**POST-FORMATION SODIUM LOSS ON THE MOON: A BULK ESTIMATE** P. Saxena, R. M. Killen, V. Airapetian, N. E. Petro, and A. M. Mandell NASA/Goddard Space Flight Center, Greenbelt, MD 20771 (prabal.saxena@nasa.gov)

**Introduction:** The Moon and Earth are generally similar in terms of composition, but there exist variations in the abundance of certain elements among the two bodies. These differences are a likely consequence of differing physical evolution of the two bodies over the solar system's history. While previous works have assumed this may be due to conditions during the Moon's formation, we explore the likelihood that the observed depletion in Sodium in lunar samples may be partially due to post-formation mechanisms. Solar effects, loss from a primordial atmosphere and impacts are some of the dominant post-formation mechanisms that we examine. We describe how our past and current modeling efforts indicate that a significant fraction of the observed depletion of sodium in lunar samples relative to a bulk silicate earth composition may have been due to solar activity, atmospheric loss and impacts. Using profiles of sodium abundances from lunar crustal samples may thus serve as a powerful tool towards exploring conditions on the Moon's surface throughout solar system history. Conditions on the Moon immediately after formation may still be recorded in the lunar crust and may provide a window towards interpreting observations from some of the first rocky exoplanets that will be most amenable to characterization. Potential spatial variation of sodium in the lunar crust may be a relevant consideration for future sample return efforts.

**Sodium Depletion in the Lunar Crust:** Lunar samples indicate the Earth and the Moon are generally very similar in composition, but that there exist significant depletions in elements that possess condensation temperatures less than 1300 K (at a pressure of $10^{-4}$ bar)[1]. Sodium appears to be approximately five times more abundant in the Bulk Silicate Earth versus the Bulk Silicate Moon, with significant variation depending on the particular lunar sample chosen. [2] Some of these abundance variations have been attributed to incomplete accretion during the formation of the Moon immediately after a hypothesized giant impact on the Earth. [2] However, processes operating after accretion of the Moon may also have influenced sodium abundance and spatial variation on the Moon.

**Post-Formation Depletion and Transport Mechanisms:** We examine several mechanisms that may have influenced sodium abundances:

*A Primordial Lunar Atmosphere.* Given a canonical Moon formation hypothesis where the Moon accreted quickly from a disk created when a planetary sized impactor hit the Earth, the Moon may have possessed a short-lived largely hemispheric metal dominated atmosphere immediately after it tidally locked to the Earth. Sodium would have been a significant (and potentially dominant) constituent of this atmosphere. Such an atmosphere was characterized by moderate pressures, high atmospheric temperatures, strong supersonic winds and large atmospheric scale heights. [3] Indeed, during the period before atmospheric collapse, the proximity of the Moon to the Earth would mean such a primordial atmosphere would reach the fluid Roche limit of the Earth at a height of only several scale heights. Simple estimates of atmospheric (and consequently sodium) escape from such an atmosphere integrated over the total time before atmospheric collapse range from 5-25% of the initial sodium content of the global lunar magma ocean. Details regarding the assumptions made that correspond to this range of loss values are given in [3]. Additionally, sodium would have been transported rapidly to regions of the Moon near or just beyond its terminator with respect to the Earth. This transport would have occurred right up to and during the beginning of lid formation and may have produced sodium depletions from sub-Earth zones while producing significant sodium abundance enhancements on rockbergs [4] that were advected towards the far side.

*Effects of Past Solar Activity.* Sodium may also have been depleted due to solar activity in the past. Recent research based on Kepler observations of solar analogues at different stages in their evolution indicate the Sun may have experienced an enhanced period of flare and CME activity earlier in its history. [5] This enhanced CME activity may have resulted in a frequency of geo-effective high energy CMEs (several orders of magnitude more energetic than the most powerful CMEs during recorded human history) on the Earth-Moon system of >1/day in the first 500 million years of the Solar System's history. Using a previously developed exosphere generation model that includes the effect of an incident CME [6], we are able to estimate the potential loss of sodium from the regolith due to solar wind and CME effects. Depending on the choice of composition (LPUM versus TWM), even with a conservative model of sputtering yields, this enhanced solar activity may explain anywhere from 10-100% of the observed sodium depletion. Estimates regarding the total percentage of sodium depletion that can be explained by past solar activity for a variety of different assumptions are given in Figure 1. Regolith assumptions regarding the Moon are that the near side

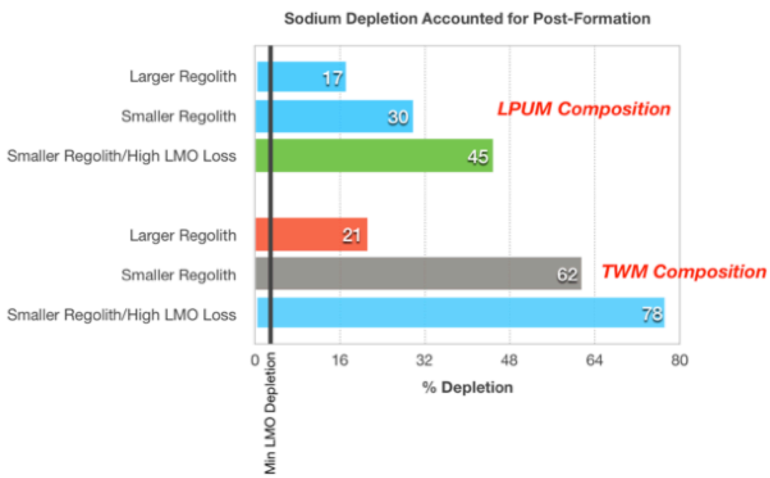


Figure 1: Post-formation sodium depletion from the lunar regolith due to solar activity. Total depletion accounted for by solar activity is given for two different compositions, different regolith volumes and different primordial atmospheric loss scenarios.

regolith thickness is ~5 meters while the far side highlands terrain is 10-15 meters thick (the smaller vs larger regolith cases). The total sodium loss during a potential primordial Lunar atmosphere phase is conservatively assumed to be 5% of the total observed depletion. The range of depletion values in Figure 1 demonstrate that while these assumptions can significantly effect the total impact of solar activity on sodium loss, even in the most conservative scenarios, such loss can explain a significant and measurable portion of the total sodium depletion.

*Effects of Impacts.*

In addition to estimates of the effect of solar activity, we are also examining the effect of impacts on sodium abundance in the regolith. Using an impedance matching technique, we are estimating the total delivery and loss of sodium during a variety of different impacts. Current modeling examines the total sodium delivery and loss due to impactors of a range of sizes (up to and including sizes corresponding to those believed to have produced some of the largest basins on the Moon), velocities (corresponding to different source populations for the impactors) and compositions (iron rich versus iron poor compositions). Impacts are a critical process for tracking sodium abundance variations for several reasons. Due to the greater frequency of impacts during the early history of the solar system, specifically during a period when solar activity may also have been much greater [7], regolith churn that occurred may have left detectable abundance variations in lunar stratigraphy that may help to constrain these early solar system processes. Additionally, for impactors of large size and velocity, their large penetration depth means that such impacts may have vaporized material at depths below the regolith, resulting in significant corresponding spatial abundance anomalies.

*Discussion and Future Work.*

Additional knowledge regarding the potential nature of solar activity and impacts during solar system history coupled with modeling of the effects of such processes on the lunar surface suggests that a significant portion of the observed depletion in sodium in lunar samples may be due to post-formation processes. This is critical for two reasons. First, such contributions mean the initial formation process of the Moon is less tightly constrained by moderate volatile depletion requirements during accretion. This may enable a wider range of formation scenarios that include those that better fit other observed constraints. Excitingly, such post-formation depletion should also then be recorded in the stratigraphy of the lunar regolith. The information recorded in such stratigraphy could be used to connect vertical profiles of sodium abundances in lunar samples to physical mechanisms that modified the lunar surface through history. Connecting these variations in abundance to the effects of these physical processes may allow for constraints on past solar activity, impacts and surface processes on both a global and local level for the Moon.

Our immediate future work will focus on estimating the total depletion of sodium from the lunar regolith that may be due to the combined effects of past solar activity and impacts for a range of different scenarios.

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