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LETTER

Letter to the Editor

CI fine-structure emission from non-equilibrium PDRs

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Abstract. We present computations of [CI] 609 μm and 370 μm fine-structure line emission from non-equilibrium clouds which are suddenly shielded from initially intense far-ultraviolet radiation fields. After the incident UV fluxes are diminished the initially abundant C^+ ions rapidly recombine, and the neutral atomic carbon is then slowly incorporated into CO molecules. The cloud cooling times are longer than the CI formation times, and intense [CI] emission persists as the clouds cool. The [CI] emission is thus much brighter from cooling clouds than in equilibrium photon dominated regions. We argue that if UV-scattering is inefficient the extended [CI] emission observed in star-forming regions may be better explained by non-equilibrium models than by steady state models.

Key words: Line: formation - ISM: clouds - ISM: molecules - Radio lines: interstellar

1. Introduction

The [CI] $^3P_1 \rightarrow ^3P_0$ 609 μm fine-structure emission line has been observed in several galactic star-forming molecular clouds including M17, S140 and Orion (Phillips & Huggins 1981; Keene et al. 1985; White & Padman 1991; Hernichel et al. 1992; Minchin et al. 1993; Plume et al. 1994; Tauber et al. 1995). [CI] emission has also been observed in the nuclei of the starburst galaxies IC 342, NGC 253 and M82 (Büttgenbach et al. 1992; Schilke et al. 1993; Harrison et al. 1995; Israel et al. 1995; Stutzki et al. 1997). In the standard interpretation, the [CI] emission arises in narrow cloud layers in the C^+/C/CO transition zones of photon-dominated regions (PDRs) (Tielens & Hollenbach 1985; Sternberg & Dalgarno 1989, 1995). In galactic sources the [CI] emission is observed to be much more extended than would be expected from a single narrow [CI] emission layer at the molecular cloud surface. This behavior together with a similarly large [CII] extent has been understood with the recognition that molecular clouds are clumpy (cf. Stutzki et al. 1988).

In clumpy clouds the incident ultraviolet photons penetrate the low density components but are absorbed by a distribution of embedded high density (and unresolved) clumps each containing a PDR with its [CI] emission layer. The low density gas is a negligible source of [CI] emission because atomic carbon is predominantly ionized in this component. If this picture is correct then the [CI] emission should be well correlated with low- and mid-J CO rotational line emission which is also efficiently produced in dense PDRs (Köster et al 1994). However, observations indicate (Keene et al. 1985; Plume et al. 1994; Tauber et al. 1995) that most of the CI emission originates from regions deeper into the molecular clouds than the mid-J CO emission lines. It appears that the CI emission may not arise preferentially in the hot and dense clumps which produce the CO rotational emission.

In this *Letter* we propose an alternative scenario in which the bulk of the [CI] emission is actually produced in low-density regions which have been recently shielded from the UV radiation fields by the dense (and optically thick) clumps moving around in the cloud. We present the results of model calculations of [CI] emission from non-equilibrium clouds which are suddenly shielded from initially intense far-ultraviolet radiation fields. We show that intense [CI] emission is produced in such clouds and persists for up to 10^4 years as the clouds cool and the carbon is incorporated into CO. In §2 we describe our model, and in §3 we discuss the results of our calculations. We present a summary in §4.

2. Time Dependent PDRs

Several theoretical studies of time-dependent effects in PDRs have been presented in the literature (Hill & Hollenbach 1978; Roger & Dewdney 1992; Goldshmidt & Sternberg 1995; Hollenbach & Natta 1995; Bertoldi & Draine 1996). However, these models focussed primarily on the evolution of the atomic-

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to-molecular (H/H_2) hydrogen dissociation fronts that form in clouds exposed to stellar radiation. Monteiro (1991) presented time-dependent computations of the distributions of C^+, C, and CO in rotating (spherical) clouds which are illuminated by radiation from a single direction. In Monteiro's models the average neutral atomic carbon abundance is much larger than in non-rotating clouds because of the rapid recombination of the C^+ ions in the "dark side" of the clouds.

In this paper we adopt a different approach. We follow the evolution of plane-parallel (semi-infinite) model clouds which are initially exposed to radiation for sufficiently long times such that equilibrium PDR structures become established in them. We then compute the further evolution of the coupled chemical and thermal structure of the clouds after the FUV flux is instantaneously reduced. In our models we assume that the hydrogen gas density, the elemental abundances, and gas to dust ratio, do not vary with time. The resulting time dependent behavior is then due to a combination of chemical and thermal evolution. Our computations involve the solution of a set of coupled partial differential equations as functions of time, t, and cloud depth z. Details of the mathematical formulation and numerical solution will be presented elsewhere (Störzer & Hollenbach 1997). Here we focus on the resulting behavior of the [CI] emission.

Because of computing time limitations in the time dependent models we solve only a simplified oxygen/carbon chemical network involving 164 reactions between 24 different species. We computed the photo and chemical rates using the data provided by Millar et al. (1991) and from Sternberg & Dalgarno (1995). CO and H_2 photodissociation is treated as described in Köster et al. (1994). We have not included sulphur chemistry in our calculations which contributes only modestly to the total CI column density (cf. Sternberg & Dalgarno 1995). This simplification is however not important for the PDR structure after the shadowing, because the layers where CI is formed by sulphur reactions have a very low temperature and they do not contribute much to the total CI column density. We assume an oxygen fractional abundance of 5.0×10^{-4} and a carbon fractional abundance of 3.0×10^{-4} in our models. We use a cosmic ray ionization rate of $5 \times 10^{-17}\mathrm{s}^{-1}$, the assumed line width (FWHM) is $1.2\,\mathrm{km\,s}^{-1}$.

We assume that a typical multi-phased PDR consists of high density clumps ($n \geq 10^5\mathrm{cm}^{-3}$) which are embedded and move randomly within a lower density ($n = 5 \times 10^3\mathrm{cm}^{-3}$) interclump medium. In the calculations presented here we assume that the FUV radiation field at the surface of the cloud (facing the stellar sources) equals $\chi = 10^5$ times the (Draine 1978) interstellar field. We assume that the clump sizes are $\leqq 0.1$ pc and that the clumps have a velocity dispersion of a few $\mathrm{km\,s}^{-1}$, corresponding to the observed line widths (Keene et al. 1985, Stutzki & Güsten 1990, Plume et al. 1994). We assume that an equilibrium PDR structure is initially established in the interclump medium, and we then follow the evolution of distinct regions which are (suddenly) shielded by intervening dense clumps. We assume that $\chi = 0$ in the shadowed regions.

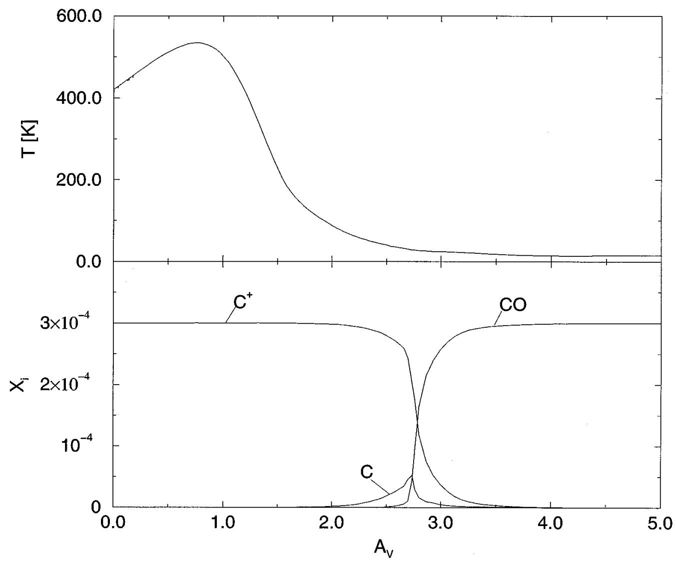

Fig. 1. Temperature structure and C^+/CI/CO abundances X_i with respect to the total hydrogen particle density for a steady-state PDR model with $n = 5 \times 10^3\mathrm{cm}^{-3}$ and $\chi = 10^5$.

3. Results

The temperature and chemical structure of the initial equilibrium PDR in the low density interclump medium is shown in Fig. 1. CI forms in the C^+/C/CO transition zone where the temperature is about 30 K. Fig. 2a shows the temperature profile at various times after the shielding has occured. The time-dependent thermal structure is governed by the equation $C_V dT/dt = \Gamma - \Lambda$ where T is the gas temperature, t is the time, Γ and Λ are the heating and cooling rates per unit volume, and C_V is the specific heat at constant volume. Our computations show that the gas cools primarily via the [CI] 609 μm and 370 μm fine structure transitions with a net cooling rate $(\Gamma - \Lambda)$ of a few $10^{-22}\,\mathrm{erg\,cm}^{-3}\,\mathrm{s}^{-1}$. At a density of $5 \times 10^3\mathrm{cm}^{-3}$ this yields a cooling time scale δt of about 10^4 yrs.

In Fig. 2b we show the CI abundance profiles at the same times after the cloud shielding has occured. In layers where the C^+ density is initially very large, and where the local radiation field is severely diminished, the carbon atoms are formed rapidly by radiative recombination $C^+ + e^- \rightarrow C + \nu$. Molecular hydrogen forms slowly on grain surfaces so that in layers where the hydrogen is atomic before the FUV field is diminished the newly formed atomic carbon is removed primarily by radiative association $H + C \rightarrow CH + \nu$. In regions where the hydrogen is molecular the carbon is removed mainly by cosmic-ray induced photo-dissociation $C + \nu_{cr} \rightarrow C^+ + e^-$ and to a minor extent by $C + O_2 \rightarrow CO + O$ and $C + OH \rightarrow CO + H$.

The time scale t_{sh} during which material of the low density interclump medium or material of higher density condensation are shadowed from a fragment with size r and velocity v is $t_{sh} \approx r/v$. For a fragment size $r \leq 0.1$pc and a velocity of a few km/sec, $t_{sh} \leq 5 \times 10^4$yr. This implies that the material is warm enough to excite both CI fine structure lines efficiently, even for relatively large fragments.

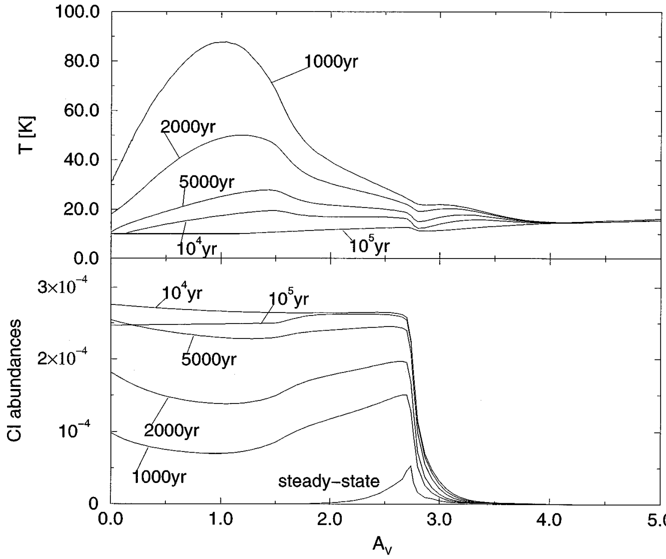

Fig. 2. Temperature structure and CI abundances with respect to the total hydrogen particle density as function of time after the low density component (n= $5 \times 10^3 cm^{-3}$) has been shadowed from the FUV radiation field (i.e. FUV field reduced to χ = 0).

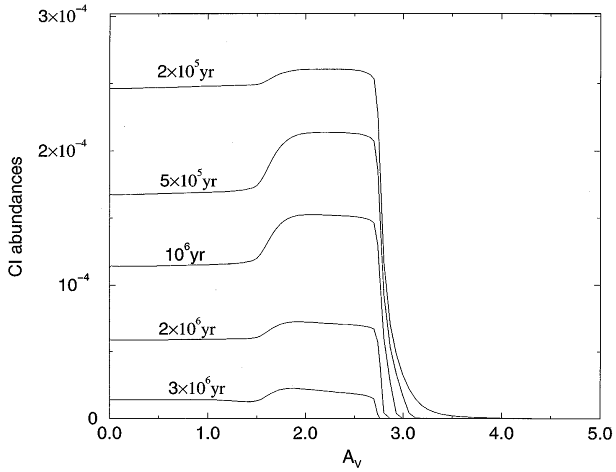

Fig. 3. CI abundances with respect to the total hydrogen particle density for larger time scales after the low density layer (n= $5 \times 10^3 cm^{-3}$) has been shadowed (χ = 0) from the FUV radiation field.

Fig. 3 shows the atomic carbon abundance as function of A_V and as function of time for longer time scales. After about 10^6 yrs half of the carbon is incorporated in CO, after 4×10^6 yrs all of the carbon is bound in CO. For models with lower densities (n= $10^3 cm^{-3}$) one third of the carbon remains in atomic form even for the steady state solution. This corresponds to the "high ionization phase" solution for dark interstellar clouds found by le Bourlot et al. (1993).

Shadowing time scales larger than 10^5 yrs are unlikely, because they can only be achieved by very large clumps. If a shadowed layer is again exposed to the strong initial FUV field of $\chi = 10^5$ and most of the hydrogen is still in atomic form, the steady state situation will be established very rapidly because the time scales t_{CI} to photoionize CI are very short ($t_{CI} \approx 200\,\mathrm{yrs}/\chi$).

In Fig. 4 we display the resulting [CI] 609 μm and 370 μm fine structure line intensities as function of time after the initial illumination of the previously fully molecular cloud. When the FUV intensitiy of $\chi = 10^5$ is switched on, the line intensities increase, until after 10^5 yrs a steady-state situation has been established. The medium is then shadowed from the FUV radiation at t $> 10^5$yrs. The line intensities increase rapidly, and attain maximum values ten times larger than in steady state approximately 1000 yrs after the shadowing. In PDRs with strong FUV fields the measured [CI] 609 μm line intensities are $\sim 10^{-6}$ erg cm^{-2} sec^{-1} sr^{-1}, this is in good agreement with the calculated line intensity of 3×10^{-6} erg cm^{-2} sec^{-1} sr^{-1} in the 609 μm line immediately after the shadowing. The factors by which the CI line intensities are enhanced after the shadowing are insensitive to the cloud density. However, the time-scale during which enhanced emission persists decreases with increasing density and shorter cooling times.

Note, that the line intensities given in Fig. 4 correspond to a face on geometry. In an edge on geometry like in M17 SW or the Orion Bar one would expect that the CI intensity peaks behind the higher density clumps. If these condensation are as large as the telescope beam the CI intensity should peak at larger distances from the cloud surface than high density indicators such as the mid-J ^{12}CO lines. If the clumps are much smaller than the telescope beam then the CI emission should peak at intermediate cloud depths where sufficient numbers of intervening dense clumps are available for shielding, but where the low-density gas can also be periodically heated by the stellar radiation. At deeper layers the amount of CI would be larger but the temperatures lower due to the longer shadowing times. For layers which are nearer to the surface the area filling factor for the shielded regions would be small. In an edge-on geometry the CI line intensities may be enhanced compared to face-on geometries when several shadowed regions lie along the line of sight.

The fraction of material newly shielded from the UV radiation within a time δt relative to the total material shielded is given by $\frac{v\,\delta t}{r}$. As shown above, this is of order unity over the time that the [CI] emission stays bright after shadowing. As the UV radiation affects the cloud only to a depth, where the clumps effectively cover the complete projected cloud surface area, and as the fraction of interclump material shadowed increases linearly with depth, the shadowed interclump material is always about half of the total PDR volume in a clumpy cloud. Combining these two estimates, one sees that up to half of the PDR interclump material may show enhanced [CI] emission. This estimate gives only an upper limit for the CI emission because we assume that the strength of the FUV field in the shadowed layers is zero. If a sufficiently large UV photon flux is scattered into a shadowed region the carbon may not be able to recombine efficiently due to continued photoionization by the scattered photons. Efficient scattering will mitigate the enhancement of CI emission from the non-equilibrium shadowed regions.

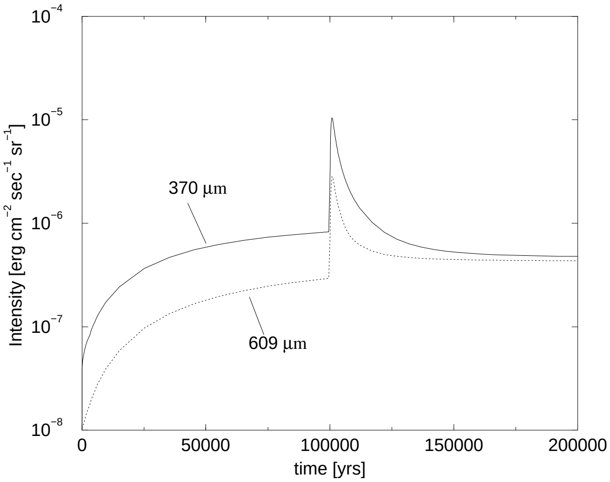

Fig. 4. CI fine structure line intensities as function of time ($\chi = 10^5$ for $t \leq 10^5 yrs$, $\chi = 0$ for $t > 10^5 yrs$) for a low density layer with n= $5 \times 10^3 \mathrm{cm}^{-3}$.

4. Summary

We have presented computations of [CI] 609 μm and 370 μm fine-structure line emission from non-equilibrium clouds which are suddenly shielded from intially intense far-ultraviolet radiation fields. After the incident FUV fluxes are diminished the initially abundant C^+ ions rapidly recombine, and the neutral carbon is then slowly incorporated into CO molecules. Our calculcations show the cloud cooling times are longer than the CI formation rates, so that intense [CI] emission persists as the clouds cool. The production of [CI] emission is much more efficient in cooling clouds than in equilibrium PDRs. We propose that in clouds in which UV scattering is inefficient most of the [CI] emission is produced in non-equilibrium regions which are effectively shadowed by intervening (and moving) optically thick clumps. In this picture the C^+ and OI fine structure lines are coming from the unshadowed layers and the surfaces of high density clumps, where the structure is well described by equilibrium models. These line intensities are therefore not very sensitive to the non-equilibrium effects. Our scenario explains why [CI] emission is not spatially coincident with tracers (such as mid-J CO emission lines) of high density clumps, but appears to originate at greater distances from the illuminating stars. This scenario also implies that up to 50% of the material in clumpy PDRs may be out of chemical and thermal equilibrium due to the time variation of the temporal shadowing by moving clumps.

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