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MOLECULAR HYDROGEN IN THE SPECTRA OF URANUS AND NEPTUNE

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In August and September 2017, on the 2-meter telescope of ShAO by using a fiber-optic echelle spectrograph (ShaFES) with dierent spectral resolutions: R = 28000 and R = 56000, the spectra of Uranus and Neptune were obtained. In the spectra of these planets, absorption lines of molecular hydrogen H_2 in the bands (4-0) λ6435.03 Å and 6367.76 Å were studied, and line $S_4(2)$ was found. The upper limits of the absorption line intensity in the spectra of Uranus and Neptune were determined. Pressure values (P = 2,1÷2,4 atm for Uranus, and P = 2÷2,3 atm for Neptune) by half-breadth of the lines λ6367.76 Å and λ6435.03 Å, in the (4-0) band of molecular hydrogen, in the spectra of Uranus and Neptune were estimated. Additionally, the rotational temperature ($90^\circ \pm 12K$ for Uranus, $101^\circ \pm 10$ K for Neptune) was determined by the ratio of the intensities of these lines at the depth at which these lines are formed. Dynamical processes occurred on Uranus can be damping processes. The nature of the circulation in the atmosphere of Neptune is regulated "from below," from the planetary interior. Such non-stationary processes cause changes in the density of aerosol particles and their distribution on height in its atmosphere, temperature, and movement rate in the clouds.

Keywords: Uranus–Neptune–molecular hydrogen– quadrupole lines– rotational temperature–helium.

1. INTRODUCTION

The study of the chemical composition of the atmospheres of planets is necessary to understand their evolution better and is considered an essential task of modern planetology. In the atmospheres of big planets, the absorption bands of various compounds were studied by primitive methods of imagining spectroscopy, and in the thirties of the twentieth sentuary , they were studied by the method

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of photographic spectroscopy with low and average dispersion. In parallel, some scientific predictions and theoretical calculations on the spectra of molecules that are part of the atmospheres of big planets appeared. The small average density and character of the atmospheres of the giant planets allows many researchers to hold to the opinion about the considerable content of hydrogen and helium in their atmospheres. The dipole moment for molecular hydrogen is zero, has no vibrational spectrum, and rotational transitions are also forbidden. Molecules consisting of identical atoms can have a nonzero quadrupole moment (the center of the electron cloud does not coincide with the center of the positive charge), i.e., the interaction between molecules is not described within the Hooke's law and turns into an anharmonic oscillator, for forbidden transitions are also allowed. It can happen with high molecular hydrogen content or when indicating the external electric field, or by mutual collisions of molecules. Consequently, instead of "vibrational lines," rotational-vibrational bands are formed near them, consisting of separate lines corresponding to different rotational transitions at the same vibrational level.

In 1938, G. Herzberg [1] predicted that the quadrupole bands of molecular hydrogen H_2 should be found in the spectra of giant planets. He firstly showed [2] that the faint, unidentified absorption line found by Kuiper [3] in the low-dispersion spectra of Uranus and Neptune is certainly the S (0) (3-0) line of the second overtone-induced H_2 band.

Later, Kiess C.C., Corliss C.H. and Kiess H.K. [4] managed to detect three lines of rotational-vibrational overtone (3-0) about 8200 Å, and Spinrad H., Trafton L.M. [5] detected two more lines of the H_2 (4-0) overtone, about 6400 Å in the spectrum of Jupiter. The lines of both bands of molecular hydrogen were detected in the spectra of all giant planets: the H_2 (4-0) overtone was distinguished by a low value of their intensity, and this allows us to assert that the H_2 (4-0) lines are not saturated even in the spectra of H_2 from deep layers atmosphere. Information about deeper layers in the atmospheres of giant planets was obtained with the help of spacecraft [8].

In work [7], it is noted that the data obtained during the eclipse of Neptune by spacecraft "Voyager-2" were used to study the thermal structure and composition of the troposphere and stratosphere of the planet.

Accurate data for the H_2 quadrupole lines, located in the visible and near regions of the IR spectrum, can ensure necessary conditions for a detailed analysis of the atmosphere of the giant planets. These lines are sensitive to hydrogen abundance, ortho-para ratio, vertical structure, cloud distribution, and the pressure-temperature profile of the planet's observed atmosphere.

The H_2 content is used in ratio to the abundance of other molecules (elements) to compare the solar abundance coefficients [8]. The abundance of H_2 is an important parameter when constructing a model of the atmosphere of giant planets. Conduct spectrophotometric studies of the atmospheres of giant planets in the region of absorption lines of molecular hydrogen and calculating some parameters of the atmosphere is an essential task for elucidating the evolution of the atmospheres of these planets.

2. OBSERVATIONS AND RESULTS OF SPECTROGRAMS PROCESSING OF URANUS AND NEPTUNE.

In August and September 2017, the spectra of Uranus and Neptune were obtained on a 2-meter telescope of ShAO by using a fiber-optic echelle spectrograph (ShaFES) with different spectral resolutions: R=28000 and R=56000. An American-made CCD camera with a 4K×4K element matrix with an element size of 15×15 μm was used as a light detector. About it and other spectrometers installed on the 2-meter telescope are written in more detail in the works of Kh.M. Mikhailov et al. [9,10]. The level of the continuous spectrum was drawn along the vertices of the peaks in each discharge when processing the obtained observational material (for more details on the details of this method, see [9,10],).
Drawing a continuous spectrum in this form makes it easier to compare the results of dierent observations. Besides, to control the accuracy of the continuum, solar lines with an intensity close to the investigated line in the planet's spectrum are selected each time.Then the accuracy of the measurements of equivalent widths and half width will be the same with measurements of the investigated lines of molecular hydrogen. The average errors in determining the equivalent widths of the solar lines [11] in our measurements vary from 4% to 10%. This accuracy also remains for the investigated lines of atmospheres of the planets.

Conducting the continuum - a crucial stage of the operation on which depends the further result of the spectral study.

As a rule, the line of the continuum is smooth and convex. If there are doubts about the correctness of the continuum in a given order, the energy distribution in neighboring orders of the spectrum can be compared. The intensities of neighboring orders in the echelle spectra are similar. The wide wings of the Hα line do not allow us to see the level of the continuous spectrum, and if we conduct a false continuum in this order, we will obtain erroneous values of the equivalent widths. Next, we choose the curves of the continuum of neighboring orders. Then we shift up this curve to the maximum value. This curve can serve as a clue - where the continuum pass. As a result, we obtain the restored continuum.

Observation of Uranus on the 2-meter telescope with a spectral resolution R = 56000 allowed us to reveal another term related to the weak quadrupole transition of molecular hydrogen - H_2 (4-0) S (2). The message on detecting an absorption

Fig. 1. shows the absorption lines of molecular hydrogen H_2 located in the visible region of the spectrum of Uranus λ6367.76 Å and λ6435.03 Å in the H_2 (4-0) band.

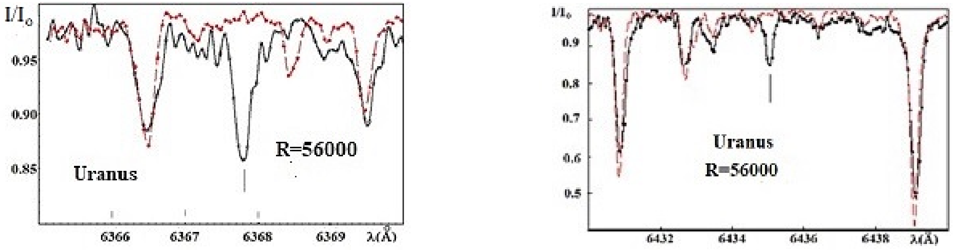
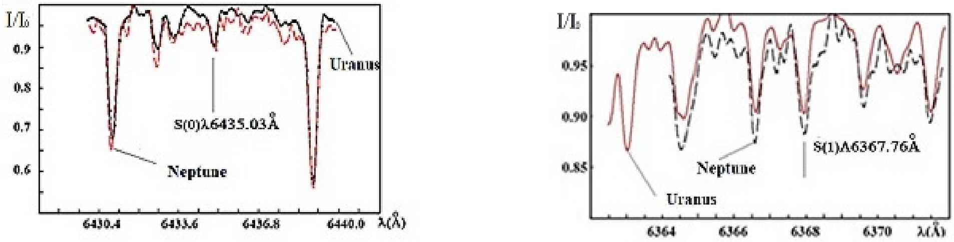


Fig. 2. The absorption lines of molecular hydrogen H_2 in the band (4-0) λ6435.03Å and 6376.76 Å in the spectrum of Neptune: R=28000. At high spectral resolution, the lines on λ 6367.76 Å and λ 6435.03 Å are well visible.



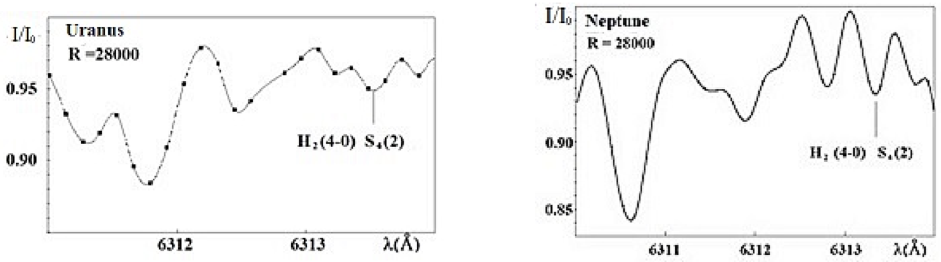
line on a wavelength of 6313.4 Å was first published by Enkrenes et al. [12] and later in work [13]. It should be noted that in work [12], the upper absorption limit in the H_2 (4-0) S (2) line was previously estimated, namely < 2 m Å.

The H_2 (4-0) S (2) line in the spectrum of Saturn was also detected during our observations. While processing the observational material of the H_2 (4-0) S (2) line profile in the Saturn spectrum, its intensity was determined, according to our measurements turned out to be $<$ 3mÅ. According to Smith's estimates [13], the intensity of the H_2 (4-0) S (2) line in the spectrum of Jupiter - $\sim$1m Å, which corresponds to our estimates, $\sim$1.5 m Å in work [12]. According to [12], the intensity of H_2(4-0) S(2) in the spectrum of Uranus - $<$ 1m Å (Fig. 2 and 2). According to our observations, the intensity of the H_2 (4-0) S(2) line in the spectrum of Uranus is $<$ 4 mÅ, and in the spectrum of Neptune within $5\div8$ mÅ. (Fig. 3).

Fig.3. Profile of the H_2 (4-0) S(2) line in the spectra of Uranus (left) and Neptune (right), obtained with spectral resolution R = 56000 and R = 28000, respectively.

There is also a weak telluric line at S(1) λ6367.76 Å in the spectral region, where the absorption line 6368.46 Å is located. The corresponding lines of the solar spectrum were considered as a comparison when determining the equivalent

Fig. 3. Profile of the H_2 (4-0) S(2) line in the spectra of Uranus (left) and Neptune (right), obtained with spectral resolution R = 56000 and R = 28000, respectively.



width and correcting the Doppler displacements.The quadrupole lines of molecular hydrogen in the visible region in the spectra of Uranus and Neptune are weak, unsaturated, and different rotational levels of molecular hydrogen are unequally populated. It should be noted that the reason for the excitation of rotational levels is the collisions during heat motions typical in the atmospheres of planets. In addition, estimates of the temperature of the planet's atmosphere, independent from heat emission measurements, can be determined on the intensity of rotational lines in molecular absorption bands on the reflected spectra of the planet. In case the frequency of transitions at collisions (without emission) exceeds the frequency of spontaneous transitions, the population of rotational levels is determined by the Boltzmann formula [12,14]. It should be noted that by knowing the ratio of the populations of the two rotational levels, determined on the equivalent widths of these lines, it is possible to determine the rotational temperature of that layer of the atmosphere where the main absorption in these lines is created.

$$170 = TLn[5.49W_{S(0)}/W_{S(1)}], \tag{1}$$

Where $W_{S_{(0)}}$ and $W_{S_{(1)}}$ equivalent line widths S(0) and S(1) .

The rotational temperature for the atmospheres of Uranus and Neptune was calculated by the intensity ratios S(0) 6435.03 Å and S(1) 6367.76 Å (Table 1). By the half-breadth of the λ6367.76 Å and λ6435.03 Å lines in the spectra of Uranus and Neptune, in the (4-0) band of molecular hydrogen with consideration of the instrumental half-breadth, the pressure values were estimated at the depth, at which these lines are formed, by using the formula given in work

$$P = \frac{\Delta\nu}{\alpha}(\frac{T}{300})^{1/2} \tag{2}$$

In formula (2) α - line half-breadth at normal pressure P =1 atm and temprature $T = 76°K$ (for Uranus [16]), T= 72°(for Neptune [16]) $\Delta\nu$ line half-breadth (sm^{-1}) in spectrum.

Table 1. Half-breadths and equivalent widths of molecular hydrogen lines S(0), S(1), the calculated values of pressure and rotational temperature at the formation levels in the atmospheres of Uranus and Neptune.

Parameters	Uranus		Neptune	
	S(0)	S(1)	S(0)	S(1)
$\Delta\lambda$(Å)	0.3	0.25	0.25	0.29
P_0(atm)	2.4		2.0	
P_1(atm)		2.1		2.3
W(mÅ)	39.8	33.3	40.4	41.3
T(K)	90.4		101	
Measurment error	11%		10%	

Belton et al. [17] show that the H_2 quadrupole lines related to vibrational-rotational transitions in the 4-0 band give a temperature of 118° ± 40° K. According to observations of spacecraft "Voyager-2," measurements of heat flows coming from the planet showed that in the sub-cloud atmosphere, already at the level P = 2.3 bar, the temperature reaches 100^0 K. Higher, at a pressure level of 0.6 bar, the temperature at the equator and the light and dark poles is the same and equals 64° K, and in the middle latitudes is 2° K lower. The minimum temperature (53°K) was observed at a pressure level of 0.1 bar (higher than the visible cloud surface). For several nights, in order to study the profiles of the lines S(0) 6435.03 Å and S(1) 6367.76 Å in the spectrum of Neptune, the observations of this planet were carried out by the authors [18]. The authors of work [18] have registered ∼ 20% change in equivalent widths in the indicated lines over the past 15 years. Authors note that the change of the equivalent widths within the measurement errors is related to change in the amount of tropospheric aerosol in the atmosphere of Neptune, where temporary brightening of methane clouds occurs (increasing of brightness in the centers of moderate and strong absorption bands). The limits of change in the temperature of the atmospheres of Uranus and Neptune, indicated in work [13], consistent with our measurements for the rotational temperature $T_r = 90^0 - 114^0$ K and the pressure P = 2.1÷2.3 atm.

3. DISCUSSION

If Uranus and Neptune emitted only the heat that they receive from the Sun, then their temperature (equilibrium) would be at the level of 57° and 47° K, respectively. However, when actual measurements of heat flows were carried out, it turned out that these two planets have the same effective temperature: 56°−58°K. It can only mean one thing: Uranus almost has no energy sources of its own, while Neptune has, and quite powerful ones, approximately 2.7 times more than what the planet receives from the Sun. The temperature of heat emission from Neptune reaches 59.3°K, even higher than that of Uranus (59.1°K). In work [6], the mole fraction of helium in the upper troposphere of Uranus, equal to 0.152 ± 0.033 (by volume), was determined on radio-eclipse and infrared spectroscopy data conducted by "Voyager-2". The corresponding mass fraction is Y =0.262 ± 0.048 (Table 2), close to the protostellar mass fraction of helium, equal to 0.28±0.01. This value is consistent with recent solar helium abundance estimates, making it possible to suggest that helium differentiation did not occur on Uranus. Comparisons with the values obtained earlier for Jupiter and Saturn show that helium migration to the core began long ago on Saturn and may have recently begun on Jupiter. Data [7] covers the altitude interval for the atmosphere of Neptune up to 250 km. In the upper layer of Neptune, associated with the atmosphere and accessible for measurements, contains hydrogen and helium, and the average helium content is higher than on Uranus. Comparison with infrared observations shows that the gas in the tropopause, observed near the 100-mbar level, is 77-85% hydrogen by density, and the rest is mainly helium. Estimates of the molecular hydrogen content in the atmospheres of Uranus and Neptune were carried out on different models of the atmosphere. If the formation of quadrupole lines of, molecular hydrogen is only clear absorption, $U_{H2} = 1460$ km·atm (U_{H2} is the molecular hydrogen content), or only scattering occurs, different authors estimate this value decreases to 560 km·atm. According to data [8], helium differentiation (nuclear migration) has not been observed in these planets yet, and it is considered that the initial relative numbers within Uranus and Neptune are closer to the Sun. This factor is the same for Uranus, and Neptune does not explain the same extra emission of heat energy 6% of the first (Uranus) and 170% of the other (Neptune). Although, both of them are close in many of their characteristics.

Table 2. The relative fraction of hydrogen and helium in the atmospheres of the giant planets and the protosun according to data of work [8].

Gas	Element	Protosun *	Jupiter	Saturn	Uranus	Neptune
H_2	H	0.835	0,8645	0.88	~0.83	~0.82
He	He	0.162	0.136	0.119	~0.15	~0.15
He	New data on the mass fraction of helium in the atmospheres of planets			0.11 [16]	~0.26 [6]	~ 0.25 [7]

It is clear that the cores of these planets vary significantly by size, even if they are identical by chemical composition. According to observations at the ShAO of Uranus and Neptune, it is found that in the center of the strong absorption band of methane λ6190 Å, Neptune is brighter than Uranus [19] It is shown that this effect is clearly performed and increases at the centers of other strong absorption bands of methane (Fig. 4). One more important observed result can be added to this. It was established that the monochromatic absorption in the spectrum of Uranus in the central region of the CH_4 methane band at λ6190 Å is greater than in the spectrum of Neptune, even though the intensity of other absorption bands increases during transiting from Uranus to Neptune. In weak and moderate absorption bands, Neptune is darker than Uranus. In the central parts of strong absorption bands, Neptune becomes brighter. Sometimes brightening (increase in brightness) disappears in moderate absorption bands and is observed only in relatively strong absorption bands of methane [21]. It is more probable that the core of Neptune is more enriched by isotopes of heavy elements than Uranus.

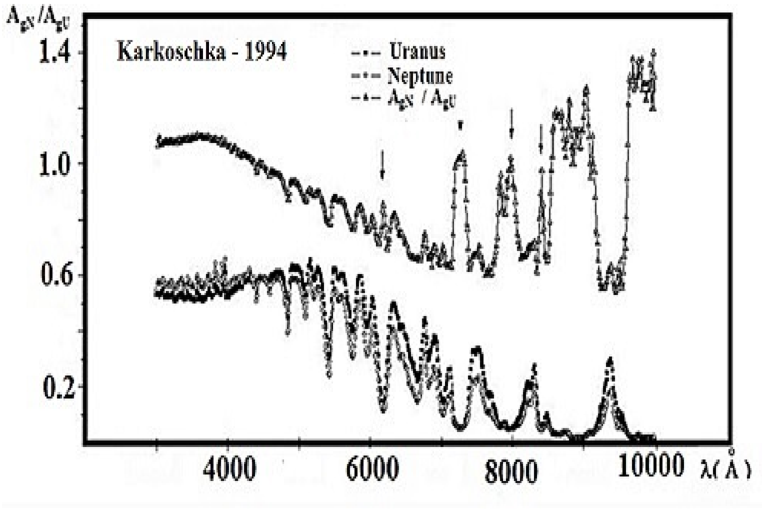


Fig. 4. According to the observed data, the ratio of monochromatic intensities of absorption bands in the spectra of Neptune and Uranus is [20]. The arrows show the central parts of the methane absorption bands.

4. CONCLUSIONS

1. Based on the results of observations of Uranus and Neptune, it was found that changes in the intensity (equivalent breadth) of the S(0) 6435.03 Å and S(1)

6367.76 Å lines do not exceed the measurement errors. The pressure values determined by the half-breadths of the indicated lines vary in the range from 2÷2.4 atm.

2. The temperatures of Uranus and Neptune vary within $90 \div 118^0$ K, at the depth at which the H_2 (4-0) lines are formed, which is almost comparable for Jupiter and Saturn, which have internal sources of energy.

3. If Uranus has some internal energy sources, they do not exceed 6% of the heat received from the Sun. Then the emerging dynamic processes on Uranus can be damped processes.

In the atmosphere of Neptune, the nature of the circulation is regulated "from below," from the interior of the planet. Such nonstationary processes cause changes in aerosol particles density and their distribution on height in its atmosphere, temperature, rate of movement in the clouds. Furthermore, this leads to changes in the parameters for the atmosphere of Neptune, which we obtain from spectral and photometric observed materials.

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