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ON DETERMINATION OF THE COSMIC RAY FLUX USING MOLECULAR HYDROGEN ABSORPTION LINES

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SUMMARY: We outline a procedure for estimating the cosmic ray flux at remote locations where molecular hydrogen absorption lines have been detected. The method relies on several assumptions whose validity in the local Galactic ISM has been independently verified, so it might be useful for much less accessible objects, especially damped Lyα absorption systems. Since most of low-energy cosmic rays in the Galactic environment are thought to originate in supernovae remnants, the link to the rate of high-mass star formation could, in principle, be established. We applied the method to a particular case of high redshift damped Lyα absorption system towards 0528−250 and obtained an estimate of proton density and some useful constraints.

Key words. Molecular processes – ISM: molecules – quasars: absorption lines

1. INTRODUCTION

Cosmic rays (henceforth CR) represent one of the most important, and yet the most elusive components of the interstellar medium (henceforth ISM) in disks of spiral galaxies. Although their origin and transport after almost a century of research are still not sufficiently understood, many of their properties have been recently quantitatively established, at least for the local CR flux (e.g. Grieder 2001). One of the important roles of CR is initiating the molecular cloud chemistry through ionization, since they are the only agents capable of penetrating into depths of giant molecular clouds. They are the ultimate cause of the entire network of rich interstellar chemistry. Simultaneously, they contribute to, and possibly dominate, the heating budget of molecular gas (e.g. Suchkov, Allen and Heckman 1993). In addition, low-energy CR flux has important astrobiological and even climatological consequences (Shaviv 2002, Carslaw, Harrison, and Kirkby 2002).

Thus, we are well-motivated for attempts at determination of the CR ionization rate at different locations in the disk of our Galaxy and other galaxies, including their high-redshift counterparts. It has been impossible so far to perform such measurements directly. Hereby, we would like to elaborate in some detail upon an additional indirect method of estimating, or at least constraining, the CR ionization rate at distant locations. As we shall show below, this indirect method is operational for objects, like the damped Lyα absorption systems, detected at very high redshift.

The basic necessary condition for applying this method is the detection of absorption lines of molecular hydrogen, H_2. Investigation of the Lyman- and Werner-band molecular hydrogen lines offers a plethora of useful information for determination of the physical properties of the absorbing gas cloud(s). Spectroscopy of these molecular lines usually gives column densities of various excited rotational levels of the H_2 molecule $N(H_2|J'')$. The relative populations of these rotational levels can be used to derive the kinetic and excitation temperatures of the absorbing material, which are defined by the Boltzmann distribution:

$$\frac{N(H_2|J'')}{g_{J''}} = \frac{N_0}{g_0} \exp\left(-\frac{E_{J''}}{k_B T}\right), \qquad (1)$$

where $N(H_2|J'')$ is the column density of rotational level J'', g_J'' is the statistical weight of rotational level J'', $E_{J''}$ is the excitation energy of rotational level J'', and k_B is the Boltzmann constant.

Major unknown parameter in any attempt to build a detailed physical model of an ISM cloud in either local or the high-redshift universe is the total physical density n_0 of matter in the cloud. Even in the simplest one-component models, it is difficult to obtain this value unambiguously, and the values estimated by different methods are frequently in disagreement in practical work. When H_2 is observed, one rather instructive criterion is the formation-destruction balance of molecular hydrogen. Our theoretical knowledge of processes of production of H_2 is complete enough, and these are not supposed to differ elsewhere from those successfully modelled in the Galactic ISM. These processes are the following (Hollenbach, Werner and Salpeter 1971, Jura 1974, 1975a, b, Watson 1975):

(1) Formation on grains: two H atoms stick onto the surface of a dust grain, and form an H_2 molecule, which is released from the grain taking part of the 4.5 eV excess energy in form of kinetic energy.

(2) Associative detachment: gas-phase reaction $H + H^- \to H_2 + e$.

(3) Radiative attachment of proton: gas-phase reaction $H^+ + H \to H_2^+ + h\nu$ (followed by quick recombination of the H_2^+ ion).

(4) Chemical networking: reactions like $OH + H^+ \to O + H_2^+$ (followed, as above, by a recombining reaction with an electron), and many others in which H_2 or its ion are producted.

In the Milky Way, the dominant process is **(1)** in all but the hottest parts of ISM where molecular hydrogen is detected. In diffuse galactic clouds (and in dense molecular clouds even more so) grain formation is 3–4 orders of magnitude more efficient than all other processes taken together. This is certain in spite of the fact that it has traditionally been difficult to give an exact formation rate, since the details of the solid surface chemistry as well as the distribution of dust are not well known. The only exception to the domination of dust formation mechanism are hot regions in the intercloud medium (Hill and Silk 1975, Hill and Hollenbach 1976) which are devoid of dust, where the rate coefficient for H^- reactions (which behaves $\propto \sqrt{T}$) is sufficiently high for this process to become the major source of molecular hydrogen. Process **(3)** is of limited importance due to very low fractional ionization in both diffuse and molecular phase of ISM. Mechanism **(4)** is quite negligible, since abundances of all other reactive species are usually very low, and is mentioned here just for the sake of completeness.

Overall, the abundance of molecular hydrogen is determined by equilibrium between the formation and the destruction rates:

$$R\, n_H\, n(H) = \Gamma(H_2)\, n(H_2), \qquad (2)$$

where R is the formation rate coefficient, $\Gamma(H_2)$ is the destruction rate coefficient (summed over all viable processes), n_H is the total number density of hydrogen atoms, i.e. $n_H \equiv n(H) + 2n(H_2)$, and is approximately equal to the total gas density (i.e. $n_H \approx n_0$), $n(H)$ and $n(H_2)$ are the number densities of H I and H_2 respectively. In any case, the physical density is given as $\rho \approx n_H \mu m_H$, where the mean molecular weight μ is taken to be 1.33.

The rate coefficient for the process **(1)** is proportional to the number density of dust (which is usually expressed through the universal dust-to-gas ratio in the context of galactic ISM). On the other hand, it is a reasonable (although, maybe, too simplified) assumption, in all usually employed models of chemical evolution, that the dust-to-gas ratio k is proportional to metallicity, independently of the exact composition of interstellar dust which is still subject to considerable controversy. *This means that the molecular formation on grains is roughly one order of magnitude less efficient at redshift of about $z \sim 3$ than it is in the Milky Way.* Although there have been some speculations to that effect for quite some time, the current study is the first one in which this has been demonstrated quantitatively. Parenthetically, chemistry in general is inhibited in a low-metallicity environment, making the process **(4)** even less important than it is in Galactic clouds. Important question is, therefore, whether the formation on dust grains is still the dominant source of molecular hydrogen at high redshift.

It is important to keep in mind that it is not possible to give unambiguous answer to that question without knowledge of another crucial parameter: the CR ionizing flux. Low energy (in MeV range) CRs do not only initiate almost all interstellar chemistry, but present the single important source of electrons inside both the neutral and molecular regions of the ISM, thus being necessary for gas-phase reactions to proceed. In regions with very high CR ionization rate (young stars' birthplaces, for example), we expect the processes **(2)** and **(3)** to play more important role than in the general ISM. Another effect (albeit of secondary importance in HI regions) is the heating of ISM through CR ionizations of both molecular and atomic gas (Field et al. 1969), which determines the kinetic temperature of gas, thus affecting *all* abovelisted processes of H_2 formation.

2. ESTIMATING PROTON DENSITY AND CR IONIZING FLUX

Detection of HD (or a successful constraint on its column density) enables us to estimate the proton (H^+) number-density. The reaction which produces HD is (e.g. Jura 1974, Watson 1975)

$$D^+ + H_2 \rightarrow HD + H^+, \qquad (3)$$

with the rate coefficient $\alpha_1 = 1.0 \times 10^{-9}$ cm^3 s^{-1} (Fehsenfeld et al. 1973). The high efficiency of this process is actually due to the speed of near-resonant charge exchange reaction

$$D + H^+ \rightarrow H + D^+, \qquad (4)$$

which produces enough D^+ to make reaction (3) the dominant process. The rate for reaction (4) is $\alpha_2 \approx 10^{-9} \exp(-43\ K/T)$ cm^2 s^{-1}.

Reactions with other species are negligible in this respect (Watson 1975). Now, the important factor here is that the process which destroys HD is the same as the one which destroys unshielded H_2, namely, the UV dissociation. From reactions (3) and (4), the predicted abundance of HD relative to D is given by

$$\frac{n(HD)}{n(D)} = \frac{\alpha_2 n(H^+)}{\Gamma_0(HD)} \frac{\alpha_1 n(H_2)}{\alpha_2^* n(H) + \alpha_1 n(H_2)}, \qquad (5)$$

where $\Gamma_0(\mathrm{HD}) \equiv \Gamma_0(H_2)$ is the unshielded ultraviolet dissociation rate (no self-shielding of HD which is everywhere optically thin) and $\alpha_2^* \approx 10^{-9}$ cm^3 s^{-1} is the rate coefficient for the reverse reaction of Eq. (4). Eq. (5) is very rough in the sense that, to a first approximation, it depends neither on the major unknown parameter n_0 nor on the abundance ratios of other species, and the temperature dependence is, for a reasonable range of possible temperatures, relatively weak.

In the one-component model (of the core component) we can apply the following approximations (capital Ns denote *column* densities of respective species):

$$\frac{n(HD)}{n(D)} = \frac{N(HD)}{N(D)} = \frac{N(HD)}{N_H} \frac{N_H}{N(D)} =$$

$$= \frac{N(HD)}{N(H) + 2N(H_2)} \frac{1}{F_D(z)}, \qquad (6)$$

where $F_D(z)$ denotes the "cosmic abundance" of deuterium at a given epoch z and N_H stands for the total hydrogen column density in the cloud (or a component of the complex absorption line system). Since the chemical evolution of galaxies is rather poorly known, in the following crude estimate we shall consider just two extreme cases: the present value $F_D(z=0) = 1.4 \times 10^{-5}$ found in the local ISM (Rogerson and York 1973, Linsky et al. 1995), and the highest observationally claimed value of $F_D = 2.5 \times 10^{-4}$ at redshift $z = 3.32$ (Songaila et al. 1994, Rugers and Hogan 1996); an improved calculation should take into account the effects of astration to interpolate $F_D(z)$ at a given redshift z. The high value seems to be disproved in recent years, but we keep it in the example below for the sake of comparison, and because the issue of "true" primordial abundance of D is not yet completely settled.

In the realistic case of a multicomponent cloud, one can expect Eq. (6) to underestimate $n(HD)/n(D)$ ratio, since D is probably more uniformly distributed even inside the core component, and HD is concentrated in denser regions with higher molecular abundances. This will effect further tightening of constraints calculated here.

Now, from Eqs. (5) and (6) we derive an expression for $n(H^+)$:

$$n(H^+) = \Gamma_0(H_2) \frac{\alpha_2^* n(H) + \alpha_1 n(H_2)}{\alpha_1 \alpha_2 n(H_2)}$$

$$\frac{N(HD)}{N(H) + 2N(H_2)} \frac{1}{F_D(z)}. \qquad (7)$$

The second step in our analysis consists in using an ingenious procedure developed by O'Donnell and Watson (1974) for galactic diffuse clouds, to constrain the CR flux using observations of HD molecule. Since low energy CRs are believed to originate in supernova remnants, the connection with the star formation rate can, in principle, be established.

Since the relation (5) is insensitive to details of the process of neutralization of H^+, and since ultraviolet ionizing flux cannot penetrate the core region of the absorber, this relationship can be used to put an absolute constraint to the CR ionization rate ξ inside the cloud. This is true under the assumption that cosmic rays are main source of protons inside the cloud. There are at least two reasons to rely on this assumption for high-redshift clouds: (1) Chemical networking—a competing source of H^+ if ξ is very low—is weaker inside low metallicity clouds; and (2) the CR density is generally expected to be higher at early epochs, since it is proportional to the supernova rate and, consequently, the star formation rate (Suchkov et al. 1993).

To find an upper limit to the CR ionization rate ξ, we follow the calculation procedure outlined by O'Donnell and Watson (1974) and Watson (1975). In a crude approximation, we consider only the reaction

$$CR + H \rightarrow H^+ + e + CR, \qquad (8)$$

and neglect the contribution from ionization of molecular hydrogen, via

$$CR + H_2 \rightarrow H + H^+ + e + CR \qquad (9)$$

(rate coefficient $\approx 0.08\,\xi$ per H_2 molecule s^{-1}) and

$$CR + H_2 \rightarrow {H_2}^+ + e + CR \qquad (10)$$

(rate coefficient $\approx 1.6\,\xi$ per H_2 molecule s^{-1}; this reaction is supposedly followed by $H_2{}^+ + H_2 \rightarrow H_2 + H^+ + H$ channels). On the other hand, we assume *maximum neutralization* through the usual radiative recombination $H^+ + e \rightarrow H + h\nu$ (rate $\alpha_1 \approx 7 \times 10^{-11} T^{-1/2}$ cm^3 s^{-1}) as well as by non-resonant charge exchange with other species (mainly oxygen): $H^+ + O \rightarrow O^+ + H$ [with rate $\alpha_2 = 1 \times 10^{-9} \exp(-232\ K/T)$ cm^3 s^{-1}], followed rapidly by $O^+ + H_2 \rightarrow OH^+ + H$ ($\alpha_3 = 2 \times 10^{-9}$ cm^3 s^{-1}).

The electron number density $n(e)$ is typically an order of magnitude higher than the proton density, $n(H^+)$, in the Milky Way (Watson 1975), and varies with metallicity.

3. APPLICATION: DAMPED Ly-α SYSTEM TOWARD 0528–250

The damped $Ly\alpha$ absorption systems (henceforth DLASs) seen in the spectra of high-redshift QSOs are thought to represent disks of young galaxies (Wolfe et al. 1986, Lanzetta, Wolfe and Turnshek 1995). The $z = 2.81$ DLAS toward 0528−250 is one of such objects studied in most detail (Smith, Jura, and Margon 1979, Morton et al. 1980, Levshakov and Varshalovich 1985, Foltz, Chaffee, and Black 1988, Meyer and Roth 1990); still, its properties are not fully understood. Here, we use the method outlined above to estimate the proton density and the cosmic-ray ionizing flux in the core component of this absorption system. HD has not been detected in this absorber, but the tight constraint enables us to give the upper limit to the CR flux, as follows from Eq. (7) above. The primary motivation for this DLASs is the investigation of the Lyman- and Werner-band molecular hydrogen lines, since this is one of the very small number of DLAS in which H_2 has been positively identified. However, this simultaneously offers an unprecendented opportunity to study the kinematics of the absorbing galaxy, when coupled with the recent detections of its Lyα emission (for the relevant kinematical details, see Ćirković 2003).

The total column density of molecular hydrogen in this DLAS (summed over all rotational levels) is

$$\log N(H_2) = 18.45 \pm 0.02, \tag{11}$$

which gives the fractional molecular abundance of

$$f = (9.8 \pm 0.3) \times 10^{-3}. \tag{12}$$

The strong upper limit to the abundance of the HD molecule given by empirical limit

$$\log N(HD) < 13.59 \tag{13}$$

sets an upper limit on the average proton density (and thus to the degree of ionization as well) in the absorber toward 0528−250.

Until recently, the debate on the exact value of high-redshift abundance of D plagued the clear application of this method. Two discordant values were in play, as mentioned above.

1. Low D/H case: Assuming the inferred value of $\Gamma_0(HD) = 3.6 \times 10^{-10}$ s^{-1} and a kinetic temperature of $T = 260$ K, we obtain the following relation:

$$n(H^+) = 6.6 \times 10^{-15} N(HD). \tag{14}$$

Since we have only the upper limit to $N(HD)$ given by Eq. (13), we obtain

$$n(H^+) < 2.5 \times 10^{-1}\ cm^{-3}. \tag{15}$$

This upper limit is an order of magnitude or more higher than the inferred proton abundances in Galactic clouds—$n(H^+)_{\alpha Cam} = 6 \times 10^{-3}$ cm^{-3}, $n(H^+)_{10 Lac} = 3 \times 10^{-2}$ cm^{-3}—but it still can be useful. It turns out that the *exact* HD column density cannot be much lower than the upper limit given in Eq. (13), since both the Γ_0 and F_D will tend to be enhanced in more realistic calculations.

2. High D/H case: Here we obtain

$$n(H^+) < 1.4 \times 10^{-2}\ cm^{-3}, \tag{16}$$

which represents a more stringent limit and is quite comparable to values in the local ISM (e.g. Reynolds 1989).

In a simple model, we obtained the upper limits on ξ for metallicities (in units of solar metallicity $Z_\odot$) of 1.0, 0.5 and 0.1, for both low and high D/H cases. Results are shown in Fig. 1. We note that, in the case of low deuterium abundance, the upper limit to ξ is rather insensitive to metallicity in the range of physically interesting densities (and the constraint is generally weak). On the other hand, if D/H is near the large value 2.5×10^{-4}, these results are in clear disagreement with $\xi \sim 10^{-15}$ s^{-1}, discussed in the context of heating and cooling of galactic interstellar clouds (Field et al. 1969, Field 1975). For the high D/H case, strong starbursts are thus precluded, and severely limited even for the low-D case. Also, we see that the constraints are strongest for the most realistic metallicity ($Z = 0.1\,Z_\odot$). Although these are clearly only order-of-magnitude values, it seems that—considering the high kinetic temperature inferred for this absorber—it is necessary, in the high D/H case, to invoke another heating mechanism beside CR heating (Suchkov et al. 1993). Hopefully, future observations of carbon ionization states will show whether or not ionization of metals by UV flux or ionization by soft X-rays can provide sufficient contributions. Allowed region for the CR ionization rate is generally consistent with $\xi = (1-7) \times 10^{-17}$ s^{-1} inferred for Galactic clouds (Black et al. 1990, van Dishoeck and Black 1991, Wolfire et al. 1995). This gives further support for our conclusion that the physical conditions within this DLAS are not very different from those observed in the local ISM. In particular, this runs contrary to conclusions of Hartquist and Dyson (1984) about the alleged absence of the high-redshift equivalents of the local diffuse cloud phase.

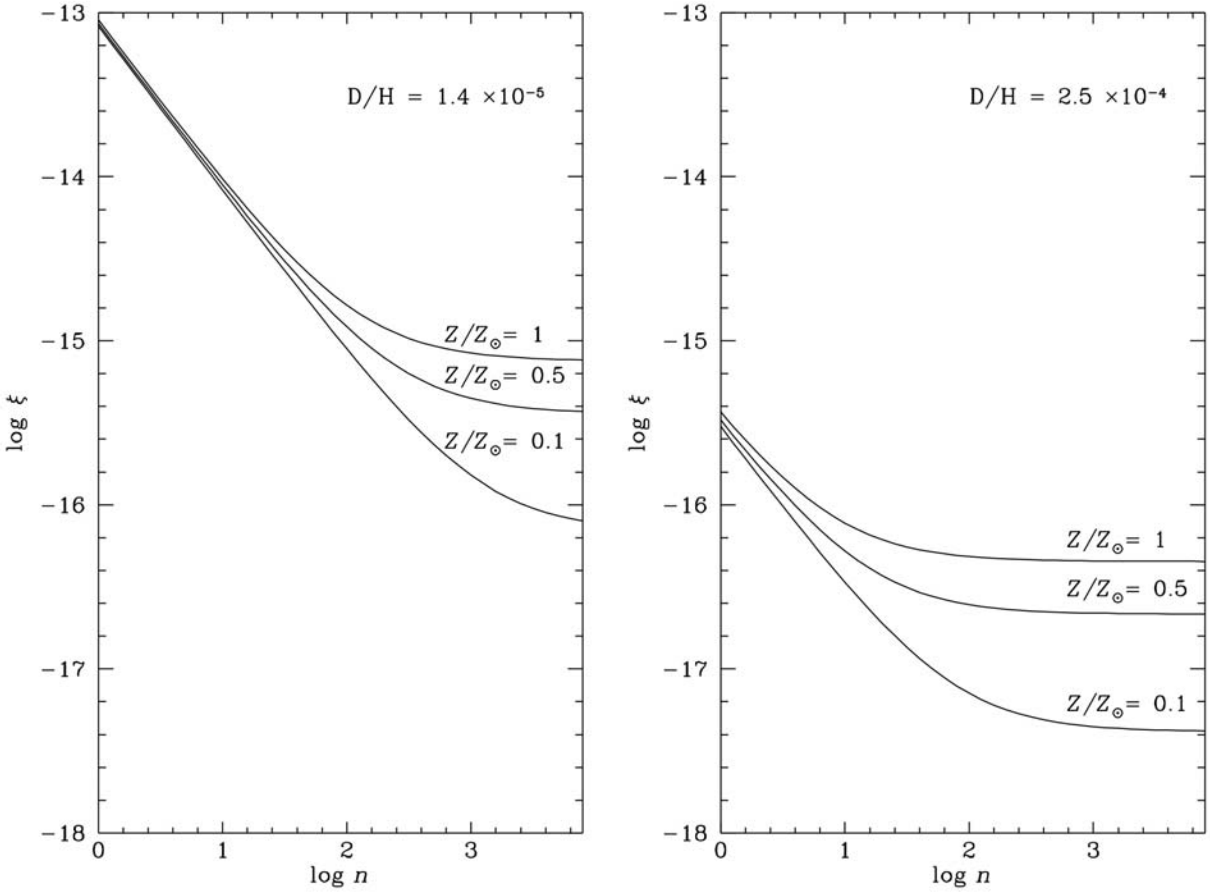

Fig. 1. *Upper limit on the cosmic ray ionization rate* ξ*, as a function of total hydrogen density* n_H*, in the two extreme cases of deuterium abundance. Three plausible metallicities are shown in the graph. We notice that for the case (now largely considered spurious) of high D abundance, limits are very stringent, even compared to the situation in the local ISM.*

DISCUSSION

We outlined a procedure for estimating proton density and CR flux at remote locations where molecular hydrogen absorption lines have been detected. The method relies on detection of H_2 and HD. It is not necessary to actually detect HD, which is often a laborious task; a sufficiently strong upper limit suffices. Assumptions about the nature of chemical processes taking place in the gas have been independently verified in the local Galactic ISM, so that the method might be useful for much less accessible locations, especially the damped Lyα absorption systems. Since most of low-energy cosmic rays in the galactic environment are thought to originate in supernova remnants, the link to the rate of high-mass star formation could, in principle, be established. We have applied the method to a particular case of high redshift damped Lyα absorption system towards 0528−250 and obtained values for the proton density similar to those in diffuse Galactic ISM and meaningful constraints for the CR ionizing flux. Further research will investigate how the relationship of CR flux to local star formation can be quantitatively established.

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О ОДРЕЂИВАЊУ ФЛУКСА КОСМИЧКИХ ЗРАКА КОРИШЋЕЊЕМ АПСОРПЦИОНИХ ЛИНИЈА МОЛЕКУЛАРНОГ ВОДОНИКА

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Оригинални научни рад

У овом раду скицирамо процедуру за процењивање флукса космичких зрака на удаљеним локацијама где су детектоване апсорпционе линије молекуларног водоника. Ова метода се ослања на неколико претпоставки чија је ваљаност у локалној галактичкој међузвезданој материји независно проверена, тако да се може показати корисном за много недоступније објекте, посебно пригушене Лајман-алфа апсорпционе системе. Пошто се сматра да већина космичких зрака ниске енергије у Галактичком окружењу потиче из остатака супернових, веза са формирањем звезда великих маса може, у принципу, бити успостављена. Ми примењујемо ову методу на конкретан случај пригушеног Лајман-алфа система у спектру квазара 0528−250 и добијамо неколико смислених ограничења.