IMPACT MELTING OF REGOLITH PARTICLES BY MICROMETEORITES AS A MECHANISM OF SOIL MATURATION. L. V. Starukhina, Astronomical Institute of Kharkov University, Sumskaya 35, Kharkov, 61022, Ukraine, starukhina@astron.kharkov.ua

Introduction: The mechanisms of maturation of the regolith on the surfaces of atmosphereless celestial bodies were discussed from the very beginning of the studies of lunar soils. The most puzzling feature of a mature soil is presence of 1000 Å-thick amorphous rims containing nanometer size grains of reduced iron (npFe^0) on the surfaces of regolith particles [1]. One group of researchers (e.g., [2]) suggests that the rims with npFe^0 are due to solar wind (SW), whereas the alternative hypothesis was condensation of impact vapor in meteoritic bombardment [3]. Here a new approach to rim formation is presented, with an emphasis on the importance of impact melting of regolith particles, especially, melting of their surfaces in the impacts of submicron scale. The contributions of solar wind, impact evaporation, and impact melting to rim formation are compared.

Experimental basis: There are experiments indicating that heating of Fe-bearing silicate materials to melting or submelting temperatures is enough for formation of npFe^0, provided that oxygen pressure is low enough. Subsolidus reduction of Fe^{2+} ions in olivine Fo89 and pyroxene En88 was observed in [4]. An indication to Fe reduction in silicate melt may be found in laser heating experiments [5]. On the irradiated olivine particles, amorphous rims with npFe^0 were observed, whereas in the irradiated pyroxene powder neither no amorphous rims with npFe^0 were detected. Yet a small number of large (~100µm in size) dark amorphous enstatite particles that contained npFe^0 distributed over all the particle volume were found. Such particles were obviously formed from melt due to poor thermal contact with the neighbors, and not from condensed vapor that covers continually the surfaces of all particles and contribute to rim formation.

The important resemblance of both types of experiments [4,5] is that formation of Fe^0 grains occurred only at the sites of enhanced diffusion: at crystal surface, planar defects (grain boundaries, cleavage planes, [4]) or in liquid phase or solidifying glass [5]. I. e., even at high submelting temperature, mobility of atoms is too low to form Fe^0 grains in crystalline phase. This is consistent with the observation that in lunar regolith npFe^0 occur in amorphous rims and in glasses.

The importance of impact melting: Even at the sites of enhanced diffusion, such as grain boundaries or amorphous material, elevated temperature is required to provide mobility of the atoms high enough for association of isolated Fe^0-atoms into nanometer grains. The duration of the laboratory experiments on subsolidus reduction (e.g., [4]) was a few hours, which corresponds to cooling times of material heated in impact events of meter scale and higher. However, most frequent heating of the upper regolith layers is due to micrometeorites for which cooling times of heated material is typically <<1 s. Thus, though at negligible oxygen pressure on the lunar surface, reduction of Fe may occur at subsolidus temperature, high temperature lasts too little time for association of Fe atoms into grains in solid silicates. Here we show that fast association is possible in impact melt due to much higher diffusion coefficients D in melts as compared to solids.

Is formation of npFe^0 possible in impact melting of particle rims?: *npFe^0 formation times*. Compare the time required for formation of npFe^0 grains of the observed average radius $r_1 \approx 25$ Å [6] and solidification time of impact melt created on the surface or all over the volume of a regolith particle. Kinetics of nFe^0 growth has been considered in [7] on the base of ripening theory [8]. The formation time t_1 for a population of npFe^0 grains of a radius r_1 is $t_1 \approx r_1^2/2D\xi_0$ [8], where D is diffusion coefficient of Fe in silicate matrix and $\xi_0 \approx 0.6$ [7]. In melts, $D \approx 10^{-5}$ cm^2/s, so $t_1 \approx 5 \cdot 10^{-9}$ s.

Rim solidification times. The shortest time of solidification is typical of impact melt formed by submicron projectiles on the surfaces of the regolith particles. Note that the thickness of the melted zone formed by submicron projectiles is the same as that of amorphous particle rim $h \approx 1000$ Å. In this case, cooling occurs by heat conduction to the solid particle material of heat conduction coefficient $\eta \approx 10^5$ erg·cm^{-1}·s^{-1}·K^{-1} and heat capacity per unit volume $c_v \approx 10^7$ erg/cm^3. Solidification time is $t_s \approx h^2 c_v/2\eta \approx 5 \cdot 10^{-9}$ s. Thus, even in the impact events of submicron scale, impact melt survive long enough for formation of nFe^0 grains.

Surface melting times. Taking the mass spectra of submicron micrometeorites [9], and assuming melted mass ≈10 projectile masses, we obtain that more than 95% of the exposed surface of lunar regolith is melted by submicron projectiles in $3 \cdot 10^3$ to $6 \cdot 10^3$ years. This is about the average duration of each of 30 exposures of a particle on regolith surface, i. e., more than an order of magnitude shorter than its total exposure age $1.5 \cdot 10^5$ years [10]. Most traces of microcraters are removed due to fast surface diffusion at submicron scale [11].

However, next cycles of impact melting during the 30 particle exposures do not result in considerable growth of nFe^0 grains (from ≈50 to ≈60 Å only) because their growth is much slower than their formation [7,8]. On the other hand, the cooling time is short enough for solidification of the melted silicate material in amorphous state even on a crystalline substrate. This is not the case for nonsilicate materials, such as ilmenite, that are not apt to form glasses and are not observed in amorphous state either as glass particles or as rims [12]. Thus impact melting and subsequent cooling, being fast enough for amorphization of the melted material, are slow enough for formation of $npFe^0$ grains of the average diameter 50 Å.

Melting of the bulk of regolith particles. According to [9], the largest contribution into micrometeorite mass (and hence into impact melt) is made by projectiles of sizes from ~10 μm to ~1 mm that cause melting of one or a few regolith particles as a whole. The probability of total melting of a regolith particle during surface exposure is ≈10%, the rest of the glass particles being due to subsurface melting. Because of poor interparticle contacts, the cooling mechanism for an entirely melt regolith particle is irradiation, and solidification time is $\sim 10^{-2}$ s for a typical single particle (60μm in diameter) and ~0.1 s for a 1 mm droplet of silicate material. Estimates on the base of [7,8] show that this time is enough for growth of nFe^0 grains up to ~1000 Å in diameter in the bulk of the glass particles.

Rates of different maturation processes in space: Let us compare the formation time of amorphous rims due to submicron impact melting to such a time for SW and condensation of impact vapor.

Solar wind. Amorphization time is the shortest for this mechanism. Indeed, $\tau_{aSW} \approx 4hn_0/N_d j$, where $n_0 \approx 10^{23}$ cm^{-3} is the number of atoms per unit volume of a solid material, $h \approx 10^{-5}$ cm is the maximum penetration depth of SW, $N_d \approx 2$ is the average number of atomic displacements per SW particle, and j is the normal flux of SW, factor 4 being due to rotation of a celestial body. Then $\tau_{aSW} \approx 8 \cdot 10^9$ s ≈ 300 years near the Earth orbit ($j = 2.4 \cdot 10^8$cm^{-2}s^{-1}) and $\tau_a \approx 1500$ years in the Main asteroid belt ($j \approx 4.5 \cdot 10^7$cm^{-2}s^{-1}). However, this fast amorphization occurs on cold surface, so impact heating is required to form $npFe^0$ grains out of isolated Fe^0-atoms.

Condensation of impact vapor. On the base of the data about micrometeorite flux [9], in the assumption that the mass evaporated in an impact is about the projectile mass, we obtain the evaporation rate of ≈0.1 Å/year. The vapor is distributed in a few upper particulate layers of regolith and condenses on the surfaces of the particles there, so the 1000 Å-thick layer of condensate covers the particles in 10 upper layers in $\approx 10^5$ years. This shows that condensation of impact vapor contributes to the composition of particle rim, but rim formation by this mechanism is much slower than by melting in submicron impacts. Besides, condensate may be deposited in multiple events by layers of thickness <100 Å, whereas melting occurs each time to a depth 500 – 2000 Å, which provides cooling slow enough for $npFe^0$ formation in each impact event.

Conclusions:

(1) Impact melting of the upper zones of regolith particles by submicron projectiles enables formation of nanophase Fe^0 grains of the observed average diameter 50 Å in melt, subsequent cooling being fast enough for preservation of the amorphous structure of particle rim formed in solar wind bombardment.

(2) Impact melting of the bulk of regolith particles favors growth of $npFe^0$ grains up to ~1000 Å observed in agglutinitic glasses.

(3) Impact melting involves an order of magnitude larger volumes than the other mechanisms; in particular, melting of the particle rims occurs much faster than condensation of a film of impact vapor of the same thickness. This makes impact melting the most effective mechanism of formation and growth of $npFe^0$ on the surface and volume of regolith particles.

Thus, impact melting can provide the observed characteristics of mature soils without any additional maturation mechanisms. Consequently, the mechanism may cause regolith maturation both on bodies shielded from solar wind irradiation, such as Mercury, and on asteroids, where collision velocities do not provide impact evaporation but is enough for impact melting.

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