

**FORGOTTEN SOLAR-WIND IRON IMPLANTED IN LUNAR REGOLITH.** Y. G. Shkuratov, Astronomical Institute of Kharkov V. N. Karazin National University, 35 Sumskaya Street, Kharkov 61022, Ukraine, [Yuriy\\_Shkuratov@hotmail.com](mailto:Yuriy_Shkuratov@hotmail.com)

**Introduction:** Iron is an important rockforming element enters into the composition of the Moon. The lunar surface contains ~7 wt.% of FeO or ~2 at.% of Fe [1]. Iron is most abundant in lunar mare minerals and glasses in the form of oxides. Small quantities of free iron metal also exist, coming from metallic asteroids and meteoroids that have impacted the Moon. There is also nano-phase iron (npFe<sup>0</sup>) [2,3], the amount of which is on average 0.1 wt.%. It is believed that this submicroscopic metallic iron resulting from the reduction of ferrous iron via so-called space weathering processes – micrometeorite impacts and the action of solar wind [3]. With the lack of water and air on the Moon, this metal has not rusted into iron oxide. Grains of npFe<sup>0</sup> are believed to be produced with several mechanisms:

(1) Ferrous ions are reduced by direct chemical interaction with solar wind protons (hydrogen) [4] and by stimulation of this interaction with impact melting of mineral particles ( $\text{FeO} + 2\text{H} \rightarrow \text{Fe} + \text{H}_2\text{O}$ ) [2,3].

(2) Preferential sputtering of volatile elements (e.g., O) and preferential condensation of heavy elements (e.g., Fe) induced by solar wind ions [5,6].

(3) Preferential condensation of heavy elements at impact melting processes and involving these materials in formation of bulk npFe<sup>0</sup> at agglutination [3].

(4) Subsolidus reduction also may produce bulk metallic iron [7].

For lunar regolith particles the condensation coatings contained npFe<sup>0</sup> have been found, and the condensation mechanism seems to be dominated among the mentioned above [8].

In all these mechanisms lunar iron is involved in the npFe<sup>0</sup> formation. We here consider an additional source of npFe<sup>0</sup> – iron from the solar wind, SW-Fe.

**Estimating the solar wind iron:** The relative atom concentration of solar wind species are presented in Table 1 adopted from [9]. As can be seen, for iron this is about 10<sup>-2</sup>%, though other estimates suggests 6x10<sup>-3</sup> [10]. If we consider the proton solar wind flux equals 3.8x10<sup>8</sup> cm<sup>-2</sup> s, than the averaged SW-Fe flux is ~3x10<sup>4</sup> cm<sup>-2</sup> s. Then, the total mass of SW-Fe ions fell on a square meter during the last billion of years is about 0.88 kg. This is 0.3 wt.% of total iron mass contained in a cubic meter of the "average" lunar regolith. Moreover, this value equals the abundance of npFe<sup>0</sup> in mature lunar soils [3]. If the iron mass 880 g is imagined as a tagger of m<sup>2</sup>, its thickness is equal to 110 μm.

Although the "forgotten" iron is presented with a noticeable amount, this component has not been seriously considered yet as a potential contributor to the npFe<sup>0</sup> formation. On the other hand, example of <sup>3</sup>He show that, although its abundance is appreciably low than SW-Fe (see Table 1), there are great expectations how to use this substance as safety fuel in future thermonuclear reactors [11].

Table 1. Element percentage in solar wind [9]

Element	%	Element	%
H	96	O	5.1 10 <sup>-2</sup>
<sup>4</sup> He	3.8	Ne	8,6 10 <sup>-3</sup>
<sup>3</sup> He	1.7 10 <sup>-3</sup>	Mg	7.6 10 <sup>-3</sup>
C	3.4 10 <sup>-2</sup>	Si	9.6 10 <sup>-3</sup>
N	7.6 10 <sup>-3</sup>	Fe	9.6 10 <sup>-3</sup>

Using approach presented in [12], one may easily estimate the saturation time for SW-Fe in upper zones of lunar regolith particles: It is one million of years; in case of SW hydrogen this is a hundred of years. During 1 Ma micrometeorite and ion-sputtering erosion may be significant factors. The rate of the erosion is determined very unreliably: from optimistic ~0.5 [13] to ~0.04 [14] and even to pessimistic ~0.003 Å/yr [15,16]. The difference can be related to that [13] used powders with particles of 1-μm sizes, whereas [16] used samples with flat surfaces. Bibring et al. [13] shown also that feldspars are eroded at a faster rate (near 10 times) than ilmenite grains; this was confirmed by [17]. At the rate 0.5 Å/yr during one million of years the very upper layer of thickness 5x10<sup>5</sup> Å can be scraped away. This gives no chance for SW-Fe to survive, as the maximum of implanted Fe ion concentration is 1500 Å. Even the lowest rate 0.003 Å/yr is too high to provide the SW-Fe saturation.

Moreover, it should be noted that the rate of micrometeoroid erosion is much higher than the solar-wind scraping; the contemporary rate of microimpact regolith formation is estimated to be up to 10 Å/yr [18]. Additionally, for 10<sup>6</sup> years the uppermost millimeter is turned over a few tens of times and the outermost 0.1 mm a few hundred times.

Thus, it seems that we should again forget about the contribution of SW-Fe. However, following this logic, we should also refuse the existence of <sup>3</sup>He and other volatile element (e.g., C and Ne) of implanted from solar wind.

There is an obvious explanation of this contradiction. At the micrometeorite and SW-ion erosion of powdered surfaces, an example of which is the lunar

regolith, a significant portion of the erosion products may be re-condensed on the surface of regolith particles. The products of vaporization may be extended over several hundreds of layers of regolith particles [19]. That SW-Fe cannot contribute directly in the rim  $\text{npFe}^0$  is clear from the isotope composition. While in solar wind the ratio  $^{54}\text{Fe}/^{56}\text{Fe}$  is higher than in the terrestrial case [20], mature lunar soils having high  $I_s/\text{FeO}$  values demonstrate lower ratio  $^{54}\text{Fe}/^{56}\text{Fe}$  than terrestrial and lunar rocks [6]. This means that the SW-Fe should be involved in processes of isotope separation.

How can one detect the SW-Fe in lunar soils?

An excess of iron could be in highland soils for which the abundance of intrinsic iron is rather low. The excess should be observed for the most altered portion of the regolith, i.e. for agglutinates. Chemical studies of lunar soil samples, which were carried out by the LSCC research consortium [21], showed that, relative to the crystalline fraction, the highland agglutinates are in fact enriched in Fe [22].

This result was confirmed [23] with mapping the parameter  $\text{FeO}^{(\text{agg})}/G(\text{FeO})$  that is the ratio of iron content in agglutinates ( $\text{FeO}^{(\text{agg})}$ ) to  $G$  and  $(\text{FeO})$  that are, respectively, agglutinate and total iron contents. To map the parameter, we used the mosaics with 1-km resolution obtained by the Clementine UVVis imagery in five wavelengths of the visible/NIR spectral range and the spectral/chemical data carried out by the LSCC research consortium [23].

**Conclusion:** Thus, the SW-Fe suggests an additional source of  $\text{npFe}^0$  in the lunar regolith. The SW-Fe can be involved in maturation of the lunar regolith, which may provide an excess of heavy Fe isotope. The mass-dependent isotopic variation of Fe can be explained by: ion sputtering, volatilization by micrometeorite impacts, and redeposition of some sputtered or volatilized matter after gravitational fractionation. Direct calculations of the SW-Fe are difficult, but indirect qualitative estimates are possible. Indeed, the SW-Fe source can be important, since much more volatile  $^3\text{He}$ , having lower SW-contribution than SW-Fe, is nevertheless detected in the lunar regolith and even suggested as a fuel [11].

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