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Neutral carbon in the diffuse cold neutral medium

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Abstract. We discuss the relative abundance of C I/H_2 in the diffuse cold neutral medium. Using semi-analytical formalism, we describe how C I/H_2 depends on the main parameters of the medium: number density, metallicity, strength of the UV field and cosmic ray ionization rate. We show that observed relative abundance of C I/H_2 in the high-redshift damped Lyman alpha systems can be reproduced within our model assuming the typical expected conditions in the diffuse cold medium. We also discuss that the observed relative abundance of C I/H_2, when coupled with data on the population of the fine structure levels of neutral carbon and the rotational levels of molecular hydrogen can be used to derive the cosmic ray ionization rate in the low-metallicity interstellar medium.

Keywords: galaxies, interstellar medium, cosmic rays

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Нейтральный углерод в диффузной фазе холодной нейтральной среды

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Аннотация. В работе обсуждается относительная распространенность C I/H_2 в диффузной холодной нейтральной межзвездной среде. Используя полуаналитический формализм, мы описываем, как C I/H_2 зависит от основных параметров в среде: объемной концентрации, металличности, интенсивности УФ поля и скорости ионизации космическими лучами. Показано, что наблюдаемая относительная концентрация C I/H_2 в демпфированных Лайман-альфа системах на больших красных смещениях воспроизводится нашей моделью в предположении типичных условий для холодной диффузной среды. Также обсуждается, что наблюдаемая относительная распространенность C I/H_2 вместе с измеренными населенностями уровней тонкой структуры нейтрального углерода и вращательных уровней молекулярного водорода может использоваться для оценки скорости ионизации космическими лучами в межзвездной среде низкой металличности.

Ключевые слова: галактики, межзвездная среда, космические лучи

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Introduction

Cosmic rays are an important component of the interstellar medium, affecting its dynamics, thermal and chemical evolution. In the neutral interstellar medium, low-energy cosmic rays, due to their penetrating power, are the main source of residual ionization, which determines the formation of most molecules. Previously, indirect methods were used to estimate the cosmic ray ionization rate (CRIR), based on the observations of the abundance of a number of molecules that are sensitive to the degree of ionization of the medium. These methods show that there is a large spread in the measured CRIR: from 10^{-17} to ~ 10^{-15} s^{-1}. Such a scatter can be caused by both the natural inhomogeneity of the CRIR in the interstellar medium, associated with the locality of sources and the effects of cosmic ray propagation, and by systematic effects in the methods of estimation used.

To estimate the CRIR one should use the elements sensitive to the ionization state of the medium. There are several molecules (such as H_3^+, OH^+, H_2O^+) used for this in the past (see e.g. [1, 2]) However, these species mostly trace dense molecular gas, while there were few attempts made to constrain CRIR in diffuse gas based on the HD (see [3] and references therein). In turn, the carbon is one of the most abundant elements in the interstellar medium. In neutral diffuse ISM it is mostly present in the ionized form, C ıI, since the ionization potential of C ı is less than H I. However, in the cold phase of neutral ISM the number density and ionization fraction can be sufficiently high to maintain observable fraction of C ı, which produced by C ıI recombinaa tion. Since C ıI recombination rate can be sensitive to the degree of ionization in the interstellar medium, this may allow constraining on the cosmic ray ionization rate.

The C ı chemistry in diffuse ISM was comprehensively considered by e.g. [4, 5]. However, these studies described the observations obtained in our galaxy, i.e., considered only the local ISM. Nevertheless, currently there is a very large number of the observations performed at high-redshift DLAs, i.e., remote galaxies. These observations mostly associated with the low-metallicity gas ($z \leq 0.3$), where one can expect the changes in the ionization and thermal balance (see e.g. [6–8]) which is an important ingredient for the presence of C ı.

In this work, we have developed a formalism to describe C ı abundance in diffuse ISM. We studied the effect of the metallicity on presence of C ı and developed the method for estimating the CRIR based on measuring the relative abundance of neutral carbon, C ı, and molecular hydrogen, H_2 as well as the population of the fine structure levels of neutral carbon, C ı, and the rotational levels of molecular hydrogen, H_2

Relative abundances of C I and H_2.

We used a similar formalism to calculate relative C ı/H_2 abundances as was applied previously for HD/H_2 and OH/H_2 in [7, 9]. As in mentioned papers we consider the homogeneous (specified by the total hydrogen number density n_H^{tot}) and isothermal (with temperature $T = 100$ K, corresponding to cold diffuse ISM) medium with metallicity, Z, that is exposed by the UV field of strength, χ, and cosmic rays with ionization rate, ζ (the primary ionization rate per hydrogen atom, in units of ~10^{-17} s^{-1}).

The formalism is based on the analytical description of H I/H_2 transition proposed recently by [10, 11], where H_2 number density as a function of H_2 column density, N_{H_2} can be written as

$$n_{H_2} = n_H^{tot} / (\alpha S_{H_2}(N_{H_2}) e^{-\sigma_g (N_H + 2N_{H_2})} + 2), \quad (1)$$

where N_H is atomic hydrogen column density, S_{H_2} is self-shielding function, $\sigma_g = 1.9\times10^{-21} Z$ cm^2 is the dust Lyman-Werner photon absorption cross-section per hydrogen atom, and α is the ratio of free space H_2 photo-dissociation and H_2 formation on the dust grains.

The abundance of neutral carbon can be expressed as

$$n_{\rm CI} \approx n_{\rm C}^{\rm tot}(1-f_{\rm C^+}) \equiv n_{\rm H}^{\rm tot}x_c(1-f_{\rm C^+}) \equiv n_{\rm H}^{\rm tot}[{\rm C/H}]_\odot Zd_{\rm C}(1-f_{\rm C^+}), \tag{2}$$

where $x_{\rm C} \equiv [{\rm C/H}]_\odot Zd_{\rm C}$ is a gas phase abundance of carbon, $[{\rm C/H}]_\odot \approx 2.7\times10^{-4}$ is the solar abundance of carbon, $d_{\rm C}$ is depletion of the carbon on dust grains that depends on Z, and was taken following [6], and $f_{\rm C^+}$ is the carbon ionization fraction, i.e., $f_{\rm C^+} \equiv n_{\rm C^+}/n_{\rm C}^{\rm tot}$. The latter can be determined from the balance equation for C^+, where it mainly forms by the photoionization of C I and destructed by the recombination with free electrons and dust

$$n_{\rm CI}\chi D_{\rm CI} = n_{\rm C^+}n_e\alpha_{\rm C}^{\rm rec} + n_{\rm C^+}n_{\rm H}^{\rm tot}\alpha_{\rm C}^{\rm gr}, \tag{3}$$

where n_e is an electron density, and $D_{\rm CI} \approx 2.6\cdot10^{-10}e^{-3.76A_V}$ is the neutral carbon photoionization rate determined by [12]. $\alpha_{\rm C}^{\rm rec}$ and $\alpha_{\rm C}^{\rm gr}$ are recombination rates with free electrons [13] and dust, respectively. In terms of $f_{\rm C}$ it can be written as

$$\chi D_{\rm CI}(1-f_{\rm C^+}) = f_{\rm C^+}n_{\rm H}^{\rm tot}(x_e\alpha_{\rm C}^{\rm rec} + \alpha_{\rm C}^{\rm gr}), \tag{4}$$

where electron fraction $x_e \equiv n_e/n_{\rm H}^{\rm tot}$ can be approximated as

$$x_e = f_{\rm H^+} + x_c f_{\rm C^+}, \tag{5}$$

where $f_{\rm H^+}$ is the hydrogen ionization fraction, which can be obtained using the balance equation for H^+. We follow the similar description as was presented in [7] except we did not consider the contribution of minor reactions and used the exact form for electron density given in Eq. 5. Then,

$$k_\zeta^{\rm eff}(1-f_{\rm H^+}) = f_{\rm H^+}(x_e\alpha_{\rm H}^{\rm rec} + \alpha_{\rm H}^{\rm gr}), \tag{6}$$

where $\alpha_{\rm H}^{\rm rec}$ and $\alpha_{\rm H}^{\rm gr}$ are recombination rates of H with free electron and dust, respectively, and $k_\zeta^{\rm eff} = k_\zeta^{\rm H}(1-f_{\rm H_2}) + \tilde{k}_\zeta^{\rm H_2}f_{\rm H_2} + k_\zeta^{\rm H_2}f_{\rm H_2}\left(1+k_1f_{\rm H_2}/2k_2(1-f_{\rm H_2})\right)^{-1}$, where $k_\zeta^{\rm H} = 1.7\zeta$, $\tilde{k}_\zeta^{\rm H_2} = 0.17\zeta$ and $k_\zeta^{\rm H_2} = 3.4\zeta$ and $k_1 = 2.1\cdot10^{-9}$ and $k_2 = 6.4\cdot10^{-10}$ cm^3 s^{-1}.

To derive $f_{\rm C^+}$ and $f_{\rm H^+}$ Eqs. (4), (5) and (6) should be solved together numerically, since the $\alpha_{\rm C}^{\rm gr}$ and $\alpha_{\rm H}^{\rm gr}$ are the functions of the combination of the physical parameters (see for example [14]). For $\alpha_{\rm H}^{\rm gr}$ we used parametrization from [14], while for C^+ [5] noticed an importance of the C^+ recombination with polycyclic aromatic hydrocarbons (PAHs), that lead to significantly (up to 100 times) enhanced grain-assisted recombination coefficients if there is a relatively large fraction of the negatively charged PAHs. The fraction of charged PAHs in turn depends on the physical parameters [5] and should be found self-consistently, but for simplicity, here we assume an intermediate case of C^+ recombination rate, that was set to be ten times higher than the rate proposed in [14].

Following presented formalism, $f_{\rm C^+}$ and hence $n_{\rm CI}$ are functions of the $N_{\rm H_2}$, since the reaction rates in Eqs. (4) and (6) depend on it, i.e., the depth within the cloud. Therefore, one can get the $N_{\rm CI}$ as a function of $N_{\rm H_2}$ by numerical integration to compare with observational data.

Results

In Fig. 1 we compare the observed and calculated dependence of C I and H_2 column densities. The observed C I and H_2 abundances was compiled from the all-known H_2-bearing DLAs detected at high redshifts using quasar spectra (see [3, 15, 16] and references therein). For calculated ones we used doubled value of C I column density at half observed H_2 column density, i.e., $N_{\rm CI}^{\rm obs} \equiv 2N_{\rm CI}(N_{\rm H_2}/2)$. Such procedure roughly emulates the slab medium of a given $N_{\rm H_2}$ but exposed by radiation field and cosmic rays from both the sides, due to our calculations are based on one-side radiation field models (inherited from formalism by [10]).

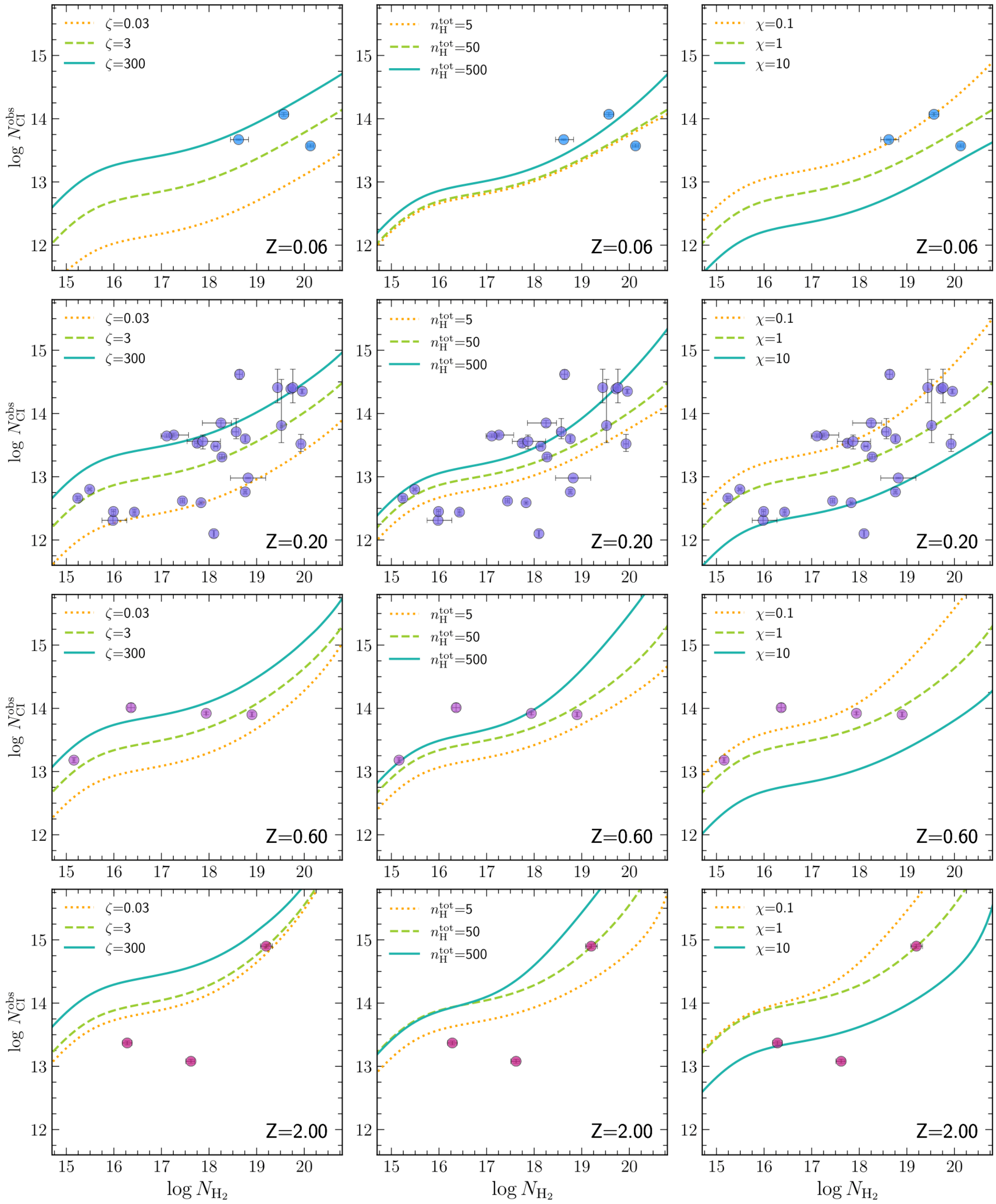

Fig. 1. The dependence of the column densities of C I on H_2. The colored points represent an observed abundances in high-redshift DLAs ([15, 16, 3] and references therein) binned by the metallicity, where systems in each bin shown in rows, with mean metallicity within the bin provided in the right bottom corner of the panel. The calculated dependences using described formalism are presented by solid, dashed and dotted lines, that correspond to the variation on one of the parameter from the base model with $n_{\rm H}^{\rm tot} = 50$ cm^{-3}, $\zeta = 3$ and $\chi = 1$.

The abundance of C I strongly depends on the metallicity, and it is known that the observational data on the metallicity spans about two orders from log $Z \sim -1.5$ to 0.5. Therefore, to compare the measurements with calculated ones we divide the sample in the four metallicity bins ≈ 0.5 size and calculate theoretical $N_{\rm CI}^{\rm obs}(N_{\rm H_2})$ profiles for the mean values in the bins. It is also evident that C I abundance depends on the three other global parameters of the cloud: the number density, $n_{\rm H}^{\rm tot}$, CRIR, ζ, and UV field strength, χ. To show the variation on these parameters, we constructed the base model with $n_{\rm H}^{\rm tot} = 50$ cm^{-3}, $\zeta = 3$ and $\chi = 1$ and varied independently each of the parameter within two dexs (for CRIR we varied in four dexs, that is motivated by recently obtained quadratic dependence of CRIR on χ [3]), that correspond to the typical measured variations [3, 16]. The resulted profiles of C I/H_2 abundances are shown in Figure 1. One can see that the observed data are reproduced within chosen ranges of the physical parameters relatively well.

One can see that C I/H_2 abundance is mostly sensitive to the variation of the UV field at each redshift bin. This is simply because the UV field directly scaled the C I abundance by photoionization. However, for low metallicity medium (corresponding to the most DLAs data), C I/H abundance also becomes quite sensitive to CRIR, since at this metallicity, the C II recombination rate depends on the electron abundance, which in turns depends on the H ionization fraction, which is sensitive to CRIR. Once metallicity approaches solar value, the electron densities start to be determined solely by the carbon abundance (see Equation 5) and hence C I/H_2 becomes little sensitive to CRIR (the bottom left panel in Fig. 1). Interestingly, that at low metallicities, C I/H_2 abundance becomes almost insensitive to the number density (the top central panel in Fig. 1), at the typically observed number densities $n_{\rm H}^{\rm tot} < \text{few} \times 100\text{cm}^{-3}$.

Physical conditions

Since the C I/H_2 abundance is sensitive to the physical parameters, the observed values can be used to derive them. However, since the dependence is quite complex, the C I/ H_2 abundance alone will provide very vast constraints, and likely on the combination of the parameters, e.g., $\sqrt{\zeta n_{\rm H}^{\rm tot}}/\chi$ for low metallicities. However, since C I/H_2 abundances are obtained using absorption line spectroscopy, in most cases (especially, if high-resolution spectrum was used) these data is accompanied with the measurements of the population of C I fine structure and H_2 rotational levels. The modelling of these populations may provide tight constraints on the number density, $n_{\rm H}^{\rm tot}$, and UV field strength, χ, see, e.g., [15, 16]). Obviously, these constraints may be exploited to determine CRIR using observed C I/H_2 abundances. In other words, C I/H_2 abundances coupled with population of C I fine structure and H_2 rotational levels will provide tight constrains jointly on the three key main parameters on the diffuse ISM: $n_{\rm H}^{\rm tot}$, χ and CRIR.

Conclusions

We describe the semi-analytical formalism to describe the relative abundance of C I/H_2 in the diffuse cold neutral medium and its dependence on the physical parameters. We show that it quite well reproduces the observation data on C I/H_2 from high-redshift DLAs and may provide the measurement of CRIR using additional constraints comes from the population of C I fine structure and H_2 rotational levels. However, we note that these results are sensitive to the value of grain assisted C^+ recombination rate. The latter strongly depends on the fraction of the charged PAH, that determines not only by the physical conditions, but also the dependence of the dust (or PAH) abundance on the metallicity, which as shown by recent studies (e.g. [17]) may have non-trivial behaviour and indicate a large natural dispersion. Therefore, to obtain the quantitative comparison with observed data and determine the CRIR from the C I/H_2 abundances this formalism needs to be supplemented with a proper modelling of the fraction of the charged PAH, coupled with an assumption of the dependence of the PAH abundance on the metallicity or observational constrains on it.

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