The Influence of the Local Bubble on the Ionization of the Local Interstellar Cloud

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Abstract. The ionization of the the Local Interstellar Cloud (LIC) is quite unusual compared with most warm ($T \sim 10^4$ K) interstellar gas. Hydrogen and helium are both partially ionized with helium surprisingly more ionized than hydrogen. Directly observed ionization sources including nearby stellar EUV sources and the diffuse emission of the Soft X-ray Background (SXRB), do not provide enough ionization and heating to account for both the ionization state and temperature of the LIC. We propose that an evaporative boundary between the LIC and the hot gas of the Local Bubble can provide the necessary ionizing radiation. Results of detailed models of the emission from the interface are presented and shown to be adequate to explain the observations.

1 Introduction

Recent measurements including both *in situ* measurements (see Frisch 1995 and references therein) and line of sight (column density) observations using *EUVE* (see Vallerga 1996) have shown that the Local Interstellar Cloud (LIC) has $N_{\rm HI}/N_{\rm HeI} \approx 10-14$, $X_{\rm H} \lesssim 0.4$, and $X_{\rm He} \lesssim 0.5$ (where $X_{\rm H} \equiv n_{\rm H^+}/n_{\rm H\,tot}$, and $X_{\rm He} \equiv n_{\rm He^+}/n_{\rm He\,tot}$). The velocity structure of the nearest interstellar gas is complex, but the lowest observed HI column densities observed are consistent with a column density for the local cloud alone of $\sim 5-10 \times 10^{17}\,{\rm cm}^{-2}$.

Both this absolute level of ionization of H and the relative ionization of H and He are unlike that observed in the warm ionized regions in the ISM. Reynolds (1989) finds that H must have a high degree of ionization, $X_{\rm H} > 0.67$, due to the lack of observable [O I] $\lambda 6300$ Å emission associated with observed Hα emission. The low level of He ionization in the WIM, $X_{\rm He} \lesssim 0.27 X_{\rm H}$, is determined from the weakness of observed the He I $\lambda 5876$ (Reynolds & Tufte 1995).

The directly observed sources of ionizing radiation fall into two categories: stellar EUV sources and diffuse soft x-ray emission. The former have all been observed by *EUVE* and the combined spectrum from the brightest sources has been presented by Vallerga (1996). The spectrum is unexpectedly dominated by the two B stars, ϵ CMa and β CMa. The most important part of the SXRB for ionization of the LIC is the low energy Be and B band radiation.

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Vallerga (1996) has shown that the stellar EUV sources are not capable of providing the observed He ionization. We show below that emission from a 10^6 K, collisional ionization equilibrium plasma with emission measure sufficient to explain the SXRB, is also incapable of accounting for the observed ionization.

2 Radiation from the Boundary of the LIC

Most models of the Local Bubble assume it contains hot gas (but see Breitschwerdt & Schmutzler 1994) in order to explain the SXRB. If this is the case, then a warm cloud such as the LIC should be evaporating via thermal conduction. In the evaporative interface, gas is heated to temperatures intermediate between the cloud temperature, $T \approx 7000\,\mathrm{K}$, and the hot gas temperature, $T \sim 10^6\,\mathrm{K}$. At these temperatures the gas radiates strongly in the EUV. The mean ionizing photon energy of the interface radiation is $\bar{E} = 33\,\mathrm{eV}$ (376Å), making it efficient at ionizing He^0. Figure 1 shows a comparison of the stellar EUV field (de-absorbed to the edge of the LIC) and the spectrum from an evaporating cloud boundary model.

We have created models of the evaporative boundary which are similar to those of Slavin (1989). We assume steady flow evaporation and spherical symmetry and include the effects of radiative cooling, non-equilibrium ionization and saturation of heat flux. The spectra (as well as necessary ionization, recombination and cooling rates) are calculated using the Raymond & Smith plasma emission code (Raymond & Smith 1977 and updates).

The parameters for the model are as follow: $R_{cl} = 3\,\mathrm{pc}$, $n_{cl} = 0.22\,\mathrm{cm}^{-3}$, $T_f = 10^6\,\mathrm{K}$, $B_0 = 5.26\,\mu\mathrm{G}$, $\eta = 0.5$, where T_f is the temperature at an outer cutoff radius (30 pc), B_0 is the strength of the tangential magnetic field and η is the conductivity reduction factor. The mass loss rate for this model is $\dot{M} = 0.413\,M_\odot\,\mathrm{Myr}^{-1}$.

3 Ionization of the LIC

We take the cloud boundary spectrum we have generated and combine it with the stellar EUV spectrum and additional soft x-ray emission from hot gas to use as the flux incident on the LIC. To calculate the ionization in the cloud we employ the radiative transfer/thermal equilibrium code CLOUDY (Ferland 1996). CLOUDY calculates the detailed radiative transfer, including absorption and scattering, of the incident field and the diffuse continuum and emission lines generated within the cloud. The thermal and ionization balance is calculated at each point within the cloud.

Figure 2 shows the ionization resulting from the cloud boundary model as revealed by the column density ratio $N_{\mathrm{HI}}/N_{\mathrm{HeI}}$ vs. depth into the cloud. Also

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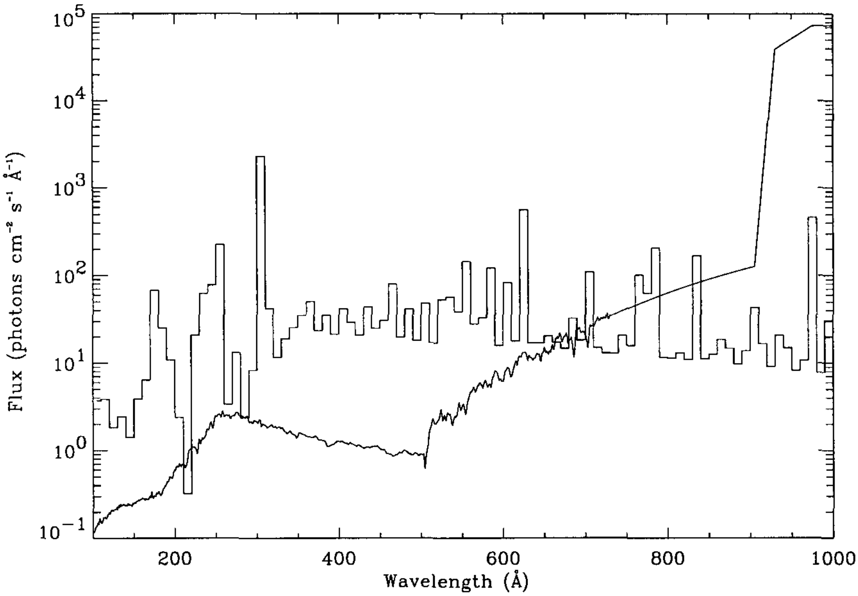

Fig. 1. Comparison of combined spectrum of stellar EUV sources with the model spectrum from an evaporative boundary on the LIC. The model spectrum is the histogram, binned at 10Å resolution. The stellar spectrum has been de-absorbed by $N_{\rm HI} = 9 \times 10^{17}\,{\rm cm}^{-2}$ to approximate the flux incident on the face of the LIC. The stellar spectrum between 730Å and 912Å is an extrapolation.

shown in the figure is the ionization which results from only including the radiation from the stellar EUV sources ("stars only") or from only including the boundary radiation ("interface only"). It is clear that without the interface radiation, the observed He ionization relative to H, $\langle N_{\rm HI}/N_{\rm HeI}\rangle \approx 10-14$, cannot be achieved. In addition, the heating rate without the interface radiation is too low, leading to a predicted cloud temperature of $T \lesssim 6000\,{\rm K}$.

An additional conclusion of our work on the ionization is that dust plays a critical role in the thermal balance of the cloud. Without dust we cannot achieve the observed temperatures, $T \approx 7000\,{\rm K}$, in the LIC. Both through grain photoelectric heating and reduced cooling due to depletion, the presence of dust raises the temperature.

4 Summary

An evaporative interface at the boundary of the LIC appears to be the only source of ionizing radiation capable producing the observed level of He ionization. Even with this source of radiation, however, there is insufficient heating

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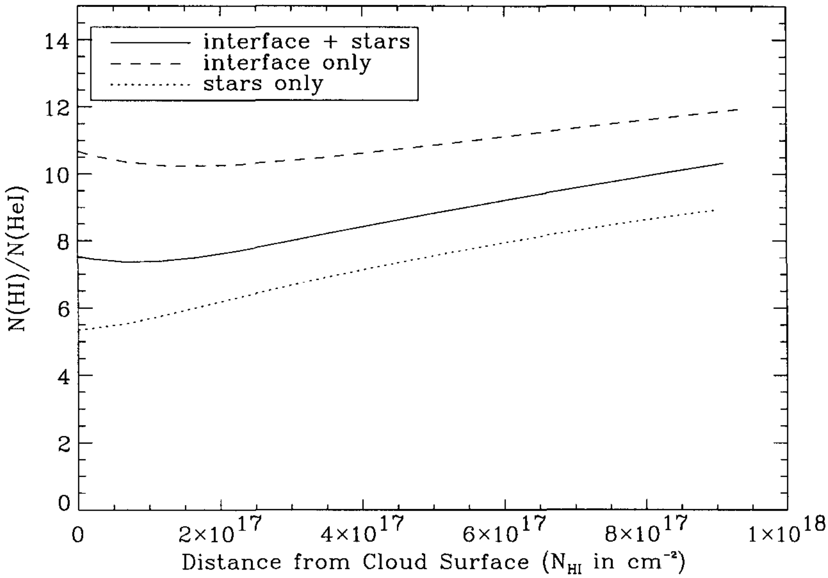

Fig. 2. Ratio of hydrogen to helium column density vs. depth into the cloud (expressed in terms of neutral hydrogen column density) for different incident fluxes. Here "stars" refers to the stellar EUV source flux. "Interface" refers to the radiation from the evaporative boundary between the LIC and the hot gas of the Local Bubble.

unless dust is present. More directly observed sources of radiation, i.e. stars and the SXRB, provide neither the ionization nor the heating necessary to produce the ionization and temperature observed in the LIC. The model of the ionizing radiation field will face tighter constraints as the ionization of the cloud is better determined by *in situ* measurements and line of sight observations towards nearby stars.

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