HD Molecular Lines

in an Absorption System at Redshift $z = 2.3377$

D.A. Varshalovich$^1$, A.V. Ivanchik$^1$

P. Petitjean$^2$, R. Srianand$^3$, C. Ledoux$^4$

$^1$ Ioffe Physical Technical Institute RAS, St.-Petersburg
$^2$ Institut d’Astrophysique de Paris – CNRS, France
$^3$ IUCAA, Pune, India
$^4$ ESO, Munchen, Germany

We have analyzed the spectrum of the quasar PKS 1232+082 obtained by Petitjean et al. (2000). HD molecular lines are identified in an absorption system at the redshift $z = 2.3377$. The column density of HD molecules in the system is estimated, $N(\text{HD}) = (1 - 4) \times 10^{14} \, \text{cm}^{-2}$. The temperature of excitation of the first rotational level $J = 1$ relative to the ground state $J = 0$ is $T_{\text{ex}} = (70 \pm 7) \, \text{K}$. This is, to our knowledge, the first detection of HD molecules at high redshift.

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INTRODUCTION

The relative abundance of deuterium [D]/[H] formed during Big Bang nucleosynthesis is one of the key parameters of contemporary cosmology because it is the most sensitive indicator of the baryon density in the Universe.

Deuterium abundance at early cosmological epoch (10-14 Gyrs ago) may be determined from high-redshift quasar spectra. Until now, only atomic lines of D I and H I have been used for measuring relative abundances of D I and H I. However, this method meets serious difficulties. D I and H I wavelengths almost coincide, viz $\lambda$(H I)/$\lambda$(D I) = 1.00027. Moreover the column densities of DI and HI differ by a factor of $10^{-4}$ – $10^{-5}$. Therefore, D I lines are very weak and practically undetectable when the column density of hydrogen is low. In case the hydrogen column density is high enough, H I lines are saturated and broadened, so that D I lines are lost in the H I lines. In addition, one cannot be sure that the lines treated as D I lines are actually D I and not produced by an intervening weak H I cloud shifted in velocity by $-80$ km/s. (The latter explanation is possible because the lines in question are situated within Ly-$\alpha$ forest where absorption features are numerous). The above difficulties may be the reasons why [D]/[H] values determined from the atomic lines by different authors differ by more than one order of magnitude. For example, $2 \cdot 10^{-4}$ (Webb et. al, 1997), and $1.6 \cdot 10^{-5}$ (Pettini & Bowen, 2001).

The above difficulties do not arise if one measures the relative abundances of molecules [HD]/[H$_2$] since the appropriate wavelengths differ considerably while the redshift parameter is the same. It may be difficult however to derive [D]/[H] from [HD]/[H$_2$] because of uncertainties in the chemistry. Nevertheless this is an independent access to the deuterium abundance in these remote clouds. Up to now HD lines have not been identified in quasar spectra. Moreover, for a long period, from 1985 to 1997, the only molecular absorption system was known, viz H$_2$ system at $z_{abs} = 2.811$ imprinted in the spectrum of PKS 0528-250 (Levshakov & Varshalovich, 1985). Today only four reliable absorption systems of molecular hydrogen H$_2$ are known in quasar spectra (Petitjean et al., 2000; Levshakov et al., 2001) and no other molecules are detected in their optical spectra.
RESULTS OF ANALYSIS OF PKS 1232+082 SPECTRUM

Here we report on identification of HD lines of absorption system at $z_{\text{abs}} = 2.3377$ in the spectrum of PKS 1232+082 ($z_{\text{em}} = 2.57$ and $m_V = 18.4$). It is the first identification of redshifted HD molecules, to our knowledge.

The high resolution spectrum of PKS 1232+082 was observed using UVES with the 8.2-m Telescope VLT of ESO by Petitjean et al., (2000). The spectrum contains a strong absorption system of molecular hydrogen H$_2$ at $z_{\text{abs}} = 2.3377$ found earlier by Ge & Bechtold (1999).

We have found several HD lines of Lyman series $B^1\Sigma^+ - X^1\Sigma^+$ corresponding to R(0) transitions from the ground state $J = 0$, $v = 0$, and some tentative lines R(1) from the first rotational level $J = 1$, $v = 0$. Fig.1 shows fragments of the observed spectrum of PKS 1232+082, and our synthetical fit of HD lines. One can see R(0) lines in L 5-0, L 4-0, L 3-0, and L 0-0 bands and some possible R(1) lines whereas HD lines in L 2-0 and L 1-0 bands are heavily blended by H$_2$ lines. Parameters of identified HD lines are presented in Table 1. The spectroscopic data of laboratory lines are taken from measurements by Dabrowski & Herzberg (1976) and oscillator strengths by Allison & Dalgarno (1970).

The weighted mean value of the redshift parameter for the HD absorption system measured reads

$$z_{\text{abs}}(\text{HD}) = 2.337700(5),$$

in good agreement with $z_{\text{abs}}(\text{H}_2) = 2.33771$ (Petitjean et al., 2000).

According to our estimates, the column densities of HD molecules in the ground state $J = 0$ and the first rotational state $J = 1$ are

$$N_{J=0}(\text{HD}) = (1 - 3) \cdot 10^{14} \text{ cm}^{-2},$$
$$N_{J=1}(\text{HD}) = (4 - 8) \cdot 10^{13} \text{ cm}^{-2}.$$

The population of the first rotational level relative to the ground state may be characterized by the excitation temperature:

$$T_{\text{ex}} = 70 \pm 7 \text{ K}.$$
However, the R(1) lines have low S/N ratios, so that this value may be considered as an upper limit of $T_{ex}$. New observations with higher S/N are necessary to confirm the lines from the J=1 level.

A detailed analysis of the relative abundances of [HD]/[H$_2$] and corresponding estimates of [D]/[H] will be done elsewhere. Note that an additional problem of interstellar chemistry (concerned with formation and destruction of the molecules) has to be solved for the determination of [D]/[H] from [HD]/[H$_2$].

In conclusion, we emphasize that the detection of HD molecules in absorbing matter at such high redshift may be important to understand the formation of the first generation of stars because HD molecules might be important cooling agents in the primordial condensations where heavy elements were in deficit.

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Figure 1: Fragments of PKS 1232+082 spectrum obtained by Petitjean et al. (2000). The bold solid line shows the HD theoretical spectrum.
Table 1: Parameters of the identified lines of HD molecules in the spectrum of PKS 1232+082 in the system at $z_{abs} = 2.3377$

| Transition | $\lambda_{lab}$, Å | $\lambda_{obs}$, Å | $z_{abs}$ |
|------------|---------------------|---------------------|-----------|
| L 5-0 R(0) | 1042.854            | 3480.729(3)         | 2.337695  |
|            | R(1)                | 1043.299            | 2.337699  |
| L 4-0 R(0) | 1054.298            | 3518.935(4)         | 2.337704  |
|            | R(1)                | 1054.734            | 2.337711  |
| L 3-0 R(0) | 1066.279            | 3558.923(3)         | 2.337703  |
|            | R(1)                | 1066.706            | 3560.34$^b$ |...
| L 2-0 R(0) | 1078.835            | 3600.83$^b$         | ...       |
|            | R(1)                | 1079.248            | 3602.21$^b$ |...
| L 1-0 R(0) | 1092.006            | 3644.79$^b$         | ...       |
|            | R(1)                | 1092.404            | 3646.12$^b$ |...
| L 0-0 R(0) | 1105.845            | 3690.972(2)         | 2.337694  |
|            | R(1)                | 1106.221            | 3692.23   |...

$^b$ HD line is blended