

GLOBAL MIXING AS A MECHANISM FOR COMPOSITIONAL ANOMALIES OF AGGLUTINITIC GLASSES. L. V. Starukhina and Yu. G. Shkuratov, Astronomical Institute of Kharkov University, 35 Sumskaya St., Kharkov, 61022, Ukraine, starukhina@astron.kharkov.ua

Introduction: Agglutinitic glasses, the most space-weathered portion of the lunar soils, were shown to have chemical composition different from the bulk samples [e.g., 1]. Mare agglutinitic glasses turned out to be Al-enriched and depleted of Fe, Ti, and Cr, whereas highland ones are depleted of Al and enriched in Fe, Ti, and Cr. Thus the contents of these elements in agglutinitic glasses turned out to be on the mare-highland mixing line [1]. The same minerals can hardly be supposed to enter preferentially highland glasses and do not enter those of maria. This suggests a global mixing process that affects predominantly the particles most exposed to the cosmic environment, i. e. agglutinates. Here we simulate the compositional evolution of the lunar regolith taking different mechanisms of global mixing into account.

Mechanisms of global mixing: Global mixing of materials of mare and highland regions can occur due to different mechanisms.

Ejection from craters. Ejection from craters (contribution of <1 mm projectiles highly dominates [2]) is the most known mechanism of mare-highland mixing. The ejecta that take part in mare-highland exchange collide with the surface at velocities from about 1 km/s to 2.37 km/s (escape from the Moon). Such velocities are below the sound speed in solid material, so the physical phenomena at the secondary impacts of ejecta differ from those at initial meteorite impacts that are ultrasonic. The main difference is that ultrasonic impact is explosion-like and occurs on the very surface of material. The subsonic impacts of small projectiles occur similar to flying of a bullet that penetrates into the depth of porous material without melting the target and is buried at a depth of a few bullet sizes. Thus, the distant ejecta provide mixing of mare and highland regoliths up to depths of a few cm and contribute mostly to the bulk composition of a soil. This mechanism cannot explain selective changes of chemical composition of agglutinitic glasses. Only the finest component of the ejecta (<5 μm) cannot remove the target particles and is likely to remain on their surfaces.

Fine dust grains (~1 μm) lifted above the lunar surface by charging due to electron emission process and following the terminator [3] could potentially contribute to the migration of fine dust. However, there are no sufficient data to estimate this contribution.

Atomic transport through the lunar exosphere. Beside dust transport, there is a global mixing mechanism that may be called atomic. The lunar regolith is exposed to solar wind protons, which results in sputtering

of the upper atomic layers, and to meteoritic bombardment that produces impact vapor. The velocity of a part of the sputtered and of the most of the evaporated atoms is less than that of the escape from the Moon [4]. On the other hand, the velocity of most of such atoms is about the orbital velocity, so they become a part of the lunar exosphere, where each of them makes one ballistic jump to a random position on the lunar surface. This is a mechanism of global transport of atoms all over the lunar surface [4]. In particular, the atoms from mare regions can jump to highlands and vice versa.

Note that this mechanism acts only at the very surfaces of regolith particles directly exposed to sputtering and re-deposition of the sputtered and evaporated atoms. This means selective action of the mechanism on the surfaces of the particles most exposed to the lunar environment. The action stops after a particle is buried. The most frequent reason for this is redistribution of material in formation of small (mm-scale) craters. Less frequent is direct hit of hypervelocity micrometeorite, which results in melting of the target regolith particle (probably, together with its neighbors) and formation of agglutinitic glasses. Thus the glasses are expected to be more exposed and to contain more foreign material than the bulk of a soil.

Evidence of global mixing: An indication to atomic mixing of regolith material at all scales of distances can be derived from the data [5] on maturity degree I_s/FeO of lunar soils with different FeO content. In absence of interchange of rim material between different particles, the correlation coefficient between these two characteristics would tend to zero. The mixing of the rim material should increase the content of Fe^0 and, hence, the maturity degree for FeO-poor particles and decrease Fe^0 content in the rims of FeO-rich particles. Thus mixing should result in anti-correlation between FeO and I_s/FeO . In many cases this is actually observed. For instance, the correlation coefficient is -0.66 for Apollo 15 soils studied in [5]. Thus, Fe-rich particles are depleted in nano Fe^0 -grains as compared to Fe-poor ones. This means that large scale mixing of the rim material takes place, though the local mixing is stronger than the global one.

Chemical composition of agglutinitic glasses [1] is another evidence of global mixing that can also be ascribed rather to atomic mixing. Here we develop mare-highland mixing model [4] and apply it to simulate compositional trends observed in [1].

Global and local mixing: Beside gravitational capture of ejecta particles and the atoms with the low-

est energies, there is another reason for the ejected, evaporated, or sputtered material to remain on the Moon. The reason relates to the lunar surface microtopography due to which collisions of the material with neighbor regolith particles and deposition on them take place. This provides local mixing at scales from particle size to the characteristic height of the local microtopography. To distinguish between local and global mixing, we used the fractions of the evaporated and sputtered atoms that contribute to the local mixing calculated in [4]. For the calculations, the indicatrix of sputtering for a regolith particle was obtained by computer simulation of sputtering with TRIM program [6]. The probability for an atom starting at a given angle from a regolith-like surface to collide with the surface is taken from [7]. The fraction of the atoms that contribute to the local mixing was found to be 0.50 for sputtering and 0.71 for ejection and evaporation [4]. The rest of the material either contributes to global mixing or leaves the Moon, if its velocity is higher than that of the escape.

Mass-dependence of atomic global mixing: For dust mixing, the limit point (and hence the direction) of compositional trends is determined by the composition of the lunar regolith averaged over all the lunar surface. As distinct from dust transport, the global transport of atoms is atomic mass dependent, which causes preferential accumulation of heavier atoms in the lunar exosphere. As the escape velocity and energy distributions are the same for all sorts of sputtered or evaporated atoms [4], the fraction of atoms that remain on the Moon increases with atomic mass, e.g., the fraction of sputtered atoms that cannot overcome the lunar gravity was found to be 0.087, 0.15, and 0.28 for O, Al, and Fe, respectively. Therefore, in the material resulting from atomic global mixing, Fe content is increased as compared to dust mixing mechanisms. This will shift the limit point and the direction of compositional change to higher Fe content than for dust mixing (see Fig. 1). If both atomic and dust mixing take place, the limit point of compositional trends is between the two limit cases as in Fig. 1. This may be used to distinguish between the atomic and dust mechanisms.

Rates of global mixing: To reproduce the directions of the compositional trends [1], we took ~30% mixing via lunar exosphere and 70% via fine dust particles of distant ejecta. In Fig. 1 simulation of the chemical evolution of mare (red points) and highland (blue points) particles is shown. Starting points are compositions of mare and highland <10 μ m size fractions taken from [1]; the end points of the trends are close to those reported in [1]. For a particle size 10 μ m, time interval between the points in Fig. 1 is $6.5 \cdot 10^4$ yr, so the total evolution time is from $5.2 \cdot 10^5$ to $6.5 \cdot 10^5$ yr that exceeds the average exposition time for a regolith particle [8] no more than by a factor of 4.4.

Conclusions: Our simulation of the chemical evolution of a regolith particle exposed to lunar exosphere and to fine dust particles of ejecta have shown that global mixing can account for the difference in the composition observed for agglutinitic glasses [1] as compared to the bulk of mare and highland lunar soils.

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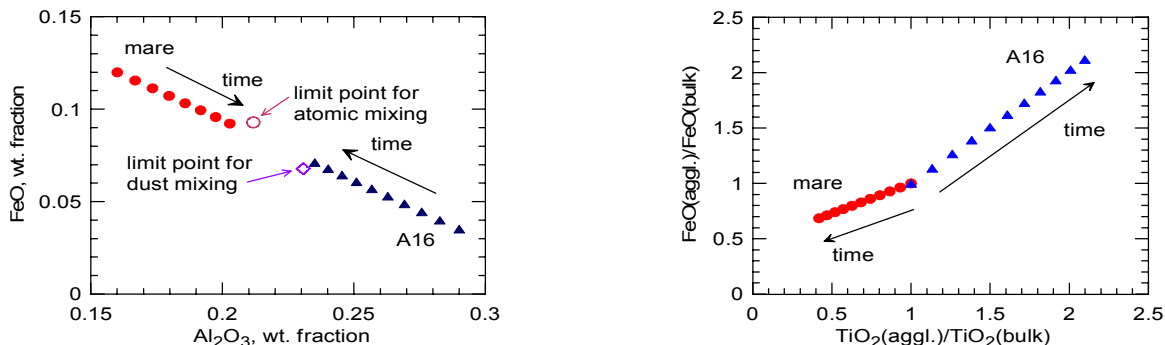


Fig. 1. Simulation of the evolution of mare (red points) and highland (blue points) chemical composition.