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2022, Vol. 17, № 1

Contents

Pleochroism Properties of the Cometary Minerals <i>I. A. Simonia</i>	4
Relation of brightness variations of short-period comets 28P/NEUJMIN 1, 53P/VAN BIESBROECK, 63P/WILD 1 with the activity of the sun <i>A. G. Safarov, H. G. Asoev</i>	12
On the possibility of asteroid matter composition estimation near perihelion <i>A. A. Savelova, V. V. Busarev, M. P. Shcherbina, S. I. Barabanov</i>	18
Spectrophotometry of asteroids: the assessment composition of primitive asteroids near perihelion <i>M. P. Shcherbina, V. V. Busarev, S. I. Barabanov</i>	24
Dynamics of natural satellites of planets and Asteroids based on observations <i>N. V. Emelyanov</i>	35
Molecular absorption bands in studies of Jupiter's atmosphere <i>A. A. Atai, V. D. Vdovichenko, E. E. Humbatova, A. M. Karimov P. G. Lysenko, V. G. Teifel, Z. S. Farziyev, V. A. Filippov G. A. Kharitonova, A. P. Khozhenets</i>	42
Influence of stellar approaches on Jupiter's orbit <i>A. H. Mammadli</i>	72

PLEOCHROISM PROPERTIES OF THE COMETARY MINERALS

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The present article deals with the phenomenon of luminescence of the mineral halos of the comets. It is shown that luminescence will be provided as a precondition for a stable and long-term coloration of mineral halos of the comets. It is proposed also that the pleochroism of the biaxial minerals of cometary halo will provide rapid changes or alternations of the colors of this halo. A mechanism of a rapid coloration of the cometary halo is proposed. Possible minerals responsible for such a rapid coloration are considered. Numerical conditions of occurrence of such the phenomenon are provided.

Keywords: comets—dust—mineral—pleochroism—luminescence

1. INTRODUCTION

Comets, as the small bodies of the Solar System, consisting of the icy, dust and gaseous components of matter, exhibit unique physical properties when moving on orbits during the evolutionary periods, and interact with external factors and forces. The icy nucleus of the comets surrounded by the gas, dust shells, is characterized by corresponding spectral and photometric features. Namely, the optical spectra of comet consist of the emissive and reflective components. The gas molecules of the cometary comas fluoresce resonantly. The dust and icy halos of comets, representing the clouds and shells of variously dispersed dust and ice grains, scatter the solar continuum [1]. Today, a number of daughter molecules and ions of cometary comas formed as a result of photo dissociation and photo ionization processes, are known and include C_2 , C_3 , CN , CH , CO_2 , OH , CO , NH , NH_2 , CH_{II} , CO_{II} etc. [2]. There are known also the parent molecules – sources of the daughter ones. They include:

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H_2O , HCN , C_2H_2 , CH_3OH , C_2H_6 , H_2CO [3]. These lists are incomplete and permanently expanding.

The following minerals and their classes detected in comets: glassy silicate minerals, organic refractory material, iron sulfide [4]; crystalline iron silicates, magnesium and mixed iron-magnesium silicates [5,6]; osbornite, gellenite, spinele, diopside [7]; Pyrrhotite, pentlandite [8,9]; forsterite, fayalite, orthoenstatite, magnesite [10,11]; crystalline Mg-rich silicates, Fe sulfides, glassy phases including GEMS [12]. These authors noted that “the Deep Impact mission excavated material from the surface of comet 9P/Tempell. The mid-infrared spectra of the dust ejected by the impact into the coma were interpreted as resulting from a mix of grains with compositions of amorphous carbon, amorphous pyroxene, amorphous olivine, crystalline Mg-rich olivine and crystalline pyroxenes. “The mineralogy of CP-IDPs mostly consists of anhydrous crystalline phases such as Mg-rich olivines and pyroxenes, low-Ni Fe sulfides and sub-micrometer glassy phases called GEMS. “In the comets Halley, Hale-Bopp, Hyakutake, and C/2001Q4 (NEAT) were found crystalline olivine, orthopyroxene, various silicates and other minerals [13]. Mentioned authors had noted: “even though the proportion of GEMS grains that are presolar is not well established, it is clear that cometary dust is a mixture of grains with very divers origins.”

According to the theory proposed [14–17] the frozen hydrocarbon particles of the icy halo of comets luminesce under the influence of solar electromagnetic and corpuscular radiations, while this, in its turn, is manifested in the presence of narrow emission lines in the optical spectra of comets. As proposed in [14,17] not only the icy particles of the cometary halo luminesce but the mineral dust of the cometary halo, as well. Thus, when approaching to the Sun, a comet (nucleus and a gas-dust shell), resonantly fluoresces(gases), photo-luminesces (ice, mineral dust) and scatters (dust, ice, and nucleus) the solar radiation which stimulate the complex of the relict cometary matter to release and, evaporate. The released pristine matter of the comets is being photo-transformed rapidly, with losing its primary properties. In addition, regarding to relatively long and consistent processes, the fast-flowing and repetitive phenomena occur in the comets, namely, a quick color change of the cometary atmospheres. Let us consider a possible nature of this phenomenon.

2. PLEOCHROISM OF THE COMETARY MINERALS

The solar electromagnetic radiation (X-ray, UV) excites the photoluminescence of the icy and dust shells of the comets, while the fluxes of energetic electrons and protons of the solar wind excite the cathodoluminescence of these shells [14]. These processes are becoming strengthened with reducing the heliocentric

distances of the comets, moreover, for the case of photoluminescence of halo the process is stationary, while for the case of cathodoluminescence of the cometary dust - of an episodic, and is characterized by flaring nature. Each of these processes will have their own features: positions and profiles of luminescence emissions, the quantum yield of the luminescence, after glow periods, and luminescence quenching curves.

Luminescence of the cometary ice and dust stimulated by the solar radiation may be responsible for changing the color index of the cometary halo. However, this is appropriate for the long time intervals (weeks, months). There can also be rapid changes in the color index of the cometary halos (a period of several tens of hours). For this phenomenon another mechanism of "coloration" of the comet shells may be responsible.

Among the cometary minerals revealed by [18], there is the ones with well-expressed properties of pleochroism - enstatite. We listed below some of minerals with pleochroism properties. Thus, to the composition of the icy, mineral halo of comets, these transparent or translucent minerals with the properties of pleochroism can belong in the form of biaxial crystals of different shapes and masses. All listed minerals has belong to mineral classes (types) which were discovered in comets (see references in section 1). We have derived data of mineral pleochroism from: webmineral.com; mindat.org; mineralcatalog.com.ua; gemdat.org; [19]. Minerals with pleochroism properties are diopside $CaMgSi_2O_6$ (clinopyroxene, transparent/translucent, color of pleochroism: yellow, green, blue); enstatite $Mg_2Si_2O_6$ (orthopyroxene, translucent, color of pleochroism: red, yellow, green); bronzite $(Mg, Fe^{2+})_2[SiO_3]_2$ (orthopyroxene, transparent, color of pleochroism: yellow, green); fayalite $Fe_2^{2+}SiO_4$ (olivine, transparent/translucent, color of pleochroism: red, yellow).

Listed minerals has clear color of pleochroism or some color tints. A comet approaching to the Sun, surrounded by the mineral halo consisting of a complex of the biaxial (or uniaxial) micro-crystals, will be exposed to integral solar light - the radiation of the optical range 4000 – 8000 Å. When the integral solar light passes through these biaxial multi-dispersed micro-minerals, they will become to color in one of the possible colors e.g. red, yellow green, or blue. For the terrestrial observer in case of the phase angle of a comet ($\alpha = 90^\circ$) and the perpendicular location of the optical axis of the micro-mineral grain to the line of sight, this will be expressed in a particular color index ($m_B < m_R$). Over time, a spatial orientation of the extended dust micro-particles of the halo will be changed due to the axial rotation (or turn) of the cometary nucleus.

Consequently, the angle between the direction of the solar light passing and the optical axis of the corresponding micro-crystal will also be changed. In this case, the optical axis of the crystal (a micro-mineral grain) will already be posi-

tioned along the line of sight. This, in turn, will lead to replacement of the color with the opposing one – red, as expressed in the condition $m_B > m_R$. In other words, an terrestrial observer, in the first case will fix the color index of the halo at the moment of pass of the solar light along the optical axis of the crystals, while in the second case the observer will fix another color index when the sunlight passes perpendicularly to the optical axis of the micro-crystals, comprising the mineral halos of the comets. The axial rotation of the comet nucleus and correspondingly, turning of the comet shells in a form of the heavy dust clouds, will mostly predetermine a spatial orientation of the asymmetric micro-mineral dust particles, with alternating positions of their optical axes in longitudinally and perpendicularly the line of sight of the terrestrial observer. In other words, for terrestrial observer the comet appears to be something more relatively blue or something more relatively red. Such alternation will occur quickly over several ten hours. Biaxial micro-crystal (mineral dust particle of halo) may also rotate around its optical axis. It will provide appearance of additional color or tint – yellow or green, and etc. Let us list here the necessary minimum of the conditions for observing this kind of phenomenon: $\alpha \leq 90^\circ$ and $\Delta T \approx 1/4P$, where α is the phase angle of the comet, ΔT is the period of change of the color index, and P – is the period of the axial rotation of comet nucleus. These conditions are obvious for both the cases of the phase angle and the orientation of the conditional sub-solar point of the cometary halo, that suffered a change by 90° during $1/4$ part of the period of axial rotation of the comet nucleus. Pleochroism, of cometary halo micro-minerals, may occur with a rapid alternation of the color index of the cometary halo. We suggest naming such a phenomenon as a rapid coloration of the cometary halo.

Observation, fixing of this kind of phenomenon will make it possible to determine:

- 1) an approximate period of axial rotation of the comet nucleus; and
- 2) chemical- mineralogical composition of the mineral component of the cometary halo.

Peculiarities of such a phenomenon or difficulties of its detection may be associated with inclination of the cometary orbit to the ecliptic plane or inclination of the axis of rotation of the comet nucleus to the plane of its orbit and the specific content of minerals (biaxial micro-crystals, characterized by pleochroism) in the gas-dust shells of the comets.

Nevertheless, we suppose that in most cases of the orbital configuration of the comet, content of corresponding minerals of the cometary halo, would be satisfactory for the ground-based detection and investigation of this phenomena. Regarding observability and detectability of a rapid coloration of the cometary halo, it seems to be necessary to envisage the following circumstances:

- 1) possible spatial heterogeneity and irregularity of the mineral halos of the comets;
- 2) possible different spatial orientation of individual micro-grains - comprising components of the halo;
- 3) transparency (or Translucence) of each individual mineral micro-grain in general.

These circumstances are essential for the observability aspect of the research. However, if taking into consideration a higher probability of the chemical and mineralogical homogeneity of the mineral halo of the comets and the fact that the dust micro-minerals are transparent in most cases, as well as the factor of the light pressure (the solar light), we may conclude that a phenomenon of a rapid coloration of the cometary halo will be observable and detectable by the ground-based optical instruments and receivers. Recently, it was shown in the works [20–22] that for the comets C/2013 UQ4 (Catalina), 41P/Tuttle-Giacobini-Kresak in case of the phase angle $\alpha = 48^\circ$ a rapid change of the B-R color index of the cometary halo is observed, that takes place during 2 – 3 days. In our opinion, this indicates a rapid coloration of these mineral halo of the comets, while the periods of alternation of “color” (2- 3 days) can be 1/4 period of the axial rotation of their nucleuses. We do not exclude that for deeper understanding of the process of a rapid coloration of the cometary halo, the orbital instruments may become necessary. In fact rapid color variation of the cometary coma may be indirect sign of silicates, GEMS and oxide micro-minerals presence.

3. DISCUSSION

As the comets approach to the sun, the gas-dust shells of their nucleuses begin to form. The evaporating (released) matter of the comet nucleuses forms the gas comas and the icy and mineral dust halos. Under the impact of a hard solar electromagnetic radiation and the fluxes of the energetic charged particles of a solar wind, the parent molecules – the relict substances of the comet nucleuses are disintegrated into the daughter fragments, various derivatives, with losing primary properties of pristine matter. The spectral and photometric investigations of cometary atmospheres are in fact an analysis of the secondary properties of the cometary matter acquired with the constant interaction of cometary gas and dust with external factors and forces - solar radiation and gravity. For detection and further research the cometary relict matter, some different methods and approaches are required. As we have already indicated above, time and color of the cometary halo, in other words, a rapid variation of color, are the key factors in this issue. The icy and mineral halo of the comet nucleuses can luminesce intensely under the influence of the solar short-wavelength electromagnetic ra-

diation and the fluxes of fast electrons and protons of the solar wind. Periodic rapid alternation of the color of comet halos may indicate chemical and mineralogical features of the minerals comprising these halos. Namely, spectra of the cathodoluminescence of a number of minerals may be characterized by two excesses (peaks) in the blue and red regions. We have proposed also that here it may be another explanation too - a different mechanism, that predetermines a rapid variation of color of the cometary halos. An integral solar light passing alongside the optical axis of the biaxial micro-crystals will get a certain color. The same light passing through the same micro-crystals (mineral halos of comets) but in this case perpendicularly to their optical axes will colorize these micro-crystals in another color (or tint). Taking into account the axial rotation of the comet nucleus when turning the sub-solar point of the halo by 90° , for the ground-based observer in the system the Sun - Comet - the Earth, a color of the cometary halo will be alternate and becoming first bluish and after a few tens of hours yellowish or reddish, and etc. The solar light pressure or electric, magnetic properties of micro-minerals of cometary dust halo may provide the same spatial orientation of all micro-minerals of the halo for the short time. This phenomenon, that we have named as a rapid coloration of the cometary halo conditioned by pleochroism of minerals, may become an effective channel of information about the physical and chemical properties of cometary minerals. It should be noted that an investigation of alternation of color of the cometary halo, regardless of its predetermining mechanisms - luminescence, pleochroism (immediately after the cometary bursts, flares), provides the possibilities for detection of the relict matter of the comets.

The phenomenon of a rapid coloration may have an unstable, episodic nature that will be conditioned by heterogeneity of cometary halo; the differences in the chemical-mineralogical composition and orientation of halo's micro-mineral dust particles. We do not exclude the cometary mineral halos may contain another classes or sub-classes of pleochroic minerals.

4. CONCLUSION

A color alternation of the comet halos is optical phenomenon. We have proposed mechanisms explaining such alternations through discussing the actual question - is it the luminescence of comet halo minerals or the pleochroism of the same minerals? Observation and a correct interpretation of this phenomenon open up a new opportunity in understanding the nature and features of the solid cometary matter.

Special international observational program for the study of these phenomena as well as the analysis of archival data allow us to make a critical breakthrough in understanding the nature of icy and mineral comet halos, with confirming, reject-

ing, or modernizing and deepening our proposed explanations of these physical phenomena.

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RELATION OF BRIGHTNESS VARIATIONS OF SHORT-PERIOD COMETS 28P/NEUJMIN 1, 53P/VAN BIESBROECK, 63P/WILD 1 WITH THE ACTIVITY OF THE SUN

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The report examines the relationship between the brightness variation of the daily mean values of comets 28P/Neujmin 1, 53P/Van Biesbroeck, 63P/Wild 1 with the activity of the Sun. The correlation coefficient of the mean daily brightness of comets versus Wolf number and the area of sunspots for each orbital period of the above comets have been determined. It turned out that the influence of solar activity in comet 28P/Neujmin 1 is insignificant in comparison with comets 53P/Van Biesbroeck, and 63P/Wild 1. Only in the appearance in 1966 the value $r(W) = 0.92$ $r(S) = 0.94$, in other occurrences (1931, 1984, 2002 and 2020), the value of the correlation coefficient is insignificant. Although the diameter of the comet's nucleus is larger than that of other short-period comets, and the albedo in the R filter is only 0.03. The values of the correlation coefficient for comet 53P/Van Biesbroeck in the appearances (1978, 1991, 2003, and 2016) are in the range $0.56 \div 0.77$ (for the Wolf number) and $0.54 \div 0.71$ (for the sunspot number).

Keywords: comets – brightness – Solar activity – correlation coefficient

1. INTRODUCTION

Investigation of the evolution of photometric parameters of short-period comets has made it possible to detect a very important regularity, namely, the inverse dependence of the velocity of incidence of the absolute brightness of some short-period comets on the perihelion distance of their orbit. This confirms the gradual overgrowth of the icy cometary nucleus by the refractory mineral crust

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and the evolution of such comets into asteroids-like bodies. Subsequent studies of Comet 1P/Halley, 9P/Tempel 19P/Borrelly, 81P/Wild 2 and 67P/Churyumov-Gerasimenko using spacecraft (VEGA-1, 2, Giotto, Deep Impact, Deep Space 1, Rosetta) confirmed the presence of a dark refractory crust on the surface of the nucleus of these comets [1].

There are families of short-period comets of other major planets. The number of such comets in the second place are short-period comets of the family of the planet Saturn. Because the period of rotation around the Sun of comets of this family is much larger than the period of rotation of short-period comets of the Jupiter family, the number of observations of these comets is less than the number of observations of comets of the Jupiter family [2], [3], [4], [5].

The purpose of this work is to reveal the relationship between the photometric parameters of short-period comets 28P/Neujmin 1, 53P/Van Biesbroeck, 63P/Wild 1 with the activity of the sun for each orbital period.

2. OBSERVATION

Comet 28P/Neujmin 1 was discovered on September 3, 1913 by G.N. Neujmin (Simeis Observatory, Crimea, Russia). The object was stellar and of magnitude 10,0. [6]. The comet's orbital period P is about 18 years. The diameter of the comet's nucleus is 21.4 km and its albedo is very low (0.025) [7]. Comet 53P/Van Biesbroeck was discovered on September 1, 1954 [6]. The comet's orbital period around the Sun is 12.53 years. The diameter of the comet's nucleus is 6.66 km and its albedo is 0.03 [7]. Comet 63P/Wild 1 was discovered on March 26, 1960, since the comet was not found in 1986, it was discovered on February 4, 1973 [8]. The comet's orbital period around the Sun is 14.90 years. The diameter of the comet's nucleus is 2.9 km and its albedo is 0.03 [7]. The comet was observed in investigation in 1999 and 2012. Its next orbital perihelion transition will take place on July 6, 2026.

In this work, the investigation of comet 28P/Neujmin 1 in 1931, 1966, 1984, 2002 and 2020 is studied, for comet 53P/Van Biesbroeck, the investigation of 1978, 1991, 2003 and 2016 is considered, and for comet 63P/Wild 1, the investigation of 1960, 1999 and 2013.

3. METHOD

For the analysis of the light curve of comets, more than a dozen estimates of the integrated visual brightness for individual comets were used. Integral visual brightness of comets borrowed from the archives of the International Comet

Quarterly, Comet Section of BAA and IAUC. For the most accurate information, the comet's brightness estimates were reduced to the standard telescope aperture using the Morris method [9], and the daily mean apparent brightness of the comet was derived. The obtained values were reduced to a unit geocentric distance according to the technique given in [10].

The method of qualitative comparison of features is convenient for studying cometary phenomena, which was first used by O.V. Dobrovolsky [11]. The essence of the method is to divide the entire observation period T of the comet into n equal time intervals, so that at each of them there is no more than one maximum of the Sun's activity or the brightness of the comet m . We have chosen the daily average apparent brightness and have chosen daily Wolf numbers and sunspot area as solar activity.

For an accurate determination of the correlation coefficient between the daily average apparent brightness with the activity of the Sun, there is such a pattern [11]:

$$r = \frac{N_{mW}N - N_W N_m}{\sqrt{\bar{N}_W \bar{N}_{\bar{W}} \bar{N}_m \bar{N}_{\bar{m}}}}, \quad (1)$$

and its standard is:

$$\sigma = \frac{1 - r^2}{\sqrt{n}}, \quad (2)$$

where N_{mW} is the number of intervals with maxima W and m , N_W is the number of intervals with maxima W but no maximum m , N is the number of intervals without maxima m , N_m is the number of intervals without a maximum W , but with a maximum m , $\bar{N}_W$ is the total number intervals with maxima W , $\bar{N}_{\bar{W}}$ is the number of intervals without maxima W , $\bar{N}_{\bar{m}}$ is the number of intervals without maxima m and n is the total number of intervals.

4. RESULTS AND DISCUSSION

The results of the study of the relationship between the brightness variation of the daily mean values of comets 28P/Neujmin 1, 53P/Van Biesbroeck, 63P/Wild 1 with the activity of the Sun showed that for comet 28P/Neujmin 1 the influence of solar activity, with the exception of 1966, is insignificant. In 1966, the value of the correlation coefficient for 40 daily average brightness after the moment of passing the perihelion of the orbit for the area of sunspots is 0.94 and for the Wolf number 0.92. Hence it follows that the variation in the daily brightness of the comet 28P/Neujmin 1 correlates with the activity of the Sun. Comet 28P / Neujmin 1 is not activity nucleus, the nuclei rotation period is 12.75 hours [7]. During

the past centuries, the comet made only two close approaches to the Earth, but as many as five approaches to Saturn. As a result, the approach to the Earth at a distance of 0.55 AU. September 2, 1913 contributed to the discovery of the comet. The second time at a distance of 0.87 AU. from Earth on August 10, 1984. Most comets of the Saturn family depend on the disturbing force of Jupiter.

Table 1. The value of the correlation coefficient for short-period comets 28P/Neujmin 1, 53P/Van Biesbroeck and 63P/Wild 1

Years of observation	Sunspot area (S)			Wolf numbers (W)		
	γ	R	σ	γ	r	σ
Comet 28P/Neujmin 1						
1931	50	0.75	± 0.06	50	0.77	± 0.06
1966	40	0.94	± 0.02	40	0.92	± 0.02
1984	60	0.80	± 0.02	60	0.81	± 0.04
2002	100	0.63	± 0.06	100	0.60	± 0.06
2020	70	0.40	± 0.10	70	0.43	± 0.09
Comet 53P/Van Biesbroeck						
1978	43	0.70	± 0.06	43	0.77	± 0.06
1991	60	0.54	± 0.09	60	0.56	± 0.09
2003	130	0.68	± 0.04	130	0.69	± 0.04
2016	140	0.71	± 0.04	140	0.70	± 0.04
Comet 63P/Wild 1						
1960	43	0.97	± 0.01	43	0.83	± 0.05
1999	80	0.69	± 0.05	80	0.67	± 0.06
2013	130	0.54	± 0.09	130	0.60	± 0.09

The table 1 shows the moments of comet observation, the number of the total average daily visual brightness of the comet γ , the values of the correlation coefficient r and the standard σ .

The results of the correlation of the average daily total brightness of comet 53P/Van Biesbroeck show that the values for the sunspot area vary from 0.54 to 0.71, and the values of the Wolf number from 0.56 to 0.77. Results of the study by Kresak et al. [12], comet 53P/Van Biesbroeck is a secondary fragment of a hypothetical comet that fragmentation in March 1845.

The results showed that for comet 63P/Wild 1, the values of the total daily brightness varied with the area of sunspots only in 1960. For other cases, the values of the correlation coefficients for comet 63P/Wild 1 vary from 0.54 to 0.83.

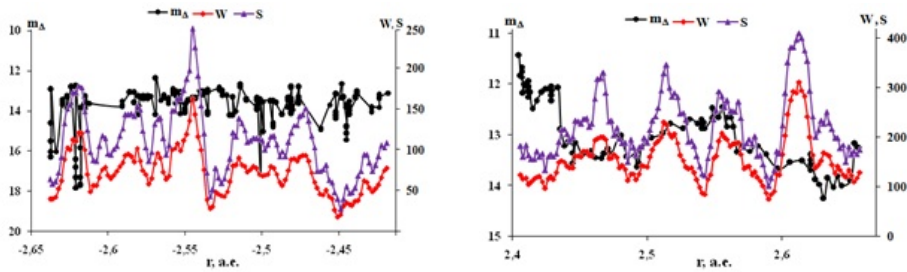


Fig. 1. Brightness variation of short-period comets 53P/Van Biesbroeck in 2003 before and 1991 after the orbital perihelion distance and solar activity

The results of the study by Bettio et al. [13] showed that the absolute stellar magnitude of the comet during the observation period of January and April 2013 is 16 magnitudes. Lowry and Fitzsimmons [8] research shows the comet's nuclei radius to be 0.6 km and Betty et al. [13] results show the comet's nucleus radius to be 1.5 km.

5. CONCLUSIONS

The correlation coefficient of the mean daily brightness of comets 28P/Neujmin 1, 53P/Van Biesbroeck, 63P/Wild 1 versus Wolf number and the area of sunspots for each orbital period of the comets. It turned out that the influence of solar activity in comet 28P/Neujmin 1 is insignificant in comparison with comets 53P/Van Biesbroeck, and 63P/Wild 1. Only in the appearance in 1966 the value $r(W) = 0.92$ $r(S) = 0.94$, in other occurrences (1931, 1984, 2002 and 2020), the value of the correlation coefficient is insignificant. The values of the correlation coefficient for comet 53P/Van Biesbroeck in the appearances (1978, 1991, 2003, and 2016) are in the range 0.560.77 (for the Wolf number) and 0.540.71 (for the sunspot number).

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ON THE POSSIBILITY OF ASTEROID MATTER COMPOSITION ESTIMATION NEAR PERIHELION

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Two programs in the MATLAB environment for studying chemical and mineralogical composition of asteroids from their visible-range reflectance spectra were previously developed by us. The first one is used for estimation of mineral composition of the asteroid surface matter on the basis of spectral characteristics of known meteorite and mineral analog samples. The second program allows estimation of a taxonomic class of an asteroid. As follows from our analysis of asteroid spectral characteristics, reflectance spectra of some of asteroids obtained near perihelion at good photometric conditions turned out to be very different in comparison with their spectra from SMASSII database and those of their probable meteorite analogs. We suggested that presence of a scattering media, like a dust exosphere arising due to sublimation of subsurface deposits of water ice on primitive-type asteroids near perihelion (at the highest subsolar temperatures), might have been an obstacle for a correct determination of their chemical and mineral matter composition by the spectral method. At the same time, such phenomenon (if present) could be used as an indication of a considerable H₂O content in interiors of asteroids considered.

Keywords: Asteroids, composition – Meteorites – Spectrophotometry

1. INTRODUCTION

Studying of asteroids is important because of several reasons. Along with the fundamental importance of the research of these most ancient small bodies, "near-Earth asteroids" (NEAs) could be potentially hazardous or may be sources of valuable mineral sources (including H₂O). Nowadays over 1 million asteroids

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is discovered and every year this number rises quickly. Thus, an amount of information to analyze is great, and it would be useful to accelerate and automatize studying the composition of asteroids. For this purpose two computer programs were written (see Section 2).

In December 2020, new spectral data for 10 main-belt asteroids (19, 52, 102, 177, 200, 203, 250, 266, 379, 383), when they were moving near their perihelia, were obtained. We applied our programs to analyse these data. Results of this study are presented in this paper.

2. PROGRAMS

The first program (that is called OSVAS, [1]) is used to find mineral and meteorite analogues for the surface matter of asteroids using their reflectance spectra. For the purpose of OSVAS performance, our own database of normalized reflectance spectra of minerals and meteorites was created. It was made using mainly the RELAB database [2] and that of the University of Winnipeg's Planetary Spectrophotometer Facility (PSF; aka HOSERLab) [3].

The algorithm of OSVAS is as follows. Some control points are chosen equidistantly on a normalized reflectance spectrum of an asteroid under study. Then the program selects spectra of minerals or meteorites from our database that differ minimally from the spectrum of the asteroid in the control points. After that, the program finds a linear combination of these spectra of minerals or meteorites that is fit to the spectrum of the asteroid by the total minimum of quadratic deviations. Thus, we can obtain a quantitative approximation of asteroid surface mineral composition by means of a "geographic" combination of those of mineral or meteorite analog samples. The second program is used to estimate a taxonomic class of an asteroid [4].

Consider a coordinate system "Normalized reflectance spectrum - wavelength". Let us call as "template" the boundaries in which normalized reflectance spectra of all known asteroids of each taxonomic class are put. These "templates" for all taxonomic classes were calculated according to SMASSII and Tholen classifications using SMASSII database [5]. Then reflectance spectrum of an asteroid in question is compared with "templates" of all spectral classes and its overlapping coefficients with the boundaries of each "template" are calculated. Also albedo of the asteroid (if known) is compared with albedo boundaries of taxonomical classes. Analyzing this information, one can estimate taxonomical class of asteroid observed.

3. RESULTS

Meteorite analogues for asteroids 102 Miriam (Frontier Mountain 99040 (CO3), Fig. 1) and 266 Aline (67% Nogoya (CM2) + 33% Murchison (CM2), Fig. 2) were found. These meteorite analogues agree well with known taxonomic types of these asteroids: SMASSII C class of 102 Miriam and Ch of 266 Aline. Also, estimated taxonomic types of these asteroids determined by our program coincided with the taxonomic classes.

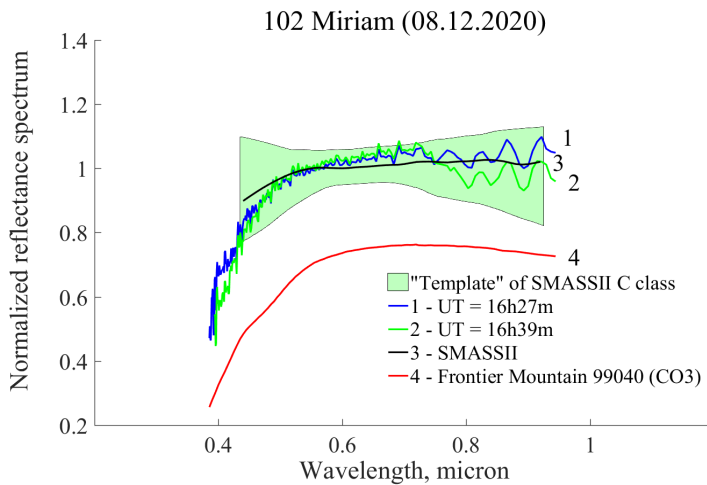


Fig. 1: Normalized to unity at 0.55μ reflectance spectra of 102 Miriam (1-2) placed on the "template" of SMASSII C class. Also a "reference" reflectance spectrum of the asteroid from the SMASSII database (3) and the spectrum of the meteorite analogue (4) are shown. Time (UT) for all observations is given on the figure.

Asteroid 203 Pompeja has not yet been assigned to a specific taxonomic class (e. g., [6]). Our program estimated its SMASSII taxonomic class as C using its three reflectance spectra in the wavelength range of 0.38-0.7 microns (Fig.3). However, the reflectance spectra of Pompeja in the range of 0.70-0.95 microns turned out to be outside the template of C-class because of probable influence of a dusty exosphere of the asteroid near perihelion [7]. The same reason did not allowed us to find a meteorite analogue for this asteroid.

Attempts to find meteorite analogues for other 7 asteroids (19, 52, 177, 200, 250, 379, 383) were also unsuccessful. Fig. 4 illustrates that reflectance spectra of the asteroids do not coincide with their "reference" reflectance spectra from the SMASSII database. For most of the asteroids of the program suggests three the

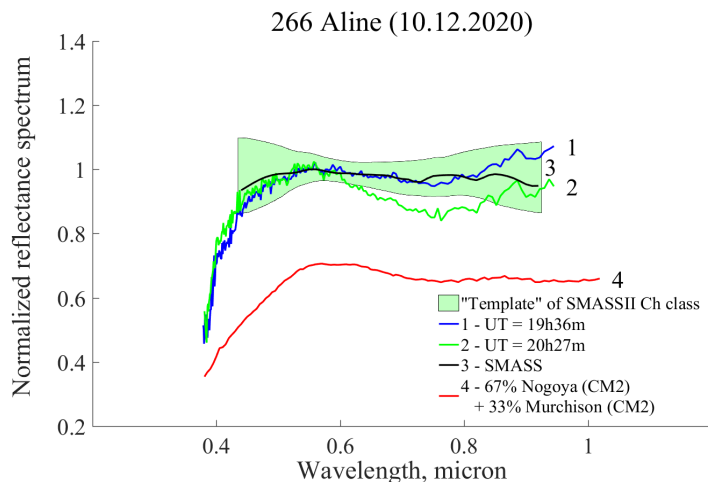


Fig. 2: Normalized to unity at 0.55μ reflectance spectra of 266 Aline (1-2) placed on the "template" of SMASSII Ch class. Also there is a "reference" reflectance spectrum of the asteroid from the SMASSII database (3) and the spectrum of the mix of the meteorite analogues (4). Time (UT) for all observations is given on the figure.

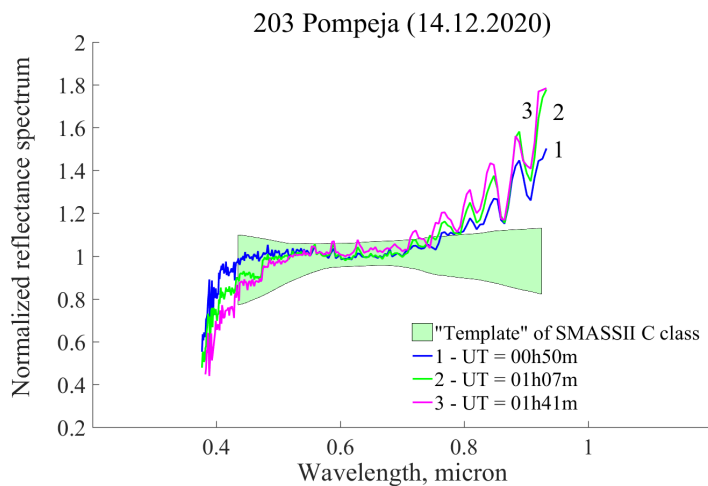


Fig. 3: Normalized to unity at 0.55μ reflectance spectra of 203 Pompeja (1-3) placed on the "template" of SMASSII C class. Time (UT) for all observations is given on the figure. There is no "reference" spectrum in the SMASSII database for the asteroid.

most possible classes, but in any case these asteroid spectra badly match with their “templates”. It should be noted that most of the asteroids (with the exception of 200) were observed at good photometric conditions [7]. Then a reasonable explanation could be that the observed differences were caused by light scattering in a sublimation-driven dust exosphere of the primitive-type asteroids, which probably formed near perihelia of their orbits at the highest subsolar temperatures (e. g., [8]). As model calculations show (e. g., [9]), because of a high porosity of the surface matter of such main-belt asteroids (and, hence, its low thermal conductivity) water ice could survive in their interiors for billions of years.

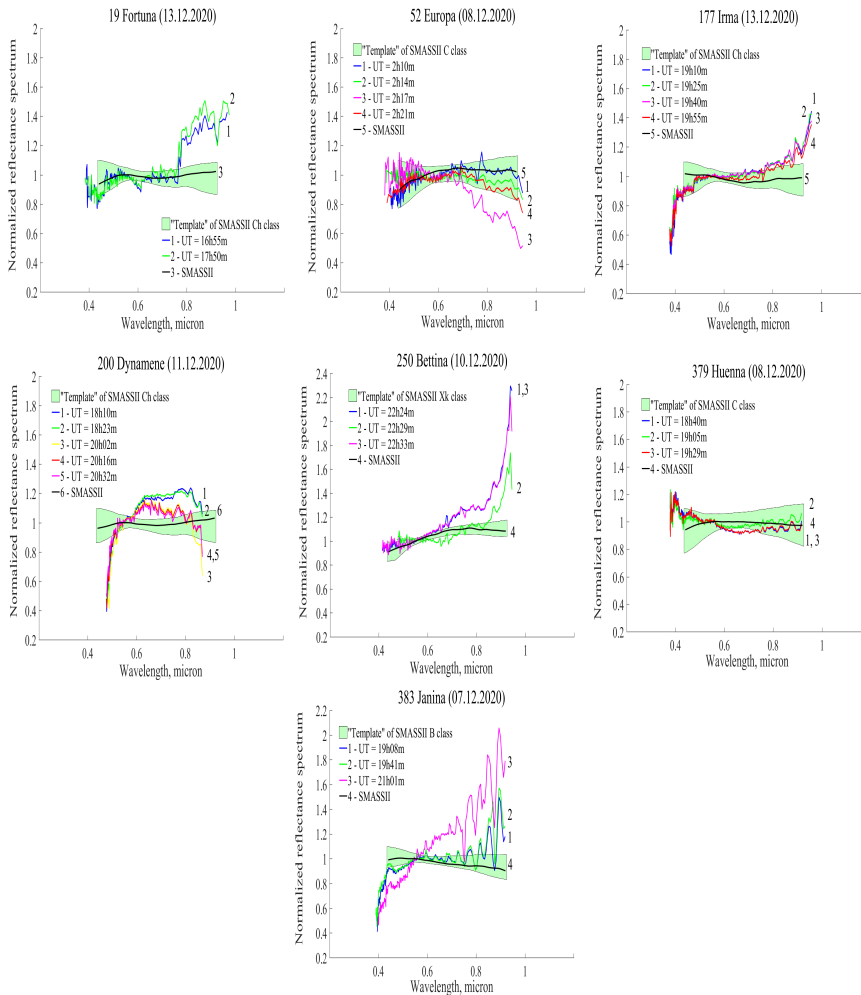


Fig. 4: Normalized reflectance spectra of other seven asteroids compared with "templates" of their known SMASII classes.

4. CONCLUSION

Thus, it seems that at observation of primitive-type asteroids passing near perihelion, there is a high probability of distortion of their reflectance spectra due to influence of their sublimation-driven exosphere [8]. In this case determination of taxonomic class of an asteroid and estimation of its surface composition with its reflectance spectra could be incorrect. In our opinion, it should be borne in mind when choosing time for observation of asteroids. On the other hand, spectral signs of a dust exosphere around a primitive asteroid passing near perihelion (e. g., [8]) could be used as an indication of a considerable H₂O content in its interiors.

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SPECTROPHOTOMETRY OF ASTEROIDS: THE ASSESSMENT OF THE MATERIAL COMPOSITION OF PRIMITIVE ASTEROIDS NEAR PERIHELION

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Using a qualitative interpretation of the reflectance spectra of asteroids, one can indirectly judge the mineralogy of the surface matter of these bodies. The spectral absorption bands are wide enough for correct interpretation even at low resolution. Thus, it is possible to assess the taxonomic class, as well as the prevailing type of mineralogy (low-temperature or high-temperature). In addition to the classical definition of the spectral type, one can use such a feature of the asteroid as the appearance of a temporary exosphere, which affects the shape of the reflectance spectrum. Recently, the number of events of registration of sublimation activity among primitive asteroids has been increasing. We have obtained and analyzed the reflectance spectra of 12 asteroids of the Main Belt, mainly of primitive type. The aim of the study was to study the influence of the temporal exosphere on the correct determination of the spectral type of the asteroid. If the influence of the exosphere is small, then the correct determination of the asteroid's class was possible. It is concluded that the data on asteroids of an unknown taxonomic class during their perihelion passage may give an incorrect idea of the prevailing type of mineralogy.

Keywords: asteroids –spectrophotometry –reflectance spectrum – sublimation activity

1. INTRODUCTION

Asteroids are ideal objects for spectrophotometric ground-based observations. Mineralogical absorption bands in reflectance spectra of asteroids are wide enough

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to use a low resolution ($R \sim 100$), which makes it possible to expand the range of the asteroid magnitudes and observe more faint objects. The analysis of the reflectance spectra of asteroids makes it possible to qualitatively assess the prevailing type of mineralogy of their matter, using the classifications of Tholen [1] and Bus-Binzel further referred as SMASS [2]. To check the correctness of such estimates, the features of the reflectance spectra of asteroids are compared with the reflectance spectra of the corresponding groups of meteorites. We use the reflectance spectra of meteorites from open databases such as RELAB (Brown University, USA) [3] and the database of the University of Winnipeg (Canada) [4]. Thus, a qualitative assessment of the mineralogy of each asteroid is based on a comparison of its reflectance spectra with the reflectance spectra of meteorites [5]. But we also admit the possibility of discovering new connections between existing groups of meteorites and classes of asteroids.

The Institute of Astronomy of the Russian Academy of Sciences, together with SAI MSU, participates in the international program "Astronomy in the Elbrus region" on spectral observations of asteroids and comets, including those approaching the Earth, based on the use of the Zeiss-2000 (telescope with a low-resolution spectrograph) at the Terskol branch of INASAN. In December 2020, we obtained and analyzed new reflectance spectra of the main belt asteroids: 13 Egeria, 19 Fortuna, 52 Europe, 102 Miriam, 177 Irma, 200 Dynamene, 201 Penelopa, 203 Pompeia, 250 Bettina, 266 Aline, 379 Huenna and 383 Janina. The purpose of these observations was to study the effect of maximum temperatures on the surface matter of the listed asteroids (which have significant orbital eccentricities), including hydrosilicates and probably ice inclusions.

2. THE QUALITATIVE ASSESSMENT OF THE MINERALOGY OF ASTEROIDS

2.1. 13 Egeria

A brief description of the characteristics of asteroid 13 Egeria is given in Table 1. Here is a summary from other publications. The AKARI (Japanese infrared satellite) mission confirmed the presence of hydrated minerals on Egeria [6]. The observations revealed significant inhomogeneities in the distribution of the chemical and mineralogical composition of the surface matter of the asteroid, which could manifest at different phases of rotation. The inhomogeneity of the surface matter of Egeria could arise during dehydration and heating of the matter in the places where large impact craters were formed [7].

The normalized (at $0.55 \mu\text{m}$ here and further) reflectance spectra are shown in Figure 1. The spectrum has a broad absorption band centered at $0.7 \mu\text{m}$, which

is a sign of the presence of hydrated silicates [5]. However, there are weak bands at $0.52\ \mu\text{m}$ (a sign of Fe^{2+}) and $0.62\ \mu\text{m}$ (a sign of oxidized metal compounds) [8]. The meteorite analogue, selected according to the similarity of the spectra with the minimum square deviation, is Boriskino (CM2), which corresponds to the low-temperature type of mineralogy of the asteroid's surface matter. However, signs of the presence of components of a high-temperature nature lead to the idea of the inhomogeneity of the substance, which was noted earlier.

2.2. 19 Fortuna

A brief description of the characteristics of asteroid 19 Fortuna is given in Table 1. The reflectance spectra are shown in Figure 2. There is a broad absorption band centered at $0.7\ \mu\text{m}$, which is a sign of hydrated silicates [5], as well as weaker absorption bands at 0.44 and $0.62\ \mu\text{m}$ [7].

At the same time, there is a sharp increase in reflectivity at wavelengths greater than $0.78\ \mu\text{m}$, which is inconsistent with the canonical SMASS spectrum of this asteroid and asteroids of this type. Perhaps the reason is the reflectance and scattering of sunlight from the mobile dusty exosphere of the asteroid, which arose near perihelion.

Meteorite analogue: best match is CM2 class meteorites, i. g. Lonewolf Nunataks (CM2).

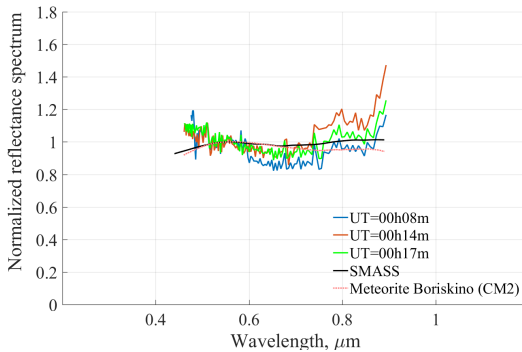


Fig. 1. Reflectance spectra of asteroid 13 Egeria (2020/12/09), reflectance spectrum according to SMASS data and reflectance spectrum of the selected analogue, the meteorite Boriskino (CM2)

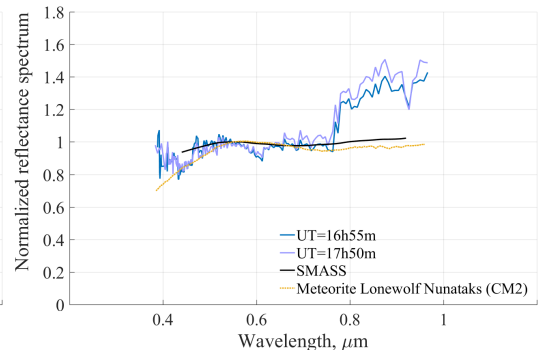


Fig. 2. Reflectance spectra of asteroid 19 Fortuna (2020/12/13), reflectance spectrum according to SMASS data and reflectance spectrum of the selected analogue, the meteorite Lonewolf Nunataks (CM2)

2.3. 52 Europe

A brief description of the characteristics of asteroid 52 Europe is given in Table 1. Here is a summary from other scientific works. The Japanese infrared satellite AKARI has detected the presence of hydrated minerals on Europe [6].

Spectral research also showed the presence of olivine and various pyroxenes in the rocks of the asteroid [9]. The reflectance spectra are shown in Figure 3. The shape of the spectrum is consistent with the C-type. The short-term variability of the spectra can be associated with the presence of a dusty exosphere with the inclusion of ice particles [7]. The selection of meteorite analogues does not provide an unambiguous classification: both representatives of high-temperature mineralogy and low-temperature mineralogy are suitable. This fact indicates a variable composition of the asteroid's surface matter, which is confirmed by other scientific papers cited above.

2.4. 102 Miriam

A brief description of the characteristics of asteroid 102 Miriam is given in Table 1. Originally classified as a D-type asteroid, it was later classified as a C-asteroid, most likely due to the presence of phyllosilicates on the surface [10].

The reflectance spectra are shown in Figure 4. There is a weak band at $0.44 \mu\text{m}$ (a probable sign of the presence of hydrosilicates) [7]. The object rotates extremely slowly, however, in the two spectra we obtained, there are some differences, which can be explained by the result of light scattering by an extremely rarefied dusty exosphere. The selected meteorite analogue Lewis Cliff (CM2) is in a good agreement with the spectrum of the asteroid, confirming the low-temperature nature of the surface matter.

2.5. 177 Irma

A brief description of the characteristics of asteroid 177 Irma is given in Table 1.

The reflectance spectra are shown in Figure 5. There is a broad absorption band at $0.7 \mu\text{m}$ (which is a sign of the presence of hydrated silicates) [5], as well as a weak band at $0.44 \mu\text{m}$. In addition, a short-term change and growth with wavelength of all reflectance spectra may indicate the presence of a temporary dusty exosphere. The reflectance spectrum of the asteroid is in good agreement at shorter wavelengths with the reflectance spectra of many samples of CM2 meteorites, for example, Elephant (CM2), but there is some agreement with the reflectance spectra of other types of meteorites, implying a higher temperature mineralogy.

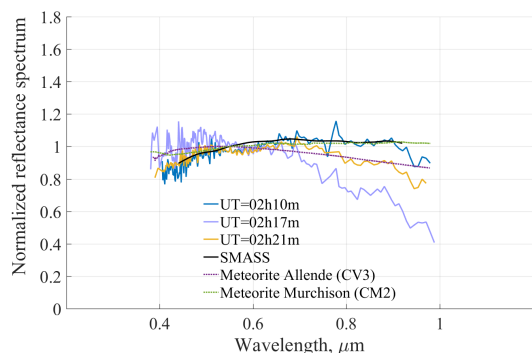


Fig. 3. Reflectance spectra of asteroid 52 Europe (2020/12/08), reflectance spectrum according to SMASS data and reflectance spectra of the selected analogues, the meteorites Allende (CV3) and Murchison (CM2)

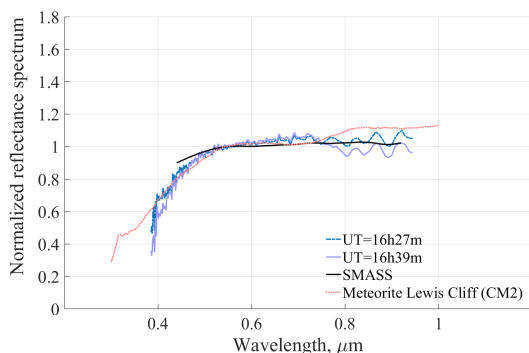


Fig. 4. Reflectance spectra of asteroid 102 Miriam (2020/12/08), reflectance spectrum according to SMASS data and reflectance spectrum of the selected analogue, the meteorite Lewis Cliff (CM2)

2.6. 200 Dynamene

A brief description of the characteristics of asteroid 200 Dynamene is given in Table 1. Spectra of the asteroid show signs of hydrated compounds [11].

The reflectance spectra are shown in Figure 6. The shape of the reflectance spectra of Dynamene does not coincide with the SMASS spectrum. Apparently, such a change in the reflectance spectrum is associated with the scattering of light in the exosphere of silicate particles [7]. It was not possible to select a meteorite analogue, as well as to identify some absorption bands.

2.7. 201 Penelopa

A brief description of the characteristics of asteroid 201 Penelopa is given in Table 1. Even though the asteroid belongs to the class M, it contains a significant amount of silicate components [12]. The presumed presence of phyllosilicates on the surface is due to the water change of high-temperature silicates [12].

The reflectance spectra are shown in Figure 7. There is a weak absorption band at $0.7 \mu\text{m}$, which indicates the presence of hydrated silicates [5]. The selection of a meteorite analogue shows correspondence with different types of meteorites, which is an additional sign of a mixed composition of the surface matter.

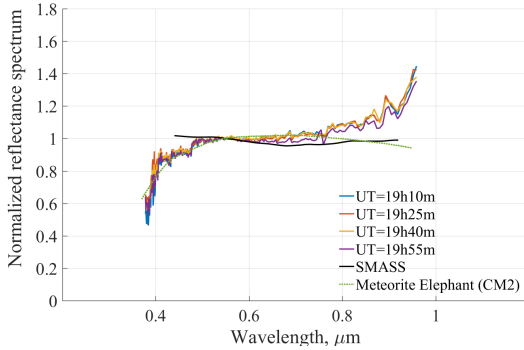


Fig. 5. Reflectance spectra of asteroid 177 Irma (2020/12/13), reflectance spectrum according to SMASS data and reflectance spectrum of the selected analogue, the meteorite Elephant (CM2)

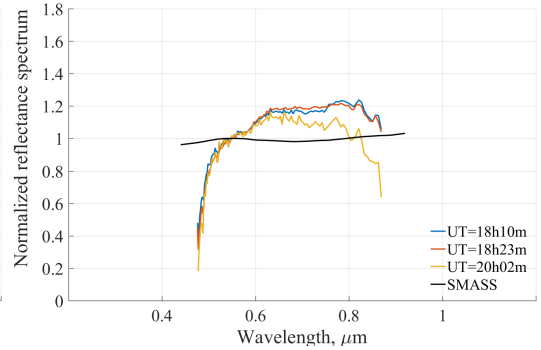


Fig. 6. Reflectance spectra of asteroid 200 Dynamene (2020/12/11) and reflectance spectrum according to SMASS data. It was not possible to select a meteorite analogue

2.8. 203 Pompeia

A brief description of the characteristics of asteroid 203 Pompeia is given in Table 1. Previously, other researchers did not assess the belonging of this asteroid to any taxonomic class. However, it turned out that the visible spectrum of the asteroid has a pronounced red color, which is more characteristic of objects in the Kuiper belt, and not for asteroids in the main belt. This feature of the spectrum is explained by the outer organic-rich layer on its surface and the fact that it could have formed in the outer part of the solar system outside the asteroid belt [13].

The reflectance spectra are shown in Figure 8. The spectrum view corresponds to C-type. There is possibly a very weak absorption band at $0.44 \mu\text{m}$, connected possibly with presence of hydrated silicates [7]. Growth in the long-wavelength part may be due to the presence of a combined exosphere (ice-silicates-organic). The selected meteorite counterpart meets the expectations for a low temperature class C (Elephant (CM2)).

2.9. 250 Bettina

A brief description of the characteristics of asteroid 250 Bettina is given in Table 1. Classes of meteorites consistent with the asteroid class are iron meteorites, possibly with silicate inclusions; enstatite chondrite.

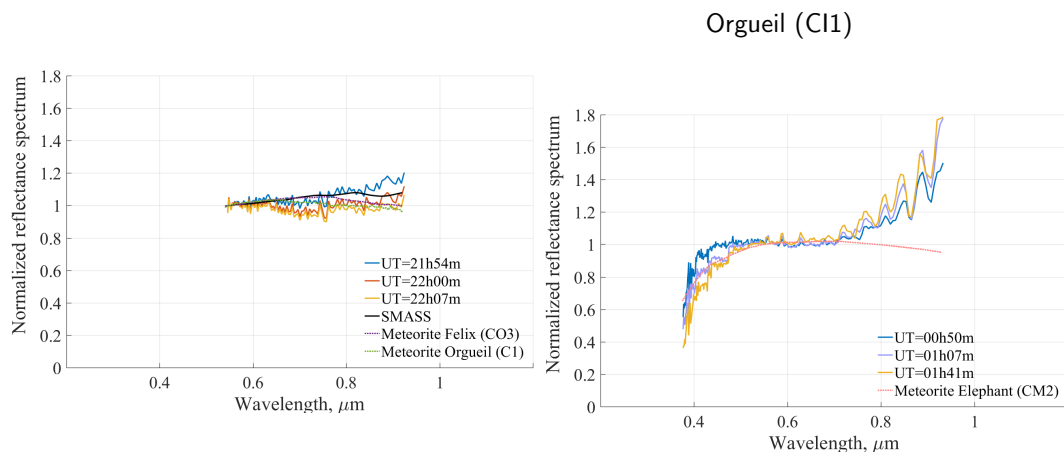


Fig. 7. Reflectance spectra of asteroid 201 Penelopa (2020/12/08), reflectance spectrum according to SMASS data and reflectance spectra of the selected analogues, the meteorites Felix (CO3) and

Fig. 8. Reflectance spectra of asteroid 203 Pompeia (2020/12/14) and reflectance spectrum of the selected analogue, the meteorite Elephant (CM2)

The reflectance spectra are shown in Figure 9. The shape of the reflectance spectrum corresponds to the SMASS spectrum, and the selected meteorite analogue is well suited to this taxonomic class of the asteroid (Jiddat al Harasis (Eucrite)).

2.10. 266 Aline

A brief description of the characteristics of asteroid 266 Aline is given in Table 1.

The reflectance spectra are shown in Figure 10. The shape of the spectrum corresponds to the reflectance spectrum of class C. There is an increase in the range of 0.85-0.9 μm , which may be a sign of a dusty exosphere. The selected meteorite analogues that showed the best similarity to the asteroid's reflectance spectrum are Elephant (CM2) and Orgueil (CI1), which is an additional indication of the correctness of the asteroid's class estimate.

2.11. 379 Huenna

A brief description of the characteristics of asteroid 379 Huenna is given in Table 1. This asteroid has a satellite orbiting its parent body at a significant distance, about 3400 kilometres. In 2011, studies of the spectra of Guenna and its

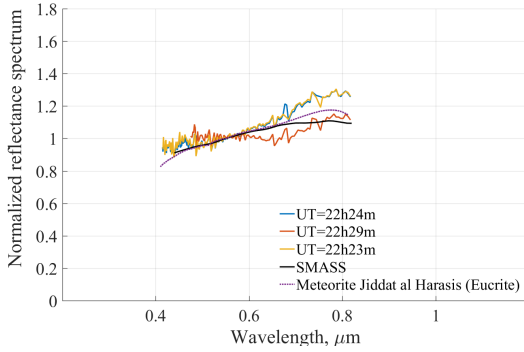


Fig. 9. Reflectance spectra of asteroid 250 Bettina (2020/12/10), reflectance spectrum according to SMASS data and reflectance spectrum of the selected analogue, the meteorite Jiddat al Harasis (eucrite)

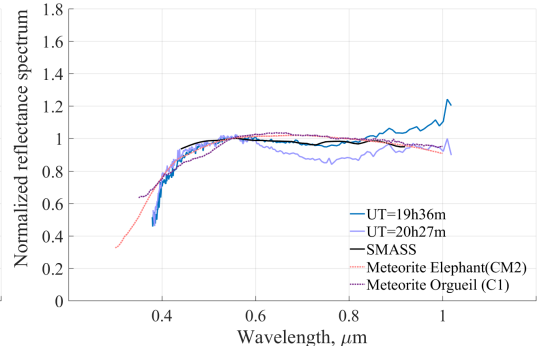


Fig. 10. Reflectance spectra of asteroid 266 Aline (2020/12/10), reflectance spectrum according to SMASS data and reflectance spectra of the selected analogues, the meteorites Elephant (CM2) and Orgueil (CI1)

satellite, carried out by an international group of scientists from several countries, were published. According to the research results, it was suggested that S / 2003 (379) 1 is either a fragment of Guenna, or a former member of the Themis family, which became its companion because of gravitational capture [14].

The reflectance spectra are shown in Figure 11. The reflectance spectrum has an indication of the presence of hydrosilicates in the composition of the surface substance, namely, it has an absorption band near $0.7 \mu\text{m}$ [5]. The change in the reflectance spectrum can be caused by the appearance of a predominantly icy exosphere [15]. It was not possible to select a meteorite analogue.

2.12. 383 Janina

A brief description of the characteristics of asteroid 383 Janina is given in Table 1.

The reflectance spectra are shown in Figure 12. The reflectance spectrum has probably an absorption band at $0.44 \mu\text{m}$. Some coincidence of the short-wavelength part of the spectra among meteorite analogues was shown by meteorites of the CI1 and CM2 classes, which may be confirmation of the low-temperature mineralogy of the asteroid.

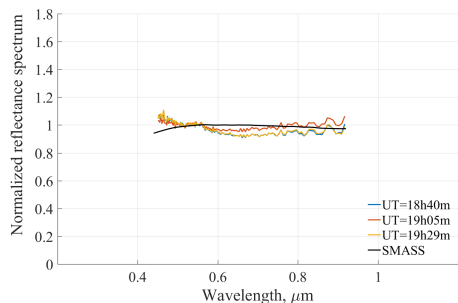


Fig. 11. Reflectance spectra of asteroid 379 Huenna (2020/12/08) and reflectance spectrum according to SMASS data. It was not possible to select a meteorite analogue

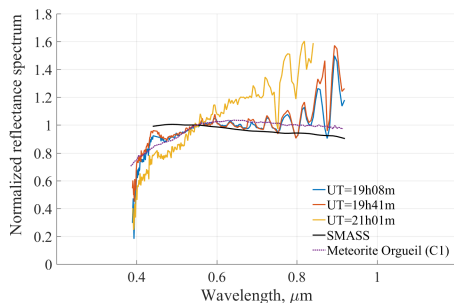


Fig. 12. Reflectance spectra of asteroid 383 Janina (2020/12/07), reflectance spectrum according to SMASS data and reflectance spectrum of the selected analogue, the meteorite Orgueil (C1)

3. CONCLUSION

Almost all considered asteroids (except for the M-type asteroids 201 Penelope and 250 Bettina) may have low-temperature mineralogy (typical minerals are hydrosilicates with probable inclusions of water ice). It could be based on the previously defined taxonomic class C. We deliberately chose the time of observations so that all these bodies were near the perihelion, where their sublimation activity and the formation of a dusty exosphere were possible [15], [16], [17]. Therefore, we probably obtained the reflectance spectra of these asteroids, partially distorted by the influence of a rarefied dusty exosphere, consisting of submicron conglomerates of particles of ice, silicate and tholins's composition. The effect of such dusty exosphere on the reflectance spectra of asteroids is in good agreement with the modelling of light scattering by the above components [17]. If such distortions were insignificant, then it is possible to estimate taxonomic types and mineralogy of the considered asteroids mainly by the short-wavelength part of these spectra. The estimates obtained are in good agreement with the known data on these objects, as well as with geometric albedo and reflectance spectra of meteorites of proper groups.

It was not always possible to find a suitable meteorite analogue for asteroid spectra. This may be due to both the mixed composition of the asteroid's surface matter and the incompleteness of the terrestrial collections of meteorite's matter.

For 203 Pompeia, the spectral type was assessed for the first time.

Table 1. A brief description of the characteristics of asteroids [18]

Asteroid	Day of observation	Confirmed class	Diameter,m	Albedo	Rotation period,hrs
13 Egeria	2020 12 09	G (Ch)	207.64	2	7.05
19 Fortuna	2020 12 13	G (Ch)	200	0.037	7.44
52 Europe	2020 12 08	C	302.5	0.0578	5.63
102 Miriam	2020 12 08	C	83	0.0507	23.61
177 Irma	2020 12 13	Ch	73.22	0.0527	13.86
200 Dy-namene	2020 12 11	Ch	128.36	0.0533	37.39
201 Penelopa	2020 12 08	X (M)	68.39	0.1604	3.74
203 Pom-peia	2020 12 14	?	116.25	0.041	24.05
250 Bettina	2020 12 10	Xk (M)	79.75	0.2581	5.05
266 Aline	2020 12 10	Ch (C)	109.09	0.0448	13.02
379 Huenna	2020 12 08	C	92.33	0.0587	14.14
383 Janina	2020 12 07	B	45.52	0.0926	6.40

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DYNAMICS OF NATURAL SATELLITES OF PLANETS AND ASTEROIDS BASED ON OBSERVATIONS.

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The article presents the justification and results of the author's activity in creating means of modeling the motion of satellites of giant planets and satellites of asteroids. The necessity of this activity is due to the possibility of using planetary satellites as the most suitable places for landing spacecraft and expanding the human habitat. Therefore, it is necessary to calculate the position of satellites in space with the most excellent possible accuracy to get there with minor energy costs. It could be done by developing satellite motion models. Such models, also called ephemeris, are the result of studying the dynamics of these bodies since they are based on all our knowledge, including all available observations. The study of the dynamics of satellites by constructing models of motion is also a means of ensuring the familiarization of the solar system and the extraction of new fundamental knowledge. The result of the work was a database of observations of satellites of planets and a server of ephemeris of satellites. All are available to any user via the internet.

Keywords: Satellites of the planets – Ephemeris – Observations.

1. INTRODUCTION

The solar system, containing many large and small bodies, is a space - potentially possible to expand the human habitat. In their desire to develop new lands, Europeans stumbled across America. Before heading over there, it is better first to study the planets and satellites. Because outer space poses more dangers and uncertainties for a man than the open ocean, the question will inevitably arise in free flight between the planets: where to land? Then, of course, the planets will capture us with their gravity, but we will want to return to Earth. It should be

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taken enough rocket propellant to overcome the gravity of another planet. Flying back and forth requires much energy.

On the way there, we will see that the planets have satellites. They have less gravitation and are not far from the planet: observe it as much as possible. Furthermore, the satellite itself is interesting. What is it made of? Where did it come from? It is the best place to live away from Earth. To land on a satellite, one needs to aim well. However, satellite flies as it pleases. We will have to calculate the coordinates beforehand.

Moreover, if we are wrong? Will there be enough rocket fuel to correct the trajectory? No, it is better to study the dynamics of the satellite on Earth. It is necessary to learn how to calculate its motion. The satellite is far away, but we have computers here. It would be great if the satellite model were on the computer! Then study the dynamics as much as possible. However, the satellite in the computer must fly in the same way as it does in space. It should be necessary to observe from the Earth its behavior, i.e., motion. Satellites are far away, but astronomers learned to see them and accurately measure their coordinates. Galileo, in 1610 saw the first 4 satellites of Jupiter. And it began. However, mainly very slowly at first. In 1950, people knew 30 satellites, and in 2000 - 70. Powerful new telescopes were built at the end of the twentieth century. What were they looking for? First, of course, the hazards of falling asteroids on Earth. It was actual. Sometimes it was impossible to determine the asteroid's orbit, and it turned out to be not an asteroid but a satellite of Jupiter or Saturn. Thus, many new satellites began to be discovered. And not only for Jupiter and Saturn but also for Uranus and Neptune. Now 209 satellites of the planets are known. Furthermore, now new ones are discovered.

It means that the satellite must fly in the computer as it does near the planet. For this, the motion should be measured. Astronomers have long been used to calling such measurements observations. Observations are carried out using telescopes. However, to accurately measure the position of a satellite in the sky, a telescope should have good cameras. Nowadays, they are CCD cameras. Measurements should be carried out as accurately as possible. To aim better at the satellite and have enough rocket propellant to return. Here we depend on telescope-developing technology and electronics. With this, things are moving slowly yet. The circumstances of the motion of satellites and other solar system bodies are such that the accuracy of coordinates precomputation on time points in the future depends on the time interval of observations.

The possible most extensive interval is needed. It is even necessary to use observations conducted before discovering the satellite. The French scientist Urbain Le Verrier had done just that. He understood in 1846 that the planet Uranus was not moving as his theory predicted. Instead, Le Verrier thought that Uranus was

affected by the gravitation of some unknown planet. An observer familiar to him looked where Le Verrier pointed and discovered a new planet there. Later, it was named Neptune. Le Verrier was looking for a new planet on old photographic plates. Moreover, he found that what was previously taken for a star was a new planet precomputed by him. Nowadays, it is also worth looking for satellites on old photo plates to increase the maximum observation time interval necessary for us. As a result, it turns out that observations are the basis of our knowledge about the motion of planetary satellites-however, not just observations. Many things impact the motion of satellites. For example, there is a planet near the satellite that attracts it. The satellite even feels by its motion that the planet is not round. Nowadays, it is known that all giant planets are compressed at the poles.

Our spacecraft will be gravitated by the massive planet when approaching the satellite. We need to know the planet's mass to calculate the trajectory. Where get it? The planet cannot be weighed on a scale. Let spacecraft fly there. Let us determine the planet's mass from the deviations of their trajectories. However, this is very expensive. Well, the satellites of the planet therein fly wholly free. Let us measure their motion. In former times, the planets' masses were determined only by the motion of satellites. So, we can determine the mass of the planet and its compression. The compression of the planet also impacts the motion of satellites. That is not all. There is also the Sun. It is very far away but very massive. The Sun's gravity should be considered in the motion of the satellite. As a rule, the satellite of the planet is not one. All satellites gravitate to each other. It also should be considered. As a result, the theories of the motion of planetary satellites turn out to be the most complex in celestial mechanics.

But, back to observations. These data will make the satellite model in the computer move in the same way. All observations that have been conducted around the world are necessary. It was evident not only to the author. In 1996 our French colleagues invited the author to Paris to collect a database of satellite observations. We looked for observations everywhere. For example, in the Kazan City Astronomical Observatory's writings and such an old "exotic" publication as "Manuscripts deposited at VINITI." Therefore, it was necessary to collect data and organize a database and even provide access to it via the internet.

It was done to any colleagues in the world who could benefit from our papers' results. There is no other suchlike database in the world. Moreover, the message about creating the database was published in a high-rated scientific journal [1].

Thus, by compiling huge computational programs, it was possible to make the satellites move in the computer in the most similar way as they move around the planet. So it is for all known 209 satellites of the giant planets from Mars to

Pluto.

Undoubtedly, we are interested in using models of satellite motion for everyone who needs it. Nowadays, this is done by creating so-called ephemeris servers on the internet. We created such a server. Accordingly, this was published in a high-rated scientific journal [2]. Such servers have only Americans (JPL, California Institute of Technology), and options that are very limited in terms of satellite composition are at the International Minor Planet Center (MPC) and Institute of Applied Astronomy of the Russian Academy of Sciences (RAS). Our ephemeris server for all satellites of the planets called MULTI-SAT is available on the website of the GAISH MSU at the address: <http://www.sai.msu.ru/neb/nss/indexr.htm>. A so-called mirror of these pages is hosted on the website of the French Institute of Celestial Mechanics and Ephemeris Computation (IMCCE) at <http://nsdb.imcce.fr/multisat/>. The French colleagues have no other such server with satellites. The MULTI-SAT ephemeris server makes it possible to calculate the ephemerides of the Moon and the Sun simultaneously. As for the satellites of minor planets, namely asteroids, the situation is more egregious.

At present are known about 250 asteroids that have satellites. About all satellites we know are that they exist. Asteroid satellites are separated from their main bodies by the interval of no more than a 1-second arc. It is very complicated to measure differential coordinates under such conditions. It requires adaptive optics to compensate for image jitter due to light refraction in the Earth's turbulent atmosphere. The ingenious method of speckle interferometry is also applied. Otherwise, the coordinates cannot be measured in any way. Various authors were able to determine the orbits of asteroid satellite.

At one time, the American V. Grundy and his colleagues succeeded. They determined the orbits of 38 satellites [3, 4]. For these reasons, there are very few observations of satellites of asteroids. All of them are collected in our unique database. Accordingly, it is published in [5]. Under these conditions, the author set to work. It was possible to determine the orbits of 64 satellites of asteroids. It is the maximum that can be done from the available astrometric observations. All of these ephemerides are included in the server MULTI-SAT. The message was published in the international scientific journal *Icarus* [6].

Knowing the orbits of asteroid satellites gives us the value of the total mass of the principal component with the satellite. It is almost the only way to determine the mass. Another way - launch a spacecraft to fly past. The mass also can be determined by measurements of the apparatus's deviations due to the asteroid's gravitation.

However, this is very expensive. When determining the orbit of the satellite Linus of the asteroid Kalliope, an unresolved mystery arose. The observations

of this satellite were carried out at the Caucasian Mountain Observatory of the GAISH MSU. We have collected quite a few observations of this satellite with other previous observations on a long-time-interval. Thus, this made it possible to determine the extension of the principal component.

Since the asteroid rotates rapidly, its gravitational field impacts the satellite as the field of a compressed body. Because of this action, the satellite's orbit must precess in the counter direction concerning the satellite's orbital motion. However, the determination of the orbit from observations shows the opposite, a direct precession of the orbit. Jointly with the GAISH observers, our message about this unexplained effect was published in a high-rated scientific journal [7]. Regarding this riddle, we have only hypotheses.

As noted above, the success of observations and modeling of satellite motion depends on progress in telescope optics and electronics. However, some practitioners of celestial mechanics were not expecting gifts from this but looking for new ways to obtain positional data on planetary satellites. It turns out that the orbits of some of the principal satellites of the planets lie approximately in the same plane, inclined to the plane of the planet's orbit. For this reason, when observing from the Earth, satellites can cover (obscure) each other. In addition, during these periods, one satellite can fall into the shadow of another. In this case, the total brightness of the satellites decreases.

The decrease can be measured by observing satellites from Earth. Furthermore, by measured light curve can be determined the differences in satellite coordinates. The accuracy of such determinations is better than that of conventional astrometric observations. Phenomena occur within 9-15 months once in half-turn of the planet around the Sun.

For the satellites of Jupiter, this is once every six years. The duration of mutual covering or mutual eclipse is 5-15 minutes. Such short-term phenomena simultaneously can be observed only at a part of ground-based observatories. Therefore, international campaigns for such observations are organized. The processing of satellite photometry during these mutual events, namely, obtaining the mutual coordinates of the satellites by the light curve, is a very complex process.

An original method was developed for this by the author. As a result, the observations of all international campaigns from 2003 to 2021 were processed by the author in the GAISH. The obtained results were published in a high-rated journal, and all the participated observers in the observations became co-authors of the article. See publication [8] and references to the bibliography in this article. As a result, high accurate positional data were obtained. Together with other observations of the satellites, these data allowed the french colleagues to determine the parameters of the viscosity of the matter of the satellites [9,10]. These results allowed us to explain some of the past mysteries in the motion of satel-

lites. In solving the problems described in the present article, original findings and achievements appeared.

Let us look at a couple of the most significant of them. When modeling the motion of distant satellites of Jupiter, a unique opportunity arose to determine the mass of one of the satellites of Himalia by its gravitational impact on some other satellites. This influence was reflected in the results of observations. Before that, the mass of satellites was found from measurements of their brightness with the acceptance of several uncertain hypotheses about the properties of the surface and the density of the matter of the satellites. The mass value obtained by the author significantly differed from the value published in handbooks.

It was done in 2005 [11]. Only 12 years later, the found value of the mass of Himalia was confirmed in the work of American colleagues [12]. When publishing and using ephemerides of celestial bodies, one rarely thinks about the accuracy of ephemerides.

However, the issue of the accuracy of the ephemeris of the distant satellites of the giant planets is considered by the author. Three methods for assessing accuracy were developed [13]. Accuracy estimates conducted in 2010 showed that the accuracy of the ephemeris of some satellites is half-turn of the satellite around the planet. That is, satellites can be considered lost. Such conclusions were made for 21 satellites of Jupiter. Later in 2012, the conclusions about the loss of satellites were confirmed in the work of American colleagues [14]. They carried out new observations and found some of the lost satellites, but not all. All developed methods and solutions obtained by the author are collected in the book [15]. The book was translated into English and published by Elsevier's international publishing house [16].

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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 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 $\lambda_0 = 643.503\text{nm}$, $\lambda_1 = 636.776\text{nm}$.

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 pa-

rameters 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 $(1.54 \pm 0.09) \cdot 10^{-4} \text{ sm}^1 \text{ km}^{-1} \text{ amagat}^{-1}$, and for S(0) it is $0.88 \pm 0.32 \text{ sm}^1 \text{ km}^1 \text{ amagat}^1$ [5, 10]. These estimates are in good agreement with the theoretically predicted values $S(0) = 1.63 \cdot 10^{-4} \text{ sm}^{-1} \text{ km}^{-1} \text{ amagat}^{-1}$ for S(1) and $S(0) = 0.95 \pm 0.14 \text{ sm}^1 \text{ km}^1 \text{ amagat}^{-1}$ 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 Å/pixel and 4.3 Å/pixel, respectively.

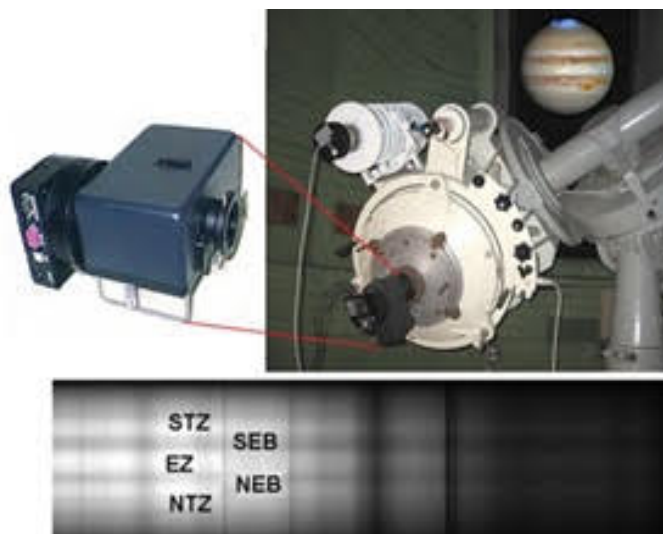


Fig. 1. Spectrograph with a CCD camera on the RC-600 telescope. Below is a sample of the spectrogram of Jupiter and the cloud structures studied on it.

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-

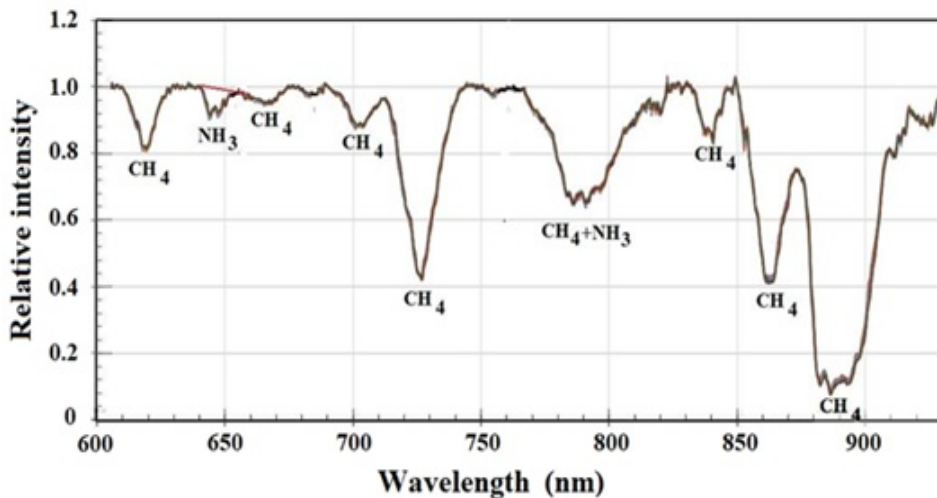


Fig. 2. The studied absorption bands of methane and ammonia in the spectrum of Jupiter

tra with a resolution of $R = 14000$ were obtained using an echelle spectrometer with a camera (580×530 pc, element size $24 \times 18 \mu m$) 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 under study 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.

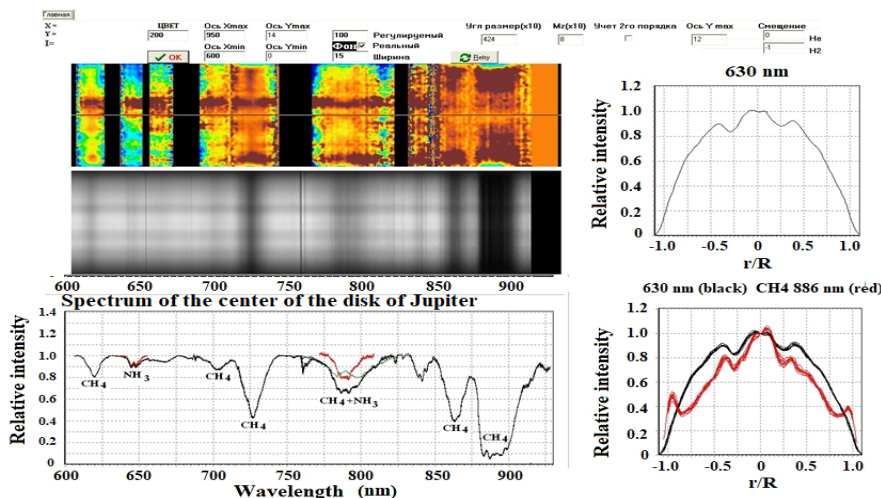


Fig. 3. Screenshot of the main tab of the program "Colored absorption map along with the Jupiter disk" with a demonstration of the main controls. A significant part of the observational material, including the series of zonal spectra, was processed using the programs of the Excel spreadsheet package.

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

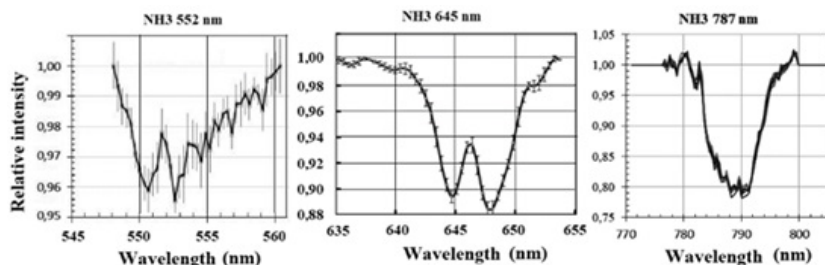


Fig. 4. Profiles of absorption bands of ammonia

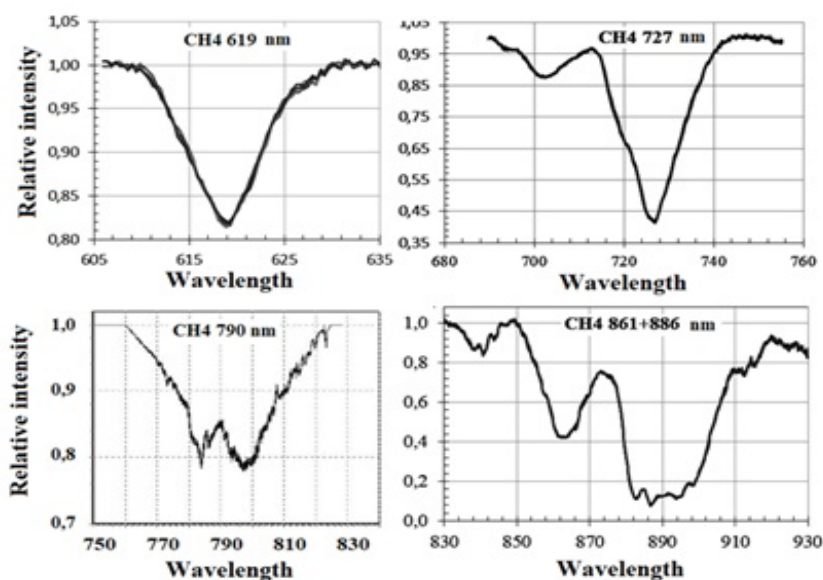


Fig. 5. Profiles of methane absorption bands

wavelength of about $\lambda 667$ 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

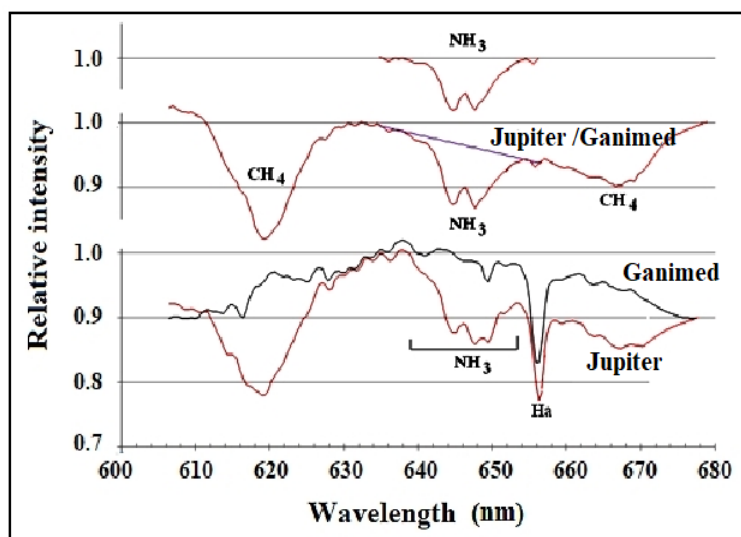


Fig. 6. Fragments of the spectra of Jupiter, Ganymede, their relationship and "pure" spectrum ammonia in the region of 645 nm (top) after the relation to the continuous spectrum.

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).

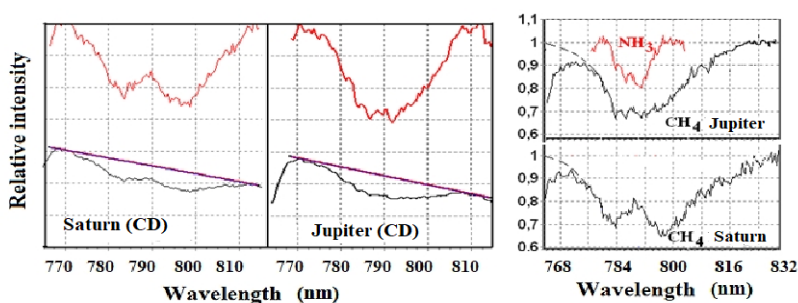


Fig. 7. Fragments of methane spectra in the 770-810 nm region for the center of the disk of Saturn and Jupiter (left) and the result of their ratio in the form of a spectrum of ammonia NH_3 on Jupiter (right, top).

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).

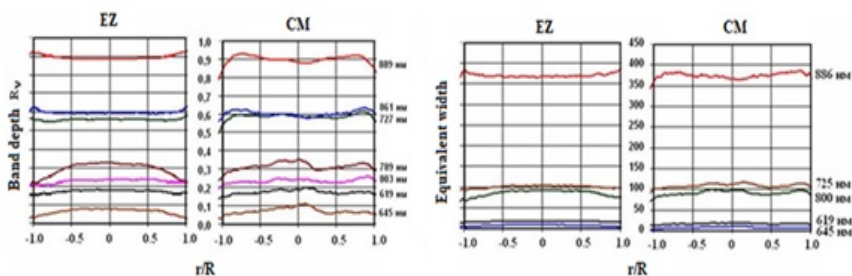


Fig. 8. The course of the central depths and equivalent widths of the absorption bands of methane and ammonia of varying intensity along the equator and along the central meridian.

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

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

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 gas (Figure 9).

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

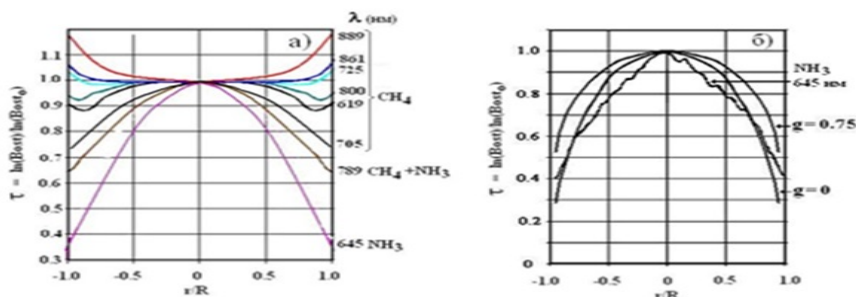


Fig. 9. a) - Normalized to the center of the disk, the variation of ammonia and methane along the bright equatorial zone EZ. b) Comparison of the course of absorption of ammonia at 645 nm along the equator with model calculations performed on the basis of theoretical calculations [31]

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, 861, and 889 nm.

According to Figure.10, for solid and moderate absorption bands of methane, as in previous years, an almost 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).

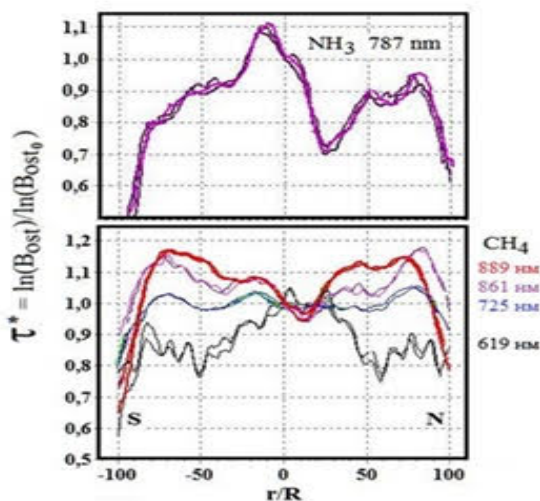


Fig. 10. Comparison of variations in the absorption intensity of methane and ammonia along the central meridian of Jupiter in 7 absorption bands in 2016.

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].

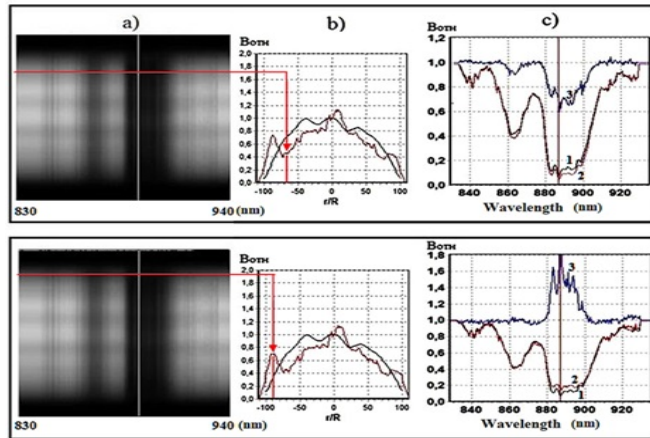


Fig. 11. Change in the absorption intensity in the 889 nm methane band. a) - a fragment of the spectrogram in the 830-950 nm spectral region, b) - meridional section in the continuous spectrum of 830 nm and the center of the methane absorption band at 884 nm, c) - profiles of the CH_4 absorption band 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.

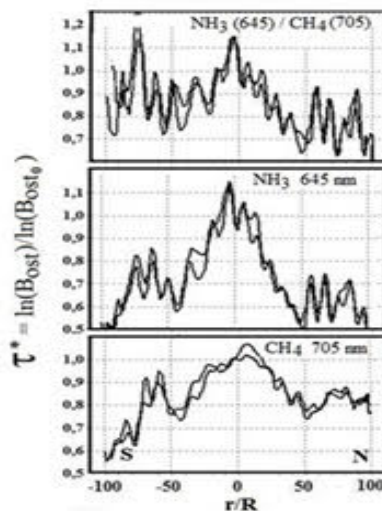


Fig. 12. Distribution of τ^* along the central meridian of Jupiter in the strip.

Figure 13 compares the effective optical paths τ^* NH_3 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

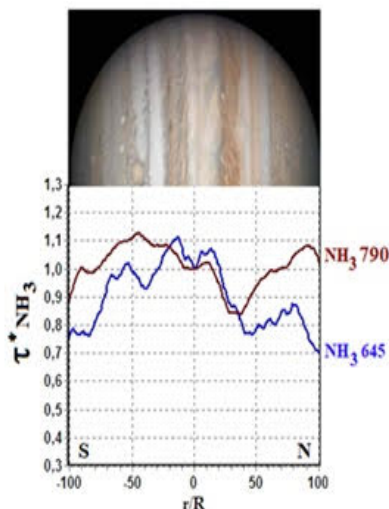


Fig. 13. Variations in the meridional course of ammonia absorption in two absorption bands at 645 and 787 nm.

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.

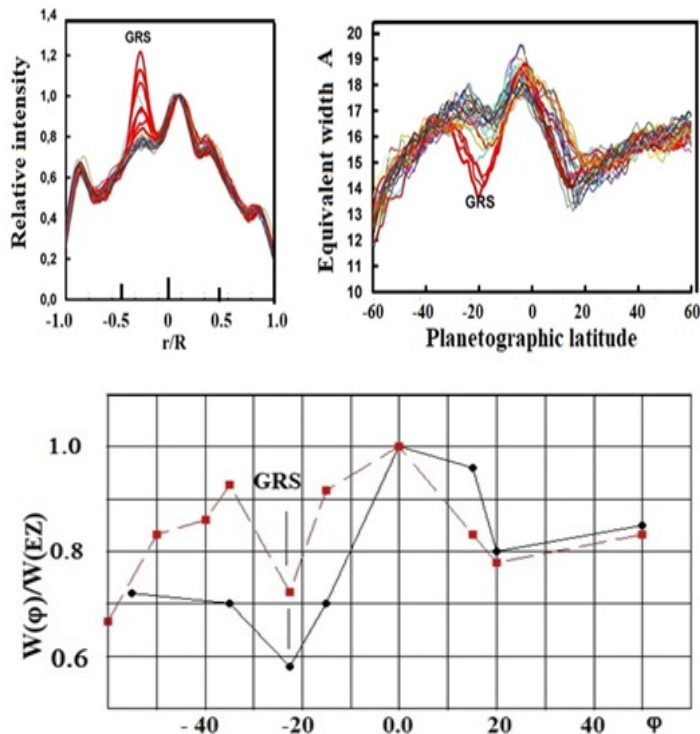


Fig. 14. The left side (A) of Figure [14] shows the brightness profiles of Jupiter's CM in the center of the intense methane absorption band at a wavelength of 887 nm in the longitude range from 240° to 310° at the time of the passage of the Great Red Spot (GRS) through the central meridian. Right - 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 $\lambda 645$ nm 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 $\lambda 645$ 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

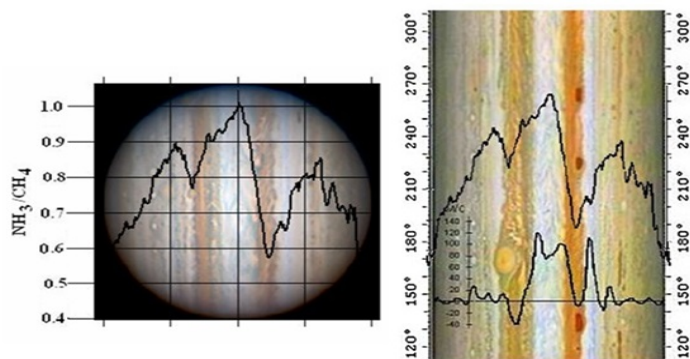


Fig. 15. Comparison of the variation of the ammonia content with the zonal cloud structure along with the CM of Jupiter (left) and with the wind map (right)

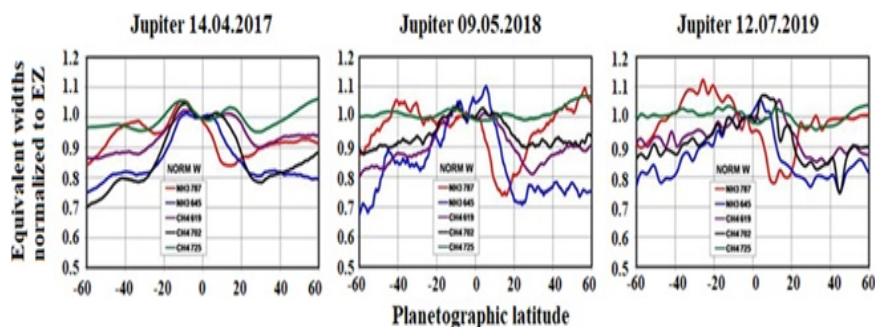


Fig. 16. Shows the latitudinal variations of the equivalent widths of the absorption bands of methane and ammonia normalized to the equatorial zone from observations in 2017-2019.

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.

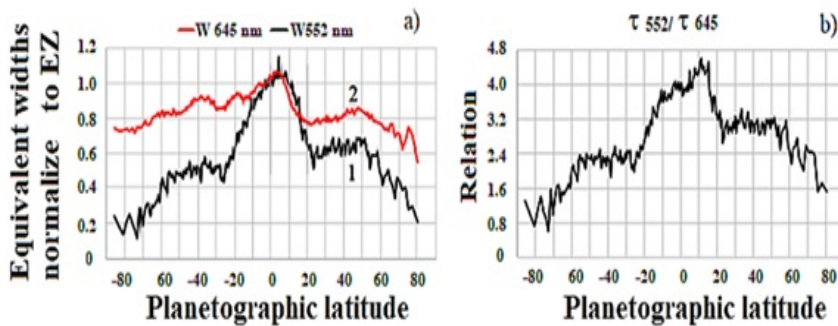


Fig. 17. - (a) - Normalized to the center of the meridional disk course of equivalent widths $W_{NH_3} 5529 \text{ \AA}$ (1) and $W_{NH_3} 6450 \text{ \AA}$ (2). (b) ratio of $\tau_{NH_3} 5529 \text{ \AA}$ to $\tau_{NH_3} 6450 \text{ \AA}$

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.

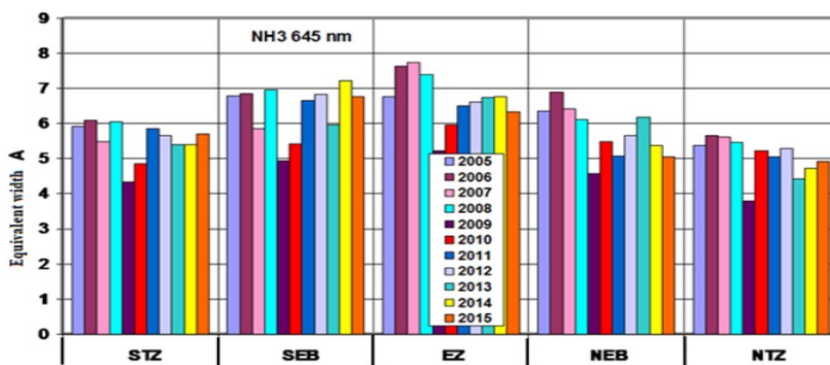


Fig. 18. Time variations over the years of the equivalent width of the absorption band NH_3 645nm

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,

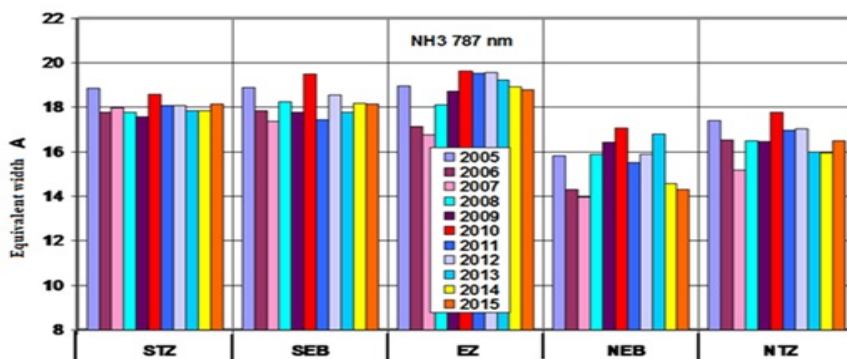


Fig. 19. Time variations over the years of the equivalent absorption band of NH_3 787 nm.

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 NH_3 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 $4.7 - 4.8 \mu m$. 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 $4.7 \mu m$ 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

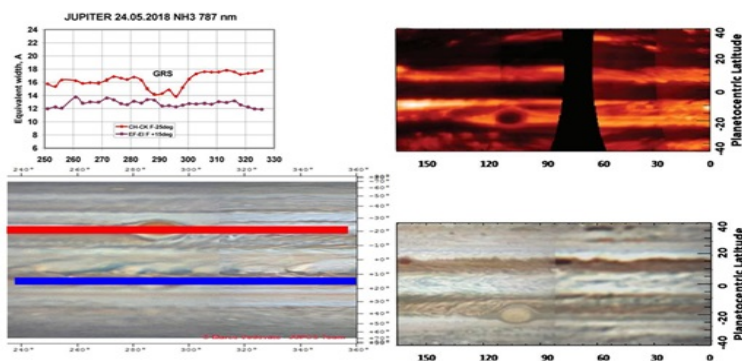


Fig. 20. Left: comparison of the longitudinal variation of ammonia absorption in the SEB and NEB belts for the NH_3 787 nm band. Right: a fragment of the map of the distribution of brightness temperatures on Jupiter at a wavelength of $4.7 \mu m$ [36]

[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.

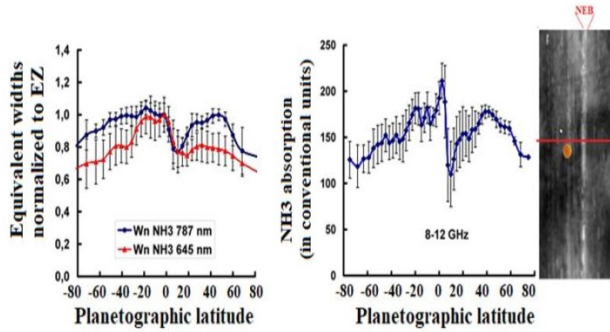


Fig. 21. Comparison of latitudinal variations in ammonia absorption in the NH_3 645 and 787 nm bands (left) and NH_3 absorption in the millimeter radio band (right)

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

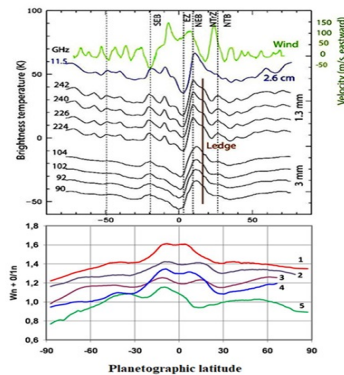


Fig. 22. Comparison of latitudinal variations in brightness temperatures in several ranges of microwave radio emission [38] and equivalent widths of methane and ammonia absorption bands normalized to the equator in the visible region of the spectrum

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 $0.69 \div 0.06$ (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 f_p 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 . An analysis 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 pho-

tons 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 $107 \div 112$ K (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 19th 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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INFLUENCE OF STELLAR APPROACHES ON JUPITER'S ORBIT

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The spatial motion of a passively gravitating body is investigated within the restricted three-body problem. The exact expression of the force function without expansion in series is used. The influence of the perturbing star as it approaches the Sun on the orbit of Jupiter is investigated. It is shown that a star of one to five solar masses that approaches the Solar System in a hyperbolic orbit within a minimum distance of 50 to 100 AU significantly affects the size and shape of Jupiter's orbit only in the case when the sample star is at the perihelion, and Jupiter is in conjunction or in opposition to it. The results are shown in the form of figures and tables.

Keywords: celestial mechanics—restricted three-body problem—force function—orbital elements of Jupiter

1. STATEMENT OF THE PROBLEM. EXPRESSION OF THE DISTURBING FUNCTION

The planar averaged three-body problem is considered in [1, 2] by Mamedov, and the doubly averaged parabolic three-body problem is considered by Mammadli [3]. It is shown that in the case of a moderate approach of the disturbing body to the central body, the dimensions and shape of the orbit of the central body remain constant, and only its orientation changes. The disturbing body is taken to be a solar-mass star; the planetary orbits are studied in the case of its approach toward the Sun.

Kholshevnikov and Mishchuk [4] considered a restricted hyperbolic three-body problem and estimated the influence of a solar-mass star on the orbits of the planets in the case of its approach to the Sun at a distance q' of 100 to 1152 AU. It was shown that under a moderate encounter of such a star with the Sun, the

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dimensions of the planetary orbits do not exhibit changes. If the star approaches the Sun at a distance $q' \geq 100$ AU, rather minor changes in the inclination, eccentricity, longitude of the ascending node, and argument of the perihelion of the planetary orbits are observed.

In the paper, Holman & Wiegert [5] has numerically investigated the long-term stability of planets near one of the stars in a binary system. The mass ratio μ and the binary eccentricity e are determined for the range $0 < e < 0,8$ and $0,1 < \mu < 0,9$ can be used to guide searches for planets in binary systems. The stability of a mutually interacting system of planets orbiting one star of a binary system is examined.

The authors Adams & Laughlin [6] constrain the star formation environment of the Sun within the scenario of external radioactive enrichment by a massive star. They came to this conclusion using the observed properties (the isotopic compositions of meteorites and the regularity of the planetary orbits) of our Solar system. According to the authors the Sun is most likely to have formed within a stellar group containing about 2000 ± 1100 members. In this case the probability of a star formation in this type of environment is only about 1 out of 120 solar systems are expected to form under similar conditions.

According to the author Zwart [7] the initial mass and radius of the star cluster in which the Sun was born constrain to $M \approx 500 - 3000 M_{\odot}$ and $R \approx 1 - 3 pc$, respectively.

The authors Hao, Kouwenhoven & Spurzem [8] demonstrate that multi planet systems are prone to instabilities as a result of frequent stellar encounters in these star clusters much more than single planet systems. They consider two types of planetary configurations orbiting Sun-like stars and find that in the equal-mass planet model, 70 percent of the planets with initial semimajor axes $a > 40$ au are either ejected or have collided with the central star or another planet within the life time of a typical cluster, and that more than 50 percent of all planets with $a < 10$ au remain bound to the system. Planets with short orbital periods are not directly affected by encountering stars. However, secular evolution of perturbed systems may result in the ejection of the inner most planets or in physical collisions of the innermost planets with the host star, up to many thousands of years after a stellar encounter.

In the paper Li & Adams [9] considered scattering encounters between solar systems and passing cluster members. The authors calculate the corresponding interaction cross-sections for eccentricity increase, inclination angle increase, planet ejection and capture four giant planets - Jupiter, Saturn, Uranus and Neptune. They find a universal formula that gives the cross - sections as a function of stellar host mass $M_*(0.25 M_{\odot} \leq M_* \leq 2 M_{\odot})$, cluster velocity dispersion $\nu_b (1 \leq \nu_b \leq 16)$ in km/s, starting planetary orbital radius, and final eccentricity.

The present study is concerned with the evolution of Jupiter's orbit during stellar encounters with the Solar System within the restricted hyperbolic three-body problem. This work is of great interest in the context of the evolution of the initial orbit of the passively gravitating body (planet) after the passage of the perturbing body (star) in a hyperbolic orbit around the central body (the Sun).

The relevance of such tasks lies in solving the cosmogonic problem in relation to the solar system, namely, the evolution and origin of the planets. After all, the formation of the planets of the solar system is not excluded, and its present state can be connected just with the approach of a massive star to it, or a collision with it. The availability of observational materials in relation to such problems is not possible. Therefore, for comparison, above are the results obtained in the works of other authors devoted to similar problems.

Let the disturbing body be a star P' with a mass m' , which moves relative to the central body, the Sun P_0 with a mass m_0 , in a hyperbolic orbit. The motion of the passively gravitating body, Jupiter P with a mass m , needs to be studied.

Let us choose a rectilinear Cartesian coordinate system with the origin at the center of the body P_0 . In this coordinate system, the differential equations of motion of the passively gravitating body P will be written as follows [1–3, 10]:

$$\frac{d^2x}{dt^2} = \frac{\partial U}{\partial x}, \quad \frac{d^2y}{dt^2} = \frac{\partial U}{\partial y}, \quad \frac{d^2z}{dt^2} = \frac{\partial U}{\partial z} \quad (1)$$

where the force function $U=U(x,y,z,x',y',z')$ depends on the coordinates x, y and z and x', y' and z' of the bodies P and P' and is determined by the equation

$$U = U_0 + R, \quad U_0 = \frac{G(m_0 + m)}{r}, \quad R = \frac{Gm'}{r'^2} \left(\frac{r'^2}{\Delta} - r \cos \theta \right). \quad (2)$$

Here, G is the gravitational constant, U_0 is the force function of the undisturbed motion, and R is the disturbing function. Therefore, the system of equations (1) at $U = U_0$, or, equivalently, $R=0$, is the system of equations of the undisturbed motion. Additionally, r is the radius-vector of the body P , and r' and Δ are the distances of the disturbing body from the central body P_0 and from the point P :

$$r^2 = x^2 + y^2 + z^2, \text{ and } r'^2 = x'^2 + y'^2 + z'^2 \quad (3)$$

$$\Delta^2 = (x - x')^2 + (y - y')^2 + (z - z')^2 = r^2 + r'^2 - 2rr' \cos \theta. \quad (4)$$

Here, θ is the angle between the radius-vectors r and r' , and the cosine of this angle is determined by the equation

$$\cos \theta = \frac{xx' + yy' + zz'}{rr'} = \alpha\alpha' + \beta\beta' + \gamma\gamma' \quad (5)$$

The following expressions are used for the rectangular coordinates x , y and z [10–12]:

$$\begin{aligned} x &= r\alpha, \quad \alpha = \cos u \cos \Omega - \cos i \sin u \sin \Omega, \\ y &= r\beta, \quad \beta = \cos u \sin \Omega + \cos i \sin u \cos \Omega \\ z &= r\gamma, \quad \gamma = \sin i \sin u \end{aligned} \quad (6)$$

If all variables in (6) are primed, we obtain similar expressions for the coordinates x, y , and z [10, 12]. Here, $u = v + \omega$ and $u' = v' + \omega'$ are the arguments of latitude, Ω and Ω' are the longitudes of the ascending node, i and i' are the orbital inclinations of the bodies P and P' to the main plane, ω and ω' are the arguments of pericenters (for Jupiter's orbit, the argument of perihelion), and v and v' are the true anomalies of their orbits.

It should be noted that eq.(6) is the solution of equation system (1) for the undisturbed motion, i.e., at $U = U_0$, (or $R = 0$) [10]. For the disturbed motion ($R \neq 0$), the solution of equation system (1) is also represented as (6), under the condition that the orbital elements u', Ω', i', a' and e' of the disturbing body are considered known, and the orbital elements u, Ω, i, a and e of the body P are determined from differential equations, such as the Lagrange equations (see the next section), for the osculating elements [10, 12].

Now let us express the disturbing function R via the orbital elements. For this we will use the orbital equation of the body P :

$$r = \frac{p}{1 + e \cos v}, \quad p = a(1 - e^2) \quad (0 < e < 1). \quad (7)$$

For the hyperbolic motion of the disturbing body P' , we have

$$r' = \frac{p'}{1 + e' \cos v'}, \quad p' = a'(e'^2 - 1) = q'(1 + e'), \quad (e' > 1). \quad (8)$$

Thus, the disturbing function R from (4), using the above mentioned formulas (5)–(8), is expressed via the orbital elements as follows:

$$R = \frac{Gm'}{r'^2} \left(\frac{r'^2}{\sqrt{r^2 + r'^2 - 2rr' \cos \theta}} - r \cos \theta \right) \quad (9)$$

For brevity, expressions (7) and (8) for r and r' , as well as expression (5) for $\cos \theta$ in (9), are not substituted. This substitution is performed in the computer numerical integration of the Lagrange equations for osculating elements.

2. LAGRANGE EQUATIONS FOR OSCULATING ELEMENTS

Let us write out the Lagrange equations for Keplerian osculating elements in the restricted threebody problem(see [10, 12]) in the new independent variable v' . In these equations, the equation relative to v will be considered instead of the equation relative to the mean anomaly M . For this, the following equations can be used [12]:

$$\mu = G(m_0 + m) = n^2 a^3, \quad \mu' = G(m_0 + m') \\ \frac{\partial R}{\partial M} = \frac{\partial R}{\partial v} \frac{\partial v}{\partial M}, \quad \frac{dv}{dt} = \frac{\partial v}{\partial M} \frac{dM}{dt} + \frac{\partial v}{\partial e} \frac{de}{dt}, \quad r'^2 dv' = \sqrt{\mu' p'} dt \quad (10)$$

$$\frac{\partial v}{\partial M} = \frac{\partial v}{\partial M_0} = \frac{a^2 \sqrt{1-e^2}}{r^2}, \quad \text{and} \quad \frac{\partial v}{\partial e} = \frac{a \sin v}{r} \left(1 + \frac{p}{r}\right) \quad (11)$$

where the radius-vectors r and r' , as well as focal parameters p and p' , are determined earlier with eqs. (7) and (8). Let us write out the Lagrange equations as

$$\begin{aligned} \frac{da}{dv'} &= \frac{2a\delta^2}{\sqrt{p}(1-e^2)} \frac{\partial \tilde{R}}{\partial v}, \quad \delta = 1 + e \cos v \\ \frac{de}{dv'} &= \frac{1}{e\sqrt{p}} \left[\delta^2 \frac{\partial \tilde{R}}{\partial v} - (1-e^2) \frac{\partial \tilde{R}}{\partial \omega} \right] \\ \frac{di}{dv'} &= \frac{1}{\sin i \sqrt{p}} \left(-\frac{\partial \tilde{R}}{\partial \Omega} + \cos i \frac{\partial \tilde{R}}{\partial \omega} \right) \\ \frac{d\Omega}{dv'} &= \frac{1}{\sin i \sqrt{p}} \frac{\partial \tilde{R}}{\partial i} \\ \frac{d\omega}{dv'} &= \frac{1}{\sqrt{p}} \left(-\frac{\cos i}{\sin i} \frac{\partial \tilde{R}}{\partial i} + \frac{(1-e^2)}{e} \frac{\partial \tilde{R}}{\partial e} \right) \end{aligned} \quad (12)$$

and

$$\begin{aligned} \frac{dv}{dv'} &= \frac{\delta^2 \mu}{p\sqrt{p}} \frac{r'^2}{\sqrt{\mu \mu' p'}} + \\ &+ \frac{1}{ep\sqrt{p}} \left[-2a^2 \delta^2 e \frac{\partial \tilde{R}}{\partial a} - p \delta^2 \frac{\partial \tilde{R}}{\partial e} + a \delta^2 (1 + \delta) \sin v \frac{\partial \tilde{R}}{\partial v} - p(1 + \delta) \sin v \frac{\partial \tilde{R}}{\partial \omega} \right] \end{aligned} \quad (13)$$

Here, a , e , and p are the semimajor axis, eccentricity, and focal parameter of the orbit of the body P , while i , Ω , and ω are the inclination to the main plane xy , longitude of the ascending node, and the argument of perihelion, respectively.

In system of equations (12), the function $\tilde{R}$ is related to the disturbing function R from (9), as follows:

$$\tilde{R} = \frac{r'^2 R}{\sqrt{p'} \mu \mu'} = A \left(\frac{r'^2}{\sqrt{r^2 + r'^2 - 2rr' \cos \theta}} - r \cos \theta \right) \quad (14)$$

where

$$A = \frac{m'}{\sqrt{p' (m_0 + m) (m_0 + m')}}. \quad (15)$$

The function $\tilde{R}$ is expressed in the orbital elements by substituting expressions (7) and (8) for r and r' , as well as expressions (5) and (6) for $\cos \theta$, into (14). This allows the partial derivatives of the function $\tilde{R}$ with respect to the orbital elements to be calculated. For brevity, no such substitution is not shown here, although it is performed in the computer numerical integration of the Lagrange equations for osculating elements.

Thus, solving the system of equations (12) and (13) using numerical integration, we find the osculating elements

$$a = a(v'), e = e(v'), i = i(v'), \Omega = \Omega(v'), \omega = \omega(v'), v = v(v'),$$

and calculate the mean motion $n = n(v')$ and mean anomaly $M = M(v')$ with the formulas

$$n = \sqrt{\frac{\mu}{a^3(v')}}, \quad M = M_0 + n(t - t_0).$$

Further, we find the relation between the independent variable v' and time t . In the case of a hyperbolic orbit ($e' > 1$) of the disturbing body, this relation is established by the equation [10]

$$t - t_0 = \frac{q' \sqrt{q'}}{\sqrt{\mu' (e' - 1)^3}} \left[e' \tan F - \ln \tan \left(\frac{F}{2} + \frac{\pi}{4} \right) \right], \quad \tan \frac{F}{2} = \sqrt{\frac{e' - 1}{e' + 1}} \tan \frac{v'}{2}, \quad (16)$$

where the mass parameter μ' is determined by Eq. (10).

3. SPECIAL CASES OF THE LAGRANGE EQUATIONS

In the case of small inclinations, it is convenient to use the Lagrange variables $\tilde{p}$ and $\tilde{q}$ instead of the elements i and Ω [12] :

$$\tilde{p} = \tan i \sin \Omega, \tilde{q} = \tan i \cos \Omega, i = \arctan \sqrt{\tilde{p}^2 + \tilde{q}^2}, \Omega = \arctan \frac{\tilde{p}}{\tilde{q}} \quad (17)$$

at small eccentricities, the Lagrange variables $\tilde{h}$ and $\tilde{k}$ should be introduced instead of the elements e and ω in the following formula [12]:

$$\tilde{h} = e \sin \omega, \quad \tilde{k} = e \cos \omega, \quad e = \sqrt{\tilde{h}^2 + \tilde{k}^2}, \quad \omega = \arctan \frac{\tilde{h}}{\tilde{k}}. \quad (18)$$

As a rule, the variables $\tilde{h}$ and $\tilde{k}$ are introduced instead of the elements e and $\tilde{\omega} = \omega + \Omega$. Since we are interested in the variations in the elements e and ω , we use Eq. (18).

Now the disturbing function $\tilde{R}$ from (14), which is involved in the system of equations (12) and (13), should be expressed through the Lagrange variables:

$$\tilde{R} \equiv \tilde{R}(v, \tilde{h}, \tilde{k}, \tilde{p}, \tilde{q}, u', i', \Omega') = A \left(\frac{r'^2}{\sqrt{r^2 + r'^2 - 2r'r' \cos \theta}} - r \cos \theta \right) \quad (19)$$

To do this, it is sufficient to replace the orbital elements e, ω, Ω , and i for $\cos \theta$ and r in expressions (5), (6), and (7) with the Lagrange variables due to Eqs. (17) and (18). Then, we can calculate the partial derivatives of the function $\tilde{R}$ with respect to the Lagrange variables. For brevity, such a substitution is not shown here. Thus, the Lagrange equations (12) and (13) in the new variables will have the form

$$\begin{aligned} \frac{da}{dv'} &= \frac{2a\delta^2}{\sqrt{p} \left(1 - \tilde{h}^2 - \tilde{k}^2 \right)} \frac{\partial \tilde{R}}{\partial v}, \\ \frac{d\tilde{h}}{dv'} &= \frac{\tilde{h}\delta^2}{(\tilde{h}^2 + \tilde{k}^2) \sqrt{p}} \frac{\partial \tilde{R}}{\partial v} + \frac{1 - \tilde{h}^2 - \tilde{k}^2}{\sqrt{p}} \frac{\partial \tilde{R}}{\partial \tilde{k}} - \frac{\tilde{k} (1 + \tilde{p}^2 + \tilde{q}^2)}{\sqrt{p} (\tilde{p}^2 + \tilde{q}^2)} \left(\tilde{p} \frac{\partial \tilde{R}}{\partial \tilde{p}} + \tilde{q} \frac{\partial \tilde{R}}{\partial \tilde{q}} \right), \\ \frac{d\tilde{k}}{dv'} &= \frac{\tilde{k}\delta^2}{(\tilde{h}^2 + \tilde{k}^2) \sqrt{p}} \frac{\partial \tilde{R}}{\partial v} - \frac{1 - \tilde{h}^2 - \tilde{k}^2}{\sqrt{p}} \frac{\partial \tilde{R}}{\partial \tilde{h}} - \frac{\tilde{h} (1 + \tilde{p}^2 + \tilde{q}^2)}{\sqrt{p} (\tilde{p}^2 + \tilde{q}^2)} \left(\tilde{p} \frac{\partial \tilde{R}}{\partial \tilde{p}} + \tilde{q} \frac{\partial \tilde{R}}{\partial \tilde{q}} \right), \end{aligned} \quad (20)$$

$$\begin{aligned} \frac{d\tilde{p}}{dv'} &= \frac{\tilde{p} (1 + \tilde{p}^2 + \tilde{q}^2)}{\sqrt{p} (\tilde{p}^2 + \tilde{q}^2)} \left(\tilde{k} \frac{\partial \tilde{R}}{\partial \tilde{h}} - \tilde{h} \frac{\partial \tilde{R}}{\partial \tilde{k}} \right) + \frac{\sqrt{(1 + \tilde{p}^2 + \tilde{q}^2)^3}}{\sqrt{p}} \frac{\partial \tilde{R}}{\partial \tilde{q}}, \\ \frac{d\tilde{q}}{dv'} &= \frac{\tilde{q} (1 + \tilde{p}^2 + \tilde{q}^2)}{\sqrt{p} (\tilde{p}^2 + \tilde{q}^2)} \left(\tilde{k} \frac{\partial \tilde{R}}{\partial \tilde{h}} - \tilde{h} \frac{\partial \tilde{R}}{\partial \tilde{k}} \right) - \frac{\sqrt{(1 + \tilde{p}^2 + \tilde{q}^2)^3}}{\sqrt{p}} \frac{\partial \tilde{R}}{\partial \tilde{p}}, \\ \frac{dv'}{p\sqrt{p}} \frac{r'^2}{\sqrt{\mu\mu'p'}} + \frac{1}{\sqrt{\tilde{h}^2 + \tilde{k}^2} p\sqrt{p}} &\left\{ -2a^2\delta^2 \sqrt{\tilde{h}^2 + \tilde{k}^2} \frac{\partial \tilde{R}}{\partial a} + a\delta^2 (1 + \delta) \sin v \frac{\partial \tilde{R}}{\partial v} - \right. \\ &\left. -p \left[\frac{\delta^2 \tilde{h}}{\sqrt{\tilde{h}^2 + \tilde{k}^2}} - \tilde{k} (1 + \delta) \sin v \right] \frac{\partial \tilde{R}}{\partial \tilde{h}} - p \left[\frac{\delta^2 \tilde{k}}{\sqrt{\tilde{h}^2 + \tilde{k}^2}} - \tilde{h} (1 + \delta) \sin v \right] \frac{\partial \tilde{R}}{\partial \tilde{k}} \right\}. \end{aligned} \quad (21)$$

Here,

$$\delta = 1 + \sqrt{\tilde{h}^2 + \tilde{k}^2} \cos v, \quad p = a \left(1 - \tilde{h}^2 - \tilde{k}^2 \right)$$

The system of equations (20) for osculating elements is applicable for determining the elements and studying the evolution of Jupiter's orbit, since its inclination and eccentricity are rather small.

4. CHANGE IN THE ORBITAL ELEMENTS OF JUPITER DURING A STELLAR ENCOUNTER WITH THE SOLAR SYSTEM

As an example, we will take a sample star approaching the Solar System with mass m' , heliocentric distance q' (in AU), and orbital eccentricity e' . These parameters vary within

$$M_{\odot} \leq m' \leq 5M_{\odot}, 50 \leq q' \leq 100, 1 < e' \leq 5, \quad (22)$$

where $M_{\odot}$ is the mass of the Sun. Additionally, the angular elements i' , Ω' , and ω' of the sample star are referred to the coordinate system $Oxyz$ with its origin at the center of the Sun; these elements vary within

$$0^\circ \leq i' \leq 90^\circ, 0^\circ \leq \Omega' \leq 180^\circ, 0^\circ \leq \omega' \leq 180^\circ \quad (23)$$

The initial values of Jupiter's orbital elements are taken from the Astronomical Yearbook of 1988 and are determined as

$$a_0 = 5.2026032 \text{ AU}, \quad e_0 = 0.04849485, \quad i_0 = 1^\circ 18' 11.77'',$$

$$\lambda_0 = 34^\circ 21' 05.34'', \quad \pi_0 = 14^\circ 19' 52.71'', \quad \Omega_0 = 100^\circ 27' 51.198''.$$

Jupiter's angular elements i_0, λ_0, π_0 , and Ω_0 are referred to the ecliptic and equinox of the epoch J2000.0, and the gravitational constant equals the Gauss constant: $G = k^2 = 0.000295936$. Additionally, the elements ω_0 and M_0 for Jupiter are determined by the equations $\omega_0 = \pi_0 - \Omega_0$ and $M_0 = \lambda_0 - \pi_0$.

Using the above-mentioned initial values for Jupiter's orbital elements, differential equation system (20) is numerically integrated in the Lagrange variables at the initial value of the independent variable $v'_0 = -3\pi/4$. The orbital elements of the sample star are taken as $e' = 1.15$, $i' = 5^\circ$, $\Omega' = 80^\circ$, and $\omega' = 40^\circ$. These elements play an important role in the construction of the diagrams and tables.

Figures 1 and 2 show the variations in the semimajor axis a (with the initial value $a_0 = 5.2026032 \text{ AU}$) of Jupiter's orbit as a function of the true anomaly v' of the star moving in a hyperbolic orbit ($e' > 1$) relative to the Sun at certain values of its mass m' (Fig.2) and focal parameter of its orbit p' (Fig.1). The focal

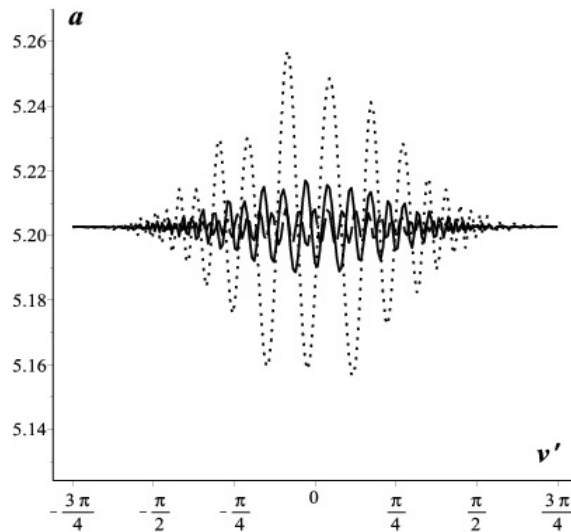


Fig. 1. Variations in the semimajor axis a of Jupiter's orbit depending on the true anomaly v' of the sample star moving in a hyperbolic orbit with $e' = 1.15$ and $m' = 5M_{\odot}$: dotted line corresponds to $p' = 107.5\text{AU}$ ($q' = 50\text{AU}$), solid line corresponds to $p' = 161.25\text{AU}$ ($q' = 75\text{AU}$), and dashed line corresponds to $p' = 215\text{AU}$ ($q' = 100\text{AU}$).

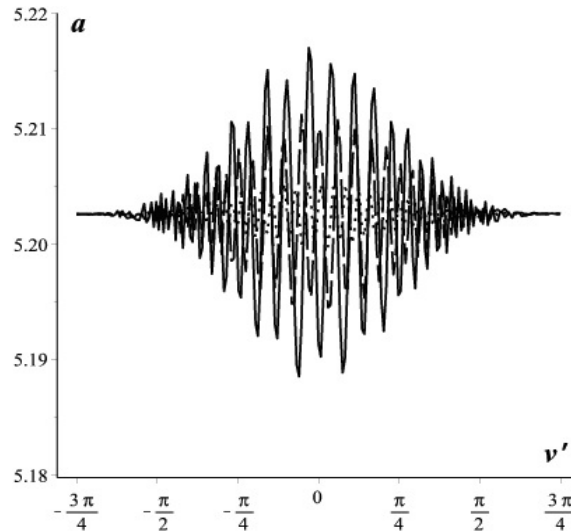


Fig. 2. Variations in the semimajor axis a of Jupiter's orbit at $p' = 161.25\text{ AU}$: dotted line corresponds to the mass $m' = M_{\odot}$ of the sample star. Dashed line corresponds to $m' = 3M_{\odot}$, and solid line corresponds to $m' = 5M_{\odot}$.

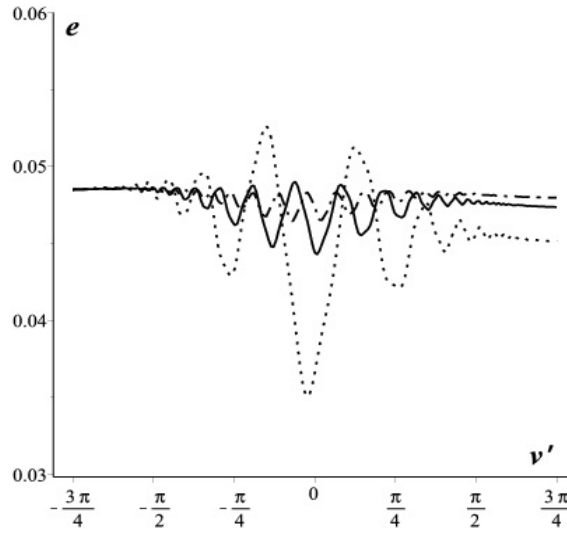


Fig. 3. Variations in the eccentricity e of Jupiter's orbit depending on the true anomaly v' of the sample star moving in a hyperbolic orbit with $e' = 1.15$ and $m' = 5M_{\odot}$: dotted line corresponds to $p' = 107.5\text{AU}$, solid line corresponds to $p' = 161.25\text{AU}$, and dashed line corresponds to $p' = 215\text{AU}$.

parameter p' and perihelion distance q' are related via the equation $p' = q'(1 + e')$ for the hyperbolic orbit of the star.

Figures 3 and 4 illustrate the variations in the eccentricity e (with an initial value $e_0 = 0.04849485$), while Figs.5 and 6 show the variations in the inclination i (with the initial value $i_0 = 1^{\circ}.30327$) of Jupiter's orbit with similar changes in the mass and perihelion distance of the star with the orbital eccentricity $e' = 1.15$, depending on the true anomaly v' , respectively. As can be seen from the figures, after the star recedes to a large distance from the Sun, Jupiter's orbital elements a , e , and i slightly change and differ from the initial values a_0 , e_0 , and i_0 . However, the maximum changes in the size and shape of Jupiter's orbit occur only in the case when the sample star is at perihelion, and Jupiter is in opposition.

Table 1 lists the changes in the orbital elements of Jupiter Δa , Δe , and Δi depending on the parameter p' for the hyperbolic ($e' = 1.15$) orbit of the star and on its mass m' . As can be seen from the table, the changes in the orbital elements of Jupiter (semimajor axis a and eccentricity e) are minor. The maximum changes in the elements a and e occur where a star with a mass $m' = 5M_{\odot}$ at a distance $q' = 50\text{AU}$ (or $p' = 107.5\text{AU}$) approaches the Solar System in a hyperbolic orbit.

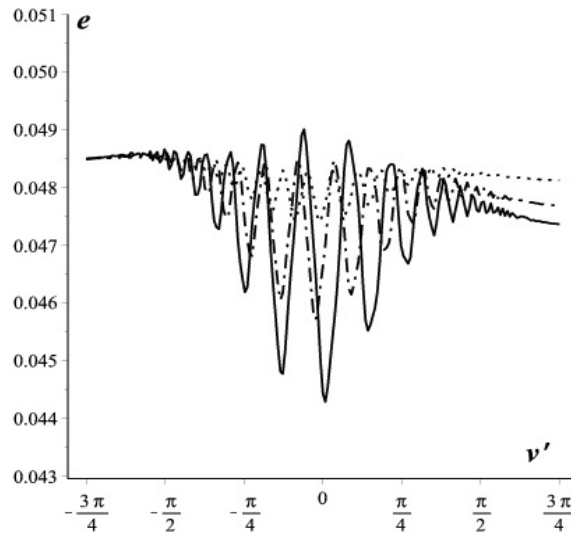


Fig. 4. Variations in the eccentricity e of Jupiter's orbit at $p' = 161.25\text{AU}$: dotted line corresponds to the mass $m' = M_{\odot}$ of the sample star, dashed line corresponds to $m' = 3M_{\odot}$, and solid line corresponds to

$$m' = 5M_{\odot}.$$

Table 1. Changes in the orbital elements of Jupiter $\Delta a, \Delta e$, and Δi depending on the focal parameter p' for the hyperbolic orbit ($e' = 1.15$) of the star and on its mass m'

$p'(\text{AU})$	m'	$\Delta a(\text{AU})$	Δe	$\Delta i(\text{deg})$
107.5	$M_{\odot}$	-0.009631	0.000214	0.07275
	$3M_{\odot}$	0.025592	-0.003532	0.169424
	$5M_{\odot}$	-0.030154	-0.012621	0.238626
161.25	$M_{\odot}$	0.002507	-0.001059	0.039625
	$3M_{\odot}$	0.007816	-0.002124	0.087279
	$5M_{\odot}$	-0.012734	-0.004218	0.121404
215	$M_{\odot}$	0.001077	-0.000491	0.025249
	$3M_{\odot}$	0.003302	-0.001224	0.055089
	$5M_{\odot}$	0.005928	-0.001482	0.076197

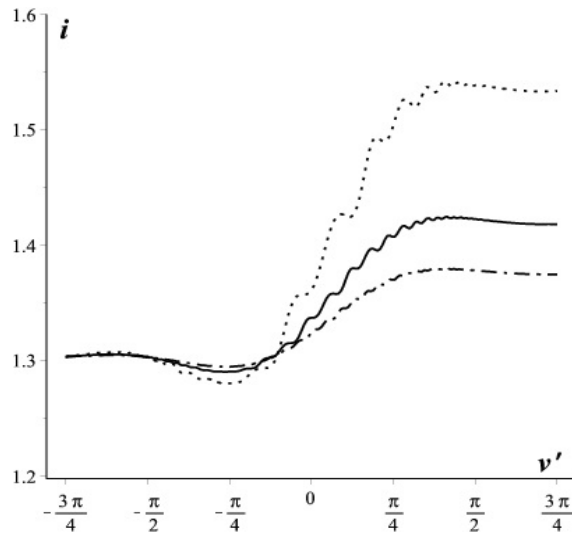


Fig. 5. Variations in the inclination i of Jupiter's orbit depending on true anomaly v' of the sample star moving in a hyperbolic orbit with $e' = 1.15$ and $m' = 5M_{\odot}$: dotted line corresponds to $p' = 107.5\text{AU}$, solid line corresponds to $p' = 161.25\text{AU}$, and dashed line corresponds to $p' = 215\text{AU}$.

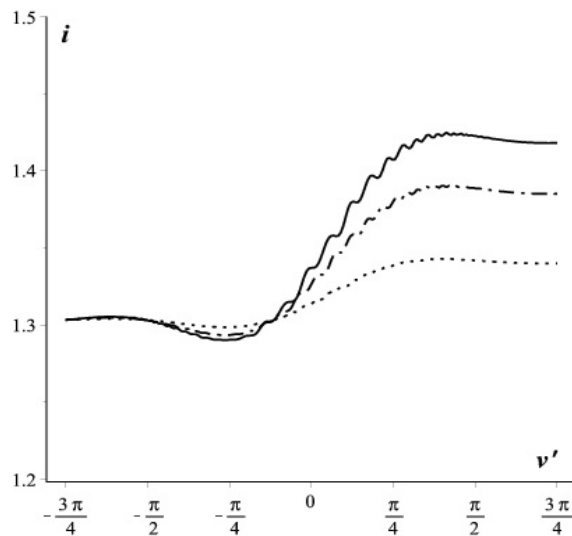


Fig. 6. Variations in the inclination i of Jupiter's orbit at $p' = 161.25\text{AU}$: dotted line corresponds to the mass $m' = M_{\odot}$ of the sample star, dashed line corresponds to $m' = 3M_{\odot}$, and solid line corresponds to $m' = 5M_{\odot}$.

5. CONCLUSIONS

The problem of the evolution of Jupiter's orbit during stellar encounters with the Solar System has been considered within the restricted hyperbolic three-body

problem. The influence of a disturbing body (a star) as it approaches the center body (the Sun) in a hyperbolic orbit on the orbit of a passively gravitating body (Jupiter) has been studied. The exact expression of the force function has been used without expansion in series. Variations in the orbital elements of Jupiter depending on the true anomaly of the star moving in a hyperbolic orbit relative to the central body have been determined. Also, the variations in the orbital elements of Jupiter depending on the perihelion distance of the star (or the focal parameter of its orbit) and on its mass have been found. The results are presented in figures and tables.

It has been shown that a star with a mass of one to five solar masses approaching the Solar System in a hyperbolic orbit at a minimum distance between 50 and 100 au from the Sun significantly influences the shape and dimensions of Jupiter's orbit only in the case when the sample star is at the perihelion, and Jupiter is in opposition.

This work allows us to predict the change in the elements of the orbit, or its evolution with a possible approach to the solar system of a star. The results of this work can be used to describe the evolution of planets in a planetary system when a star approaches this system. Another application is to study the evolution of stellar orbits in one galaxy as a result of the passage of another galaxy at a hyperbolic velocity relative to the other.

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