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Japan's Space Capabilities for Lunar and Planetary Exploration

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1 Introduction

The National Aeronautics and Space Administration (NASA) of the United States of America has initiated a manned lunar and Mars exploration program for the first time since the Apollo Program pursuant to the vision of space exploration announced by President George W. Bush on January 14, 2004. Not only new space transportation and crew exploration vehicle systems are being developed to replace the Space Shuttle, which is scheduled to retire in 2010, but also unmanned lunar missions are planned to collect information on lunar surface to select a landing site, resources such as water ice necessary for sustainable development of human activities there, the radiation environment that may affect human health, and other features to prepare for human lunar exploration. Furthermore, based on the recommendations of a report[1] on exploration of the Solar System published by the National Research Council (NRC) in July 2002, NASA is also carrying out unmanned science missions.

The European Space Agency (ESA) is also carrying out unmanned science missions, either independently or in cooperation with NASA, and is planning a Mars mission by a robotic rover under the Aurora Programme, envisioning a future manned Mars mission. China and India have also initiated unmanned lunar exploration programs called Chang'e and Chandrayaan respectively, to acquire new spacecapabilities.

Japan has already achieved impressive scientific results in a challenging effort in which its asteroid explorer HAYABUSA (Muses-C) made detailed scientific observations of asteroid Itokawa and collected samples from its surface. In recognition of this accomplishment, "Science," an American scientific journal, devoted a Special Issue to HAYABUSA (June 2, 2006). Japan's lunar orbiter KAGUYA (SELENE) is conducting the first full-scale scientific exploration of the Moon since the end of the Apollo Program to study the mysteries of the origin and evolution of the Moon. A series of scientific results from this mission are now beginning to appear, and have attracted keen interests, both in Japan and abroad. On February 12, 2008, the Japan Aerospace Exploration Agency (JAXA) became the first organization other than those of the United States to receive the Jack Swigert Award for Space Exploration, which recognized JAXA for the "groundbreaking scientific discoveries" being made by HAYABUSA and KAGUYA, together with the SUZAKU X-ray astronomy satellite, the AKARI infrared astronomy satellite, and the HINODE (Solar-B) solar observation satellite, and its contribution to expanding the frontiers of human knowledge.[2] This award was established in 2004 to honor Mr. Jack Swigert, who was elected to the U.S. House of Representatives after being an astronaut in Apollo 13, which made a miraculous return to the Earth after an oxygen system failure. Other past recipients include NASA's Martian exploration team, U.S. President George W. Bush, the Jet Propulsion Laboratory (JPL), and the astronomical observation division of the California Institute of Technology (Caltech).

This paper analyzes Japan's space development capabilities, after having compared the HAYABUSA and KAGUYA missions with similar missions by other nations.

2 Continually changing solar system images

2-1 Definition of planet

Astronomers wondered whether Pluto should be considered a planet for a variety of reasons such as that its diameter is only approximately 2,390km, which is smaller than that of the Earth's Moon (approx. 3,476km), that both the eccentricity and inclination of its orbit are larger than those of the other planets, and that an object called Eris, which has a diameter of approximately 2,400km, has been discovered in the vicinity of Pluto.

In August 2006, the International Astronomical Union (IAU) adopted the definition of a planet (Figure 1),[3] and Pluto was declassified as a planet. Although this adoption reduced the number of planets to eight from the traditional nine (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto), our image of the Solar System is continually changing to a ever-richer one thanks to technical progresses of astronomical ground-based telescopes, as well as remarkable observations by the Hubble Space Telescope and other astronomical probes, which observe heavenly bodies from space through various wavelengths, without being affected by the problems of absorption, scattering, and fluctuation caused by the Earth's atmosphere.

Based on the above-mentioned decision of the IAU, the IAU Subcommittee and the Astronomy and Astrophysics Subcommittee, Physical Sciences and Engineering Section Meeting of the Science Council of Japan, have recommended classification of celestial objects in the Solar System other than the planets as "trans-Neptunian objects (TNOs)," "dwarf planets," "small solar system bodies," and "plutoids," as shown in Table 1.[3]

1) A celestial body is classified as a planet if it meets the following three conditions:
   (a) Is in orbit around the Sun.
   (b) Has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (near-round) shape.
   (c) Has mechanically cleared other celestial bodies in the neighborhood around its orbit.
2) Celestial bodies which satisfy (a) and (b) but do not satisfy (c), and are not satellites, are classified as "dwarf planets."
3) All other celestial bodies except satellites which orbit the Sun shall be referred to as "small solar system bodies."

Figure 1 : Definition of a planet by the International Astronomical Union (IAU)

Source : Reference[3]

Although Pluto is one of the TNOs, it is also classified as a dwarf planet because of its size, and its name has been adopted in the definition of "plutoids." Thus, its reasons of existence have remained. On the other hand, on February 28, 2008, Kobe University Researcher Patryk S. Lykawka and Prof. Tadashi Mukai published the results of a numerical simulation suggesting the existence of an unknown outer planet outside the TNO belt.[4] It may be noted that the region where the TNOs exist is also the birthplace of the short-period comets.

The asteroids, which belong to the small solar system bodies, exist mainly in the asteroid belt between Mars and Jupiter. Asteroid Itokawa, which was explored by Japan's HAYABUSA," is one of those asteroids. The region which is called the Oort cloud, because its existence was predicted in 1950 by Dutch astronomer Jan Oort based on the orbits of long-period comets, extends from 10,000 to 100,000AU and is thought to contain innumerable lumps of ice and stone.

2-2 Solar system formation theory

Solar System formation theories based on modern physics were proposed in the 1970s by two groups, one led by Dr. Chushiro Hayashi of Japan's Kyoto University and the other led by Dr. A.G.W. Cameron of Harvard University in the United States of America. Both groups hypothesized that the Solar System formed from a primeval solar nebula consisting of dust and gas surrounding the primeval Sun (the nebular hypothesis), and that small celestial bodies called planetesimals formed from this dust (the planetesimal hypothesis). The Kyoto University group proposed that the mass of the solar nebula was one hundredth of that of the Sun, while the Harvard University group held that its mass was on the same order as that of the Sun. The current standard model of the Solar System formation is as shown in Figure 2.[5]

The planets of the Solar System can be classified into three types; that is, (1) "terrestrial planets" consisting of rock and iron (Mercury, Venus, Earth, and Mars), (2) "Jovian planets," which consist mainly of gaseous atoms and molecules

Table 1 : Classification of Solar System bodies other than planets

Class	Outline
Trans-Neptunian objects (TNOs)	· Celestial bodies which are covered with ice and are distributed around the Sun from the vicinity of Neptune, which is approximately 30 astronomical units (AU)[NOTE 1] from the Sun, to a distance of approximately 50AU or further; this class includes Pluto. Since 1992, more than 1,000 TNOs have been discovered (as of April 2007). · Formerly called Edgeworth-Kuiper Belt Objects
Dwarf planets	· A total of three celestial bodies have been classified as “dwarf planets” (as of April 2007), these being Pluto (diameter: approx. 2,390km) and Eris (approx. 2,400km), and Ceres (approx. 950km), which is the largest object in the asteroid belt. · Because it is difficult to determine whether a celestial body is a dwarf planet or not, there is room for study in the definition.
Small solar system bodies	· All celestial bodies in the solar system other than planets, dwarf planets, and satellites (asteroids with the exception of Ceres, TNOs with the exceptions of Pluto and Eris, comets, and the like).
Plutoid	· Is a celestial body which is classified as both a TNO and a dwarf planet. · Although resolved by the General Assembly of the IAU in 2006, the official English name has not been determined.[NOTE 2] · Pluto and Eris fall under this class (as of April 2007). Because other TNOs which may satisfy this definition also exist, it is possible that their number will increase in the future.
[NOTE 1] One astronomical unit (AU) is the average distance between the Earth and the Sun; its value is approximately 150 million km. [NOTE 2] According to a press release by the IAU dated June 11, 2008, the English name “Plutoid” has been adopted. (See http://www.iau.org/public_press/news/release/iau0804)	

Source : Reference[3]

of hydrogen, helium, etc. (Jupiter and Saturn), and (3) “Uranian planets” consisting of icy water, methane, ammonia, etc. (Uranus, Neptune).[5] Although the standard model of the Solar System formation still has several drawbacks, it can generally explain the basic features of today’s Solar System. In order to better refine the model to deepen our understanding of the Solar System, remote sensing observations by exploration probes, in-situ observations by landers and rovers, and detailed analyses on Earth of samples taken by exploration vehicles as well as ground-based telescope observations are necessary.

3 Trends in small solar system body exploration by Japan and other nations

3-1 Why explore small solar system bodies?

The small solar system bodies include asteroids, comets, and other objects (Table 2). According to the standard model of the Solar System formation, it is thought that, through collision and coalescence, protoplanets formed from planetesimals, and today’s planets from these protoplanets (Figure 2). On the other hand, there exists the asteroid belt, consisting of asteroids resembling planetesimals, between Mars and Jupiter (Figure 3). To explain the existence of the asteroid belt, one theory postulates that because the orbital eccentricities and inclinations of objects in the asteroid belt became large due to Jupiter’s massive gravity effects resulting in their relative speeds becoming very high, they were shattered by violent collisions with each other, and it became impossible for them to grow into planets. However, because the total mass of all the objects in today’ s asteroid belt is less than that of the Moon, the Earth’s satellite, another theory speculates that the amount of dust in the asteroid belt was originally small. There is also a theory that the origin of life on Earth was falling nuclei of comets to earth,

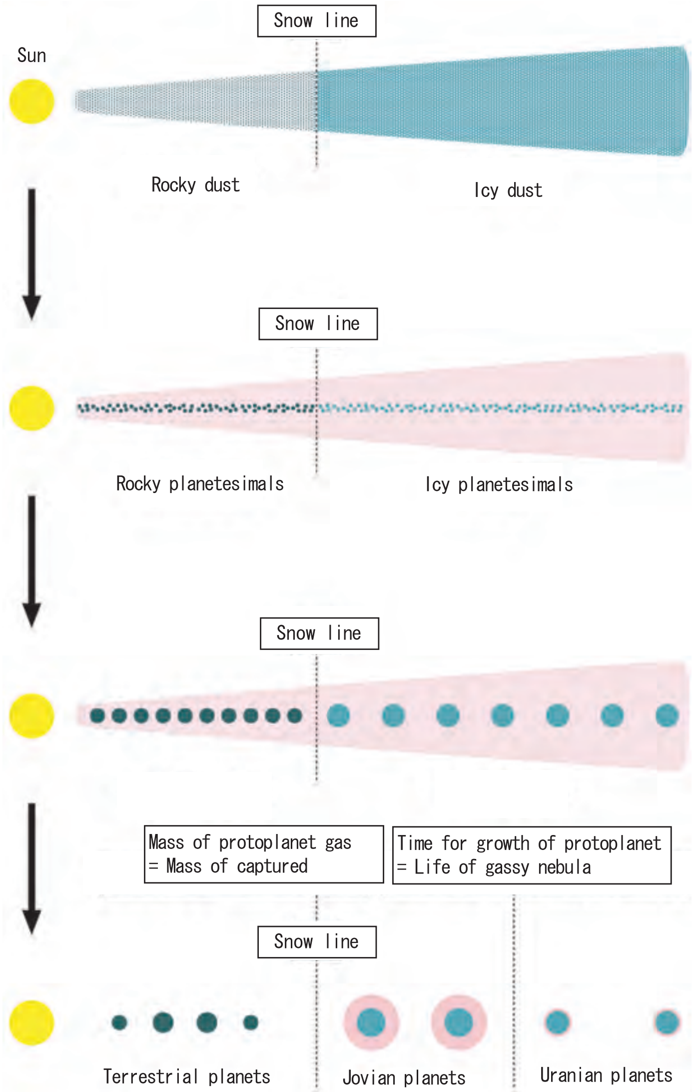
1. Formation of the primeval solar nebula

· 4.6 billion years ago, part of a molecular cloud of hydrogen, helium, and other gases, fine lumps of dust of metals, minerals, etc. which were floating in space began to condense under its own gravitational force, occasioned by the explosion of a nearby supernova or other cause, and the Sun was born in the center of this mass.

· A primeval solar nebula revolving around the sun formed from gas and dust. The total mass of the nebula was approximately 1% that of the Sun, and approximately 1% of this was large dust on the µm order. The main components of this dust inside a boundary called the “snow line”, which is located approximately 3AU from the Sun, were rock and metals. Outside of the snow line, the main component was ice.

2. Formation of planetesimals (10^6 years)

· The dust in the primeval solar nebula settled onto the ecliptic plane as a result of the perpendicular component of the Sun’s gravity, forming a dust layer. When the dust layer exceeded a critical density, it became gravitationally unstable and split into fragments.



· The fragments coalesced rapidly, forming small celestial bodies called planetesimals (mass of approximately 10^{15}-10^{18}kg).

3. Formation of protoplanets (10^6-10^7 years)

· The planetesimals grew by mutual collision and coalescence while revolving around the Sun. Larger planetesimals grew more rapidly by collecting the surrounding planetesimals with their stronger gravitational force. (This phenomenon is called “runaway growth.”)

· Celestial bodies (10^{23}-10^{26}kg) called protoplanets formed by runaway growth of planetesimals. When the protoplanets reached a certain size, their growth slowed because the surrounding planetesimals were shaken by their gravity, and neighboring pairs of protoplanets grew while maintaining a certain distance due to gravitational interaction.

4. Formation of planets (10^7-10^9 years)

· In the region of the terrestrial planets (inner Solar System), rocky terrestrial planets formed by collision between protoplanets.

· In the region of the Jovian and Uranian planets (ice giants), large protoplanets formed, and the Jovian and Uranian planets formed by gravitationally attracting gas from the primeval solar nebula.

Figure 2 : Route of norovirus infection in humans

Source: Reference[5]

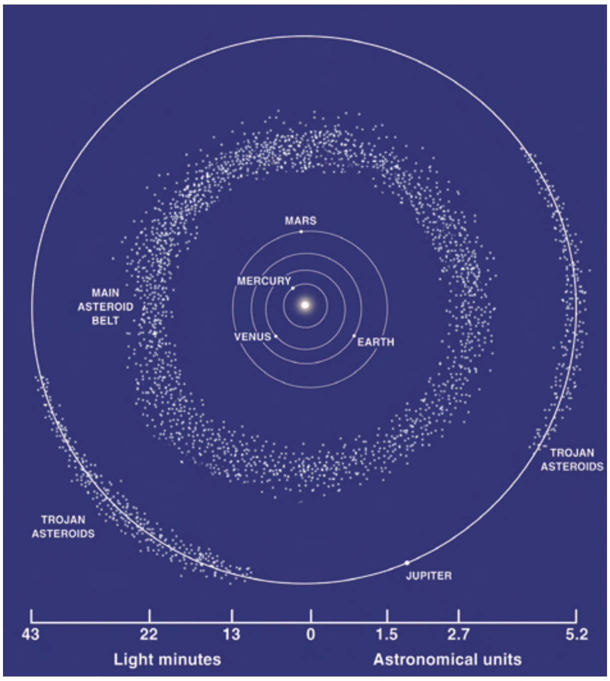


Figure 3 : Asteroid belts

Source: NASA

which contained organic matters. Thus, asteroids and comets, which are also called "primitive bodies," may hold information on the formation of the Solar System and its early evolution. From this viewpoint, exploration of these celestial bodies is also important.[6]

3-2 Trends in Japan and other nations

The missions exploring small solar system bodies carried out since the 1980s are shown in Table 2.[7] Here, it should be noted that this section will treat, as small solar system body exploration missions, exploratory missions to dwarf planets Ceres and Pluto and its moons, in addition to those to the small solar system bodies.

Exploration of Halley's Comet in the 1980s involved joint observations by the former Soviet Union's VEGA 1 and VEGA 2, Japan's SAKIGAKE and SUISEI, Europe's Giotto, and the United States' ICE (International Cometary Explorer) joining after exploring comet Giacobini-Zinner. In the 1990s, the Galileo spacecraft made close approaches (hereinafter, referred to as "flyby") to asteroids Gaspra and Ida while en route to Jupiter, and Giotto, which had observed Halley's Comet, made a flyby of comet Grigg-Skjellerup.

The main specifications of probes after Galileo are shown in Table 3. NEAR Shoemaker was the first spacecraft in the U.S. Discovery Program[8] that promotes small solar system body exploration missions. In this program, upper limits are set on mission budgets, and researchers are invited to submit proposals, which are then selected for actual missions. The main purpose of the NEAR Shoemaker mission was to approach (hereinafter, referred to as "rendezvous") an asteroid for the first time and to make detailed remote sensing observations.[9] The spacecraft took detailed images while making a controlled landing on the asteroid, and continued to send back data before the end of its mission.

Deep Space 1 was the first mission in the U.S. New Millennium Program, the main purpose of which is in-space testing of new technologies.[10] The world's first solar electric ion propulsion

Table 2 : Main missions to small solar system bodies

	1980s	1990s	2000s
Flyby/impact	·1985[NOTE 1]: <Comet Giacobini-Zinner> ICE ·1986: <Halley's Comet> VEGA 1, VEGA 2, SAKIGAKE, SUISEI, Giotto, ICE	· 1991 <Asteroid Gaspra> Galileo · 1992 <Comet Grigg-Skjellerup> Giotto · 1993 <Asteroid Ida> Galileo · 1997 <Asteroid Matilda> NEAR Shoemaker · 1999 <Asteroid Braille> Deep Space 1	· 2001 <Comet Borrelly> Deep Space 1 · 2002 <Asteroid Annefrank> Stardust · 2004 <Comet Wild 2> Stardust · 2005 <Comet Tempel 1> Deep Impact
Rendezvous /landing	[NOTE 1] Year when the probe arrived at the small solar system body. Same in the following. [NOTE 2] Excludes satellites of Solar System planets. Spacecraft in flight toward object celestial bodies are Rosetta, arriving 2014 at Comet Churyumov-Gerasimenko, New Horizons, arriving 2015 at Pluto and Charon, and Dawn, arriving 2011/2015 at Vesta/Ceres.		·2000 <Asteroid Eros> NEAR Shoemaker ·2005 <Asteroid Itokawa> HAYABUSA (Muses-C)
Sample return			·2004 <Comet Wild 2> Stardust (returned in 2006) ·2005 <Asteroid Itokawa> HAYABUSA (scheduled to return to Earth in 2010)

Source: Reference[7]

engine for interplanetary space flight was among the technologies tested in space by this mission.

Stardust was the fourth spacecraft in the Discovery Program. The main purpose of the mission was to, as the world’s first, sample and return dust discharged from the nucleus of a comet and cosmic dust in interstellar space (hereinafter, referred to as “sample return”).[11] In order to reduce launch costs by optimizing the amount of propellant carried by the spacecraft, a flight path circling the sun almost three times was adopted. As the first circuit required about 2 years, and the second and third circuits required approximately 2.5 years each, the total duration of this mission was approximately 7 years.

The main purpose of HAYABUSA was to demonstrate in space the technologies which would be essential and key to small solar system body exploration.[12] The technologies to be demonstrated in space were (1) interplanetary flight using an ion engine as the main propulsion system, (2) rendezvous and landing on a celestial body via autonomous guidance and navigation using optical information, (3) collection of samples from the surface of a celestial body under microgravity conditions, (4) sample recovery by reentering an capsule into the Earth’s atmosphere from an interplanetary trajectory, and (5) combined use of orbit transfer by terrestrial gravity (hereinafter, referred to as “swing-by”) and the ion engine. Return to Earth was postponed from June 2007 to June 2010 due to an accident involving leakage of the craft’s chemical propellant.

Rosetta, which is a large-scale science project of the European Space Agency (ESA), consists of an orbiter and a lander called Philae. Its main purpose is to observe comet Churyumov-Gerasimenko.[13] The lander will actually descend to its nucleus, where it will make detailed observations, while the orbiter will pass the perihelion together with the comet and will continue its observations over a period of approximately one year to investigate the comet. By the way, comets are sometimes described as “dirty snowballs.”

The Deep Impact probe was the eighth mission in the Discovery Program. Its main purpose was to collide an impactor into comet Tempel and observe substances emitted due to this collision to investigate the elemental composition of the comet’s interior.[14] The impactor, whose gross weight was approximately 372kg, was released from the probe on July 3, 2005 at a distance of approximately 880,000km from the comet, and impacted into the comet about one day later at a relative velocity of approximately 10.3km/s. The mechanical energy released by the impact was approximately 19GJ, which is estimated to be equivalent to about 45 tons of TNT.

New Horizons is the first mission in the United States’ New Frontiers Program, which promotes medium-class planetary missions. The program caps mission costs and selects missions from proposals submitted by researchers. The main purpose of New Horizons is to observe Pluto and its satellite Charon, and other bodies.[15] Launched by a large rocket, the spacecraft escaped from the Earth’s gravitational field at a velocity of approximately 16km/s, which was the fastest among the missions launched by rockets, and reached the Moon’s orbit around the Earth ,whose orbital radius is approximately 384,000km, in approximately 9 hours after launch. Because the craft uses a radioisotope thermoelectric generator (RTG) and doesn’t need to orient toward the Sun to generate power, it is to be placed in a hibernation mode after a swing-by of Jupiter in order to reduce operating costs and avoid wear of onboard electronic devices. Excluding when course adjustments and periodic inspection are made approximately once a year, the power supplies to one of the redundant systems are cut off, and the craft travels in a spin stabilized mode at about 5rpm, with its antenna pointed toward the Earth. After arriving at Pluto, it will turn toward observation targets using its attitude control system propulsion units.

Dawn is the ninth mission in the Discovery Program. Its main propulsion system consists of the same type of ion engines as that used for Deep Space 1, and its main purpose is to rendezvous with asteroid Vesta and dwarf planet Ceres.[16] Except when its antenna is turned toward the Earth several hours a week for communication, the ion engine operates continuously during interplanetary flight. The engine is also used for orbit insertion.

Table 3 : Main specifications of small solar system body probes of various countries

	NEAR Shoemaker	Deep Space	Stardust	HAYABUSA (MUSES-C)
Country (organization) developed by	USA (NASA)	USA (NASA)	USA (NASA)	Japan (JAXA)
Launch date	Feb. 17, 1996	Oct. 24, 1998	Feb. 7, 1999	May 9, 2003
Launch vehicle	Delta II	Delta II	Delta II	M-V
Dimensions of body (m)	[NOTE 1]	(Unknown)	1.7×0.66×0.66[NOTE 3]	1.0×1.6×1.1
Launch weight (kg)	805	486.3	385[NOTE 4]	510[NOTE 7]
Power generated (W)	1,800@1AU 400@2.2AU	2,500@1AU	170~800[NOTE 5]	2,600@1AU
Attitude control method	3 axes	3 axes	3 axes	3 axes
Mission period	To Feb. 28, 2001	To Dec. 18, 2001	To Jan. 15, 2006[NOTE 6]	June 2010 (scheduled)
Mission cost (million USD)	224.1	149.7[NOTE 2]	168.4	(Approx.¥23.5 billion)

[NOTE 1] Octagonal body comprising 8 aluminum panels with area of approximately 1.7m^2.
[NOTE 2] 1995-1999 U.S. accounting years.
[NOTE 3] Dimensions of recovery capsule: φ0.8m x 0.5m.
[NOTE 4] Includes sample recovery capsule: 46kg.
[NOTE 5] Generated power varies depending on the distance from the Sun.
[NOTE 6] Date of return to Earth of sample recovery capsule.
[NOTE 7] Includes reentry capsule: 16kg, target marker: 280g x 3, surface probe Minerva: 591g.

	Rosetta	Deep Impact	New Horizons	Dawn
Country (organization) developed by	EU (ESA)	USA (NASA)	USA (NASA)	USA (NASA)
Launch date	March 2, 2004	January 12,2005	January 19.2006	Sept. 27, 2007
Launch vehicle	Ariane V	Delta II	Atlas V	Delta II
Dimensions of body (m)	2.8×2.1×2.0	3.3×1.7×2.3[NOTE 10]	0.7×2.1×2.7[NOTE13]	1.64×1.27×1.77
Launch weight (kg)	3,000[NOTE 8]	973[NOTE 11]	478	1,217.7
Power generated (W)	850@3.4AU 400@5.2AU	750 (max.)[NOTE 12]	234@Jupiter 200@Pluto	10,300@1AU 1,300@3AU
Attitude control method	3 axes	3 axes	3 axes/spin	3 axes
Mission period	To Dec. 2015 (scheduled)	To Aug. 2005	To July 2015 (scheduled)[NOTE 14]	To July 2015 (scheduled)
Mission cost (million USD)	Approx. 1.0 billion Euros[NOTE 9]	333	700	357.5

[NOTE 8] Includes comet surface lander Philae: 100kg.
[NOTE 9] Includes additional costs of approximately 70 million Euros due to launch delay caused by problems with Ariane V.
[NOTE 10] Dimensions of impactor: φ1m x 1m.
[NOTE 11] Probe: 601kg + impactor: 372kg.
[NOTE 12] At rendezvous with comets : 620W
[NOTE 13] Shape is a roughly triangular prism.
[NOTE 14] Date of scheduled arrival at Pluto.

Source: Reference[9-16]

3-3 Technologies necessary for small solar system body exploration

For asteroid exploration, remote sensing observation devices are used to investigate elemental compositions, mineral compositions, topographies, shapes and sizes, and other characteristics of asteroids. Asteroids' gravitational fields are measured by analyzing asteroid probes' tracking data to study asteroids' masses and densities. For comet exploration, in addition to remote sensing observation devices like those used for asteroid exploration, comet probes are also equipped with such devices as sounders to investigate comets' nuclei, dust flux and composition analyzers to study comets' comas, plasma measurement devices to investigate interactions between comets and the Sun.

On the other hand, the dust collector of Stardust, the surface sampling technology of HAYABUSA, the in-situ observation by Rosetta's lander, and the impactor of Deep Impact are unique when compared with other probes' instruments, and researches done by new techniques like these seem to become increasingly more important in the future. Therefore, this section will discuss the ion engine, sampling, and reentry capsule technologies considered necessary for sample return that enables Solar System sample analyses on the ground.

(1) Ion engine technology

While one approach to send a probe to a target celestial body is to launch the probe by a large rocket like New Horizons to obtain a high initial velocity to escape the Earth's gravitational field, followed by inertial flights combined with swing-bys, the other approaches, which employ smaller rockets desirable to reduce mission costs, include onboard propellant optimization by selecting flight trajectories as done for the Stardust mission as well as the use of ion engines as main propulsion systems as done for the Deep Space 1, HAYABUSA, and Dawn missions.

The approximate launch capabilities of the United States' Delta II and Atlas V,[17] Europe's Ariane V,[18] and Japan's M-V and, for reference, H-IIA[19] are shown in Table 4. The launch capability of M-V is significantly lower than those of the other rockets, but thanks to the creative ingenuity of Japanese scientists and engineers concerned, the HAYABUSA mission, which was in no way inferior to the efforts of other nations, was indeed realized.

Chemical propulsion systems generate thrusts by discharging high temperature gases generated by combustion or catalytic reaction processes of chemical propellant, whereas ion engines ionize xenon propellant and accelerate ions in electrical fields, and the ions are discharged after being neutralized by bonding with electrons.

The rocket equation where no propellant is replenished during space flight is shown in Figure 4.[20] Ion engines are not suitable for escaping from the Earth's gravitational field because their thrust forces (i.e. horsepower) are much smaller than those of chemical propulsion systems, but because their specific impulses are approximately ten times higher than those of chemical propulsion systems, hey can obtain the same amount of orbit transfer as with chemical propulsion systems while consuming only one tenth as much propellant (meaning lower fuel consumption). Therefore, in addition to lowering launch weight by reducing the amount of propellant onboard and enabling launching with a smaller rocket, an ion engine, after escaping from the Earth's gravitational field, enables flight to a distant celestial body by realizing a greater amount of orbit transfer than a rocket, as was demonstrated by HAYABUSA.[21] Furthermore, the drawback of longer-term flight with lower thrust conversely enables flexibility in orbital trajectory planning, enebliing an extended launch window period.

The orbital lifetime of a satellite is effectively determined by the amount of propellant onboard the satellite. Since the 1980s, American commercial geostationary telecommunications satellites have been equipped with ion engines for orbital control in order to extend their orbital lifetime by taking advantage of the feature of high specific impulse (i.e. lower fuel consumption). Orbital control is performed by operating the ion engines approximately 0.5 to 5 hours daily. In this connection, it may be noted that Japan's KIKU 8 is also equipped with an ion engine for orbital control.

The first use of an ion engine onboard a space probe was a NSTAR engine aboard the U.S. Deep Space 1 mission, which was followed byμ10 engines aboard Japan's HAYABUSA mission and a PPS1350 engine aboard European lunar probe SMART-1, which will be discussed later. The main specifications of these engines and their flight results are presented in Table 5.[22] The U.S.'s Dawn is also equipped with three NSTAR units, and the total empty weight of the ion engine system is approximately 129kg. The μ10 ion engine system onboard HAYABUSA, which holds the record for the longest total operating time, generates approximately 24mN of thrust with electric power consumption of approximately 1.1kW and a maximum of three of four units in

Table 4 : Launch capabilities of Japanese, U.S., and European rockets

	Delta II	Atlas V	Ariane V	M-V	H-IIA
GTO(kg)	900 - 2,120	4,950 - 13,000	6,000 - 9,600	—	3,700 - 5,700
LEO(kg)	2,450 - 5,430	9,750 - 29,420	21,000	1,850	10,000

Source: Reference[17-19]

$$\Delta v = V_{ex} \ln(M_i/M_f),\ V_{ex} = gI_{sp}$$

- Δv: change of velocity or orbit transfer.
- V_{ex}: exhaust velocity; ln is a natural logarithm.
- M_i and M_f: initial and final masses of a probe before and after operation of the propulsion system.
- I_{sp}: specific impulse; value obtained by dividing V_{ex} by the acceleration of gravity of the Earth (approximately $9.8 m/s^2$).

➢For a given value of Δv, the conditions for higher performance of a propulsion system are arrival at the target object with a larger final mass M_f relative to the initial mass M_i, in other words, achievement of a larger exhaust velocity V_{ex} with the same amount of propellant consumption (= lower fuel consumption).

Figure 4 : Rocket equation

Source : Reference[20]

Table 5 : Main specifications and mission results of Japanese U.S., and European ion engines

Mission	Deep Space 1	HAYABUSA (MUSES-C)	SMART-1
Ion engine	NSTAR	μ10	PPS1350
Number of engines	1	4	1
Empty weight (kg)	64.4	59	(Unknown)
Power consumption (W)[NOTE 1]	2,300	350	1,500
Specific impulse (s)	3,280	3,200	1,650
Thrust (mN)[NOTE 2]	91	8[NOTE 3]	88
Orbit transfer (m/s)	4,300	1,400	3,700
Total operating time (hr)	16,265 (approx. 678 days)	25,800 (approx. 1,075)	4,958 (approx. 207)
Propellant consumption (kg)	73.4	22	81.7
Ground life test (hr)	30,352	20,000	10,530

[NOTE 1] Specific impulse and thrust are values for the power consumption shown in figure.
[NOTE 2] 1N: 0.1kg weight, 1mN: 0.1g weight.
[NOTE 3] Value per engine. When 3 engines are in operation, 24mN.

Source: Reference[22]

operation at one time. The number of units in operation and the thrust generated vary depending on power conditions. As of October 18, 2007, following the chemical propellant leak accident, this ion engine system had set a new record for total operating time of approximately 31,400 hours (approximately 1,308 days), and had achieved orbit transfer of approximately 1,700m/s. The remaining orbit transfer necessary for return to the Earth is approximately 400m/s. This craft has recorded the longest operating time for a single engine of approximately 13,400 hours (approximately 558 days).[23]

SMART-1's PPS1350 engine was developed by SNECMA, a French company, based on an ion engine manufactured by Russia, and generated approximately 9.1-65.7mN of thrust with power consumption of approximately 462-1,190kW. Among Dawn's three NSTAR units, one is operational (system redundancy), generating approximately 19-91mN of thrust with power consumption of approximately 500-2,300W. The estimated total operating time is approximately 2,000 days, and the xenon consumption amounts necessary to reach Vesta and Ceres are approximately 288kg and 89kg, respectively.

Extremely long operating times are necessary for ion engines to accomplish interplanetary flights. While NSTAR's ion-forming electrodes are thought to be susceptible to deterioration, μ10, which is a microwave discharge ion engine that forms ions by a microwave generator instead of electrodes, is thought to be less susceptible to deterioration.[24]

To realize high performance propulsion systems for interplanetary flight, NASA is developing a next-generation ion engine called NEXT as a successor to NSTAR, and a lightweight, high temperature combustion type bipropellant chemical propulsion system called AMBR (the Advanced Material Bipropellant Rocket) using advanced materials,[25] and recommends to study their use in making proposal for the third mission in the New Frontiers Program.[26] Likewise, Japan is now engaged in research and development on the increased thrust type μ20 ion engine (thrust: approx. 30mN, specific impulse: approx. 2,500s with power consumption of approx. 1kW) and the increased specific impulse type μ10Hisp engine (thrust: approx. 30mN, specific impulse: approx. 10,000s with power consumption of approx. 2.5kW) as successors to the μ10 engine, aiming to be main propulsion systems for the HAYABUSA Mk-II (Marco Polo) primitive body probe and the Solar Powered Sail mission to Jupiter, respectively.[27,28]

(2) Sampling and reentry capsule technologies

The Stardust mission (Figure 5) sampled dust from comet Wild 2 while flying before and after its nearest approach to the comet on January 2, 2004, and also sampled dust in interplanetary space while flying for a total of approximately 195 days during its first (February to May 2000) and second circuits (August to December 2002). Its tennis racket-shaped dust catcher used jelly-like solid silicon called aerosol, which had an ultra-low density, was inert, and had a high void ratio. The dust sampling area of the front and back surfaces was approximately 1,000cm2 each. The front and back surfaces were used in passive sampling of the dust from the comet and sampling from interplanetary space, respectively. The sample recovery capsule housing this dust catcher reentered the Earth's atmosphere on January 15, 2006, and after deceleration using a parachute, fell to the Earth and was recovered in the state of Utah in the United States.

The recovered dust samples were processed at NASA's Johnson Space Center, and samples were then distributed to initial analysis teams consisting of a total of approximately 187 participating researchers from more than 100 institutions in nine countries. Chemical composition analysis, infrared spectroscopy analysis, mineral and rock analysis, isotope analysis, organic analysis, and impact crater analysis were carried out over a period of about six months.[29] With the exception of meteorites, whose original celestial bodies are difficult to identify, this was the first time that extra-terrestrial samples had been recovered from a body in the Solar System since the Apollo Program and the former Soviet Union's Luna Program. Research on the Moon has progressed using samples from the lunar surface taken in the Apollo Program. Because comets are thought to retain the original materials of the Solar System, the scientific significance of returning the substances which make up comets to the Earth and direct analysis utilizing various types of analytical equipment is considered enormous. The analysis work for which Japanese researchers were responsible included nondestructive analysis by synchrotron radiation using the facilities of the High Energy Accelerator Research Organization (KEK) and SPring-8.

HAYABUSA (Figure 6) performed sampling by an active technique, in which the surface of asteroid Itokawa was crushed by metal balls weighing several grams which were shot into the surface at approximately 300m/s, and the fragments which scattered from the surface under the microgravity conditions of the asteroid were collected in a container in the probe via a sample horn.[12] Diversification[30] of surface sampling techniques, and higher heating resistance and reduced weight of the return capsule[31] are currently being studied in order to meet the requirements of various missions using Japan's sample return technology, which uses a combination of technologies including the ion engine of long-term operation.

In addition to the S type asteroid explored by HAYABUSA, other potential targets for sample return include asteroids which are classified as the C, P, and D types,. based on differences in their solar reflectivity, and dead comets, or "Comet-Asteroid Transition Objects (CAT)," which are considered to be the remnants of comets captured in the asteroid belt. Thus, there are still many small solar system bodies from which researchers hope to receive samples for detailed analysis on the ground.

4 Trends in lunar exploration in Japan and other countries

4-1 Significance of lunar exploration

The Moon was born approximately 4.5 billion years ago, in the same period as the Earth, but because the Moon, unlike the terrestrial planets, has not been affected by plate tectonics, volcanic activities, weathering, and other phenomena, it offers a faithful record of the history of its early evolution. Moreover, because it is relatively close to the Earth, it is a favorable object for research in planetary science.[32] The United States of America made a total of six successful manned landings on the Moon in its Apollo manned space exploration program, during which astronauts made various scientific observations and collected a total of approximately 400kg of samples from the Moon' s surface. In spite of steady progress in lunar research, for example, various theories explaining the mystery of the Moon's origin have been advacated, including (1) the "fission hypothesis," which holds that part of the Earth was spun off due to its high rotational speed, and that part formed the Moon, (2) the "co-formation hypothesis," which stipulates that the Moon formed from an accretion disk of rock and gas near the Earth, (3) the "capture hypothesis," which says that a celestial body which had formed in a region different from the Earth was captured by the Earth, and (4) the "giant impact hypothesis," which has been prevalent since the Apollo Program and proposes that the Moon formed from debris resulting from a collision between the proto-Earth and a protoplanet with the size of Mars or larger. However, this mystery has not yet been resolved.

4-2 Trends in Japan and other nations

The Clementine probe was a joint project of the United States' National Aeronautics and Space Administration (NASA) and Department of Defense (DOD). Its main purpose was to evaluate the long-term resistance of sensors and components to the space environment.[33] The probe was launched on January 25, 1994. After insertion into a lunar orbit on February 21 of the same year, remote sensing observation was performed for a period of approximately two months. In order to research the topography of the Moon, the Clementine took images of the lunar surface in the ultraviolet, visible light, and infrared wavebands and measured the altitude of the lunar surface with a laser altimeter. The probe was also equipped with radar in order to investigate the existence of ices of water and other volatile substances in the permanently shadowed areas in the Moon's polar regions. The surface layer of the Moon was surveyed by directing radio waves at the Moon from the probe and measuring the waves reflected from the Moon's surface with receivers on Earth. Observational data suggesting the existence of frozen water in the Moon's southern polar region were obtained in certain orbits, but such data were not obtained in other orbits.

Japan launched lunar orbiter KAGUYA to conduct the first full-scale scientific exploration of the Moon since Apollo. This was followed by

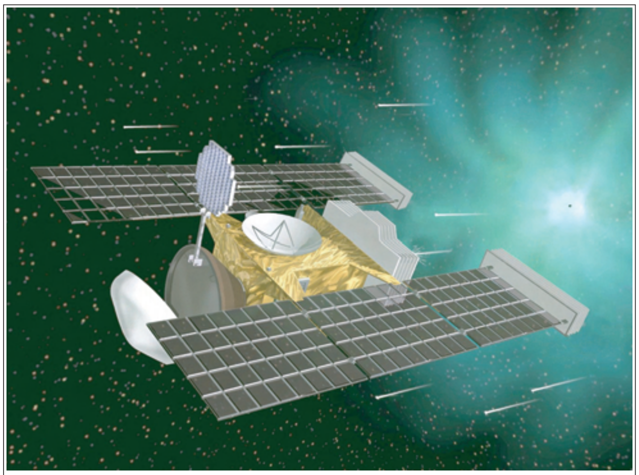


Figure 5 : Stardust (artist's conception)

Source: NASA

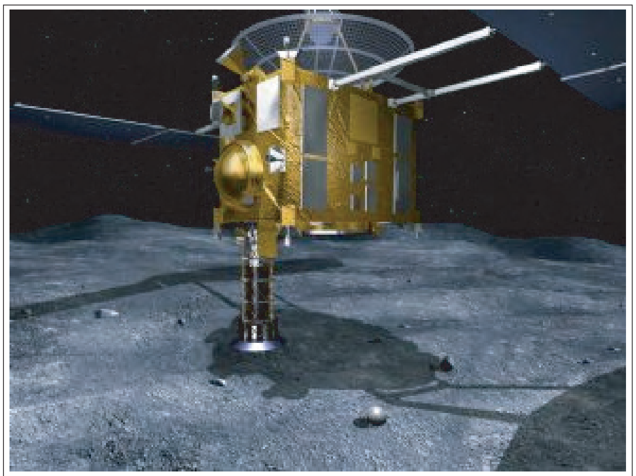


Figure 6 : HAYABUSA (MUSES-C) (artist's conception)

Source: JAXA

China's launch of Chang'e 1 and by India's launch of Chandrayaan 1, both with the aim of acquiring new space capabilities of lunar exploration technology. Thus, the beginning of the 21st century marked the start of renewed activities in lunar exploration. The main specifications of the major lunar missions since Clementine are shown in Table 6.

As a Moon orbiting observation mission , KAGUYA observes the Moon's surface elemental distribution, mineral composition and distribution, topography and surface layer structure, global gravitational field, magnetic anomalies, plasma environment, and other lunar characteristics with the aim of studying the mystery of the origin and evolution of the Moon.[34] Also being Japan's

Table 6 : Main specifications of lunar probes of various countries

		KAGUYA (SELENE)	Chang'e 1	Chandrayaan 1	SMART-1
Country (organization) developed by		Japan (JAXA)	China (CNSA)	India (ISRO)	Europe (ESA)
Launch date		Sept. 14, 2007	Oct. 24, 2007	Oct. 22, 2008	Sept. 27, 2003
Launch vehicle		H-IIA	Chang Zheng (Long March) IIIA	PSLV	Ariane V
Dimensions of body (m)		2.1×2.1×4.8	2.0×1.7×2.2	1.5×1.5×1.5	1×1×1
Launch weight (kg)		2,885[NOTE 1]	2,350	1,304[NOTE 3]	366.5
Power generated (W)		3,486	(unknown)	700	1,850
Orbit	Altitude (km)	100[NOTE 2]	200	100	300×3000
	Type of orbit	Polar orbit	Polar orbit	Polar orbit	Polar orbit
Attitude control method		3 axes	3 axes	3 axes	3 axes
Mission period		1 year[NOTE 2]	1 year	2 years	1.5 years[NOTE 4]
Mission cost		Approx. ¥55.0 billion	Approx. 1.4 billion yuan	Approx. 3.86 billion Indian rupee	Approx. 110 million Euros

[NOTE 1] Main satellite: 2,779kg, sub-satellites: 53kg x 2
[NOTE 2] After steady operation, was changed to an orbital altitude of 40-70km.
[NOTE 3] 590kg @ lunar orbit.
[NOTE 4] Initially scheduled for half-year, but extended by 1 year.

		Lunar Prospector	LRO	LCROSS	GRAIL
Country (organization) developed by		USA (NASA)	USA (NASA)	USA (NASA)	USA (NASA)
Launch date		Jan. 1, 1998	Feb. 27, 2009 (scheduled)		Sept. 2011 (scheduled)
Launch vehicle		Athena II	Atlas V		Delta II
Dimensions of body (m)		φ1.37×1.28	(Unknown)	(Unknown)	(Unknown)
Launch weight (kg)		202	1,846	834[NOTE 5]	466.1[NOTE 7]
Power generated (W)		3,486	1,850	600	(Unknown)
Orbit	Altitude (km)	100	50	(Elliptical earth orbit by performing swing-by with Moon.)	50
	Type of orbit	Polar orbit	Polar orbit		Polar orbit
Attitude control method		Spin	3 axes	3 axes	3 axes
Mission period		1.5 years	1 year	Approx. 86 days[NOTE 6]	Approx. 90 days[NOTE 8]
Mission cost (million USD)		63	421		375

[NOTE 5] At time of lunar impact, probe: 700kg, upper stage of rocket: 2,000kg.
[NOTE 6] Time to lunar impact.
[NOTE 7] Two vehicles will be launched simultaneously. Weight when launching 1 vehicle: 202.4kg.
[NOTE 8] After completion of the mission, the twin satellites will be impacted on the Moon.

Source: Reference[34-41]

first lunar probe, the orbiter aims to establish the lunar orbit insertion technology, and the tri-axial attitude control, orbit control and thermal control technology in lunar orbit. Chang'e 1 is the first in a series of lunar exploration missions planned by China. Its technical aims includes acquisition of lunar probe development and launch capabilities, verification of technologies necessary for lunar exploration and establishment of requisite technical infrastructure, and accumulation of experience for subsequent missions.[35] Its scientific objectives are to obtain 3-dimensional images of the Moon' s surface and measure the distribution of surface elements and the thickness of the surface soil as well as to investigate resources such as helium 3 fuel for nuclear fusion. Chandrayaan 1 is developed by the Indian Space Research Organisation (ISRO), and was India's first lunar probe. Its aims are to verify and improve India's space development technologies and to obtain data on the Moon's surface.[36]

SMART-1 is a probe which was launched by the European Space Agency (ESA) with the aim of space testing of technologies, such as an ion engine, which will be necessary for future missions.[37] This probe was transferred from Earth orbit to lunar orbit by its ion engine. After reaching lunar orbit, the probe collected scientific data associated with the geology, topography, mineral and elemental composition, near-Moon environment and other lunar characteristics, and finally made a hard landing on the Moon's surface. Because it was equipped with an ion engine, its power generation was larger than that of other spacecraft.

Lunar Prospector was the third mission in the NASA Discovery Program. Its objectives were to collect data on the elemental composition of the Moon's surface, the existence of water ice in the permanently shadowed areas in the polar regions, magnetic anomalies, the gravitational field, and other lunar features.[38] Observational data suggesting the existence of frozen water were obtained by neutron spectroscopy, and the craft then crashed into the Moon's surface in an attempt to verify the presence of water ice, but confirmation was not possible from Earth-based telescope observations of the resulting plume.

NASA's Lunar Reconnaissance Orbiter (LRO) is the first mission in the Lunar Precursor Robotic Program being carried out in anticipation of a resumption of manned lunar exploration activities.[39] Its purpose is to obtain detailed information on the Moon's surface topographical structure, usable resources such as water ice deposits, radiation environment, and other characteristics in order to decide future landing sites and locations for the construction of lunar bases. The Lunar Crater Observation and Sensing Satellite (LCROSS) will be launched together with the LRO to investigate the existence of ice deposits in the permanently shadowed lunar polar regions. In this mission, the upper stage of the rocket and the observation vehicle will be crashed successively into the Moon, and the resulting plumes will be observed.[40] It is estimated that the energy released by crashing the upper stage into the Moon at a relative velocity of about 2.5km/s will be approximately 6.25GJ, or the equivalent of approximately 1.5 tons of TNT. Japan's KAGUYA will make observations of the Moon's entire gravitation field, including the farside of the Moon, by 4-way Doppler measurements and differential VLBI (Very Long Baseline Interferometry) observation using a pair of smaller satellites. In contrast, NASA's GRAIL (the Gravity Recovery and Interior Laboratory) is planned to measure the global gravitational field of the Moon by measuring the changes of the relative distance between twin lunar orbiters.[41]

4-3 Technologies necessary for lunar exploration

KAGUYA is engaged in observations including (1) as science of the Moon, its distribution of elements, distribution of minerals, topography and surface layer structure, and global gravitational field, (2) as science at the Moon, its magnetic anomalies, radiation environment, plasma environment, and ionosphere, and (3) as science from the Moon, the Earth's plasma environment. Views of KAGUYA at the time of testing on the ground and an outline of the instruments carried onboard KAGUYA are shown in Figure 7 and Table 7, respectively.

The instruments carried onboard the lunar probes of each nation are listed in Table 8. Because the purpose of LRO, LCROSS, and GRAIL is to collect information in anticipation of manned activity, an outline of these missions is shown separately in Figure 8.

From Table 8, it can be deduced that the objective of KAGUYA is precisely the full-scale scientific investigation of the Moon. For research on elemental/mineral distribution, KAGUYA carries observational equipment similar to those of other nations; however, it is also equipped with a radar sounder for measurement of the weak reflected radio waves from the surface and a depth of several kilometers underground, and a lunar magnetometer which enables measurement of magnetic anomalies with an accuracy of 0.1nT or smaller. It will also measure the farside gravitational field of the Moon by 4-way Doppler measurements with ground stations on the Earth via a relay satellite, OKINA (RSAT), which is a world's first. It will make precise measurements of the Moon's gravitational field by differential VLBI observation using sub-satellite OUNA (VRAD) and OKINA (RSAT), and will observe the Moon's rarified ionosphere by detecting phase changes in the radio waves transmitted by OUNA (VRAD). Thus, this mission is conducting comprehensive lunar exploration not seen in other nations' missions.

Regarding the laser altimeter, on April 9, 2008, the Japan Aerospace Exploration Agency (JAXA) publicized a map of the entire Moon, which was prepared jointly by the National Astronomical Observatory of Japan and the Geographical Survey Institute.[42] Altitude data on approximately six million points had been obtained as of April 9, 2008, greatly exceeding the results of previous observations, and also including the Moon's polar regions for the first time. A topographical map of the Moon prepared using observational data from a 2-week period of January 7-20, 2008 was published. Regarding the High Vision (high definition television: HDTV) camera, on April 11 of the same year, an image of the rising full Earth was taken, which could be observed from lunar orbit when the Sun, Moon, satellite orbit, and the Earth were aligned along a straight line, and an image of the entire Earth, which appears bright blue, was published.[43]

A distinctive feature of India's Chandrayaan 1 is international cooperation with Europe and the United States of America. In addition to five units of observational equipment supplied by India itself, this mission includes two units provided by NASA (M3, MiniSAR), three provided by ESA (C1XS, SIR-2, SARA), and one unit provided by Bulgaria (RADOM), for a total of 11 instruments, and can therefore be considered a good example of international cooperation to obtain richer scientific

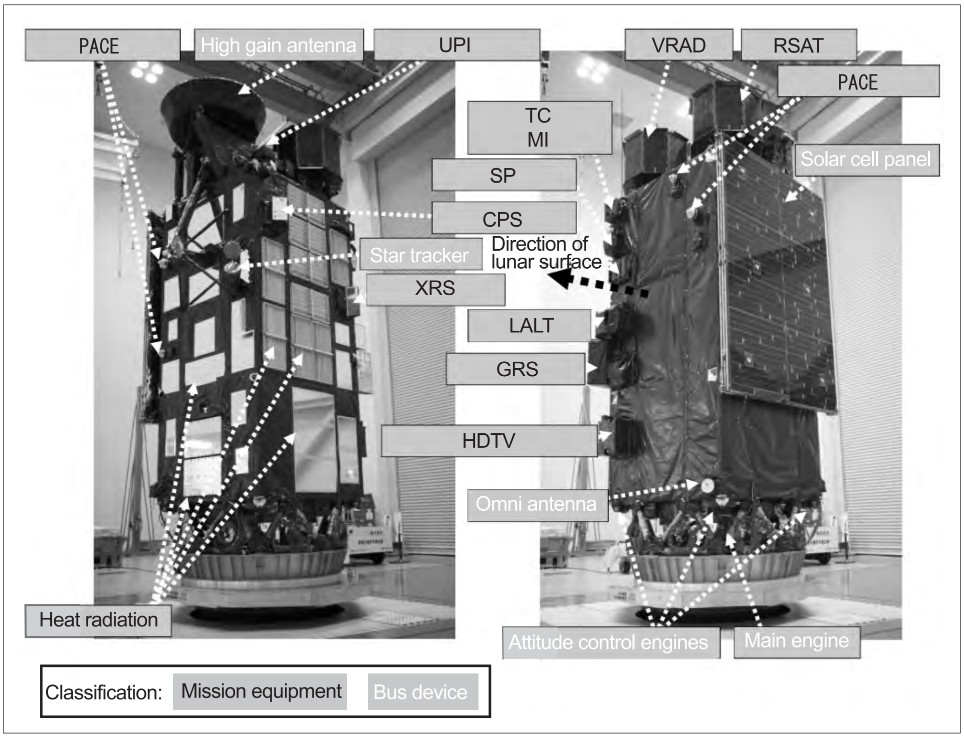


Figure 7 : KAGUYA (SELENE) during testing on Earth

Source : JAXA

Table 7 : Outline of instruments aboard KAGUYA (SELENE)

Elemental distribution of lunar surface	X-Ray fluorescence Spectrometer (XRS)	Observes X-ray fluorescence emitted by elements at the lunar surface as a result of solar X-rays; surveys the elemental distribution of Mg, Al, Si, S, Ca, Ti, Fe, etc.
	Gamma Ray Spectrometer(GRS)	Observes gamma rays emitted from elements at the lunar surface; surveys the elemental distribution of U, Th, K, H, O, Mg, Al, Si, Ca, Ti, Fe, etc.
Mineral distribution of lunar surface	Multi-band Imager (MI: visible light/ infrared radiometer)	Observes visible and infrared light from the lunar surface in 9 wavelength bands; surveys mineral distribution.
	Spectral Profiler (SP: visible light/infrared spectrometer)	Observes the continuous spectrum of visible and infrared light from the lunar surface; surveys mineral distribution.
Topology and surface layer structure of Moon	Terrain Camera (TC)	Photographs with 2 cameras having resolution of approximately 10m; used in preparing 3-dimensional images of the lunar terrain.
	Laser Altimeter (LALT)	Obtains the distance between the satellite and the lunar surface by irradiating a laser beam on the lunar surface and measuring the round-trip time until its return; measures changes in terrain and altitude.
	Lunar Radar Sounder (LRS)	Investigates the surface layer structure of the Moon to a depth of several km underground based on reflected radio waves from the Moon.
Global gravitational field of Moon	Relay Satellite (RSAT)	Observes disturbances in the orbit of the main satellite by relaying radio waves from the main satellite while travelling on the farside of the moon and Doppler measurement of those radio waves by ground stations on Earth; used to obtain data on farside gravitational field.
	Differential VLBI Radio source (VRAD)	Makes high accuracy determination of the orbit of the sub-satellite by differential VLBI * measurement by ground stations of the radio sources transmitted by the two sub-satellites (RSAT, VRAD), and accurately measures the gravitational field of the Moon. (* : Very Long Baseline Interferometry. Used to obtain the position of a radio source from differences in paths of radio waves.)
Environment at lunar surface	Lunar Magnetometer (LMAG)	Observes the distribution of magnetism at the lunar surface and in the vicinity of the Moon.
	Charged Particle Spectrometer (CPS)	Observes cosmic rays in the vicinity of the Moon, high energy radiation emitted by the Sun, and alpha rays emitted by radon on the lunar surface.
	Plasma energy Angle and Composition Experiment (PACE)	Measures the distribution of electrons and ions in the vicinity of the Moon originating from solar wind, etc.
	Radio Spectrometer (RS)	Measures changes in the phase of radio waves from the VRAD satellite; used in research on the rarified lunar ionosphere.
Terrestrial plasma environment	Upper atmosphere and Plasma Imager (UPI)	Image sensor observation of the Earth's magnetosphere and plasmasphere from lunar orbit.
Imaging	High Definition Television (HDTV) Camera System	High definition imaging of the Earth and Moon, for example, photograph of "Earthrise."

Source: Reference[34]

results. It may be noted that two of the ESA devices (C1XS and SIR-2) are improved versions of those carried onboard SMART-1.

NASA is continually investigating the presence of water ice on the Moon. In addition to the fact that water will be indispensable for manned activities, it can also be used to form hydrogen and oxygen, which could become propellant for space transport vehicles, by electrical decomposition using solar power generation. Because transportation of water from the Earth would be extremely expensive, mission costs can be greatly reduced if water ice deposits exist on the Moon and these can be extracted and processed into water.

5 Japan's space capabilities demonstrated by the HAYABUSA and KAGUYA missions

(1) Establishment of Japanese original space technologies unrivaled by other nations

The United States of America succeeded in one-way interplanetary space travel with an ion engine with its Deep Space 1, and in sample

Table 8 : Instruments aboard lunar probes of various countries

		KAGUYA (SELENE)	Chang'e 1	Chandrayaan 1	SMART-1	Lunar Prospector
Elemental distribution of lunar surface	X-ray fluorescence spectrometer	○ (XRS)	○	○ (C1XS)	○ (D-CIXS)	—
	Gamma ray spectrometer	○ (GRS)	○	○ (HEX)[NOTE 3]	—	○ (GRS)
Mineral distribution of lunar surface	Visible-infrared radiometer	○ (MI)	○ [NOTE 1]	○ (HySI,M3) [NOTE 1]	—	—
	Visible-infrared spectrometer	○ (SP)	—	○ (SIR-2)[NOTE 4]	○ (SIR)[NOTE 4]	—
Topography and surface layer structure of Moon	3D camera	○ (TC)	○	○ (TMC)	○ (AMIE)[NOTE 6]	—
	Laser altimeter	○ (LALT)	○	○ (LLRI)	—	—
	Radar sounder	○ (LRS)	○ [NOTE 2]	—	—	—
Global gravitation field of Moon	Main- and sub-satellite system	○ (RSAT,VRAD)	—	—	—	— ○ (DGE)
Environment at lunar surface	Magnetometer	○ (LMAG)	—	—	—	○ (MAG,ER)
	Charged particle spectrometer	○ (CPS)	○	○ (RADOM)	—	○ (APS)
	Plasma observation device	○ (PACE)	○	○ (SARA) [NOTE 5]	○ (SPEDE)	—
	Radio observation	○ (VRAD)	—	—	—	—
Others	Terrestrial plasma environment	○ (UPI)				
	High definition television	○ (HDTV)				
	Water-ice at lunar poles			○ (MiniSAR)		○ (NS)
	Lunar impact			○ (MIP)		
	Motion on Moon's axis of rotation				○ (RSIS)	

[NOTE 1] Imaging spectrometer.
[NOTE 2] Measurement of thickness of lunar soil by microwave radiometer.
[NOTE 3] Observation to hard X-ray region.
[NOTE 4] Near-infrared spectrometer.
[NOTE 5] Measurement of neutral atoms pulled from lunar surface by solar wind.
[NOTE 6] 2-dimensional multi-color image.

Source: Reference[34-38]

return involving passive capture of cometary and interstellar dust and capsule recovery with Stardust. However, Japan's "HAYABUSA" succeeded in demonstrating a sample return technology by round-trip interplanetary flight utilizing its ion engine system, active collection of samples from the surface of the object celestial body, and capsule return (scheduled for demonstration in June 2010). As a total package, this can be considered one technical system for future exploration of small solar system bodies. Thus, it can be said that Japan has established an original space technology which is unrivaled by other nations.

(2) Integration of Japan's intellectual resources by an inter-university research system

The Institute of Space and Astronautical Science (ISAS), which is part of the Japan Aerospace Exploration Agency (JAXA), functions as an inter-university research institute, requesting

LRO
(Purpose) To collect information on the topography of the Moon, obstacles to landing/inclination, water-ice and other resources, the radiation environment, and temperature, illumination conditions, and terrain, etc. in polar regions at candidate lunar bases. 1. Lunar Orbiter Laser Altimeter (LOLA) · Produce a high-resolution global topographic model for development of precise and safe landing and exploratory activities. Characterize the polar illumination environment and identify ice in permanently shadowed polar regions. High resolution: 0.1m (approx.) 2. Lunar Reconnaissance Orbiter Camera (LROC) · Observe obstacles/illumination conditions at candidate landing sites. · Narrow angle (resolution: approx.0.5m), wide angle (resolution: approx. 100m) 3. Lunar Exploration Neutron Detector (LEND) · Observe distribution of water-ice and hydrogen, radiation environment. Spatial resolution: 10km (approx.) 4. Diviner Lunar Radiometer Experiment (DLRE) · Observe temperature distribution at lunar surface. Temperature measurement accuracy: 5°C (approx.) 5.Lyman-Alpha Mapping Project (LAMP: ultraviolet imaging spectrometer) · Detect ice/frost in surface layer of permanently shadowed areas, observe topography. Wavelength resolution: 3.5nm (approx.), spatial resolution: 260m (approx.) 6.Cosmic Ray Telescope for the Effects of Radiation (CRaTER) · Observe galactic cosmic rays, etc. in order to assess effects on human body using tissue-equivalent plastic. Spatial resolution: 77km (approx.) 7. Miniature Synthetic Aperture Radar (mini-RF) · Observe water- ice and other volatile substances in polar regions.

Source: Reference[39]

LCROSS
Lunar Crater Observation and Sensing Satellite (LCROSS) (Purpose) To conduct a survey in connection with the existence of water-ice in the permanently shadowed areas of the lunar surface. · Comprises the upper stage of the Centaur launch rocket and an observation vehicle (Shepherding Space Craft: S-S/C). Will be launched together with the LRO. · The upper stage rocket will be inserted into an impact trajectory with the permanently shadowed area under control by the S-S/C, and the plume produced by the impact of the upper stage will be observed by the S-S/C and earth-based telescopes. The S-S/C will then impact into the Moon's surface. · In the past, the Lunar Prospector was also crashed into the Moon's surface for the same purpose, but the existence of water-ice remained unconfirmed.

Source: Reference[40]

GRAIL
(Purpose) To measure the global gravitational field of the Moon for research on the internal structure from the mantle to the core and the thermal evolution of the Moon. The 10th mission in the Discovery Program. ·Rate of change in the distance between twin probes in polar orbit around the Moon at a relative distance of 175-225km and altitude of approximately 50km will be measured in order to measure the global gravitational field of the Moon. ·Spatial resolution is approximately 30km x 30km; gravitational field measurement accuracy ≦ 10mGal (approx.). ·Images taken by remote control of onboard cameras will be used for educational purposes. ·After scientific observations for approximately 90 days, the vehicles will be impacted into the lunar surface by orbit control. Data will be analyzed over a period of about 12 months.

Source: Reference[41]

Figure 8 : Outline of unmanned lunar probes in NASA's Lunar Precursor Robotic Program

broad participation by researchers from Japanese universities, research institutes, and other related organizations. while promoting space science projects based on consensus among these researchers, it also cooperates in graduate school education in the space and aeronautics field through a joint graduate school program responding to the request from universities.

Sample return from small solar system bodies such as asteroid Itokawa is considered to be easier than return from celestial bodies where the effect of gravity is larger. However, because primitive bodies such as asteroids are thought to hold information on the early formation of the Solar System, investigation and research on primitive bodies, including sample analysis on the Earth, has great scientific value. Furthermore, autonomous descent, landing, and takeoff ("touch & go") using optical information is an advanced engineering technology. ISAS is involved in planning and promoting missions of both scientific and engineering significance, like HAYABUSA, by integrating the intellectual resources of Japan's researchers and engineers.

The successful touchdown of HAYABUSA on an asteroid, which was the world's first, and the recovery from the near-fatal propellant leak accident following the successful landing, are evidence of the presence in ISAS of outstanding researchers and engineers who have an indomitable spirit which remains steadfast in the face of unexpectedly difficult events, and the capabilities to respond appropriately and in a timely manner to such events. For Japan, which is an export-dependent nation with few natural resources and low food self-sufficiency, human resources are the source of the nation's power. Thus, training of the next generation of human resources by researchers and engineers like those of ISAS is a critical function. It may be noted that the operation of HAYABUSA and KAGUYA and the planning and promotion of their successor missions are now being carried out under the responsibility of a newly-established lunar and planetary exploration program group in JAXA, that is, the Space Exploration Center (JSpEC).

(3) Promotion of comprehensive lunar scientific research

KAGUYA was truly the world's most advanced full-scale scientific lunar exploration mission since the Apollo Program, as it not only carried high performance instruments for observation of the elemental/mineral distribution and topography/surface layer structure of the Moon, but also resulted in the creation of a detailed topographical map of the entire Moon, including the polar regions, which was the world's first, and measured the global gravitational field of the Moon, including the farside, which was another world's first, using a unique Japanese main- and sub-satellite system. In comparison with the missions of other nations, this mission also suggests the sincere attitude of the Japanese researchers toward seeking a comprehensive elucidation of the mysteries of the origin and evolution of the Moon as a pure scientific research object. In order to realize a radar sounder for detecting weak reflected radio waves so as to observe the surface layer structure of the Moon, and a magnetometer for measuring the Moon's weak magnetic anomalies, high technical capabilities were necessary in all the stages of design, manufacture, and testing.[44] Thus, the success of these efforts demonstrated the high level of Japan's space development technologies. There are also strong interests among the general public in high definition television images such as the earthrise image of the full Earth.

6 Recommendations and future directions

(1) Continuing development of unique Japanese space technologies unrivalled by other countries and promotion of international cooperation

Researchers from Europe and Japan jointly proposed Marco Polo, which is a sample return mission from primitive bodies such as comet-asteroid transition objects (CAT) as part of ESA's Cosmic Vision program. This proposal has passed the first selection process.[45] According to this proposal, Japan would develop a probe to perform sample return, which is one of Japan's unique technologies, taking advantage of its experience in the development of HAYABUSA, and the European side would be responsible for the development and launch of a lander, utilizing its experience in the development of Rosetta.

Perhaps because Japan's solar observation satellite HINODE carried three advanced, high performance instruments (SOT, XIT, EIS), to which there were no instruments comparable in other countries, and perhaps because these instruments also attracted strong interests from foreign researchers, satellite operation and research activities are being planned with the participation of researchers from the United States and the United Kingdom, as well as Japanese researchers, in observation planning meetings held at the JAXA Sagamihara Campus, and international researchers are also making long-term stays at the campus.[46]

These examples show that international cooperation can be promoted, either on an equal basis or under Japanese leadership, based on Japan's unique advanced technologies. In Solar System exploration, including small solar system bodies, it is expected that Japan should further continue to develop its unique technologies which are unrivalled by those of other nations, as exemplified by the sample return using the ion engine, and to promote international cooperation with its friendly nations to maintain and strengthen its relationship of trust with those nations.

On March 12 2008, NASA proposed the concept of an International Lunar Network (ILN) and called on Japan and other countries to participate. As a successor mission to KAGUYA, Japan is studying an unmanned lunar soft lander/surface exploration vehicle/overnight stay technology.[47] High expectations are placed on the development of unique Japanese technologies and various forms of international cooperation. Japan once planned the LUNAR-A project, originally intended to explore the interior structure of the Moon by constructing an observation network of lunar seismographs and thermal flux meters on the lunar surface using two spear-shaped penetrators to penetrate the lunar surface, rather than the conventional remote sensing observation. Although this project was cancelled due to difficulties in the development of the penetrators,[48] both the United Kingdom's MoonLITE (the Moon Lightweight Interior and Telecoms Experiment) mission[49] and the United States' New Frontiers Program[50] study the feasibility of Solar System exploration using penetrators, and the potential of this technology is high.

Lunar and planetary exploration is generally said to require approximately 10 to 20 years from mission planning to mission completion. Thus, if next missions are planned based on results of prior completed missions, the base of researchers and engineers will be lost due to retirement. From this viewpoint, systematic planning and promotion of missions are necessary.

(2) Promotion of science and mathematics education activities for young generations

Since the publication of the still and video images of the lunar surface, earthrise, and others taken by KAGUYA, JAXA has received numerous requests for images from science museums, high schools, universities, and other educational institutions in Japan and from educational institutions and research institutes in other nations. In response to these requests and the high domestic and international interests, JAXA recorded images and prepared an educational DVD which also includes a voice commentary, and began free-of-charge distribution to educational institutions in Japan and other nations at the end of May 2008.[44] Thus, it can be said that the results of lunar and planetary exploration are a good example which inspires interests in science and technology of young generations. In order to secure the science and engineering human resources required for the future, it is expected that Japan should continue and strengthen its outreach activities based on the scientific achievements of its lunar and planetary exploration missions.

NASA is also actively developing science and mathematics education activities for young generations, for example, by preparing excellent educational materials based on each of its missions in the Discovery, New Frontiers, and other programs. Perhaps due to the high global reflection of the high definition television images taken by Japan's KAGUYA, NASA is also planning educational activities using the images taken by an onboard camera on its GRAIL mission.[41]

Furthermore, may be triggered by the performances of the HAYABUSA, KAGUYA, and other Japanese missions, students at Tokyo Institute of Technology, Nihon University, and other universities are now engaged in planning, design, manufacture, launch, and operation of ultra-small micro-satellites (sometimes called "nano-satellites") under a cycle of approximately 2 years, and graduates who have experienced the total process of "monozukuri" (distinctively Japanese manufacturing) in this work are finding jobs not only in the aerospace sector, but also in the automobile manufacturing industry and other sectors.[51] In space development, it is necessary to construct systems which achieve mission requirements by assembling various subsystems, components, and alike, and even the handmade satellites manufactured by these students must function in space of severe high vacuum, radiation, and heat environments. We can expect that graduates who have acquired system engineering techniques through above activities should continue to play an active role in Japan's manufacturing industries.

In order to support such small satellite development activities, JAXA provides opportunities for piggyback launching of small satellites with other mission, utilizing H-IIA rocket extra launch capacity. Four small satellites from Waseda University, Kagoshima University, and other Japanese universities and organizations were selected as candidates for such piggyback launch with Venus probe PLANET-C.[52] JAXA intends to maintain and strength these support activities in the future as well. As part of NASA's educational activities, it is studying a concept called the American Student Moon Orbiter (ASMO) in order to nurture the next generation of American aerospace engineers, and is planning to provide technical support by NASA engineers, use of its facilities, and other support for the design, manufacture, launch, and operation of a small lunar orbiter by American students.[53] Similarly, the European Space Agency (ESA), as part of its educational activities, is also making efforts to train the next generation of European aerospace engineers by launching a European Student Moon Orbiter (ESMO) and European Student Earth Orbiter (ESEO).[54]

7 Conclusion - Various images of the terrestrial planets

The earthrise image of the full Earth taken by KAGUYA shows the blue, watery planet Earth rising over a desolate Moon in the pitch-black darkness of space (Figure 9). Amid urgent voices speaking of the crisis of global warming caused by anthropogenic environmental pollution, this image makes us recognize anew the importance of our irreplaceable home, the planet Earth.

The focus of this paper has been exploratory missions which have taken up the challenge of elucidating the mysteries of the origin and evolution of the Solar System. On the other hand, the author would like to point out that research on the unique and universal features of the planets of the solar system is also important, and this is in no way inferior to the work of these missions. The Earth on which humankind lives is a blue, watery planet. In contrast, the environments of the other terrestrial planets, Mercury, Venus, and Mars, are too severe for us humans to live. Like the Earth, Mercury has an intrinsic magnetic field, but its atmosphere is extremely rarefied, and the daylight side, which is illuminated by the Sun, is a world of scorching heat where the surface temperature reaches approximately 430°C, while the nighttime side is a world of extreme cold, at approximately 180°C below freezing point. On Venus, which is roughly similar to the Earth in size and distance from the Sun and is sometimes called our twin planet, 96% of the thick atmosphere is carbon dioxide. Due to the greenhouse effect of this CO_2, the surface temperature reaches 460°C, and the atmospheric pressure at the planet’s surface is thought to be approximately 90 times that on the Earth. Mars, which is also called the Red Planet, is a cold planet covered with an atmosphere which is rarefied, at only about 1% that of the Earth, and consists mainly of CO_2. However, the observational data suggest that abundant water may have existed on that planet in the past.

Figure 7 : KAGUYA (SELENE) during testing on Earth

Source : JAXA

In spite of the fact that the terrestrial planets consist of the same elements, such as rock and iron, each has taken a completely different evolutionary course. From this viewpoint, researching the individual differences of these planets and the universal features that they have in common is considered to be of great significance for understanding our present Earth and predicting its future. NASA’s Phoenix Martian lander will investigate the existence of subsurface water ice, and Japan is also currently developing BepiColombo as a joint Japanese-European Mercury exploration program and Venus probe PLANET-C.

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References

For general trends in connection with the Solar System, the author referred to the Newton publication “More that We’d Like to Know about the Solar System: The Science of the Planets – A Succession of Recent Results,” published July 20, 2007, by Newton Press (Japanese).

[1] "New Frontiers in the Solar System: An Integrated Exploration Strategy," Solar System Exploration Survey, National Research Council: http://www.nap.edu/catalog/10432.html
[2] Homepage of the Space Foundation (United States of America), "Japan Aerospace Exploration Agency Wins 2008 Jack Swigert Award for Space Exploration, Colorado Springs, Colo. (February 12, 2008): http://www.spacefoundation.org/news/story.php?id=459Bbsp
[3] External report: "The Second Report on a New Image of the Solar System – The Shape of the Solar System Revealed – ," Science Council of Japan, Physical Sciences and Engineering Section Meeting, IAU Subcommittee and the Astronomy and Astrophysics Subcommittee, June 21, 2007: http://www.scj.go.jp/ja/info/kohyo/pdf/kohyo-20-t39-3.pdf (Japanese)
[4] Homepage of Kobe University: "Bulletin: Is there an unknown planet at the outer edge of the Solar System?": http://www.kobe-u.ac.jp/info/topics/t2008_02_28_01.htm (Japanese)
[5] Official Site of Chronological Scientific Tables: "Special Edition on Pluto - What Happened in the Solar System in the Summer of 2006? : Mercury, Venus . . . Neptune, Pluto Now": http://www.rikanenpyo.jp/top/tokusyuu/index.html (Japanese)
[6] "Exploration of Small Solar System Bodies as Program Exploration," Makoto Yoshikawa, Japan Aerospace Exploration Agency, Proceedings of the 29th Symposium on Solar System Science 2007, pp. 58-61, December 19-20, 2007. (Japanese)
[7] "JAXA Briefing: JAXA Program for Exploration of Primitive Bodies in the Solar System," Makoto Yoshikawa, Japan Aerospace Exploration Agency, Journal of the Japanese Society for Planetary Science, Vol. 17, No. 1, pp. 50-53, 2008. (Japanese)
[8] Homepage of NASA Discovery Program: http://discovery.nasa.gov/index.html
[9] Homepage of NEAR Shoemaker: http://near.jhuapl.edu/
[10] Homepage of Deep Space 1: http://nmp.jpl.nasa.gov/ds1/
[11] Homepage of Stardust: http://stardust.jpl.nasa.gov/home/index.html
[12] Homepage of Institute of Space and Astronautical Science, JAXA, "Asteroid Explorer HAYABUSA": http://www.isas.jaxa.jp/j/enterp/missions/hayabusa/index.shtml (Japanese)
[13] Homepage of European Space Agency (ESA), "Rosetta": http://www.esa.int/SPECIALS/Rosetta/index.html
[14] Homepage of Deep Impact: http://solarsystem.nasa.gov/deepimpact/index.cfm
[15] Homepage of New Horizon: http://pluto.jhuapl.edu/science/scienceOver.php
[16] Homepage of Dawn: http://dawn.jpl.nasa.gov/
[17] Homepage of ULA, "Products and Services": http://www.ulalaunch.com/index_products_services.html
[18] Homepage of ESA, "Launchers": http://www.esa.int/SPECIALS/Launchers_Home/index.html
[19] Homepage of JAXA "Rockets and Transportations Systems": http://www.jaxa.jp/projects/rockets/index_j.html (Japanese)
[20] "Seminar: Space Probe "HAYABUSA" and Plasma Engineering: 2. 'Microwave Discharge Ion Engine Aboard the "HAYABUSA" Asteroid Explorer,'" Hiroshi Kuninaka, Japan Aerospace Exploration Agency, Journal of Plasma and Fusion Research, Vol. 82, No. 5, pp. 300-305, May 2006. (Japanese)
[21] Forefront of Space Science, "Presentiments of an Age of Great Space Voyages – The Asteroid Explorer 'HAYABUSA' and Ion Engine Technology," Hiroshi Kuninaka: http://www.isas.jaxa.jp/j/forefront/2004/kuninaka/02.shtml (Japanese)
[22] Information provided by Prof. Hiroshi Kuninaka, JAXA Institute of Space and Astronautical Science, May 16, 2008. (Japanese)
[23] "Deep Space Travel Using the Ion Engine of

HAYABUSA Probe," Hiroshi Kuninaka, Special Materials of JAXA, "Collected Papers on Space Missions Using Low Thrust/Continuous Acceleration," (JAXA-SP-07-020), Japan Aerospace Exploration Agency, ISS1349-113X, pp. 1-6, February 2008. (Japanese)

[24] JAXA Press Release, "Current Status of No. 20 Science Satellite (MUSES-C) 'HAYABUSA'": http://www.jaxa.jp/press/2005/03/20050316_sac_hayabusa_j.html

[25] Homepage of NASA In-Space Propulsion: http://www.grc.nasa.gov/WWW/InSpace/ (accessed August 19, 2008)

[26] "Discovery & New Frontiers News – New Frontiers Program Announcement," NASA, May 14, 2008: http://discoverynewfrontiers.nasa.gov/news/news_archive/2008/news_051408.html

[27] Information provided by Prof. Hiroshi Kuninaka, JAXA Institute of Space and Astronautical Science, May 19, 2008. (Japanese)

[28] "Plans for Demonstration of Solar Powered Sail," ISAS News No. 288, March 2005: http://www.isas.ac.jp/ISASnews/No.288/mission-05.html

[29] "The Shape of the Primeval Solar System Explained by the Stardust Mission," Takashi Mikouchi, Journal of the Japan Society of Planetary Science, Vol. 16, No. 4, pp. 270-273, 2007. (Japanese)

[30] "Improvement and New Development of Sampling Techniques Aiming at a Successor to the HAYABUSA," Saburo Matsunaga et al., Proceedings of the 29th Symposium on Solar System Science 2007, pp. 54-67, December 19-20, 2007. (Japanese)

[31] "Marco Polo Capsule and DASH-II Program," Tetsuya Yamada, Proceedings of the 29th Symposium on Solar System Science 2007, pp. 72-74, December 19-20, 2007. (Japanese)

[32] "The Scientific Context for Exploration of the Moon: Final Report," Committee on the Scientific Context for Exploration of the Moon, National Research Council, 2007.: http://www.nap.edu/catalog/11954.html

[33] Homepage of the NASA Space Science Data Center, "Clementine Project Information": http://nssdc.gsfc.nasa.gov/planetary/clementine.html

[34] Homepage of the JAXA Institute of Space and Astronautical Science, "Moon Orbiter KAGUYA": http://www.isas.jaxa.jp/j/enterp/missions/kaguya/index.shtml (Japanese)

[35] Homepage of the NASA Space Science Data Center, "Chang'e 1": http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2007-051A

[36] Homepage of ISRO, "Chandrayaan": http://www.isro.org/chandrayaan/htmls/home.htm#

[37] Homepage of ESA, "SMART-1": http://www.esa.int/SPECIALS/SMART-1/index.html

[38] Homepage of Lunar Prospector: http://lunar.arc.nasa.gov/

[39] Homepage of LRO: http://lro.gsfc.nasa.gov/

[40] Homepage of LCROSS: http://lcross.arc.nasa.gov/

[41] Homepage of GRAIL: http://moon.mit.edu/

[42] JAXA Press Release, "Publication of Topographical Map Using Global Observation Data of the Moon Obtained with the Laser Altimeter of the Moon Orbiter 'KAGUYA (SELENE)' – Measurement of the Altitude of the Moon at Approximately 6 Million Points, 10 Times the Former Data," April 9, 2008: http://www.jaxa.jp/press/2008/04/20080409_kaguya_j.html (Japanese)

[43] JAXA Press Release, "Success in Photographing 'Earthriese: Full Earth Rising over the Moon' by the High Vision Camera (HDTV) of the Moon Orbiter 'KAGUYA (SELENE),'" April 11, 2008: http://www.jaxa.jp/press/2008/04/20080411_kaguya_ j.html (Japanese)

[44] Interview with Dr. Yoshisada Takizawa, Project Manager, SELENE, JAXA, May 9, 2008. (Japanese)

[45] "First Selection of Candidate Missions for CV2015 Assessment Studies," ESA, October 18, 2007.: http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=41438

[46] ISAS News, "Special Edition on the Solar Observation Satellite 'Hinode,'" JAXA Institute of Space and Astronautical Science, No. 323, February 2008: http://www.isas.jaxa.jp/ISASnews/No.323/ISASnews323.pdf (Japanese)

[47] Homepage of the JAXA Space Exploration Center (JSpEC): http://www.jspec.jaxa.jp (Japanese, with link to English)

[48] Homepage of the JAXA Institute of Space and Astronautical Science, "Lunar Probe LUNAR-A": http://www.isas.jaxa.jp/j/enterp/missions/lunar-a/index.shtml (Japanese)

[49] "Lunar exploration - Potential UK and US collaboration," British National Space Centre, February 15, 2008: http://www.bnsc.gov.uk/content.aspx?nid=7208&hl=MoonLite

[50] "Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity," Committee on New Opportunities in Solar System Exploration: An Evaluation of the New Frontiers Announcement of Opportunity, pp. 28-32, National Research Council: http://www.nap.edu/catalog/12175.html

[51] Materials of the 18th Meeting of the Space Activities Commission (MEXT), "18-1 Committee Report on the Trends in the Development of Micro-Satellites by Universities and the Development, Launch, and Operation of SEEDS2 and Cute-1.7 + APDII," Saburo Matsunaga, Yasuyuki Miyazaki, May 21, 2008. (Japanese)

[52] JAXA Press Release, "Results of Selection of Small Satellite to Piggyback on PLANET-C": http://www.jaxa.jp/press/2008/07/20080709_sac_sat_j.html (Japanese)

[53] Homepage of ASMO: http://asmo.arc.nasa.gov/

[54] Educational homepage of ESA: http://www.esa.int/esaED/index.htm

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