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ON THE IONIZATION OF THE INTERCLOUD MEDIUM BY ULTRAVIOLET STARS

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ABSTRACT

We analyze a recently proposed model of the ionization of the intercloud medium by ultraviolet stars, deriving the gas parameters and the ionization structure in the steady-state approximation. A comparison of the theoretical results with satellite ultraviolet observations, if these latter are typical of the intercloud gas and the effect of stellar H II regions is negligible, suggests that the model is unsatisfactory. The main disagreement is in the predicted relative abundances of the higher ionization stages of the trace elements, and in the ratios of successive stages.
Subject headings: abundances, nebular — interstellar matter — spectra, ultraviolet

I. INTRODUCTION

With the advent of high-resolution ultraviolet spectroscopy from satellites, the study of the physical properties of the interstellar gas enters a new phase. The first results of the OAO-3 satellite *Copernicus* (Spitzer *et al.* 1973) include results on the ionization structure in the direction of four unreddened stars (Rogerson *et al.* 1973), which could be typical of the intercloud medium. Although the sample is as yet small, and the analysis of the data still preliminary, the reported results suggest that the ionization structure may not be explainable by any single, simple mechanism, such as cosmic rays or X-rays in their usual form. While admitting the possibility that new refinements to these theories, or a reinterpretation of the data, may yet eliminate the discrepancies, it seems desirable at this point also to inquire whether perhaps some other mechanism can be invoked, which is able to reproduce in a simple manner an ionization structure such as is observed. One possible mechanism has been proposed by Hills (1972), who argued that ultraviolet dwarfs may contribute significantly towards ionizing and heating the intercloud medium (ICM). Subsequent investigations (Silk 1973; Rose and Wentzel 1973) have further pointed out that such sources would be capable of explaining some of the main observational features of the intercloud gas. It appears therefore of importance to investigate whether an intercloud medium ionized entirely or in part by ultraviolet stars does predict the right distribution of trace elements among the different ionization stages, which is perhaps the crucial test that a model must pass. In addition to this, the gas temperature, the average electron density, and the ionized fraction x are other observationally known parameters that must be reproduced by the model, and in what follows we address ourselves to these questions.

II. A MODEL FOR ULTRAVIOLET STARS

The ultraviolet dwarfs considered by Hills are stars that are evolving from the planetary nebula to the white-dwarf stage. The details of the evolution of these pre-white dwarfs are uncertain, due to the lack of knowledge concerning the importance of neutrino emission. According to Vila's (1966) calculations of evolutionary sequences, the lifetime in this stage is of the order of 10^7 years if neutrino emission is negligible, and of a few times 10^4 years if neutrino emission is included. There is weak evidence in favor of the second case, in that planetary nuclei fall in the H-R diagram along a path

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that seems compatible with lifetimes of $\sim 10^4$ years (Seaton 1966). However, the uncertainties in determining parameters for planetary nuclei are large, and the notable discrepancy between neutrino emission theory and observations in the case of the Sun suggest that it may not be unreasonable to consider the no-neutrino case as a serious possibility.

In this case, the space density of ultraviolet stars can be computed by assuming that all red giants will ultimately evolve into white dwarfs. If n_G and τ_G are the space density and lifetime of red giants, and $n_{\rm UV}$, $\tau_{\rm UV}$ those of the ultraviolet dwarfs, then

$$n_{\rm UV} = \frac{\tau_{\rm UV}}{\tau_G} n_G \simeq 10^{-5}\ {\rm pc}^{-3}\,, \tag{1}$$

where we have taken $n_G = 6 \times 10^{-5}$ pc^{-3}, $\tau_G \simeq 4 \times 10^7$ years, and $\tau_{\rm UV} \simeq 10^7$ years (Allen 1963; Vila 1966). That is, the mean distance between sources is $d_{\rm UV} \simeq 45$ pc. In order to compute the radius of influence of each source, a Strömgren-sphere type of analysis is not adequate, since there is no sharp delimitation between totally ionized and neutral gas, due to the fact that most of the radiation is in the hard-ultraviolet region. A solution of the radiative transfer problem is required to find out whether all of the ionization and heating of the ICM can be attributed to these sources. The clouds present such a high optical depth to the ultraviolet radiation that their heating source cannot be the same; the two problems, however, can be treated separately in the first approximation, and we shall not include clouds in this treatment.

The first thing worth noting is that, while the time scale for luminosity changes of the star is $\tau_{\rm UV} \simeq 10^7$ years, the recombination time in the ICM around it is

$$\tau_r \simeq \frac{10^5}{n_0 x} T_4^{1/2}\ \text{years}\,, \tag{2}$$

which, for the gas parameters considered here, has a value $\tau_r \simeq 4 \times 10^6$ years. Furthermore, a typical parcel of gas is under the influence of more than one star (see § III), and by the time one has decayed, another one has replaced it. Under these circumstances it appears that a steady-state approximation may be used, in which the stars are assumed to have a constant average luminosity, effective temperature, and radius, and in which the ionization rate in the gas is equal to the recombination rate. Although it is interesting to consider the dynamical effects associated with luminosity changes (Rose and Wentzel 1973), it is unlikely that these could alter significantly the average gas parameters, and in particular the ionization structure, derived from the steady-state approximation employed here. This, we should again emphasize, hinges on the assumption of negligible neutrino emission. We shall discuss very briefly the case of significant neutrino emission in § VI.

The average stellar parameters we shall adopt, consistent with Vila's negligible-neutrino case, are $R_* \simeq 7 \times 10^8$ cm, $T_{\rm eff} \simeq 1.5 \times 10^5$ ° K, and $L \simeq 50\, L_\odot$. The temperature, in particular, is slowly varying, and this is rather fortunate, as there exist model atmosphere calculations by Böhm and Deinzer (1966) for high-gravity, unit-solar-mass objects at a temperature of 1.5×10^5 ° K, which can be used for our purposes. The higher ions of C, N, O, and Ne give self-absorption features that depress significantly the high-energy end of the spectral distribution below the value expected from a blackbody curve at the corresponding temperature. The absorption edge of He II at 54 eV is also pronounced, and the serrated shape of the spectrum makes it easy to fit the spectrum, in different energy ranges, by either constants or power-law functions, which simplifies the calculations considerably.

We should point out here that, although the source parameters were chosen to correspond to a particular model of pre–white dwarfs, other objects may have similar

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characteristics. For instance, if weak soft X-ray sources had a thermal spectrum which became optically thick with a turnover at 50 eV, this could give a spectrum resembling that considered here.

III. THE RADIATION FIELD IN THE GAS

Three density regimes will be considered to cover all the range conceivably available to ICM, (a) $n_0 = 3 \times 10^{-2}$, (*b*) $n_0 = 10^{-1}$, and (*c*) $n_0 = 1\ \mathrm{cm}^{-3}$. Case *a* is that attributed by Hills to represent the average ICM. There are, however, observational reasons (§ V) suggesting that a higher value is more adequate. In this low-density case *a*, most of the gas is ionized, as will be seen, and the mean free path of a typical photon is longer than the half-distance between ultraviolet stars. It is necessary then to define a diffuse flux of ultraviolet starlight, which for simplicity can be taken to be isotropic. It is a simple matter to compute, given the values of $dF/d\nu$ [ergs cm^{-2} s^{-1} sterad^{-1}] of Böhm and Deinzer, the stellar radius adopted R_* and the density of ultraviolet stars n_{UV}, the volume emissivity $\mathfrak{E}_E$ [photons cm^{-3} s^{-1} keV^{-1}]. The latter units are chosen for consistency with X-ray units, since the X-ray diffuse flux will also be included in the calculations. If L' is the photon mean free path at a certain energy, then we obtain the diffuse ultraviolet flux, $\phi_E^{\mathrm{UV}} = (4\pi)^{-1}\mathfrak{E}_E L'$ photons cm^{-2} s^{-1} keV^{-1}. This mean free path has to be less than or equal to the mean separation between clouds, and this must be equal in turn to the mean distance between ultraviolet stars, hence a value of $L' \simeq$ 45 pc is indicated. This happens to be also the mean free path against absorption in the ICM, at typical photon energies. The ionization rate of hydrogen, and of the other elements, is then computed by means of the expression

$$\zeta = 4\pi \int_{E_0}^{\infty} \eta \phi_E(E) \sigma(E) dE\,, \tag{3}$$

where E_0 is the ionization threshold energy, η is the ionization efficiency, $\sigma(E)$ is the ionization cross-section, and the diffuse photon flux $\phi_E(E)$ is a sum of the stellar (ultraviolet) flux and the isotropic X-ray background, $\phi_E^{\mathrm{XR}}(E)$. This latter flux is the actual observed flux, which can be written (Dalgarno and McCray 1972) as

$$\begin{aligned} \phi_E^{\mathrm{XR}}(E) &\leq 55\, E^{-1.4} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \qquad 0.15 < E < 0.3 \text{ keV} \\ &= 11\, E^{-1.4} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \qquad 0.3 < E < 18 \text{ keV}\,, \end{aligned} \tag{4}$$

so the $\phi_E(E)$ that enters equation (3) is

$$\phi_E(E) = \phi_E^{\mathrm{UV}}(E) + \phi_E^{\mathrm{XR}}(E)\,. \tag{5}$$

Notice that the value quoted for the soft X-ray flux is an upper limit over all directions. Since $\phi_E(E)$ can be fitted by constants or power laws, in different energy ranges, and the cross-sections $\sigma(E)$ of all elements under consideration can also be expressed as power laws, the integration in equation (3) is straightforward. The actual values of ϕ^{UV} used are as follows (for $n_0 = 3 \times 10^{-2}\ \mathrm{cm}^{-3}$):

$$\begin{aligned} \phi^{\mathrm{UV}} &= 4 \times 10^{4} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \quad \text{for } 0.013 < E < 0.054 \text{ keV} \\ &= 1.5 \times 10^{4} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \quad \text{for } 0.054 < E < 0.072 \text{ keV} \\ &= 4.5 \times 10^{13} E^{-12} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \quad \text{for } 0.072 < E < 0.2 \text{ keV}\,. \end{aligned} \tag{6}$$

In the higher-density regimes, (*b*) $n_0 = 10^{-1}$ and (*c*) $n_0 = 1\ \mathrm{cm}^{-3}$, the photon mean free path in the ICM is correspondingly smaller, and it is more advantageous to consider the ionization due to a single star as a function of distance. In this case we can

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write the ionization rate ζ^{UV} as a function of distance as (Werner, Silk, and Rees 1970)

$$\zeta^{\mathrm{UV}} = \frac{1}{4\pi r^2}\int_{E_0}^{\infty} \eta F_E(E)\sigma(E)e^{-\tau(E)}dE \simeq \frac{1}{4\pi r^2}\int_{\epsilon}^{\infty} \eta F_E(E)\sigma(E)dE \,. \tag{7}$$

Here, r is the distance from the star, η is the ionization efficiency (a function of both E and the ionization fraction x), $F_E(E)$ is the unattenuated stellar flux at r, $\tau(E)$ is the optical depth at r, and ϵ is the cutoff energy, which can be defined from the condition $\tau(E) = 1$ as

$$\epsilon = E_0[n_0(1 - x)\sigma_0 r]^{1/3} \,. \tag{8}$$

Since for ultraviolet energies most of the opacity is due to H, and the cross-sections for He do not differ very much from those of H, it is permissible to lump them together and treat He as just another H atom. Also, the recombination radiation of He was neglected. This, in the higher density cases, is just the usual on-the-spot approximation, namely, one assumes that every He recombination gives rise to a photon which ionizes an H atom in the immediate vicinity of the spot where the recombination took place, and consequently the total flux of photons capable of ionizing H is unaffected by the presence of He. In the low-density model, this approximation must be modified, since the He recombination photons have a mean free path which is no longer small compared to the half-distance between sources. However, for this same reason, one expects that statistically the number of He recombinations producing photons that leave a particular region should be equal to the number of H ionizations there, due to He recombination photons coming from other regions, and again the flux of photons capable of ionizing H is not influenced by the presence of He.

In cases b and c, to the expression ζ^{UV} given by equation (7) we must add an expression similar to (3), namely,

$$\zeta^{\mathrm{XR}} = 4\pi \int_{E_0}^{\infty} \eta \phi_E^{\mathrm{XR}}(E)\sigma(E)dE \tag{9}$$

to give

$$\zeta = \zeta^{\mathrm{UV}} + \zeta^{\mathrm{XR}} \,. \tag{10}$$

The X-ray contribution is important not only for outer-shell ionizations but also because of the role it plays in the Auger effect.

IV. THE IONIZATION STRUCTURE

In the steady-state situation envisaged, the ionization equilibrium equations are

$$n_z \zeta_z^{\mathrm{eff}} = n_e n_{z+1} \alpha_{z+1} \,, \tag{11}$$

where n_z, ζ_z^{eff}, and α_{z+1} are the number density, effective ionization rate, and the recombination rate coefficient of the $(z - 1)$ times ionized atom. We shall apply the same Auger effect formalism as Weisheit and Dalgarno (1972), namely, we shall define

$$\begin{aligned} \zeta_z^{\mathrm{eff}} &= \zeta_z & (z = 1) \\ &= \zeta_z + n_e \alpha_z (\zeta_{z-1}^{K}/\zeta_{z-1}^{\mathrm{eff}}) \,, & (Z > Z - z \geq 2) \\ &= \zeta_z & (2 > Z - z \geq 0) \end{aligned} \tag{12}$$

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where $\zeta_z = \zeta_z^K + \zeta_z^L$ is the sum of the K-shell and L-shell ionization rates, and Z is the nuclear charge. In the case of oxygen, equation (11) was modified to include the charge-exchange reaction rate for the process O I + H II ⇆ O II + H I (Field and Steigman 1971). The K and L ionization cross-sections for C, N, and O given by Weisheit (1973) were fitted by power laws to facilitate the integration in the expressions for ζ.

In all three density regimes, then, ζ was first computed for H, via equation (3) or (10), and then $x = n_e/n_0$ was computed from equation (11). Since, however, the ionization efficiency η and the cutoff energy ϵ depend on x, an iterative procedure was employed to determine them consistently. Furthermore, since in the case of equation (7) ζ and x depend on r, this equation was solved by considering successive values of r, and adopting an average value of x in equation (8). In all three cases (a, b, and c) the spatial mean of the electron density obtained, defined through $\langle x \rangle = [\int rx(r)dr]/(\int rdr)$, where the integration is from 0 to $L'/2$, is compatible with the values derived from pulsar dispersion measurements, as seen from table 1. Implicit in this calculation was the assumption that the ionization equilibrium of the trace elements will not affect that of hydrogen, or that the number of electrons contributed by the trace elements is negligible compared with that coming from hydrogen and helium, and this assumption is seen to hold up, as x is larger than the trace-element abundance fraction.

Next, the same set of ionization equilibrium equations was solved for the elements C, N, and O. In cases b and c this was done considering one source only (nearest-neighbor approximation) for a parcel of gas at a distance of $r = 15$ pc. For the recombination coefficient in equation (11) we used a hydrogenic expression due to Seaton (1959)

$$\alpha_z = 1.033 \times 10^{-11} T^{-1/2} (z - 1)^2 f([z - 1]^2 I_{\mathrm{H}}/n^2 kT) , \tag{13}$$

who also has tabulated the function f. Here $z = 1$ means neutral, $z = 2$ once ionized etc, I_{H} is the ionization potential of hydrogen, and n is the principal quantum number of the ground state of the recombining ion. The hydrogenic approximation appears adequate for our purposes, in view of other simplifications made in computing ζ. The dependence of the recombination rate on the gas temperature, both here and in the computation of x, is weak, and once the temperature of the gas was calculated (see below) an iteration procedure yielded self-consistent values of all these quantities. For the ultraviolet and X-ray fluxes considered, the Auger effect turned out to be a very small correction. The resulting ionization structure is shown in figure 1.

The gas temperature was computed in thermal equilibrium, since the cooling time is shorter than the recombination time. The heating rate can be expressed as

$$\Gamma = \zeta^{\mathrm{pr}} n_0 (1 - x) E_h , \tag{14}$$

where ζ^{pr} is the primary ionization rate for hydrogen, given by equation (3) or (10) without the η factor, and E_h is the heat per primary ionization. This quantity E_h depends on the photon energy, and also on x, and has been tabulated by Dalgarno and McCray. The cooling is from electron and neutral-hydrogen collisional excitation of fine-structure levels of the trace elements. A tabulation of the relevant transitions and corresponding rates is given by Jura and Dalgarno (1972), and the temperature is computed by imposing the condition that the heat gain rate Γ should equal the heat loss rate, Λ. The resulting temperatures are listed in table 1, where the main cooling processes are also identified.

V. DISCUSSION

We now have enough information to submit the neutrinoless ultraviolet-star ionization model to a critical examination. The key discriminating factor, as pointed

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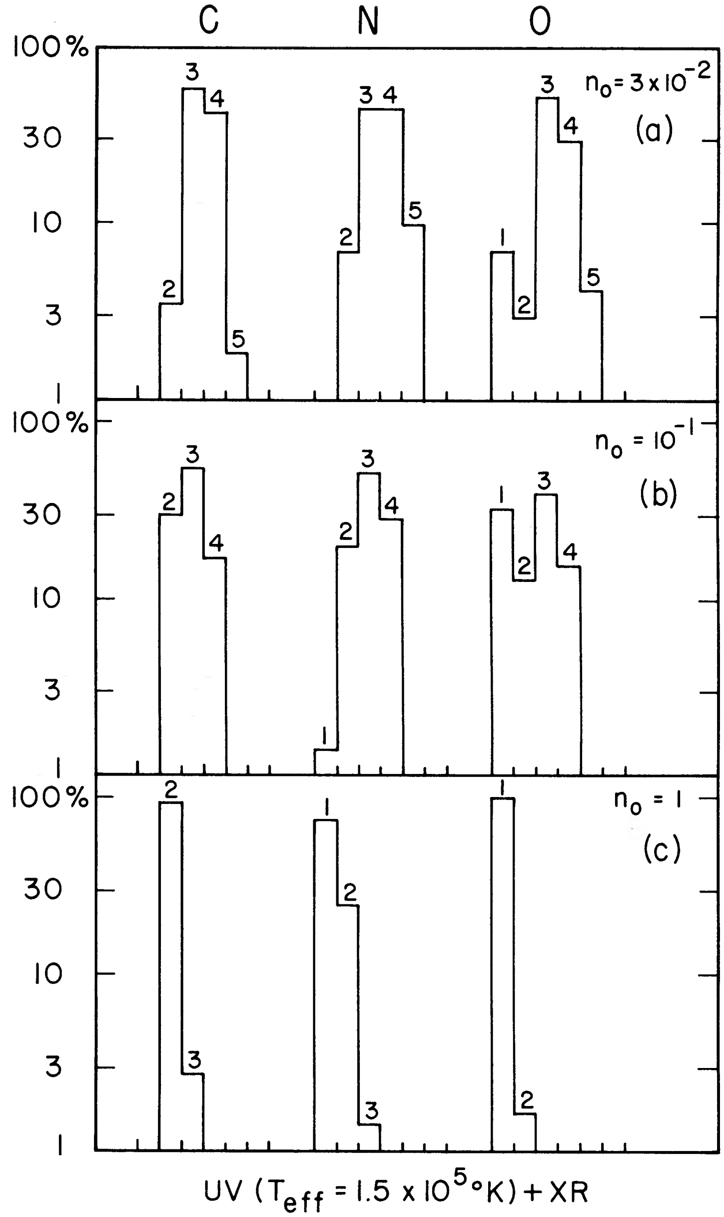

FIG. 1.—The percent (by number) of the elements C, N, and O in the different ionization stages (in abscissa), labeled on top of the histograms with numerals 1 (neutral), 2 (once ionized), etc. The three density regimes considered are labeled *a*, *b*, and *c*, the corresponding baryon density being n_0, in cm^{-3}.

TABLE 1

PHYSICAL PARAMETERS OF THE MODELS DISCUSSED

Model	n_0 (cm^{-3})	$\langle x \rangle$	$\langle n_e \rangle$ (cm^{-3})	Main Coolants	T (° K)	ρ_E (ergs cm^{-3})	p/k (cm^{-3} ° K)
a......	3×10^{-2}	0.82	2.5×10^{-2}	e^- (C III, C IV, O III)	18,000	2×10^{-13}	980
b......	10^{-1}	0.24	2.4×10^{-2}	e^- (O II, O III)	15,000	3.9×10^{-13}	1860
c......	1	0.02	2×10^{-2}	H I (O I)	7000	1.4×10^{-12}	7000

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out earlier, will be the ionization structure, since most of the other predicted gas parameters appear to be consistent with observations. Indeed, the mean electron density n_e for all three densities (table 1), is 2–2.5 $\times$ 10^{-2} cm^{-3}, consistent with pulsar dispersion measurements, and the gas densities themselves were chosen to cover the possible ranges of gas density deduced for the ICM. The gas temperature, derived from absorption and emission measurements at 21 cm (Hughes, Thompson, and Colvin 1971; Radhakrishnan *et al.* 1972), usually only give a lower limit, $T \geq 700°$ K, and this is consistent with the model's prediction. Also, the thermal energy densities ρ_E, in ergs cm^{-3}, appear reasonable, being of the same general order of magnitude as the density of energy in other forms, such as magnetic fields, turbulence, cosmic rays, etc. The thermal pressures obtained are also consistent with the two-phase picture of the interstellar medium (e.g., Field, Goldsmith, and Habing 1969), in that the values of the pressure (in units of the Boltzmann constant) listed in table 1 are of the same general value as expected from cold clouds [$n_{\rm H} = 10$, $T = 10^2$, $(p/k) = 10^3$; $n_{\rm H} = 10^2$, $T = 50$, $(p/k) = 5 \times 10^3$].

If we look now however at the ionization structure, figure 1, and compare this with the observationally determined ionization structure (Rogerson *et al.* 1973, or our table 2), we see that models *a* and *b* predict an unacceptably large proportion of the higher ionization stages. The difference amounts, in some cases, to orders of magnitude, as can be seen from table 2, although there are also variations from star to star. In general, model *c* is the one that comes the closest to the observed ionization structure, in that it predicts C, N, and O to be either mostly neutral, or mostly once ionized. An objection to this model *c* might be that it requires a large intercloud gas density, $n_0 = 1$ cm^{-3}, to give an ionization equilibrium peaked at the low stages, the reason for this being that the higher density provides a larger opacity to the ultraviolet photons, and also an increased recombination rate. Such a density is higher than the values suggested by 21-cm observations, and the values deduced from the *Copernicus* measurements. However, it must be kept in mind that there is a fairly large degree of latitude in these determinations. For instance, the value of 0.2 cm^{-3} is deduced from an extensive statistical study of the 21-cm profiles, and actual observational limits could accommodate a value of $n_{\rm H} = 1$ (e.g., Mebold 1972 and references therein). Likewise, the *Copernicus* observations suggest a value of $0.02 \leq n_0 \leq 0.2$ cm^{-3} by measuring the column density of trace elements, and then deriving a hydrogen density by assuming solar abundances and a uniform distribution along the line of sight. However, these values could be increased by a factor ~ 5, since all four stars discussed show evidence for what might be interpreted as depletion of the trace elements by a factor of that order (Rogerson *et al.* 1973). The actual values deduced from the solar-abundance argument are $n_{\rm H} = 0.02$, 0.07, 0.23, and 0.05 for α Leo, α Eri, λ Sco, and υ Sco. Thus, the gas density in the direction of λ Sco could be as high as $n_{\rm H} = 1$ cm^{-3}, although against this we have the OAO-2 measurements of Lα (Savage and Jenkins 1972), which indicate a value of $n_{\rm H} = 0.2$, reinforcing the earlier estimate. One could argue that the hydrogen is mostly ionized, but this would be inconsistent with our case *c*, where the ionization fraction is $x = 2 \times 10^{-2}$. Even if this difficulty were overcome somehow, λ Sco has recently become suspect of being a soft X-ray source (Bleeker *et al.* 1973) and so perhaps should not be considered typical. As for the other stars, an increase by a factor 5 is not sufficient to raise n_0 up to the value of 1 cm^{-3}, the highest coming up only to 0.35 cm^{-3}, but clumpiness could be invoked in the gas distribution along the line of sight to raise this value even further. Clumpiness, in fact, is to be expected in a realistic model.

However, even if the density argument were overcome by considering a clumpy distribution, the agreement in the ratios C I/C II, C II/C III, N I/N II and N II/N III is not really satisfactory, except perhaps for α Leo, and even here one cannot tell for sure since C II/C III and N II/N III are not available. It is worth noting that the disagreement

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TABLE 2

REPRESENTATIVE IONIC ABUNDANCE RATIOS FOR THE MODELS DISCUSSED, AND FOR THE STARS OBSERVED BY THE SATELLITE *Copernicus*

RATIO	MODEL			OBSERVATIONS			
	a	*b*	*c*	α Leo	α Eri	λ Sco	υ Sco
C I/C II	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 3 \times 10^{-2}$	...	1.6×10^{-3}	$< 2.6 \times 10^{-3}$
C II/C III	6×10^{-2}	0.57	35.	...	$> 4.6 \times 10^{4}$	2×10^{4}	$> 6.5 \times 10^{3}$
N I/N II	< 0.14	0.07	3.	1.4	0.45	2.4×10^{-2}	6.2×10^{-2}
N II/N III	1.5×10^{-1}	3.8×10^{-1}	1.75×10^{1}	...	4.2×10^{2}	7.2×10^{2}	$> 2.3 \times 10^{3}$

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could not be lessened by taking into account time-dependent effects, such as luminosity changes, since in this case one could increase the ratios C II/C III and N II/N III, thanks to the recombinations, but at the same time would also increase C I/C II and N I/N II.

VI. CONCLUSION

From the previous discussion, it transpires that the model does not seem to reproduce too well the presently available information on the ionization structure. In view of the fact that the sample of stars is small, as yet, and that the effect of the star's own Strömgren spheres have not been investigated, it may be too early to interpret this as indicating that the ultraviolet stars are unimportant for the energetics of the ICM. If, however, further observations confirm the ionization structure described in the first *Copernicus* reports, and if this is positively identified as arising in the ICM and not in the stellar H II regions, then we should have reasons to doubt that the heating and ionization is due to the neutrinoless ultraviolet stars. In fact, this could be further interpreted as another reason for arguing in favor of planetary nuclei evolving into white dwarfs with a significant neutrino emission, since this would reduce considerably the total output rate of luminous photons from these sources into the Galaxy. Preliminary computations indicate that in this case the ultraviolet photons emitted would not have any significant effect on the bulk of the gas, at least in the solar neighborhood, although they could be important in regions where red giants are much more numerous, such as in galactic nuclei. The question of the identification of the sources of the heating and ionization of the intercloud gas is, then, still open, although the answer seems not too far away. The ionization structure seems to be a sensitive discriminating factor, and conceivably a composite model including starlight and cosmic rays or X-rays (eventually in a time-dependent scheme, although this may not be necessary) could be developed in the future to bring agreement with the observations.

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