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The Kaguya Mission Overview

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Abstract The Japanese lunar orbiter Kaguya (SELENE) was successfully launched by an H2A rocket on September 14, 2007. On October 4, 2007, after passing through a phasing orbit 2.5 times around the Earth, Kaguya was inserted into a large elliptical orbit circling the Moon. After the apolune altitude was lowered, Kaguya reached its nominal 100 km circular polar observation orbit on October 19. During the process of realizing the nominal orbit, two subsatellites Okina (Rstar) and Ouna (Vstar) were released into elliptical orbits with 2400 km and 800 km apolune, respectively; both elliptical orbits had 100 km perilunes. After the functionality of bus system was verified, four radar antennas and a magnetometer boom were extended, and a plasma imager was deployed. Acquisition of scientific data was carried out for 10 months of nominal mission that began in mid-December 2007. During the 8-month extended mission, magnetic fields and gamma-rays from lower orbits were measured; in addition to this, low-altitude observations were carried out using a Terrain Camera, a Multiband Imager, and an HDTV camera. New data pertaining to an intense magnetic anomaly and GRS data with higher spatial resolution were acquired to study magnetism and the elemental distribution of the Moon. After some orbital maneuvers were performed by using the saved fuel, the Kaguya spacecraft finally impacted on the southeast part of the Moon. The Kaguya team has archived the initial science data, and since November 2, 2009, the data has been made available to public, and can be accessed at the Kaguya homepage of JAXA. The team continues to also study and publish initial results in international journals. Science purposes of the mission and onboard instruments including initial science results are described in this overview.

Keywords Kaguya · Lunar exploration · Lunar science · Origin and evolution of the moon · Remote-sensing

Abbreviations

SELENE	Selenological and engineering explorer

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JAXA	Japan aerospace exploration agency
ISAS	Institute of space and astronautical science
NASDA	National space development agency of Japan
NAOJ	National astronomical observatory of Japan

1 Introduction

The Apollo missions marked the beginning of scientific exploration of the Moon. The observation of moonquakes provided a rough understanding of the lunar interior. The Moon consists of a three-layer structure: crust, mantle, and core (Toksöz et al. 1973), which is a common feature of terrestrial planets. Collected rock samples revealed the formation ages and helped derive a new model for the origin of the Moon. According to the magma ocean model, a "rockberg" floated over a magma ocean during the intial stage of lunar formation around 4.6 billion years ago (Longhi 1978). During the 1980s there was a relative lack of lunar missions: only small robotic missions such as the US missions, Clementine (Nozette et al. 1994) and the Lunar Prospector (Binder 1998), and a Japanese mission were sent to the Moon. The US missions observed the entire Moon by focusing on elemental and mineral abundances, topography, and gravitational and magnetic fields. The Japanese "Hiten" mission was a technology demonstration mission (Uesugi 1996). After these precursors, the Kaguya (SELENE) project was promoted to explore the Moon from the viewpoint of further lunar studies and future utilization (Kato et al. 2000; Sasaki et al. 2003).

The lunar orbiter Kaguya was launched successfully on September 14, 2007 from the JAXA Tanegashima Space Center (TKSC) (Fig. 1). On October 19, 2007, Kaguya was inserted into a nominal orbit at an altitude of 100 km for remote-sensing the whole Moon. Acquisition of scientific data was carried out for a nominal mission period of 10 months and an extended period of 8 months during which saved fuel was used. The Kaguya mission was completed on June 10, 2009; after the thruster fuel had been consumed the orbiter impacted on the rim of the Gill-B crater of the lunar nearside after consuming thruster fuel on June 10, 2009. Figure 2 shows the impact flash of the Kaguya spacecraft captured by telescopes of the Anglo-Australia observatory and Mt. Abu observatory in India.

Fig. 1 Launch of the Kaguya spacecraft. The spacecraft was lifted off by No. 13 H2A rocket from Tanegashima Space Center TKSC at 2007-09-14T01:31:01 UT

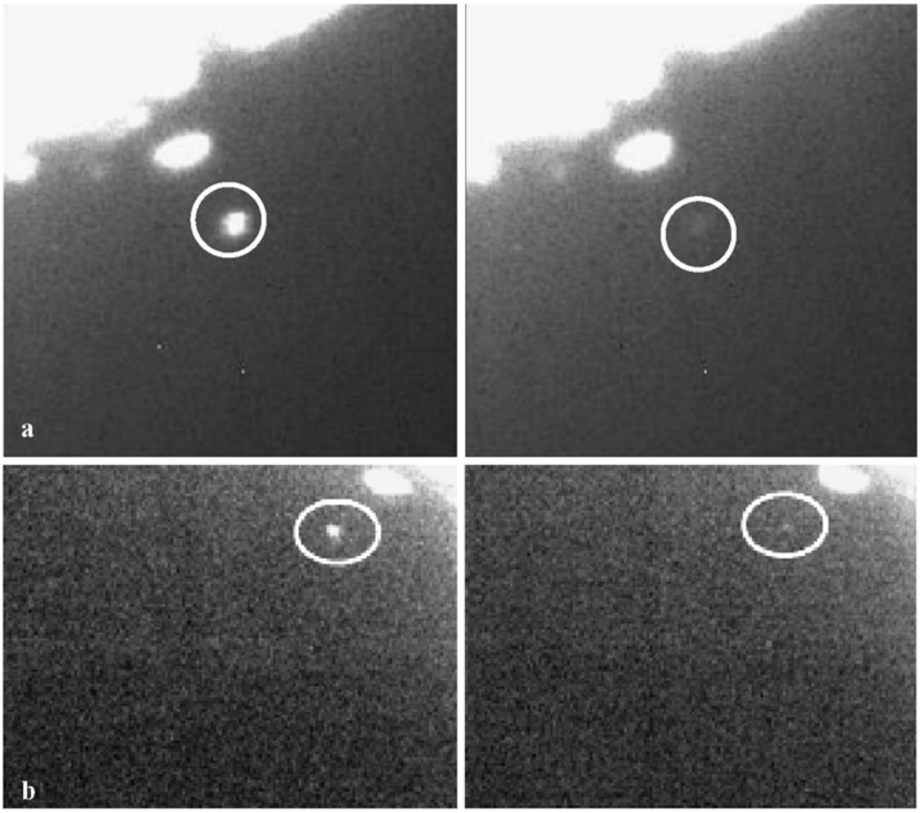

Fig. 2 Impact flash of the Kaguya spacecraft. Telescope images taken by the Anglo-Australia Observatory of University of South Wales (**a**), and the Mt. Abu Observatory of Indian Space Research Organization (**b**). *Upper images* are taken at 1.6-seconds interval, and *lower images* at 1.0-second interval

2 Mission Overview and Onboard Instruments

2.1 Spacecraft Configuration and Mission Profile

The Kaguya (SELENE) consisted of three spacecraft: a three-axis-controlled main orbiter, and two spin stabilized subsatellites (Table 1). Dimensions of the main orbiter were 2.0 × 2.0 × 4.3 m, a rectangular parallelepiped, and the two sub-satellites were both octagonal prisms of 0.9 × 0.9 × 1.1 m and 50 kg. The total wet mass at launch was about 3 tons, which included 1.1 tons of fuel, the two subsatellites, and about 300 kg of total science instruments.

The main orbiter carried the two subsatellites on its roof. Deployments of a solar array paddle and a high-gain antenna, and mid-course maneuvers for phase adjustment were carried out in a transfer orbit to the Moon. Initially, on October 3, 2007, the Kaguya was inserted into an elliptical orbit with a perilune 100 km altitude and an apolune 13,000 km of an inclination 90 degrees. The two subsatellites were released halfway to the circular orbit of 100 km altitude. The altitude of the apolune was gradually lowered by decelerations at the perilune to the nominal orbit. During this time one subsatellite, the relay satellite (Okina) was cast off by spinning on an elliptical orbit of 100 km and 2,400 km, and the other subsatellite, the VLBI satellite (Ouna) was released by spinning on an elliptical orbit of 100 km

Table 1 Kaguya spacecrafts characteristics

Main Orbiter Kaguya	
Mass	Dry Mass: 1,791 kg Launch Mass: 3,020 kg incl. fuel 1,115 kg, two subsatellites, and science instruments 275.4 kg
Orbit	Circular orbit of altitude 100±30 km with inclination 90 deg. in nominal mission period
Electric Power	3.260 kW @ Beta 0 deg. and 1.831 kW @ 90 deg.
Attitude Control	Three-axis controlled using momentum wheels
Mission Period	One year nominal and extended Extend mission started on November 1, 2008 and terminated on June 10, 2009 by impact
Dimension	Upper module: 2.1 m × 2.1 m × 2.8 m parallelpipe Lower module: 2.1 m × 2.1 m × 1.4 m parallelpipe
Propulsion	500N × 1, 20N × 12, 1N × 8 thrusters
Relay satellite Okina and VLBI satellite Ouna	
Mass	57 kg each incl. science instruments RSAT-1 12.94 kg and VRAD-1 2.20 kg for Okina, VRAD-2 10.46 kg for Ouna
Orbits	Elliptical orbits of altitudes 100 × 2400 km for Okina and 100 × 800 km at separation with inclination 0 deg. Orbital periods; 240 min. for Okina and 150 min. for Ouna
Electric Power	69 watt @ Beta 0 deg.
Attitude Control	Spin stabilized within 20 deg. normal to the lunar orbital plane
Mission Period	One year nominal Okina impacted on lunar farside February 12, 2009, Telemetry command operation terminated on June 29, 2009 for Ouna
Dimension	0.99 m × 0.99 m × 0.65 m octagonal prism

and 800 km. On October 19, 2007, about a month after launch, the Kaguya was settled into the nominal circular orbit of 100 km altitude (Fig. 3).

2.2 Onboard Science Instruments

Fifteen science experiments and observations (Kato et al. 2008) listed in Table 2 were selected for the Kaguya mission after a review process by the Space Science Committee of the ISAS. The scientific instruments were categorized into five groups depending on their purposes. The groups are as follows: (1) x-ray spectrometer (XRS) and gamma-ray spectrometer (GRS) to determine the elemental abundance (Shirai et al. 2008; Hasebe et al. 2008); (2) multi-band imager (MI) and spectral profiler (SP) to determine the distribution of mineral abundance (Ohtake et al. 2008); (3) terrain camera (TC), lunar radar sounder (LRS), and lunar laser altimeter (LALT) to measure the topography of the lunar surface and subsurface (Haruyama et al. 2008; Ono et al. 2008; Araki et al. 2008); (4) relay satellite transponder (RSAT) and very long baseline interferometry (VLBI) radio source (VRAD) to measure the gravity field of the lunar farside and nearside (Matsumoto et al. 2008; Hanada et al. 2008; Kikuchi et al. 2008); and (5) charged particle spectrometer (CPS), lunar magnetometer (LMAG), plasma energy, angle, composition experiment (PACE), radio science (RS), and upper atmosphere plasma imager (UPI) to determine the impact of cosmic radiation and/or solar wind on the Moon and the Earth (Shimizu et al. 2008; Saito et al. 2008; Imamura et al.

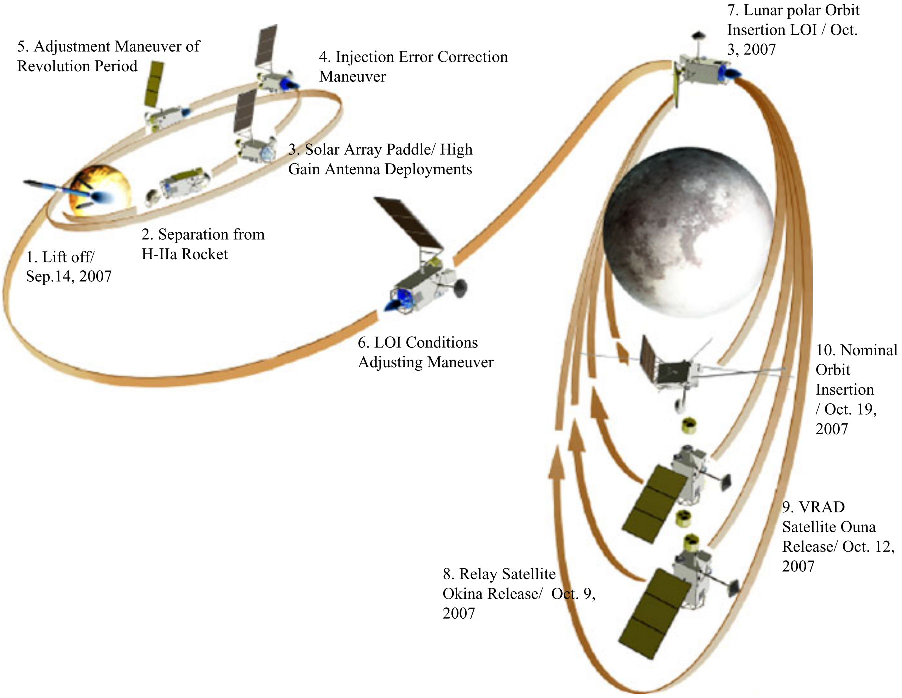

Fig. 3 The Kaguya's Mission Profile

2008; Yoshikawa et al. 2008). In addition, a high-definition television (HDTV) was used for public outreach (Yamazaki et al. 2010). Each instrument was subjected to an onboard performance test beginning on October 19, 2007; the nominal observations began on December 21, 2007, and lasted for approximately 18 months (Hanada et al. 2010; Namiki et al. 2010; Imamura et al. 2010; Kodama et al. 2010; Ohtake et al. 2010; Saito et al. 2010).

Figure 4 shows the positions of the sensor heads located on the panels of the spacecraft body. Many sensors were installed on the +Z panel, which faced the lunar surface to observe the Moon. Some sensors were fixed on the −Z panel to observe particles incident on the lunar surface. Just after the Kaguya settled into nominal 100 km altitude orbit, the LMAG mast, which was 12 m long, was used to isolate the electromagnetic noise generated by instruments in the spacecraft from the signals of very weak magnetic field (less than 0.1 nT) (Matsushima et al. 2010); and two pairs of LRS antennas (tip to tip: 30 m) were extended to transmit and receive electromagnetic waves (Ono et al. 2010). The mast and the antennas had been folded in the thermal insulator of the spacecraft body before they were extended.

3 Science and Perspectives

3.1 Scientific Objectives

All of the instruments had high-end specifications and were expected to provide valuable data for lunar studies. Various topics of lunar science can be studied comprehensively by integrating data obtained from several complementary instruments appropriate to the topic.

Table 2 Kaguya instruments summary

Instrument	Instrument Classification	Principal Investigator/Affiliation	Measurements Targets	Main Characteristics	Mass	Max. Electric Power	Data Rate
XRS	X-ray Spectrometer	Tatsuaki Okada/ JAXA	Global mapping of major elements, Al, Si, Mg, Fe distribution	100 cm^2 CCD: Spatial resolution 20 km @ 100 km altitude, 0.7–8 keV energy range, solar monitor	21.9 kg	40.4 watt	32 kbps
GAP	Gamma-ray and Particle Spectrometer				52.2 kg	157.9 watts	24 kbps
GAP/GRS	Gamma-ray Spectrometer	Nobuyuki Hasebe/ Waseda University	Global mapping of U, Th, K, major elements distribution	250 cm^3 pure Ge detector: Spatial resolution 160 km, energy range 0.1–10 MeV			
GAP/CPS	Charged Particle Spectrometer	Takeshi Takashima/ JAXA	Measurements of high-energy Cosmic ray	Li doped Si detector: energy ranges 1–14 MeV, 2–240 MeV, Alpha particle detector: 4–6.5 MeV			
LISM	Lunar Imager and Spectrometer				54.0 kg	143.5 watts	
LISM/MI	Multi-band Imager	Makiko Ohtake/ JAXA	Global mapping of mineral distribution	UV-VIS-NIR reflectance imager: CCD & InGaAs detectors, 9 band filters with 0.4–1.6 microns, Spatial resolution 20–60 m, 20–30 nm spectral resolution			3.4 Mbps
LISM/SP	Spectral Profiler	Tsuneo Matsunaga/ National Institute for Environmental Studies (NIES)	Precise mineral identification	Grating spectrometer: spectral range 0.5–2.6 microns, spectral resolution 6–8 nm, spatial resolution 500 m			14 kbps

Table 2 (*continued*)

Instrument	Instrument Classification	Principal Investigator/Affiliation	Measurements Targets	Main Characteristics	Mass	Max. Electric Power	Data Rate
LISM/TC	Terrain Camera	Junichi Haruyama/ JAXA	3-D global imaging	Two linear CCD stereo camera: spatial resolution 10 m, swarth width 35 km @100 km altitude			3.3 Mbps
LRS	Lunar Radar Sounder	Takayuki Ono/ Tohoku University	Active sounding of subsurface structure, and passive detection of natural radio wave from the Sun and planets	Radio frequency 5 MHz, 800 watts output power, Echo observation range 5 km under surface, Range resolution 75 m, natural wave detection 10 kHz to 30 MHz	24 kg incl. 2 pairs of 30 m tip to tip dipole antenna of 7.8 kg	51 watts	492 kbps
LALT	Laser Altimeter	Hiroshi Araki/ National Astronomical Observatory of Japan (NAOJ)	Global measurements of topography	Nd:YAG laser transmitter: 100 mJ output power, Range resolution 5 m, Spatial resolution of 1400 m with pulse rate of 1 Hz, Beam divergence 3 mrad.	20.0 kg	44.2 watts	48 bps
RSAT	Relay Satellite-Transponder	Noriyuki Namiki/ Kyushu University* *Now, Chiba Institute of Technology	Gravimetry of farside by 4-way Doppler measurements	Initial relay satellite orbit: 100 km perilune and 2400 m apolune, Doppler accuracy 1 mm/s	12.9 kg, and 3.9 kg transponder opposed to Rstar	69.5 watts	
VRAD	VLBI Radio Source	Hideo Hanada/ National Astronomical Observatory of Japan (NAOJ)	Differential VLBI Observation	Radio source onboard VSTAR and RSTAR, 3 S bands and 1 X band,	10.5 kg incl. 1.7 kg radio source onboard RSTAR	26.5 watts	
MAP	Magnatic Field and Plasma Experiment				39.1 kg	84.1 watts	48 kbps

Table 2 (*continued*)

Instrument	Instrument Classification	Principal Investigator/Affiliation	Measurements Targets	Main Characteristics	Mass	Max. Electric Power	Data Rate
MAP/ LMAG	Lunar Magnetometer	Hideo Tsunakawa/ Tokyo Institute of Technology	Precise measurements of magnetic field	Flux-gate magnetometers: accuracy 0.5 nT	incl. 12 m length mast		
MAP/ PACE	Plasma Energy Angle and Composition Experiment	Yoshifumi Saito/ JAXA	Low energy plasma analysis	Electron spectrum analyzer: range 5–15 keV, 10% energy resolution, ion mass and energy analyzer: 5–28 keV/q energy range, 1–60 mass range			
RS	Radio Science	Takeshi Imamura/ JAXA	Detection of tenuous lunar ionosphere	S-and X-band transponders onboard RSTAR and VSTAR			
UPI	Upper-atmosphere Plasma Imager	Ichiro Yoshikawa/ University of Tokyo	Observation of terrestrial plasmasphere	Two telescopic detectors: Extremeultraviolet 30.4 nm and 83.4 nm, and visible range	44.5 kg	69.4 watts	48 kbps
HDTV	High Definition TV System	Junichi Yamazaki/ Japan Broadcasting Corporation (NHK)	Broadcasting movies of the Earth and Moon	Two HDTV camera systems	16.5 kg	49.5 watts	7.6 Mbps

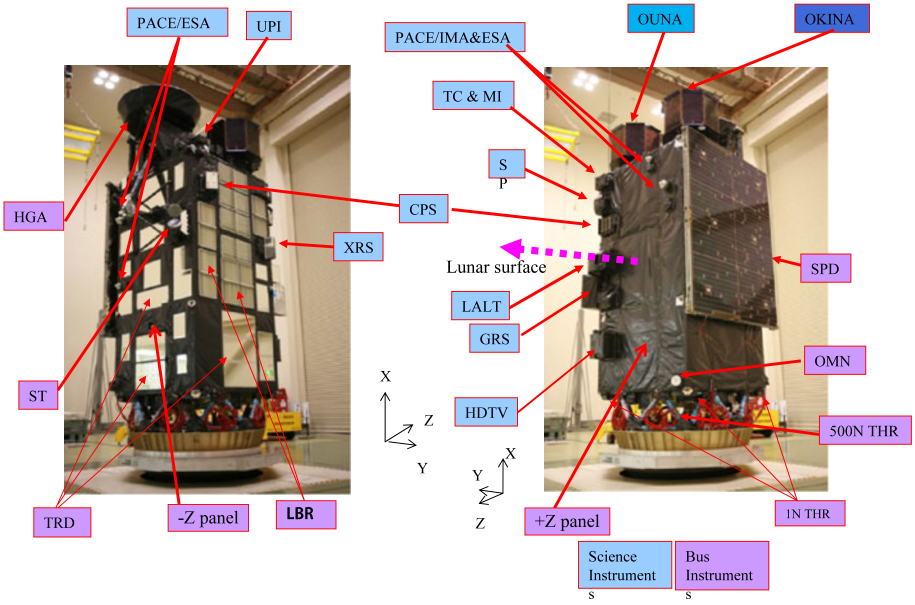

Fig. 4 The science and bus instruments onboard the Kaguya spacecraft. Most instruments observing the lunar surface are allocated on the +Z panel. HGA: High Gain Antenna, ST: Star Tracker, TRD: Thermal Radiator, LBR: Thermal Lubber, SPD: Solar Paddle, OMN: Omni directional antenna, THR: Thruster

For example, XRS can be used in combination with GRS; the XRS with a moderate spatial resolution of 20 km can be used to measure major elements such as Mg, Al, and Si, and the GRS with a low spatial resolution of 100 km can be used to measure complementary elements such as K, Th, and U.

Lunar studies have advanced with the integration of scientific data from various categories. The intention, first results, and perspectives of each type of data gathered by the Kaguya mission are described in following subsections:

- Chemical constituents of the Moon
- Interior structure of the Moon
- Dichotomy of nearside and farside of the Moon
- Differentiation in the magma ocean
- Origin of the lunar magnetic field
- Lunar tectonics.

These science targets are still being integrated to study the origin and evolution of the Moon.

3.2 Chemical constituents of the Moon

Determining the chemical constituents of the Moon has been the first priority from the viewpoint of studying the origin of the Moon and the chemical distribution in the inner zone of the primordial solar system. Many model compositions have been proposed since the Apollo missions (e.g., Morgan et al. 1978; Wänke et al. 1977; Ringwood 1977; Ringwood and Kessen 1977). However, these compositions were estimated on the basis of geophysical and cosmochemical constraints; for example, global rock distributions of the lunar surface were not taken into consideration. The ratio of core and mantle/crust could not be considered because the size of iron core had not been accurately estimated.

Two categories of data, namely, elemental abundance of the lunar surface (obtained by XRS and GRS) and mineral composition (obtained by MI and SP) define the rock types and their distribution on the lunar surface. Information about the subsurface constituents in the lunar crust can be acquired by investigating the central peaks of the craters that were formed by the rebound of impact shock during crater formation (Cintala and Grieve 1998). These lunar craters have been observed to be greater than 15 km in diameter. Large basins such as the South Pole-Aitken (SPA) basin having a diameter of 2500 km and a depth of approximately 10 km expose interior materials of the lower crust or extrude the upper mantle of the Moon. It is possible to estimate the deep crust components by remote analysis of central peaks, crater walls, and outcrops in large basin crater bored to deep interior. However, only 15% the volume of the Moon has been accessed to obtain information about the chemical constituents of the whole Moon.

The Kaguya /MI and/ SP determined the ubiquitous distribution of pure anorthosite in the lower crust layers by showing the global distribution of pure anorthosite on the central peak outcrops of large craters (Ohtake et al. 2009; Matsunaga et al. 2008). The origin of pure anorthosite is still controversial, because the anorthosite returned by Apollo, about 92% plagioclase and Mg-suite, was thought to have been formed in chemical equilibrium by floating in the magma ocean of early lunar history (e.g., Walker et al. 1973; Warren 1990; Longhi 2003). Therefore, further study of the formation of anorthosite is necessary.

The Kaguya /SP also provided lithology data about the central peaks of craters in the SPA basin: they are composed of orthopyroxene, olivine, and agglutinate (Nakamura et al. 2009).

In order to estimate the size of the lunar core, gravity-field measurements are used to determine the polar moment of inertia of the Moon. The data obtained by the Lunar Prospector were used to determine the iron core radius, which was estimated to be 220 to 450 km (Konopoliv et al. 1998). Kaguya measured the gravitational anomaly of the whole Moon, using a four-way Doppler technique employing the relay sub-satellite Okina, to track the Kaguya spacecraft flown in the lunar farside. The gravity free-air anomaly of multi-ring type in the farside can be compared with the mass-concentration type anomaly in the nearside (Namiki et al. 2009). An error of low-degree spherical harmonic coefficients which contribute to the polar moment of inertia and the k_2 Love number was also reduced in the Kaguya gravity model SGM100h comparing with the Lunar Prospector model LP100K. The differential VLBI technique by the Kaguya/VRAD can be employed to refine further the coefficients by precise orbital determination (Matsumoto et al. 2010).

The results obtained from the Kaguya mission as well as the 90s' lunar missions such as the Lunar Prospector are limited, and cannot be used to determine accurately the elemental abundance of the entire Moon. This is because the spacecraft did not carry any instruments, such as a seismometer in the Apollo missions for in situ measurement of parameters that provide information regarding the lunar interior. However, the Kaguya data will considerably improve knowledge about the chemical constituents of the Moon's lower crust and upper mantle material when they are compared to the Apollo seismological investigation results.

3.3 Interior Structure of the Moon

As mentioned in the previous subsection, the size of the lunar core can be estimated by the polar moment of inertia of the Moon, which was determined from gravity-field measurements. In the Kaguya mission the shallow interior and subsurface structures were investigated using LRS. Radar soundings using a 5 MHz radio wave revealed the subsurface layer structure, including the density and/or material discontinuities, up to a depth of approximately 5 km. Initial LRS data revealed the subsurface structure of the mare region spreading in the nearside (Ono et al. 2009). Multiple discontinuities were found in Mare Imbrium and Oceanus Procellarum, which possibly correspond to magma eruption ages and titanium contents (Oshigami et al. 2009; Pommerol et al. 2010).

Gravity data obtained using RSAT and VRAD and topography data obtained using LALT, will be used to more precisely estimate the thickness of the entire lunar crust. The crust in the basin areas and mares on the lunar nearside is mostly thin, and the highland on the farside is overlaid on a thick crust. The Kaguya mission was successful in determining the crustal thickness with greater accuracy (Ishihara et al. 2009). The maximum thickness of lunar crust is found in the Dirichlet-Jackson crater rim of the farside, where the highest altitude was evidently identified by the Kaguya /LALT. The minimum thickness is estimated to be under Mare Moscoviense of the farside, where an almost 0-m thickness of crust was recorded under lava basalt of 600 m thickness (Morota et al. 2009). Mantle uplift occurred after formation of the impact basin.

3.4 Dichotomy of Nearside and Farside of the Moon

The dichotomy of the Moon has been determined from the topography and rock distributions in the lunar nearside and farside. Large mares occupy 60% of the lunar nearside. A large altitude difference (more than 19 km) has been observed between the rim of the Dirichlet-Jackson crater and the bottom of an unnamed small crater in the Antoniadi crater of the SPA basin (Araki et al. 2009). The dichotomy was determined by geological study of the material distribution and crustal thickness. The formation ages of farside mare areas were re-estimated by counting craters using high spatial resolution Terrain Camera images. Mare Moscoviense and the Antoniadi and Apollo craters in the SPA basin have been shown to have long-lived volcanism to 2.5–2.6 Ga compared to a previous estimation of 3.5 Ga (Haruyama et al. 2009).

A large positive gravitational anomaly can be seen in nearside mare and basins. A circular, positive, flat 300 to 500 mGal of free-air anomaly reflects spreading basalt mares. Co-axial multi-ring type anomalies repeating positive and negative values analyzed by the Kaguya/RSAT are preserved in the formation of multi-ring craters distributed in the farside.

The Kaguya/GRS with high-energy resolution determined the distribution of radioactive elements K, U, and Th, which are incompatible elements partitioned into mare materials of the nearside (Yamashita et al. 2010; Kobayashi et al. 2010).

3.5 Differentiation in the Magma Ocean

If the Moon did in fact originate from the formation of the magma ocean, the same evidence must be globally retained on the lunar surface. The rock distribution could thus be used as evidence for the differentiation of the magma ocean. The formation of the SPA basin and large mares due to flooded magma in the nearside are the main geological events that occurred after the formation of the magma ocean 4.6 billion years ago. Therefore, geological recovery or reburying of the basin and mares is necessary to reproduce the magma ocean age. A detailed geological study by the Kaguya mission clarified the origin of the magma ocean. The magma ocean model suggests that the Moon was formed after a giant impact. A short period of accretion to the Moon after the giant impact led to the heating up of its surface; this induced the formation of molten magma. The ubiquitous occurrence of anorthosite in the central peaks of large craters is attributed to the existence of anorthosite layers under the lunar surface. Detailed distribution of mafic rocks which coexisted with anorthosite in the magma ocean must be globally confirmed in the lunar surface. Spectrometric studies by the Kaguya/ MI, SP, and the M^3 onboard the Indian lunar orbiter Chandrayaan-1 (Pieters et al. 2009) are expected to provide information on the global distribution of minerals and rocks.

3.6 Origin of the Lunar Magnetic Field

Apollo rock samples contain magnetic minerals that indicate magnetization in a weak but ambient magnetic field. A previous study (Hood et al. 2001) suggested that the most probable sources of the ancient lunar magnetic fields were (1) a former core dynamo during a high-field epoch and (2) transient magnetic fields generated by the interaction of impact plasmas with the ambient field during brief periods of ejecta emplacement. The Kaguya/LMAG mission aimed at finding weak magnetic remnants (less than 0.1 nT) by three-axis fluxgate magnetometers isolated from the electromagnetic noise of the onboard electronic instruments by using an expandable long mast and electromagnetic cleanliness procedures before launch (Matsushima et al. 2010). Distribution of magnetic anomalies less than 1 nT were definitely confirmed in the Crisium-, the Serenitatis-, and the Imbrium- antipodes in the SPA basin and in the Lemonosov-Fleming, the Crisium, the Moscoviense, the Apollo basins, isolated anomalies such as the Reiner Gamma identified by Richmond and Hood 2008, and newly identified eleven isolated anomalies from the 100 km altitude orbit (Tsunakawa et al. 2010). The Kaguya/LMAG data, including low-altitude measurements, are expected to reveal more details regarding anomalies and to help understand the origin of lunar magnetic anomalies.

3.7 Lunar Tectonics

The evolution of the Moon is recorded not only in ubiquitous crater formation, but also in various features of the subsurface structure. Volcanic activities to about 3.0 billion years after the origin of 4.6 billion ago should be preserved in large mares and basins. The Kaguya/LRS has provided evidence of intermittent magma eruption, and detailed tectonic feature of stratification in the southern Mare Serenitatis (Ono et al. 2009). Undulating strata shown there also indicate ridge formation by horizontal shortening due to global cooling 2.84 billion years ago.

4 Origin and Evolution of the Moon

The ultimate objective of lunar studies is to determine the origin and evolution of the Moon. Advanced scientific studies such as those described in the previous section may lead to the realization of this objective. The Kaguya mission is expected to provide new insights for lunar studies.

5 Solar Wind Interaction on the Moon

The above mentioned studies are concerned with Science of the Moon, in which the main focus is the origin and evolution of the Moon. However, the Kaguya mission carried instruments for experiments on Science on the Moon. In particular, interesting results have been obtained from Kaguya/PACE; these results include evidence that 0.1 to 1.0% of the solar wind (SW) protons are reflected back from the lunar surface (Saito et al. 2008); He^+, C^+, O^+, Na^+, K^+, and probable Ar^+ originating from the Moon are detected by the ion mass analyzer IMA (Yokota et al. 2009). The perpendicular entry of SW protons into the near-Moon wake is studied (Nishino et al. 2009a); SW protons coming into the deepest lunar wake have been studied (Nishino et al. 2009b); IMA has directly detected ions originating from the Moon in the Earth's magnetosphere (Tanaka et al. 2009).

6 Conclusions

The Kaguya mission was completed when the Kaguya spacecraft impacted on a target location on the Moon after final maneuver of delta V of 2.5 m/sec at 45 minutes before impact. The Kaguya science team has archived the Kaguya data and has made them available to the public (Hoshino et al. 2010); the team is involved in various studies in which the Kaguya data are used. Although data analysis and science study are ongoing, the major scientific achievements to date are summarized as follows:

- Identification of ubiquitous pure anorthosite in outcrops of central peaks of large craters by MI and SP.
- Discovery of multiple reflectors of radio waves under large mares and ocean in the near-side by LRS.
- Use of RSAT for confirmation of free-air gravity anomaly in the whole Moon and identification of farside anomalies that are different from nearside mass concentration anomalies.
- Confirmation of lunar global topography by LALT.
- Re-estimation of crustal thickness by Kaguya data of gravity and topography.
- Re-estimation of the formation ages of farside mares by crater countings using high-resolution images of TC.
- Confirmation of magnetic anomalies and mini-magnetosphere by LMAG and PACE.
- Reconfirmation of global distribution of radio-active elements K, U and Th by GRS.
- Discovery of SW proton reflection from the lunar surface, SW entry into lunar wake, and interaction with the Moon by PACE.
- Confirmation of the polar illumination rate by LALT topographic data.

The Kaguya mission followed the Clementine and Lunar Prospector science- oriented precursor missions, and has played a significant role as a frontier mission. The Chinese orbiter Chang'E-1, the Indian orbiter Chandrayaan-1, and the US LRO/LCROSS mission dedicated to landing site investigation for human exploration were sent to the Moon after the Kaguya launch. Cross-referencing of the data acquired by these missions and international collaborative studies are indispensable in advancing the science of the Moon

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