THE EFFECT OF UV STARS ON THE INTERGALACTIC MEDIUM

II: *Its Temperature and Ionization Structure*

A. E. SONNANSTINE and J. G. HILLS

Department of Astronomy, University of Michigan, Ann Arbor, Mich., U.S.A.

(Received 27 January, 1976)

Abstract. We have investigated the effect of ionizing radiation from the UV stars (hot prewhite dwarfs) on the intergalactic medium (IGM). If the UV stars are powered only by gravitational contraction they radiate most of their energy at a typical surface temperature of 1.5×10^5 K which produces a very highly ionized IGM in which the elements carbon, nitrogen and oxygen are left with only one or two electrons. This results in these elements being very inefficient coolants. The gas is cooled principally by free-free emission and the collisional ionization of hydrogen and helium. For a typical UV star temperature of $T = 1.5 \times 10^5$ K, the temperature of the ionized gas in the IGM is $T_g = 1.2 \times 10^5$ K for a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1} and a hydrogen density $n_H = 10^{-6}$ cm^{-3}. Heating by cosmic rays and X-rays is insignificant in the IGM except perhaps in H I clouds because when a hydrogen atom recombines in the IGM it is far more likely to be re-ionized by a UV-star photon than by either of the other two types of particles due to the greater space density of UV-star photons and their appreciably larger ionization cross-sections. If the UV stars radiate a substantial fraction of their energy in a helium-burning stage in which they have surface temperatures of about 5×10^4 K, the temperature of the IGM could be lowered to about 5×10^4 K.

1. Introduction

It has been proposed by Hills (1972a, 1973a, b) that hot prewhite dwarfs (UV stars) may significantly affect the interstellar medium (IM). In particular they may provide the source of ionization of the intercloud medium. It was also shown by Hills (1972b) that the UV stars in galaxies may radiate enough ionizing photons into intergalactic space to keep all the intergalactic medium (IGM) ionized at the present epoch.

In this paper we present calculations of the temperature and ionization structure of the IGM resulting from its photoionization by the radiation from the UV stars. These serve as building blocks for use in more elaborate theoretical calculations of the structure of the IGM as a function time which will be explored in a later paper. They also permit a more concrete determination of the emission properties of the IGM which will be of use to observers planning observational tests of the theory.

2. Ionization and Heating

The principal source of heating is photoionization by the radiation from the UV stars. Hot white dwarfs powered only by gravitational contraction radiate nearly as black bodies with most of the ionizing photons being emitted while the stars have surface

Astrophysics and Space Science **45** (1976) 125–132.

temperatures in the range $T_{UV}=(1\text{–}3)\times 10^5$ K with $T_{UV}=1.5\times 10^5$ K being about the effective mean radiation temperature. Hills (1972b) estimates that at the present epoch the white dwarfs in all galaxies produce ionizing photons at an average rate of $n_{*t}=1.7\times 10^{-23}$ photons cm^{-3} s^{-1}. At least in spirals most of the ionizing radiation from the white dwarfs is absorbed by the gas within the galaxies. Hills (1973a) finds that in the disk of the Galaxy in the solar neighborhood only 10% of this ionizing radiation escapes the Galaxy. However, most of the radiation from the white dwarfs in the central bulge of the Galaxy likely escapes into the IGM. For the entire Galaxy the overall escape rate of the ionizing photons from the UV stars is likely to be at least 20%. We can also anticipate most of the ionizing radiation from elliptical galaxies escaping into the IGM. Thus, conservatively, we estimate that 20% of the ionizing radiation emitted by the white dwarfs in all galaxies reaches the IGM which implies a volume emissivity in the IGM of $n_*=3.4\times 10^{-24}$ ionizing photons s^{-1} cm^{-3} from the white dwarfs.

As noted in Hills (1974) a star contracting down to becoming a white dwarf will pause near the helium-burning main sequence to burn any residual helium which was not consumed in an asymptotic-branch stage. Such a UV star has a surface temperature of about 5.0×10^4 K. Potentially such stars could be radiating several times as many ionizing photons into the IGM as the white dwarfs powered only by gravitational contraction. It was also noted in this paper that UV stars more massive than 0.8 $M_\odot$ will burn their carbon to magnesium just before becoming white dwarfs. Such stars have surface temperatures of about 1.0×10^5 K. Potentially, they could also be radiating more ionizing photons into the IGM than that calculated for stars powered only by gravitational contraction. Because of the uncertainties associated with these nuclear-powered UV stars we shall confine our discussion only to the radiation emitted by the UV stars powered by gravitational contraction. If the UV stars also emit ionizing photons during these nuclear-burning stages, the effect of this additional radiation on the IGM may be easily assessed from the results presented in this paper based on the radiation emitted by the white dwarfs.

The energy density in ionizing photons in the IGM at the present epoch resulting from the emission from the UV stars is given approximately by

$$\langle U\rangle = 0.350(n_*/H_0)\,\langle\varepsilon\rangle \tag{1}$$

(Henry *et al.*, 1968), where H_0 is the Hubble constant which we assume to be 75 km s^{-1} Mpc^{-1} and $\langle\varepsilon\rangle$ is the average energy of an ionizing photon.

In order to determine the ionization structure of the IGM we need to relate $\langle U\rangle$ to the energy density in ionizing photons present in a cavity with a wall temperature equal to the surface temperature, T_{UV}, of the UV stars. This is

$$U_{bb} = 7.6\times 10^5 T_5^4 R_2(X_0)\ (\text{erg}), \tag{2}$$

where $T_5=(T_{UV}/10^5\text{ K})$ and R_2, a factor of the order unity, is the fraction of the black body energy density which is in the form of ionizing photons. This is one of a set of commonly occurring functions of the form

$$R_n(X_0) \equiv \int_{x_0}^{\infty} \frac{X^{n+1}\,\mathrm{d}X}{e^x - 1} \Bigg/ \int_{0}^{\infty} \frac{X^{n+1}\,\mathrm{d}X}{e^x - 1}, \tag{3}$$

where $X_0 = h\nu_0/(kT_{UV}) = 1.439/T_5$, and $h\nu_0 = 13.6$ eV is the ionization energy of hydrogen. To calculate $\langle\varepsilon\rangle$ we average over the black body distribution from $\varepsilon = h\nu_0$ to ∞. This gives

$$\langle\varepsilon\rangle = 3.729 \times 10^{-11} T_5 [R_2(X_0)/R_1(X_0)], \tag{4}$$

where R_1 and R_2 are defined by Equation (3). From Equations (1)–(4) we find the dilution factor for ionizing photons to be

$$W \equiv \langle U\rangle/U_{bb} = \frac{0.350 n_* \langle\varepsilon\rangle}{H_0 U_{bb}} = \frac{7.099 n_*}{T_5^3 R_1(X_0)}, \tag{5}$$

where we have used $H_0 = 75$ km s^{-1} Mpc^{-1}. We note the linear dependence of W on n_* in this equation. Putting in the previously derived value of n_*, we find that $W = 2.4 \times 10^{-23} [T_5^3 R_0(X_0)]^{-1}$.

In the presence of a black body radiation field of temperature T_{UV} having a dilution factor W, the ratio of the number density of ions in two consecutive ionization states i and $i+1$ of the same atomic species is given by the modified Saha equation,

$$\frac{N_i + 1}{N_i} = \left[\frac{2g_{i+1}}{g_i}\left(\frac{2\pi mk}{h^2}\right)^{3/2}\right]\left[\frac{W T_{UV} T_g^{1/2}}{N_e}\right] \mathrm{e}^{-\chi_i/kT_{UV}} \tag{6}$$

(Münch, 1968). Here T_g is the gas temperature, N_e is the electron density, χ_i is the ionization potential from the ground level of the ith ionization state, and (g_{i+1}/g_i) is the ratio of statistical weights of the two ionization states which at the low densities present in the IGM is just the ratio of statistical weights of the ground levels. For hydrogen densities $N_H < 10^{-3}$ cm^{-3}, even a preliminary calculation shows that hydrogen and helium are nearly completely ionized and the heavier elements in the (C, N, O, N_e) group are left with only two or three electrons. As a result, at these low densities we can let $N_e = 1.22 N_H$ with negligible error. In this case on combining Equations (5) and (6) we find

$$\frac{N_i + 1}{N_i} = 0.955 \left[\frac{T_4}{N_H T_5^2 R_1(X_0)}\right] \frac{g_i + 1}{g_i} \exp\left[-0.116(\chi_i/\mathrm{e.v.})/T_5\right], \tag{7}$$

where $T_4 = (T_g/10^4$ K). We note that the ionization structure of the gas is completely specified by the parameters N_H, T_g, and T_{UV}.

We shall now consider the heating of the gas by the photoionization of H I and He II; He I photoionization is negligible because He is almost completely doubly ionized. We assume an equilibrium between photoionization and recombination and we assume that the electrons recombining into upper levels cascade to the ground level before being photoionized. Under these conditions, the heating rate due to photoionization out of some ionization state i is

$$\gamma = 2.05 \times 10^{-11}(Z^2/T^{1/2})N_e N_{i+1} \times \\ \times [\phi_2\langle E_2\rangle - kT_g X_2] \quad \text{erg cm}^{-3}\,\text{s}^{-1} \tag{8}$$

assuming a hydrogenic approximation (Spitzer, 1968; p. 130). Here Z is the charge on the atom in the $(i+1)$th ionization state and N_{i+1} is the number density of the ions in this ionization state. Spitzer tabulates the dimensionless parameters ϕ_2 and X_2 as a function of (Z^2/T_g). In Equation (8), $\langle E_2\rangle$, the average energy of an ejected photon, is $\langle E_2\rangle = [\langle\varepsilon\rangle - h\nu_0]$, where $\langle\varepsilon\rangle$ is again the average energy of the photons capable of causing a photoionization from the ith to the $(i+1)$th ionization state and $h\nu_0$ is the energy of ionization between these two states. Equation (4) can be used to find $\langle\varepsilon\rangle$. The normalized heating rates for the photoionization of atoms from ionization state i are then given by

$$\Gamma_i \equiv \frac{\gamma}{N_e N_{\mathrm{H}}} = 2.05 \times 10^{-11}(Z^2/T^{1/2})(N_{i+1}/N_{\mathrm{H}}) \times \\ \times [\phi_2\langle E_2\rangle - kTX_2]. \tag{9}$$

The total normalized heating rate for the IGM is then taken as

$$\Gamma = \Gamma_{\mathrm{H\,I}} + \Gamma_{\mathrm{He\,II}}.$$

3. Cooling

Because of the highly ionized states of the heavier elements when $N_{\mathrm{H}} < 10^{-3}\,\text{cm}^{-3}$ the important cooling processes are free-free emission and the collisional ionization and excitation of hydrogen and helium. At higher densities the collisional excitation of the fine structure levels in the heavier elements becomes important.

The normalized power loss per unit volume by the free-free emission due to electrons interacting with positive nuclei of charge Z and space density N_i is given by the usual formula

$$\Lambda_{ff}(i) = \frac{\varepsilon_{ff}(i) \quad [\text{erg cm}^{-3}\,\text{s}^{-1}]}{N_e N_{\mathrm{H}}} \tag{10}$$
$$= 1.435 \times 10^{-27} Z^2 T_g^{1/2}(N_i/N_{\mathrm{H}})\langle g_{ff}\rangle.$$

In the temperature range appropriate to the IGM, the average Gaunt factor is given closely by

$$\langle g_{ff}\rangle = 1.431 - 0.125 \log_{10}[1.579 \times 10^5(Z^2/T_g)], \tag{11}$$

which is a good fit to the graphical display of $\langle g_{ff}\rangle$ given by Karzas and Latter (1961). The total normalized cooling rate by free-free emission is taken as

$$\Lambda_{ff} = \Lambda_{ff}(\mathrm{H\,I}) + \Lambda_{ff}(\mathrm{He\,I}) + \Lambda_{ff}(\mathrm{He\,II}). \tag{12}$$

Next we shall consider the excitation of H I, He I, and He II by electron collisions. Allen (1963, p. 42) gives the rate coefficient for excitation of an atom by electron collisions from the ground state to the excited stars (permitted transition) as

$$\gamma_j = 1.70 \times 10^{-3}[(gf)_j/(T_g\chi_j)]P(\chi_j/kT_g)\exp(-\chi_j/kT_g) \quad \text{excitations s}^{-1}\text{ electron}^{-1}\text{ atom}^{-1}\text{ cm}^3, \tag{13}$$

where χ_j is the excitation energy in electron volts, $(gf)_j$ is the oscillator strength-statistical weight product for the transition, and $P(\chi_j/kT_g)$, a dimensionless parameter, is tabulated by Allen for neutral and singly ionized atoms. The normalized cooling rate for atomic species i is the sum over the excitation states of the atom – i.e.,

$$\begin{aligned}\Lambda_{\mathrm{CE}}(i) &= (N_i/N_{\mathrm{H}})\,\Sigma\,\chi_j\gamma_j \\ &= 2.72 \times 10^{-15}(N_i/N_{\mathrm{H}})T_g^{-1}\sum_j (gf)_j P(\chi_j/kT_g)\exp(-\chi_j/kT_g) \times \\ &\quad \times \text{erg s}^{-1}\text{ e}^{-1}\text{ H}^{-1}\text{ cm}^3.\end{aligned} \tag{14}$$

The total normalized cooling rate by collisional excitation for the IGM is taken as

$$\Lambda_{\mathrm{CE}} = \Lambda_{\mathrm{CE}}(\text{H I}) + \Lambda_{\mathrm{CE}}(\text{He I}) + \Lambda_{\mathrm{CE}}(\text{He II}). \tag{15}$$

We included 39 excitation levels in the H and He II summation and 11 levels in the He I summation.

The calculation of the cooling due to collisional ionization is somewhat more involved. The ionization rate is

$$\gamma = \langle U\sigma(U)\rangle \quad \text{ionizations s}^{-1}\text{ e}^{-1}\text{ atoms}^{-1}\text{ cm}^3, \tag{16}$$

where U is the velocity of the electron relative to the atoms and $\sigma(U)$ is the ionization cross-section. When the average is taken over a Maxwellian distribution of relative velocities,

$$\gamma = (4/\pi^{1/2})(m/2kT_g)^{3/2}\int_0^\infty \sigma(U)U^3\exp(-mU^2/2kT_g)\,\mathrm{d}U. \tag{17}$$

Allen (1963, p. 41) gives the cross-section as

$$\sigma(U) = 1.63 \times 10^{-14}(n/\chi^2)q(\varepsilon/\chi; Z)\text{ cm}^2, \tag{18}$$

where n is the number of optical electrons, χ is the ionization potential in electron volts, Z is the charge on the ionized atom, $\varepsilon = \frac{1}{2}mU^2$ is the kinetic energy of the electron relative to the atom and $q(S, Z)$ is a dimensionless parameter which is tabulated by Allen for $Z = 1, 2$. If we combine Equations (17) and (18) the rate coefficient becomes

$$\gamma = 2.21 \times 10^{-24}[n/(kT)^{3/2}]\int_0^\infty Sq(S, Z)\exp[-(x/kT)S]\,\mathrm{d}S. \tag{19}$$

The normalized cooling rate by ionization for atomic species i is then

$$\Lambda_{\mathrm{CI}}(i) = (N_i/N_{\mathrm{H}})\chi_i\gamma_i \quad \mathrm{erg\ s^{-1}\ e^{-1}\ H^{-1}\ cm^3}, \tag{20}$$

where χ_i is now the ionization energy in ergs. The total normalized cooling rate by collisional ionization is taken as

$$\Lambda_{\mathrm{CI}} = \Lambda_{\mathrm{CI}}(\mathrm{H\ I}) + \Lambda_{\mathrm{CI}}(\mathrm{He\ I}) + \Lambda_{\mathrm{CI}}(\mathrm{He\ II}), \tag{21}$$

while the total normalized cooling rate for the IGM is taken as

$$\Lambda(T_g) = \Lambda_{ff} + \Lambda_{\mathrm{CE}} + \Lambda_{\mathrm{CI}}. \tag{22}$$

4. The Effect of Cosmic Rays and X-rays

Except within H I clouds where the ionizing photons from the UV stars cannot penetrate, cosmic rays and X-rays have little effect on the IGM. In the H II portion of the IGM the photons from the UV stars dominate the ionization and heating. The reason for this is that when a proton recombines with an electron to form a neutral hydrogen atom, the chances of it being reionized by a UV-star photon are very much greater than by an X-ray or cosmic ray. This results from the greater space densities and ionization cross-sections of the UV-star photons compared to those of the other two types of particles. To illustrate this quantitatively let us consider a model in which there is an equal amount of energy per unit volume in UV-star photons with typical energies $\varepsilon_{\mathrm{UV}} = 20$ eV, in cosmic rays with typical energies $\varepsilon_{\mathrm{CR}} = 10^{10}$ eV, and in X-rays with typical energies $\varepsilon_x = 0.3$ keV. This probably exaggerates the true space densities of the X-rays and cosmic rays. The rate of heating per unit volume resulting from the ionization of hydrogen by each type of particle is $E_i \propto \sigma_i n_i(\varepsilon_i - 13.6\ \mathrm{eV})$ where σ_i is the ionization cross section, n_i is the number density of the particles, and ε_i is the average energy lost per ionization. For photons ε_i is just the photon energy, but for cosmic rays $\varepsilon_i \simeq 80$ eV (Spitzer, 1968; p. 101). Here we have ignored any secondary ionizations by the ejected electrons since these are not important if the medium is predominantly ionized as we have assumed. First, we consider the relative heating efficiencies of the two types of photons, $(E_x/E_{\mathrm{UV}}) = (\sigma_x/\sigma_{\mathrm{UV}})(n_x/n_{\mathrm{UV}})(\varepsilon_x - 13.6\ \mathrm{eV})/(\varepsilon_{\mathrm{UV}} - 13.6\ \mathrm{eV}) = (20/300)^4$ $(286.46/6.4) = 8.8 \times 10^{-4}$. From the usual relations we find that $\sigma_{\mathrm{UV}} = 2.1 \times 10^{-18}$ cm^2 (Spitzer, 1968; p. 113) and $\sigma_{\mathrm{CR}} = 9.8 \times 10^{-20}$ cm^2 (Spitzer, 1968; p. 101) which finally gives us $(E_{\mathrm{CR}}/E_{\mathrm{UV}}) = 9.7 \times 10^{-10}$. It is evident that the effect of the cosmic rays and the X-rays on the IGM is negligible except possibly in any H I regions present in the IGM where the photons from the UV stars cannot penetrate.

5. Calculation of the Equilibrium Temperature

The gas temperature, T_g, is determined by the equilibrium condition $\Gamma(T_g) = \Lambda(T_g)$. These normalized heating and cooling rates depend explicitly on T_g, T_{UV}, and the element abundances. While they do not depend explicitly on N_e and N_{H}, they do depend implicitly on them through the modified Saha equation which determines the ionization structure of the gas. For the element abundance we have assumed $N_{He}/N_H = 0.1$ and for the heavier elements of interest we use the compilation of Spitzer (1968, p. 122). To calculate the equilibrium temperature we picked T_{UV} and N_H and then we found T_g from the equilibrium condition by numerical iteration.

6. The Results

Figure 1 shows the equilibrium gas temperature T_g plotted against the hydrogen density, N_H, in the IGM for various UV star temperatures, T_{UV}. At very low densities where the cooling is almost entirely by free-free emission by default of any other mechanism, T_g asymptotically approaches a value a little under T_{UV} as was predicted by Hills (1972b). The second law of thermodynamics assures that $T_g < T_{UV}$. As the density increases, collisional ionization becomes a progressively more important coolant due to the increasing fraction of neutral hydrogen atoms. This lowers T_g. At the highest

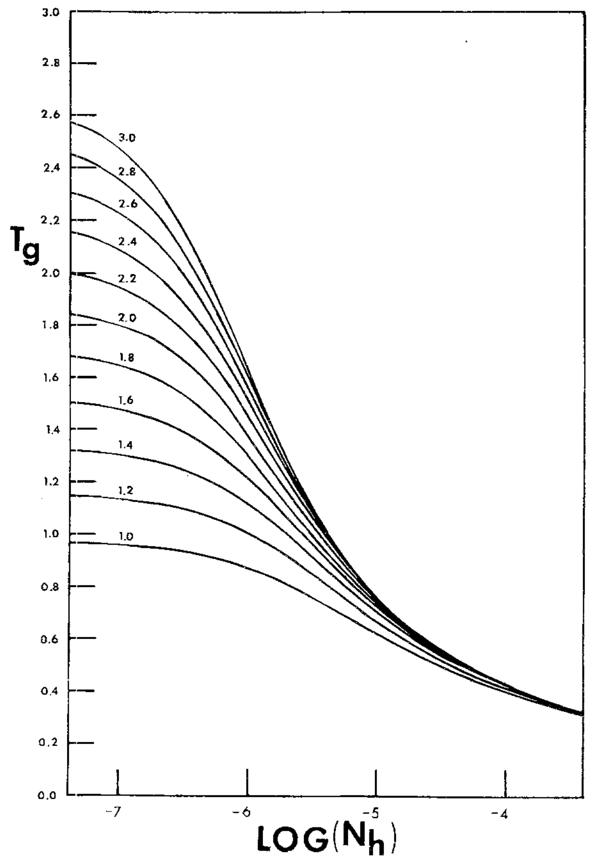

Fig. 1.

densities shown on the plot collisional ionization dominates the cooling and the temperature falls off relatively slowly with increasing density. The most rapid change in T_g with increasing N_H occurs where the two cooling mechanisms are roughly comparable. We find that He I is never an important coolant and that collisional excitation makes little contribution to the cooling.

As mentioned earlier, the total hydrogen density, N_H (protons as well as neutral hydrogen), enters the calculation of T_g only through its presence in the modified Saha equation, where its dependence is of the form $(N_{i+1}/N_i) \propto (W/N_H)$. Since $W \propto (n_*/H)$ where n_* is the emissivity of ionizing photons radiated by galaxies into the IGM and H is the Hubble constant, it is evident that n_* and N_H only enter the calculations in the ratio (m_*/N_H). Thus models in which $[(n_*/N_H)H^{-1}]$ is constant have identical values of T_g. Thus from Figure 1 we can easily estimate, for example, how uncertainties in n_* and H affect the calculated T_g. Given an evolutionary cosmological model which specifies n_*, N_H, and H as a function of time we can also easily determine T_g as a function of time in an evolving universe.

The state of ionization of each element in the gas can also be easily calculated at each epoch by using the modified Saha equation. As noted earlier the high ionization state of the gas results in the electron density being nearly a constant fraction of the hydrogen density; $N_e = 1.22 N_H$.

At the present epoch assuming $T_{UV} = 1.5 \times 10^5$ K, $N_H = 1 \times 10^6$ cm^{-3}, and $H_0 =$ 75 km s^{-1} Mpc^{-1}, we find from Figure 1 that the most probable value of T_g is $T_g = 1.2 \times 10^5$ K.

As a final note, we deduce from the discussion in this paper that if the UV stars should be radiating a substantial fraction of their energy in a helium-burning stage in which they have a surface temperature of about 5×10^4 K, the temperature of the IGM could be lowered to about 5×10^4 K.

References

Allen, C. W.: 1963, *Astrophysical Quantities*, Athlone Press, London.
Henry, R. C., Fritz, G., Meekins, J. F., Friedman, H., and Byram, E. T.: 1968, *Astrophys. J.* **153**, L11.
Hills, J. G.: 1972a, *Astron. Astrophys.* **17**, 155.
Hills, J. G.: 1972b, *Astrophys. Lett.* **12**, 9.
Hills, J. G.: 1973a, *Astron. Astrophys.* **26**, 197.
Hills, J. G.: 1973b, *Astron. Astrophys.* **28**, 63.
Hills, J. G.: 1974, *Astrophys. J.* **190**, 109.
Karzas, W. J. and Latter, R.: 1961, *Astrophys. J. Suppl.* **6**, 167.
Mészáros, P.: 1973, *Astrophys. J.* **183**, 469.
Münch, G.: 1968, in B. M. Middlehurst and L. H. Aller (eds.), *Interstellar Absorption Lines in Nebulae and Interstellar Matter*, University of Chicago Press, p. 380.
Spitzer, L.: 1968, *Diffuse Matter in Space*, Interscience, New York.