Introduction: Micrometeorite bombardment is one of the main sources of the lunar exosphere. A plausible hypothesis asserts a proportionality between atomic metal abundances in the lunar exosphere and elemental abundances in the regolith. Earth-based spectroscopic observations of the lunar atmosphere, however, do not indicate the presence of Al, Mg, Ca, or Ti, which are major constituents of the regolith [1]. A possible explanation is that metal species other than Na and K may be present in the lunar exosphere as oxides. We investigate this possibility by modeling theoretically the chemical composition of fireballs formed during micrometeorite impacts.

Computational model: Meteorites typically strike the Moon with velocities between 10 and 40 km/s. These hypervelocity impacts cause vaporization of meteoritic matter and the regolith, along with physical redistribution of multiphase meteoritic matter and lunar soil. After the meteorite impact, the Moon captures a part of the ejected material.

The thermochemical calculations begin at a moment soon after impact with initial fireball temperatures and pressures set equal to \( T_0 = 10000 - 15000 \) K and \( P_0 = 1000 - 30000 \) bars, respectively [3, 4]. The fireball is assumed to cool adiabatically. The value of \( \gamma (C_p/C_v) \) decreases as the fireball chemical composition changes. The elemental composition of the fireball was taken to be that of a mixture of equal masses of CI chondrites and the lunar regolith. Thermodynamic calculations based on quenching theory [5] were conducted in order to estimate the chemical composition of the fireball as it cooled to the point where chemical reactions effectively stopped. Specifically, it was assumed that chemical reactions end when two quantities, the chemical and hydrodynamic time scales became comparable. For a typical meteorite size of about \( 10^{-4} - 10^{-5} \) m [6], the hydrodynamic time scale is \( 10^{-9} - 10^{-8} \) s at the fireball expansion speed of about 10 km/s adopted from numerical calculations [3].

Parameters of quenching of chemical reactions: To estimate the chemical time scale we use equilibrium chemical composition and rate constants taken from the NIST database [7] extrapolated to higher temperatures. Comparisons of reaction rates reveal that the main processes determining SH, S, H₂O, OH, SO, SO₂ contents are the reactions \( O + SH = SO + H \), \( S + H_2 = SH + H \), \( H + H_2O = H_2 + OH \), \( H_2 + OH = H_2O + H \), \( H + SO = S + OH \), \( SO_2 + M = SO + O + M \), respectively. Quenching of reactions with participation of H₂, O₂, and S-containing species occurs at \( T_{\text{quench}} \sim 3000 - 4000 \) K and \( P_{\text{quench}} \sim 30 - 100 \) bars (see Fig. 1).

Results of thermodynamic calculations: At quenching of the chemical composition the major components of a fireball are H₂O, CO₂, and CO (see Fig. 2). Water is the main component of the fireball for a wide range of \( T_{\text{quench}} \) and \( P_{\text{quench}} \). Thus, micrometeorite impact may be considered as a significant source of water molecules on the Moon.

Zn and Cu are present as atoms in the gas phase at reasonable temperatures and pressures. Na, Fe, K, Ca, Al, Mg are in the gas phase mainly as atoms at temperatures higher than 3500, 3500, 4500, 6500, 7000, and 8000 K, respectively. At lower temperatures NaOH, FeO, KOH, CaO, AlO, and MgO are abundant. Even at 6500 K Ti is presented not as the atoms but as molecules of TiO(g), at lower temperatures TiO₂ is the main Ti-containing compound. At low temperatures Ca is present in the form of Ca, CaOH, and Ca(OH)₂ in the gas phase (see Fig. 3). This result is consistent with the presence of very hot Ca atoms in the exosphere of Mercury which was explained by [8] through CaO photoionisation released to the exosphere by meteoritic impacts.
Figure 2. Equilibrium chemical composition of the fireball consisted of equal masses of CI chondrites and lunar regolith. Fireball is adiabatically cooling starting at $T_0=10000$ K and $P_0=1000$ bars.

PHOTODISSOCIATION OF NaOH, NaO AND KOH, KO MAY BE RESPONSIBLE FOR PRESENCE OF VERY HOT Na AND K ATOMS IN THE LUNAR ATMOSPHERE. FROM A COMPARISON OF BALLISTIC FLIGHT TIME ($\sim 10^3$ s) AND TYPICAL PHOTOLYSIS LIFETIME ($10^7$-$10^8$ s) IT IS CLEAR THAT ONLY SMALL FRACTION OF ATOMS OF METALS OF METEORITIC ORIGIN CAN BE DELIVERED TO THE LUNAR ATMOSPHERE THROUGH PHOTOLYSIS OF HYDOXIDES AND OXIDES OF THESE METALS.

AT QUENCHING, THE FRACTION OF Na (SEE FIG. 4) AND K PRESENT AS ATOMS IN THE FIREBALL IS ESTIMATED AS 0.5 AND 0.3, RESPECTIVELY. THIS VALUE IS EVEN LOWER FOR Fe, Mg, Ca, AND Al BECAUSE THESE ELEMENTS MAY CONDENSE TO FORM SOLIDS (IN EQUILIBRIUM FeO, MgO, CaO, AND Al$_2$O$_3$, RESPECTIVELY). THUS, CHEMICAL REACTIONS IN THE FIREBALL SIGNIFICANTLY REDUCE FRACTION OF METALLIC ATOMS DELIVERED TO LUNAR EXOSPHERE DURING MICROMETEORITE IMPACTS.


CONCLUSIONS: Based on quenching theory the chemical composition of gas-phase species released to the lunar atmosphere during micrometeorite impacts has been estimated. Quenching occurs after about $10^8$ s by which time Ca, Mg, Al, Fe, and Ti have formed oxides. The concentrations of the metal atoms are therefore much lower than calculated from the bulk composition of regolith material. NaOH and KOH are produced during collisions between meteorites and the Moon also. Laboratory impact experiments would be useful for more accurate determination of quenching parameters of chemical composition of fireballs produced by micrometeorite impacts with the Moon.