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Behavior of metal-containing species during entries of meteoroids into atmospheres of Mars, Jupiter, and Titan

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Chemical composition of impact-produced clouds during meteor events on Mars, Jupiter, and Titan is studied. The intensities of brightest atomic lines of meteoroid origin of Martian and Titan's bolides are comparable to that of Earth's bolides because in all these atmospheres abundances of metal monoxides, atoms and ions are comparable while the electronic density is determined by the matter of meteoroid origin. The most intensive lines in visible spectra of Martian and Titan's meteors are lines of atoms and ions of Na, Fe, Mg, and Ca. In spectra of Jupiter's superbolides the intensity of lines of atoms is higher than that of ions.

ПОВЕДЕНИЕ МЕТАЛЛО-СОДЕРЖАЩИХ МОЛЕКУЛ ПРИ ВХОЖДЕНИИ МЕТЕОРОВ В АТМОСФЕРЫ МАРСА, ЮПИТЕРА И ТИТАНА, Бережной А.А. — Исследован химический состав ударно-образованного пара во время метеорных явлений в атмосферах Марса, Юпитера и Титана. Интенсивность наиболее ярких линий атомов метеороидного происхождения для болидов на Марсе и Титане сравнима с интенсивностью этих линий в спектрах земных болидов, так как в атмосферах этих тел содержания оксидов металлов, атомов металлов и ионов металлов сравнимы, в то время как концентрация электронов определяется веществом метеороидного происхождения. Наиболее яркими линиями в спектрах метеоров Марса и Титана являются линии атомов и ионов Na, Fe, Mg и Ca. В спектрах суперболидов Юпитера интенсивность линий атомов выше, чем линий ионов.

ПОВЕДІНКА МЕТАЛОВМІСНИХ МОЛЕКУЛ ПРИ ВХОДЖЕННІ МЕТЕОРІВ В АТМОСФЕРИ МАРСА, ЮПІТЕРА ТА ТИТАНА, Бережной А.А. — Досліджується хімічний склад парів під час метеорних явищ в атмосферах Марса, Юпітера та Титана. Інтенсивність найяскравих ліній атомів метеороїдного походження для болідів Марса та Титана майже така ж сама, як для болідів Землі, бо в атмосферах усіх цих тіл концентрація окисів металів, атомів металів та їхніх іонів майже така ж сама, а концентрація електронів залежить головним чином тільки від речовини метеороїдного походження. Найяскравішими лініями в спектрах метеорів Марса та Титана є лінії атомів та іонів Na, Fe, Mg та Ca. У спектрах суперболідів Юпітера інтенсивність ліній атомів більша, ніж ліній іонів.

Ключевые слова: метеорные явления в атмосферах Марса, Юпитера, Титана; интенсивность спектральных линий метеороидного происхождения.

Key words: meteor events in atmospheres of Mars, Jupiter, and Titan; intensity of spectral lines of meteoroid origin.

1. INTRODUCTION

Meteoroid impacts are important sources of exospheres of the Moon and Mercury. Entries of meteoroids into planetary atmospheres lead to creation of ionospheric layers in the upper atmospheres. The Mars Express Orbiter radio science experiment on the European Mars Express spacecraft observed a new ionospheric layer at altitudes between 65 and 110 km [1]. Its origin has been attributed to ablation of meteors and change exchange between meteoritic Mg and Fe atoms [2]. Meteoroid's impacts could also affect the ionospheric structure of Titan, the largest Saturnian moon, and produce an ionospheric layer at around 700 km [3]. Meteoric Mg ions are expected to produce the radical MgNC. The highly polar MgNC radical should provide an excellent nucleation site for condensation of polar and highly unsaturated neutral species at comparatively high altitude, leading to precipitation of Mg-doped tholin-like material [4]. Ablation of meteoroids is also an important source of O-bearing species in Titan's atmosphere [5].

Meteor event in Martian atmosphere was already detected during observations from the surface of the red planet by the rover Spirit [6]. Impact of 10 m body on Jupiter was detected by video observations of this planet by 28 cm and 37 cm telescopes on June 3, 2010 [7]. However, spectral observations of Martian and Jupiter's meteors were not performed yet. Meteor events on Titan were not detected yet, but these events can be detected by Titan's landers. For preparation of such observations and further study of chemical reactions in the upper atmospheres of these bodies we need to study the chemical processes occurring during meteor events in the atmospheres of Mars, Jupiter, and Titan.

2. CALCULATIONS

Study of the chemical reactions during meteor events on Mars was performed based on the approach of quenching theory [8] already developed for the case of Earth's bolides. The elemental composition of the impact-produced cloud was taken to be that of mixture of CI chondrites and the atmospheric gases. In particular, the composition of Martian atmosphere is accepted to be that 0.03 wt% H_2O, 0.07 wt% CO, 0.13 wt% O_2, 1.6 wt% Ar, 2.7 wt% N_2, 95.32 wt% CO_2. The composition of Titan's atmosphere is accepted as a mixture of 95% N_2, 3% CH_4, and 2% Ar by volume [9]. The composition of Jupiter's upper atmosphere is accepted as a mixture of 86.4% H_2, 13.4% He, 0.18% CH_4, and $3 \cdot 10^{-5}$% NH_3 by volume [10]. The elemental composition of CI chondrites was taken from [11]. It was assumed that in impact-produced clouds the volume of gases of meteoroid origin is 30 times smaller than the volume of atmospheric gases based on values of meteoritic-to-atmosphere pressure ratio in Earth's bolides [12]. Thermodynamic calculations based on the quenching theory were conducted in order to estimate the equilibrium chemical composition of the cloud. The cloud temperature is studied in the range between 1500 and 7000 K with step of 500 K. Two values of pressures ($4 \cdot 10^{-5}$ and $6 \cdot 10^{-3}$ bars) were considered for both atmospheres. Pressure equal to $6 \cdot 10^{-3}$ bar corresponds to explosions of relatively big and slow meteoroids near the surface of Mars while the explosion pressure of $4 \cdot 10^{-5}$ bar corresponding to majority of bolides exploded at the altitude of 80 km in the Earth's atmosphere. For Jupiter's atmosphere higher values of pressure (10^{-3} and 0.1 bar) were considered because Earth-based observations are able to detect just massive bodies with radiuses more than 5–10 m which can penetrate deeper into the atmosphere in comparison with Titan's and Martian meteors.

3. RESULTS

Thermodynamic calculations were performed with CHET program using standard methods of Gibbs free energy minimization techniques. This code allows calculating equilibrium composition for up to 102 species made from up to 15 elements. Thermodynamic properties of the considered species were taken mainly from the database [13].

Based on the quenching approach chemical reaction end and chemical composition became unchanged when the chemical and hydrodynamic time scales are comparable. It was assumed that the quenching temperature is equal to 1500–2000 K for the train phase at $6 \cdot 10^{-3}$ bar as for the case of Earth's bolides [8]. If equilibrium condensation takes place, for Martian meteors the main Na-, Fe-, Ca-, Mg-, Al-, Si-bearing species at the quenching moment are Na, NaOH, FeO, Ca, Mg, AlO, and SiO, respectively. For Titan's meteors the main Na-, Fe-, Ca-, Mg-, Al-, Si-bearing species at the quenching moment are Na, Fe, Ca, Mg, Al, Si, and SiO, respectively (see Fig. 1 and 2). For Jupiter's superbolides at 0.1 bar the main metal-containing

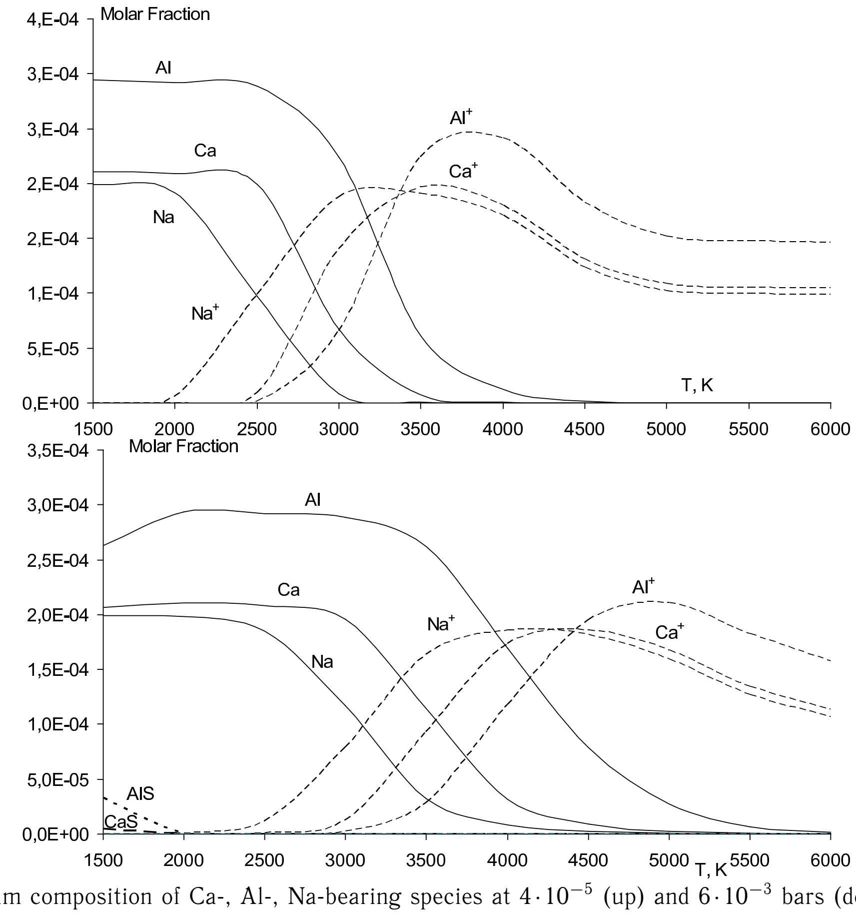

Fig. 1. Equilibrium composition of Ca-, Al-, Na-bearing species at $4 \cdot 10^{-5}$ (up) and $6 \cdot 10^{-3}$ bars (down) in impact-produced clouds in the atmosphere of Titan as a function of temperature.

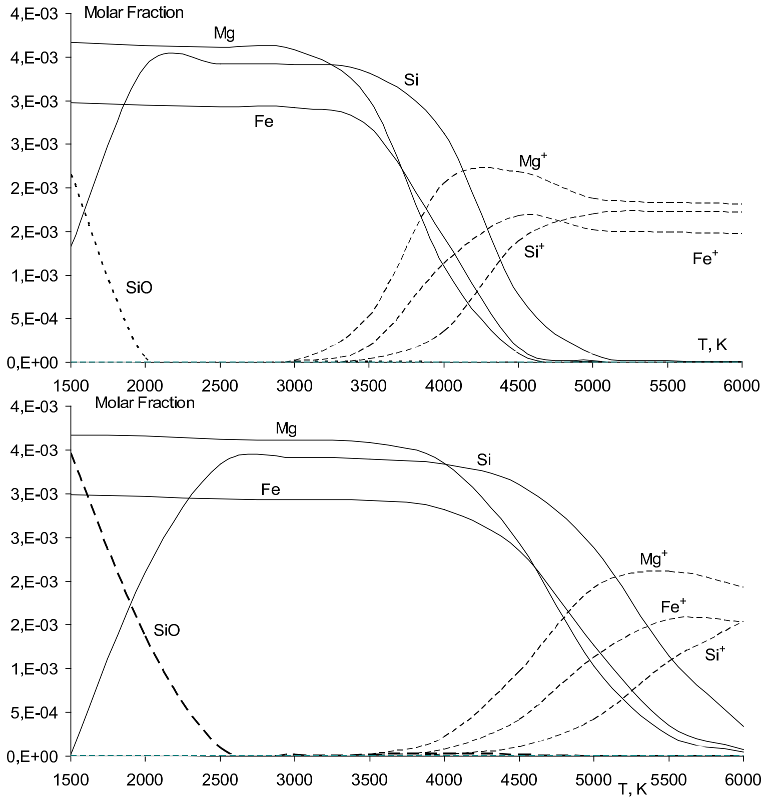

Fig. 2. Equilibrium composition of Mg-, Si-, Fe-bearing species at $4 \cdot 10^{-5}$ (up) and $6 \cdot 10^{-3}$ bars (down) in impact-produced clouds in the atmosphere of Titan as a function of temperature.

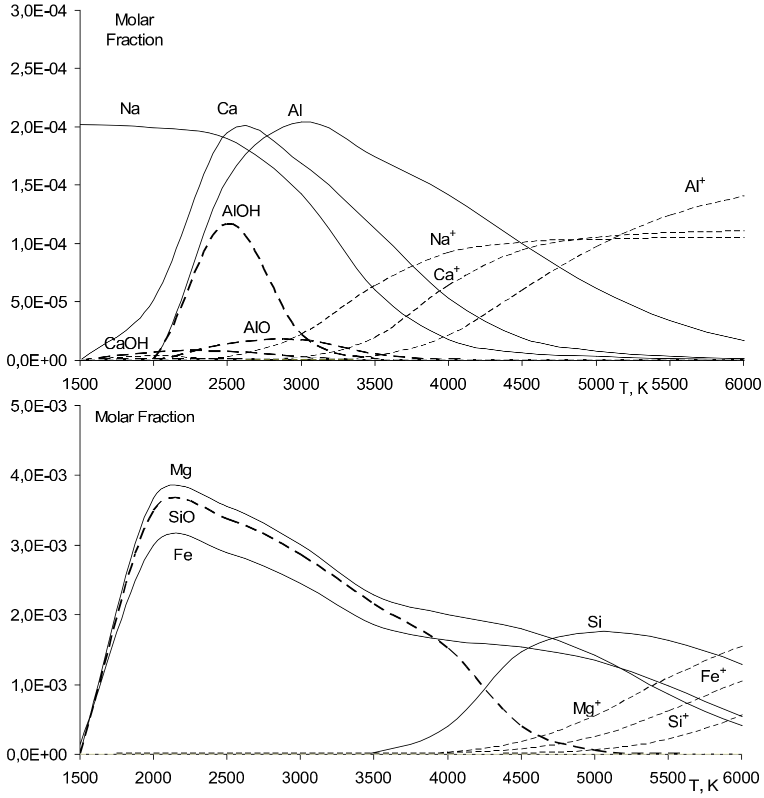

Fig. 3. Equilibrium composition of Ca-, Al-, Na-bearing species (up) and Mg-, Si-, Fe- bearing species (down) in impact-produced clouds in the atmosphere of Jupiter at 0.1 bar as a function of temperature

species during train phase are Na, Fe, Ca, CaOH, Mg, Al, AlOH, and SiO (see Fig. 3).

For Earth's bolides at $4 \cdot 10^{-5}$ bar the quenching temperature is about 2000–2500 K at the train phase while during the bolide phase the chemical equilibrium between metal atoms and metal monoxides is not reached due to too short hydrodynamic time scale [8]. However, chemical equilibrium between atoms and ions is usually reached during bolide phase because ion-neutral reactions are very fast. If equilibrium condensation takes place, for Martian meteors the main Na-, Fe-, Ca-, Mg-, Al-, Si- bearing species at the quenching are Na, Fe, Ca, Mg, Al, AlO, and SiO, respectively. For Titan's meteors the main Na-, Fe-, Ca-, Mg-, Al-, Si- bearing species at the quenching moment are Na, Na^+, Fe, Ca, Mg, Al, and Si, respectively (see Fig. 1 and 2).

4. DISCUSSION

During the train phase chemical reactions occur until temperature falls down below 1500–2500 K. At such low temperature and $6 \cdot 10^{-3}$ bar for Martian meteors the abundances of molecules (mainly, in form of monoxides) are relatively high for Na, Fe, Al, and Si. Decreasing of pressure leads to decrease of abundances of molecules and shift of maximal abundances of molecules to lower temperatures. In Titan's atmosphere the abundance of oxygen is very low, for this reason the content of oxides is lower than that in Martian atmosphere, only SiO molecule is abundant.

Let us note that spectra of Earth's meteoroids during bolide phase can be obtained easier than during train phase. For this reason we expect that first spectra of Martian, Jupiter's and Titan's meteors will be obtained during bolide phase. The brightest lines in visible spectra of Earth's bolides are lines of atoms and ions of Na, Fe, Mg, and Ca [14]. Let us consider the behavior of these elements during entries of meteoroids into Martian, Jupiter's, and Titan's atmospheres. At typical temperatures of Earth's bolides, 4000–5000 K, for Martian meteoroids the main Na-, Al-, Si-, Fe-, Mg-, Ca- bearing species are Na^+, Al, Si, Fe, Mg, and Ca^+ at $6 \cdot 10^{-3}$ bar, and Na^+, Al^+, Si, Fe^+, Mg^+, and Ca^+ at $4 \cdot 10^{-5}$ bar, respectively. The same behavior of ions is expected for Titan's atmosphere. For Jupiter's superbolides at 0.1 bar the main metal-bearing species are Na^+, Al, Si, SiO, Fe, Mg, and Ca^+, for bolides at 10^{-3} bar — Na^+, Al^+, Si, Fe, Fe^+, Mg, Mg^+, and Ca^+. Equilibrium abundances of atoms and ions during bolide phase are almost the same with accuracy of about 10% for Earth's, Titan's, and Martian meteors because in these atmospheres the electron density is determined by the matter of meteoroid origin. It means that abundances of ions of atmospheric origin (O^+, N^+, N_2^+, C^+ and so on) are much smaller than abundances of ions of meteoritic origin (Na^+, Fe^+, Si^+ and so on). Thus, relative intensities of lines in visible spectra of Titan's, Martian and Earth's meteors are comparable if the elemental composition of these meteoroids and cloud temperature and pressure are assumed to be the same. For the case of Jupiter's superbolides due to higher pressure in the impact-produced cloud the intensity of lines of ions Mg^+, Fe^+, Si^+, Ca^+, and Al^+ is smaller than that for the case of Earth's bolides.

However, at $4 \cdot 10^{-5}$ bar ions of atmospheric origin are the main sources of electrons at temperatures higher than 5200 K for Martian, 6000 K for Earth's, and 6500 K for Titan's meteors, and 7500 K for the case of Jupiter's superbolides at 0.1 bar. It means that ions of atmospheric origin must be taken into account for study of the composition and emission of the hot meteor component usually having temperature of about 10000 K.

5. CONCLUSIONS

Chemical composition of impact-produced clouds during meteor events on Mars, Jupiter, and Titan is studied. The intensities of brightest atomic lines of meteoroid origin of Martian and Titan's bolides are comparable to that of Earth's bolides because in all these atmospheres abundances of metal monoxides, atoms and ions are comparable while the electronic density is determined by the matter of meteoroid origin. Similar chemical processes are expected to occur during meteor events in CO_2-dominated upper atmosphere of Venus as for the case of Martian meteors.

The most intensive lines in visible spectra of Martian and Titan's meteors are lines of atoms and ions of Na, Fe, Mg, and Ca. In spectra of Jupiter's superbolides the intensity of lines of atoms is higher than that of ions. Similar chemical processes as for the case of Jupiter's meteors are expected to occur during meteor events in H_2-dominated upper atmospheres of Saturn, Uranus, and Neptune.

Spectral observations of Martian, Titan's, and Jupiter's meteors will be useful for estimation of the elemental composition of meteoroids at the orbits of Mars, Jupiter, and Saturn.

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1. *Pätzold M., Tellmann S., Häusler B., et al.* A sporadic third layer in the ionosphere of Mars // Science. — 2005. — **310**. — P. 837–839.
2. *Whalley C.L., Plane J.M.C.* Meteoric ion layers in the Martian atmosphere // Faraday Discussion. — 2010. — **147**. — P. 349–368.
3. *Molina-Cuberos J.G., López-Moreno J.J., Arnold F.* Meteoric Layers in Planetary Atmospheres // Space Science Reviews. — 2008. — **137**, Is. 1–4. — P. 175–191.
4. *Petrie S.* Products of meteoric metal ion chemistry within planetary atmospheres. 1. Mg^+ at Titan // Icarus. — 2004. — **171**, Is. 1. — P. 199–209.
5. *Ip W-H.* Meteoroid ablation processes in Titan's atmosphere // Nature. — 1990. — **345**. — P. 511–512.
6. *Selsis F., Lemon M.T., Vaubaillon J., Bell J.F.* Extraterrestrial meteors: a Martian meteor and its parent comet // Nature. — 2005. — **435**. — P. 581–581.
7. *Hueso R., Wesley A., Go C., et al.* First Earth-based detection of a superbolide on Jupiter // Astrophys. J. Lett. — 2010. — **721**, Is. 2. — P. L129–L133.
8. *Berezhnoy A.A., Borovička J.* Formation of molecules in bright meteors // Icarus. — 2010. — **210**, P. 150–157.
9. *Yelle R.V.* Non-LTE models of Titan's upper atmosphere // Astrophys. J. — 1991. — **383**. — P. 380–400.
10. *Irwin P.G.J.* Cloud structure and composition of Jupiter's atmosphere // Surveys in Geophysics. — 1993. — **20**, Is. 6, P. 505–535.
11. *Lodders K.* Solar system abundances and condensation temperatures of the elements // Astrophysical Journal. — 2003. — **591**. — P. 1220–1247.
12. *Borovička J.* A fireball spectrum analysis // Astron. Astrophys. — 1993. — **279**. — P. 627–645.
13. *Gurvich L.V., Alcock C.B., Veyts I.V., et al.* Thermodynamic properties of individual substances, 4th edition in 5 volumes, Hemisphere Pub. Co., New York, 1989.
14. *Borovička J., Koten P., Spurný P., et al.* A survey of meteor spectra and orbits: evidence for three populations of Na-free meteoroids // Icarus. — 2005. — **174**. — P. 15–30.

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