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HD molecules in the Magellanic Clouds

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Abstract. We present the detection of HD absorption lines in the Magellanic Clouds using FUSE space telescope archival data. We found HD in five (including one known) absorption systems in the Large Magellanic Cloud and three systems in the Small Magellanic Cloud. The measured HD column densities, N(HD), vary from $2\cdot10^{13}$ to $2\cdot10^{15}$ cm^{-2} for associated H_2 column densities, NH_2, in the range $3\cdot10^{19}$ to $5\cdot10^{20}$ cm^{-2}. Using Hubble Space Telescope archival data, we also determined the population of CI fine-structure levels and metallicities in these systems. The modelling of obtained observational data for HD, H_2 and C I allow us to estimate physical conditions in the interstellar medium of the Magellanic Clouds associated with these absorption systems, namely, the cosmic ray ionization rate, ultraviolet field intensity and number density.

Keywords: galaxies, ISM, molecules, cosmic rays

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Молекулы HD в Магеллановых Облаках

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Аннотация. Мы представляем детектирование абсорбционных линий молекул HD в Магеллановых Облаках в архивных данных космического телескопа FUSE. Мы нашли HD в пяти (включая одну уже известную) абсорбционных системах в Большом Магеллановом Облаке и в трех системах в Малом Магеллановом Облаке. Полученные лучевые концентрации HD, N(HD), варьируются от $2\cdot10^{13}$ до $2\cdot10^{15}$ см$^{-2}$, концентрации N(H_2) находятся в диапазоне от $3\cdot10^{19}$ до $5\cdot10^{20}$ см$^{-2}$. Используя архивные данные космического телескопа «Хаббл», мы также оценили относительную населенность уровней тонкой структуры C I и металличность в этих системах. Моделирование полученных результатов для HD, H_2 и C I позволило оценить физические условия в межзвездной среде в Магеллановых Облаках, а именно, скорость ионизации космическими лучами, интенсивность УФ поля и объемную концентрацию.

Ключевые слова: галактики, МЗС, молекулы, космические лучи

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Introduction

One of the most important constituent of the galaxies is the interstellar medium (ISM) due to its tight connection to galaxy evolution and star formation processes. The cold phase of ISM, which is an important step of the medium on its way to gravitational collapse, can be in principle traced by molecular hydrogen H_2, which is the most abundant molecule in the Universe. In case when H_2 abundance is large enough, one can detect its isotopoloque, deuturated hydrogen (HD), see e.g. [1–3] and references therein. However, the detection of H_2 and HD in emission is a quite challenging task even in our Galaxy, so the main way of learning about these molecules is the absorption line spectroscopy. The resonant HD and H_2 absorption lines are located in ultraviolet domain, so a bit paradoxically, their observations are simplified at high redshifts, $z \gtrsim 2$, since the lines are shifted in the optical domain and quasar can be used as a background sources, that allow to exploit large ground telescopes with high resolution spectrographs (see e.g. [4, 5]). Nevertheless, UV space telescopes (e.g. Copernicus, Far Ultraviolet Spectroscopic Explorer (FUSE)) were extensively used for the measurements of H_2 and HD in the Milky Way [1, 6, 7] and in the local galaxies, mostly including Magellanic Clouds [8].

The Large and Small Magellanic Clouds are one of the closest galaxies to ours (with distance ~50 and ~60 kpc, respectively) have significantly lower metallicities, ~0.5 and 0.2 of solar, respectively. The distance to Magellanic Clouds allows one to observe individual bright stars, that were used by [8] to obtain a sample of the H_2 absorption systems with FUSE. We recently showed [9], that HD abundance may significantly enhance at low metallicities (that is corroborated by observations at high redshifts), therefore the Magellanic Clouds may provide as important test to further study this behaviour. Additionally, HD/H_2 ratio is sensitive to physical conditions in the cloud, especially, to the cosmic ray ionization rate (CRIR) [9], which was exhaustively studied in Milky Way, but is quite poorly known in other galaxies. Finally, obtained estimates [3] were performed only towards individual sightlines within each remote galaxy, at the same time, the proximity of the Magellanic Clouds gives a good opportunity to study CRIR towards multiple sightlines within the galaxy.

Therefore, we decided to make an extensive search for HD absorption lines in the Magellanic Clouds. We present four and three new detection of HD in the LMC and SMC, respectively, and we reanalysed one already known system in the LMC. To derive physical conditions in the absorption systems we used the observed abundances of HD as well as C I fine-structure and H_2 rotational levels and Zn II column density.

Data and analysis

We used FUSE archival spectra to search for HD in the sample of known H_2 absorption systems associated in the Magellanic Clouds [8]. We considered the systems with H_2 column densities $\log N_{H_2} > 18$ (here and in the following text column densities are expressed in cm^{-2}). HD detection was previously reported in the system towards Sk-69 246 [10], but we reanalyzed HD and H_2 to make the analysis homogeneous. In general, we identified HD in four and three sightlines towards the LMC and SMC, respectively. We also independently reanalysed H_2 absorption lines to constrain the population of H_2 rotational levels. Metal lines were analysed in the spectra obtained using STIS and COS spectrographs on board of the Hubble Space Telescope (HST). To model line profiles we performed standard multicomponent Voigt profile fitting using the Monte Carlo Markov Chain sampler, that allow us to obtain the posterior distribution function of absorption system parameters. To report the values of fit parameters and its uncertainties we used maximum aposterior probability estimate and highest posterior density 68.3% credible intervals, respectively.

FUSE data

The sample of spectra obtained by the FUSE telescope [11, 12] towards stars in Magellanic Clouds is available in the FUSE Magellanic Clouds Legacy Project [13]. We used spectra from 1A LiF channel, as they cover most of HD and H_2 lines. Unfortunately, most of FUSE spectra have low S/N and are not properly wavelength calibrated, so we decided to improve the quality of calibration. First, we obtained a zero order coadded solution by alignment of exposures from the individual sightlines using cross-correlation procedure [14, 15] to find achromatic shift between exposures. Then we used the H_2 synthetic spectrum as a template to obtain wavelength dependent shifts for individual H_2 lines individually for each exposure. We selected narrow unblended H_2 lines and calculated cross-correlation function with the corresponding lines from the synthetic template. We fitted the wavelength dependency of the estimated shifts using piece-wise linear functions, that was finally used to correct the individual exposures before the final coadding. In most cases this procedure improves a quality of calibration.

The nominal FUSE resolution is $R = \lambda/\Delta\lambda = 20000$, but we notice that it can be likely reduced by the procedure of coadding of individual exposures, calibration routine and other systematics effects of observations. Therefore we assumed R as an independent fitting parameter. We also allowed Doppler parameters for all rotational levels to vary independently, but used the penalty function to obtain the proper H_2 excitation diagram (for details see [3, 16]).

HST data

Since, most of the metal and C I lines are not covered by FUSE, to estimate C I column densities and metallicities in the HD/H_2 absorption systems we used archival data obtained by the STIS/COS at HST and downloaded from the MAST archive[1]. Some of the systems have already been analyzed by [17, 18], but we reanalyzed them to get independent results. We fitted C I absorption lines from three fine-structure levels where we tied Doppler parameters. To obtain metallicity[2] we fitted Zn II absorption lines and used $N_{\rm H\,I}$ values obtained by [8] and solar values of $\log(\mathrm{X/H})_\odot$ from [19].

Results

We summarize our measurements of HD, H_2 and C I in Table 1. We report four and three new HD detections in the LMC and SMC, respectively. In Fig. 1 we compare the values of HD and H_2 column densities measured in the Magellanic Clouds with already known systems (at high redshifts and in the Milky Way) and D/H isotopic ratio. One can see that Galactic measurements of HD/ H_2 are well below the D/H isotopic ratio, while the measurements at high redshifts do not show such tendency. As we showed in [9], it can be explained by the difference in physical conditions, primarily by systematically lower metallicity for systems at high redshifts. Measurements in the Magellanic Clouds show the same tendency as in our Galaxy despite they have lower metallicity that is comparable (in case of the SMC) with the average of high-z values. In principle, since the HD is sensitive to the other physical conditions (e.g. CRIR, UV field intensity and column density), it can be partly explained by a higher UV field intensity (see the next section).

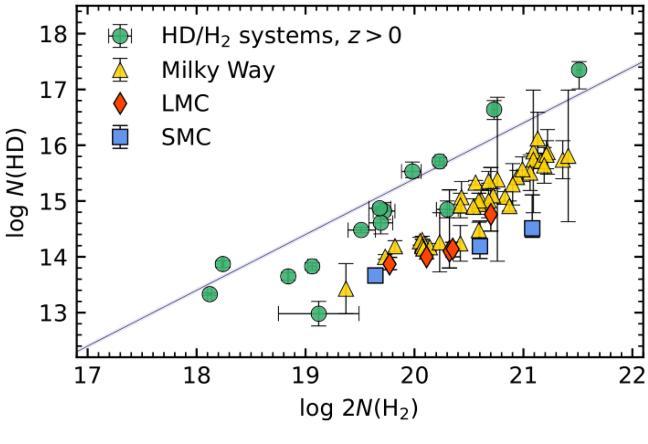

Fig. 1. Relative abundance of HD and H_2 molecules. The red diamonds and blue squares correspond to measurements in the LMC and SMC, respectively, obtained in this work. The green circles are detections at high redshifts (for references see [3]), yellow triangles are measurements in our Galaxy. The solid blue line shows the D/H primordial isotopic ratio [20].

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[1] https://archive.stsci.edu/

[2] metallicity relative to solar is $Z = [\mathrm{X/H}] = \log(\mathrm{X/H}) - \log(\mathrm{X/H})_\odot$

Table 1

Summary of measured HD, H_2, C I and Zn II column densities in the absorption systems in the Magellanic Clouds

Star	HI*	H_2	HD	C I	ZnII
Sk-67 5	21.00	$19.470^{+0.001}_{-0.001}$	$13.87^{+0.12}_{-0.10}$	$15.04^{+0.01}_{-0.01}$	$12.80^{+0.02}_{-0.01}$
Sk-70 79	21.18	$20.04^{+0.03}_{-0.04}$	$14.76^{+0.84}_{-0.30}$	$14.39^{+0.01}_{-0.01}$	$13.09^{+0.02}_{-0.02}$
Sk-68 135	21.60	$20.02^{+0.01}_{-0.01}$	$14.1^{+1.1}_{-0.3}$	$14.44^{+0.01}_{-0.01}$	$13.31^{+0.01}_{-0.01}$
Sk-69 246	21.41	$19.81^{+0.01}_{-0.01}$	$14.00^{+0.04}_{-0.04}$	$14.25^{+0.03}_{-0.02}$	$13.38^{+0.01}_{-0.01}$
BI 253	21.60	$20.05^{+0.01}_{-0.01}$	$14.14^{+0.12}_{-0.14}$	$15.31^{+0.40}_{-0.77}$	$13.49^{+0.01}_{-0.01}$
AV 80	21.81	$20.30^{+0.01}_{-0.01}$	$14.19^{+0.45}_{-0.22}$	$13.70^{+0.03}_{-0.02}$	$13.22^{+0.02}_{-0.01}$
AV 488	21.15	$19.340^{+0.001}_{-0.020}$	$13.67^{+0.09}_{-0.08}$	$13.36^{+0.03}_{-0.03}$	$12.99^{+0.02}_{-0.02}$
Sk 191	21.51	$20.78^{+0.03}_{-0.03}$	$14.51^{+0.60}_{-0.16}$	$13.87^{+0.02}_{-0.02}$	$12.55^{+0.03}_{-0.04}$

*values taken from [8]

Physical conditions

To obtain physical conditions in the systems we followed method described by [3] and based on the balance equation of HD formation and destruction processes. We have showed that this relatively simple formalism gives result close to that calculated by Meudon PDR code [21] which takes into account a large chemical network. The fit parameters of the model (that was compared with the observed HD/ H_2 ratio) are the cosmic ray ionization rate (CRIR, ξ) UV field intensity (χ), number density (n) and metallicity (Z).

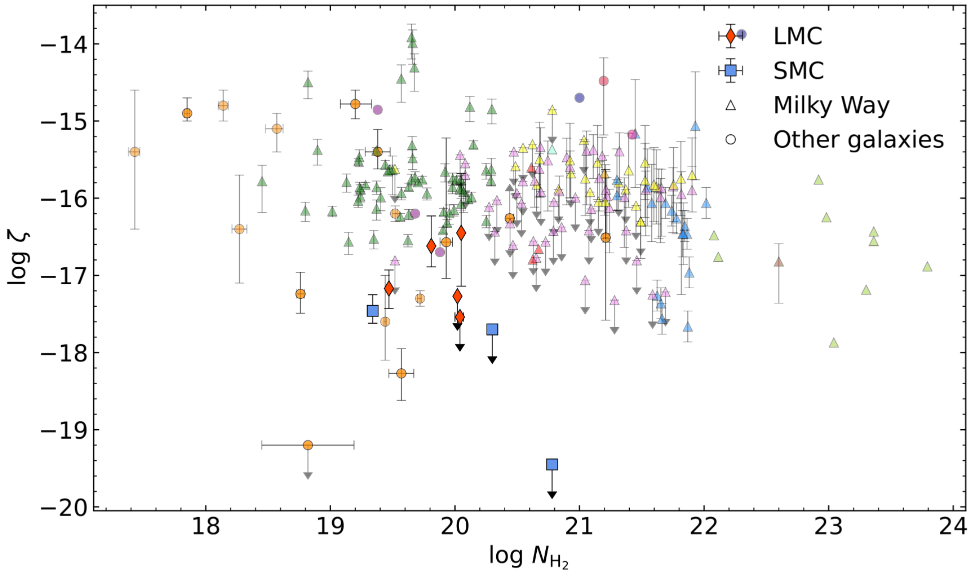

Fig. 2. Cosmic ray ionization rate as a function of H2 column density. The red squares and blue diamonds show to measurements in the Magellanic Clouds obtained in this work. The triangles are values from our Galaxy, circles are high redshifts measurements (see [3])

We used estimated Zn II and H I (measured by [8]) column densities to obtain metallicity (provided in Table 2), which was fixed in following calculations. Using the same methodology as was done in [5, 22], we consequently used the population of H_2 rotational and C I fine-structure levels to constrain the number density and UV field intensity. Finally, we used these estimates as priors (with additional flat prior for ξ) during Markov Chain Monte Carlo sampling to derive posterior probability distributions on the model parameters. The obtained parameters are shown in Table 2 and in Fig. 2 we present CRIR as a function of N_{H2} (which is connected to cloud depth). One can see that found CRIR values are lower than on average in our Galaxy, therefore HD formation rate is not enough to produce sufficient HD for self-shielding from UV radiation and hence HD column density is found to be quite low. Also the upper limit in the system towards Sk 191 may be treated as an outlier, since the system has exceptionally low metallicity, so this system requires additional study.

Table 2

Derived physical conditions in the absorption systems in the Magellanic Clouds

Star	Z[†]	log$n$	logχ	logξ
Sk-67 5	$-0.76^{+0.05}_{-0.05}$	$2.45^{+0.25}_{-0.11}$	$0.55^{+0.13}_{-0.12}$	$-17.17^{+0.24}_{-0.26}$
Sk-70 79	$-0.65^{+0.05}_{-0.05}$	$3.02^{+0.27}_{-0.31}$	$1.17^{+0.16}_{-0.11}$	$\lesssim -17.54$
Sk-68 135	$-0.85^{+0.05}_{-0.05}$	$2.52^{+0.22}_{-0.15}$	$2.1^{+0.6}_{-0.4}$	$\lesssim -17.27$
Sk-69 246	$-0.59^{+0.05}_{-0.05}$	$2.24^{+0.21}_{-0.15}$	$1.85^{+0.21}_{-0.31}$	$-16.64^{+0.41}_{-0.25}$
BI 253	$-0.67^{+0.05}_{-0.05}$	$0.87^{+0.49}_{-0.46}$	$1.58^{+0.24}_{-0.21}$	$-16.45^{+0.77}_{-0.69}$
AV 80	$-1.15^{+0.05}_{-0.05}$	$1.97^{+0.14}_{-0.23}$	$1.89^{+0.31}_{-0.24}$	$\lesssim -17.70$
AV 488	$-0.72^{+0.05}_{-0.05}$	$2.16^{+0.18}_{-0.28}$	$0.53^{+0.13}_{-0.12}$	$-17.46^{+0.21}_{-0.16}$
Sk 191	$-1.51^{+0.06}_{-0.06}$	$2.60^{+0.20}_{-0.16}$	$0.83^{+0.17}_{-0.11}$	$\lesssim -19.45$

[†] Uncertainties of solar values N_{Zn} from [19] dominate over uncertainties of Zn II column densities in the presented systems, therefore almost all metallicity uncertainties are the same

Conclusions

We present a detection of HD in five (four new) systems in LMC and three systems in SMC. We measured that HD column density varies from ~ 10^{13} to ~10^{15} cm^{-2}. We also reanalyzed H_2 absorption lines, analyzed C I lines and estimated metallicity to constrain physical conditions in the systems using population of C I fine structure and H_2 rotational levels. Using our formalism [9] we obtained the cosmic ray ionization rate in LMC and SMC to have typical values of $\xi \sim 10^{-17}$ s^{-1}.

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