

RECENT ADVANCES IN LUNAR MAGNETISM. M. Wieczorek¹, B. Weiss², D. Breuer³, M. Fuller⁴, J. Gattacceca⁵, J. Halekas⁶, L. Hood⁷, F. Nimmo⁸, R. Oran², M. Purucker⁹, K. Soderlund¹⁰, and S. Tikoo¹¹, ¹Obs. Côte d'Azur, France (mark.wieczorek@oca.eu), ²Massachusetts Institute of Technology, USA ³Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany, ⁴Univ. Hawaii, USA, ⁵CEREGE, France, ⁶Univ. Iowa, USA, ⁷Univ. Arizona, USA, ⁸Univ. California Santa Cruz, USA, ⁹NASA Goddard Space Flight Center, USA, ¹⁰Univ. Texas at Austin, USA, ¹¹Rutgers Univ., USA.

Introduction. Before the Apollo missions, it was often thought that the Moon was a primordial, undifferentiated relic of the early Solar System. It was thus a great surprise when the Apollo subsatellites and surface magnetometers detected magnetic fields originating from the lunar crust.

The initial paleomagnetic analyses of the Apollo samples indicated that some rocks cooled in the presence of a magnetic field whose intensity was similar to Earth. However, the ages of these samples were unevenly distributed, and the paleointensities were uncertain. Magnetic field measurements made from equatorial orbits led to the discovery of many strong magnetic anomalies. The origin of these anomalies, however, was complicated by the fact that most were not correlated with known geologic process, and the equatorial distribution of the orbital data left the majority of the Moon's crust unexplored. Lastly, the origin of the magnetizing field was debated, with both internal core-generated and external fields being considered.

Tremendous advancements have been made towards understanding lunar magnetism since the close of the Apollo era. Global magnetic field mapping has been achieved from orbit by the Lunar Prospector and Kaguya spacecraft. The limitations associated with lunar rocks as paleomagnetic recorders have been quantified. Models for the distribution of lunar magnetic anomalies have been proposed. The size and composition of the lunar core is now better understood, and a wide range of mechanisms for powering an internal core-dynamo field have been investigated.

In this contribution, our current understanding of lunar magnetism will be reviewed. Advances made in the past decade since the publication of the first *New Views of the Moon* book [1] will be emphasized.

Paleomagnetism. New paleomagnetic analyses have strengthened the case that the Moon once had a long-lived global magnetic field with Earth-like field strengths. These new analyses place important constraints on the paleointensity fidelity by providing minimum retrievable field strengths [2]. From a suite of modern measurements, 40-110 μT surface field strengths were present from at least 4.25 to 3.56 Ga, after which the surface strength decreased rapidly to less than 10 μT at 3.3 Ga [3]. These samples recorded their natural remanent magnetization too slowly to have been magnetized by transient impact-generated

fields and require a long-lived field such as that generated by a core dynamo. The time when the dynamo started and stopped, however, is currently unknown, in large part due to a lack of suitable young and ancient samples.

Crustal Magnetism. Magnetometer data collected by the polar orbiting Lunar Prospector and Kaguya spacecraft have permitted the construction of global magnetic field maps of the Moon [4,5,6]. Some impact basins possess weak anomalies in their interiors, where an impact melt sheet should be present [7]. The largest concentration of anomalies is however located on the farside on the northern rim of the South Pole-Aitken impact basin. These anomalies may represent the remnants of the iron-rich projectile that formed this basin [8], ejecta deposits antipodal to the largest nearside basins [9], or dikes that were later emplaced in the crust [10]. Many strong anomalies have no correlation with geologic processes, and given that most lunar rocks possess low abundances of metallic iron, the origin of these anomalies remains enigmatic.

Core dynamo modeling. Both the crustal magnetic field and paleomagnetic analyses suggest that the Moon once possessed a core dynamo. Possible scenarios for powering a dynamo include thermal convection as the core cooled quickly after lunar formation, later core crystallization, precession of the mantle spin axis, and impact-induced changes in lunar rotation. Thermal convection is a relatively short-lived process, operating during the first few 100 million years of lunar evolution [11]. Once the core begins to crystallize, between about 4-4.4 Ga [12], buoyancy driven chemical convection can power a dynamo for about a billion years [13]. More exotic energy sources have also been proposed to power the lunar dynamo. Precession of the solid mantle spin axis can power a prolonged dynamo between about 4.25 to 2.7 Ga [14], and changes in rotation of the lunar spin axis following large basin-forming impact events can potentially power short-lived dynamos for 10s of thousands of years [15].

References. [1] Wieczorek et al. (2016), [2] Tikoo et al. (2014), [3] Weiss and Tikoo (2014), [4] Richmond and Hood (2008), [5] Purucker and Nicholas (2010), [6] Tsunakawa et al. (2015), [7] Hood (2011), [8] Wieczorek et al. (2012), [9] Hood et al. (2013), [10] Purucker et al. (2012), [11] Konrad and Spohn (1997), [12] Laneuville et al. (2014), [13] Scheinberg et al. (2015), [14] Dwyer et al. (2011), [15] Le Bars et al. (2011).