SPACE WEATHERING OF LUNAR ROCKS.  S. K. Noble¹, L. P. Keller², R. Christoffersen² and Z. Rahman²,
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Introduction: All materials exposed at the lunar surface undergo space weathering processes. On the
Moon, boulders make up only a small percentage of the exposed surface, and areas where such rocks are
exposed, like central peaks, are often among the least space weathered regions identified from remote sensing
data. Yet space weathered surfaces (patina) are relatively common on returned rock samples, some of
which directly sample the surface of larger boulders. Because, as witness plates to lunar space weathering,
rocks and boulders experience longer exposure times compared to lunar soil grains, they allow us to develop
a deeper perspective on the relative importance of various weathering processes as a function of time.

Samples: Building upon our earlier work on lunar rock 76015 [1,2] we have added observations from
patina coatings on two other Apollo 17 rocks: 76237 and 72315. Both 76015 and 76237 originate from the
Apollo 17 Station 6 boulders, which were emplaced approximately 22 million years ago based on cosmic ray
exposure ages [3,4] (for comparison, a typical soil grain, has a lifetime of only ~10^4-10^5 years [5,6,7]). While
the Station 6 rocks have the same exposure age, they differ in composition; 76237 comes from within a
large plagioclase-rich clast.

Lunar rock 72315, from a Station 2 boulder, also has a space weathered patina, though its surface is con-
siderably younger than the others, only about 0.1-0.3 Ma, based on cosmic rays, solar flares, and micromete-
orite counts [8]. Looking at this younger, but still weathered, surface allows us to explore whether patinas
quickly reach a steady state or if the products seen in our preliminary studies of 76015 require longer exposure
times to develop.

Methods: After thoroughly examining the samples in SEM, regions of interest were selected for TEM
analysis. Using a FIB (Focused Ion Beam) instrument, multiple cross sections through the weathered patina
were produced from each of the samples and thinned for TEM analysis.

TEM work was done using the JEOL 2500SE 200 keV field-emission scanning-transmission electron mi-
noscope (FE-STEM) at JSC. The FE-STEM is optimized for compositional spectrum imaging using a
large-area, thin window energy-dispersive X-ray (EDX) spectrometer. Spectrum images of the sample
were acquired with a 4 nm probe whose dwell time was minimized to avoid beam damage and element
loss/mobilization during mapping.

Results and discussion: Similar sets of products are observed in all three samples (Fig 1) This includes:
1) solar wind irradiation surfaces 2) condensation of impact vaporized or solar wind sputtered material, 3)
impact melt glass, 4) recrystallized grains, 5) and entrained grains and melt spherules.

Immediately above the unaltered host rock, there
is commonly an amorphous layer with an average
thickness of ~100 nm, but ranging up to ~250 nm. This
layer is derived by solar wind ion amorphization of the
host rock’s crystalline surface. Irradiation rims on lu-
unar soil grains are typically thinner, (~20-100 nm thick
[9]), likely owing to the shorter exposure time. Above
this irradiation rim, the bulk of the patina coatings are
composed of melt glass units, ranging in size from na-
nometers in thickness and diameter to several mic-
rometers. The melt glass compositions vary widely,
similar to the range seen in lunar agglutinates and
spherules. There is no distinct difference in the aver-
age glass composition between 76015 and 76237 de-
spite the differences in their substrates. This suggests
that much of the melt is not locally derived and likely
represents melts that were transported over distances as
large as or larger than the size of the feldspathic clast
(tens of centimeters).

Most of the glass units from all three rocks contain
nanophase iron (npFe⁰). In general, smaller melt units
have higher modal concentrations of npFe⁰ inclusions
than larger ones. Vapor-deposited layers occur in se-
veral of the FIB sections, but are volumetrically a small
component of the patina overall. The npFe⁰ in the va-
por deposited layers is typically smaller than in the
melt glass, a distinction we have long recognized in
lunar soils as well [10]. The size of npFe⁰ has a pre-
dictable effect on the Vis/NIR spectra; smaller npFe⁰
reddens while larger npFe⁰ darkens [11]. Because of
the surface area differences, vapor deposits should be
less optically important for rock patina than in soils,
which have much greater surface to volume ratios, thus
we expect a weathered rock surface to be darker and
less red than comparably weathered soils.

Several samples from all three rocks contained a
notable thick iron-rich layer that appears to be a com-
mon feature of rock patina (Fig 2). In all cases the unit
is high in Fe and Si and is loaded with npFe⁰, typically
larger blebs of npFe⁰ than found in other glass units.
The thickness, often elevated Ti contents, and the com-
onal schlieren-like features are consistent with depo-
sition as a melt rather than vapor. The lack of
nickel suggests a lunar, rather than meteoritic, origin.
These iron-rich units appear to be as common in the younger patina (72315) as in the older surfaces. The patina is highly variable in thickness across even small distances; in some places it can be >10 μm thick (Fig 1a), in other places, bare rock is exposed (Fig 1b). This variability is a reflection of the stochastic nature of micrometeorite bombardment that both deposits and erodes. SEM analysis suggests that (not surprisingly), on average across the surfaces, the patina is thicker on the rocks with longer exposure times (76015 and 76237) than shorter (72315).


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Fig 1. FIB samples from (a) 76237, (b) 76015, and (c) 72315. The thickness and composition of the patinas are highly variable, not only from sample to sample, but even across very small distances within a sample.

Fig 2. Chemical maps from a FIB sample of 76015 showing a melt layer enriched in Si and Fe, particularly npFe⁰, these distinct layers are found in all three rocks.