Carbon as the dominant light element in the lunar core

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ABSTRACT

Geophysical and geochemical observations point to the presence of a light element in the lunar core, but the exact abundance and type of light element are poorly constrained. Accurate constraints on lunar core composition are vital for models of lunar core dynamo onset and demise, core formation conditions (e.g., depth of the lunar magma ocean or LMO) and therefore formation conditions, as well as the volatile inventory of the Moon. A wide range of previous studies considered S as the dominant light element in the lunar core. Here, we present new constraints on the composition of the lunar core, using mass-balance calculations, combined with previously published models that predict the metal–silicate partitioning behavior of C, S, Ni, and recently proposed new bulk silicate Moon (BSM) abundances of S and C. We also use the bulk Moon abundance of C and S to assess the extent of their devolatilization. We observe that the Ni content of the lunar core becomes unrealistically high if shallow (<3 GPa) LMO scenarios are assumed, and therefore only deeper (>3 GPa) LMO scenarios are considered for S and C. The moderately siderophile metal–silicate partitioning behavior of S during lunar core formation, combined with the low BSM abundance of S, yields only <0.16 wt% S in the core, virtually independent of the pressure (P) and temperature (T) conditions during core formation. Instead, our analysis suggests that C is the dominant light element in the lunar core. The siderophile behavior of C during lunar core formation results in a core C content of ~0.6–4.8 wt%, with the exact amount depending on the core formation conditions. A C-rich lunar core could explain (1) the existence of a present-day molten outer core, (2) the estimated density of the lunar outer core, and (3) the existence of an early lunar core dynamo driven by compositional buoyancy due to core crystallization. Finally, our calculations suggest the C content of the bulk Moon is close to its estimated abundance in the bulk silicate Earth (BSE), suggesting more limited volatile loss during the Moon-forming event than previously thought.

Keywords: Moon, lunar, core, siderophile, volatiles

INTRODUCTION

Geophysical and geochemical observations suggest the lunar core contains several weight percent of one or more light elements. One constraint on the abundance and nature of the light element inventory stems from a reanalysis of Apollo era lunar seismic records suggesting the existence of a partially molten outer core (Weber et al. 2011), which requires the presence of one or more light elements to reduce the liquidus of the core. The existence of an ancient lunar core dynamo (e.g., Cisowski et al. 1983; Collinson 1993; Shea et al. 2012) suggests the presence of one or more light elements in the lunar core, which is required to drive compositional convection in the lunar core (e.g., Laneuville et al. 2014). Light elements H, O, and Si are not expected to significantly partition into the lunar core because the oxygen fugacity during lunar core formation was either too oxidizing (Si), or because the pressure in the Moon (~5 GPa at the core-mantle boundary, ~5.3 GPa in the center; Garcia et al. 2011, 2012) is too low (Killburn and Wood 1997; Ricolleau et al. 2011; Steenstra et al. 2016b).

From molten metal alloy density and liquidus considerations, Weber et al. (2011) proposed that the lunar core contains less than 6 wt% of lighter alloying elements. Sulfur (S) was deemed the most likely candidate, because of its high solubility in Fe metal, and its ability to significantly reduce the bulk density, sound velocity and liquidus temperature of the lunar core (e.g., Hauck et al. 2006; Weber et al. 2011; Jing et al. 2014). Follow-up studies therefore primarily focused on assessing the feasibility of S in the lunar core. For example, Laneuville et al. (2013) suggested from thermochemical evolution models that ~3 wt% S would be required for the crystallization of a 240 km radius lunar inner core, whereas Zhang et al. (2013) propose lunar core S contents of ~5–10 wt%. Laneuville et al. (2014) proposed from thermochemical modeling of the lunar core dynamo an initial S core content of ~7 ± 1 wt%, or alternatively, more than 12 wt% if the Moon never crystallized an inner core. From Fe–S equation of state measurements, Jing et al. (2014) prefer a lunar core model with 4 ± 3 wt% S, whereas Antonangeli et al. (2015) propose S core contents of 8.5 ± 2.5 wt%, based on compressional and