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THE GREAT RED SPOT ON JUPITER: SOME FEATURES OF THE AMMONIA ABSORPTION

Abstract. In April 2017, we carried out five cycles of spectral observations of Jupiter to study some optical features of the Great Red Spot (GRS) that is a long-lived giant anticyclonic vortex. Recording the CCD spectrograms of Jupiter's central meridian in each cycle was performing consistently for two hours in the 240^0 - 310^0 longitude ranges in steps of about 2^0 each - before, during and after passage the GRS across the CM. The main objective was to investigate the behavior of the 645 and 787 nm ammonia (NH_3) absorption bands in the GRS region, which before was studied quite a little. The measurements of the profiles and equivalent widths of these bands showed explicitly that ammonia absorption in the GRS is decreased; the decrease is even more than the NH_3 depression in the Northern Equatorial Belt (NEB) that we discovered in 2004. A comparison with the results of the studies of Jupiter in the ranges of thermal infrared and millimeter radiation allowed concluding that the causes of the ammonia absorption decrease are not the same for the NEB and GRS. In the NEB, according to the radio astronomical observations, the gaseous ammonia concentration is really lowered. In the GRS, the NH_3 absorption decrease is caused by the increased cloud volume density. As a consequence of this, the absorption equivalent optical path decreases due to multiple scattering. That is also manifested in the near infrared ammonia and methane absorption bands. Quantitative interpretation requires some further complex studies because of the multiparametric nature of the models that are will be taken.
Keywords: Jupiter, Atmosphere, Clouds, Great Red Spot, Ammonia, Methane, Molecular Absorption Bands, Spectrophotometry.

Introduction

Some important and interesting objects in the study of Jupiter's atmosphere are specific optical and dynamic properties of the Jovian Great Red Spot (GRS). A number of distinctive features of this giant long-lived anticyclonic vortex are already known quite well. The period of its rotation is about 6 terrestrial days. It is known that the GRS makes its own special speed longitude drift, and it is not always regular, and for 300 years GRS has noticeably decreased in diameter [1], which, judging by the early sketches of Jupiter, had reached 40 thousand kilometers. The GRS has specific optical features, for example, its unique red-orange color, which has not yet been explained. But the coloring of Jupiter's cloud belts is also not yet fully explained, although it is very likely that ammonium hydrosulfide (NH_4SH) plays a role in this coloring, because it forms a cloud layer at great depths, below the ammonia layer [2].

In the ranges of thermal infrared [3] and millimeter [4] radiation, the brightness temperature of the GRS is lower in comparison with the surrounding regions, and that indicates a greater opacity for radiation emerging from the deep layers of the Jovian atmosphere.

It should be noted that in spectral ranges with strong methane absorption bands, the Great Red Spot looks like the brightest, or rather abnormally bright, formation on the planet. This indicates that in the GRS region the methane absorption is strongly weakened in comparison with all other regions of the visible cloud surface of Jupiter [5]. As for the morphological and dynamic properties of the GRS, the most impressive recent results are those obtained from the space probe JUNO, approaching to Jupiter at the distance of only three thousand kilometers [6]. The properties of the GRS also show themselves in ammonia absorption. In addition to the previous photometric and spectral observations of the GRS (for example, [7-9]), a special observational program for studying the spectral features of the GRS was carried out in 2017. Five cycles of recording the spectra of Jupiter's central meridian (CM) were carried out before, during and after a passage of the GRS across the CM. We report on results of this our research.

Observations: methods and results

From the end of March to the beginning of May 2017, a series of observation cycles of Jupiter was performed as an extension of regular long-term spectral studies of variations in the molecular absorption bands, and studying the structure of the planet's cloud cover. These observations covered almost all the longitudes of Jupiter (Figure 1), including 5 cycles destined to obtain spectra of longitudes near the GRS. At that time its longitude was 267^0 in the 2nd system. The GRS (or its core) has its own longitudinal coverage of about 12^0, apart from the peripheral light edging.

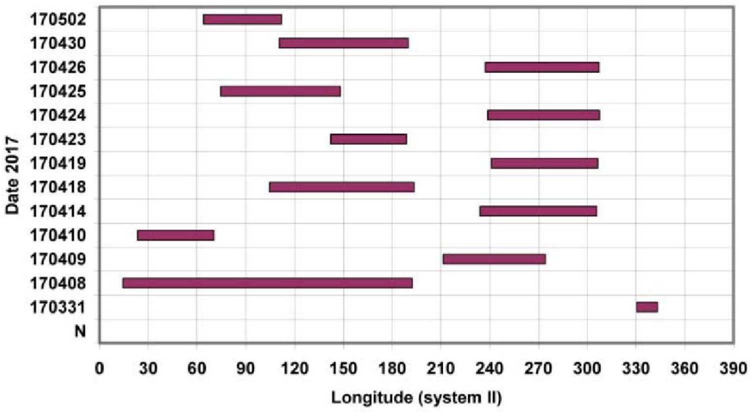

Figure 1 - Diagram of the date distribution of Jovian longitudes observed in 2017

Each cycle, timed to the GRS passage across the CM, was lasting for 2 hours. During this time, 30-32 spectra were recorded with an interval of about 4 min, which corresponded to Jupiter turn of 2.5^0. Thus, the longitudes from 240^0 to 310^0 in the second system of the Jupiter rotation were covered (Figure 2). A fragment of the map of Jupiter for April 2017, compiled by Vedovato (the site of the Association of Observers of the Moon and the planets ALPO Japan [10]), was used.

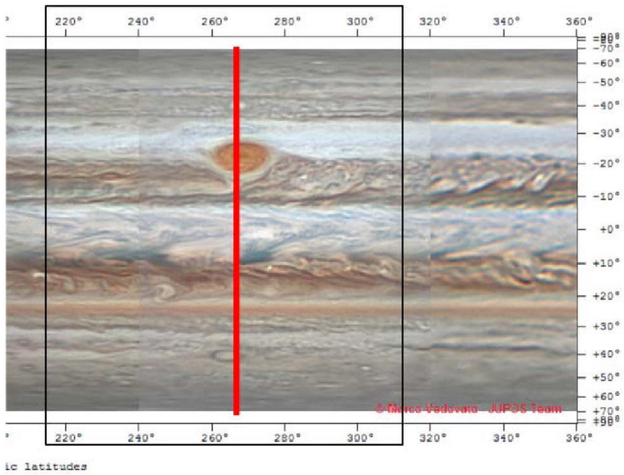

Figure 2 - Fragment of the map of Jupiter from the ALPO Japan site as of April 2017 with the area of longitude scanning

Observations were carried out using the SGS diffraction spectrograph installed in the 7.5-m Cassegrain focus of the 0.6-m RZ-600 telescope. The receiver of a spectrum image was the ST-7XE CCD camera with a matrix of 765x510 pixels. The size of one pixel is 9x9 microns and the resolving power for dispersion of 4.3 A/pixel is 8.5 A. The scale of an image on the spectrogram is 4.08 pixels /arc second. As a rule, the exposure time of one spectrum was 20", although in some cases, it increased to 100" in order to provide a better isolation of the methane absorption band in the near-IR region (800-900 nm). In total, the extensive observational material was obtained, which can be used for different further studies, including those related to the study of temporal changes in the Jovian atmosphere during the entire period of its revolution around the Sun.

Processing spectrograms of the absorption bands

For the processing and analysis of the Jupiter's CM spectra, some corresponding programs based on spreadsheets were compiled. They could provide a quick eduction of tabular and graphical results. The main attention was paid to measurements of the two ammonia absorption bands' (645 and 787 nm NH_3) profiles and to the evaluation of their intensities. These bands are weak in intensity, especially the 645-nm band. Both bands overlap with more intense methane absorption bands, so their separations require special techniques. Therefore, their behavior in the spectra of Jupiter has not been studied in detail by anyone before, except for some researchers [11-15]. Laboratory studies of these ammonia bands are also few and not yet very definite. Their analysis is contained in [16]. The 645 nm NH_3 absorption band is located in the short-wave and relatively weak wing of the methane absorption band (λ?). Therefore, its separation is carried out simply by calculating the ratio to the interpolated smooth running of the intensity in this methane band's wing. The 787 nm NH_3 band is located in the middle of another methane band, centered at the same wavelength. Filling, its less intense central part. In this case, we use the spectrum of Saturn as a reference spectrum. In it, the ammonia absorption inside this methane band is practically absent or negligible. So, the Jupiter 787 nm NH_3 band stands out well enough in calculating the ratio of the Jupiter spectrum to the spectrum of Saturn. Figure 3 shows examples of the profiles of both ammonia bands, obtained by processing one spectrogram of Jupiter's CM for all points of the meridian (from the South Pole to the North one). As a result of measurements, we obtain estimates of the equivalent widths (W) of these absorption bands at different latitudes, including the GRS region. We note that the maximum value of W in the 645 nm band does not exceed 8A, while in the 787nm band it does not exceed 20A.

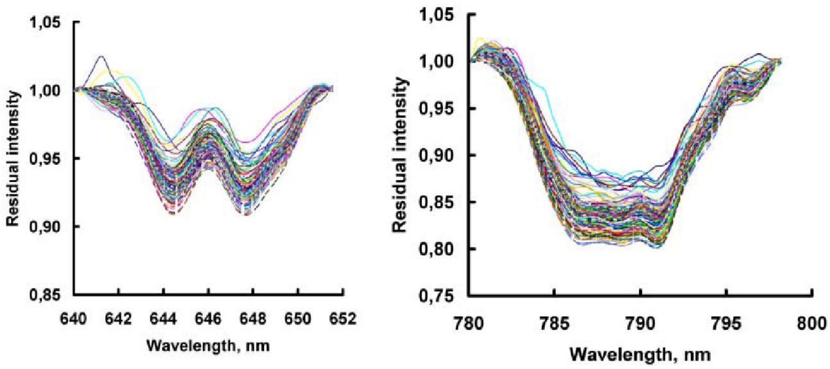

Figure 3 - The 645 and 787 nm NH_3 absorption band profiles, separated from all the lines of the Jupiter's CM spectrum

We started measurements of the 645 and 787 nm NH_3 bands in the spectrum of Jupiter in 2004. From them, we found the existence of a depression of ammonia absorption in the Northern Equatorial Belt (NEB). This depression [17, 18] is most pronounced in the 787 nm NH_3 band. In the NEB its W (W_{NEB}) is less by 2-3A in comparison with other low and moderate latitudes, where W> W_{NEB} and varies within smaller limits [19]. Further observations from 2005 to 2017 (during the complete revolution of Jupiter around the Sun) have shown that this depression remains a peculiar feature of the NEB, albeit it is variable in longitudes and in time.

Ammonia absorption in the Great Red Spot

Based on the results of spectral measurements of each observational cycle during the GRS passage across the Jupiter CM, latitudinal variations in intensities of the ammonia absorption bands were plotted. The graphs plotted together for all longitudes (Figure 4) show that along with depression in the low-latitudinal NEB, the weakening of ammonia absorption in the GRS is observed. It is most pronounced in the 787 nm NH_3 band (Fig. 4).

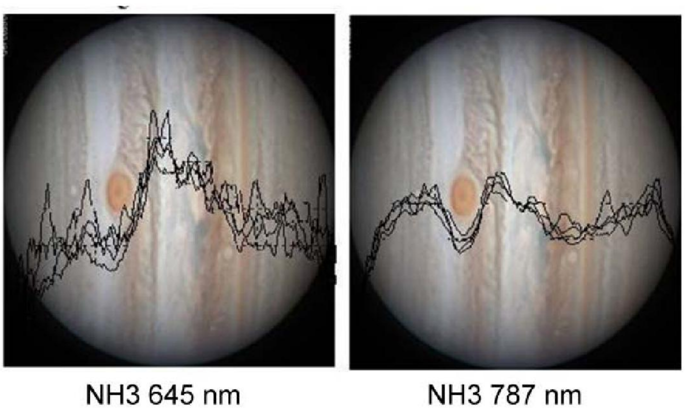

Figure 4 - Latitudinal variations of ammonia absorption in the GRS during its movement along the meridian (the images of Jupiter were taken from the ALPO Japan site)

Figure 5 shows graphs of the 645 and 787 nm NH_3 absorption bands' intensities along the CM from the measurements on April 19, 2017. The absorption profiles obtained in the 240^0-310^0 longitude ranges are averaged. The longitudinal variations of the profiles differ little, so that the standard deviation in the W values is less than 1 A everywhere, except for the GRS region. The profiles with the GRS for the longitude 272^0, corresponding to the middle of the GRS, are shown separately (red). The ammonia absorption decrease in the GRS stands out clearly. There also attracts attention the noticeable blurring of the depression of ammonia absorption in the northern hemisphere in comparison with the picture that was observed in previous years. At that time the depression was only related to the NEB. The additional processing of spectrograms obtained for other longitudes gave the same result. The reason for this is that in the Jupiter visibility season of 2017, the NTB dark band formed north of the NEB, where the ammonia absorption also turned out to be lower. Changes in the NEB cloud cover structure were occurring in the recent years, and they are described in [20].

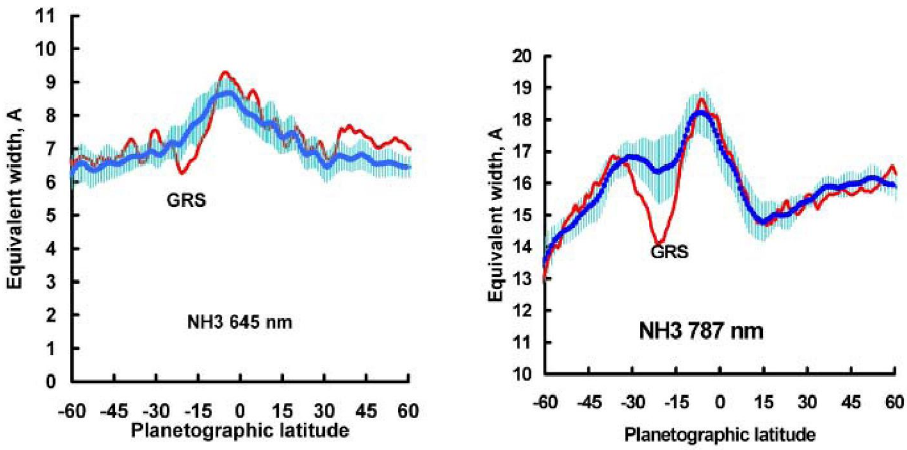

Figure 5 - Latitudinal variations in the 645 and 787 nm NH_3 absorption bands averaged over the 240^0-310^0 longitude ranges. The profiles with the Red Spot for longitude 272^0 are shown separately (red)

To illustrate the differences in the meridional variations in the NH_3 absorption at different longitudes, the W profiles of the 787 nm band are shown in Figure 6 with a vertical shift per unit of the scale. On the right, a three-dimensional representation of the ammonia absorption variations is shown. It can be seen that the absorption depression in the northern hemisphere remains at all the longitudes, whereas in the southern hemisphere only the GRS region is manifested.

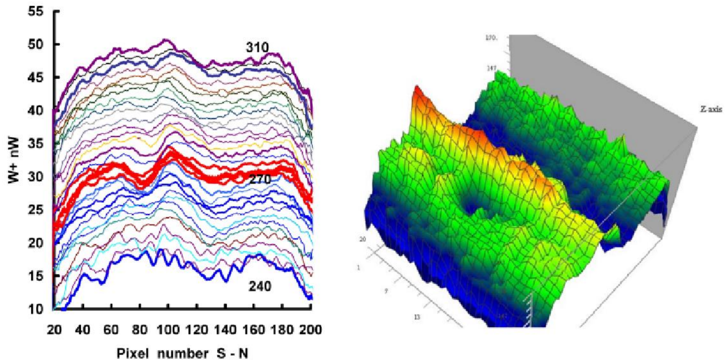

Figure 6 - Profiles of variations of the 787 nm NH_3 band's equivalent widths (on the left); 3D- representation of the ammonia absorption latitude-longitudinal variations in the 240^0-310^0 longitudinal interval (on the right)

Figure 7 compares the longitude variations of ammonia absorption at the latitude of the GRS: near the southern edge of the SEB and at the latitude that is symmetrical to it in the northern hemisphere, corresponding to the northern edge of the NEB (latitudes + $22^0 \pm 1^0$ and -$22^0 \pm 1^0$). One can see a systematic difference in W of the 787 nm NH_3 absorption band in these belts: weakening the absorption in the NEB, with the exception of the GRS, in which the absorption is even smaller than in the NEB.

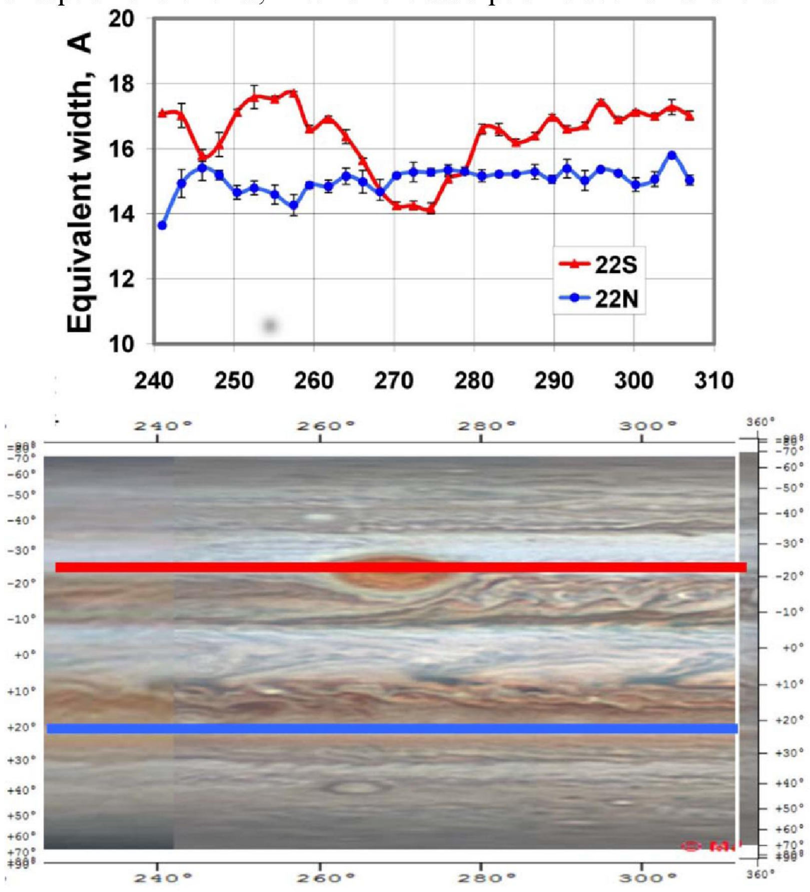

Figure 7 - Long-term variations of the ammonia absorption at symmetrical latitudes in the SEB and NEB

In the other belts of low and moderate latitudes of Jupiter, there is a relatively monotonous longitude course of the ammonia absorption, except for some oscillations caused by both inevitable errors and real variations in the intensity of the absorption band. But at each the latitude within the considered longitudinal range, the mean level changes with latitude that one can see in Figures 5 and 6.

Discussion

From the consideration of the obtained data on variations of the ammonia absorption bands on Jupiter located in the visible and near IR spectral regions, the following feature is worth serious attention. It has already been noted above that the GRS seems anomalously bright in the images obtained through the filter that cuts out the center of the strong methane absorption band at 887 nm. However, the NEB, where the ammonia absorption depression is observed, comparable to that observed in the GRS, does not show such an increase in brightness at 887 nm, as in the GRS. Apparently, one should seek the reason for this discrepancy in the difference in the structural features of the atmosphere over these regions. These features determine the mechanisms for the formation of molecular absorption bands. Here it is relevant comparing the observational data on Jupiter in very different spectral regions of the reflected radiation and the planet's native thermal radiation.

In a number of publications on Jupiter's observations in the ranges of thermal radio emission, for example, in [4, 21], the NEB's feature was noted: the brightness temperature of the radiation in it was slightly higher than in other regions of the planet. The most detailed map of the brightness temperature distribution on Jupiter was obtained using the VLF (Very Large Array) radio telescope system, in 2012-2014 [4]. Indeed, the NEB was distinguished with its high brightness temperature at frequencies of 8-14 GHz (millimeter-wave radio range). The output of increased thermal radio emission in the NEB is associated with the lower ammonia abundance in this latitudinal belt. It is ammonia in this range that reduces the radio emission absorption and determines the process of its transfer from the deep layers of the Jovian atmosphere. A cloudy layer with particle sizes of one or even tens of micrometers is transparent to radio waves and cannot affect their passage, so we can specifically speak about the reduced ammonia abundance in the NEB. Accordingly, the depression of ammonia absorption in the visible and near-IR spectral regions observed in the NEB, one can explain by a real decrease in the gaseous NH_3 abundance. However, in the absorption band formation in this spectral region, the cloud layer plays a certain role. In this layer the gaseous molecules' absorption optical path increases with the cloud particle multiple scattering.

The GRS demonstrates a different situation. We see that in the 645 and 787 nm NH_3 bands, the absorption in the GRS is lowered in comparison with the surrounding regions by almost as much as in the NEB. However, radio measurements do not show such an increase in the brightness temperature in the GRS, as in the NEB. On the maps, the Spot does not stand out for its brightness. A similar effect of reduced thermal IR radiation is observed in the GRS both in the 8-12 μm ranges [4, 22] and near 5 μm [23]. As for IR measurements, they require special analysis and discussion in the future. But judging by radio observations, in the GRS region the gaseous NH_3 concentration is not lowered as in the NEB. Hence, weakening the ammonia absorption bands in the GRS has to be caused by other causes. It should be remembered that in the strong 887 nm methane absorption band, the GRS looks abnormally bright in comparison with any other morphological details of the Jupiter disk. In the temperature conditions of the Jovian atmosphere the methane does not condense, so its vertical distribution is mainly described by the barometric formula. Therefore, in the atmospheric layer above the clouds, the methane abundance is still quite appreciable for the absorption band formation. Absorption in the strong 887-nm methane band forming above the clouds can play an even greater role than inside the clouds, since the number of acts in multiple scattering decreases with increasing the absorption. So the methane absorption abrupt decrease in the GRS is most likely due to the fact that the upper boundary of the cloudiness in the Spot is higher than in its surroundings. Formation of the ammonia absorption bands occurs practically only within the cloud layer, since the concentration of NH_3 over it becomes smaller by several orders of magnitude. It follows that the decrease in the intensities of the NH_3 absorption bands in the GRS mainly occurs because of the increased bulk density of the clouds inside it. This reduces the equivalent absorption path, which determines the observed intensities of the 645 and 787 nm ammonia bands. They are relatively weak.

In the region of IR thermal radiation, the GRS looks like a dark spot surrounded by a light rim. The effect of cloud density on IR thermal radiation in the GRS (especially at λ 5 μm) depends on the particle sizes both in the upper ammonia cloud layer and in the deeper layer of clouds consisting of ammonium hydrosulfide NH_4SH. Interpretation of measurements in this range is still ambiguous and depends on the adopted models and initial parameters of the structure and temperature regime in the troposphere at different latitudes and depths.

Conclusion

This paper presents the first experience of studying the behavior of the 645 and 787 nm ammonia (NH_3) absorption bands in the region of the GRS on Jupiter. We found that these ammonia bands were sufficiently weakened in the GRS as compared to the surrounding areas of the visible cloud surface of the planet. In terms of magnitude, this depletion is comparable to the previously observed depression of the 787 nm NH_3 band intensity in the NEB. Our long-term (since 2004) spectral observations have shown that such the NEB feature is peculiar to this belt, although it reveals some longitude and temporal changes. However, based on a comparison with the results of observations of Jupiter in the ranges of thermal IR optical and millimeter radio emission, one can assume that the mechanism of ammonia absorption depression in the GRS and in the NEB is not the same, but is determined by some different causes. Of course, further observations and analysis of different models of formation of the absorption bands and their role in the transport of visible and thermal radiation in different atmospheric layers of Jupiter are needed. In this atmosphere, apart from the usual zonal circulation and the vortex structure, unusual and unpredictable large-scale changes occur at times, such as the disappearance of the SEB dark belt in 2010 or the formation of a quasi-periodic structure of the NEB belt observed in the strong 887 nm methane (CH_4) absorption band in photographs in 2018. Accordingly, we plan new observations on molecular absorption studies in the visible and near-IR spectral regions for the next few years.

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БОЛЬШОЕ КРАСНОЕ ПЯТНО НА ЮПИТЕРЕ: НЕКОТОРЫЕ ОСОБЕННОСТИ АММИАЧНОГО ПОГЛОЩЕНИЯ

Аннотация. В апреле 2017 года мы провели пять циклов спектральных наблюдений Юпитера для изучения некоторых оптических особенностей Большого Красного Пятна (БКП) – долгоживущего гигантского антициклонального вихря. Запись ПЗС-спектрограмм центрального меридиана Юпитера в каждом цикле производилась в в течение двух часов последовательно в интервале долгот от 240 до 310 градусов с шагом около 2 градусов – до, во время и после прохождения БКП через центральный меридиан. Основной задачей было исследование мало изученного ранее поведения в БКП полос поглощения аммиака NH_3 645 и 787 нм.

Измерения профилей и эквивалентных ширин этих полос показали определенно, что в БКП аммиачное поглощение ослаблено, присеем даже в несколько большей степени, чем у депрессии NH_3 в Северном экваториальном поясе (NEB), обнаруженной нами еще в 2004 году. Сравнение с результатами исследований Юпитера в диапазонах теплового инфракрасного и миллиметрового излучения приводят к заключению, что причины ослабления аммиачного поглощения не одинаковы. В NEB, согласно данным радиоастрономических наблюдений, понижена концентрация газообразного аммиака . В БКП ослабление поглощения NH_3 вызвано повышенной объемной плотностью облачной среды. Из-за этого уменьшается эквивалентный оптический путь поглощения в процессе многократного рассеяния, что проявляется и в полосах поглощения аммиака и метана в ближней инфракрасной области. Для количественной интерпретации необходимы дальнейшие комплексные исследования ввиду многопараметричности принимаемых моделей.

Ключевые слова: Юпитер, атмосфера, облака, Большое Красное Пятно, аммиак, метан, молекулярные полосы поглощения, спектрофотометрия.

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ЮПИТЕРДЕГІ ҮЛКЕН ҚЫЗЫЛ ДАҚ: АММИАКТЫ ЖҰТЫЛУДЫҢ КЕЙБІР ЕРЕКШЕЛІКТЕРІ

Аннотация. 2017 жылдың сәуірінде біз ұзақ өмір сүретін антициклондық сызық Үлкен Қызыл Дақтың (ҮҚД) кейбір оптикалық ерекшеліктерін зерттеу үшін Юпитердің спектрлік бақылауларының бес циклін жүргіздік. Орталық меридиан арқылы ҮҚД өту кезінде және одан кейін шамамен 2 градус қадаммен 240 тан 310 дейін градуста бойлық интервалында тізбекті Юпитердің орталық меридианының ЗБА-спектрограммының жазбасы әрбір циклде екі сағат аралығында жүргізілді. Ертеректе аз зерттелген ҮҚД NH_3 645 және 787 нм аммиакты жұтылудың бағытын зерттеу негізгі міндет болды.

Бұл эквиваленттік ендіктерде бағытты өлшеу біз 2004 жылы тапқан Солтүстік экваторлық белдіктегі (NEB) NH_3 депрессиясына қарағанда бірнеше үлкен дәрежеде жүрелейміз аммиакты жұтылудың әлсізденгенін айқын көрсетеді. Жылу инфрақызыл және миллиметрлік сәулелену диапазондарында Юпитердің зерттеулері нәтижелерімен салыстыру аммиакты жұтылудың әлсізденуәнәі себептері бірдей емес деген қорытындыға әкеледі. NEB радиоастрономиялық бақылаулардың мәліметтеріне сәйкес, газ тәрізді аммактың концентрациясы төмен. ҮҚД NH_3 жолағының әлсізденуі қоршаған ортаның артқан көлемді тығыздығынан туындаған. Осыған байланысты көп есе шашырау процессінде жұту жолағының эквивалентті оптикалық жолы азаяды, бұл жақын инфрақызыл аймақта аммиак және метан жұту жолақтарында көрінеді. Сандық интерпретациялар үшін қабылданатын моделдердің көп параметрлігі түрінде кешенді зерттеулер қажет.

Түйін сөздер: Юпитер, атмосфера, бұлт, Үлкен Қызыл Дақ, аммиак, метан, жұтудың молекулалық жолақтары, спектрофотометрия.

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