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SELENE MISSION : SCIENTIFIC OBJECTIVES

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Abstract

Phase-B study has started for the Japanese Moon-orbiting mission SELENE (Selenological and Engineering Explorer) aiming at scientific research and technology development for future lunar exploration. The mission consists of a main orbiting satellite at about 100 km altitude near the polar circular orbit and a relay satellite on an elliptical orbit with apolune at 2,400 km. The scientific objectives of the mission are ; 1) study of the origin and evolution of the Moon, 2) in-situ measurement of the lunar environment, and 3) observation of the solar-terrestrial plasma environment from the lunar orbit. SELENE will carry the instruments for scientific investigation, including mapping of lunar topography and surface composition, measurement of the gravity and magnetic fields, and observation of lunar and solar-terrestrial environments. After 1-year remote-sensing mission, the propulsion module of the main orbiter is separated for soft-landing testing. After landing, differential VLBI mission is conducted for two months by radio sources both on the relay satellite and the lander. The launch by H-IIA rocket is currently planned for 2003.

1. Introduction

The Moon has been attracting scientist's interests as the most familiar planetary body in the solar system. Since 1950's, the Moon has been explored repeatedly by unmanned and manned missions. Especially, the Apollo program from 1969 to 1972 provided a lot of new findings about the Moon and brought about a significant progress in the field of lunar science. However, although the Moon has been studied more extensively than any other planetary body, the most basic question in lunar science concerning the origin and early evolution of the Moon is still left open. The study of the Moon is particularly important in planetary science because it is directly related to the origin and evolution of the earth and other terrestrial planets.

During 20 years after the Apollo program, the data obtained in the initial phase of lunar exploration have been well examined and the planetary scientists are now ready to proceed to next-step exploration. There is an international movement to challenge the study of the origin and evolution of the Moon using advanced observation technologies. The Clementine mission was conducted in 1994 for mineralogical and topographical mapping of the lunar surface. Another lunar orbiter mission Lunar Prospector [1] for characterization of surface composition, measurement of magnetic and gravity fields, and study of lunar outgassing events just started in January 1998. The Japanese Moon explorer Lunar-A [2] , a penetrator mission, is now at the last preparation stage for launch in 1999.

There are several important aspects in lunar science. The major theoretical models concerning the origin of the Moon are based on the assumption that the Moon was born in the neighborhood of the earth. In that case, the gravitational force from the Moon must have given a significant influence to the dynamical as well as thermal evolution of the earth. Thus, clarification of the early stage of the Moon is important to understand the origin and evolution of the earth. For the terrestrial planets, the differentiation of the crust is believed to have started soon after the formation of the body. For the Moon, because of its smallness, the differentiation was completed within several hundred million years after the birth and the structure of the crust has been well preserved since then. The study of the Moon crust will contribute to understanding the process of differentiation and evolution of other terrestrial planets. Furthermore, the records of the meteorites bombardment on the lunar surface more than 4 billion years ago are also well preserved without significant erosion, which will provide information on the meteoroid environment of the early solar system.

Four major models have been proposed for the origin of the Moon ; fission, capture, binary accretion, and accretion by giant impact. In order to address the question concerning the origin of the Moon, further exploration is required more elaborately than before as for the constitutional materials, interior's structure, and magnetic fields. The chemical composition of the constitutional material of the planetary body represents the birth place in the early solar system. With an accurate information on chemical composition of the Moon, and comparing it with that of the earth, we will be able to identify where and how the Moon was born. Judging from the data of the chemical composition obtained so far, although a lot of ambiguities are still included, the Moon is relatively more abundant of nonvolatile elements than the cosmic standards. On the other hand, from a viewpoint of the oxygen isotope, the Moon is closely correlated to the earth, but is quite different from the meteoroids and other planets. If we get reliable measurements of the chemical composition of the Moon to be comparable to those of the earth, the relationship between the earth and Moon will be well understood. For example, if the Moon is more abundant of nonvolatile elements as a whole than the earth, the scenario of fission or binary accretion is unlikely. The information of the interior's structure and state of the Moon also gives definite constraints to the model of its origin. If we assume the Moon was produced by accretion of the primitive meteoroids, then the core of the Moon is estimated to be larger than 360 km to explain the abundance of metal in the lunar rocks. On the other hand, if the Moon was made of the same material of the earth mantle, the radius of the core must be less than 285 km. The information of the internal structure can be obtained by precise measurement of the gravity and libration of the Moon. The global mapping of the lunar magnetic field could verify the theory of dynamo that could have taken place 3 to 4 billion years ago. The evidence of the dipole magnetic field if detected will give a decisive constraint to the structure and thermal state at the initial stage of the Moon.

The topographical feature of the Moon is generally classified into the ocean of the near side and high land of the far side. There are some indications that the crust in the far side is more than 100 km thick which is much thicker than the near side, typically 60 km. The same nature of global differentiation possibly related to the evolution process is often seen for other planets. The global observation of gravity field, element abundance, mineralogical composition, and geological features will characterize the difference between the near and far sides and give constraints to the lunar evolution models. One of the outstanding questions in the lunar thermal evolution is the hypothesis of a global melting stage known as the "magma ocean". This hypothesis explains the low-density aluminum rich minerals floated to form the lunar crust, while the high-density olivine and pyroxene sank to the bottom of the magma ocean to form the mantle. The differentiation process would have formed the characteristic structure of the crust which can be identified by detailed observation of mineralogical and chemical composition. The surface tectonics of the Moon are reflective of the history of internal thermal evolution. The change of the distance between the earth and Moon in the early stage possibly caused an internal stress responsible for the geological features such as the graben and wrinkle ridge. Observation of the surface and subsurface structure by imaging instruments and rf radar will give a better understanding of the lunar evolution from a view of tectonic history.

In addition to "science of the Moon" addressing the lunar science concerning the origin and evolution, great importance has recently been recognized for "science on the Moon" and "science from the Moon", especially for the future utilization of lunar environment for science. One of the potential applications is construction of astronomical observatories in the polar region utilizing its extremely low-noise and low-temperature environment. The lunar surface will provide an excellent base for observation of solar-terrestrial environments. For the preparation of scientific facilities, the geographical survey to make accurate maps for the site of candidates is required by remote-sensing observations of the lunar surface. The lunar environments especially concerning the meteoroid and radiation are important for the future utilization of the Moon, as well as the associated science. Because of the absence of the atmosphere, all kinds of meteoroids and particles directly hit the lunar surface. The statistical analysis of the craters based on the observation will reveal the history of the meteoroid environment of the early solar system.

The SELENE mission is planned primarily to study the origin and evolution of the Moon by means of global mapping of element abundances and mineralogical composi-

Table 1 Mission Summary.

Launch	H-IIA Launch in 2003
Orbit	Hohmann Transfer into Lunar Polar Orbit 100km Altitude, Inclination 95°
Configuration	Orbiter(including Landing Module) and Relay Satellite
Size	2mx2mx4m(Orbiter), 1m ϕ x1m(Relay Satellite)
Power	3.5kW(Orbiter)
Attitude Control	3-axis Control(Orbiter), Spin Stabilized(Relay Satellite)
Mission Period	1 year for remote sensing observation plus 2 months for dedicated VLBI experiment(nominal)
Orbiter Data Downlink Rate	10 Mbps
Orbiter Data Recorder	10 GBytes
Weight	Launch 2,900kg Lunar Orbiter (Initial Phase) 2,100kg Science Payload 275kg Relay Satellite 40kg (Landing Module 360kg)

tion, surface geographical mapping including subsurface radar sounding, and gravity and magnetic field measurements. The element abundances are measured by x-ray and γ -ray spectrometers. Alpha particle spectrometer is used to detect the radiation from the radon gas and polonium. The mineralogical characterization is performed by a multiband imager at a high spatial resolution. The mineralogical composition can be identified by a spectral profiler, a continuous spectral analyzer in visible and near infrared bands. The surface topographic data are obtained by high resolution stereo cameras and a laser altimeter. The subsurface structure is probed by an rf radar sounder experiment. Radio sources on the relay satellite and landing module are used to conduct differential VLBI observations from ground stations. Doppler tracking of the orbiter via the relay satellite when the orbiter is in the far side is planned for the study of gravimetry and geodesy. A magnetometer and electron detectors will provide data on the lunar surface magnetic field. Although the methodology of SELENE observation is conventional except for the gravimetry research, state of art technologies are fully utilized for the instruments to maximize the scientific return. Measurement of the lunar environment and observation of the solar-terrestrial environment are also planned in the mission. The study of the lunar environment includes the measurement of high energy particles, electromagnetic field, and plasma. For the solar-terrestrial observation, the orbiter will carry imaging instruments to observe the dynamic structure of the earth plasma environment. High-sensitivity wave receivers are also onboard for detection of the planetary radiation.

2. Mission Scenario

The concept of SELENE is summarized in Table 1. The mission profile is illustrated in Fig.1. The spacecraft will be launched by the H-IIA rocket and directly injected into the lunar transfer trajectory. It takes about five days to reach the lunar orbit. A mid-course maneuver is required twice on its way to the Moon. The spacecraft is captured by the Moon into an elliptical orbit with apolune at 15,000 km and perilune at 100 km. The spacecraft will finally reach a circular 95 degrees-inclination orbit at about 100 km altitude after 6 orbit-transfer maneuvers. During the orbit transition, the relay satellite is released on an elliptical orbit with apolune at 2,400 km. Upon arriving at the final circular orbit, the orbiter extends the antennas for the radar sounder experiment and the mast for the magnetometer, and starts the scientific mission operation. Remote-sensing observation of the lunar surface and observation of the lunar and solar-terrestrial environments will be performed for about one year. If the fuel to control the orbit is available to extend the observatory mission, the orbiter will be lowered and maintained at 40-70 km altitude for another two months to measure the lunar magnetic and gravity fields more precisely.

The configuration of the orbiter is shown in Fig. 2. The orbiter moves towards +x or -x direction in the figure. Most of the sensors for the remote-sensing observation are installed on the z-plane which is controlled to direct the lunar surface by a three-axis attitude control system. Two pairs of the antenna for radar sounding are configured to cross perpendicularly to each other. The mast for the magnetometer is deployed in +x direction. The plasma imager to observe the earth ionosphere is installed on a movable platform of the high-gain antenna to direct the earth. The solar array panel deployed in the -y direction will rotate along the y-axis to track the sun.

The orbital period is about 2 hours. The distance of the adjacent orbit is about 35 km on the equator. The orbiter

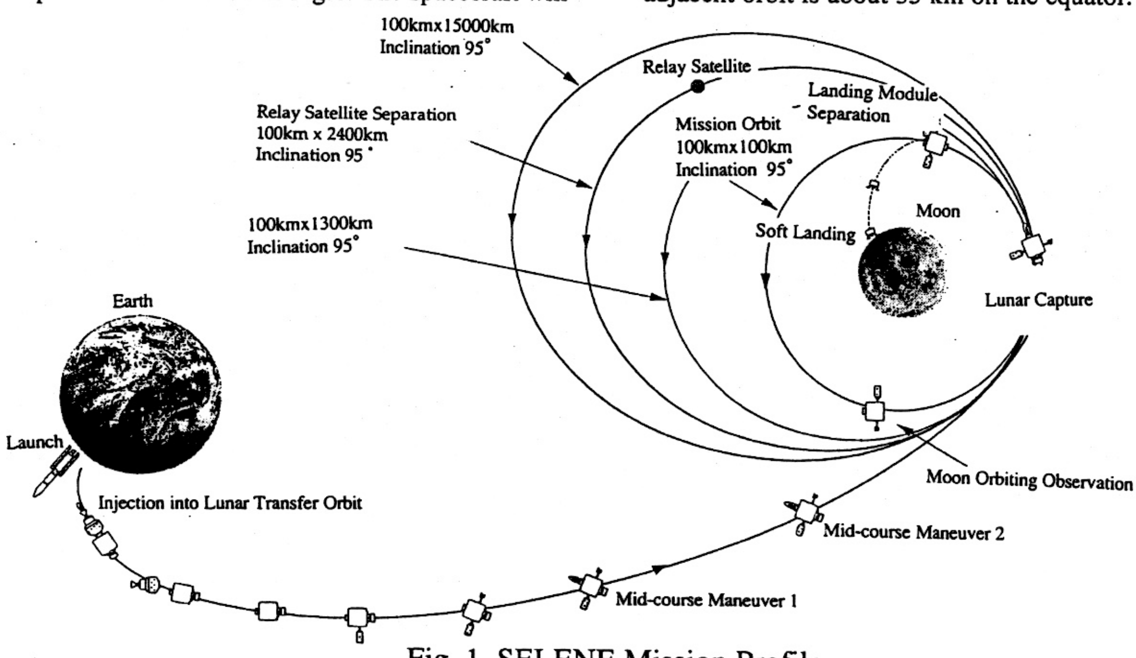

Fig. 1 SELENE Mission Profile.

returns the initial orbit every month if the orbital perturbation is negligible. By adjusting the orbital latitude, global mapping with a high-latitude resolution less than 35 km on the equator is possible. Totally four maneuvers to keep the orbit are planned during one year. The capability for data recording and data downlink is expected to be approximately 10 GBytes and 10 Mbps, respectively.

After the orbital observatory mission for one year or possibly more months, the propulsion module is separated from the orbiter for soft landing testing. At the separation, the capability of attitude control for the orbiter is lost and the observatory mission is terminated. The landing module carries radio sources for differential VLBI experiment in combination with the radio sources on the relay satellite. Although the capability of the telemetry and commanding of the landing module is terminated during the first lunar night, the radio sources will survive for about two months using dedicated batteries.

The relay satellite consisting of S and X-band transponders will relay the Doppler signal between the ground and the orbiter when in the far side. It will be designed to survive at least 14 months after injection to the lunar orbit.

3. Scientific Subjects

The global characterization of the lunar surface and investigations of the interior in SELENE are categorized into 5 fields of observation ; element abundance, mineralogical composition, geological features, global gravity, and magnetic field. The integrated research scenario based on the observation towards the origin and evolution of the Moon is illustrated in Fig.3. Totally 14 scientific instruments including those for the observation of solar-terrestrial and lunar environments will be developed as listed in Table 2.

3.1 Global Mapping of Element Abundances

Global mapping of the lunar element abundances and mineralogical composition will enable us to estimate the entire lunar chemical composition, which will give constraints to the origin of the Moon. The element abundances are measured by the x-ray and γ -ray spectrometers. The x-ray spectrometer up to 10 keV with a large aperture CCD totally 100 cm^2 will be capable of measuring the major elements such as Mg, Al and Si at a 20 km resolution. The γ -ray spectrometer up to 10 MeV using a high-purity germanium crystal of 250 cm^3 will measure the natural radioactive elements, such as U, Th, and K, and major chemical constituents of some 10 kinds at a 160 km resolution. A Stirling refrigerator will be used to achieve the operational temperature about 80° K for the crystal. Since the solar activity is relatively high in early 2000's, induction of x-ray and γ -ray from the lunar surface by the solar radiation is expected to be stronger than usual. As a consequence, the measurement with a higher S/N ratio is expected in that time frame. Alpha particle spectrometer with a wide detection area typically 500 cm^2 with anti-coincidence will be used to detect alpha particles from the radon gas and polonium. The observation of the gas ejection will contribute to understanding the lunar tectonic activity.

3.2 Global Mapping of Mineralogical Composition

The mineralogical characterization is performed by a multiband imager with 9 spectral bands ranging from 0.4 to 1.6 μ m at a high spatial resolution typically 20 m. The spatial resolution is nearly 10 times higher than that of the Clementine. The identification of mineralogical composition, such as pyroxene, olivine, and anorthite, is performed by the spectral profiler with a continuous spectrophotometry from 0.5 to 2.6 μ m at a 500 m spatial resolution. Electric cooler is used for the IR sensor. The comprehensive data from the multiband imager and the spectral profiler

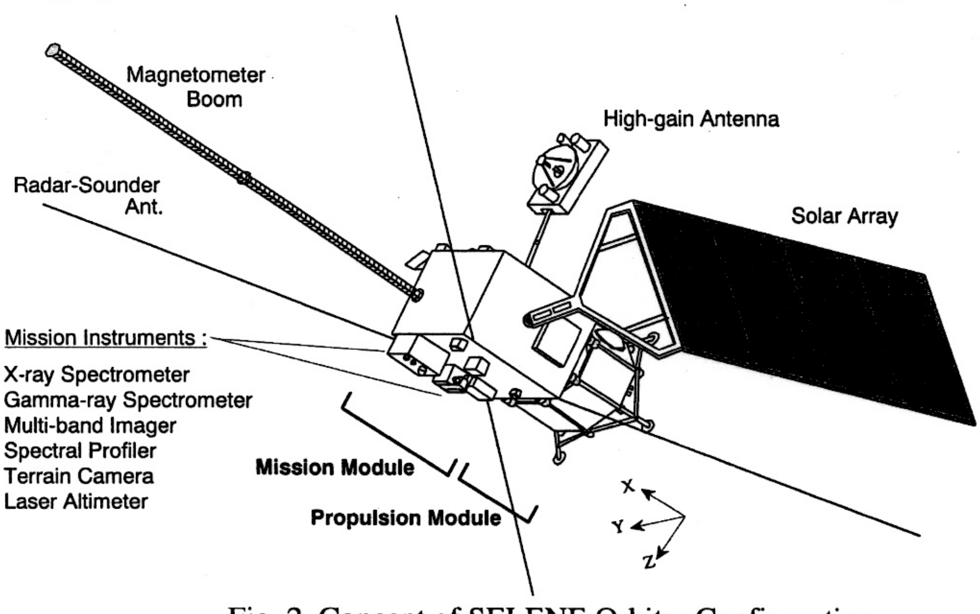

Fig. 2 Concept of SELENE Orbiter Configuration.

are combined to map the mineralogical composition. The data inversion from the multispectral data to the mineralogical composition requires a data base which will be generated by laboratory simulation experiments in the mission preparation phase. Besides the surface mapping function, the spectral profiler is expected to identify the mineralogical composition of the deep crust material which possibly appears at the lunar surface, such as inside the large-scale impact craters.

3.3 Global Mapping of Lunar Surface

The surface topographic data are obtained by the high resolution stereo cameras and the laser altimeter. The stereo camera has a field view of 35 km with a spatial resolution of 10 m to provide images in three dimensions. The angle between the lines of sight for the two cameras is 32 degrees. The laser altimeter measures the altitude every 800 m with a vertical resolution of 5 m and a spot size of 30 m diameter. These data are used to produce global topographical maps with a higher accuracy than before. Combining topographic data with the spectral data from the multiband imager and spectral profiler, the mineralogical composition will be identified for indivisual geologic units which would make it possible to identify the origin of the geologic structure. The structure below the surface regolith, such as dislocation, volcano and lava flow, can be probed by the radar sounder using a 5 MHz transmitter. The sounder experiment will reveal the inside structure up to 5 km below the surface with a vertical resolution of 100 m. The survey of the high land will provide important information on the hypothesis of "magma ocean". The observation of lunar surface enables us to understand the history of impact cratering, volcanism and tectonism. The topographic data can be used to investigate construction of the scientific facilities on the Moon such as the astronomical observatories in the future.

3.4 Gravity Field Measurement

The radio sources on the relay satellite and landing module are used to conduct differential VLBI observation from the ground stations. Waves at 4 frequencies in the S and X bands are radiated from each system. The observation enables us to determine the location of the radio source with a high accuracy. This will provide accurate information of the low-order gravity field, the libration and the moment of inertia of the Moon, typically 10 times better than before. With information of size of the core if any to be obtained by the preceding Lunar-A mission, the composition of the core can be determined. This will greatly contribute to the study of the origin and evolution of the Moon. On the other hand, the Doppler measurement of the orbiter via the relay satellite when the orbiter is in the far side is used to determine the local gravity field of the far side. The relay satellite is tracked by the 64 m dish at Usuda station and the accuracy is expected to be 1 mm/sec for 10 sec integration. The gravity anomalies typically less than 100 km will be determined for geodesy. The global gravity modeling will provide detailed information on the global crustal asymmetry as well as the internal lunar structure.

3.5 Magnetic Field Measurement

The magnetometer of 0.5 nT accuracy will provide global data on the lunar surface magnetic field and the lunar induced magnetic dipole. In order to estimate the lunar magnetic field separating from the magnetic field of the solar wind, the solar wind plasma is simultaneously measured by the plasma detectors. The electron energy analyzer of the plasma detectors which is capable of detecting the reflected electrons by the lunar magnetic field will show the surface distribution of the magnetic field. The data of

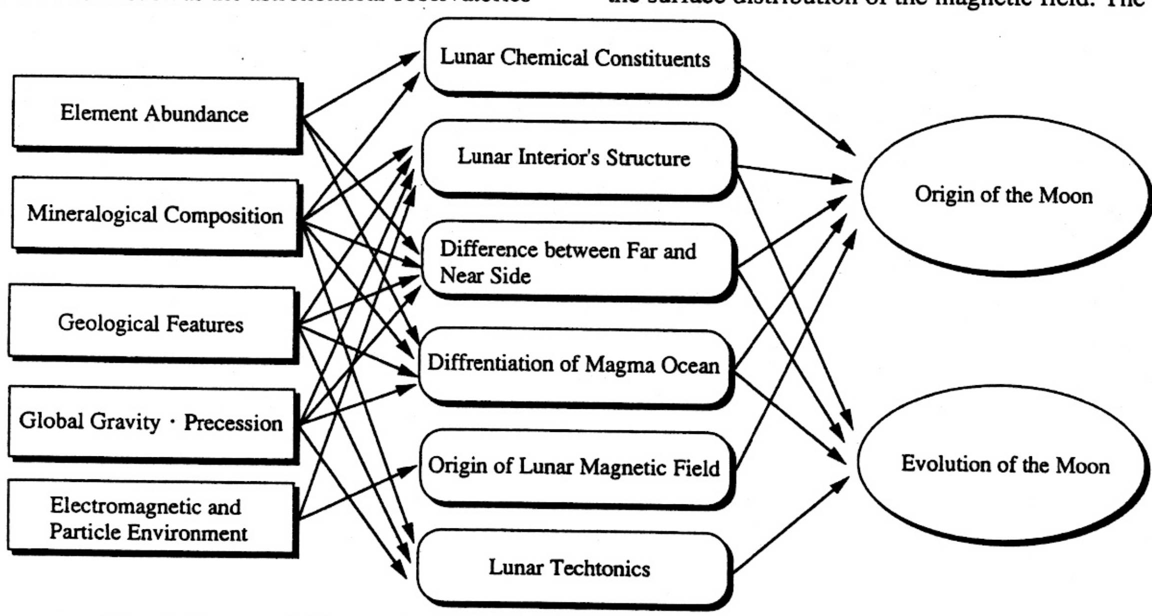

Fig. 3 Research Scenario towards the Origin and Evolution of the Moon.

Table 2 SELENE Scientific Instruments.

X-ray Spectrometer	CCD(Charge Coupled Device), AI, Si, Mg, Fe distribution, spatial resolution 20 km
Gamma-ray Spectrometer	Global mapping of U. Th. K distribution using high pure Ge crystal, spatial resolution 160 km
Multi-band Imager	UV-VIS-IR imager, spectral bandwidth ranging from 0.4 to 1.6 μ m, 9 bands (Spectral resolution 20-30 nm), spatial resolution 20 m
Spectral-Profiler	Continuous spectral profile ranging from 0.5 to 2.6 μ m (Spectral sampling 5 nm), spatial resolution 500 m
Topographic Camera	High resolution stereo camera, spatial resolution 10 m
Radar-Sounder	Mapping of subsurface structure using active sounding (frequency 5 MHz), maximum depth 5 km (resolution 100 m)
Laser Altimeter	Nd:YAG laser altimeter, height resolution 5 m, spatial resolution 800m (pulse rate 2Hz)
Differential VLBI Radio-source	Differential VLBI observation from ground (up to 3 stations), selenodesy, and gravitational field, onboard relay satellite and landing module
Relay Satellite	Far-side gravimetry using 4 way range rate measurement from ground station to orbiter via relay satellite, perilune 100 km, apolune 2,400 km
Magnetometer	Magnetic field measurement using flux-gate type magnetometer, sensitivity 0.5 nT
Plasma Imager	Observation of magnetosphere from lunar orbit, XUV to VIS
Charged Particle Spectrometer	Measurement of high-energy particles: 1-30 MeV (LID) and 8-300 MeV (HID), Alpha-ray spectrometer: 4-6.5 MeV
Plasma Analyzer	Charged particle energy and composition measurement (10 eV/q-30 keV/q)
Radio Science	Detection of the tenuous lunar ionosphere using S and X-band carriers

the lunar magnetic field will provide an understanding of the origin of lunar paleomagnetism and paleomagnetism induced by impacts. The measurement of the electromagnetic response to the change of the solar wind magnetic field will allow us to estimate the internal conductivity and temperature profile, which gives constraints to the size and composition of the lunar core.

3.6 Lunar Environment

The study of the lunar environment, such as high energy particles, electromagnetic field and plasma, is required for the future manned and unmanned utilization of the Moon. It also includes a valuable scientific aspect in each field. The observation of the energetic particles including heavy cosmic particles will contribute to study the composition of solar and interstellar matter and their evolution. The solar wind plasma detectors including ion mass/energy analyzer plus electron energy analyzer and electromagnetic wave receivers will be used to study not only the solar wind and the geomagnetic tail, but also the interaction of the solar wind with the Moon. The radio science using coherent x and s band carriers from the orbiter will make it possible to detect the tenuous lunar ionosphere which has not been confirmed yet.

3.7 Observation from the Moon

Two kinds of solar-terrestrial observation from the lunar orbit are planned. One is the imaging observation of the earth in the wavelength ranging from extreme ultraviolet to visible radiation, which is expected to clarify the global dynamics of the terrestrial plasma environment and auroral activities. For imaging of the OI emission at 130.4 nm free from the background of Lyman- α , an active filter using a hydrogen absorption cell will be assembled in. Another is the observation of planetary radiation up to 30 MHz from Jupiter and Saturn under the extremely low noise environment in which the dominant radiations from the sun and earth are shielded by the Moon itself. For the observation, the four 15 m antennas are shared with the radar sounder experiment.

4. Summary

The scientific background and objectives of the Moon-orbiting observatory mission SELENE are described. SELENE will carry 14 scientific instruments on the orbiter, relay satellite and landing module. The mission aims at mapping lunar topography and surface composition, and measuring the gravity and magnetic fields. The phase-A feasibility study for two years demonstrated that the mission will greatly contribute to lunar science concerning the origin and evolution of the Moon. It was also shown that the mission will provide a unique opportunity to study the lunar environment and the solar-terrestrial environment from the lunar orbit. Phase-B study started in April 1998 as a national space program to be conducted jointly by ISAS and NASDA.

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