Publ. Astron. Obs. Belgrade No. 54 (1996), 25 – 29 *Contributed paper*

MOLECULAR HYDROGEN AT HIGH REDSHIFT: RULE OR EXCEPTION?

M. M. ĆIRKOVIĆ
Dept. of Earth & Space Sci. SUNY at Stony Brook
Stony Brook, NY 11794-2100, USA
E–mail cirkovic@sbast3.ess.sunysb.edu

Abstract. New high resolution spectroscopy of the damped Lyα absorption system at $z = 2.8108$ toward QSO 0528−250, and results of a simple modelling of physical parameters of the absorbing region, serve as a motivation for several considerations on the origin, physical condition and role of the molecular hydrogen in disks of primeval galaxies. Since to this day this system is quite unique, uncritical extrapolation of the results may be unwarranted.

1. INTRODUCTION

It is well known that the molecular hydrogen constitutes a large fraction of the galactic interstellar medium (ISM), probably about 50% by mass. Similar situation is detected in spiral galaxies in nearby Universe. In view of this fact, it is suprising to note that the damped Lyman-alpha systems, which are considered to be precursors galactic disks (Lanzetta, Wolfe & Turnshek, 1989) are very molecule-poor. In spite of careful searches performed in the last decade (Levshakov & Varshalovich, 1985; Foltz, Chaffee & Black, 1988; Levshakov *et al.* 1992; Varshalovich & Levshakov, 1993) the single high–redshift object in which H_2 is unambiguosly detected by this day is the $z = 2.8108$ absorption system toward quasar QSO 0528−250, which is the topic of this report.

The dilemma presented in the title is amplified by the fact that this absorption system occurs at redshift *greater* than the emission redshift $z_{em} = 2.779$ of the background QSO. This indicates that the absorber is located within the immediate vicinity of the QSO, and perhaps (although it is very difficult to establish) is affected by the intense ultraviolet (UV) radiation field of the QSO. Very deep imaging through a narrow-band filter centered on Lyα performed recently by Moller and Warren (1993) successfully detected several candidate objects, one of them having impact parameter of only 9 kpc ($q_0 = 0.5$). Present knowledge is inadequate to determine whether the high UV flux detected along the line of sight to the QSO is due to intense star formation, or vicinity of QSO.

2. FORMATION OF MOLECULAR HYDROGEN

Major unknown parameter is the physical density n in the absorber. Even in one-component model, it is difficult to obtain this value unambiguosly, and the values estimated by different methods are frequently in disagreement. The author and his collaborators took the viewpoint that the strongest criterion is the formation–destruction balance of molecular hydrogen. Our knowledge of processes of production of H_2 is complete enough, and they are not supposed to differ from those successfully modelled in the Galactic ISM. These processes are (Hollenbach, Werner & Salpeter, 1971; Watson, 1975; Jura, 1974):

(1) *Formation on grains:* two H atoms stick onto the surface of 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 $H + H^- \rightarrow H_2 + e$.

(3) *Radiative attachment of proton:* gas-phase reaction $H^+ + H \rightarrow H_2^+ + h\nu$.

(4) *Chemical networking:* reactions like $OH + H^+ \rightarrow O + H_2^+$ (followed by neutralization with an electron), and many others in which H_2 or its ion are products.

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 molecular the more so) grain formation is 3–4 orders of magnitude more efficient than all other processes taken together. The only exception are hot regions in the intercloud medium (Hill & Silk, 1975; Hill & Hollenbach, 1976) which are devoid of dust, where the rate coefficient for H^- reactions (which behaves as $\sqrt{T}$) is sufficiently high for this process to become the major source of molecular hydrogen. Process (3) is of very limited importance due to very low fractional ionization in both diffuse and molecular phase of ISM. Mechanism (4) is quite negligible, since the abundances of all other reactive species are usually very low, and is mentioned just for the sake of completeness.

Major inherrent difference between the galactic environment and that in the absorber at high redshift (like that toward 0528−250) lies in the different stage reached by chemical evolution. Although existing models of chemical evolution of spiral galaxies are by and large insufficient to make any such extrapolations, we can use lots of existing empirical data on metallicity of Lyman alpha absorption systems gathered in last decade. Rate coefficient for process (1) is proportional to 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 existing models of chemical evolution, that the dust–to–gas ratio k is proportional to metallicity: $k/k_\odot = Z/Z_\odot$ (independently of exact composition of interstellar dust which is still subject to considerable controversy). *This means that the grain formation is roughly one order of magnitude less efficient at redshift of about $z \sim 3$ than it is in the Milky Way.* Parenthetically, chemistry in general is inhibited in low–metallicity environment, making process (4) even less important than in galactic clouds. Important question is, therefore, whether the formation on dust grains is still the dominant source of molecular hydrogen at high redshift.

3. THE IMPORTANCE OF COSMIC RAYS

Before I give a brief assessment of the observational evidence and the simplest model for 0528−250, 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 cosmic-ray (CR) flux. Low energy (in MeV range) cosmic rays do not only initiate almost all interstellar chemistry, but present the only important source of electrons inside both the neutral and molecular regions of 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 processes (2) and (3) to play more important role than in 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, which determines the kinetic temperature of gas, thus affecting *all* abovelisted processes of H_2 formation.

Using ingenious procedure developed by O'Donnell and Watson (1974) for galactic diffuse clouds, it is possible to constrain the CR flux using observations of HD molecule. Since low energy CRs are believed to originate in the supernova remnants, the connection with the star formation rate can, in principle, be established. The same considerations put limit on proton number densities. Unfortunately for the application of that algorithm to early epochs, the results strongly depend on fractional abundance of deuterium atoms, subject which became very confusing after realizing in last few years (Songaila *et al.* 1994; Rugers & Hogan, 1996) that D/H at redshift of about 3 is almost full order of magnitude higher than canonic value for the Galaxy. Preliminary results for the 0528−250 absorber (Ćirković *et al.* 1996) seem to preclude the CR fluxes much higher than those observed in the Milky Way in the entire physically interesting range of densities.

4. FIRST DIFFUSE CLOUD AT HIGH REDSHIFT?

The column density of molecular hydrogen in the absorber toward 0528−250 is $\log N_{H_2} = 18.45 \pm 0.02$, which gives the fractional molecular abundance of $f = (9.8 \pm 0.3) \times 10^{-3}$ (Ćirković *et al.* 1996). Rotational populations for $J'' = 0$ through 6 are obtained, as well as the upper limit on column density of $J'' = 7$ level. HD is not detected, and the 3σ upper limit on its column density is $\log N(\mathrm{HD}) < 13.59$. This, in turn, implies low proton density, $n(H^+) < 0.13\ \mathrm{cm}^{-3}$ for standard D abundance ($0.0078\ \mathrm{cm}^{-3}$ for high D abundance). [1] The assumption of Boltzmann equilibrium between the lowest two rotational states implies kinetic temperature of 136 ± 16 K, while the best fit temperature for levels 0 through 3 is $T = 260 \pm 27$ K. Both values are somewhat higher than average for galactic clouds, and although modelling of exact thermal equilibrium is beyond the scope of this research, it is in agreement with a higher UV photodissociation rate, which, according to Jura's theory of H_2 destruction, turns out to be $\Gamma \simeq 1.2 \times 10^{-10}\ \mathrm{s}^{-1}$.

[1] Standard $\mathrm{D/H} = 1.4 \times 10^{-5}$ (Rogerson & York, 1973), and high $\mathrm{D/H} = 2.5 \times 10^{-4}$ (Songaila *et al.* 1994).

All those data point out that we are dealing with high redshift analogue of the diffuse H I clouds observed in the plane of Milky Way and other disk galaxies, first well-established example of the warm ISM at early epochs. H_2 column density is high enough to rule out a pure *intercloud* interpretation of the absorption in Lyman and Werner bands, since it is at least four orders of magnitude higher than that expected *for Galactic metallicity* at considerably higher temperature (Hill & Hollenbach, 1976). Of course, velocity component containing molecular hydrogen can easily accommodate several distinct clouds along the line of sight, separated by a hot, rarefied, intercloud medium.

Metallicity of the absorber is confirmed (mainly by observations of S^+ this time; for earlier data, see for example Meyer & Roth 1990) to be 10 – 20% of the solar value. If the dust-to-gas ratio is correspondingly smaller (and in accordance with the absence of detectable extinction), the efficiency of grain formation of H_2 is considerably reduced. Still, in the simplest one-component model, it turns out that this process is by about one order of magnitude more efficient than the H^- mechanism, for the best fit physical density (~ 200 cm^{-3}). Of course, this conclusion rests on assumption that the dust grains are only quantitatively (in abundance) and not qualitatively (in size or adsorbing energies, for example) different from those observed in our Galaxy. Unfortunately, poor knowledge of the details of solid surface chemistry prevents us from relaxing the assumptions in this respect.

5. SUMMARY

I have used a new, high-resolution spectrum of the Lyα forest region of QSO 0528$-$250 to determine the abundances and rotational distribution of molecular hydrogen in the $z = 2.8108$ damped absorber, the unique such system where H_2 is known to exist. In spite of some noticeable differences, physical conditions in the absorbing region seem in general to be similar to those of the H I clouds of our Galaxy, the major differences being the lower metal content and the higher UV dissociating flux. These results present further evidence for the identification of damped Lyα absorption systems with the disks of young galaxies.

Simple, time-independent, one-component model of the absorbing region containing H_2 was constructed, and although probably unrealistic, it still provides a coherent picture which accounts for the existing observations. Further theoretical study including multiple cloud models should show significant improvement in explaining the data and indicate the effects of chemical and thermal evolution of diffuse matter at high redshift. On the observational side, the detection of more species (CO and C II for example) is a necessary requirement for discrimination between various possible chemical models. Future work will also show how exceptional the $z = 2.8108$ damped Lyα absorber toward 0528$-$250 is; molecular hydrogen in other absorption systems which still remains undetected, would provide us with fascinating array of new data on conditions in very young galaxies.

Acknowledgements

I would like to thank my advisor, Prof. Ken Lanzetta, without whom this work would not be possible. Also, I wish to hereby express sincere gratitude to Ms. Silvana Nikolić, M.Sc., for invaluable technical help.

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