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Chemistry of impact events on the Moon

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ABSTRACT

Based on the equilibrium thermochemical approach and quenching theory, the formation of Na-, K-, Li-, Si-, Ca-, Al-, Mg-, and Fe-bearing molecules and dust particles in impact-produced clouds formed after collisions between meteoroids and the Moon is considered. Photolysis lifetimes and energies of photolysis products of oxides and hydroxides of the main elements are estimated. The estimated fraction of uncondensed species, and list of the main molecules and their properties regarding photolysis during impact processes may be useful for the analysis of future observations of atoms of alkali and refractory elements in the exospheres of the Moon and Mercury.

1. Introduction

The species found in the lunar exosphere come mainly from the interactions of solar photons and the solar wind with the lunar regolith. Properties of the extended Na atmosphere are explained by a 15% contribution of micrometeoroid impact vaporization occurring uniformly over the surface and an 85% contribution of photon-induced desorption dependent on solar-zenith angle over the sunlit hemisphere (Mendillo et al., 1999). Photon-simulated desorption is found to be the main source of equatorial Na atoms and is continuously decreasing as we move away from the sub-solar point, so that impact vaporization over the terminator and poles may account for up to 50% (Sarantos et al., 2010). In addition to this, the contribution of micrometeoroid bombardment is expected to be even more important during major meteor showers and on the night side of the Moon where solar particles effects are shielded by the Moon itself. A bright Na spot in the lunar orbit was detected after maximum of Leonid 1998 meteor shower, but was absent at other times (Smith et al., 1999). Thus, meteoroid impacts lead to the production of sodium atoms which are able to escape the lunar exosphere. These observations agree with the estimate of the typical velocity of Na atoms in the outer lunar exosphere during lunar eclipses, being close to the escape velocity for the Moon, 2.38 km/s (Wilson et al., 2003).

If all elements are delivered to the exosphere by the same effective mechanism, then we expect proportionality between column abundances of atoms 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 Si, Al, Mg, Ca, and Fe, which are major constituents of the regolith (Flynn and Stern, 1996; Stern et al., 1997). Let us note that Flynn and Stern (1996) observed the lunar exosphere looking for metal atoms delivered to the exosphere due to photon-induced desorption because these observations were performed during activity of sporadic meteoroids and at the sub-solar point on the lunar surface. Theoretical study of sputtering as a source of the lunar exosphere shows that the abundances of all considered elements, with the exception of Ca, are well below the obtained upper limits (Wurz et al., 2007). Recently, Sarantos et al. (2012) showed that meteoroid bombardment is the main source of Ca, Si, Ti, Fe, Al, Mn, and Mg atoms at the polar regions of the lunar exosphere while meteoroid bombardment and photon-simulated desorption are responsible for formation of about 10% and 90% of Na atoms, respectively, in the same region. During meteoroid bombardment, the low condensation temperatures of Na- and K-containing species favor the retention of these elements in the gas phase (Berezhnoy and Klumov, 2008).

The majority of theoretical studies of impact-produced atoms on the Moon (see, for example, Bruno et al., 2007) assume that impacts lead to delivery of alkali elements to the exosphere only in the form of atoms. However, chemical reactions in the impact-produced cloud can produce metal-containing molecules in Earth's atmosphere (Self and Plane, 2002), the martian atmosphere (Pesnell and Grebowsky, 2000), the Hermean and lunar exospheres (Berezhnoy, 2010; Killen et al., 2005). In this paper we develop our model (Berezhnoy and Klumov, 2008; Berezhnoy, 2010) considering the behavior of Li during impact events, different initial pressures in the impact-produced cloud, and photolysis of metal dioxides and hydroxides.

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2. Properties of impact-produced atoms in the lunar exosphere

In accordance with Eq. (2) of (Berezhnoy, 2010), the surface zenith column density $N_{zen0}(X)$ of impact-produced atoms of considered element X can be calculated as

$$N_{zen0}(X) = F_{ret}\{X\}\tau_{loss}(X)f_{atom}(X)F_{unc}(X)F_{imp}(Y+1)/m(X), \quad (1)$$

where F_{ret} is the retention factor defined as the mass fraction of the impact-produced cloud captured by the Moon, $\{X\}$ is the mass fraction of element X in the cloud; $\tau_{loss}(X)$ is the lifetime of atoms of X in the exosphere; $F_{unc}(X)$ is the fraction of uncondensed species of element X in the gas phase; F_{imp} is the mass flux of incoming meteoroids in units of g cm^{-2} s^{-1}; Y is the target-to-impactor mass ratio in the impact-produced vapor cloud; and $m(X)$ is the mass of atoms X in grams. The term $f_{atom}(X)$ is the ratio of the abundance of atoms of the element X produced directly during impact and by photolysis to the total abundance of X-containing species in the gas phase of the cloud. Namely,

$$f_{atom}(X) = \frac{\sum_i P'_{phot}(X_i)P(X_i)}{\sum_i P(X_i)}, \quad (2)$$

where $P'_{phot}(X_i)$ is the probability of photolysis with formation of atoms of the element X and $P(X_i)$ is the partial pressure in the impact-produced cloud of the compound X_i. For the case of atoms $P'_{phot}(X) = 1 - P_{ion}(X)$, where $P_{ion}(X)$ is the probability of photoionization of atoms X.

Increasing the impact velocity from 20 to 60 km/s leads to a decrease of the retention factor F_{ret} value from about 0.9–0.6 (Berezhnoy, 2010), detailed explanation of used approach is given in Berezhnoy and Klumov (2008). To calculate the content of impact-produced atoms in the lunar exosphere we also need to know the elemental composition of the impact-produced cloud. The average elemental composition of the lunar highlands corresponds to a mixture of ferroan anorthosites and norites with mass ratio of about 1:1 (Berezhnoy et al., 2005). For this reason the elemental composition of the lunar regolith is assumed to be the same as the composition of the mixture of ferroan anorthosites and norites, namely, 0.28 wt% for Na (Lodders and Fegley, 1998). The elemental composition of impacting meteoroids is assumed to be the same as composition of CI chondrites, namely, 0.5 wt% for Na (Lodders and Fegley, 1998). In accordance with Cintala (1992) target-to-impactor mass ratio Y in the impact-induced hot cloud is estimated to be 50 for the case of high-speed impacts of meteoroids from the main meteor showers (59 km/s for Perseids, 72 km/s for Leonids), target (anorthosite) density of 1.8 g/cm^3, impactor (diabase) density of 3 g/cm^3. Approach of Ahrens and O'Keefe (1987) at the same assumptions as in Berezhnoy and Klumov (2008) gives similar Y values within factor of 1.5. The elemental composition of the impact-produced cloud composed from the mixture of ferroan anorthosites, norites, and CI chondrites at $Y = 50$ is shown in Table 1.

Other important parameters are the lifetimes $\tau_{loss}(X)$ of considered atoms in the exosphere. The residence time τ_{res} of Na atoms at the surface is equal to 0.7 s at 100 K for adsorption of Na atoms at quartz and rapidly decreases with increasing temperature (Hunten et al., 1988). However, residence times of refractory elements at the lunar surface τ_{res} remain unknown. If $\tau_{res}(X) \ll \tau_{bal}(X)$ then $\tau_{loss}(X)$ is determined by ionization lifetime $\tau_{ion}(X)$ if atoms do not loss kinetic energy during collisions with the surface. For example, $\tau_{ion}(Na) \sim 6.2 \times 10^4$ s (Huebner et al., 1992), $\tau_{ion}(Na)/\tau_{ion}(Li) \sim 14$ (Sullivan and Hunten, 1964), $\tau_{ion}(Ca) \sim 1.4 \times 10^4$ s (Killen et al., 2005), for other main elements Mg, Ti, Fe, and Si $\tau_{ion} \gg \tau_{obs}$, only $\tau_{ion}(Al) \sim 1500$ s (Sarantos et al., 2012). However, Na atoms may lose a significant fraction of their kinetic energy during collisions with the surface of the Moon (Hunten et al., 1988) and in this case after several collisions with the surface impact-produced Na atoms may become indistinguishable from low-temperature Na atoms delivered to the exosphere by other mechanisms. Assuming that atoms of alkali elements become undetectable after the second collision with the lunar surface, with the temperature of impact-produced atoms of 3000 K, and also taking into account existence of an escaping component we adopt that $\tau_{loss}(K) = 2 \times \tau_{bal}(K)$, $1/\tau_{loss}(Na) = 0.9/(2 \times \tau_{bal}(Na)) + 0.1/\tau_{ion}(Na)$, $1/\tau_{loss}(Li) = 0.5/(2 \times \tau_{bal}(Na)) + 0.5/\tau_{ion}(Li)$. We adopt the generally accepted opinion that $\tau_{res} \gg \tau_{bal}$ for atoms of refractory elements such as Al, Ca, Mg, Si, and Fe. In this case $\tau_{loss}(X) = \tau_{bal}(X)$ and atoms of refractory elements are captured by the lunar surface after its first ballistic hop.

Table 1
Elemental composition of impact vapor, ferroan anorthosite, norite, and CI chondrite. Elemental composition of lunar rocks and CI chondrite is taken from Lodders and Fegley (1998). Symbol "–" means that the values are unavailable. Impact vapor is consisted from the mixture of ferroan anorthosite, norite, and CI chondrite with ratio of 25:25:1 by mass.

Element	Units	Ferroan anorthosite	Norite	CI chondrite	Impact vapor
O	wt%	45.9	45	46.4	45.6
Si	wt%	20.5	24.2	10.64	22.1
Al	wt%	18.6	8.1	0.865	13.1
Ca	wt%	14.4	6.6	0.926	10.4
Fe	wt%	0.16	7.8	18.2	4.2
Mg	wt%	0.15	7.7	9.7	4.0
Na	wt%	0.27	0.3	0.5	0.29
S	wt%	<0.01	–	5.31	0.12
Ti	wt%	0.012	0.2	0.044	0.1
K	ppm	120	1500	550	800
C	ppm	9	–	34,500	700
Mn	ppm	45	1270	0.194	680
H	ppm	–	–	20,200	400
Ni	ppm	9	2	11,000	220
Cl	ppm	150	–	700	90
Ba	ppm	6.2	176	2.35	90
N	ppm	–	–	3180	70
Li	ppm	–	12.3	1.5	6

3. Physics and chemistry of collisions between meteoroids and the Moon

Si, Ca, Al, Fe, and Mg are the main elements of the lunar highlands. To study the behavior of Na-, K-, Li-, Si-, Ca-, Al-, Fe-, Mg-bearing species during collisions between meteoroids and the Moon we apply a model of chemical processes in the impact-produced clouds (Berezhnoi and Klumov, 1998; Herzog et al., 2009; Berezhnoy, 2010). Thermodynamic calculations based on quenching theory are conducted in order to estimate the chemical composition of the vapor cloud upon adiabatic cooling to the point where the chemical reactions effectively stopped. Specifically, it is assumed that chemical reactions stop at quenching temperature T_q and pressure P_q when the two quantities, the chemical τ_{chem} and hydrodynamic τ_{hydro} time scales, become comparable. Estimates of temperature and pressure of the impact-produced cloud are uncertain. For example, the initial temperature and pressure in the cloud formed soon after the collisions with the Moon of 1- and 10-cm Leonid meteoroids (at velocity of 72 km/s) are estimated to be about T_0 = 10,000 K and P_0 = 1000 bar, respectively (Artem'eva et al., 2001). However, during laser experiments corresponding to impact velocities of about 100 km/s temperature and pressure of outer edge of the laser-induced vapor cloud are estimated as 7500 K and 0.1 bar, respectively (Kurosawa and Sugita, 2010).

For this reason calculations of equilibrium chemical composition of the vapor cloud were performed at the same values of the initial temperature set to T_0 = 10,000 K, the adiabatic index