1.6 \times 10^7$ cm s^{-1}. The relevant rows of Table 1 are the $T_{tr} = 2.2 \times 10^5$ K and $T_{tr} = 4.7 \times 10^5$ K ones, depending on the sizes of the cooling regions. The column densities in Table 1 must be multiplied by 1.6 to obtain the predicted column densities for the Galactic corona. The accuracy of this scaling factor is no better than a factor of 2; the accuracy within a row depends on uncertainties in the atomic physics and in the elemental abundances.

The model column densities are thus N(C IV) = (4.3-7.9) × 10^{13} cm^{-2}, N(O VI) = (5.8-6.0) × 10^{14} cm^{-2}, N(N V) = (2.8-3.6) × 10^{13} cm^{-2}, and N(Si IV) = (3.3-6.4) × 10^{12} cm^{-2}. Observed values perpendicular to the galactic plane are N(C IV) = 10^{14} cm^{-2}, N(N V) = 3 × 10^{13} cm^{-2}, and N(Si IV) = 2.5 × 10^{13} cm^{-2} (Pettini and West 1982; Savage and Massa 1985). The cooling model predicts value for N(N V) that is in excellent agreement with the observations. In contrast, photoionization model values for N(N V) typically fall short of the observed values by about an order of magnitude (e.g. Fransson and Chevalier 1985). On the other hand, photoionization models predict the observed amount of Si IV while the cooling model underproduces Si IV by almost an order of magnitude. C IV can be produced in substantial quantity in either model, although the cooling model value may fall short of the observed value.

As expected, the cooling model predicts a substantial column density of O VI. There are no data on O VI in the halo, but it has been observed locally in the disk with a column density through the disk of about 2 × 10^{13} cm^{-2} (Jenkins 1978). This column density is considerably smaller than the model value obtained here; column densities of C IV and Si IV through the disk (Savage 1984) are also smaller than our model values. This may imply that supernova heated gas does not cool in the galactic disk (see also Cox 1981). Another possibility is that the cooling occurs under high pressure conditions so that n_o for the cooling gas is high. For example, if supernova remnants expand into gas with hydrogen density of about 0.2 cm^{-3}, the shocked gas would have a density close to 1 cm^{-3}, and the column densities would be correspondingly decreased.

Feldman, Brune, and Henry (1981) claim to have detected ultraviolet emission lines from the interstellar medium. They find fluxes of 9500 ± 3500 (Si IV λ1397 + O IV] λ1406), 10,000 ± 4000 (N IV λ1488), 8000 ± 3000 (C IV λ1549), and 17,000 ± 4000 (O III λ1663) in units of photons cm^{-2} s^{-1} sr^{-1}. In the cooling model discussed above, C IV λ1549 (summing both members of the doublet) is the strongest line in the wavelength region of interest and it has a predicted flux of 890 photons cm^{-2} s^{-1} sr^{-1} for isobaric evolution (see Table 2). This is an order of magnitude smaller than the claimed observation and, while there may be ways of increasing the prediction, it is necessary not to violate the limit on N(C IV). Another problem with the claimed detections is that N IV λ1488 is observed to be comparable in strength to C IV λ1549, while it is predicted to be considerably weaker. Thus, while models for the ultraviolet emission lines can be found (e.g. Paresce et al. 1983), the most plausible cooling model is not consistent with the claimed detections.

ii) Galaxies and Clusters of Galaxies

Other spiral galaxies may have properties similar to our Galaxy, so that the above model approximately applies. Except for observations of supernovae, we have no information on column densities of highly ionized atoms in external galaxies. Absorption lines of C IV λ1549, Si IV λ1397 and possibly N V λ1241 were observed in the ultraviolet spectrum of SN1979c in M100 (Panagia et al. 1980), but it was not possible to clearly resolve the Galactic and M100 features. Deharveng et al. (1986) searched for ultraviolet emission lines from a hot gaseous halo in the edge-on galaxy NGC 4244. An upper limit of about 10^{-6} erg cm^{-2} s^{-1} sr^{-1} was set on any emission line. This is a factor of > 10 larger than the prediction for the strongest line in the standard cooling model.

Some galaxies may have substantially smaller heavy element abundances than the 'cosmic' values used in § II. From eqn. (1), it can be seen that a decrease in n_Z/n_H is compensated for by a decrease in Λ provided that emission from heavy elements dominates the cooling and that the relative abundances of the heavy elements remain constant. However, the increased cooling time allows the ionization to approach collisional equilibrium and the column densities are correspondingly decreased.

Early-type galaxies and clusters of galaxies are thought to have cooling inflows that are roughly spherically symmetric. Mass flow rates are inferred to be 0.02 - 3 $M_\odot$ yr^{-1} in elliptical galaxies (Thomas et al. 1986) and up to 400 $M_\odot$ yr^{-1} in clusters of galaxies (Fabian, Nulsen, and Canizares 1984). The luminosities in various ultraviolet lines can be found directly from Table 2 with the appropriate $\dot{M}$ scaling. Models of steady cooling flows (Mathews and Bregman 1978; White and Chevalier 1984) show that the gas cools through the temperature range of interest here over a small range in radius. Thus we find

$$\frac{\dot{N}_H}{n_o} = \frac{\dot{M}}{4\pi R^2 \rho_o} = v_{in}, \tag{4}$$

where R is the radius at which the cooling occurs and v_{in} is the infall velocity at radius R. Models show that v_{in} varies over a relatively small range. For elliptical galaxies with core radii in the range 10-500 pc, White and Chevalier (1984) found v_{in} in the range 150 - 300 km s^{-1}. For cluster cooling flows with $\dot{M}$ of 3 to 100 $M_\odot$ yr^{-1}, Mathews and Bregman (1978) found v_{in}

of 350 to 550 km s^{-1}. The column densities in Table 1 should be multiplied by a factor in the range 1.5 - 5.5 for these cooling flows. A significant difference from the Galactic case is that the densities in the temperature regime of interest can be large, e.g. $n_o = 1\ cm^{-3}$ for $T = 10^6$ K in the cluster models of Mathews and Bregman (1978). Under these circumstances, the cooling is likely to be isochoric in the region of interest.

These results show that the detection of ultraviolet absorption lines in cooling flows is quite plausible if there is a suitable background continuum source. Cluster flows with nuclear continuum sources include Virgo, A1795, and Perseus (Hu, Cowie, and Wang 1985). Observations of the ions discussed here will cover a temperature regime intermediate between that covered by X-ray emission and that covered by optical emission. At present there is a discrepancy between the small cooling region indicated by optical observations and the large cooling regions indicated by X-ray observations (Hu, Cowie, and Wang 1985). Ultraviolet observations should help to clarify this discrepancy.

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TABLE 1

Column densities, cm^{-2}, scaled to $\dot{N}_H/n_o$=1.0×10^7 cm s^{-1}.

	C IV	N V	O VI	Si IV	S IV	S VI
isochoric	1.14(14)	4.68(13)	6.54(14)	9.90(12)	1.61(13)	7.12(12)
$T_{tr}=4.7\times10^5$ K	4.94(13)	2.24(13)	3.63(14)	4.04(12)	6.29(12)	4.01(12)
$T_{tr}=2.2\times10^5$ K	2.68(13)	1.75(13)	3.73(14)	2.09(12)	2.99(12)	3.57(12)
isobaric	1.36(13)	1.64(13)	3.83(14)	4.14(11)	1.36(12)	3.29(12)
equilibrium	1.47(13)	1.54(13)	3.69(14)	3.38(11)	1.27(12)	3.27(12)

TABLE 2

UV Emission Line Luminosities: $\dot{M} = 1\ M_\odot\ yr^{-1}$

(1.0×10^{38} erg s^{-1})

species	wavelength (Å)	isochoric	isobaric
Ne VI	1006.0	0.214	0.346
Ar VI	1008.0	0.191	0.317
O VI	1031.9	7.11	11.0
O VI	1037.6	3.55	5.50
S III	1198.0	0.300	0.493
S V	1199.0	0.023	0.039
Si III	1206.5	0.271	0.517
O V	1218.0	0.816	1.37
N V	1238.8	0.524	0.805
N V	1242.8	0.262	0.402
Si IV	1393.8	0.053	0.082
O IV	1402.0	0.590	0.974
Si IV	1402.8	0.026	0.041
C IV	1548.2	0.955	1.52
C IV	1550.8	0.478	0.759

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