METEORITE BOMBARDMENT AS A SOURCE OF LUNAR ATMOSPHERE

A. A. Berezhnoy[1, 2]
[1]Rutgers University, Piscataway, New Jersey, USA
[2]Sternberg Astronomical Institute, Moscow State University, Moscow, Russia

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 γ (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^{-8} - 10^{-9} 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, H_2O, OH, SO, SO_2 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 H-, O-,

and S-containing species occurs at $T_{quench} \sim$ 3000-4000 K and $P_{quench} \sim$ 30-100 bars (see Fig. 1).
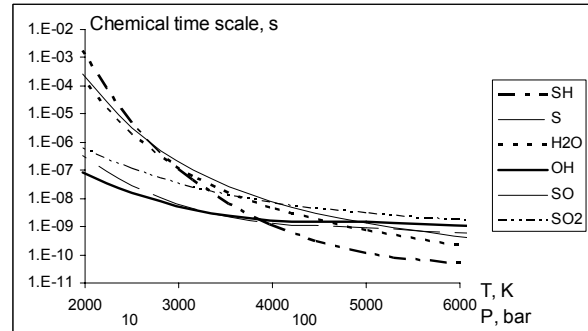

Figure 1. Time scale of several chemical reactions involving H-, O-, S- containing species in the fireball starting its adiabatical cooling at T_0=10000 K and P_0=1000 bars.

The main reactions in which Na-, K-, Ca- containing species participate are NaOH+M=Na+OH, Na + OH +M, KOH+M = KO+M, K+O_2+M=KO_2+M, $Ca(OH)_2$ = CaOH+OH, CaO+H_2O=$Ca(OH)_2$, CaOH + OH = $Ca(OH)_2$. The time scales of these reactions are comparable with hydrodynamic time scale (10^{-9}-10^{-8} s) at $T_{quench} \sim$ 3000-4000 K and $P_{quench} \sim$ 30-100 bars if T_0=10000 K and P_0=1000 bars. Reactions in which Mg-, Al-, Fe-containing species participate have similar quenching temperatures and pressures.

Results of thermodynamic calculations: At quenching of the chemical composition the major components of a fireball are H_2O, CO_2, and CO (see Fig. 2). Water is the main component of the fireball for a wide range of T_{quench} and P_{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 TiO_2 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.
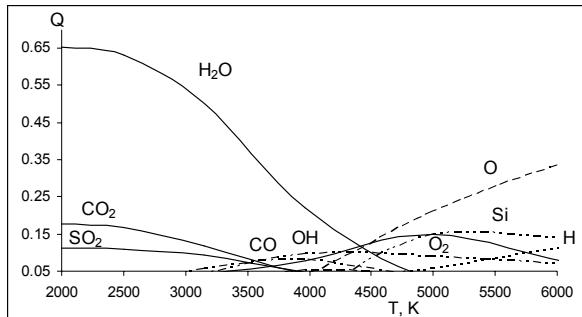
Figure 2. Equilibrium chemical composition of the fireball consisted of equal masses of CI chondrites and lunar regolith. Fireball is adiabatically cooling starting at T_0=10000 K and P_0=1000 bars.
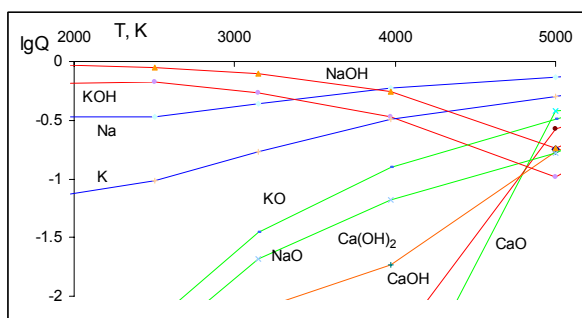

Figure 3. Equilibrium fraction of gas-phase Na, K, Ca-containing species in the fireball versus temperature. Fireball is adiabatically cooling starting at T_0=10000 K and P_0=1000 bars.
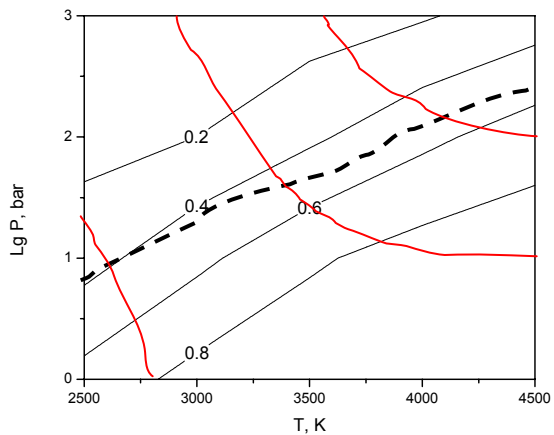

Figure 4. Equilibrium Na fraction among Na-containing species and chemical reactions time scale versus T and P. Contours labeled 0.2, 0.4, 0.6, 0.8 correspond to Na fraction equal to these values. Red lines show T and P contours for which the time scale of reaction $NaOH+H=Na+H_2O$ is equal to 10^{-7} s (left line), 10^{-8} s (central line), 10^{-9} s (right line), respectively. The dashed line shows changing temperature

and pressure of the fireball during its 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 (10^4-10^6 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 hydroxides 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_2O_3, respectively). Thus, chemical reactions in the fireball significantly reduce fraction of metallic atoms delivered to lunar exosphere during micrometeorite impacts.

Sulfur is in the gas phase when the chemical composition quenches because the formation of solid FeS is kinetically prohibited [5]. The main S-containing species at the quenching are SO and SO_2.

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.

References: [1] Flynn et al. (1996) *Icarus, 124,* 530-536. [2] Housley R. M. (1979) *Proc. of 10th Lunar and Planetary Science Conference, 2,* New York, Pergamon Press, 1673-1683. [3] Artem'eva et al. (2001) *Solar System Research, 35,* 177-180. [4] Klumov et al. (2005) *Physics-Uspekhi, 48,* 733-742. [5] Berezhnoy et al. (2003) *PASJ, 55,* 859-870. [6] Bruno M. et al. (2006) *MNRAS, 367,* 1067-1071. [7] http://kinetics.nist.gov/kinetics/ [8] Killen R.M. et al. (2005) *Icarus, 173,* 300-311.