Lunar-A

Lunar-A mission: Outline and current status

H Mizutani*, A Fujimura, S Tanaka, H Shiraishi and T Nakjima

Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Yoshinodai 3-l-l, Sagamihara, Kanagawa 229 8510, Japan.
**e-mail: mizutani@planeta.sci.isas.ac.jp*

The scientific objective of the Lunar-A, Japanese Penetrator Mission, is to explore the lunar interior by seismic and heat-flow experiments. Two penetrators containing two seismometers (horizontal and vertical components) and heat-flow probes will be deployed from a spacecraft onto the lunar surface, one on the near-side and the other on the far-side of the moon. The data obtained by the penetrators will be transmitted to the earth station via the Lunar-A mother spacecraft orbiting at an altitude of about 200 km.

The spacecraft of a cylindrical shape, 2.2 m in maximum diameter and 1.7 m in height, is designed to be spin-stabilized. The spacecraft will be inserted into an elliptic lunar orbit, after about a half-year cruise during which complex manoeuvering is made using the lunar-solar gravity assist. After lunar orbit insertion, two penetrators will be separated from the spacecraft near perilune, one by one, and will be landed on the lunar surface.

The final impact velocity of the penetrator will be about 285 m/sec; it will encounter a shock of about 8000 G at impact on the lunar surface. According to numerous experimental impact tests using model penetrators and a lunar-regolith analog target, each penetrator is predicted to penetrate to a depth between l and 3 m, depending on the hardness and/or particle-size distribution of the lunar regolith. The penetration depth is important for ensuring the temperature stability of the instruments in the penetrator and heat flow measurements. According to the results of the Apollo heat flow experiment, an insulating regolith blanket of only 30 cm is sufficient to dampen out about 280 K lunar surface temperature fluctuation to <3 K variation.

The seismic observations are expected to provide key data on the size of the lunar core, as well as data on deep lunar mantle structure. The heat flow measurements at two penetrator-landing sites will also provide important data on the thermal structure and bulk concentrations of heat-generating elements in the Moon. These data will provide much stronger geophysical constraints on the origin and evolution of the Moon than has been obtained so far.

Currently, the Lunar-A system is being reviewed and a more robust system for communication between the penetrators and spacecraft is being implemented according to the lessons learned from Beagle-2 and DS-2 failures. More impact tests for penetrators onto a lunar regolith analogue target will be undertaken before its launch.

1. Introduction

The internal structure of the Moon (e.g., Toksoz *et al* 1974; Goins *et al* 1981; Nakamura *et al* 1982; Nakamura 1983) is mainly based on Apollo seismic data, in which the useful seismic waves penetrate to a depth of about 400 km. Therefore the seismic structure of the Moon below 400 km depth is not constrained by the Apollo data. Moreover the long-believed crustal thickness of about 60 km obtained by Toksoz *et al* (1974) and Nakamura (1983) are being questioned by

Keywords. Lunar-A; penetrator; lunar exploration; lunar interior; lunar seismology; heat flow.

J. Earth Syst. Sci. **114**, No. 6, December 2005, pp. 763–768

the recent reanalysis of Apollo data which propose a much thinner crust (Khan *et al* 2000; Chenet *et al* 2000). These recent studies indicate that our current understanding of lunar internal structure is very limited even in the shallow part of the Moon. Unless we can significantly narrow the uncertainty of seismic velocity structure, mineralogical or geochemical interpretations of the lunar interior (Kuskov 1995; Kuskov and Kronrad 1998) should be regarded as quite ambiguous. In particular, more precise determination of the deep lunar internal structure and core size is important to interpret the observed depletion of siderophile elements in lunar rocks (Newsome and Drake 1983; Newsome 1986; Ringwood and Seifert 1986), as well as the mantle density distribution which, in turn, constrains the Mg number of the mantle.

The bulk abundance of refractory elements is also tightly connected with geophysical observations, because the global lunar U concentration may be estimated from heat flow measurements. The Apollo 15 and 17 heat flow probes gave the heat flow values of 21 and 16 mW/m^2 respectively (Langseth *et al* 1976), from which Keihm and Langseth (1977) estimated a mean heat flow of 14 to 18 mW/m^2. This range of heat flow values corresponds to a global lunar U concentration of 33 to 44 ppb, if a steady-state balance between heat loss (flow) and heat production is assumed. However, derivation of globally representative averages of the heat flow from the two Apollo sites is difficult, because the Apollo heat flow data may contain a rather significant effect of heat-flow-focusing effect due to very low thermal conductivity of megaregolith (Rasmussen and Warren 1985). Therefore the global U abundance estimated by Keihm and Langseth (1977) has a large uncertainty, as pointed out by Rasmussen and Warren (1985) who claimed that the lunar bulk concentration of U may be as low as that in the earth's mantle. Since the bulk abundance of refractory elements in the Moon, as compared with that in the Earth, is important for delineating lunar origin, more measurements of heat flow at different geological settings are desirable to derive a reliable global heat flow average and hence a global U abundance in the Moon.

The Lunar-A mission is planned to provide some important clues to address the abovementioned problems. In order to achieve the scientific objectives, penetrators were thought to be the most effective means, because they can deploy scientific instruments at different sites in one mission. This mission will be the first to deploy scientific instruments on the lunar surface after the Apollo and Luna missions.

2. Mission outline

The Japanese lunar penetrator mission, Lunar-A, will be launched from the Uchinoura Space Center of the Institute of Space and Astronautical Science, JAXA, Japan, using the M-V launch vehicle which can send a spacecraft of about 550 kg into a lunar transfer orbit. Although the launch date was changed several times in the past for various reasons, the essential mission concept has been retained. The spacecraft will be first inserted into an elliptic lunar orbit ($i = 30$ deg, perilune = 40 km altitude, and apolune = 200 km altitude), after about a half-year cruise during which complex manoeuvering is made using the lunar-solar gravity assist (Uesugi *et al* 1989). The gravity-assist manoeuvering of the spacecraft significantly reduces the propellant required to insert the spacecraft into lunar orbit and allows an increase in the payload mass. After lunar orbit insertion, two penetrators will be separated from the spacecraft near perilune, one by one, and will be landed on the lunar surface.

The penetrator, which is described in more detail in the next section, will be deorbited by a small solid-propellant motor, canceling completely the spacecraft orbital velocity, and will fall freely from about 25 km altitude onto the lunar surface. During the free fall descent, the penetrator will be reoriented to become vertical to the lunar surface using a side-jet. The deorbit motor and attitude controller attached to the penetrator will be jettisoned after they become useless and before the penetrator hits the lunar surface.

The final impact velocity of the penetrator will be about 285 m/sec; it will encounter a shock loading of about 8000 G at impact on the lunar surface. According to numerous experimental impact tests (e.g., ISAS Lunar Penetrator Team 1993) using model penetrators and a lunar-regolith analog target, each penetrator is predicted to penetrate to a depth between 1 and 3 m, depending on the hardness and/or particle-size distribution of the lunar regolith. The penetration depth is important for ensuring the temperature stability of the instruments in the penetrator and heat flow measurements. According to the results of the Apollo heat flow experiment (Keihm and Langseth 1977), an insulating regolith blanket of only 30 cm is sufficient to dampen out about 280 K lunar surface temperature fluctuation to < 3 K variation. Thus the penetrator instruments will not require any temperature controller system, which helps to save the power consumption of the Lunar-A penetrator system.

It will require about two weeks to deploy the two penetrators at two widely spaced sites. One penetrator will be placed on the near-side of the Moon and the other on the far-side. The site of the near-side penetrator is located near the Apollo 12 or 14 site, enabling us comparison of the Lunar-A data with Apollo network data. The far-side penetrator will be placed at a position near the antipodal point of a deep moonquake source. After releasing both the penetrators, the spacecraft will make a trajectory control manoeuver and will be injected onto a near-circular orbit whose altitude is about 200 km from the lunar surface.

The data gathered by the scientific instruments will be numerically compressed and stored in a recorder within the penetrator and will then be transmitted to the Earth via the carrier spacecraft which will come over each penetrator about every 15 days. A UHF ($f = 400\,\mathrm{MHz}$) hybrid telemetry system will be used for communication between the deployed penetrators and the relay spacecraft, while communication between the spacecraft and ground station will be by S-band ($f = 2\,\mathrm{GHz}$). Since the lunar regolith is relatively transparent to radio-waves (Carrier *et al* 1991), there will be essentially no attenuation of the radio signal from the antenna, which also will be buried between 1 and 3 m depth in the regolith, The data transfer rate from the penetrator to the mother spacecraft will be up to 1 kbits/sec and that from the spacecraft to the ground station will be 8 kbits/sec.

The communication link among the penetrator, the orbiting spacecraft, and the ground station is schematically shown in figure 1. Besides the scientific instruments within the penetrator, the orbiting spacecraft will also carry a monochromatic imaging camera whose spatial resolution will be about 30 m. Because the Lunar-A imaging camera is designed to take images at low sun angle, the data obtained will give much clearer images with higher contrast than Clementine UV/VIS camera (Pieters *et al* 1994).

3. Instruments onboard the penetrator

The penetrator itself, excluding a retro-motor and an attitude control system is of a cylindrical shape with an ogive-shape nose (see Mizutani *et al* 2003 for more details) and weighs about 13.5 kg. It contains a two-component seismometer and a heat flow probe together with other supporting instruments such as a tiltmeter and an accelerometer. The tilt meter is used to know the attitude of the penetrator in the regolith and the accelerometer is used to estimate the depth of the penetrator.

The seismometer used in the Lunar-A penetrator is a short-period electromagnetic seismometer with a natural period of about 1 sec. Since the penetrator will not be placed in the lunar regolith in an exact vertical direction, a rotation mechanism is installed to reorient the seismometers to the desired direction. The seismometers are designed to be approximately 5 times as sensitive as either the Apollo short-period or long-period seismometer at a frequency of around 1 Hz (Latham *et al* 1969). The high shock-durability is attained by reducing movable components to a minimum. The ground motion will be recorded for signals larger than a threshold level in order to reduce power consumption. The threshold level can be adjusted by a command from the ground. Although the lunar seismic signal for one event usually lasts more than one hour, signals will be recorded for only a limited period for each event to save memory size and power consumption in the nominal operation mode. The recording duration will depend on the size of the moonquakes, which will be automatically assessed 256 s after the recognition of an event.

The heat-flow probe consists of nineteen temperature sensors and five thermal conductivity measurement sensors attached to the wall of the penetrator (Tanaka *et al* 1999). Although the lunar surface temperature varies from 100 K at night to 400 K in daytime, the temperature oscillation is damped out very quickly with depth due to the very low thermal diffusivity of the lunar regolith. Therefore it will be possible to determine the subsurface temperature gradient by measuring the temperature at several points deeper than 50 cm from the surface. The thermal conductivity of the lunar regolith is measured by recording the temperature variation associated with the heat output from a point source attached on the interface between the penetrator and regolith.

All the instruments are powered by Li-SOCl2 batteries which have a power density of about 430 W/kg. Although the instruments are designed to have low power-consumption, the life-time of the instruments are limited to one year due to the limitation of the battery size in the penetrator.

4. Scientific experiments

Seismological observation of the Lunar-A mission will study deep moonquakes whose sources are located by Apollo seismic network. Since each deep moonquake has its own characteristic waveform and an origin-time versus tidal-phases correlation (Toksoz *et al* 1974; Nakamura *et al* 1982), the focus of a deep moonquake may be determined by the data obtained at a single station near the Apollo 12 or 14 stations and its comparison with the data of Apollo 12 and 14 site. Because a deep moonquake from each source occurs about once per month, we will be able to accumulate a rather comprehensive data set over a wide range

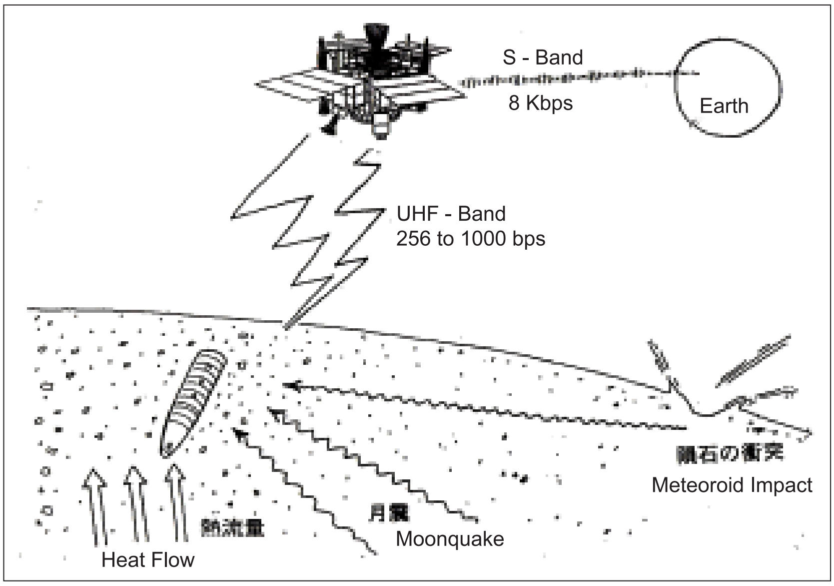

Figure 1. Schematic diagram of the Lunar-A penetrator operation.

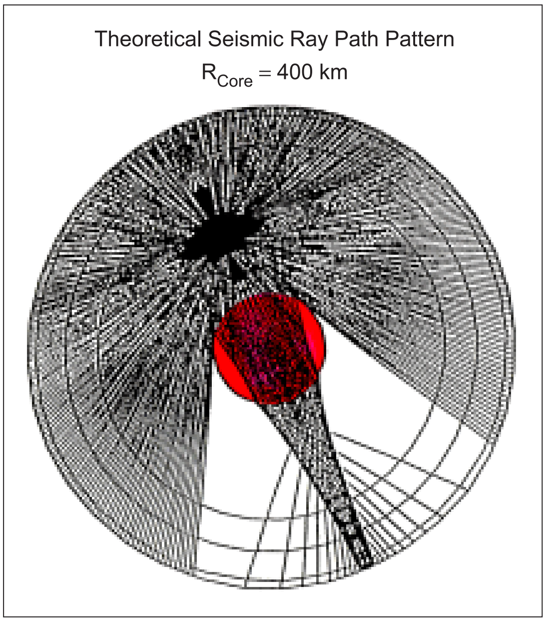

Figure 2. Theoretical seismic ray paths from a deep moonquake located at a depth of 900 km. The strong ray focusing is observed at an antipodal site of the epicenter.

of angular distance during a one-year observation period.

If we can determine the foci of moonquakes, the amplitude and travel times of the seismic-waves will provide important data on the internal structure. Figure 2 shows the ray-path patterns of seismic waves from a deep moonquake for a model with an iron liquid core of 400 km in radius: the crust and mantle structure is taken from Nakamura *et al*'s model (Nakamura *et al* 1982). As is shown in figure 2, the core with radius as large as 400 km will act as a large lens for seismic wave propagation, causing a strong convergence of ray-paths at the antipodal point of the epicenter and a rather wide shadow zone. If the lunar core is smaller than 300 km, we will not observe a strong focusing effect. Therefore by observing seismic waves at two different sites from many deep moonquakes, we will be able to gradually delineate the true ray-path pattern and eventually determine the size of the core in the Moon. If the core radius is found to be as large as 400 to 500 km, then the bulk abundance of the siderophile elements is not so much depleted from Cl chondrite abundance as has been inferred from returned lunar rocks. Since the bulk abundances of lunar siderophile elements is a key factor for constraining the origin of the Moon (Newsome and Drake 1983; Newsome 1986), determination of the lunar core size has significant implications for the origin of the Moon.

Determination of the heat flow is made by a combination of the thermal conductivity measurement and temperature gradient measurement in the lunar regolith. The temperature field in the regolith around the penetrator will be significantly disturbed by penetrator emplacement. Therefore the determination of intrinsic temperature gradient in the regolith is not a simple task. In order to avoid thermal disturbances due to power consumption within the penetrator, the heat flow measurement will be made before and after full operation of the seismometers. Moreover a detailed analysis of the temperature field within and around the penetrator will be required for a quantitative determination of the heat flow values. Although the accuracy of the determined heat flow depends on the accuracy of the modeling, quantitative assessment using the finite element method on the temperature field around the penetrator indicates that we can estimate the heat flow value to within about l5% (Tanaka *et al* 1999).

Heat flow observations by a penetrator deployed on the near-side of the Moon will provide the heat flow value for Procellarum KREEP terrain, where very high thorium abundance was observed (Lawrence *et al* 1999; Jolliff *et al* 200l). On the other hand, a penetrator on the far-side provides the heat flow data for the Feldspathic Highlands Terrane where low thorium abundance was observed (Jolliff *et al* 2001). Therefore, comparison of the heat flow values at two different sites, together with the result of the Apollo heat flow experiments, will enable us to estimate the heat flow from the mantle and also the global average of lunar heat flow values.

5. Current status

The Lunar-A mission was originally supposed to be launched in 2004 but it was postponed due to the necessity of a replacement of the valves used in the RCS propulsion system of the spacecraft, following a recall issued by the manufacturer who found a malfunction of similar valves. On the other hand the internal review for launch readiness is made and the review board recommended that the improvement of the communication link between the penetrator and the orbiting spacecraft should be made, based on lessons learned from the DS-2 and Beagle-2 failure of their communication link. Improvement for a more robust communication link requires more impact tests of the penetrator qualification, and hence the launch will be delayed by more than two years and may occur in 2007.

6. Conclusions

The Lunar-A mission is expected to provide important information about lunar internal structure and the thermal state of the Moon. This mission will also demonstrate the usefulness of the penetrator technology for future planetary missions. We believe that application and modification of the Lunar-A penetrators will expand the horizons of future planetary exploration.

The Lunar-A mission is the first mission dedicated to studying the lunar internal structure but this mission alone will not be sufficient to reveal the fine details. It is clear that we need more seismic stations and a longer operation period in order to clearly understand the lunar crust, mantle, and core structure. Since the Moon is the most easily accessible planet body, our effort to study the lunar interior should be continued and expanded after the Lunar-A mission.

Acknowledgements

We wish to thank the members of the Lunar-A Science team, Drs H Murakami, I Yamada, J Koyama, K Yomogida, N Kobayashi, M Hayakawa, N Takeuchi, for their contribution to this project. We are also grateful for the ISAS engineering team of Lunar-A mission for their effort of solving many technical problems related to this mission.

References

Carrier W D III, Olhoel G R and Mendell W 1991 Physical Properties of the Lunar Surface in Lunar Source Book; A Users Guide Book (eds) G Heiken, D Vaniman and B M French (London: Cambridge University Press) pp. 475–594.

Chenet H, Gagnepain-Beyneix J P, Lognonne P and Vinnik L 2000 Reprocessing of the Apollo lunar seismic data: A thinner lunar crust; EOS Transaction AGU **8l** F771.

Goins N R, Dainty A M and Toksoz M N 1981 Lunar seismology: The internal structure of the moon, *J. Geophys. Res.* **86** 5061–5074.

ISAS Lunar Penetrator Team 1993 Report of the 13th penetrator impact experiment in Japanese SES-TD-93-004; *Inst. Space Astronaut Sci.*, p. 239.

Jolliff B L, Gillis J I, Haskin L A, Korotev R L and Wieczorek M A 2000 Major lunar crustal terranes: Surface expressions and crust-mantle origins; *J. Geophys. Res.* **109** 4197–4216.

Keihm S J and Langseth M G 1977 Lunar thermal regime to 300 km; *Proc. Lunar Sci. Conf. 8th*, pp. 499–514.

Khan A, Mosegaard K and Rasmussen K L 2000 A new seismic velocity model for the Moon from a Monte Carlo inversion of the Apollo seismic data; *Geophys. Res. Lett.* **27** 1592–1594.

Kuskov O L 1995 Constitution of the Moon: 3 Composition of middle mantle from seismic data; *Phys. Earth Planet. Int.* **90** 55–74.

Kuskov O L and Kronrad V A 1998 Constitution of the Moon: 5 Constraints on composition density temperature and radius of a core; *Phys. Earth Planet. Int.* **107** 285–306.

Langseth M G, Keihm S J and Peters K 1976 Revised lunar heat flow values; *Proc. Lunar Sci. Conf. 7th*, pp. 3143–3171.

Latham V L, Ewing M, Press F, Sutton G, Dorman J, Toksoz N, Wiggins R, Nakamura Y, Derr J and Duennebier F 1969 Passive seismic experiment Apollo ll; Preliminary Report NASA SP-214, pp. 143–161.

Lawrence D J, Feldman W C, Barraclough B L, Binder A B, Elphic R C, Maurice S, Miller M C and Prettyman T H 1999 High resolution measurements of absolute thorium abundance on the lunar surface; *Geophys. Res. Lett.* **26** 268l–2684.

Mizutani H, Fujimura A, Tanaka S, Shiraishi H and Nakajima T 2003 Lunar-A mission: Goals and Status; *Adv. Sci. Res.* **31** 2315–2321.

Nakamura Y 1983 Seismic velocity structure of the lunar mantle; *J. Geophys. Res.* **88** 677–686.

Nakamura Y, Latham G V and Dorman H J 1982 Apollo lunar seismic experiment – final summary; Proc. Lunar Planet Sci. Conf. l3th; *J. Geophys. Res.* **87** A117–A123.

Newsome H E and Drake M J 1983 Experimental investigation of the partitioning of phosphorous between metal and silicate phases: Implication for the earth, moon and eucrite body; *Geochim. Cosmochim. Acta* **47** 93–100.

Newsome H E 1986 Constraints on the origin of the Moon from the abundance of molybdenum and other siderophile elements; In: *The Origin of the Moon* (eds) Hartmann W K, Phillips R J and Taylor G J (Houston: Lunar and Planetary Institute) pp. 203–230.

Pieters C M, Staid M I, Fischer S and Tomplins G H 1994 A sharper view of impact craters from Clementine data; *Science* **266** 1844–1850.

Rasmussen K L and Warren P H 1985 Magaregolith thickness, heat flow and the bulk composition of the moon; *Nature* **313** 121–124.

Ringwood A E and Seifert S 1986 Nickel–Cobalt abundance systematics and their bearing on lunar origin; In: *The Origin of the Moon* (eds) W K Hartmann, R J Phillips and G J Taylor (Houston: Lunar and Planetary Institute) pp. 249–278.

Tanaka S, Yoshida S, Hayakawa M, Horai K, Fujimura A and Mizutani H 1999 Development of the heat flow measurement system by Lunar-A penetrators; *Adv. Space. Res.* **23** 1825–1828.

Toksoz M, Dainty N A M, Solomon S C and Anderson K 1974 Structure of the Moon; *Rev. Geophys. Space Phys.* **12** 539–567.

Uesugi K, Kawaguchi J, Ishii S, Kimura M and Tanaka K 1989 Design of double lunar swing by orbits for MUSES-A and Geotail; *Advance Astron. Sci.* **69** 319–331.

Wood J A 1986 Moon over Mauna Loa: A review of hypotheses of formation of Earth's Moon; In: *The Origin of the Moon* (eds) W K Hartmann, R J Phillips and G J Taylor (Houston: Lunar and Planetary Institute) pp. 17–56.