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ScienceDirect

Chemie der Erde 69 (2009) 3–43

CHEMIE der ERDE GEOCHEMISTRY

www.elsevier.de/chemer

INVITED REVIEW

The Moon 35 years after Apollo: What's left to learn?

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Received 11 December 2007; accepted 29 July 2008

Abstract

With the cancellation of the Apollo program after Apollo 17 returned from the Moon in 1972, the focus of NASA switched to other areas of the Solar System. Study of the Moon did continue through analysis of the returned samples and remotely sensed data sets (both orbital and surface), as well as through Earth-based telescopic studies. In the 1990s, new orbital data were obtained from several missions (fly-by and orbital), the first being Galileo that allowed the lunar farside to be mapped, followed by global mapping by the Clementine and Lunar Prospector missions.

Interest in the Moon started to increase at the beginning of the 21st century as other nations focused their space exploration programs on the Moon. The speech by President Bush in January 2004 put the Moon back into the critical exploration path for NASA, paving the way for humans to return to the lunar surface by 2020. This return will be critical for developing technologies and protocols for the eventual human exploration of other parts of the solar system. At the time of writing (June 2008), the SELENE/Kaguya mission (Japan and Chang'e-1 (China) are orbiting the Moon, with Chandrayaan-1 (India) and Lunar Reconnaissance Orbiter (USA) being scheduled to launch later in 2008.

The past (and present) exploration of the Moon begs the question "what's left to be done?" With the renewed focus on the Moon, now that it is on the pathway for the exploration of Mars (and beyond) a similar question has been raised – what should the astronauts do on the Moon? The publication of the *New Views of the Moon* book [Jolliff et al., 2006. New Views of the Moon, Reviews in Mineralogy, vol. 60. American Mineralogical Society, 721pp] highlighted a number of important scientific questions that remain unanswered as well as posing many more on the basis of the currently available data. These questions resonated in three Lunar Exploration Analysis Group (LEAG) reports pertinent to this discussion, which were also published (on line) during 2006 (http://www.lpi.usra.edu/leag), and in the National Research Council of the National Academies [2007. The Scientific Context for Exploration of the Moon. National Academies Press, Washington, DC, 112pp] report entitled "The Scientific Context for Exploration of the Moon". This paper synthesizes these recent studies, along with those from the 1980s and 1990s, to emphasize the lunar science questions that remain unanswered. In addition, it summarizes the missions already flown to the Moon along with those that are planned in order to give the reader an idea of exactly what lunar science has been and will be conducted in the hope that it will inspire proposals for missions to address the outstanding science questions.

Keywords: Lunar; Exploration; Moon; Mission; In situ resource utilization; Science; Remote sensing; Sample return; Impact; Lunar magma ocean

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doi:10.1016/j.chemer.2008.07.002

1. Introduction

The study of the Moon has produced amazing insights not only about Earth's only natural satellite, but also into planetary and solar system evolution. The *New Views of the Moon* (Jolliff et al., 2006) synthesized the data collected and models produced from it, covering the period up to and including Lunar Prospector in 1998. The combination of orbital remote sensing data with geophysics measurements (both from orbit and the lunar surface) and sample return data has demonstrated clearly that an integrated approach to exploration yields the most information regarding origin and evolution of any solid planetary body. The geophysics experiments deployed at the Apollo sites gave a first glimpse into the lunar interior and allowed mantle models inferred from mare basalt compositions to be tested, albeit at a rudimentary level. Lunar exploration has clearly shown that planetary evolution via a magma ocean is a tenable hypothesis (e.g., Smith et al., 1970; Wood et al., 1970; Warren, 1985) and that the unique nature of the Earth's Moon, relative to the moons of other planets in the solar system, is consistent with an unusual origin, such as the Earth colliding with a Mars-sized planetesimal and the Moon forming from the debris thus created (Benz et al., 1989; Cameron and Benz, 1991; Cameron, 1997, 2000; Canup and Asphaug, 2001; Canup et al., 2001, 2002). In addition, the combination of returned samples and remote observations has allowed the cratering rate through time to be explored and has put absolute ages on some of the larger impact events on the Moon and gives a few fixed points to which the cratering rate can be used to date the surfaces of the planets in the inner solar system. This has allowed identification of much younger lunar basalts (~0.9–1.2 Ga) around the Aristarchus Plateau and Marius Hills (Schultz and Spudis, 1983; Hiesinger et al., 2003) than are represented in the existing sample collection (~3.1–4.25 Ga; Dasch et al., 1987; Nyquist and Shih, 1992). The recognition of lunar meteorites (Bogard and Johnson, 1983) has increased the diversity of samples from the Moon, including the identification of the youngest mare basalt in the sample collection (Borg et al., 2004).

The data sets that have been used in the studies outlined above, as well as many others, were collected by a variety of missions to the Moon over several decades, and have benefitted from continued analysis of returned and meteoritic samples. Integrating these diverse data sets has been a challenge, but it has produced a fundamental leap forward in our knowledge of the Moon. So what is left to be done? In order to address this question, we need to understand how we got to this point in our understanding of the Moon.

This paper gives a broad outline of what we have learned from past exploration of the Moon and from this, a non-exhaustive list is developed of science questions that still remain. In addition, a description of the objectives and instrumentation on lunar missions that are currently at the Moon or those that are scheduled for launch in the near future is given, and finally a description of missions that are currently being planned (pre-phase A) is also given.

2. Previous investigations of the Moon: a timeline

2.1. Missions to the Moon

The exploration of the Earth's Moon actually began in earnest with the invention of the telescope in the early 17th century to dispel some of the myths initiated by the philosophy of Aristotle (384–322 BCE) that postulated that the Moon belonged to the "realm of corruption". Englishman Thomas Harriott is credited with the first telescopic observations in August of 1609 (Shirley, 1974). This preceded Galileo's lunar study by several months (Galileo, 1610, translated and annotated by van Helden, 1989). Many hypotheses put forth regarding the Moon (it harbored life, contained oceans, bright areas were rhyolitic in composition) were still being debated at the turn of the 20th century and some up to the Apollo program. It was only by visiting the Moon, making observations on the lunar surface, and returning samples for detailed (and still ongoing) analyses, that our understanding of Earth's celestial neighbor took a giant leap forward.

Unmanned missions to the Moon began in 1959 with the Soviet Luna-1 fly-by mission that arrived at the Moon on 3 January 1959 (Table 1). Luna 1 passed within 5995 km of the lunar surface and discovered that the Moon had no global magnetic field. This was followed closely by the American Pioneer 4 fly-by mission that arrived at the Moon on 4 March 1959 (Table 1). The capsule contained a lunar radiation experiment but was too high above the lunar surface (~60,000 km) for the experiment to register any radiation from the Moon. Between the time of Pioneer 4 and the beginning of Apollo (Apollo 8, launched on 21 December 1968), a total of 37 missions were launched to the Moon: 16 from the Soviet Union (Luna 2–14; Zond 3, 5, and 6) and 21 from the USA (Ranger 1–9; Surveyor 1–7; Lunar Orbiter 1–5; see Table 1).

Six Apollo spacecraft + astronauts landed on the Moon between 1969 and 1972, each returning lunar samples to Earth (Apollo 11, 12, 14, 15, 16, 17; Tables 1 and 2; Fig. 1). Between 1970 and 1976, three robotic Luna spacecraft landed and also returned lunar samples (Luna 16, 20, 24; Tables 1 and 2; Fig. 1). In addition to these returned samples, meteorites from the Moon have