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Next-generation electromagnetic sounding of the Moon

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Abstract

Electromagnetic (EM) sounding of the Moon, largely performed during the Apollo program, provided constraints on core size, mantle composition, and interior temperature. We present new analytical and numerical models that demonstrate the abilities of a next generation of EM sounding to (1) determine the electrical structure of the outermost 500 km and its lateral variability, specifically to understand the extent of upper-mantle discontinuities and the structure of the Procellarum KREEP Terrane; (2) determine the temperature and composition of the lower mantle; and (3) better constrain core size. New EM sounding need not rely on the Apollo methodology, which analyzed the magnetic transfer function between a surface station and a distantly orbiting satellite. Instead, a network of magnetometers (as few as two) can be used, or a complete sounding can be performed from a single station by measuring both electric and magnetic fields. Furthermore, in the magnetotail or lunar wake, sensors can operate from orbit, at altitudes up to the desired investigation depth. The twin-spacecraft ARTEMIS mission will test these methods and a lunar geophysical network will provide definitive results.

Keywords: Moon; Interior; Mantle; Core; Electromagnetic sounding; Induction

1. Introduction

The Moon provides unique insights into early planetary differentiation, as its small size slowed internal activity early in Solar System history. Accretion from a giant impact, formation of a magma ocean, and global compositional asymmetry are some of the key characteristics relevant to the lunar interior (NRC, 2007). Largely enabled by surface sensors emplaced by the Apollo program, some general features of the internal structure of the Moon have been revealed (see Hood and Zuber, 2000 for a review). The National Research Council (NRC, 2007) called for a next generation of geophysical measurements to (a) determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability; (b) characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle; (c) determine the size, composition, and state of the core. These measurements will be used to (d) characterize the thermal state of interior and elucidate workings of the planetary heat engine.

A suite of geophysical methods provides complementary data that best characterize planetary interiors. The Apollo Lunar Surface Experiment Packages (ALSEP) included four global-geophysics experiments: seismometer, heat-flow probe, laser retroreflector, and magnetometer. Not all instruments flew on every mission. Due to instrument design and mission constraints, only the Apollo 12 magnetometer was used for subsurface sounding. This same suite has been recommended for the International Lunar Network (ILN CIWG, 2009) and has been incorporated into recent Discovery/M-Class mission concepts (Neal et al., 2010; Mimoun et al., 2011).

Electromagnetic sounding measures the electrical conductivity σ(S/m) of a target from its response to a time-varying source. Conductivity is sensitive to both temperature and composition, and thus is complementary to seismology and heat flow in understanding planetary interiors. The overall electrical conductivity structure of the

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Moon as inferred from Apollo (Fig. 1) reveals three broad zones of interest. The lower mantle, from normalized radius $r' \sim 0.3$ to ~ 0.7, is the best characterized. The difference in the bounding envelopes of Dyal et al. (1976) and Hood et al. (1982) is likely due to systematic errors related to the different kinds of measurements performed (see below). Nonetheless, the conductivity near their overlap can be roughly approximated as $\log \sigma = -4r'$. A stepwise profile, modified from Khan et al. (2006), is also approximated by the exponential. Larger uncertainties are associated with both the presumed core region ($r' < 0.3$, or dimensional radius $r < 500$ km) and the upper mantle ($r' > 0.7$, or depth $d < 500$ km. The core region is poorly resolved because it is just a few percent of the lunar volume and EM signals that can sense it are already effectively going through the entire Moon. The crust and upper mantle are poorly resolved due to the skin-depth effect (see below): the highest frequency measurable by the Apollo-era sensors still penetrated hundreds of kilometers, obscuring shallow detail.

Next-generation EM sounding of the Moon can improve characterization of all three zones. The primary objective is to determine the electrical structure of the outermost 500 km and its spatial variability (ILN CIWG, 2009). This zone may represent global upper-mantle melt residuum or it could be laterally anomalous because Apollo geophysical data were collected within or adjacent to the Procellarum KREEP Terrane (PKT: Jolliff et al., 2000). The PKT encompasses Oceanus Procellarum, Mare Imbrium, and the adjoining mare and highlands, and is distinguished by unique geochemistry and extended volcanic history. Imaging the three-dimensional (3D) electrical structure of PKT compared to its surroundings could help distinguish an exogenic vs. endogenic origin, i.e., crustal thinning due to a Procellarum impact vs. a degree-one convection signature (see Wieczorek et al., 2006, for a review).

The second objective of renewed lunar EM sounding is to improve knowledge of the lower mantle (ILN CIWG, 2009). This requires both reducing the error bounds on the mean radial profile and searching for lateral heterogeneity. The Apollo results are dominated by several dozen time series taken over several months (e.g. Dyal et al., 1974; Hood et al., 1982): it is easy to imagine an order of magnitude more data, which could reduce the error on the radial conductivity profile by up to three-fold. This will improve constraints on temperature and composition, e.g., the role of alumina (Hood and Sonett, 1982 vs. H_2O (Grimm and McSween, 2009) as the source of conductivity-enhancing defects in silicates.

The third EM objective is detection and characterization of the core (ILN CIWG, 2009). Spatially distributed seismometers in a future network are the best way to image the core, but there has been progress inferring core radius using the relatively compact Apollo array (330 ± 20 km;

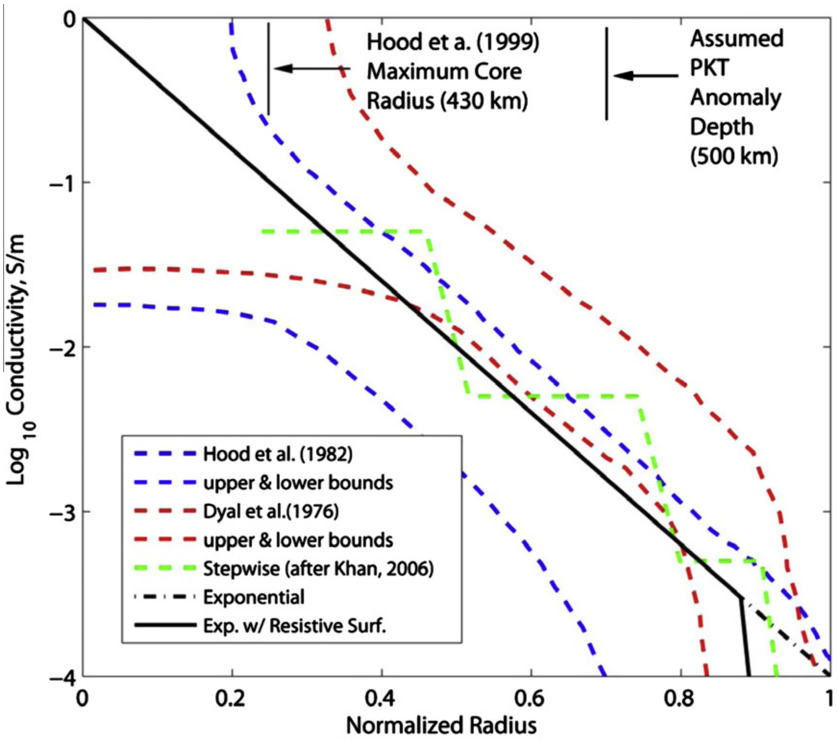

Fig. 1. Conductivity models treated here, superposed on prior results for lunar electromagnetic (EM) sounding. Dyal et al. (1976) and Hood et al. (1982) bounding envelopes are derived from measurements in a geomagnetic tail lobe and the dayside solar wind, respectively. Stepwise profile exaggerates apparent discontinuities from Khan et al. (2006) for discussion purposes. Exponential law is $\log \sigma = -4r$, where r is normalized radius. Resistive model adjusts surface conductivity to 10^{-9} S/m (Dyal et al., 1977). Anomalous PKT models adjust conductivity of the uppermost 500 km. Note that core-radius limits lie near or within region of effectively unbounded conductivity.