Astronomical and Astrophysical Transactions (*AApTr*), 2013, Vol. 28, Issue 2, pp. 121–134,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Spectrophotometric study of Saturn's atmosphere during a 16-year period (1995–2010)

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Received 15 February, 2013

The latitudinal variations of the methane absorption bands on Saturn at a wavelength range of 580–900 nm from Saturn's 1995 equinox till 2009 equinox are considered. Significant differences were detected in the behavior of absorption bands in the S- and N-hemispheres which may be connected with the differences in heliocentric distances of Saturn before the 1995 equinox and before the 2009 equinox.

Keywords: Saturn; Spectra; Molecular absorption; Seasonal changes

1 Introduction

Study of the Solar System (the Sun, planets, small bodies, dust matter) keeps the urgency and necessity not only for expansion of our fundamental knowledge about the space bodies, their physical properties and evolution, but also in connection with a rather important problem of climate change on Earth. Being limited only to studying processes on our planet and knowing nothing about the influence of the space factors (solar activity, seasonal variations of the inflow of solar energy etc.) on them, we hardly could find an explanation of all climatic changes on the Earth that were happening in the past, are in the present and will be in the future.

The study of non-stationary processes on the giant planets just gives us a possibility to divide and estimate roles of the space factors and purely terrestrial ones that cause climate changes on the Earth. It should be noted that this problem is not too simple and it cannot be solved "with a swoop", without obtaining long-term sets of observational estimations of the state of each planet and their analysis, and without comparison and allocation of synchronous processes and phenomena on several planets that can be caused by the same space influences.

While the term "climate" can be considered as a more or less definite term to apply to the Earth, although some of its meanings differ one from another, there is still no clear similar definition to apply to the other planets of the Solar System. Which characters of a planet, obtained from its observations, can be united in the concept of "climate"? This question is worthy of a serious discussion and analysis, all the more so that each of the planets has its specific features. For each of the terrestrial

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planets (Venus, Mars) the climate is determined and defined by the absence of free water (oceans, seas, rivers and lakes) on the surface of the planet – water plays an important role in the global climate on the Earth. The climate of each of the giant planets is defined, on the one hand, by the input of solar radiation and, on the other hand, by the output of internal heat into its atmosphere, providing a higher effective temperature of the planet in comparison with the radiation equilibrium temperature, defined by only absorption and reflection of the sunlight.

Seasonal changes must be mostly expressed, except the Earth, on Mars, Saturn and Uranus, thanks to a considerable deviation of the equatorial plane to the orbital one: for Mars the inclination is 24°; for Saturn, 27°; and the axis of rotation of Uranus lies almost in the plane of its orbit. Besides, the distance of a planet from the Sun changes because of the eccentricity of its orbit. This also influences the amount of solar radiation arriving at the planet. Historically, as early as in 1985 the problem of the search for and study of the changes on the planets covered with atmospheres was formulated in the resolutions of the General Assembly of the International Astronomical Union. Then the Department of General Physics and Astronomy at the USSR Academy of Sciences approved the Soviet program planned up to 2010 and aimed (side by side with the other tasks) to study the long-term processes on the bodies of the Solar system. Coordination of works on the study of the giant planets had been assigned to the planetary laboratory of the Fessenkov Astrophysical Institute. Despite more extensive use of the space technique for missions to the planets, the role of the ground-based observations remains considerable because of the possibilities of obtaining, accumulating and analyzing some regular long-term data about the planetary atmospheres and their seasonal and irregular changes. The importance of this research, in particular, was confirmed in the international documents concerning the Solar System studying strategy, that had been developed in the USA and England: New Frontiers in the Solar System (2003), Solar System Exploration Roadmap (2006), etc. In 1997, the "Cassini" spacecraft was launched to Saturn, and in 2004 it arrived at its orbit round Saturn, and began long term observations of the planet, its rings and satellites (Guillot 2009). The probe's successful and non-failure operation allows prolongation of this mission till 2017. In connection with the mission the international program was started of astrophysical ground-based accompaniment of this mission.

2 The study of seasonal changes on Saturn

The best of the giant planets for the study of seasonal change is Saturn because its rotation period around the Sun is 29.45 years. Regular observations of Mars are complicated because of the planet's opposition occurring only once in two year period, and owing to the eccentricity of its orbit the angular size of the planet (even at an opposition) can differ almost twice (from 25 to 14 arc seconds) whereas at other times the angular diameter of Mars is smaller. Uranus, depending on its orbital longitude, sets either the equator against the Sun, or one of its poles. So, seasonal effects on it should be considerably more expressed, even despite the great distance from the Sun. Because the Uranus' cycle time is 84 years, it is rather difficult to distinguish the seasonal changes on it from the century-long ones.

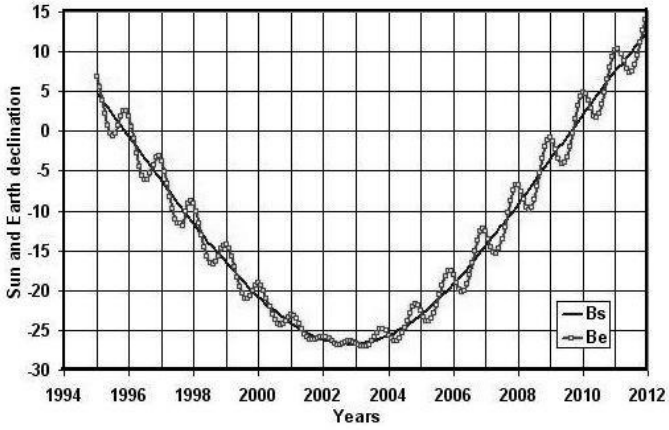


Figure 1 The saturnocentric declination of the Sun (Bs) and the Earth (Be) in 1995–2011.

Only once in 15 years both hemispheres of Saturn (northern and southern) may be observed in similar conditions of the illumination and inflow of solar radiation (Fig. 1). During these equinox periods there is a chance of comparing the optical properties and structure of the atmosphere in each of its hemispheres at equal visibility conditions. In other years, one of the hemispheres receives much less energy from the Sun than the opposite hemisphere inclined to the Sun. For a long period (more than ten years), undoubtedly, it should lead to changes in a temperature regime of the troposphere and stratosphere and in the structure of the cloudy cover. The questions, concerning the seasonal processes on Saturn, were discussed repeatedly both theoretically (variations of the solar radiation inflow and the role of shielding part of the disk by the rings (Van Hemelrijck 1982; Van Hemelrijck 1987; Levine et al. 1977; Brinkman and McGregor 1979; Perez-Hoyos and Sanchez-Lavega 2006), and in the observation aspect (comparison of the optical characters of the northern and southern hemispheres and their long-term variations (Trafton 1985; Vidmachenko 1999; Karkoschka and Tomasko 2005; Perez-Hoyos et al. 2005). The Saturn's last equinoxes fell on 1995 and 2009.

During the period from 1995 to 2009 our spectral-photometric observations were carried out with CCD cameras. As a result, rather homogeneous material had been saved up, allowing us to trace the seasonal changes on Saturn for its half orbital period.

3 Instrumentation and techniques of observations and their processing

Observations of Saturn in 1995–2003, unlike the previous years, were carried out using an ASP-9 prism spectrograph with the ST-6V CCD camera (SBIG, USA). Most observations were carried out with the RZ-600 0.6-m telescope, but some observations were carried out with the 1-m telescope at the "Assy" observatory. In particular, basic spectral-photometrical material on Saturn during its 1995 equinox had been obtained just there. Since 2004 spectral observations have been carried out by using an SGS

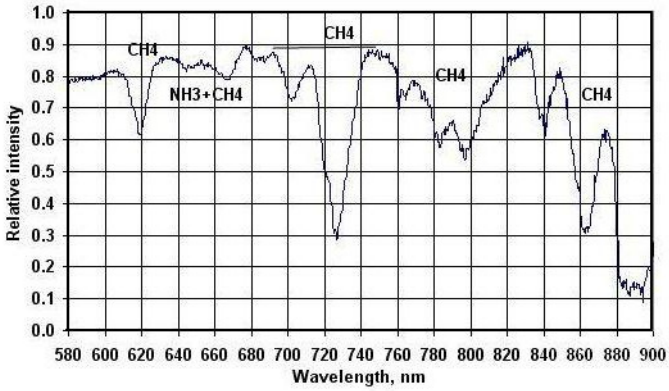


Figure 2 Profiles of the methane absorption bands in Saturn's spectrum.

diffraction spectrograph with the ST-7XE CCD-camera (manufactured by the same SBIG company). This spectrograph was mounted in the 7.5-m Cassegrain focus of the 0.6-m RZ-600 telescope. The spectrograph has two diffraction grids with a dispersion of 1 Å/pixel and 4.3 Å/pixel, respectively. A valuable quality of the CCD matrix in the ST-7XE is very fast (∼1 sec) reading of even a full frame of the image through the USB interface.

The ST-7XE camera is also equipped with the auxiliary CCD matrix used at prompting of the spectrograph slit on a studied object.

During the observations two ways of obtaining and registration of CCD spectrograms were applied. (1) An elementary method was to record spectrograms when the entrance slit of the spectrograph was oriented along the central meridian and the equator of intensity of the planet. (2) In order to obtain a more detailed picture of the absorption band latitudinal variations, the zonal spectral-photometry method was applied. It consisted in a consecutive scanning of the disk of Saturn by means of its slow displacement across the spectrograph entrance slit, which was oriented in parallel to the major axis of the Saturn's ring. At 10–20-sec expositions, about 250 spectrograms were registered consistently corresponding to different chords on the disk. Altogether, more than 5000 files of spectrograms were recorded during the observational season.

Further spectrogram computer processing was carried out using special programs, and then using EXCEL tables. The ratios of the spectra of all the points of the central meridian of the planet to the average spectrum of Saturn's ring were calculated (Fig. 2).

The ratio to the ring spectrum allows excluding the influence of the spectral dependence of CCD matrix sensitivity and telluric absorption lines and bands on the planetary absorption band profiles. Using the set of reduced values of spectral brightness, we calculated the residual intensities, profiles, central depths and equivalent widths of five methane absorption bands at the spectral range of 580–800 nm (Fig. 2).

In order to control the stability of the apparatus operating, the oxygen absorption telluric band at λ760 nm was also measured. Two ways of processing were applied to measurements of the spectra of the central meridian: a) averaging of the results

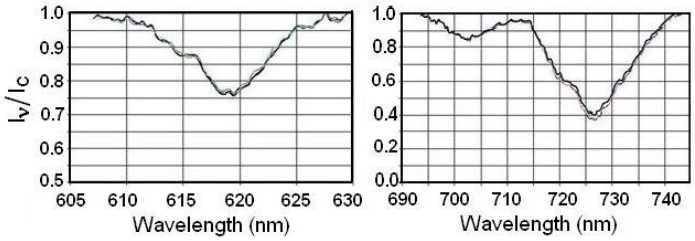


Figure 3 Fragments of the atlas of the 619 nm and 725 nm absorption band profiles derived from the zonal spectrograms.

of individual spectrum measurements and calculation of the standard deviations that determine the internal convergence of obtained values; b) preliminary addition and averaging of several spectrograms and subsequent measurements of an averaged image. The zonal spectrograms were measured in the central part of a zone by averaging, at least, 20 pixels that provided the best signal/noise ratios at short expositions. As a result, a number of atlases with absorption band profiles and their central depth and equivalent width latitudinal dependence have been prepared (Fig. 3).

4 Temporal dependence of the absorption latitudinal variations in the period between two equinoxes

During the period between 1995 and 2004 the southern hemisphere of Saturn was gradually rotating to the Sun, and in 2001–2004 the equator and the ring's inclination angle to the direction to the Sun was the greatest. It was mid-summer in the southern hemisphere (Tejfel 2004, 2005a).

Figure 4 illustrates the results of methane (CH_4) absorption band depth measurements and their latitudinal variations on the disk of Saturn in 2001, while Fig. 5

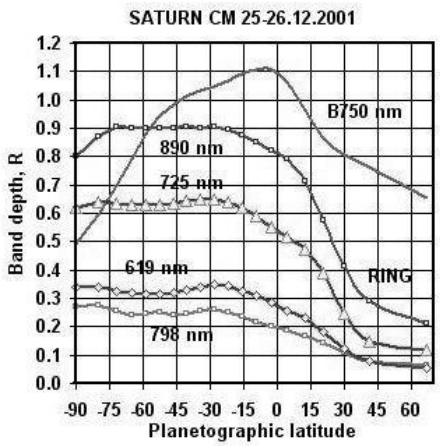


Figure 4 Latitudinal variations of methane absorption on Saturn in 2001.

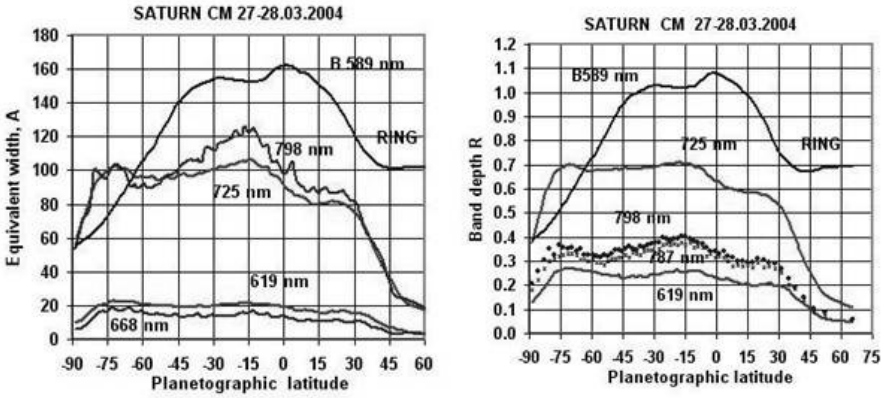


Figure 5 Latitudinal variations of the absorption band equivalent widths and depths in 2004.

shows the same variations in the season of 2003–2004 at the maximum rings' opening.

At this time the northern hemisphere was substantially screened by the ring. For the other dates of observations (during the period of the greatest inclination of the planet's southern hemisphere to the Sun) the results do not practically differ from the ones in that figure. Figure 6 shows the results of absorption measurements in 2007, when one could already observe the temperate northern latitudes of Saturn. It is seen even from simple comparison of Saturn's central meridian photometric profiles in the continuum and in the center of the λ725 nm methane absorption band that absorptions at different latitudes are distinctive. That is seen also from measurements of the equivalent widths and depths of the absorption bands. Analyzing the absorption band depths' behavior (using corresponding graphs), one can see the depths (R) show the greatest absorption to fall on planetographic latitudes between –20 and –40° with a maximum at the latitude of –30°. A higher absorption is observed also near the South Pole whereas at the range of latitudes from –40 to –80° the absorption is much weaker. The least absorption is observed in the equatorial belt of the planet (it is the brightest belt from photometric measurements). The absorption band equivalent widths' behavior is analogous to the depths' one. But there is one feature: a latitudinal dependence of the 798 nm absorption band equivalent width differs from the one of 725 nm (though they are of approximately equal strengths). The 798 nm equivalent widths, unlike the 725 nm ones, show a bigger growth at midlatitudes than at high latitudes and at the equatorial belt.

5 Comparison of the latitudinal dependence of absorption during the equinox periods

As has already been noted, in 1995 the equator of Saturn and its ring were oriented by an "edge" to the Earth and the Sun, so the insolation regime was identical both for the southern and northern hemispheres. Nevertheless, our observations (Beebe

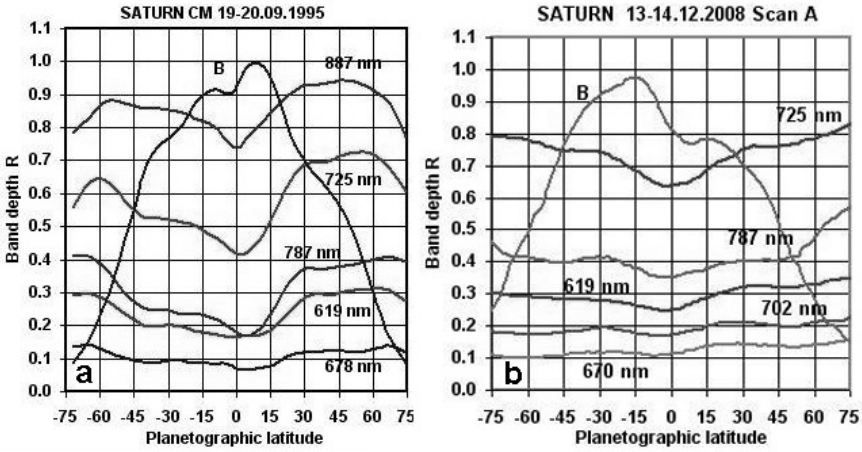


Figure 6 Latitudinal variations of the methane absorption band central depths at equinoxes in 1995 (a) and 2008–2009 (b).

and Tejfel 1996; Tejfel 1997) found a considerable asymmetry in the latitudinal distribution of molecular absorption: in the ***northern hemisphere*** absorption was much more than in the southern one at the same latitudes, and it increased from the equator to the poles, at least, up to the latitudes of 60°N and 60°S (Fig. 6a). A very considerable asymmetry has also been registered for the zonal Minnaert's limb darkening coefficients.

Here it should be noted that the northern hemisphere had been turned to the Sun until 1995, i.e., at least, for 10 previous years it had received much more solar energy than the southern hemisphere that was shaded by the ring. May be, it is the main reason of the asymmetry in absorption that is actually caused with distinctions in a volume density and height of the cloudy cover of Saturn.

Next years (after 1995) the southern hemisphere of Saturn was turning to the Sun and there was happening a redistribution of the absorption band latitudinal variations. That was clearly visible from our measurements of these variations in 1995–2003. Unfortunately, during the previous arrangement of Saturn by an "edge" of the ring and equator to the Earth and the Sun in 1980, we did not carry out such detailed spectral studies of the absorption bands. There are observations of West et al. (1982). They are the measurements of the CCD images of Saturn obtained in 1979 through optical filters centered at separate absorption bands. Processing and analysis of those data and our observations of 1972 (Tejfel 1974) led to the conclusion that during that period the greatest absorption took place in the southern hemisphere which had been turned to the Sun before 1979–1980. Processing the spectrograms obtained during the equinox of 2008–2009 (Fig. 6b) shows a large difference in the latitudinal dependence of absorption in comparison with the data of 1995 when a similar orientation of the ring took place. This fact, as well as other investigations, implies an obviously expressed seasonal character of the changes occurring in the atmosphere of Saturn. However, an expected reciprocal asymmetry in the absorption distribution in comparison with 1995 (Tejfel et al. 2009a) has not been proved to be true. The 725 nm band intensity is almost identical in both hemispheres, except the

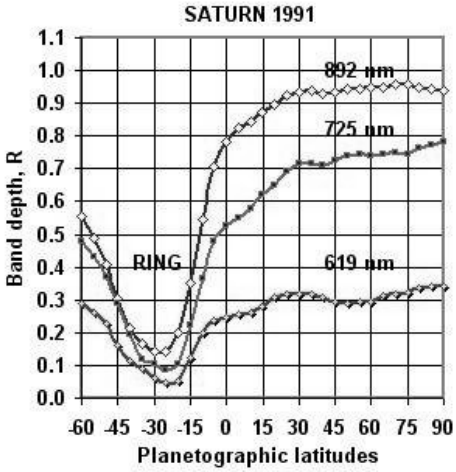


Figure 7 The methane absorption latitudinal variations on Saturn in 1991 (according to Ortiz et al. 1993).

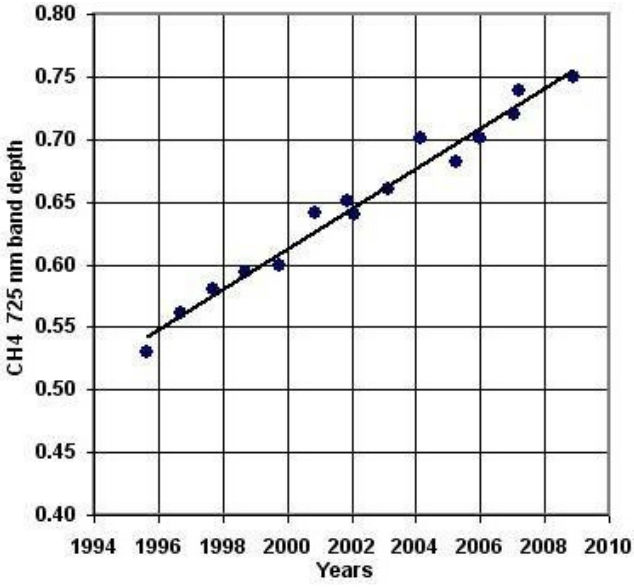


Figure 8 The trend of the 725 nm methane absorption growth at temperate latitudes of Saturn's southern hemisphere.

equatorial belt, where the minimum absorption is always observed. The weak bands show increasing absorption at midlatitudes of the northern hemisphere in comparison with the southern one, and the bands' equivalent widths show the greatest effect (Tejfel et al. 2008).

In 1991, when the Saturn-centric declination of the Sun was about +22° and the northern hemisphere was turned to the Sun, as seen from measurements of Ortiz et al.

(1993), the methane absorption in the northern hemisphere (Fig. 8) was almost the same as absorption in the southern hemisphere in 2003–2004 at the Sun declination about –25°.

However, during the period from 1995 to 2009 from our observations a regular growth of absorption at the temperate latitudes in the southern hemisphere took place: it is an almost linear trend of the 725 nm CH_4 absorption band depth (Fig. 8), which was regularly growing for this period from 0.55 to 0.75 and more.

6 Some other differences between the S- and N-hemispheres

Analysis of the changing ratios of the equivalent widths (W) of the 619 and 725 nm bands has shown significant and time-variable differences between them for the southern and northern hemispheres (Fig. 9). During the last 5 years the amplitude of a W619/W725 ratio had been gradually reducing from 0.10 to 0.03. The minimum value (0.20) is placed in a temperate zone of the southern hemisphere. The maximum ratio (0.25) is noted for a tropical zone of the northern hemisphere. These differences may be considered as evidence of different conditions for these absorption band formations in the southern and northern hemispheres of Saturn. May be, the most probable cause is a decrease of the volume density of the clouds in the N-hemisphere. But the interpretation of this peculiarity on Saturn, as well as the other variations described, is strongly model-dependent and will be an object of future work.

We have also noted a somewhat unusual change of absorption in the band conditionally designated as the 670 nm CH_4. Its depth (R) varied with latitude similar to the depths of the other weak bands centered at 702 nm and 619 nm (Fig. 10a). However, in the northern hemisphere the equivalent width of the 670 nm band increases much faster than the ones of the other bands (Fig. 10b).

It was reasonable to assume that the 670 nm band, actually, consists of two closed bands: the short-wavelength part of the band at 630-655 nm (centered at 647 nm) belongs to ammonia, and a long-wavelength part at the range of 650–680 nm (with the maximum absorption at 687 nm) belongs to methane. Certainly, such a division is conditional because the absorption methane band is partially blended with ammonia in the short-wavelength wing. According to laboratory measurements, the NH_3

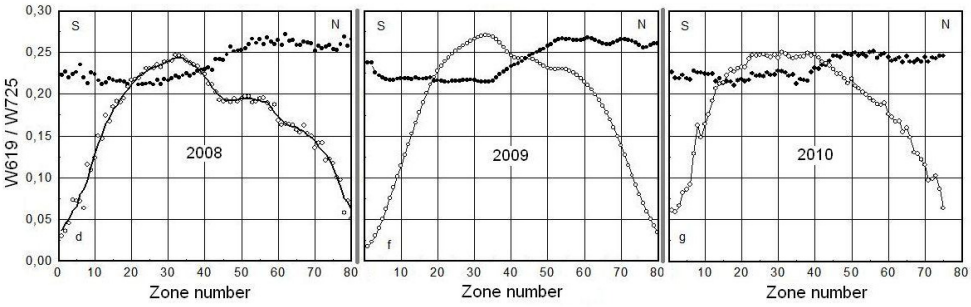


Figure 9 Zonal and temporal variations of the 619 and 725 nm band equivalent width ratios in 2008–2010.

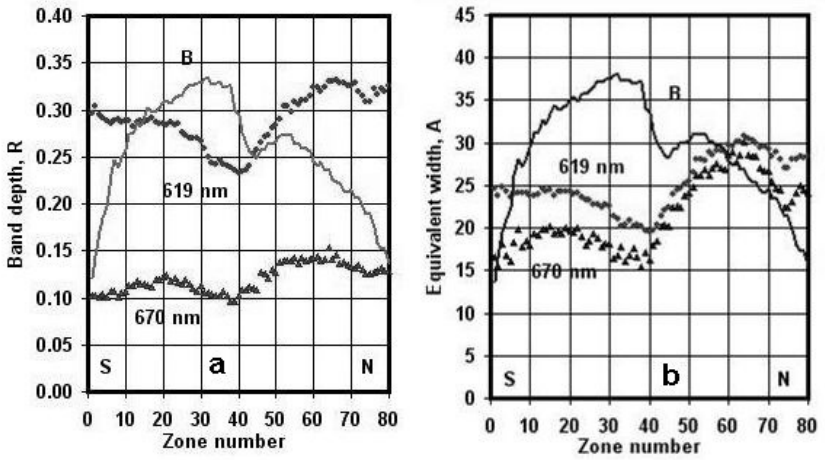


Figure 10 Central depth (a) and equivalent widths (b) of the 619 nm and 670 nm absorption bands derived from the zonal spectra in 2009.

absorption band at 647 nm consists of a set of rotation lines which are not resolved completely on the obtained spectrograms.

The laboratory spectrum (Giver et al. 1975) shows that the band has the range of 638–656 nm, so this part of the spectrum is responsible for an additional absorption observed. A research of all the combined band (NH_3+CH_4) structures has shown that the ratio of North/South (N/S) for NH_3 is less than the ratio of N/S for CH_4. This additional growth gives lesser effects on the band depth because that depth was calculated at the wavelength of 667 nm, i.e., at the maximum of methane absorption, outside the ammonia band.

7 Discussion

Because of the limit of page extent we could not describe in detail many features of the absorption space-time variations that we observed in different years. In particular, we mean the features of ammonia absorption noted by us and described in Tejfel et al. (2009b). The question is a distinction that is observed in ratios of the absorption band central depths and equivalent widths that are not described here. Such a result can be considered as a confirmation of the latitudinal distinctions in the absorption band features that are controlled by temperature regimes in their formation regions. At such temperature changes a band can extend or be compressed slightly, without changing its central depth. The first comparison of methane absorption and temperature changes on Saturn was published in Tejfel et al. (2005b) in collaboration with the American colleagues. The data obtained at that time are presented as the atlases of the absorption band profiles, and demand further analysis and corresponding theoretical interpretation taking into account some possible mechanisms of absorption formation in the scattering-absorbing cloudy cover and in the upper dust.

While interpreting the observation results we should see the problems connected with a choice of models and methane absorption coefficients which are not known with

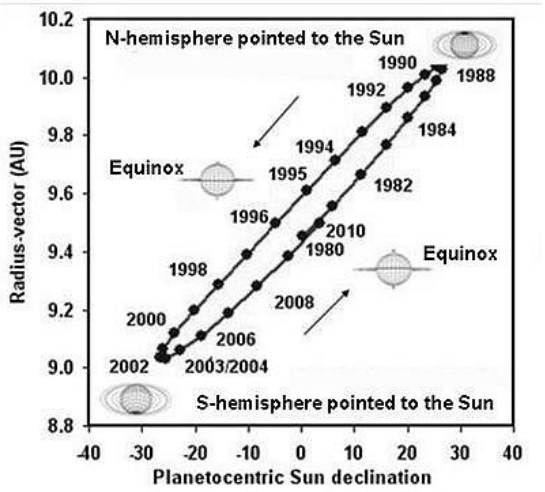


Figure 11 The planetocentric Sun declination and Saturn–Sun distance changes during the full orbital period of Saturn from 1980 to 2010.

sufficient accuracy under the low temperature atmospheric conditions that take place on the giant planets. Now they are reconsidered (see, e.g., Karkoschka and Tomasko 2010; Morozhenko 2007).

Changes of the insolation regime are bound to have an effect on the processes occurring in the upper troposphere of the northern and southern hemispheres of Saturn. Thus, from the "Cassini" data (Fig. 11) one can see very well an increased whirlwind activity of the atmosphere in the northern hemisphere in comparison with the southern one. That activity can be connected with the known effect of suppressing convection when there is a sufficient inflow of external radiation (when the temperature profile in the radiative-convective model changes). However, it is also necessary to consider that the thermal regime of the atmosphere of Saturn is also controlled by outflow of its own internal thermal energy. It becomes apparent, in particular, owing to the absolutely special near-polar atmospheric circulation: a hexagonal whirlwind round the northern pole is observed, and a circular whirlwind is at the South Pole (Sanchez-Lavega et al. 1993; Fletcher et al. 2008). It is especially seen from the measurements of seasonal variations of thermal radiation (Fletcher et al. 2010).

An explanation of both the regular growth of methane absorption in the southern hemisphere, and the observed distinctions in absorption latitudinal dependence during the periods of the 1995 and 2009 equinoxes undoubtedly lies in essential distinction of radiation regimes of the hemispheres of Saturn during the periods that had preceded both those equinoxes.

Indeed, if we compare the "extreme" positions of Saturn (at the zero inclination of the equator to a direction to the Sun and at the maximum inclination of 27°) with a heliocentric distance of the planet, as is shown in Fig. 11, it can be seen what a great distinction there is between irradiation regimes of the northern and southern hemispheres during the periods when one of them is turned to the Sun. In 1988–1989 the northern hemisphere was turned to the Sun, but at that time Saturn was at the

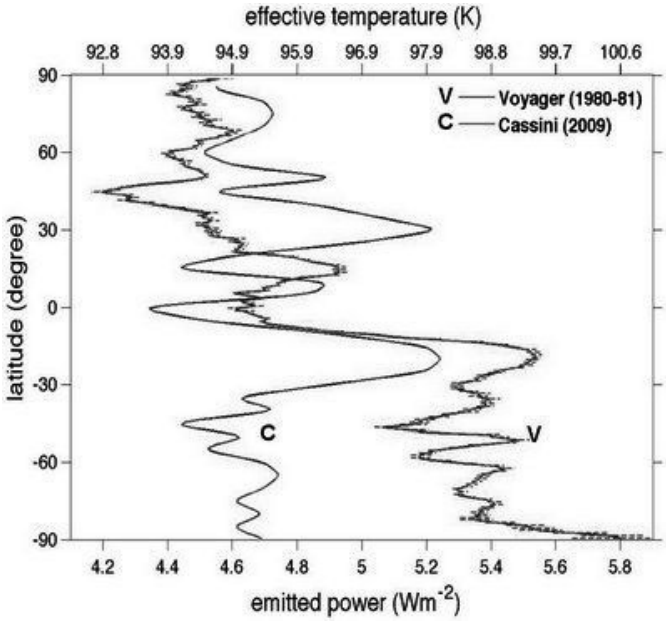


Figure 12 Latitudinal variations of the effective temperature on Saturn in 1980–81 (Voyager 2) and in 2009 (Cassini) (Fletcher et al. 2010).

maximum distance from the Sun, therefore by the equinox of 1995 (a zero inclination of the equator) a total inflow of energy to the "winter" northern hemisphere had been essentially less than the one to the summer southern hemisphere during the period from 2002 (the maximum inclination and the minimum distance from the Sun) to 2009 (the zero inclination). From Fig. 11 one can see that the maximum and minimum distances differ by the whole Astronomical Unit. That corresponds to a more than 20% distinction between the solar energy inflows.

It is obvious that observed distinctions in the methane absorption latitudinal dependence on Saturn in 1995 and in 2009 should be considered by taking into account the distinctions in the insolation regimes on the planet during the previous 15 year period. But some other causes may be effective too. A strange result was obtained (Li et al. 2010) from the comparison of the latitudinal temperature variations measured from Voyager in 1980–81 and from Cassini in 2009 (Fig. 12). In spite of almost the same orbital position of Saturn the effective temperature differences are significant, especially in the southern hemisphere. They cannot be explained by only seasonal effects.

Conclusion

Finally, it should be again noticed that the question of choice of an interpretative optical model of the cloudy structure that simulates the radiation transfer process and diffuse-reflection radiation formation at the continuum and at the absorption

bands is difficult enough and ambiguous. It is obvious that, at best, one should consider an inhomogeneous atmosphere model with the parameter values varying with altitude of the atmosphere. Those parameters must characterize the sizes of cloudy particles and their distribution, their refraction indexes, volume density, concentration of condensable gas components (ammonia, ammonium hydrosulfide, water vapor). However, with an increase in the varying parameter number, uncertainty inevitably increases, because not every optical character of the planet from all the observed ones is able to respond largely and unequivocally to those variations. At the same time one should work out quantitative criteria for estimation of global climatic characters of the planet as that is one of the primary goals of planetary monitoring in connection with the problem of climate change on the Earth.

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