MOLECULAR ABSORPTION BANDS IN STUDIES OF JUPITER'S ATMOSPHERE

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Despite more than half a century of spectral studies of Jupiter, the informational possibilities of observing the planet, even in the visible wavelength range, are far from being fully utilized. At present, the focus of attention of many researchers has shifted to the area of thermal infrared and microwave radiation of Jupiter due to the appearance and application of the largest optical and radio telescopes. Absorption by methane and ammonia molecules plays a significant role in the transfer and output of this thermal radiation. However, these gases are minor components in the chemical composition of the Jovian atmosphere. The study of the behavior of the absorption bands of methane and ammonia by estimates of their equivalent widths or high-resolution rotational lines observed in the visible spectral range can serve as a valuable addition to such studies. Formation of absorption bands observed in the wavelength range 500-940 nm. Occurs in the gas-aerosol environment of the planetary troposphere due to scattering and true absorption of incident sunlight.Therefore, without losing the value of studying space-time variations both in the total absorption of molecular bands and at their rotational-vibrational structure, it is a complex study of the behavior of weak and moderate absorption bands that can be used for the optical sounding of the Jupiter troposphere with its cloudy layers. The report presents the results based on long-term spectral observations of Jupiter. They include a description of several features in the behavior of the molecular absorption bands of methane and ammonia from measurements of their equivalent widths and measurements of the intensities of individual rotational absorption lines of ammonia and quadrupole lines of molecular hydrogen.These results indicate the possibility of detecting previously unknown features in the behavior of weak molecular absorption bands, including those correlating with those observed in the thermal radiation of Jupiter.

Keywords: Jupiter–atmosphere–clouds–Great Red Spot– spectrophotometry–ammonia–molecular absorption–brightness radio temperature

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INTRODUCTION

Molecular absorption bands that are present in the spectrum of Jupiter are not only evidence of the presence of specific components in the chemical composition of the planet's atmosphere but can also serve as an indicator of the structure of the atmosphere and the changes occurring in it. The fact is that in the atmosphere of Jupiter, as in the atmospheres of other planets, there are not only gases in their normal state but also the products of their transition to other phase states: liquid or solid in the presence of appropriate values of temperature, pressure, and concentration. As a rule, these are cloud layers located at certain levels in the atmosphere, the thickness and bulk density of which depends on a number of factors acting in a particular range of heights at different latitudes and longitudes.

The main and determining mass of Jupiter, its size, density, and internal structure is hydrogen, which is about 87 percent, and helium, practically complementing the remaining percentages. In comparison, all other components lie within one percent, if not less. In the outer layers of Jupiter's troposphere, the predominance belongs to methane and ammonia. However, at great depths, where the temperature exceeds 270 K, the presence of significant amounts of H_2O in the form of vapors and clouds is quite likely. In the visible surface of Jupiter, which is a layer of clouds predominantly consisting of crystals of frozen ammonia, the temperature is only about 120-125 K. Methane in the atmosphere of Jupiter is only in the gas phase. However, valuable for studying this planet because both methane and ammonia create well-defined and measurable absorption bands in the visible region of the spectrum. In the infrared and microwave ranges, methane and ammonia absorption significantly affects the yield of thermal radiation and its transfer from deep layers. The presence of clouds, that is, suspended solid or liquid aerosols that create a scattering-absorbing medium, significantly affects the formation of molecular absorption bands in the visible region of the spectrum, complicating this process compared to absorption in a pure gas layer. Multiple scattering by cloudy particles has a different effect on the apparent intensity of the observed absorption bands.

It all depends on the microphysical characteristics of cloudy matter - on the size of particles, their bulk density, and the optical thickness of the cloud layer. Since these characteristics can differ significantly in different regions of the planet, the observed intensity of the absorption bands reveals more or less clearly pronounced space-time variations. They can be used as one of the criteria for the state of the atmosphere and properties of the cloud cover of Jupiter.

Interest in studying the behavior of molecular absorption bands arose back in the 30-s of the last century when articles by the American astronomer Bobrovnikov and the Pulkovo astrophysicist Eropkin appeared almost simultaneously. They tried to trace how the intensity of the absorption band of methane at 619 nm changes from the center of the Jupiter disk to the edges. It was the only absorption band visible on the planet's spectrograms obtained on ordinary photographic plates of that time. The images of Jupiter themselves were too small to trace any details, but still, some center-limb differences were obtained. After a long hiatus, only in the early 60-s, a similar attempt was made by S. Hess, who also studied the 619 nm methane band. He measured its intensity at several points on the disc.

Subsequently, sporadic studies of this kind appeared in the scientific literature, including Kazakhstani researchers publications. For the planetary laboratory AFIF, they have become one of the main directions in studying the optical properties and structure of the atmospheres of the giant planets Jupiter and Saturn. Similar observations were carried out by the staff of the Main Astronomical Observatory of the Academy of Sciences of Ukraine. By using photoelectric methods for recording planetary spectra, the range of observed wavelengths was expanded. It made it possible to study the behavior of other, more intense absorption bands of methane, for example, 725 nm and 887 nm, and subsequently the absorption bands of ammonia at 645 and 787 nm. However, the most effective were spectral observations using digital technology in the form of CCD cameras with matrices of tens and hundreds of thousands of photosensitive elements, with a spectral sensitivity range of up to 1 and 0.1 μm and a dynamic range of four orders of magnitude. An essential advantage of the matrices is recording the spectrum, not of a separate small area of the planet's disk but the entire equator of the central meridian or certain latitudinal belts. In addition to observing the absorption bands of methane and ammonia, it also became 3 possible to detect and measure weak hydrogen absorption lines using high-resolution spectral equipment.

These are the pressure-induced quadrupole lines S (0), S (1) of the H_2 (4-0) band located in the visible spectral region with wavelengths λ_0 = 643.503nm, λ_1 = 636.776nm.

In 1938, Herzberg [1] predicted the presence of quadrupole lines of molecular hydrogen in the spectra of giant planets, and in subsequent works [2–5] lines S (0) and S (1) of H_2 (3-0), H_2 (4-0).

Accurate data for the quadrupole lines of molecular hydrogen H_2 may represent an excellent opportunity for a detailed analysis of the atmospheres of giant planets. These lines are sensitive to the hydrogen content, the ortho-para ratio, the vertical structure of the atmosphere, the distribution of clouds, and the pressure-temperature profile of the observed planetary atmosphere.

At present, reliable experimental estimates were obtained for the molecular parameters required for model calculations [6–8]; additional results are presented in [9]. Observations of many manifestations of H_2 in Jupiter were described in the literature (for example, in [10], observations of H_2 for Jupiter were generalized).

In [10–12], the absorption coefficients of the H_2 (4-0) S(1) quadrupole transition for the 636.776 nm line were calculated. The line strengths obtained are only 54% and 60% of the theoretical values of the matrix elements calculated in [13] and [4], respectively. It is essential to understand these differences since the interpretation of the spectra of the planets in this transition is very important for estimating the H_2 content in the atmospheres of these planets. The H_2 content is used in proportion to the content of other molecules (elements) for comparison with solar values. The H_2 content is essential for building a model of the atmosphere of major planets. More accurate data on the absorption coefficients for the H_2 (4-0) line were given in [5]. The absorption coefficient of the H_2 (4-0) S(1) transition is $(1.54 \pm 0.09)\cdot 10^{-4}$ sm^1 km^{-1}amagat^-1, $andforS(0)itis0.88$ $\pm$ 0.32 sm^1 km^1 $amagat^1$ [5, 10]. These estimates are in good agreement with the theoretically predicted values $S(0) = 1.63 \cdot 10^{-4} sm^{-1} km^{-1} amagat^{-1}$ for S(1) and S(0)=0.95 $\pm$ 0.14 sm^1 km^1 $amagat^{-1}$ for S(0), however, differs from previously published laboratory measurements [5]. In [9, 15], the measured equivalent width was used to estimate the effective ortho-parahydrogen ratio for the Jupiter troposphere. Observations of molecular hydrogen in the atmospheres of planets, in addition to the absorption coefficient, also require knowledge of the exact frequencies of transitions [16–18].

The overtone of molecular hydrogen (4-0) was most useful for quantitative studies of the atmospheres of giant planets(especially in the spectra of the first two planets). Its usefulness is partly due to its extremely low intensity, as a result of which the lines of the H_2 (4-0) band are unsaturated even in the deep layers of the atmosphere. For example, the observed equivalent width of the strongest component of the H_2 (4-0) band, the S(1) line, is only 0.8 pm in the spectrum of Jupiter [9]. Another useful property of higher rotational-vibrational quadrupole overtones predicted by McKellar [19] is a large pressure shift coefficient for center-line frequencies. Shifts of lines under pressure, formed in atmospheres of hydrostatic equilibrium, prevent the onset of saturation. If the pressure shift is equal to the value predicted in [19] for the (4-0) overtone, then the S (1) line should be unsaturated even in the spectrum of Uranus, where its observed equivalent width is about 3 pm [20, 21]. The influence of pressure shifts on the formation of H_2 quadrupole absorption lines in the atmospheres of major planets was not considered previously. It is shown that although pressure shifts are not measured for the H_2 (3-0) and (4-0) bands, they can be estimated using current experimental and theoretical knowledge. Based on these estimates, it is shown that the influence of pressure shifts is insignificant for Jupiter and small for Saturn but rather large for Uranus.

In [9, 15], it was concluded that the equatorial zones of Jupiter and Saturn show the presence of significant diurnal fluctuations in the quadrupole hydrogen absorption lines. Thus, studies of hydrogen quadrupole lines in the atmospheres of giant planets will help to reveal the essence of many phenomena that occur in their atmospheres and are reflected in the dynamics of cloud structures in the planet's atmosphere. Therefore, carrying out spectrophotometric studies of the absorption lines of molecular hydrogen in the spectra of Jupiter and Saturn and calculating some parameters of the atmosphere are very important for clarifying the essence of changes in the atmospheres of planets and the mechanism for the release of internal energy in it.

In the present article, we present some of the main findings of this kind of research over the past decade. These are studies of the absorption bands of methane and ammonia, carried out at the Astrophysical Institute. V.G. Fesenkov and studies of hydrogen quadrupole absorption carried out at the Shamakhy Astrophysical Observatory of the Azerbaijan Academy of Sciences.

1. METHANE AND AMMONIA

1.1. Direction and objectives of the research

The main direction of research of the laboratory of physics of the moon and planets of the Astrophysical Institute named after V.G. Fesenkov was and remained the study of the giant planets and, first of all, Jupiter.
Based on spectrophotometric observations of Jupiter, studies of the behavior (distribution over the disk and intensity variations) of weak and moderate absorption bands of methane at 619, 702, 725, 790, 887 nm and weak absorption bands of ammonia at 550,645, and 787 nm are carried out for many years.

One of the main tasks of long-term and methodically homogeneous observations is to search for a possible connection between variations in molecular absorption and active processes in the Jupiter atmosphere and a change in the heliocentric distance during a complete revolution around the Sun.

1.2. Instrumentation and observation technique

The main observations since 2004 were carried out by using an SGS diffraction spectrograph with an ST-7XE CCD camera manufactured by Santa Barbara Instrument Group (SBIG) (Figure 1).
The spectrograph was installed at the 7.5-m Cassegrain focus of the 0.6-m telescope RC-600. The spectrograph is equipped with two diffraction gratings with a resolution of 1 A/pixel and 4.3 A/pixel, respectively.

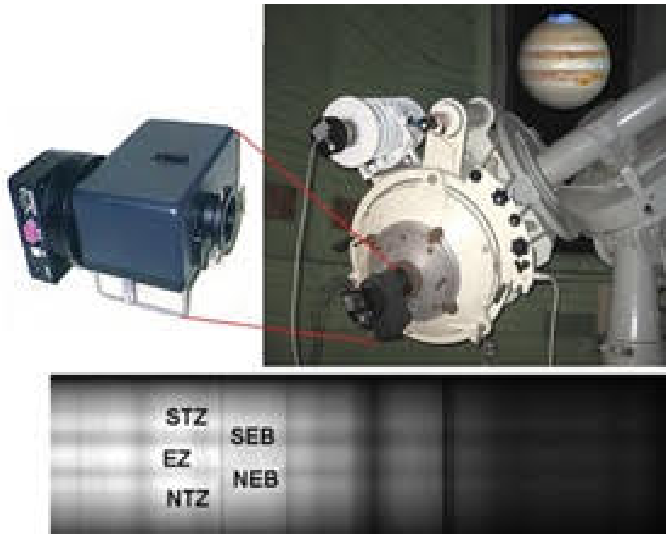

Fig. 1. Spectrograph with a CCD camera on the RC-600 telescope. Below is a sample of the spectrogram of Jupiter and the cloud structures studied on it.

The observations were carried out in two ways. The spectra of the central meridian of Jupiter were recorded, in some cases for two hours, in order to trace the longitudinal variations due to the rotation of Jupiter. To improve the accuracy of obtaining the profiles of absorption bands, we also used zonal spectra obtained as a result of scanning the Jupiter disk from the South Pole to the North Pole with the orientation of the spectrograph slit parallel to the planet's equator.

Figure 2 shows the Jupiter spectrum profile, where the studied absorption bands of methane and ammonia are indicated. The primary distortion is introduced by the relatively weak but numerous water vapor bands, especially around 720 nm. In the visible region of the spectrum, there are H_2O bands at 590 nm, 650 nm, and 720 nm. In the near-infrared region, there are the H_2O bands at 820 nm 926 - 978 nm.

The most convenient object of comparison, devoid of molecular absorption bands, is Jupiter's satellite Ganymede, which can be observed simultaneously with the planet at the same zenith distance. The ratio of the spectra of Jupiter to the spectrum of Ganymede makes it possible to almost entirely get rid of the influence of Fraunhofer lines and telluric bands and, to a significant extent, to level the spectral sensitivity of the CCD camera, which makes it possible to visually graphically represent the features of the spectrograms in the entire spectral range and to highlight areas of the continuous spectrum.

From 2014 to 2021, highly dispersed spectra of Jupiter were obtained with a 2-m telescope ShAO with different spectral resolutions R = 14000 and 56000. Spec-

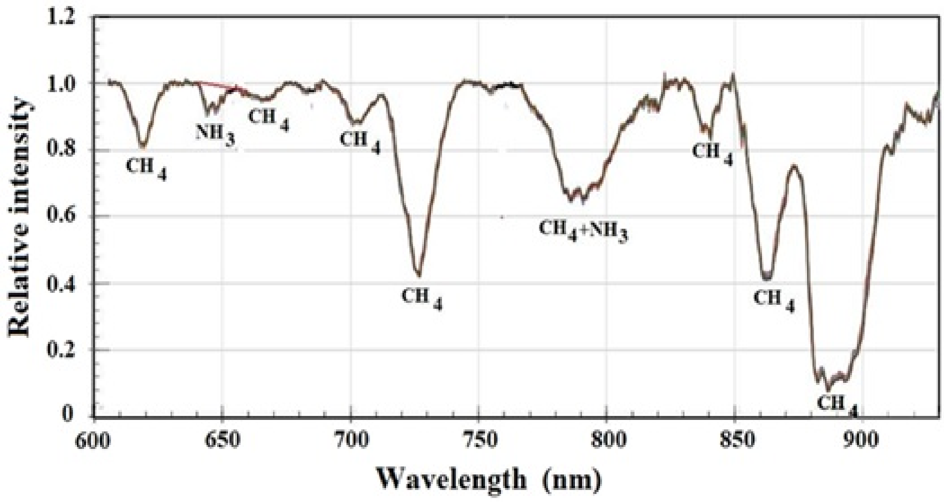

Fig. 2. The studied absorption bands of methane and ammonia in the spectrum of Jupiter

tra with a resolution of R = 14000 were obtained using an echelle spectrometer with a camera (580x530 pc, element size 24×18 μm) set in the Cassegrain focus. Spectra with a resolution of R = 56000 were obtained using a ShAFES fiber-optic echelle spectrograph. An American-made CCD camera with a matrix of $4K \times 4K$ elements with an element size of 15×15 microns was used as a light detector. It and other spectrometers installed on the 2-m telescope are described in more detail in the works of H.M.Mikhailov et al. [22, 23]
When processing the obtained observational material, the dispersion curve of the continuous spectrum was drawn along the tops of the peaks in each discharge (for more details on the details of this technique, see [22, 23]). Drawing a continuous continuum in this way makes it easier to compare the results of different observations. In addition, to control the accuracy of the continuum, each time, we selected solar lines of relative intensity to the line understudy in the planet's spectrum. Then the accuracy of measurements of the equivalent widths and half-widths of solar lines will be the same as the accuracy of measurements of molecular hydrogen lines under study.

The average errors in determining the equivalent widths of solar lines [24] in our measurements vary from 4% (in the central regions of the planet) to 10% (closer to the circumpolar regions). This accuracy is maintained for the studied lines of the atmospheres of the planets. Carrying out the continuum is a crucial stage of the operation, on which the further result of the spectral study depends. The line of the continuum is usually smooth and convex. If there are doubts

about the correctness of drawing the continuum in given spectrum order, one can compare the energy distribution in neighboring orders. The intensities of neighboring orders in the echelle spectra are close. The wide wings of the α line do not allow one to see the level of the continuous spectrum, and if a false continuum is drawn in this order, we will receive erroneous values of the equivalent widths.
Next, we select the curves of the continuum of neighboring orders. Shift this curve up to the maximum value. This curve can serve as a hint for the position of the continuum.

As a result, we get the reconstructed continuum. For each detail on the planet's disk, two or three spectra were obtained. The resulting echelle spectra were processed using the DECH-20 software package developed at the SAO RAS [25]. The spectra were processed using the new version of the DECH program. To perform processing, in addition to the spectra of the object under study, it is necessary to obtain a complete set of calibration frames: dark (or bias), flat-field, ThAr, or Sky. The CCD is cooled to very low temperatures of 130 K to reduce thermal noise. With such a degree of cooling, thermal electrons of the CCD matrix are practically absent, as a result of which the dark frame does not differ from the bias frame even at exposures of tens of minutes. In this case, it makes no sense to spend considerable time observing to obtain dark frames.

1.3. Methods of processing spectrograms

To process the spectrograms of the central meridian of Jupiter, special programs were compiled using the object-oriented language Delphi (Figure 3).

The programs have functions for setting the angular dimensions of the planet and the air mass at the time of observation. It is possible to control the background subtraction methods, the shift of the reference spectrum and water vapor, and the graphs′ scale and the color map. When the file is opened, the program determines the position of the planet's spectrogram on the working field of the CCD matrix by the method of successive approximation, cuts out the working area, brings it to a given angular size, determines the spectral background at the top and bottom of the spectrogram, interpolates it in height and subtracts it. Using the successive approximation method, the program finds the minimum in the telluric oxygen absorption band at 760 nm and then determines the position of the $H\alpha$ reference line at 656.3 nm.
A significant part of the observational material, including the series of zonal spectra, was processed using the programs of the Excel spreadsheet package.

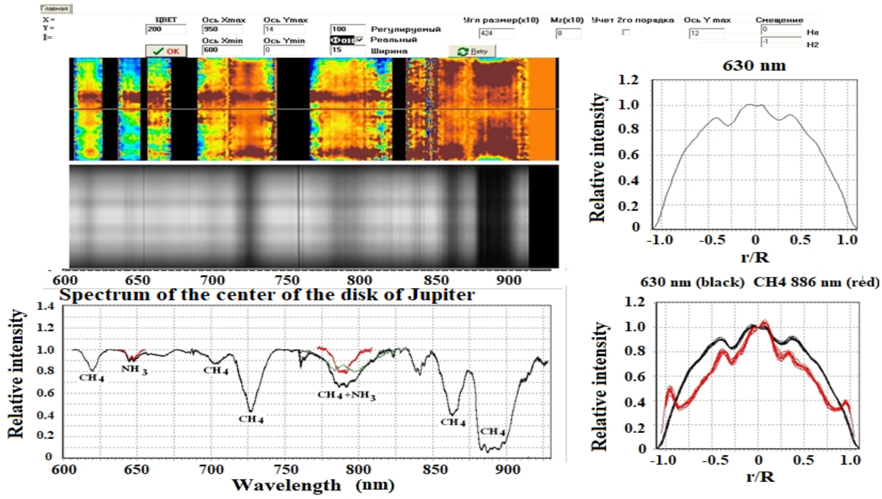

Fig. 3. Screenshot of the main tab of the program "Colored absorption map along with the Jupiter disk" with a demonstration of the main controls. A significant part of the observational material, including the series of zonal spectra, was processed using the programs of the Excel spreadsheet package.

1.4. Ammonia

Ammonia plays a vital role in the atmosphere of Jupiter, being, on the one hand, the primary agent in the formation of the visible cloud cover and, on the other hand, participating in the formation of deeper cloud layers. Despite even lower than that of methane, relative concentration, ammonia, nevertheless, can reach a saturation state under conditions of planetary temperatures. Thanks to this, ammonia is the main cloud-forming chemical compound in the upper troposphere of Jupiter.

During observations in the spectrum of Jupiter in the wavelength range of $\lambda 500 - 1000$ nm, three absorption bands of ammonia (NH_3) 551, 645 nm, and 787 nm were studied (Figure 4). For the 550 nm band, only preliminary results were obtained so far since, in previous observations, it did not fall into the range of wavelengths cut by the CCD camera. Therefore, particular test observations were carried out with the 645 nm band, which showed the possibility of a comparative study of their behavior.

However, the difficulty lies in the fact that most of the ammonia bands are entirely or partially bleached by methane absorption bands (Figure 5), and their "extraction," as shown in [26–29], requires certain methodological techniques.

The ammonia NH_3, $\lambda 645$ nm band, is located in the short-wavelength wing of the CH_4 methane absorption band, the maximum of which falls at a

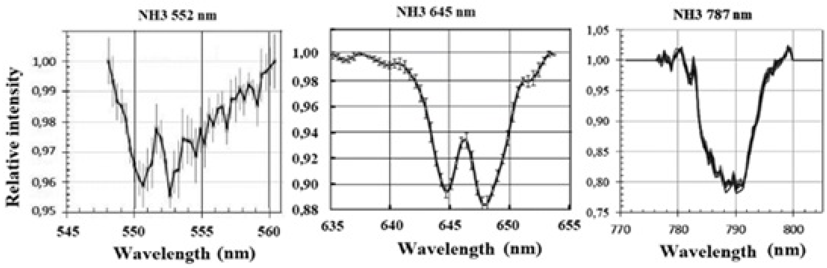

Fig. 4. Profiles of absorption bands of ammonia

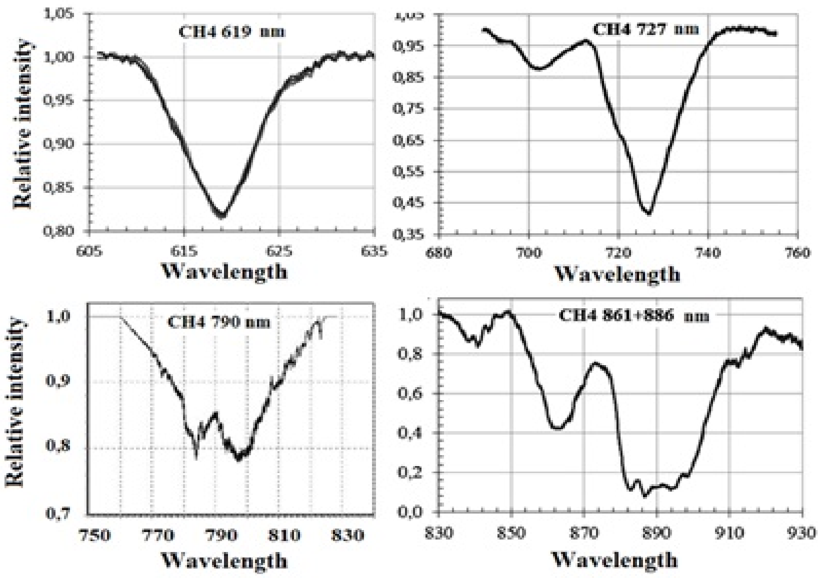

Fig. 5. Profiles of methane absorption bands

wavelength of about λ667 nm.Figure 6 shows the profile of the entire combined band obtained from observations after calculating the ratio to the reference Ganymede spectrum.

To identify the ammonia band from the compound spectrum of Jupiter in the 790 nm region, the Jupiter spectrum was sequentially divided into the Ganymede spectrum and the "pure" spectrum of Saturn's methane in this region.

As a result, the profile of the 787 nm ammonia band (Figure 7) can be distinguished from the methane spectrum on the Jupiter disk in the 790 nm region, and its intensity, equivalent to its width, can be determined.

Figure 7 - fragments of methane spectra in the 770-810 nm region for the center

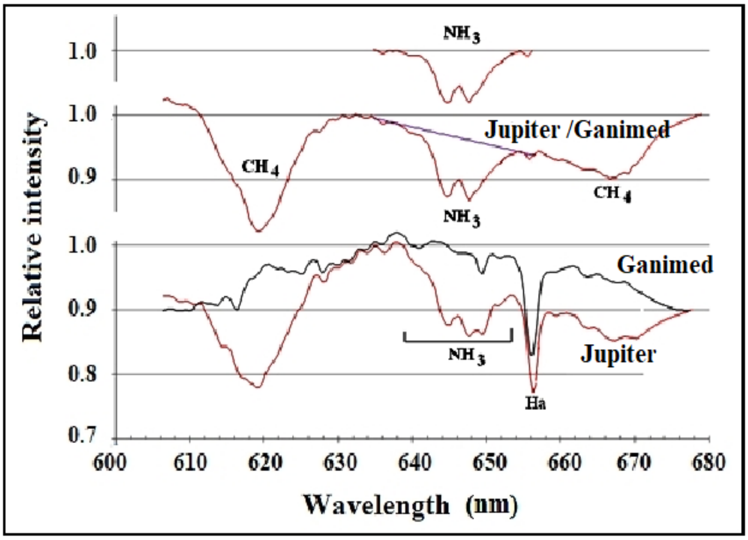

Fig. 6. Fragments of the spectra of Jupiter, Ganymede, their relationship and "pure" spectrum ammonia in the region of 645 nm (top) after the relation to the continuous spectrum.

of the disk of Saturn and Jupiter (left) and the result of their ratio in the form of a spectrum of ammonia NH_3 on Jupiter (right, top).

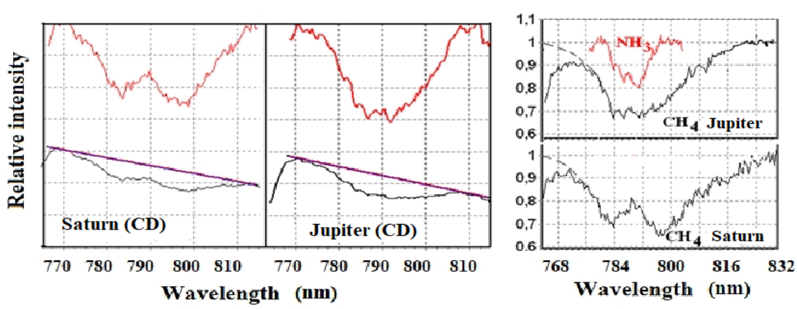

Fig. 7. Fragments of methane spectra in the 770-810 nm region for the center of the disk of Saturn and Jupiter (left) and the result of their ratio in the form of a spectrum of ammonia NH_3 on Jupiter (right, top).

For the absorption bands, the profiles of the absorption bands and the meridional or zonal distributions of the absolute and normalized to the center of the disk residual intensities at the centers of the bands, central depths, equivalent widths, logarithms of residual intensities, and correlations between the determined values were determined.

1.5. Spatial variations of absorption bands

When studying the variations in absorption on the Jupiter disk, primary attention was paid to the changes in latitude along the planet's central meridian. The main result was the estimates of the equivalent widths and central depths of the absorption bands; however, in the analysis of latitudinal absorption variations, estimates in relative units were also used. As a rule, such values were calculated concerning the equatorial zone. Although minor irregularities appear in the bright equatorial zone, it is more stable than others cloud belts, so in some cases, it can be used as a reference. Here we present only some of the results of recent years by illustration.

Consider the results of processing the spectrograms of the central meridian of Jupiter in 2016. The intensities of the studied absorption bands of methane and ammonia were measured along the central meridian of Jupiter and also along the equator (Fig. 8).

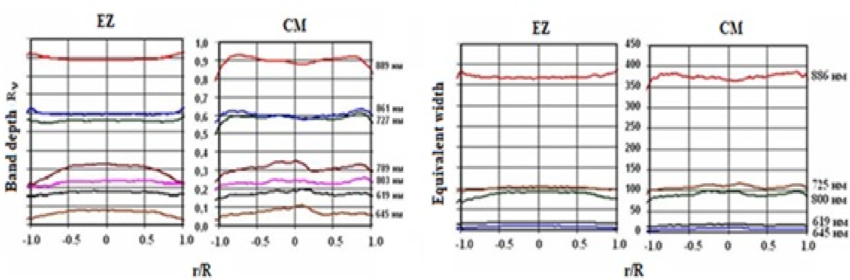

Fig. 8. The course of the central depths and equivalent widths of the absorption bands of methane and ammonia of varying intensity along the equator and along the central meridian.

However, the results presented in such a traditional form turn out to be of little informative for both qualitative and quantitative comparison. It was shown in [30] that, due to the significant difference in the intensities of the studied absorption bands, it is difficult to compare both the variations in their depths and their equivalent widths. A more vivid picture, in our opinion, is given by the variations in the residual intensities of the absorption bands B, which can be represented as

$$B_\nu = I_\nu / Ic \sim exp(-\tau)$$

where τ - in the general case represents the effective optical absorption path, the interpretation of which depends on the adopted model of the atmosphere structure and radiation transfer.

As the simplest model, one can use a two-layer model of the formation of absorption bands. A homogeneous optical semi-infinite cloud layer and a purely gaseous atmosphere are involved. For calculations using such a model, the tables of Dlugach and Yanovitsky [31] are very convenient.
Comparison with such calculations reveals the difference in the formation of ammonia and methane absorption bands.

Taking the logarithm of the distribution of residual intensities over the disk of the planet, we obtain variations in the course of $\tau_{\nu M}$ for methane or $\tau_{\nu A}$ for ammonia in different absorption bands. The results presented in this way provide adequate information about the variations in the absorption disk by the molecules of a given gaz (Figure 9).

Figure 9 clearly shows that variations in absorption along the equatorial zone in

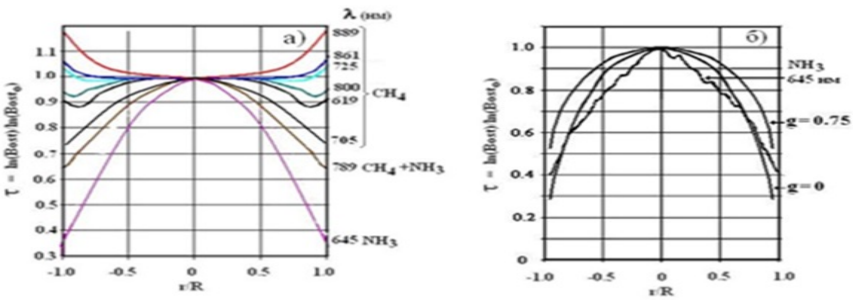

Fig. 9. a) - Normalized to the center of the disk, the variation of ammonia and methane along the bright equatorial zone EZ. b) Comparison of the course of absorption of ammonia at 645 nm along the equator with model calculations performed on the basis of theoretical calculations [31]

the absorption bands of methane at 619, 705, 725, 803, 861, 889 nm are qualitatively well within the framework two-layer model. Theoretical calculations only for a semi-infinite homogeneous cloud layer give a decrease in absorption to the edge of the planet's disk, the degree of which depends on the elongation of the indicatrix and the probability of quantum survival. In the absorption bands of methane and ammonia, located mainly in the near-infrared region of the spectrum, it increases absorption to the edge due to an increase in the equivalent path in the above-cloud atmosphere due to the secant effect increasing to the edge. The role of the supra-cloud atmosphere drops sharply with a decrease in the intensity of the absorption band, manifesting itself only near the limb itself.

For the absorption bands of ammonia, as expected, the role of the above-cloud atmosphere is practically reduced to zero due to a sharp decrease in the content of gaseous ammonia above the clouds and the stratosphere. It follows from Figure.9 that, in contrast to methane, the absorption behavior in the 645-nm ammonia band cannot be described simply by a scattering-absorbing layer with an elongation parameter g of the indicatrix in the range from 0 to 0.75. Figure 10 shows summary graphs of variations in the absorption intensity of ammonia and methane along the central meridian in 7 absorption bands. In this figure above - variations of τ^* along the central meridian in the 787 nm ammonia band; below - the same for methane bands 619, 725, 800, 861, and 889 nm.

According to Figure.10, for solid and moderate absorption bands of methane, as in previous years, analmost symmetric increase in absorption at midlatitudes and a sharp decline near the poles are characteristic. It is exceptionally well traced for the South Polar Region (Figure 11).

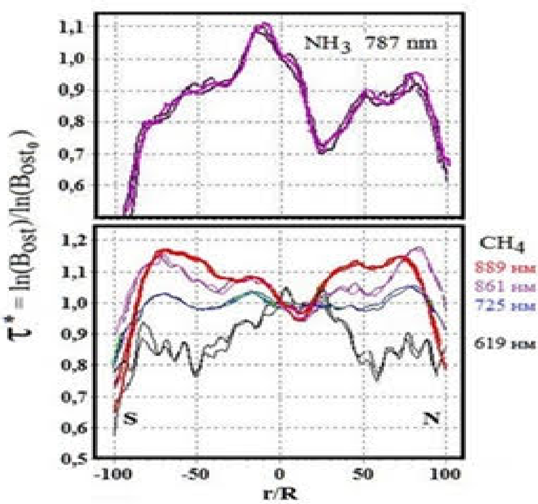

Fig. 10. Comparison of variations in the absorption intensity of methane and ammonia along the central meridian of Jupiter in 7 absorption bands in 2016.

In general, the variation in the intensity of absorption bands with latitude corresponds to the zonal structure on the Jupiter disk. The deep minimum in the NEB region and the decrease in absorption towards high latitudes near the 787 nm ammonia band are especially well distinguished. We noticed this depression of the 787 nm band in the NEB region back in 2004 [32].

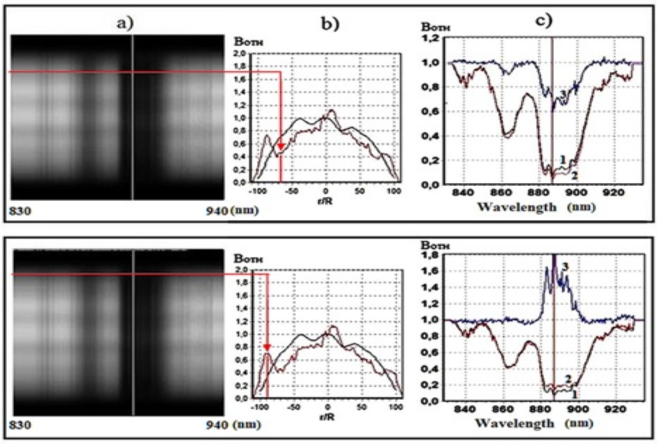

Fig. 11. Change in the absorption intensity in the 889 nm methane band. a) - a fragment of the spectrogram in the 830-950 nm spectral region, b) - meridional section in the continuous spectrum of 830 nm and the center of the methane absorption band at 884 nm, c) - profiles of the CH_4 absorption band in the center of the disk (1), in the polar region (2) and their ratio (3)=(2)/(1).

Noteworthy is the similarity of the behavior of the small absorption bands of methane at 702 nm and ammonia at 645 nm (Figure 12).
CH_4 702 nm and NH_3 at 645 nm and their ratio in 2016.

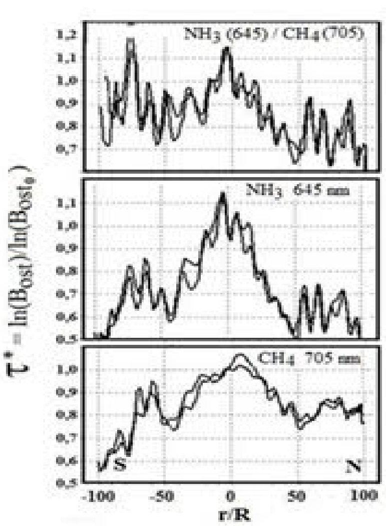

Fig. 12. Distribution of τ^* along the central meridian of Jupiter in the strip.

Figure 13 compares the effective optical paths τ^* NH3 for the two ammonia bands at 645 and 787 nm. For clarity, here is an image of Jupiter on the same date, 05/05/2018. [33].

The left side of Figure.14 shows the brightness profiles of Jupiter's CM in the

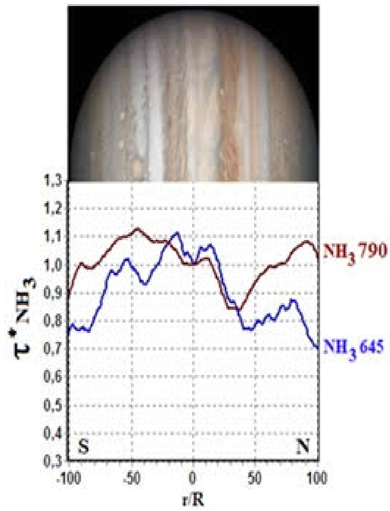

Fig. 13. Variations in the meridional course of ammonia absorption in two absorption bands at 645 and 787 nm.

center of the intense methane absorption band at a wavelength of 887 nm in the longitude range from 240^0 to 310^0 at the time of the passage of the Great Red Spot (GRS) through the central meridian. Right - latitudinal absorption variations in the 787 nm ammonia band in the same longitude interval.

The anomalous behavior of ammonia revealed by us within latitudes of $\pm 30^0$ correlates quite well with the main zonal jet streams and with the wind map on Jupiter.

Near certain latitudinal belts, extrema are observed corresponding to the minimum or maximum equivalent band widths. The general trend is that the lowest values are more in the northern hemisphere. The highest absorption values approximately correspond to light zones. It is noteworthy that the positions of the extrema in different bands do not precisely coincide with each other but reveal, although small, apparent shifts in latitude. This feature persists from year to year.

During preliminary measurements of the ammonia absorption band at 550 nm, we compared its intensity and latitudinal variations with the intensity and latitudinal variations of the 645 nm band.

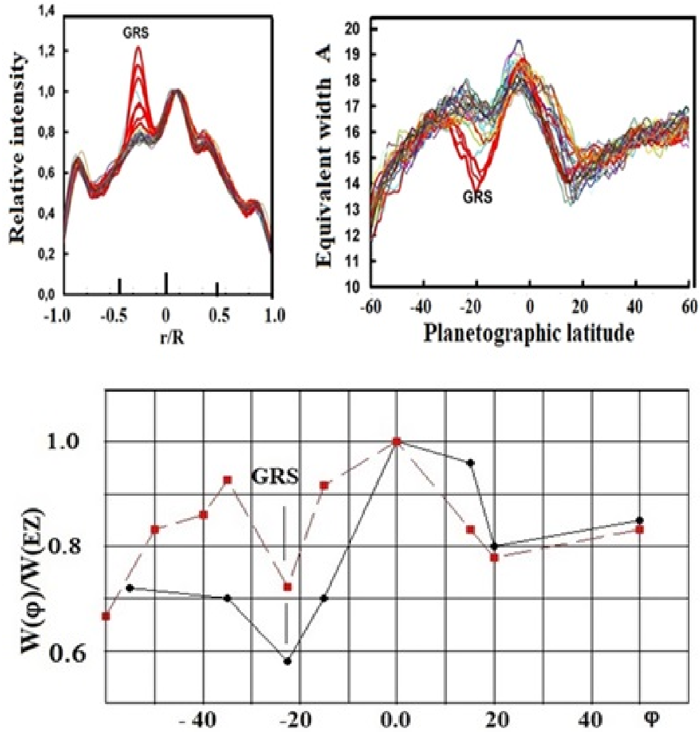

Fig. 14. The left side (A) of Figure [14] shows the brightness profiles of Jupiter's CM in the center of the intense methane absorption band at a wavelength of 887 nm in the longitude range from 240° to 310° at the time of the passage of the Great Red Spot (GRS) through the central meridian.Right - latitudinal absorption variations in the 787 nm ammonia band in the same longitude interval (A).B. Distribution of equivalent widths W (mÅ) for different parts of the Jupiter disk concerning the equatorial region according to the data of Atai [34] (black dots for all ammonia lines in the λ645nm absorption band for all ammonia lines) (The results of observations performed on spectrograph with a CCD camera on the RC-600 telescope: the meridional course of ammonia absorption in the λ645 nm absorption band).

These two bands, unlike the others, have laboratory growth curves [35]. They represent the dependence of the equivalent band width on the equivalent or effective optical absorption path. For weak bands, this dependence is linear and is expressed by the relations:

$$\tau_{550} = W_{550}/24;$$

$$\tau_{645} = W_{645}/250$$

For the center of Jupiter's disk, the equivalent optical paths are 0.108 km-am and 0.027 km-am, respectively. Thus, it turns out that for the weakest ammonia

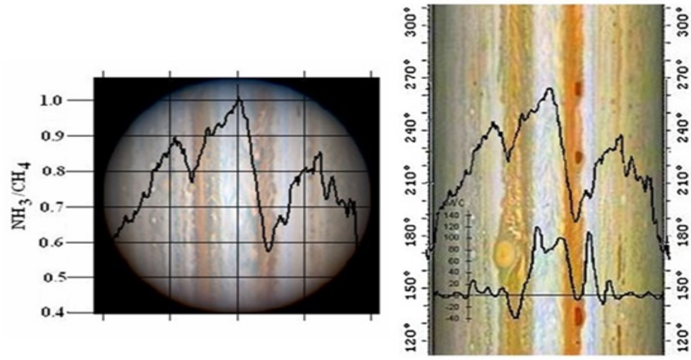

Fig. 15. Comparison of the variation of the ammonia content with the zonal cloud structure along with the CM of Jupiter (left) and with the wind map (right)

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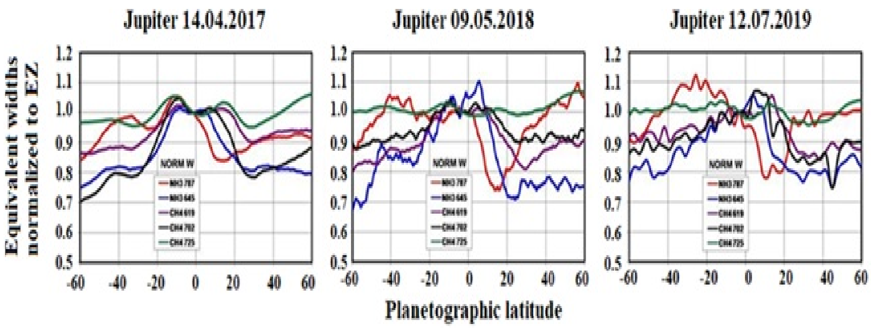

Fig. 16. Shows the latitudinal variations of the equivalent widths of the absorption bands of methane and ammonia normalized to the equatorial zone from observations in 2017-2019.

band at 550 nm, the equivalent absorption path is four times greater than that of the 645 nm band. Latitudinal variations of the calculated equivalent widths and their ratios are shown in Figure 17.

As noted earlier, the study of ammonia uptake in our program began in 2004. As a tentative study of time variations, the processing of spectrograms was carried out according to an abbreviated program. For this, five main belts were identified on the spectrograms of the central meridian: the southern and northern tropical zones (STrZ, NTrZ), the southern and northern equatorial belts (SEB, NEB), and the equatorial zone (EZ), shown in Figure 1.

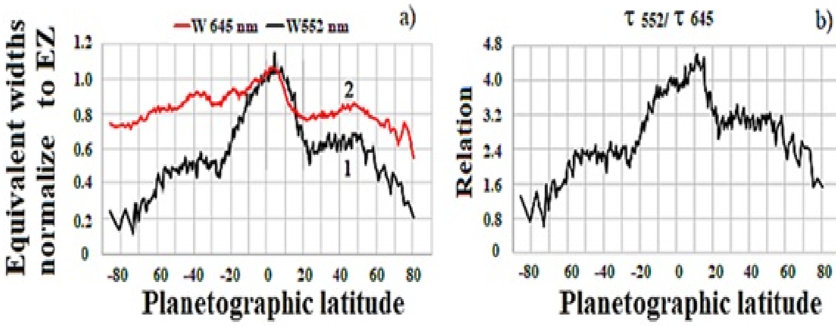

Fig. 17. - (a) - Normalized to the center of the meridional disk course of equivalent widths W_{NH_3} 5529Å(1) and W_{NH_3} 6450 Å(2). (b) ratio of τ_{NH3} 5529 Åto τ_{NH3} 6450 Å

Figures 18 and 19 show the yearly averages of the equivalent widths of the NH_3 absorption bands of 645 nm and 787 nm for the five main belts of Jupiter.

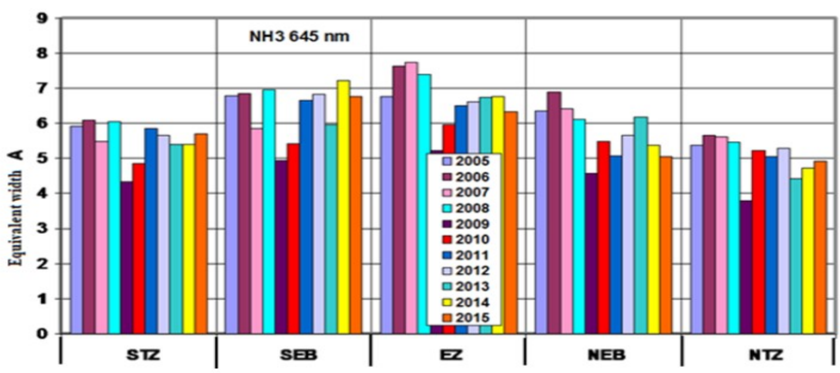

Fig. 18. Time variations over the years of the equivalent width of the absorption band NH_3 645nm

Any regular time course is not noticeable, except for a decrease in absorption in the 645 nm band in 2009 typical for all zones. It is not observed in the 787 nm band, and the reason and degree of reality of such a temporary depression in the NH_3 645 nm band in all five zones.

1.6. Comparison with infrared and microwave measurements

As noted above, many modern studies of Jupiter are devoted to the study of thermal radiation from the planet in the infrared and microwave (millimeter) wavelength ranges. The transfer of radiation in these ranges and, accordingly,

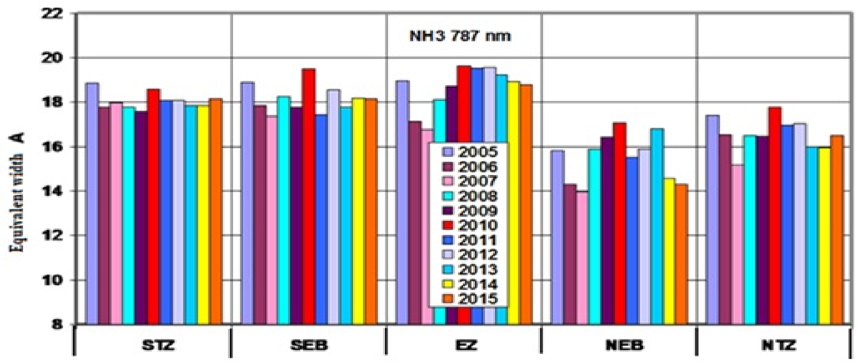

Fig. 19. Time variations over the years of the equivalent absorption band of NH_3 787 nm.

the brightness temperature of the observed output radiation largely depends on the absorption by methane and ammonia. Therefore, it is of no small interest to compare with those features of the molecular absorption of methane and ammonia in the visible region of the spectrum. In particular, attention is drawn to the features of the Great Red Spot - a giant anticyclonic vortex with a diameter of about 16.000 km. It has existed for over 200 years, remaining at the same latitude of 20 - 25 degrees in the southern hemisphere of Jupiter. In addition to the peculiarity of its color, spectral observations also reveal its unusual appearance in the absorption bands of methane and ammonia. In the visible and near-infrared regions of the spectrum, where their formation depends on the properties of the cloud layer, the GRS shows a significant weakening of the absorption intensity. In the strong 887 nm methane band, it appears to be the brightest object on Jupiter's disk. Our studies of ammonia absorption in the sunspot also showed a well-pronounced decrease in the intensity of the NH3 bands in the GRS, as shown on the left-hand side of Fig.18. These features of the GRS should most likely be associated with the unique structure of the cloud environment inside the sunspot. In the strong band of methane at 887 nm, the weakening of absorption can be attributed to the increased density of the cloudy substance or the increased height of its upper boundary compared to the surrounding cloud cover.

The latter creates a decrease in the optical thickness of the above-cloud atmosphere above the sunspot. In the strong band of methane, the absorption created in the above-cloud atmosphere is large enough and critical to the position of the cloud top. Therefore, high brightness of the spot in this strip can be achieved when its upper boundary rises even by only 10 - 20 km. However, this cannot explain the weakening of ammonia absorption in the GRS since, in the above-cloud atmosphere, the ammonia content and absorption are negligible. Therefore, the weakening of ammonia absorption can be explained by the increased density of clouds inside the GRS vortex. It is evidenced by observations at a wavelength of 4.7 - 4.8 μm. There is no methane absorption in this part of the infrared spectrum, so the cloud cover only modulates the outgoing infrared radiation. Accordingly, the observed brightness temperature at these wavelengths depends on its density. On the right side of Figure 20, it can be seen that the GRS at a wavelength of 4.7 μm looks dark against the background of the surrounding regions with a higher brightness temperature. It indicates an increased density of cloudy matter in the GRS.

Thermal radiation in the far-infrared range and the millimeter radio range has their peculiarities in variations on the Jupiter disk. Here, already cloudy matter does not affect the yield of thermal radiation, but the absorption by methane and ammonia plays a significant role. It simulates the intensity and effective depth of the outgoing thermal radiation and accordingly, its variations.These variations are well traced on the brightness temperature maps obtained with the largest optical and radio telescopes. The most prominent in the microwave range is the increased brightness temperature in a narrow belt of latitudes of about 15 degrees adjacent to the NEB. It is in this region that we found a well-pronounced depression of the absorption band of ammonia at 787 nm.

On the sweep maps of the Jupiter disk, built from the intensity of radio emission

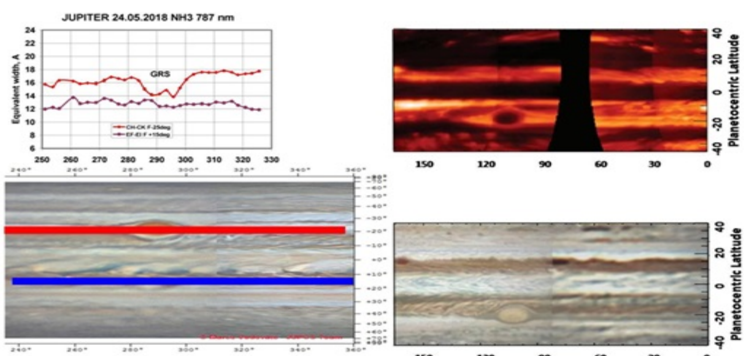

Fig. 20. Left: comparison of the longitudinal variation of ammonia absorption in the SEB and NEB belts for the NH_3 787 nm band. Right: a fragment of the map of the distribution of brightness temperatures on Jupiter at a wavelength of 4.7 μm [36]

[37] (Figure 21 on the right), it can be seen that the brightness radio temperature is increased precisely in the NEB belt.

This feature is interpreted as a result of the decreased ammonia content in the interior of Jupiter's atmosphere at the low latitudes of the northern hemisphere. Figure 21 on the left shows EZ normalized latitudinal variations of the equivalent widths of 645 and 787 nm bands. On the right the conventional values of the ammonia content are shown as a reflection of latitudinal variations in brightness temperature in the millimeter radio range.

In conclusion, it should be noted one more general feature when comparing the data of radio observations and the visible region of the spectrum (Figure 22). Although our observations of the absorption bands of methane and ammonia shown at the bottom of the figure do not have the exact high angular resolution as the radio observations indicated at the top of the figure, there is a particular general trend. Towards high latitudes, the absorption of methane and ammonia decreases,while a slight increase is observed at brightness temperatures.

A decrease in the content of absorbing gases likely leads to higher brightness temperatures.

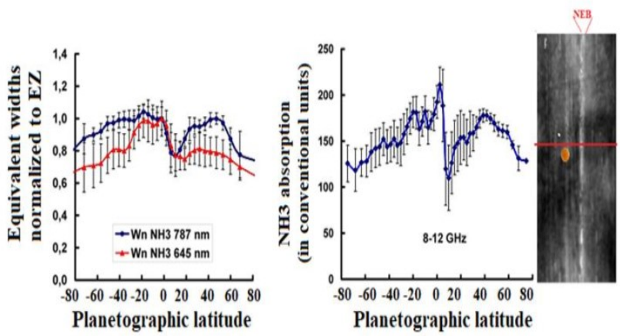

Fig. 21. Comparison of latitudinal variations in ammonia absorption in the NH_3 645 and 787 nm bands (left) and NH_3 absorption in the millimeter radio band (right)

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$1 - NH_3 645nm, 2 - CH_4 619nm, 3 - CH_4 702nm, 4 - CH_4 725nm, 5 - NH_3 787nm.$

2. DISCUSSION

1. The results presented here show that studies of the spectral properties of Jupiter in the visible and near-infrared wavelengths have not lost their relevance, even though the most successful studies of this planet are now concentrated in the thermal infrared and microwave radiation ranges. The revealed features in spatio-temporal variations in the intensity of molecular absorption bands are associated to the greatest extent with the properties of the planet's cloud cover that

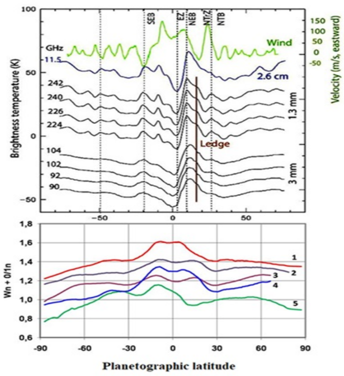

Fig. 22. Comparison of latitudinal variations in brightness temperatures in several ranges of microwave radio emission [38] and equivalent widths of methane and ammonia absorption bands normalized to the equator in the visible region of the spectrum

are inhomogeneous in the latitudinal and longitudinal directions. The formation of the observed extinction in the deeper layers of Jupiter's troposphere is also not ruled out. Thus, observations of absorption bands provide an opportunity for the optical sounding of the Jovian troposphere since the effective levels of formation of weak, moderate, and strong absorption bands can differ significantly. The value of observations in the visible region of the spectrum lies in the fact that only at these wavelengths can a cloudy medium be studied. In the long-wave region of the spectrum: infrared and radio ranges, clouds are transparent to the out going thermal radiation.

Investigations in the visible spectrum are available to fairly moderate-sized telescopes, while measurements of the planet's thermal radiation require the use of the largest optical and radio telescopes.

The main problem of interpreting the results obtained for absorption bands is related to the complexity of their formation mechanism in the gas-aerosol medium of the planetary atmosphere. With remote optical observations, it is practically impossible, with rare exceptions, to solve the inverse problem of directly obtaining the object's physical characteristics under study. It is necessary to solve the so-called direct problem, basing theoretical calculations on one or another model structure of the atmosphere and radiative transfer. The most convenient model of an optically thick and homogeneous cloud layer, which considers multiple scattering and absorption in this layer, can only be used for a preliminary interpretation of the observed variations in absorption bands on Jupiter. Within the framework of this model, it is possible to detect features that do not fit into any options for its parameters. Therefore, it is necessary to develop models with an optically and geometrically thin and translucent layer of ammonia clouds, considering the heterogeneity and duty cycle. In such cases, absorption in the space between the ammonia cloud layer and the deeper, though still hypothetical, layer of ammonium hydrosulfide clouds and water clouds will play a significant role. The presence of aerosols, which create a scattering medium, is also not excluded in the intermediate gas layer. All this can be reflected in the observed features of the behavior of the absorption bands.

Comparison of data in the visible range and measurement of the brightness temperature of thermal radiation, which depends on local differences in the ammonia content, can bring us closer to choosing the adequate model for the structure of Jupiter's troposphere. So, for observations in the visible spectrum region and model calculations, there is still a wide field for further research.

2. The papers [5, 20] present the observed values of the equivalent line widths S(0) S(1) for Saturn.
For the H_2 (4-0) band, the results of Karkoschka's calculations [15] agree with the data of Spinrad and Trafton [5]. Studies of this nature were carried out in [15] for different lines of the H_2 (4-0) band in the eastern E and western W parts of the planet's disk. The measurements of the S(0), S(1) were performed along the same meridian simultaneously. From the observations, the intensity ratio W(0)/W(1) for the centers of planetary disks varies within small limits. For Jupiter with a spectral resolution R = 14000, the value of the intensity ratio S(0)/S(1) varies within 0.69÷0.06 (2014), and for the central part and the North pole of the Saturn disk, within $(0.760 \div 0.904) \div 0.05$. According to the spectra of the center of the disks of Jupiter and Saturn with a spectral resolution of R = 56000,the value of the intensity ratios W(0)/W(1) for Jupiter was $(0.71 \div 0.73) \div 0.06$, (2016–2017) and for Saturn, approximately $\div 0.904 \div 0.06$. For the northern part of the disk of Saturn, the intensity values vary within $(0.76 \div 0.904) \div 0.06$. The results of our observations are consistent with the data obtained in [39, 43].

When studying the predominantly hydrogen atmosphere of giant planets, it is necessary to know the degree of thermal equilibrium between the para- and ortho-states of molecular hydrogen H_2 because the ratio $f_p = 1 - W(0)/W(1)$ depends on the internal energy of the atmospheric gas the number of para-ortho states [40, 47].

In [47], the H_2 $S_4(2)$ lines were found in the spectrum of Jupiter, and it was found that $W_4(1)/W_4(0) = 1.4 - 1.7$, while the nominal ratio for $W_4(1)/W_4(0)$ is approximately 2. Based on the value found for the center of the planet's disk from the nominal ratio $S_4(2)/S_4(0)$, the effective temperature was calculated on the order of 150 K, which corresponds to the depth of the atmosphere at which these quadrupole absorption lines are formed. It was found that for the center of Jupiter's disk, the nominal ratio $S_4(2)/S_4(0)$ depends on the fp fraction of the ortho-parahydrogen ratio for the equilibrium troposphere. An analysis of sequences of global cartographic data from Voyager 1, -2 shows that the para-fraction is the smallest at equatorial latitudes and approaches equilibrium at high latitudes [40, 41]. The atmospheric level sampled corresponds to a temperature of 125 K. The equatorial para-fraction will represent thermal equilibrium at about 160 K. The low-latitude minimum f_p is found to be significantly shifted north of the equatorial-temperature minimum, in contrast to the gradients found in earlier spacecraft measurements Voyager and ground-based measurements [42–46]. It was noted in [43] that in the Great Red Spot region, the values of the f_p(parahydrogen) fraction decrease approximately from 0.320 to 0.305. It should be noted that,according to the results of our observations, the content of molecular hydrogen had the lowest value in the Great Red Spot region, i.e., $f_p = 0.286$ and 0.28 in 2014 and 2016 respectively (averaged values over the entire GRS). It can be seen from the comparison that $U_{H_2}(GRS) < U_{H_2}(EZ) < U_{H_2}(STrZ)$. In addition, the analysis of the vertical structure of the atmosphere based on data from the Galileo and Voyager spacecraft on wind and temperature fields confirms the hypothesis that the upper part of the GRS is an inclined "pancake" that changes its slope with time [40–43]. As the temperature approaches 300^0K, the ortho-parahydrogen ratio fp will tend to maintain its "normal"value, i.e., 3:1 [42–46]. Therefore, it is necessary to monitor the change in the ratio $S_4(0)/S_4(2)$ along with the disk of Jupiter and Saturn in space and time. According to our measurements in 2016, the W(0)/W(2) ratio for Jupiter was 3.5 ± 0.6, and for Saturn, approximately 2.5 ± 0.4. Ananalysis of the equilibrium mechanisms shows that due to the inhomogeneity of the field associated with the admixture of H_2 hydrogen molecules,the $H_2 - H_2$ paramagnetic interaction is dominant.

Then it is not a priori evident to what extent equilibrium can be realized in a hydrogen atmosphere in vertical transfer from high to low temperatures? The conversion of ortho-para-hydrogen dramatically increases the efficiency of convection. Within Jupiter's stably stratified upper troposphere, where infrared spectra begin to form, the global change in para-fraction appears to be driven by upwelling at equatorial latitudes in response to solar heating. If so, there is a compensatory downward movement in the polar regions [40]. Hence it follows that the role of conversion should increase at the poles of Jupiter and Saturn, which is reflected by an increase in temperature at the poles to values comparable to the equatorial temperature.

Determining the hydrogen para-ortho ratio f_p, which indicates the ratio of the intensities S(0) and S(1) in Jupiter's atmosphere, can be crucial in measuring the rate of diffusion and convective processes [42]. Reflectivity measurements in the spectrum regions where gas absorption limits the depth of penetration of photons make it possible to carry out vertical sounding of the cloud structure. The features of absorption by methane and hydrogen are well suited for this purpose because these components are well mixed in the atmosphere [44].

Infrared data [43] from large ground-based telescopes such as the NASA infrared telescope in Hawaii, the European Southern Observatory VLT array, the Japanese Subaru telescope in the Hawaiian Islands, and the Gemini Observatory showed that the reddest regions of the Great Red Spots correspond to the relatively warm core of the hurricane, which has an average temperature close to 110 K [44]. There are colder eddies in its environment. It became known that the brightest orange-red part of the BKP is about three to four degrees warmer than the surrounding area, and the average temperature corresponding to the warm core of the hurricane is close to 110 K [44], which is consistent with the low-pressure value. In addition, according to the Voyager-1, -2 measurements in [41], at P = 0.15 bar, the temperature is $106.5 \div 112.5$ K (V1) and $107 \div 112K$ (V2). It would be even more interesting to follow the change in the $S_4(2)/S_4(0)$ ratio in the Great Red Spot of Jupiter,which has complex dynamics and has been developing with fluctuations since observations in the 19^{th} century. It showed tendencies towards a decrease in length, a slowing down of the drift rate and possibly, an acceleration of the internal circulation. Unlike the Earth's atmosphere, the circulation on Jupiter and Saturn is mainly due to ascending internal heat flows. In order to find answers to many questions related to the dynamics of the atmospheres of giant planets (including the origin and evolution of the GRS and other oval formations), it is necessary to observe them for a long time using ground-based and space telescopes. These observations should be carried out with a high spatial and spectral resolution to reveal the patterns of atmospheric phenomena on their disks.

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