THE SCIENCE GOALS OF ESA'S SMART-1 MISSION TO THE MOON

B. H. FOING[1], D. J. HEATHER[1], M. ALMEIDA[1] and SMART-1 SCIENCE TECHNOLOGY WORKING TEAM[2]
[1]*Space Science Department, ESA-ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands;* [2]*see acknowledgements*

Abstract. SMART-1 will be Europe's first lunar mission and represents an important step forwards in developing an international program of lunar exploration. The spacecraft will be ready for launch in late 2002, and is designed to test new technologies for use on future ESA cornerstone missions. In this respect, SMART-1 will also play a vital role in developing cutting edge technologies that could be a major part of the future of lunar and planetary science. SMART-1 will carry three remote sensing instruments that will be used during the mission's nominal six months in lunar orbit. These instruments will return data that will be relevant to a broad range of lunar studies, from bulk crustal composition and theories of lunar origin/evolution to the search for cold traps at the lunar poles and the mapping of potential lunar resources. With a perilune near the lunar south pole, the South Pole-Aitken Basin (SPA) is a prime target for studies using the SMART-1 suite of instruments.

1. Introduction

ESA's SMART-1 mission (e.g., Foing et al., 2000; Racca et al., 2001a; Marini et al., 2001) is the first in a series of Small Missions for Advanced Research and Technology, specifically designed to test technologies to be used on future ESA cornerstone programs. SMART-1 will fly to the Moon using a solar electric propulsion system that if successful, will be used on future interplanetary and deep space missions. The use of solar electric propulsion to carry the craft from within the Earth's gravity well will mean SMART-1 will have an extremely long cruise phase of the order of 12 to 15 months. This allows for some valuable cruise science and in-flight calibration to be completed prior to arrival at the Moon, after which a nominal six month lunar mapping phase will begin, with the possibility of an extension if instrument and spacecraft conditions permit. The baseline orbit is highly elliptical, with a perilune of about 300 km close to the lunar south pole. The apolune will initially be around 10,000 km but will be lowered if sufficient fuel remains, so as the science return of the mission can be optimised during the lunar mapping phase. It is hoped that apolune reduction will be achieved immediately in order to optimise the nominal six month mapping of the Moon prior to any significant degradation of the instruments that will be used.

The SMART-1 spacecraft carries six science instruments, three for spacecraft and planetary environment studies and three for lunar remote sensing. The Electric

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Propulsion Diagnostic Package (EPDP), Spacecraft Potential, Electron and Dust Experiment (SPEDE) and Radio Science Investigation with SMART-1 (RSIS) instruments will all help to demonstrate electric propulsion, the primary technological drive behind the SMART-1 mission (Racca et al., 2001a,b). Science opportunities also exist for these instruments, such as lunar exosphere studies planned for EPDP, and investigations of the planetary environment by SPEDE. Once at the Moon, global X-ray (Grande et al., 2000; Dunkin et al., 2001) and near infrared (Nathues et al., 2000, 2001) spectral mapping, and localised high spatial resolution colour imaging of the lunar surface (Josset et al., 2001) will be completed by the other three instruments carried by the mission. Together, these will provide a powerful integrated data archive that will deliver valuable scientific advances concerning our understanding of the Moon (Heather and Dunkin, 2000).

2. SMART-1 Instruments and Lunar Science Potential

The three primary lunar science instruments that will be carried by SMART-1 are D-CIXS, SIR, and AMIE. Each of these will play an important role in the continued exploration of the Moon and will allow for significant advances in lunar science.

2.1. D-CIXS (DEMONSTRATION OF A COMPACT IMAGING X-RAY SPECTROMETER)

D-CIXS will produce the first global view of the lunar surface in X-ray fluorescence (XRF), allowing for the measurement of elemental abundances of Fe, Mg, Al and Si (plus others if solar activity permits) across the whole Moon (e.g., Dunkin et al., 2001). These will be the first XRF measurements of the lunar surface since the Apollo 15 and 16 missions, which covered just 9% of the Moon and were restricted to equatorial regions (Figure 1). More importantly, D-CIXS will offer significant advances in resulting measurements, and will be able to deliver absolute elemental abundances rather than the elemental ratios derived from the Apollo measurements. The reason for this advance lies with the accompanying X-ray Solar Monitor (XSM) that will constantly monitor the solar activity that causes the lunar surface to fluoresce in X-rays. The D-CIXS instrument will also be using advanced Swept Charge Device technologies to make the photon detections, offering significantly higher sensitivity than the proportional counters used by Apollo (Grande et al., 2001).

The XRF data from D-CIXS will be important to a large number of lunar studies, including the mapping of potential lunar resources, the characterisation of the lunar crust and the refinement of bulk crustal composition estimates (Dunkin et al., 2001). The enigmatic South Pole-Aitken Basin (SPA) and other lunar basins are of particular interest to the instrument, which will have a footprint of the order of 50 km at perilune. These studies will all have a strong bearing on theories of the origin and evolution of the Moon.

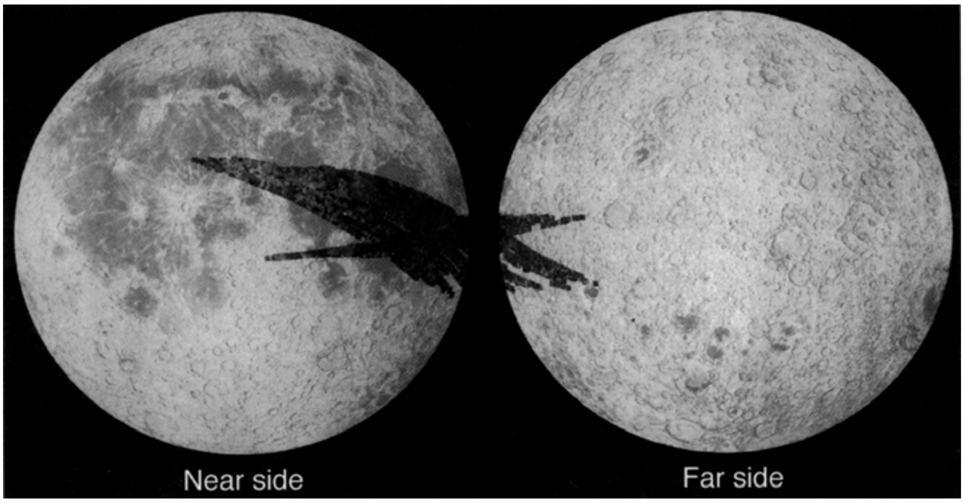

Figure 1. Measurements of the Al/Si ratio from the Apollo X-ray fluorescence (XRF) data (after Clark and Adler, 1978). The Apollo measurements cover just 9% of the lunar surface. D-CIXS will provide the first global XRF coverage as well as completing regional high resolution investigations. The D-CIXS data will greatly complement the elemental abundance maps obtained recently by the Lunar Prospector gamma-ray and neutron spectrometers. (*Courtesy of NASA.*)

Of key importance will be mapping of the global distribution of Mg and the production of global magnesium numbers (Mg#). The petrogenesis of the Mg-suite rocks which dominate much of the noritic upper crust seen by Clementine and Lunar Prospector (e.g., Tompkins and Pieters, 1999; Pieters and Tompkins, 1999), is not well understood. Although geochemical studies show the Mg-suite appear to have originated from both primitive and evolved sources, recent work by Shearer and Papike (2000) suggests that the Mg# is the only attribute to show evidence of a primitive source. All other elements seem to indicate the rocks to have formed from evolved magmas. A number of petrogenetic models that could produce this dichotomy in Mg-suite rocks were presented by Shearer and Papike (2000), ranging from an impact origin to the remelting of a magma ocean or cumulate pile. A magma ocean model will produce Mg-suite rocks that exhibit specific relations to other rock types, perhaps displaying an association with ferroan anorthosites or KREEP materials, so a more comprehensive characterisation of these will aid estimates of bulk crustal composition and theories for the evolution of the lunar crust. D-CIXS will help to address this critical issue to models of the thermal and physical evolution of the Moon. In combination with the other two remote sensing instruments on SMART-1, D-CIXS will provide global mineralogical and elemental coverage of the Moon (Dunkin et al., 2001).

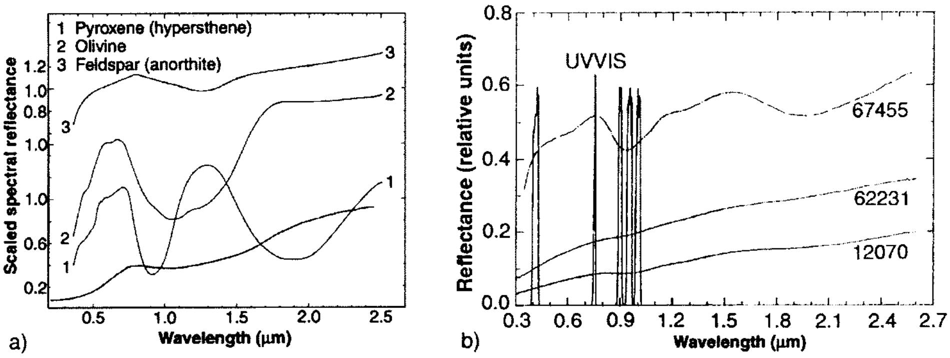

Figure 2. Spectra of key lunar minerals at UVVIS and NIR wavelengths. The left hand plot shows the spectra of pyroxenes (1) and olivines (2) and demonstrates the difference in the 1 µm absorption band shape for each of these. It is clear that the NIR measurements up to 2.4 µm that will be provided by SIR will allow for the separation of the pyroxene and olivine signatures. The plot on the right shows the spectra of some lunar samples, overlain by the wavelengths of the five filters from Clementine's UVVIS camera, which only cover the range from 0.4 to 1 µm and do not allow for this differentiation. (*Courtesy of C. Pieters.*)

2.2. SIR (SMART-1 INFRA-RED SPECTROMETER)

SIR will operate from 0.9 to 2.4 µm and will provide high spectral resolution data across the whole Moon, with a spatial resolution of 300 m from perilune (Nathues et al., 2000, 2001). This detector will use a monolithic quartz commercial grating spectrometer and will provide a high spectral resolution, with 250 channels. The resulting data will be extremely powerful, particularly in connection with existing digital data sets such as the Clementine and Lunar Prospector data, and with the other instruments to be carried by SMART-1. Reaching into the near infrared regions will allow for the opportunity to separate the pyroxene and olivine signatures in lunar soils (Figure 2). This is currently a limiting factor in our understanding of the evolution of crustal materials, as the distribution of olivine is poorly constrained in current models.

Olivine is considered by many to be a common mineral in the lunar mantle (e.g., Lucey et al., 1998), so its distribution throughout the lunar crust and across the lunar surface is of critical importance to models of crustal differentiation and evolution. A key target for observations using the SIR instrument will be the 2,500 km diameter South Pole-Aitken Basin (SPA), which may have dug through to expose materials from the lunar mantle (Lucey et al., 1998). This is strongly debated however, and many consider the anomalously mafic units in the region to represent lower crustal materials rather than lunar mantle units (e.g., Pieters et al., 1997). If measurements of the olivine and pyroxene distribution throughout the SPA can be made, the results would have a strong bearing on this contentious issue and would allow for improved models of crustal differentiation and thermal evolutionary models. SIR will help to further this study.

More generally, the SIR data will be used to refine compositional analyses already completed using Clementine and Lunar Prospector data, which is of key importance to theories of lunar origin and evolution, as a refined view of bulk crustal composition will be obtained. SIR will have a highest spatial resolution of the order of 300 m, so it will be able to resolve units on the central peaks, walls, rims and ejecta blankets of large impact craters, allowing for stratigraphic studies of the lunar crust. These will complement similar investigations made using the Clementine UVVIS camera data to investigate compositional diversity of the lunar crust (e.g., Tompkins and Pieters, 1999; Heather, 2000; Heather and Dunkin, 2001).

2.3. AMIE (ASTEROID MOON IMAGING EXPERIMENT)

During the cruise phase, the AMIE camera will make observations of the Earth, the Moon, asteroids and other celestial objects. The D-CIXS spectrometer will also perform longterm monitoring of bright X-ray cosmic sources.

The micro camera AMIE will provide high resolution CCD images of selected lunar areas, and limited multispectral reflectance data of high spatial resolution (Figure 3). The camera represents significant technological advances in micro-engineering for lightweight cameras (Josset et al., 2001) and will be used in a series of experiments in combination with other new flight technologies during the SMART-1 mission (Marini et al., 2001). The camera will image using three filters for colour analyses, with bands at 750 nm, 900 nm and 950 nm in order to provide data on the 1 μm absorption feature common to pyroxene and olivine rich mineral assemblages. The instrument will aim for an average resolution of 80 m/pixel, and near the perilune, will obtain 30 m/pixel resolution images.

The lunar south pole is a key science target area for this instrument, as SMART-1 will be near its perilune at this point. AMIE will take high resolution images of the lunar south pole that can be integrated with the corresponding Clementine data (Figure 4) to allow for the identification of permanently lit/shadowed areas. In combination with the Lunar Prospector neutron spectrometer data (e.g., Feldmann et al., 2000), the search for potential "water ice traps" or "cold traps" can be refined using data that will be obtained by AMIE. From a more visionary perspective, improved mapping of the south pole will allow for the identification and mapping of potential sites of "eternal light" and "eternal shadow" that could be used in future lunar exploration for the establishment of lunar bases and power supplies (e.g., Bussey and Spudis, 1999). Outside of these specific studies, AMIE will provide the geological context for the accompanying SIR and D-CIXS data, and will allow for the spectral information to be used to its full potential.

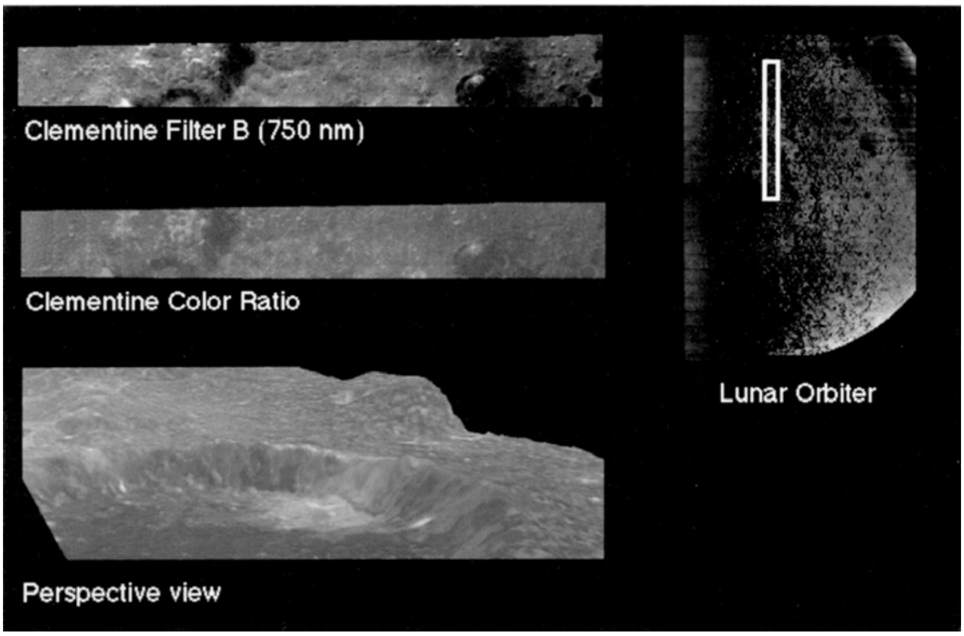

Figure 3. The AMIE camera will provide the geological and spatial context for the other SMART-1 instruments, delivering high spatial resolution (30 m/pixel) multicolour images, as well as stereo imagery for topographic studies. The figure shows the lower spatial resolution (200 m/pixel) Clementine UVVIS camera data for the Orientale Basin to illustrate the power of such studies. (*Courtesy of DLR-Berlin.*)

3. Data Integration and the Global Lunar Resource Framework

Data integration and international co-operation are being kept in mind from the outset of the SMART-1 mission. The data will be placed within the framework of a "global resource" that is now under construction at ESA's Science and Technology Centre (ESTEC) in the Netherlands. This will ease integration of the data both between the instruments and with existing data from previous missions such as Clementine and Lunar Prospector (Heather and Dunkin, 2000). In addition, talks are underway to collaborate with the upcoming Japanese Lunar-A and SELENE missions so as to optimise the science return from all three missions. In all, SMART-1 has an important role to play in the strategic exploration of the Moon, both from point of view of science return, and in the establishment of long-term internationally co-ordinated programs of lunar exploration.

4. Summary

SMART-1 represents Europe's first lunar mission and will provide some significant advances to many issues currently active in lunar science, such as our understand-

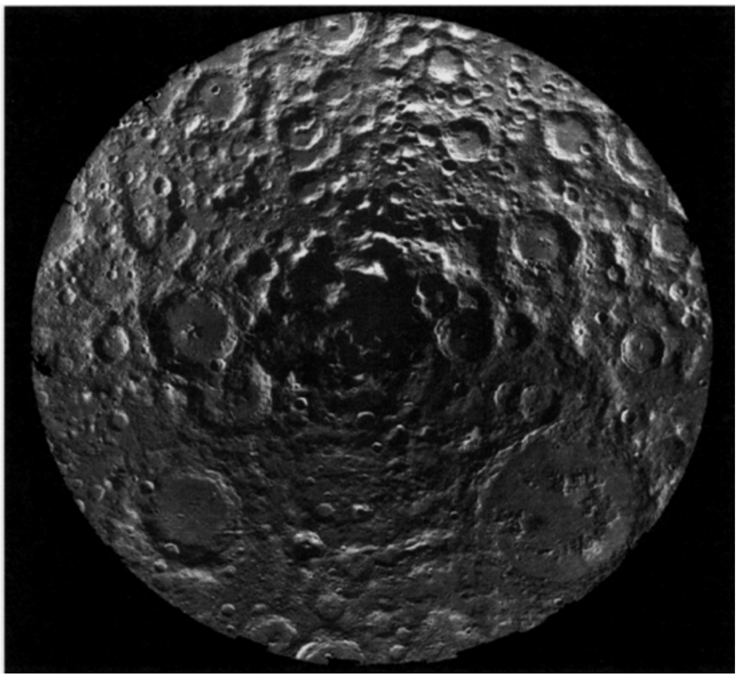

Figure 4. The six month nominal lunar mapping phase of the SMART-1 mission will provide the AMIE camera with an excellent opportunity to take high resolution images to study the illumination properties of the lunar south pole for an extended period. AMIE will be able to map the interior of dark craters, taking deeper exposures than those from the Clementine instruments. (*Courtesy Lunar and Planetary Institute*.)

ing of lunar origin and evolution. The mission also carries responsibility as an important step forwards in developing an international program of lunar exploration. The spacecraft will be ready for launch in late 2002 and will have a year-long launch window and a cruise phase of the order of 15 months.

Three remote sensing instruments, D-CIXS, SIR and AMIE, will be used during the mission's nominal six months in lunar orbit, and these will return data that will be relevant to a broad range of lunar studies. The mission will provide the first global X-ray map of the Moon, global high spectral resolution NIR spectrometry, as well as high spatial resolution colour imaging of selected regions. Combined, these will aid a large number of science studies, from bulk crustal composition and theories of lunar origin/evolution to the search for cold traps at the lunar poles and the mapping of potential lunar resources. With a perilune near the lunar south pole, the South Pole-Aitken Basin (SPA) is a prime target for studies using the SMART-1 suite of instruments.

Further information and updates on the SMART-1 mission status can be found on the ESA Science Web pages, at: *http://sci.esa.int/smart-1/*

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