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HEATING THE WARM IONIZED MEDIUM

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ABSTRACT

If photoelectric heating by grains within the diffuse ionized component of the interstellar medium is 10^{-25} ergs s^{-1} per H atom, the average value within diffuse H I regions, then grain heating equals or exceeds photoionization heating of the ionized gas. This supplemental heat source would obviate the need for energetic (i.e., $h\nu > 17$ eV) ionizing photons to balance the observed forbidden-line cooling and could be responsible in part for enhanced intensities of some of the forbidden lines.

Subject headings: atomic processes — galaxies: ISM — H II regions — ISM: general

1. INTRODUCTION

Although low-density ($\sim 10^{-1}$ cm^{-3}), warm ($\sim 10^4$ K) ionized gas is one of the principal components of the interstellar medium of our Galaxy (Reynolds 1991a) and others (e.g., Rand, Kulkarni, & Hester 1990), the source of its ionization and heating has not yet been established. Proposed sources have ranged from O stars (e.g., Mathis 1986) to dark matter (Sciama 1990a). Dettmar & Schulz (1992) have recently argued that, if the gas is photoionized, the observed forbidden-line cooling places a lower limit on the energy of the ionizing photons. They specifically addressed the 14.4 eV dark matter decay photons proposed by Sciama (1990b) and concluded that photons of this energy would not heat the gas sufficiently to account for the observed diffuse [S II] and [N II] emission. Whether or not Sciama's hypothesis is correct (see Davidsen et al. 1991 and Fabian, Naylor, & Sciama 1991 for discussions about the failure to detect the 14 eV emission line), Dettmar & Schulz have raised an important question. Do the observed forbidden-line intensities rule out in general a soft Lyman-continuum flux as the source of the diffuse ionization? We show below that at densities characteristic of the warm ionized medium "normal" photoelectric heating by grains could in fact sustain the forbidden-line cooling, even if the net heating due to the photoionization of hydrogen were zero.

2. HYDROGEN IONIZATION HEATING

In ionization equilibrium the photoionization and recombination of hydrogen provide a net heating rate per unit volume that is given by

$$G = H_i - L_r , \quad (1)$$

where $H_i = \Delta E \alpha n_e^2$ is the thermal energy deposited through photoionization from the average excess energy ΔE above the Lyman limit in the photon spectrum, $L_r = kT\beta n_e^2$ is the thermal energy removed by recombination in a gas at temperature T and density n_e, and α and β are the hydrogen recombination coefficients, standard and kinetic energy–weighted, respectively (e.g., see Osterbrock 1989). In a 7000 K H II region (case B) ionized by a 35,000 K (O8–O9) star $H_i/n_e^2 \simeq 1.5 \times 10^{-24}$ ergs cm^3 s^{-1}, corresponding to $\Delta E = 2.8$ eV, and $L_r/n_e^2 \simeq 2.3 \times 10^{-25}$ ergs cm^3 s^{-1} (Osterbrock 1989), which provide a net ionization heating rate of $G/n_e^2 \simeq 1.3 \times 10^{-24}$ ergs cm^3 s^{-1}. This equals the total cooling rate for a 7000 K H II region (Spitzer 1978; Osterbrock 1979), most of which is due to forbidden-line emission in the optical and infrared.

On the other hand, in a 7000 K region ionized by a flux of 14.4 eV photons (Sciama 1990b), $\Delta E = 0.8$ eV, and the net ionization heating rate $G/n_e^2 \simeq 2 \times 10^{-25}$ ergs cm^3 s^{-1}. This rate is not sufficient to account for even the directly observed Galactic [S II] $\lambda\lambda$6716, 6731 and [N II] $\lambda\lambda$6548, 6584 lines, which contribute $\approx 4 \times 10^{-25}$ ergs cm^3 s^{-1} to the cooling rate of the warm ionized medium (from data in Reynolds 1990), and is much less than the total cooling rate of $\Lambda/n_e^2 \approx (1.1\text{–}1.4) \times 10^{-24}$ ergs cm^3 s^{-1} expected when [O II] $\lambda\lambda$3727, 3729, free-free emission, and the FIR lines of N^+ and C^+ are included. The forbidden-line intensities are even higher in the edge-on spiral galaxy NGC 891 (e.g., Dettmar & Schulz 1992). Dettmar & Schulz thus concluded that a flux of ionizing photons with an energy $h\nu \lesssim 16$ eV could not be the source of the ionization and heating of the diffuse interstellar gas observed in the Milky Way and NGC 891.

3. GRAIN HEATING

We point out that there is an additional, potentially significant source of heat in the diffuse ionized medium, photoelectrons ejected from grains. Photoelectric grain heating is thought to be responsible for the high temperature ($T \gtrsim 6000$ K; Kulkarni & Heiles 1987) of the warm *neutral* gas (de Jong 1980). Examinations of the fine-structure excitation of the ground states of C^+ and N^+ by Pottasch, Wesselius, & van Duinen (1979) and Gry, Lequeux, & Boulanger (1992) have shown that the average cooling rate, and thus the heating rate, within the H I gas is $\sim 1 \times 10^{-25}$ ergs s^{-1} per H atom, consistent with theoretical expectations for photoelectric heating (Spitzer 1978). The data indicate that this average rate is valid even along lines of sight having mean H I densities $\bar{n}_{\rm H\,I} \lesssim 0.1$ cm^{-3}. Thus diminished photoelectric efficiencies expected at low densities due to the positive charging of grains (Spitzer 1978; Draine 1978) may not occur at "intercloud" densities. In any case, in *ionized* gas with densities down to ~ 0.1 cm^{-3} diminished heating due to grain charging should not be important (Draine 1978).

Therefore, unless there is a significant difference in grain properties between the diffuse H I and H II components, it appears likely that this average rate of photoelectric heating also occurs in the diffuse *ionized* medium, and that an additional net heating term, $G_g = 1 \times 10^{-25} n_e$ ergs s^{-1} cm^{-3}, must be added to the right-hand side of equation (1). Then, if the ionization is by O star radiation,

$$G_{0\,\mathrm{star}}/n_e^2 \simeq 1.3 \times 10^{-24} + 1 \times 10^{-25}/n_e \text{ ergs cm}^3 \text{ s}^{-1} , \quad (2)$$

and, if the ionization is by a softer, 14.4 eV photon flux

$$G_{14\,\mathrm{eV}}/n_e^2 \simeq 2 \times 10^{-25} + 1 \times 10^{-25}/n_e \text{ ergs cm}^3 \text{ s}^{-1} . \quad (3)$$

4. DISCUSSION

Since the local electron density within the 2 kpc thick layer in our Galaxy has an average value of about 0.08 cm^{-3} (Reynolds 1991b), the net grain heating in the warm ionized medium equals or exceeds the net photoionization heating in both cases. For a photon flux near the Lyman limit, the grain heating alone would provide $G/n_e^2 \simeq 1.3 \times 10^{-24}$ ergs $\mathrm{cm}^3\ \mathrm{s}^{-1}$, which is sufficient to balance the cooling in a 7000 K H II region.

For O star ionization, equation (2) suggests that within the diffuse ionized gas the total heating would be approximately twice that of a traditional (i.e., higher density) H II region. This would increase the intensities of the thermostating forbidden lines. For example, in the equilibrium H II region model presented by Osterbrock (1989), doubling of the heating rate raises the temperature from 7000 to 9700 K, and increases the [S II] λ6716/Hα, [N II] λ6584/Hα, and [O II] λ3729/Hα line intensity ratios by factors of 2.7, 2.7, and 5.3, respectively. Therefore, this supplemental heating, which is inversely proportional to gas density, could be responsible at least in part for the enhanced [S II]/Hα and [N II]/Hα intensity ratios observed in low-density ionized regions (e.g., Reynolds 1985; Rand et al. 1990; Keppel et al. 1991) and even for the observed increase in these intensity ratios with distance from the midplane (Dettmar & Schulz 1992).

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Note added in proof.—The latest values for the C^+ 158 μm line emissivities derived by C. Gry, J. Lequeux, and F. Boulanger (A&A, in press [1992]) suggest an average heating rate of 3.5 (+5.4, −2.1) × 10^{-26} ergs s^{-1} per H nucleus ($H^0 + H^+$), somewhat less than the value they reported in a preliminary draft cited above, but given the large measurement uncertainties, still consistent with the 1 × 10^{-25} ergs s^{-1} per H atom originally found by Pottasch et al. (1979). The scatter in the individual values is large, apparently due in part to real variations in the C^+ emissivity from direction to direction. A value of 1 × 10^{-25} ergs s^{-1} per ($H^0 + H^+$) is consistent with the data in more than half of the lines of sight, affirming that photoelectric heating could dominate in at least some parts of the warm ionized medium.