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RADIATIVE COOLING OF A LOW-DENSITY PLASMA

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ABSTRACT

We have calculated the radiative cooling coefficient for a low-density, optically thin gas of cosmic abundances in the range 10^4–10^8 K incorporating significant elements through nickel and many recently improved rate calculations.

Subject headings: atomic processes — plasmas

We have extended and improved the radiative cooling coefficient calculations of Cox and Tucker (1969) and Cox and Daltabuit (1971). The earlier rates apply to a plasma containing H, He, C, N, O, Ne, Mg, Si, and S. We have added Ca, Fe, and Ni. For the elements included, we have calculated many individual lines which had previously been averaged together, making reasonably accurate spectrum calculations possible with the new computer programs.

We expect greater overall accuracy for the lighter elements not only from the inclusion of more lines and processes, but also because of the new atomic data available, especially the work on highly charged ions found in the solar corona and in laboratory plasmas. For the heavier ions, the Gaunt factors of Mewe (1972), line classifications by Fawcett (1974), and collision strengths of Blaha (1971) for Fe XIV, Flower and Nussbaumer (1974) for Fe XIII, and Walker *et al.* (1974) for Fe XVII have been particularly useful. The data selected for use will appear in a subsequent paper on the spectra of hot astrophysical plasmas.

The plasma is assumed to be optically thin, with no molecules or dust; and the cosmic abundance estimates of Allen (1973), which reflect the recent increase of iron and decrease of neon compared with previous estimates, have been used. The cooling processes considered are permitted, forbidden, and semiforbidden line transitions, including contributions from dielectronic recombination and bremsstrahlung, radiative recombination, and two-photon continua.

The ionization balance is calculated in collisional equilibrium using an approximate treatment of autoionization following inner-shell excitation (Jordan 1969) and the low-density limit for the dielectronic recombination rate (Burgess 1965). While Burgess's formula was intended for light elements ($Z \leq 20$), he states that it is probably not too bad for heavier elements and uses it for Fe. No other general formula for dielectronic recombination is available, but Shore

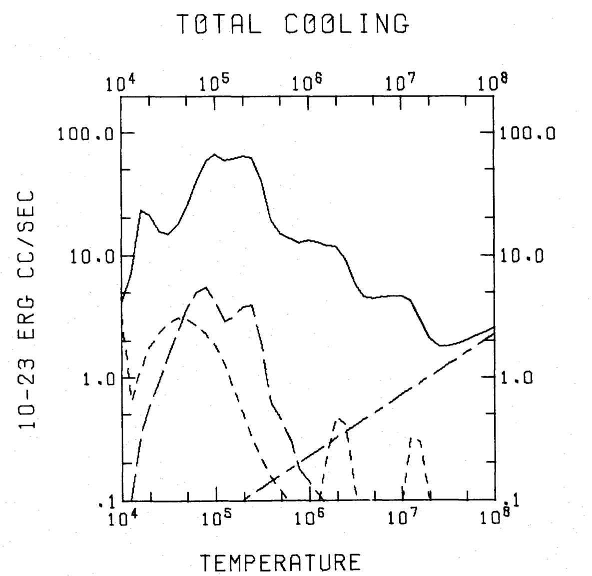

FIG. 1.—Total cooling coefficient (————), forbidden line cooling (– – – – – –), semiforbidden line cooling (— — —), and bremsstrahlung (— — — —).

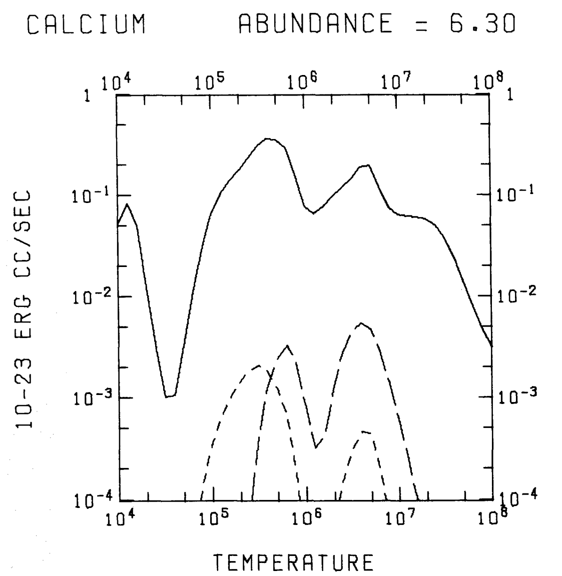

FIG. 2.—Cooling coefficient for Ca exclusive of bremsstrahlung.

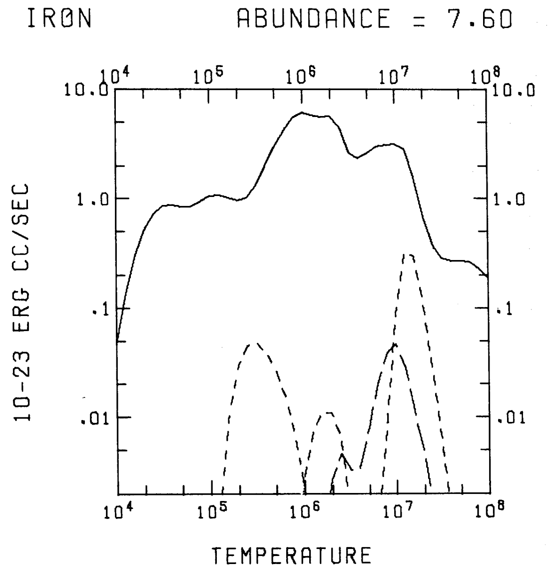

FIG. 3.—Cooling coefficient for Fe exclusive of bremsstrahlung.

(1969) suggests that Burgess's formula is correct for $\Delta n = 0$ transitions but too high by a factor of 4 if the principal quantum number changes. Making this revision to the dielectronic recombination would lower the cooling by about 25 percent and shift peaks in the cooling to slightly lower temperatures. The effect of uncertainty in the dielectronic recombination rates can be seen in the cooling curves with and without dielectronic recombination for C through S in Cox and Tucker (1969).

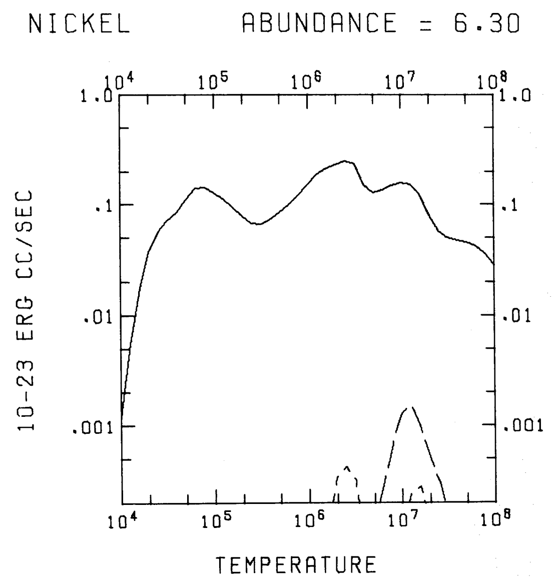

FIG. 4.—Cooling coefficient for Ni exclusive of bremsstrahlung.

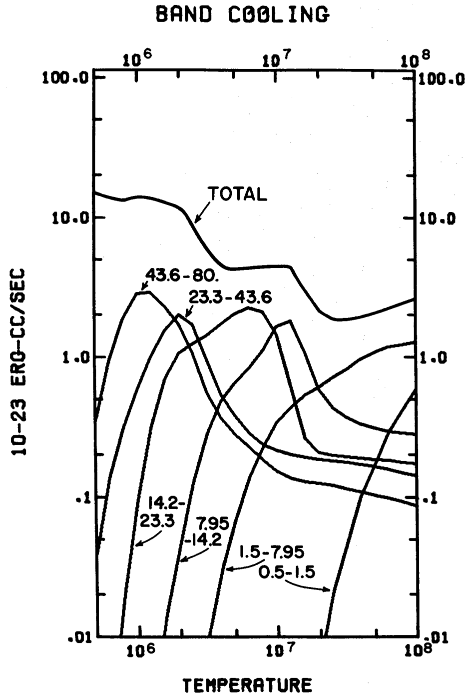

FIG. 5.—Cooling in soft X-ray bands; wavelengths indicated in Å.

In Figures 1–5 we present the cooling coefficient L as a function of temperature in units of 10^{-23} erg cm^3 s^{-1}:

$$\text{Power radiated per cm}^3 = \Lambda = L N_e N_{\rm H} ,$$

where N_e is the electron density and $N_{\rm H}$ the total (atoms and ions) hydrogen density. The total cooling coefficient is shown in Figure 1. Below about 30,000 K the collisional excitation of hydrogen (shown in Cox and Tucker but omitted in Cox and Daltabuit) and forbidden-line cooling by carbon and oxygen are important, but their rates are highly model dependent. The particular case depicted here assumes $N_{\rm H} = 1$ cm^{-3}, and N_e is calculated from collisional and background ultraviolet ionization rates. The ionization rate due to background ultraviolet appropriate to the Galaxy (Habing 1968; Witt and Johnson 1973) is used, which at this density effectively ionizes elements with ionization potential less than that of hydrogen. Most of the model dependence for $T > 10{,}000$ K is due to the hydrogen collisional excitation peak at 30,000 K which depends on the concentration of neutral H and hence on the history and environment of the gas. The care which must be exercised in applying these results is discussed in Cox and Daltabuit (1971).

Except for the hydrogen peak, the cooling in Figure 1 is similar to that given by Cox and Daltabuit up to about 5×10^5 K. Above that temperature carbon and oxygen are in helium-like, hydrogenic, or bare stages of ionization, which have no low-lying excited states and therefore cannot cool effectively.

TABLE 1

FORBIDDEN AND SEMIFORBIDDEN COOLING

Element	Peak	Ions	Wavelengths
Calcium......	2×10^5K: F	Ca v (5661 Å)	Vis
	6×10^5K: SF	Ca vii, Ca viii (826 Å), Ca ix	EUV
	4×10^6K: SF	Ca xii, xiii	X-ray
Iron.........	3×10^5K: F	Fe vii (6086.9, 3760.3 Å)	Vis
	2×10^6K: F	Fe x, xi, xii (1986 Å), Fe xiii (10.8 μ), Fe xiv	IR, Vis, UV
	10^7K: SF	Fe xviii, xix	X-ray
	1.5×10^7K: F	Fe xxii (846 Å)	EUV
Nickel.......	10^7K: SF	Ni xx, xxi	X-ray

In the previous calculations, neon contributed heavily to the cooling between 3×10^5 K and 10^6 K, but the reduced abundance assumed here lowers the total throughout this region. At higher temperatures, the heavier elements, particularly iron, begin to dominate, accounting for about half the cooling between 1 and 2×10^6 K and three-fourths at 10^7 K. The importance of iron throughout this temperature range has also been discussed recently by Pineau des Forets (1975). Toward 10^8 K these elements, too, become ionized to the K shell and beyond, and cooling is dominated by electron bremsstrahlung chiefly off stripped hydrogen and helium nuclei.

Figures 2–4 give the individual cooling for Ca, Fe, and Ni exclusive of their contributions to bremsstrahlung. Similar curves for the other abundant elements may be found in Cox and Tucker (1969), or the revised curves are available on request. Below about 5×10^5 K the cooling rates due to iron and nickel are very approximate because few collision cross sections for systems of equivalent 3*d* electrons are known. The collision strengths for Fe i–vii and Ni i–ix were estimated from oscillator strengths or the sum rule for oscillator strengths and the general behavior of the Gaunt factor with energy (van Regemorter 1962). This uncertainty has little effect on the overall total cooling rate, however, because of the large contributions of carbon and oxygen at these temperatures. The ions responsible for the peaks which appear in forbidden and semiforbidden line emission, together with wavelengths of some of the stronger lines, are listed in Table 1. Some of them may be useful as optical or ultraviolet tracers of material at these temperatures.

Finally, Figure 5 shows the cooling in various observational bands in the soft X-ray region. These results are similar to those of Tucker and Koren (1971*a*). The differences appear in the longer wavelength bands and in the total below about 2×10^7 K, both of which are higher in our results. The most significant reason for these differences is that Tucker and Koren used a long wavelength cutoff of 70 Å in their work, whereas a significant fraction of the total cooling appears at longer wavelengths. There are, in addition, small differences in abundances, and some revisions and extensions of the atomic data and interaction rates employed.

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