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THE DISTRIBUTION OF TEMPERATURE IN THE DETAILS OF JUPITER'S DISK BASED ON THE ABSORPTION LINES OF THE NH_3 λ6450 Å BAND

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ABSTRACT. In order to understand significant meteorological processes occurring in Jupiter's atmosphere, studies were carried out on ammonia NH_3 absorption lines, whose relative amount is small but whose influence could be comparable to water vapor in Earth's atmosphere. These observations were performed using a high spectral resolution échelle spectrometer installed at the Cassegrain focus of the 2-meter telescope at Shamakhi Astrophysical Observatory. Variations in the intensity of NH_3 absorption lines in the NH_3 λ 6475Å band were studied in different regions of Jupiter's disk and at the center of Saturn's disk. In this spectral region, 20 lines were selected for the center, 14 lines for the northern zone, and 11 lines for the southern zone. The obtained data were processed using the DECH 95 and DECH 30 programs. The spectrophotometric characteristics of these spectral lines, including their equivalent widths and half-widths, were determined. Based on the observational data obtained, Jupiter's rotational temperature was determined from different line pairs. The calculated temperatures vary between approximately 180 K and 80 K. The observed variations in temperature could be attributed to lightning events within these layers. Summarizing the obtained results, the average temperature in the details of Jupiter's disk was determined to be approximately 127 K, aligning well with findings reported by other authors.

Keywords: Jupiter, NH_3, λ6450 Å absorption lines, rotational temperature.

АНОТАЦІЯ. Для розуміння значущих метеорологічних процесів, що відбуваються в атмосфері Юпітера, були проведені дослідження ліній поглинання аміаку NH_3, відносна кількість яких невелика, але вплив яких може бути порівнянним з водяною парою в атмосфері Землі. Ці спостереження проводилися за допомогою ешель-спектрометра з високою спектральною роздільною здатністю, встановленого у фокусі Кассегрена 2-метрового телескопа в Шамахинській астрофізичній обсерваторії. Варіації інтенсивності ліній поглинання NH_3 у смузі NH_3 λ 6475 Å досліджувалися в різних областях диска Юпітера та в центрі диска Сатурна. У цій спектральній області було відібрано 20 ліній для центру, 14 ліній для північної зони та 11 ліній для південної зони. Отримані дані були оброблені за допомогою програм DECH 95 та DECH 30. Визначено спектрофотометричні характеристики цих спектральних ліній, включаючи їх еквівалентні ширини та напівширини. На основі отриманих даних спостережень було визначено температуру обертання Юпітера за різними парами ліній. Розраховані температури коливаються приблизно від 180 K до 80 K. Спостережувані коливання температури можна пояснити блискавками в цих шарах. Підсумовуючи отримані результати: середня температура в деталях диска Юпітера була визначена приблизно на рівні 127 K, що добре узгоджується з висновками інших авторів.

Ключові слова: Юпітер, NH_3, лінії поглинання λ6450 Å, обертальна температура.

1. Introduction

The condensation of atmospheric gases and the formation of clouds on Jupiter indicate that in the observable part of its atmosphere, at least in the lower layers, temperature decreases with increasing altitude. Until now, the temperature of Jupiter's atmosphere has been determined using various methods. For example, the rotational temperature of CH_4 and the saturation temperature of NH_3. These, of course, correspond to the deepest layers. The brightness temperature determined in the infrared range, on the other hand, characterizes the higher layers. The distribution of temperature depends on the absorption of solar radiation and the planet's own radiation at different altitudes and in various spectral regions. At the observed partial pressures and temperatures in Jupiter's atmosphere, methane does not undergo condensation, whereas H_2O, on the contrary, exists as low-pressure saturated vapor. It is not excluded that water and ice clouds form in the deep, unobservable layers of the atmosphere. The distribution of temperature depends on the absorption of solar radiation and the planet's own radiation at different altitudes and in various spectral regions.

2. The calculation of the rotational temperature

The determination of rotational temperature on Jupiter has been conducted using various molecules. For example, Zabriskie (1962) determined a rotational temperature of T_{rot}= 170K based on the relative intensities of the lines in the H_2 (3-0) band. Spinrad and Trafton (Spinrad,1963) reported a range of 120–170K; however, Spinrad later refined this value, stating that it was 120 K

The calculation of rotational temperature based on CH_4 and NH_3 lines encounters certain difficulties. This is because these molecules are non-linear and their bands have complex structures. For instance, due to its symmetry (tetrahedral), the methane molecule exhibits spherical rotation. It has four fundamental frequencies, two of which (ν_3 and ν_4) are active in the infrared region. When two or more frequencies or their overtones combine, they form combination bands. Pure overtones are distinguishable only for the ν_3 and ν_4 frequencies.

Another challenge arises from the fact that the fundamental inactive frequencies are quite close to ν_3 and ν_4. As a result, rotational levels undergo Coriolis excitation, leading to the splitting of rotational lines, which further complicates the bands. Unfortunately, nearly all CH_4 bands located in the high-resolution spectroscopy region are combination bands. Consequently, their fine structures are extremely difficult to analyze. The intensity of rotational lines depends on three quantities: transition amplitude, the statistical weight of the upper state, and the Boltzmann factor. If the molecule undergoes true spherical rotation, the distribution of rotational levels is given by the following formula:

$$N_k \sim (2k+1)^2 \, e^{-\frac{Bk(k+1)hc}{kT_r}} \qquad (1)$$

If the molecule undergoes spherical rotation due to symmetry, then the ratio in equation (1) is not real, and the statistical weight for each rotational level must be calculated taking into account the spin of the nucleus. This is applicable in the case of CH_4. The intensity of rotational lines depends on three quantities: transition amplitude, the statistical weight of the upper state, and the Boltzmann factor. The intensity,

$$I_k \sim A_k s_k e^{-\frac{Bk(k+1)hc}{kT_r}} \qquad (2)$$

Here, A_k is the transition amplitude, and S_k is the statistical weight.

$$A_k s_k = (2K+3)(5a+2b+3c) \qquad (3)$$

Here, a, b, and c are the quantities of rotational levels corresponding to the modifications of A, E, and F for a given K. Using the ratios in (1) and (2), the relative intensity of rotational lines in the T_r function can be presented in a table, and by selecting the ratios that better match the observations, the T_r-rotational temperature can be determined. Ouen (1968) determined that using this method, for the $3\nu_3$ band with K=3,4,5,6 lines, the Tr temperature is 200±25.

The rotational temperature determined by Ouen is close to the melting point of NH_3 (195K). It is likely that the lower boundary of the observable part of Jupiter's atmosphere is determined by the level of dense clouds composed of liquid ammonia. Interestingly, the rotational temperature is close to the brightness temperature in the shadow cast by the moons. A comparison of ammonia line spectra at different locations on Jupiter shows a strong variation in their intensities. This indicates horizontal inhomogeneity in the disk of Jupiter at the depths of the cloud layers that produce the observed absorption lines of ammonia. This observational data allows for the calculation of rotation. For the NH_3 λ6451.12 Å line, according to our data, the profile of this line has been constructed using approximate formulas, taking into account the instrumental profile.

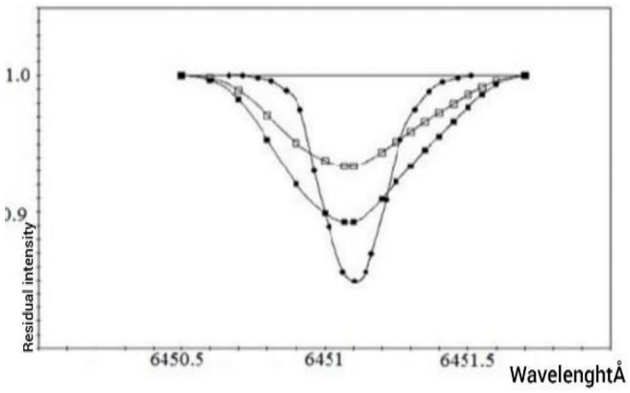
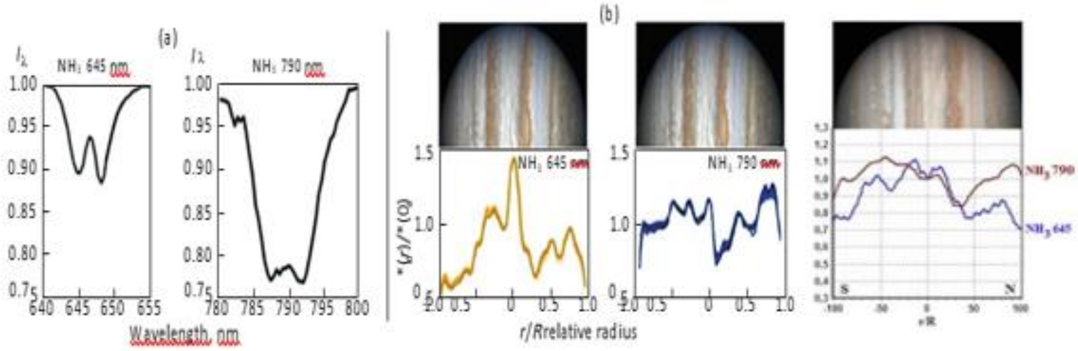


Figure 1: The profile of the NH_3 λ6451.12 Å absorption line in the spectrum of Jupiter, obtained in the SAO. (Equatorial belt – open squares – without considering the instrumental profile, black squares – with the instrumental profile taken into account) and Smith's observation (Ouen 1968) (black circles at the center of the planet's disk)

3. Calculation of the equivalent widths and half-widths of spectral lines

Long-term observations show that Jupiter's atmosphere is heterogeneous (Carlson et.al, 1987). This heterogeneity is also unstable – it changes over time. These variations are manifested in the changes in the intensity of the absorption bands observed in the molecular gas spectrum in the visible and infrared regions. These absorption lines and bands originate at different depths of the gas and cloud layers. The formation of ammonia absorption bands observed in the visible and near-infrared spectral regions occurs primarily within a multilayered cloud structure through the process of multiple scattering and in purely gaseous gaps between cloud layers. Therefore, visible variations in the intensity of NH_3 absorption bands can be interpreted as a consequence of changes in the structural characteristics of the clouds, as well as in the size and concentration of cloud particles. All of these factors are expected to influence the relative abundance of gaseous ammonia in different regions of Jupiter. In 2023, these variations were most clearly observed in the NH_3 absorption band at 6450 Å (Vdovichenko et al., 2025) Based on the intensity of spectral bands, it is possible to assess the physical conditions on the planet. In planetary physics, the study of the heterogeneity of temperature and its dependence on time is of great importance.



Fiqure 2: Variations in the meridional course of ammonia absorption in two absorption bands at 645 and 790 nm; ammnia absorption bands at 645 and 790 nm: (a) profiles.

Spectrograms of Jupiter in the λ 5200-7000 Å region were obtained by N.B. Ibrahimov at the Shamakhi Astrophysical Observatory, named after N. Tusi, using a two-meter reflector with a dispersion of 6 Å/mm (0.15 resolution) during 1970-71 (10 spectrograms) (Ibrahimov, 1975). These materials were processed and published for the central disk. In this work, spectral data from the NH_3 λ 6450 Å absorption band were used for the central equatorial zone (EZ), the northern equatorial band, and the southern equatorial band. This spectral material was obtained on 22.05.2023, using the 2-meter telescope of the N.Tusi Shamakhi Astrophysical Observatory with a CCD-matrix equipped Echelle spectrometer at a dispersion of 4 Å/mm. For this band, 20 lines were selected for the center, 14 for the northern band, and 11 for the southern band. The acquired data were processed using the DECH 95 and DECH 30 (http://www.gazinur.com/DECH-software.html) programs, and the equivalent widths and half-widths of the spectral lines were calculated. The obtained results are presented in the table below.

As seen, the equivalent width and half-width of the spectral lines are the largest at the center, and are larger in the southern region compared to the northern region. Based on the obtained results, it is possible to assess the physical conditions on Jupiter. For planetary atmospheres, the absorbing atmospheric model assumes that the formation of absorption bands or lines occurs in a uniformly mixed medium of absorbing gas and scattering aerosol. In such a medium, lines of varying intensities and different parts of the absorption band arise at different depths. Undoubtedly, this corresponds to various structural forms. In this case, the volume concentration of the gas and the volume scattering coefficient of the aerosol do not change with depth according to the same law. Even if we use a homogeneous atmospheric model for the analysis of spectrophotometric observations, in the case of actual inhomogeneity, we would obtain different values for the physical characteristics of the gas-aerosol medium depending on the intensity of the given absorption band. In real conditions, the rotational temperature is one such characteristic. The average temperature on Jupiter's disk has been determined by various authors since 1924. For instance, Zabriskie F.R. established that the temperature at the depth where hydrogen's S(0) and S(1) quadrupole lines form varies within the range of T = 170–200K, based on the intensities of these lines.

Although significant data on the study of planetary atmospheres can be obtained through Earth-based observations, results are also derived based on data provided by space probes. The data obtained from space probes have been compared with the results acquired from Earth-based observations (Simon-Miller A. et.al, 2006). It has been determined that temperature variations in the planet's lower latitudes and troposphere are associated with seasonal changes

Due to the sharp decrease in the saturated vapor pressure of ammonia, it can be assumed that the NH_3 concentration in Jupiter's outer atmosphere above the cloud layer is extremely low. The observed weak lines are practically formed within the cloud layer and are determined using the formula

$$T=\frac{E_2 - E_1}{\ln\frac{\beta 1}{\beta 2}+\ln\frac{\alpha 1}{\alpha 2}+\ln\frac{S2}{S1}+\frac{E2-E1}{T_0}} \quad (4)$$

Here, E_1 and E_2 correspond to the energy of the first and second spectral lines, respectively. α_1 represents the Lorentz half-width of the first spectral line, while α_2 represents that of the second spectral line. S_1 is the relative integral absorption coefficient of the first line, and S_2 is that of the second line. T_0 denotes room temperature and is assumed to be $T_0 = 294K$. β represents the difference between the reciprocal values of the single scattering albedo in the line and the continuous spectrum. Based on the obtained materials, the temperature has been determined for various pairs of spectral lines and is presented in the following table. The selection of spectral lines with equal intensity across different regions of the planetary disk allows for a more accurate and stable determination of physical parameters, particularly temperature. In the calculation of rotational temperature, it is crucial that the ratios of line intensities and the associated optical depths (τ) remain constant. If the intensities differ, the resulting temperature will be incorrect. For temperature determination from observed spectra, selecting regions with equal intensities is essential to correctly model the atmospheric structure and conditions. This approach ensures that the temperature estimations are not biased by local variations

Table 1: Equivalent Widths and Half-widths of Spectral Lines

center			north			south		
λ, Å	W, Å	$\Delta\lambda$1/2, Å	λ, Å	W, Å	$\Delta\lambda$1/2, Å	λ, Å	W, Å	$\Delta\lambda$1/2, Å
6327,760	0,053	0,245	-	-	-	6327,704	0,047	0,264
6433,631	0,063	0,423	6433,665	0,025	0,222	-	-	-
6435,157	0,051	0,445	6435,125	0,018	0,235	6435,139	0,020	0,376
6444,792	0,070	0,205	-	-	-	-	-	-
6445,689	0,086	0,469	6445,686	0,024	0,21	6445,667	0,040	0,303
6446,574	0,091	0,852	6446,593	0,036	0,319	6446,536	0,043	0,304
6451,236	0,087	0,494	6451,233	0,046	0,299	-	-	-
6454,522	0,052	0,312	6454,547	0,034	0,366	6454,500	0,040	0,319
6457,290	0,091	0,574	6457,255	0,064	0,337	-	-	-
6457,292	0,087	0,574	6457,276	0,075	0,36	6457,274	0,067	0,324
6459,271	0,033	0,346	6459,249	0,020	0,335	-	-	-
6460,669	0,029	0,285	6460,628	0,016	0,176	6460,634	0,026	0,247
6464,858	0,019	0,327	-	-	-	6464,771	0,018	0,277
6465,515	0,046	0,331	6465,535	0,036	0,262	-	-	-
6470,867	0,036	0,349	6470,817	0,020	0,244	6470,872	0,025	0,244
6474,388	0,065	0,366	6474,417	0,045	0,399	6474,366	0,047	0,303
6478,548	0,021	0,442	6478,552	0,019	0,319	6478,580	0,015	0,297
6489,965	0,040	0,309	-	-	-	-	-	-
6490,028	0,041	0,306	-	-	-	-	-	-
6490,037	0,048	0,305	-	-	-	-	-	-
6501,852	0,034	0,906	6501,454	0,011	0,128	6501,779	0,049	0,277

Table 2: Calculated temperature values based on selected pairs of NH_3 lines

λ(Å)	J	K	E_{inv}	hc/k	A	B	k	E	a	S	T (K)
6444,792 6451,236	3 2	1 0	-11,7 -10,1	1,43391 1,43391	5,93 5,93	10,265 10,265	1,4E-16 1,4E-16	162,025 81,0734	0,178 0,152	3,28 1,8	183,09
6444,792 6465,515	3 3	1 3	-11,7 -13,1	1,43391 1,43391	5,93 5,93	10,265 10,265	1,4E-16 1,4E-16	162,025 111,293	0,178 0,176	3,28 3,68	148,8
6445,689 6465,515	3 3	-2 3	-12,7 -13,1	1,43391 1,43391	5,93 5,93	10,265 10,265	1,4E-16 1,4E-16	142,66 111,293	0,126 0,176	4 3,68	79,81
6446,574 6457,290	3 1	3 0	-13,1 9,8	1,43391 1,43391	5,93 5,93	10,265 10,265	1,4E-16 1,4E-16	111,293 36,4644	0,152 0,178	4,8 4,61	116,82
6446,574 6459,271	3 4	3 -4	-13,1 -12,6	1,43391 1,43391	5,93 5,93	10,265 10,265	1,4E-16 1,4E-16	111,293 185,892	0,152 0,213	4,8 1,89	78,14
6451,236 6460,669	2 3	0 -3	-10,1 13,1	1,43391 1,43391	5,93 5,93	10,265 10,265	1,4E-16 1,4E-16	81,0734 130,077	0,152 0,158	1,8 1,94	104,19
6459,271 6465,515	4 3	-4 3	-12,6 -13,1	1,43391 1,43391	5,93 5,93	10,265 10,265	1,4E-16 1,4E-16	185,892 111,293	0,213 0,176	1,89 3,68	179,09

in cloud thickness, or instrumental effects, thereby improving the reliability of atmospheric diagnostics.

As can be seen, the variation in temperature for different line pairs may be caused by lightning occurring in those layers. Under such conditions, the amount of ammonia gas increases, or a thin layer consisting of ammonia ice crystals passes into a gaseous state. Calculations indicate that the temperature on Jupiter's disk is approximately 127 K, which is consistent with the results obtained by other researchers.

4. Conclusion

1. In the presented work, the lines of the λ6450Å band in the spectrum of the planet Jupiter have been studied. Spectral material obtained with a 2-meter telescope at the observatory, using a CCD matrix and a 4 Å/mm dispersion echelle spectrometer, was analyzed. In this spectral region, 20 lines for the center, 14 lines for the northern zone, and 11 lines for the southern zone were selected. The obtained data were processed using the DECH 95 and DECH 30 programs.
2. The spectrophotometric characteristics of these spectral lines, including their equivalent widths and half-widths, have been determined. The results obtained are presented in tables.
3. Based on the obtained observational data, the rotation temperature in the details of Jupiter's disk has been determined for various pairs of spectral lines. As seen, the temperature varies between approximately 180 K and 80 K for different line pairs. Such temperature changes could be caused by lightning occurring in those layers. These findings are important for understanding the dynamic and non-homogeneous nature of Jupiter's atmospheric layers.
4. By summarizing the obtained results, the average temperature in the details of Jupiter's disk is found to be approximately 127 K, which is consistent with the results obtained by other authors.

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