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# IONIZATION OF CARBON AND NITROGEN IN THE INTERCLOUD MEDIUM

M. KAFATOS,* H. GEROLA, S. HATCHETT, AND R. MCCRAY†
Joint Institute for Laboratory Astrophysics, University of Colorado and
National Bureau of Standards, Boulder, Colorado 80302
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ABSTRACT

If the intercloud medium in the solar neighborhood was suddenly ionized less than $10^6$ years ago, the subsequent relaxation of the gas can account for the very low observed column density of C III and N III yet still leave a significant fraction (~0.05) of ionized hydrogen and of C I in a cold ($T \approx 20°$ K) intercloud medium. The OAO-C *Copernicus* observations in the direction of λ Sco are consistent with cosmic abundances and a uniform-density medium, except for C III whose predicted column density from the C III ionization zone surrounding the star is a factor ~10 greater than the observed result.

*Subject headings:* abundances — interstellar matter

The observations of interstellar ultraviolet absorption lines in the directions of unreddened stars (Rogerson *et al.* 1973) by the OAO-C *Copernicus* satellite show a surprisingly low abundance of higher ionization stages of trace elements. Weisheit (1973) has calculated models for a low-density ($n = 0.1$ cm$^{-3}$) intercloud medium exposed to a steady flux of soft X-rays or of 2-MeV cosmic rays that ionize hydrogen atoms at a rate $\zeta = 2 \times 10^{-15}$ s$^{-1}$. The resulting equilibrium in the X-ray case has $T \approx 10^4$ ° K, $x = n_e/n_{\rm H} \approx 0.2$, and ion density ratio N II/N I $\simeq 15$, which is in reasonable agreement with the ultraviolet observations considering the large uncertainty in the column densities derived from the saturated lines of these ions. However, the same models predict ratios of N III/N $\simeq 0.3$ and C III/C $\approx 0.3$ that are much higher than the observed ratios of column densities $N$(N III)/$N$(N) $\lesssim 10^{-4}$ and $N$(C III)/$N$(C) $\approx 5 \times 10^{-5}$.

The observations therefore cast doubt on the existence of such a steady ionizing flux (Mészáros 1973; Weisheit and Tarter 1973) and require a rethinking of possible mechanisms for obtaining the observed ratios. Perhaps the ionizing flux in the solar neighborhood is anomalously low, but then it is difficult to understand the hydrogen ionized fraction that is indicated by dispersion measures of nearby pulsars and by the observed C I column density to be discussed below.

In this *Letter* we show that a time-dependent model for ionization of trace elements can help to explain the observations, although the low column density of C III remains a puzzle because the H II region around the observed star should contribute more C III than is observed.

In order to understand the difference between steady-state and time-dependent ionization, let us consider the relative populations of C III/C II and H II/H I. In the steady-state model, assuming negligible ionization to C IV, we have

$$\frac{C\ \text{III}}{C\ \text{II}} = \frac{H\ \text{II}}{H\ \text{I}} \frac{\zeta_{\text{C II}}}{\zeta_{\text{H I}}} \cdot \frac{\alpha_{\text{H}}}{\alpha_{\text{C III}}}, \tag{1}$$

where the ratio of ionization rates is $\zeta_{\text{C II}}/\zeta_{\text{H}} \approx 40$ for X-ray ionization (Weisheit 1973) and the ratio of recombination rates is $\alpha_{\text{H}}/\alpha_{\text{C III}} \approx 0.2$ (Tarter 1973) at $T \approx 10^4$ ° K. Therefore, C III/C II $\approx$ 8H II/H I in the steady-state case.

Now consider the extreme model in which all the C III and H II were created in a single ionizing burst. Again neglecting ionization to higher stages, the time-dependent recombination equations for C III and H II may be combined to yield

$$\text{C III}|_{\text{final}}/C\ \text{III}|_{\text{initial}} = (\text{H II}|_{\text{final}}/\text{H II}|_{\text{initial}})^{\alpha_{\text{C III}}/\alpha_{\text{H}}}. \tag{2}$$

For example, assuming an initial state of H II/H = 1, C III/C = 1, we find after a time such that H II/H$|_{\text{final}}$ $\sim 0.2$, C III/C$|_{\text{final}} \approx 10^{-4}$ H II/H$|_{\text{final}}$, which is much smaller than in the steady-state case. This single-burst analysis gives the maximum difference possible between the time-dependent and the steady-state models, and may explain how an ionizing burst can leave behind considerable H II but very little C III. Similar conclusions follow for the abundance of N III compared with H II.

The same qualitative differences between steady and time-dependent ionization occur if low-energy cosmic rays are the ionizing agents.

A more realistic time-dependent model would have the trace elements ionized by a random sequence of bursts of variable strength according to the distance from the source. In that case, the resulting abundances of ions will be intermediate between the single-burst

* Present address: NASA, Goddard Space Flight Center, Greenbelt, Maryland.

† Also Department of Physics and Astrophysics, University of Colorado.

model and the steady-state model, because repeated weak bursts from distant sources have the effect of a steady background source. Gerola, Kafatos, and McCray (1974) have developed a statistical time-dependent description for the hydrogen ionization and temperature structure of the low-density interstellar gas. We present here a brief description of the model and its extension to the ionization structure of carbon and nitrogen.

We assume a galactic disk of radius 10 kpc and thickness 200 pc filled with a gas of constant density $n = 0.3\ \mathrm{cm}^{-3}$ and cosmic abundances (cf. Dalgarno and McCray 1972). We fix our attention on a given point $P$ in the galactic plane. Bursts of soft X-rays ($\epsilon_X = 150$ eV) with total energy $E_{SN} = 7 \times 10^{50}$ ergs are assumed to occur randomly in space and time with a mean rate 1/30 per year in the galactic disk. Numerical codes already exist for the time-dependent transfer of a burst of X-rays from a point source (Gerola, Iglesias, and Gamba 1973; Schwarz 1973). We have extended these calculations to include a range of initial conditions in temperature and ionization of trace elements. For each ionizing event at distance $D$ from point $P$ we calculate the discontinuous change in temperature and ionization of hydrogen, carbon, and nitrogen at $P$. Between ionizing events we calculate the time-dependent cooling and recombination of the gas. This process of random ionization and subsequent cooling and recombination has been numerically solved by a Monte Carlo simulation. By allowing this process to continue long enough (about $10^8$ years) we may construct probability distribution functions, e.g., $P$(C III/C, $x$) which is proportional to the fraction of time that the gas spends within a given range of log C III/C and log $x$. The effect of the observed soft X-ray background was also included using rates given by Weisheit (1973).

We are modeling the gas in the galactic disk by a superposition of fossil Strömgren spheres, each of radius ~100 pc, which is comparable to the distance to the stars observed by the *Copernicus* satellite. Therefore, we expect that the physical state of the gas in the solar vicinity is dominated by the last nearby burst.

We have also extended the calculations of Weisheit (1973) to a range of values of steady ionization rate $\zeta$ in order to allow for possible spatial fluctuations in the distribution of the hypothetical sources of steady ionization.

The results of these calculations are presented in figures 1 and 2. The resulting probability distribution for temperature and ionized fraction is bimodal with probability maxima for $T \approx 3000°$ K, $X = n_e/n_H \approx 0.03$; and for $20 < T < 100°$ K, $3 \times 10^{-3} < x < 2 \times 10^{-1}$ (Gerola *et al.* 1974). The most important difference in the ($T$, $x$)-structure of the gas is a significant probability for partially ionized cold gas, which is forbidden in the case of steady ionization. Figure 1 shows the joint probability density for C III/C and ionized fraction $x$. Note the high probability for low C III/C yet reasonably high $x$, as predicted by the single-burst example above. An analogous graph for N III/N versus $x$ is almost identical to figure 1. Figure 2, which shows the joint probability density for N II/N and $x$, is qualitatively different from figure 1 because, unlike the case with C III and N III, $\alpha_{N\ II} \approx \alpha_{H\ II}$ (Tarter 1971, 1973). Since the X-ray and cosmic-ray ionization rates for N I → N II are greater than for H I → H II, it is impossible to construct a model, steady-state or time-dependent, in which N II/N I < H II/H I.

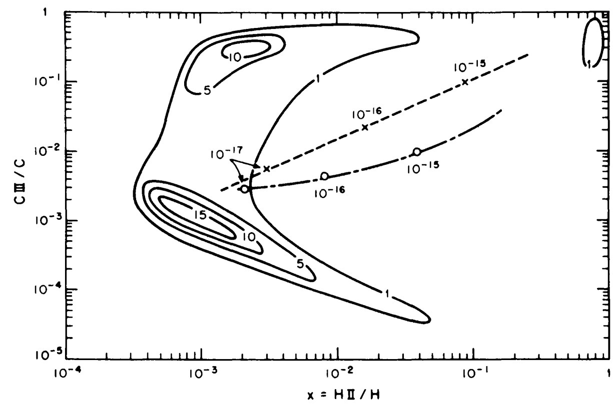


FIG. 1.—Joint probability distribution $P$(C III/C, $x$). *Solid curves*, contours of equal probability density, indicated in arbitrary units by numbers on the curves. *Dashed curve*, ratios for a steady flux of 100-eV X-rays with hydrogen ionization rates ($\mathrm{s}^{-1}$) indicated by crosses. *Dash-dot curve*, same for 2-MeV cosmic rays.

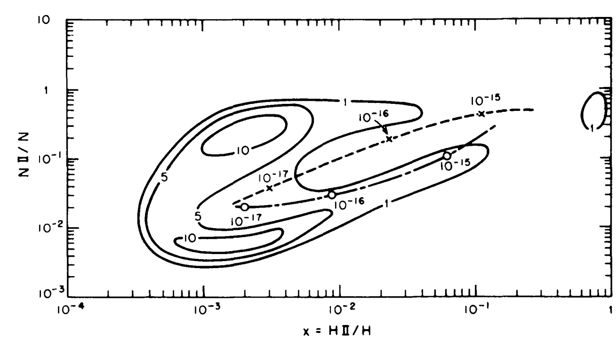


FIG. 2.—Joint probability distribution $P$(N II/N, $x$). Symbols as in fig. 1.

We consider now the interpretation of the *Copernicus* results (Rogerson *et al.* 1973) on unreddened stars, taking λ Sco as an example. Cosmic abundances H:C:N = $1{:}5 \times 10^{-4}{:}8 \times 10^{-5}$ are assumed throughout. The observed column densities log [$N$(H)cm$^{-2}$] = 19.89 and log $N$(C III) ≈ 12 then give a ratio C III/C $\lesssim 5 \times 10^{-5}$ in the intercloud medium, which according to figure 1 implies $x < 0.1$. This result in turn implies that N II/N < 0.1 in the intercloud medium; therefore the observed column density log $N$(N II) = 14.6 cannot be due to the intercloud medium, even if the gas had a temperature $10^4$ ° K and velocity dispersion $b = 10$ km s$^{-1}$.

In fact, the low value N III/N, C III/C implies that the intercloud medium must have $T \leq 100°$ K unless some steady nonionizing heat source is operative. We therefore suggest that $b \leq 4$km s$^{-1}$ is more appropriate for the intercloud velocity dispersion in the solar vicinity.

The H II region around the star λ Sco can easily account for the observed column density of N II. We have calculated the ionization zones for ions of carbon and nitrogen around the star λ Sco, assuming a distance of 112 pc and constant gas density $n = 0.22$ cm$^{-3}$. We have chosen model atmospheres that give visible spectra in accord with the observations of Watson (1972). Two sets of model atmospheres were used, the first a non-LTE calculation by Mihalas (1972) with no line blanketing and the second a LTE calculation by Kurucz, Peytremann, and Avrett (1973) with line blanketing. In calculating the ionization zones we only include opacity due to H and He. The results of these calculations agree generally with those of Weisheit and Tarter (1973). The radius of the N II ionization zone is the same as that of the H II zone, 5 pc, so that the observed column density log $N$(N II) = 14.6 with $b = 10$ km s$^{-1}$ is just about what would be expected. The ionization threshold of N II, 29.6 eV, is greater than the He I edge at 24.6 eV at which the stellar ultraviolet flux is totally absorbed very close to the star. Therefore, a negligible column density log $N$(N III) is expected in the vicinity of the star in accord with the observed upper limit.

In contrast, our calculated column density log $N$(C III) = 13.2, which agrees with that of Weisheit and Tarter (1973), is a factor 10 greater than the observed column density. This discrepancy is serious because the calculated column density of C III from the ionization zone is rather insensitive to the assumed parameters. The flux from the star in the narrow bandwidth from the C II edge at 24.38 eV and the He I edge at 24.6 eV is not significantly attenuated by absorption in the H II region. The resulting C III zone, which does not have a sharp boundary, gives a column density of

$$N(\text{C III}) \approx \tfrac{1}{2}\pi n_c R_* [\textstyle\int F_\nu \sigma_\nu d\nu / n_e \alpha_{\text{C III}}]^{1/2} , \qquad (3)$$

where $F_\nu$ is the stellar flux and the integration extends from 24.38 eV to 24.6 eV.

One possible explanation for the discrepancy might be a very large error (factor ~$10^2$) in the model atmosphere flux at the He I edge. However, the two very different models we have used give roughly the same C III column density. Perhaps the C II photoionization cross-section given by Weisheit (1973) is off by a large factor. Another possible explanation might be a very low gas density, $n \lesssim (3 \times 10^{-3})$ cm$^{-3}$, in the vicinity of the star. If so, the radius of the low-density region must be $\gtrsim 1$ pc. Perhaps expansion of the H II region could account for a lower gas density near the star (Lasker 1966), but it is uncertain whether sufficient expansion could occur to create such a low-density region. If carbon depletion by a factor ~10 is the assumed mechanism to explain the low C III column density, it must occur selectively in the vicinity of the star; otherwise, it becomes difficult to understand the observed C I column density.

The H II region cannot account for the observed column density of C I. Since C I is ionized by starlight at a rapid rate, $\zeta^* = 1.7 \times 10^{-10}$ s$^{-1}$ (Weisheit 1973), the ratio C I/C II is not affected directly by other sources of ionization, either steady-state or time-dependent. It is affected only indirectly through the temperature and ionization dependence of the C II recombination rate according to

$$[N(\text{C I})/N(\text{C II})] = [n_e \alpha_{\text{C II}}(\tau)/\zeta^*] .$$

Mészáros (1973) has called attention to the difficulty of understanding the observed $N$(C I) in the steady-state model. In this case, if the electron density in the intercloud medium is sufficient to account for the observed $N$(C I), it follows that the temperature of the intercloud medium is ~$10^4$ ° K and the column densities of C III and N III must greatly exceed the observed values. Weisheit and Tarter (1973) introduce a thick ($\Delta R \approx$ 1 pc) shell with a density $n \approx 25$ cm$^{-3}$, surrounding the H II region ($R \approx 5$ pc) to explain the observed $N$(C I). This seems unlikely if the star υ Sco is at a greater distance than λ Sco. The angular separation of 36′ between the stars corresponds to a transverse separation of 1 pc at a distance of 100 pc. The line of sight to υ Sco would then have to intersect the shell of λ Sco and yield greater column densities of all ions, in conflict with the observations. The differences in the column densities toward the two stars may indicate that some of the ob-

TABLE 1

Log Column Densities (cm$^{-2}$)

| Ion | Calculated: Intercloud Medium | Calculated: H II Region | Observed: $b = 4$ km s$^{-1}$ | Observed: $b = 10$ km s$^{-1}$ |
|---|---|---|---|---|
| H I | 19.89 | ... | 19.89 | 19.89 |
| H II | ... | 18.5 | ~18.4* | 18.4* |
| Total H | ... | ... | ... | ... |
| C I | 13.53 | ... | 13.53 | 13.48 |
| C II | 16.39† | 15.0 | 16.91 | 14.86 |
| C III | ≪12 | 13‡ | 11.99 | 11.96 |
| Total C | 16.4 | 15.0 | ... | ... |
| N I | 15.76† | ... | 15.22 | 14.07 |
| N II | 14.06 | 14.49 | 17.08§ | 14.60 |
| N III | <10‖ | ... | <11.97 | <11.97 |
| Total N | 16.0 | ... | ... | ... |

* Assuming 3% ionization in accord with pulsar dispersion measures.

† Derived from cosmic abundances.

‡ See comments in text.

§ Inconsistent with cosmic abundances.

‖ The uncertainty in the model atmospheres above the He I ionization edge is too large to make a meaningful calculation.

served ultraviolet lines originate within 1 pc of the respective stars. We find that an intercloud medium with $20^\circ$ K, $x \approx 5 \times 10^{-2}$, can easily account for the observed $N$(C I). Table 1 presents a summary of these considerations. Note that all column densities are consistent with the assumption of cosmic abundances. The resulting free-free absorption opacity $\tau$ (20 MHz) $< 1$ at a distance of 100 pc in such a medium.

In conclusion, we suggest that the *Copernicus* observations of unreddened stars provide evidence for a cold intercloud medium in the solar neighborhood that was suddenly ionized less than or about $10^6$ years ago but has not yet fully recombined.

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