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The nature of asteroid Itokawa revealed by Hayabusa

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Abstract. The spacecraft Hayabusa, which was launched in 2003, arrived at its destination, asteroid (25143) Itokawa in September 2005. The appearance of Itokawa, a small S-type near Earth asteroids, was totally unexpected. The surface is covered with a lot of boulders and there are only a few craters on it. It looks like a contact binary asteroid. The surface composition is quite similar to LL-chondrite. The estimated density is 1.9 ± 0.13 (g/cm^3), so the macro-porosity is about 40%. This means that Itokawa is a rubble pile object. In Itokawa, we may see such things that are very close to building blocks of asteroids. In this paper, we review the mission and the first scientific results.

Keywords. space missions; rendezvous; asteroid surface; asteroid landing; sample return; instrumentation; mass determination

1. Introduction

Hayabusa mission, which was originally called MUSES-C mission, is the asteroid sample return mission of Japan (The literal meaning of Hayabusa is "falcon."). The spacecraft was launched in May 2003, and it arrived at its target asteroid, (25143) Itokawa, in September 2005. Before the arrival, it was already known by ground-based observation that the size of Itokawa is rather small, about 500 m in length. This is correct. What Hayabusa saw was certainly a very tiny object as expected. However the appearance of its surface was completely unexpected. There are only a few craters on its surface but it is covered with a lot of boulders. Figure 1 shows the artistic images of Hayabusa mission before and after arriving at the asteroid. As this figure shows, the concept of small asteroid has been largely changed by Hayabusa mission.

Hayabusa stayed around Itokawa for about three months. In the first two months, Hayabusa carried out detailed scientific observations. And in the third month, November 2005, it tried to approach closely to Itokawa several times and to touch down twice. Although the sampling sequence was not executed as planed, Hayabusa became the first spacecraft that lifted off from a solar system bodies except the Earth and the Moon. After the second touchdown, some troubles occurred in the spacecraft and the communication was lost for about one and half months. Fortunately, the communication was recovered at the end of January 2006, and since then daily operations are going on. But the Earth arrival date has been delayed and now Hayabusa is planed to come back to the Earth in June 2010.

The asteroid Itokawa was known as 1998 SF$_{36}$, discovered by LINEAR (Lincoln Near-Earth Asteroid Research) team. The perihelion distance is 0.95 AU and the aphelion distance is 1.70 AU, so it is an Apollo-type NEO (Near Earth Object). The orbital inclination is about 1.7 degrees, so the orbital plane of 1998 SF36 is almost the same

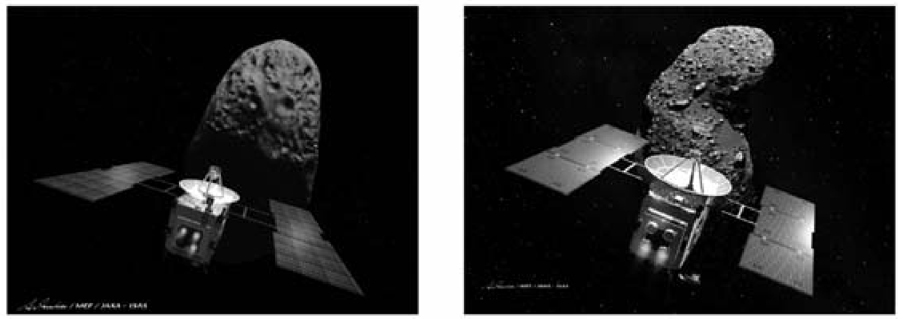

Figure 1. Artistic images of Hayabusa mission. Before arriving at Itokawa, we assumed a lot of craters on the surface (left). However, actually there were only a few craters but a lot of boulders on it (right). The illustrations were made by A. Ikeshita.

as those of the Earth and Mars. Because of this orbital character, 1998 SF36 is a good target for a space mission.

After 1998 SF_{36} was selected as the target of Hayabusa mission, a lot of observations were carried out. Therefore, it was given the number 25143 in June 2001, and in 2003 it was named Itokawa after Prof. Hideo Itokawa, who is the father of Japanese rocketry. The first launch experiment of Japanese rocket, which was called "Pencil Rocket", was done by Prof. Itokawa in 1955, exactly 50 years before Hayabusa's arrival at Itokawa. In this paper, we review the first scientific results of Hayabusa (See special issue of Science journal on 2 June 2006: Fujiwara *et al.* (2006); M. Abe *et al.* (2006); Okada *et al.* (2006); Saito *et al.* (2006); S. Abe *et al.* (2006); Demura *et al.* (2006); Yano *et al.* (2006)).

2. Mission summary

In this section, we briefly summarize the Hayabusa mission. Hayabusa was launched on 9 May 2003 by M-V rocket from Uchinoura Space Center, Japan. The launch was successful and no correction maneuvers were needed. About one month later, the ion engines were started. The orbital control is basically done by the ion engines.

For the first year, Hayabusa was orbiting near the orbit of the Earth. And about one year later, on 19 May 2004, Hayabusa passed the position of 3,700 km from the Earth and performed the Earth swingby, and its orbit was changed to the orbit that is similar to the orbit of Itokawa. About one and half months before the Earth swingby, the ion engines were stopped and accurate navigation (or targeting) was done. The error of navigation at the closest point to the Earth was about 1km in position. This was accurate enough so we did not have to carry out the correction maneuver after the swingby. Then we stared the ion engines again.

In July 2005, Hayabusa came behind the Sun from the Earth. This is the solar conjunction. We cannot keep good communication with the spacecraft at solar conjunction, because the noise by the Sun becomes very large. Therefore, we stopped the ion engines during this period. The error of orbit determination became large and at the end of the solar conjunction (at the end of July 2005), the position error of Hayabusa was almost 2000km. However, just after the solar conjunction, the optical navigation camera on board was able to take images of Itokawa. Then we started the optical navigation, so the accuracy of the orbit of Hayabusa was improved very rapidly. At the end of August 2005, the orbit error in position was about 1km. Also at the end of August, we stopped the operation of ion engines. The ion engines fulfilled their duty. In Figure 2, the orbit history up to the arrival is summarized schematically.

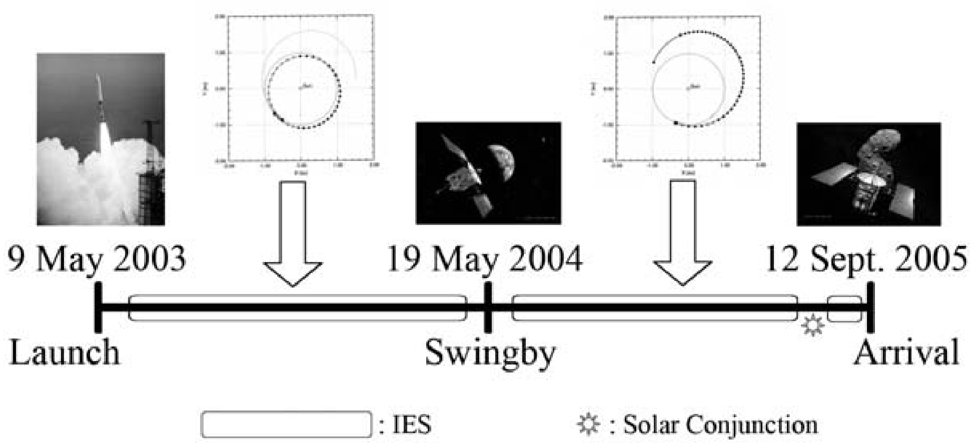

Figure 2. Orbit history from the launch to the asteroid arrival. IES means the periods when the ion engines were operated.

The approach phase was started from the end of August 2005. The distance from Itokawa became smaller and smaller everyday, and the image of Itokawa became larger and larger. We stopped the motion of Hayabusa relative to Itokawa for the first time on 12 September 2005, so we say that the arrival date is 12 September 2005. The arrival point of Hayabusa was about 20 km away from the surface of Itokawa. We call this position as "Gate position."

At first, Hayabusa was moving around this gate position, and gradually it went down toward the asteroid. At the end of September 2005, Hayabusa arrived at the position of about 7 km from the asteroid. We call this position as "Home position." Hayabusa did not revolve around the asteroid, but it moved along the line that connects the Earth and the asteroid. In October 2005, Hayabusa was located around the Home position and made some "tour" to observe Itokawa from various angles. At the end of October, Hayabusa approached to less than 4 km from the surface of Itokawa. The orbital operation is schematically summarized in Figure 3. The actual orbit and the orbital operation in detail are shown in Figure 4.

By the end of October, we almost finished the basic observations of Itokawa. We had information about the surface of Itokawa and we constructed the shape model of Itokawa. Moreover, we have selected the candidate places for touchdown. Thus, we were ready for touchdown.

In November 2005, Hayabusa tried the touchdown. The first touchdown rehearsal was executed on November 4, 2005. In this first descent to Itokawa, we encountered several problems that we did not expect, so we carried out two more descent operations on November 9 and 12. Then we had confidence to carry out touchdown, and the first touchdown was executed on November 20. In this first touchdown, totally unexpected things happened again. We learned later that Hayabusa stayed on the surface of Itokawa more than 30 minutes. However, the sampling sequence was not performed in this first touchdown, so we tried a second touchdown on November 26. All of these descent and touchdown operations are summarized in Table 1.

Table 1. Descent and Touchdown Operations

Operation	Date	Comments
Rehearsal #1	Nov. 4, 2005	
Nav & Guidance Practice	Nov. 9, 2005	Target Marker Release #1 (rehearsal)
Rehearsal #2	Nov. 12, 2005	MINERVA Lander Release
Touchdown #1	Nov. 20, 2005	Target Marker Release #2 Two Touchdowns + One Landing
Touchdown #2	Nov. 26, 2005	One Touchdown

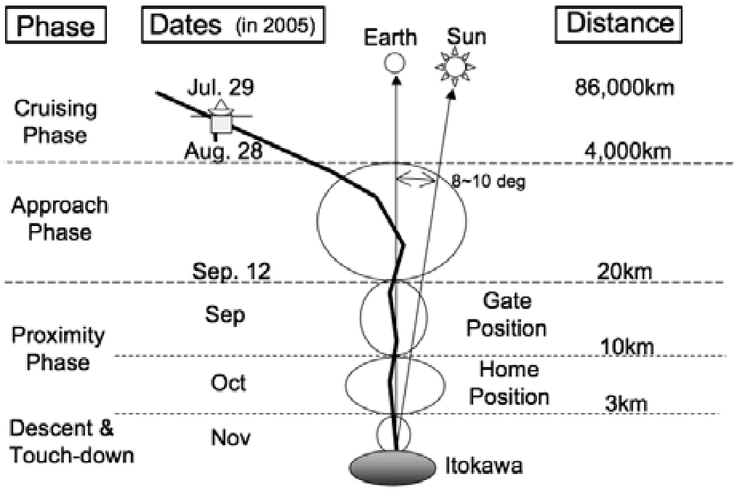

Figure 3. Schematic figure of Hayabusa operation near Itokawa.

The mission sequence was perfect in the second touchdown, so all of us thought that Hayabusa was successful in getting the surface material. However, after the liftoff from Itokawa, a fuel leak occurred. We were forced to operate Hayabusa in a very difficult status and we were not able to confirm that the bullet for collecting samples was fired at the moment of the second touchdown. Anyway, at present (November 2006) we are operating Hayabusa, and we think we can make it return to the Earth in June 2010, which is three years behind the schedule. We hope that some of the surface materials are inside the capsule of Hayabusa.

This is the short history of Hayabusa mission. We have learned a lot of engineering matters as well as we have discovered many scientifically new things. In the following sessions, we review the scientific results.

3. Features of Itokawa

3.1. *Science instruments*

Hayabusa has four science instruments, AMICA, NIRS, XRS, and LIDAR. They are shown in Figure 5.

The Asteroid Multi-band Imaging Camera (AMICA) is also called the telescopic optical navigation camera (ONC-T), and it is used both for navigation and scientific observations. AMICA has both a wide band-pass filter and seven narrow band filters, the central wavelengths of which are nearly equivalent to those of the Eight Color Asteroid Survey

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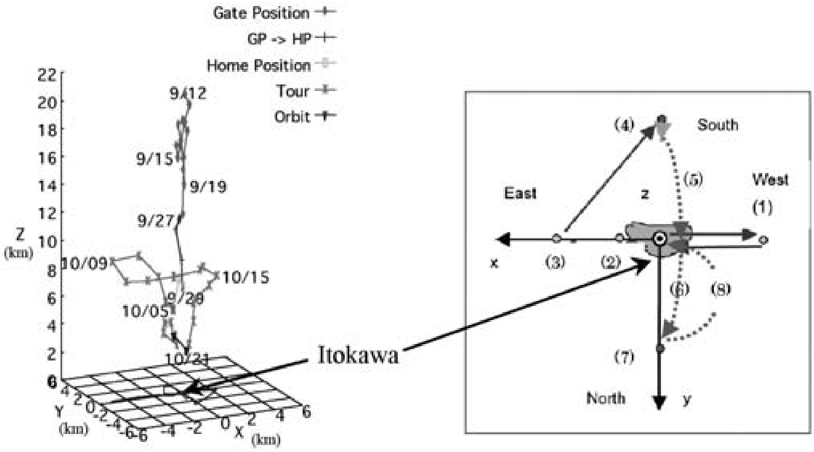

Figure 4. The orbit of Hayabusa near Itokawa. The left figure shows the actual orbit of Hayabusa near Itokawa. The Earth is located in the +Z direction. The numbers in the figure are month/date in 2005. The right figure shows the path of what we call "tour." The spacecraft undertook a tour near the asteroid after achieving the home position observation. The view is from the Sun. Arrows indicate the sequential path of the spacecraft. Dots show the hovering sites. Each spacecraft position indicated by the number in the figure corresponds to the dates as follows: (1) 8 to 10 October, westward, high phase angle; (2) 12 and 13 October, zero solar phase angle; (3) 15 October, east side high, phase-angle; (4) 17 and 18 October, south pole; (5) 20 October, south pole, low altitude (~4 km); (6) 22 October, north pole, low altitude (~4 km); (7) 23 and 24 October, north pole; (8) 27 and 28 October, low altitude observation (~3 km). Dashed lines include low-altitude observation.

(ECAS) system as follows: 380 (ul), 430 (b), 550 (v), 700 (w), 860 (x), 960 (p), and 1010 nm (zs). AMICA imaged the entire surface of Itokawa with a solar phase angle of ~10 degrees at the home position. Because the angular resolution is 0.0057 deg / pixel (99.3 micro-rad/pixel), the nominal spatial resolution is 70 cm/pixel at the home position. Four position-angle glass polarizers were mounted on an edge of the 1024 pixel by 1024 pixel CCD chip.

The Near-Infrared Spectrometer (NIRS) has a 64-channel InGaAs photodiode array detector and a grism (a diffraction grating combined with a prism). The dispersion per pixel is 23.6 nm. Spectra were collected from 0.76 to 2.1 mm. The NIRS field of view (0.1deg × 0.1deg) was aligned with the fields of view of LIDAR and AMICA.

The X-ray Fluorescence Spectrometer (XRS) is an advanced type spectrometer with a light-weighted (1.5 kg) sensor unit based on a CCD X-ray detector. This is the first time a CCD has been used for such a purpose on a planetary mission. The CCD has an energy resolution of 160 eV at 5.9 keV when cooled, which is much higher than that of the proportional counters used in previous planetary missions. In addition, the XRS has a standard sample plate (SSP) for concurrently calibrating the X-ray fluorescence when it is excited by the Sun. The SSP is a glassy plate whose composition is intermediate between those of chondrites and basalts. By comparing X-ray spectra from the asteroid and from the SSP, quantitative elemental analysis can be achieved, although the intensities and spectral profiles of solar X-rays change over time.

The Light Detection and Ranging Instrument (LIDAR) measures distance by determining the time of flight for laser light to travel from the spacecraft to the asteroid and return. The LIDAR averages the topography within the LIDAR footprint on the surface of the asteroid, which approximates 5 by 12 m at a 7-km altitude for normal

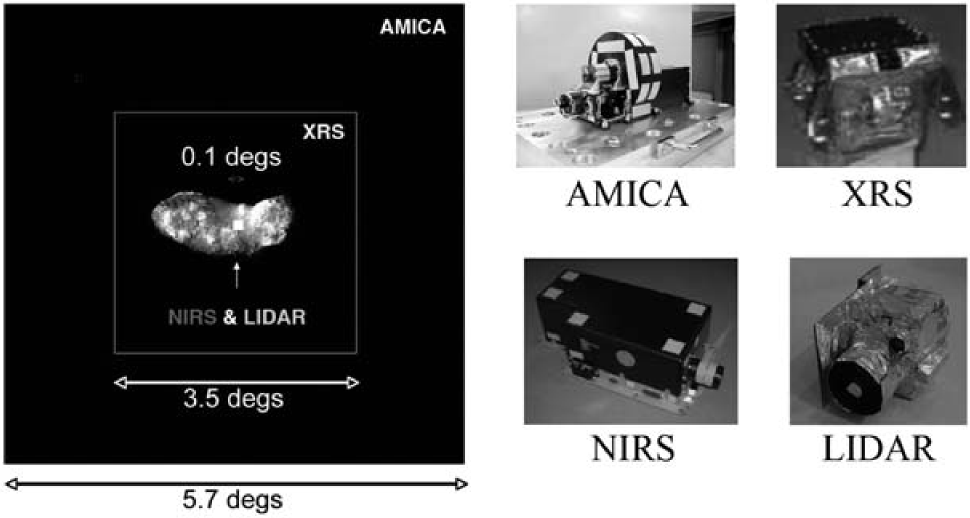

Figure 5. Science Instruments of Hayabusa and their fields of view. Left image shows the comparison of the field of view of each instrument.

incidence. The accuracy of LIDAR ranging obtained from ground calibration was 1 m from a distance of 50 m and 10 m from 50 km.

3.2. *Basic parameters of Itokawa*

There are a lot of ground based observations of Itokawa, so we knew several characteristics of Itokawa before Hayabusa arrived at Itokawa. For example, the rotational period of Itokawa is 12.1324 hours, the spin axis is almost perpendicular to the ecliptic and retrograde, and its shape is elongated, about 0.5 km long. By Hayabusa, the length of the principal axes were determined as X=535 m, Y=294 m, Z=209 m. The orientation of the spin axis in the ecliptic coordinate is $[\beta,\lambda]$=[128.5, -89.66], and the nutation was not detected.

Other important parameters are the mass, volume, and density. These were estimated as follows: mass = $(3.51 \pm 0.105) \times 10^{10}$ kg, volume = $(1.84 \pm|,0.092) \times 10^7$ m^3, density = 1.90 ± 0.13 g/cm^3. We will discuss about the mass estimation in section 3.5.

3.3. *Surface features of Itokawa*

As already mentioned, the most distinctive feature of Itokawa is the large number of boulders. Most of its surface is covered by many small and large boulders. Figure 6 shows the images of Itokawa taken from four directions. We can see some smooth areas, but such regions occupy only a small fraction in the total surface. Thus, the surface of Itokawa is clearly divided into two parts; one is rough terrains, that is boulder rich region, and the other is smooth terrains. There are several large boulders, and one of them is shown in Figure 7, which is the enlargement of the region marked in Figure 6. The sharply sticking boulder in this image is what we call "Pencil Boulder." Another large boulder is seen at the right side of Itokawa in the lower images of Figure 6. Actually this is the largest boulder on Itokawa and we call it "Yoshinodai Boulder."

Some parts of the surface of Itokawa seem to be polygonal planes (one of the examples is indicated by an arrow in Figure 6). We call such planes as "facet." We think that facets were created by collisions or they are parts of the original surface of the parent body. Facets may be the part of basic building blocks of the asteroid.

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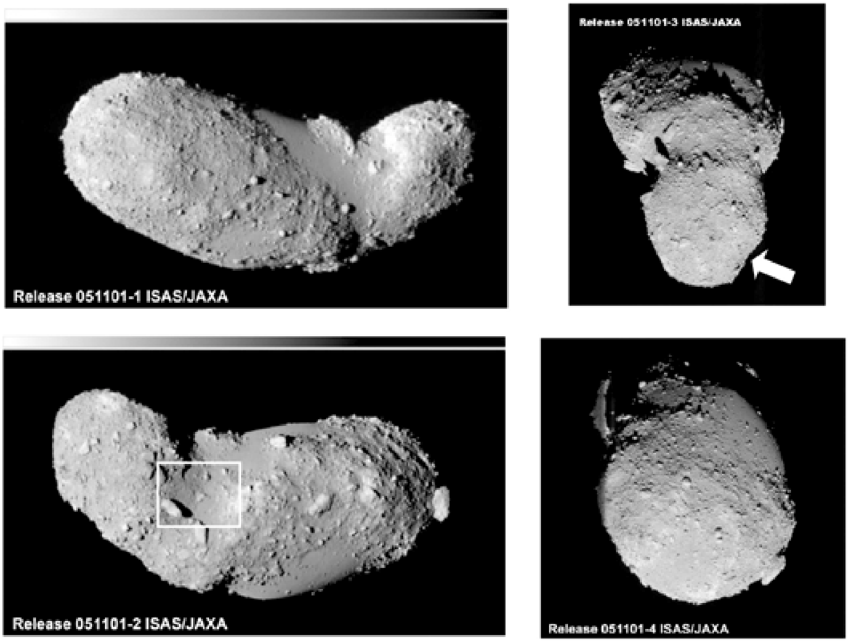

Figure 6. Images of Itokawa. The arrow in upper right figure shows facet. The region marked in lower left figure is shown in detail in Figure 8.

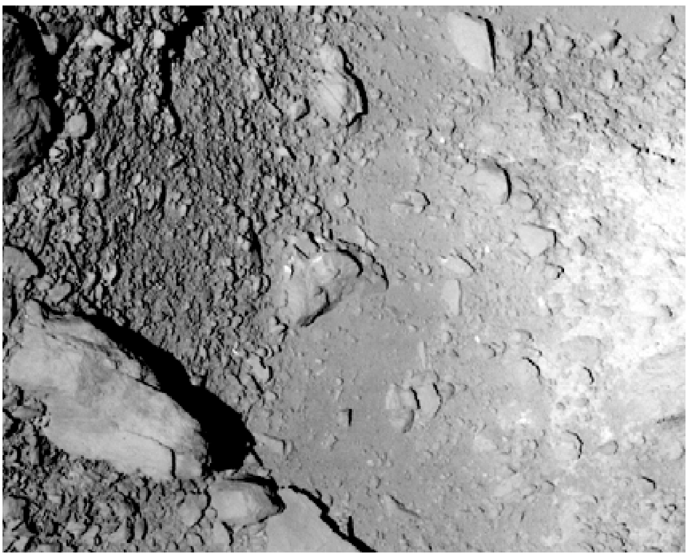

Figure 7. A part of Itokawa marked in Figure 6. The very sharp boulder in the lower left corner is called "Pencil boulder" by the mission team.

At first sight, we do not notice craters, but crates actually exist. Figure 8 shows some of the examples of craters. They are very small and maybe they were formed by impacts of small meteorites. Moreover, we found much smaller features, which might be created by impacts of small meteorites.

In Figure 9, we show two close-up views of the surface of Itokawa. One is the close-up view of one of the smooth terrains, "MUSES-Sea" (IAU officially approved name for this

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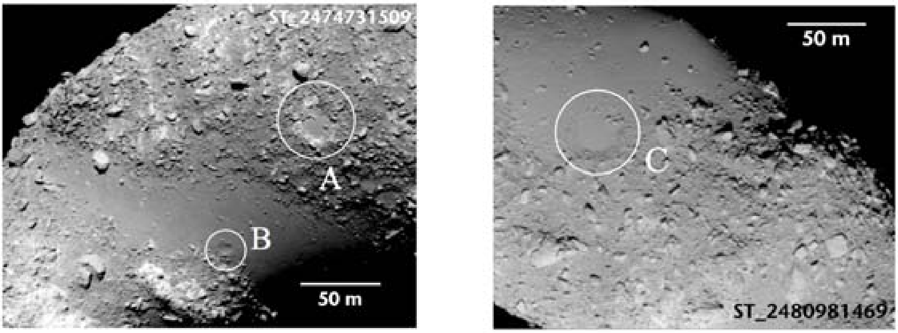

Figure 8. Some of the craters on the Itokawa. Mission team call each crater as follows ; A : Komaba crater (D=27m), B : Kamisunagawa crater (D=10m), C : Fuchinobe crater (D=36m).

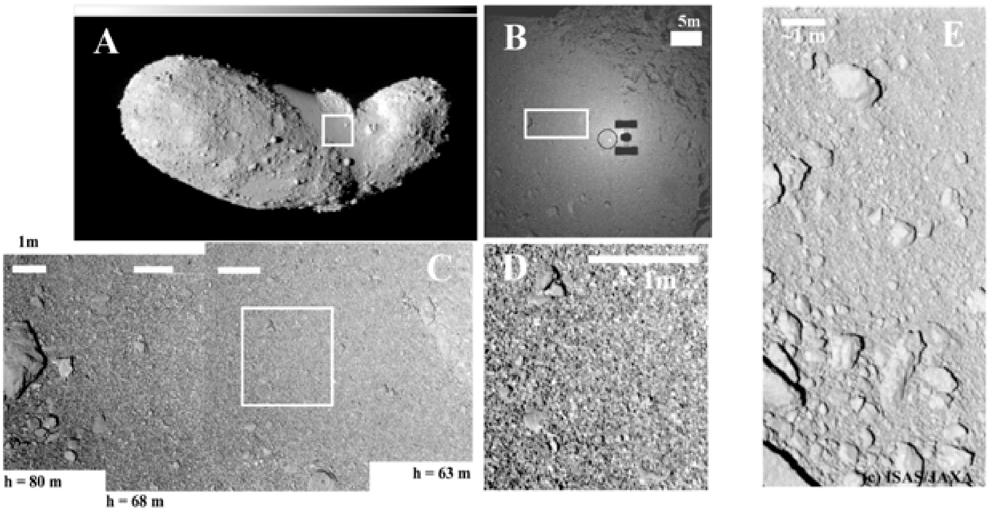

Figure 9. Images of surface close up. Images A, B, C, and D are the sequential images, and each image shows the region within the rectangular section in the previous image. The final image D shows the region where touchdown was performed. Image E is the boundary region between rough and smooth terrains.

region is “MUSES-C”). In this region, the touchdown of Hayabusa was performed. The final image, whose spatial resolution is 6-8 mm, shows that this area is covered by cm-sized gravel and it looks like pavement. Another close-up image in Figure 9 is the boundary between smooth terrain and rough terrain, which is the border of “MUSES-Sea.” The resolution is about 20 mm. We can see a clear transition of rock size distribution from the rough terrain to smooth terrain.

Local topography is also measured by LIDAR. For example, in Figure 10, we show one of the results by LIDAR, where “Tsukuba Boulder” was measured. We know the roughness of the surface and in this region it is about 2.2 m. The roughness of “MUSES-Sea” region is about 0.6 m.

Figure 11 shows the distribution of the surface potential and the surface slope. The lowest potential regions coincide with the smooth terrains, suggesting the mobility of fine materials due to external forces after the formation of the asteroid such as seismic shaking and perturbation by planetary encounters. Evolution of the smooth terrains likely

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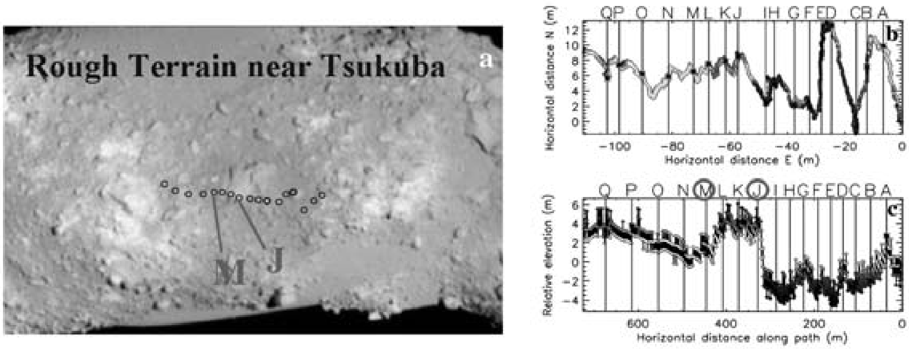

Figure 10. Local topography measured by LIDAR. Figure (a) shows the measured points and (b) is the horizontal distance between each point and (c) is relative elevation.

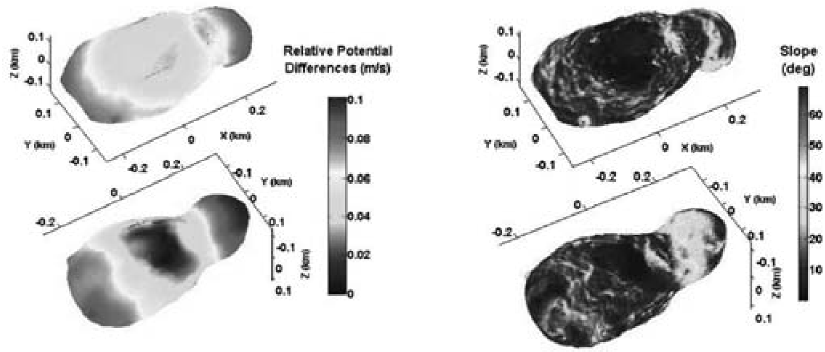

Figure 11. Potential and slope. Left figure shows the potential difference and right figure shows the slope.

involve processes for grain-size sorting and dynamical interactions between regolith and boulders, although the transport/deposition mechanisms must be carefully investigated further.

3.4. *Surface composition of Itokawa*

The surface composition of Itokawa can be investigated by NIRS and XRS. Figure 12 shows the comparison of NIRS data with the reflectance spectrum of ordinary chondrites. The features of these spectra agree well, so this indicates that the surface of Itokawa is olivine and pyroxene assemblage. NIRS took the spectrum of various part of the surface, and the spectrum was almost the same. So we can also say that the mineralogical material is almost the same all over the surface of Itokawa. Figure 13 also shows the data obtained by NIRS, and it shows the correlation of the band strength ratios for average Itokawa spectra. This figure shows that the surface of Itokawa is especially olivine-rich surface, compared with other S-type asteroids, and it supports that the surface materials of Itokawa are quite similar to LL-chondrites.

Consistent results were obtained by the analysis of XRS data. One of the XRS data is shown in Figure 14, where both spectra of the standard on-board sample and of Itokawa are plotted. X-rays from Itokawa (right) have larger Mg/Si and smaller Al/Si than those of X-rays from the standard sample (left), which indicates that Itokawa is similar to

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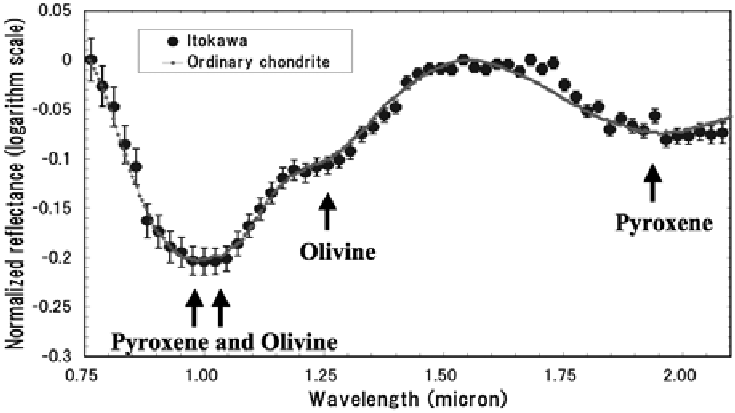

Figure 12. Near infrared reflectance spectrum. Dots show the observed data of Itokawa and the line is a spectrum of ordinary chondrite.

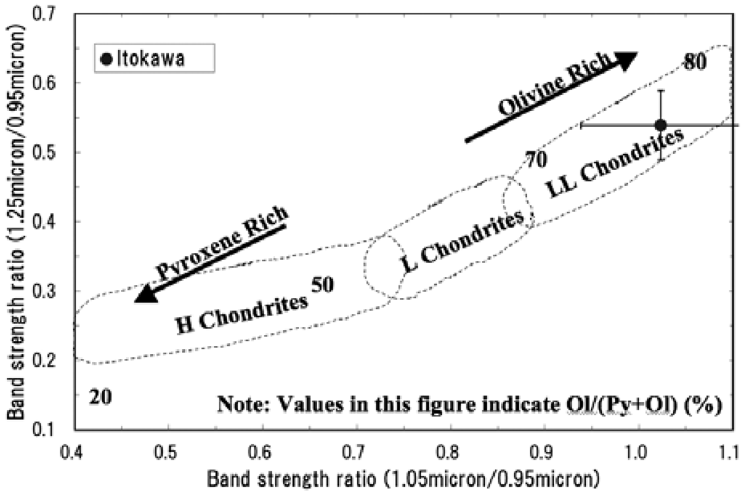

Figure 13. Natural log absorption strengths at 1.05 and 1.25 mm relative to that at 0.95 mm of average Itokawa spectra (filled circle).

ordinary chondrites in composition. Major elemental ratios obtained by XRS are Mg/Si $= 0.78 \pm 0.09$ and Al/Si $= 0.07 \pm 0.03$. This result also shows that Itokawa seems similar to ordinary chondrites, especially LL- or L-chondrites but some primitive achondrites with a small degree of melting cannot be ruled out. No substantial regional variation is found, indicating homogeneity in composition.

Thus, from the observations by NIRS and XRS, we can say that the surface composition of Itokawa is quite similar to LL-chondrites and the surface of Itokawa is homogeneous from the point of view of the composition.

However, we detected that there is heterogeneity in the distribution of the color and albedo. Figure 15 shows the image of Itokawa in enhanced composite color. We can see that some parts are brighter than the basic brightness of Itokawa. Some bright regions correspond to the borders of facets or land-slide region. So we think we can explain this by space weathering. By the effect of space weathering, the surface of asteroid becomes dark. But if meteorites collide with Itokawa or the asteroid encounters planets, it will be

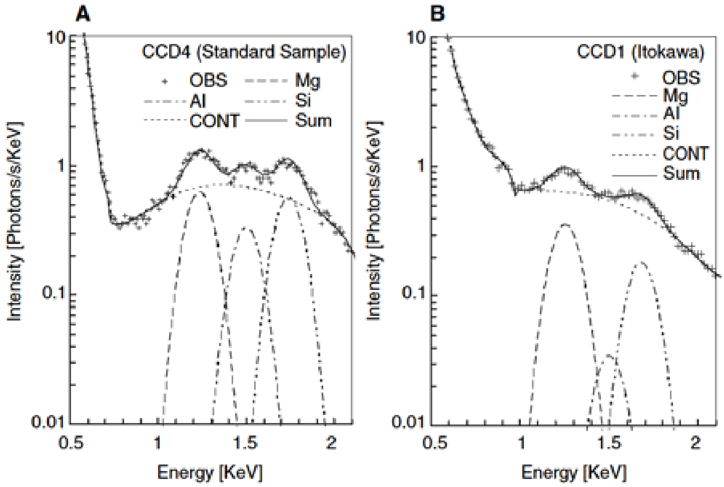

Figure 14. X-ray spectra of the onboard standard sample (A) and asteroid Itokawa (B) were simultaneously observed by the XRS at 9:27 UTC on 19 November 2005. The observed spectra (OBS) are fitted by Gaussian profiles to K- lines of major elements (Mg, Al, and Si) and by a background continuum component (CONT).

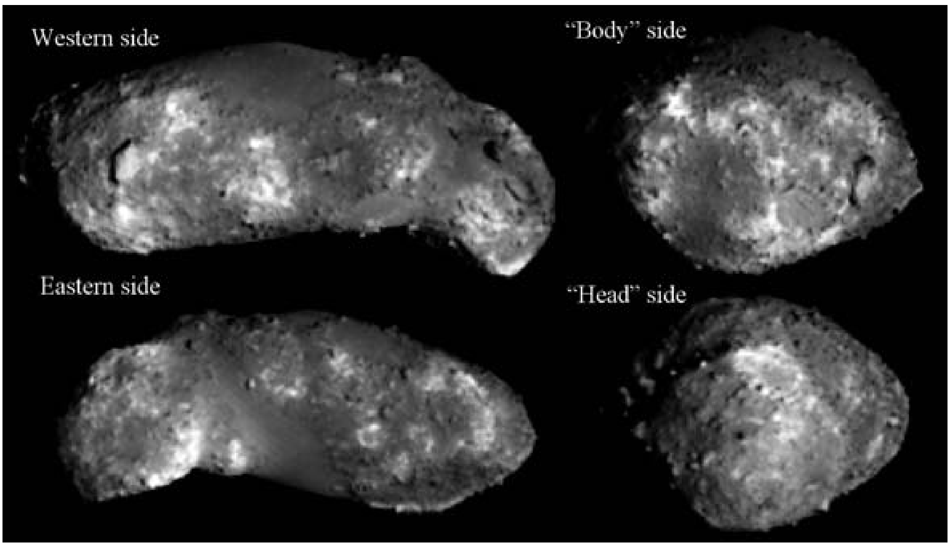

Figure 15. Color composite images constructed from b-, v-, and w-band data. The contrast adjustment was done in each image to enhance the color variation.

shaken and sub-surface fresh materials, whose color is not dark, appear on the surface. In fact, generally, the brighter area is bluer, while the darker area is redder, which supports this hypothesis of space weathering.

3.5. *Mass of Itokawa*

The mass of an asteroid is quite important because it will be an important clue to know the structure of the asteroid, when the mass is converted to the density. The mass itself is also important for the spacecraft navigation. Therefore, four independent teams tried to estimate the mass of Itokawa by using different data and different methods. In this section, we summarize the results of these mass estimations.

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Figure 16 shows the schematic image of the mass estimation. As we mentioned earlier, basically Hayabusa was moving along the line that connects the Earth and Itokawa. When Hayabusa was near Itokawa, the Sun and Earth were located almost in the same direction from Hayabusa. The forces that affect Hayabusa are the gravity from Itokawa, the solar radiation pressure, and the gravity from other celestial bodies, such as the Sun and planets. The gravitational accelerations from the Sun and the planets are well known, so we should estimate the solar radiation pressure and the gravitational attraction from Itokawa separately. In this way we can determine the mass of Itokawa. The data used for mass estimation are the range and Doppler from ground stations, the distance between Hayabusa and the surface of Itokawa measured by LIDAR, and the direction of Itokawa from Hayabusa obtained by the navigation cameras.

Figure 17 shows that the variation of the distance between Hayabusa and Itokawa. The motion of Hayabusa, which was mentioned in the previous section, can be understood clearly in this figure. In Figure 18, the periods when the mass estimations were carried out are marked by circles of A to D. Here we briefly summarize what were done in each phase.

The first mass estimation was done when Hayabusa moved around the gate position and the home position (A). Hayabusa had acceleration toward the asteroids, partly due to the gravitational attraction from Itokawa, but mainly due to the solar radiation pressure. When Hayabusa was around the gate position (about 20 km from Itokawa), the effect of the solar radiation pressure was about 20 times larger than that of the gravitational attraction by Itokawa. Using the range and Doppler data, the mass of Itokawa was estimated. The estimation error is about 15%. This error is rather large because in this period, the effect of the gravitational attraction by Itokawa was much smaller than that of the solar radiation pressure.

The mass estimation in the period "A" was successful, so we expected that we would perform a more precise mass estimation when the spacecraft approached the asteroid

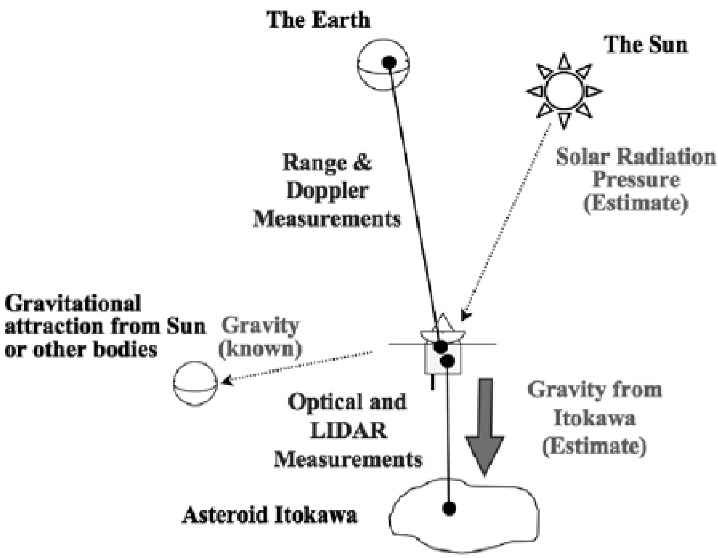

Figure 16. Schematic image of the estimation of the mass of Itokawa. The gravity of Itokawa and the solar radiation pressure act in similar direction, so we should estimate these effects separately.

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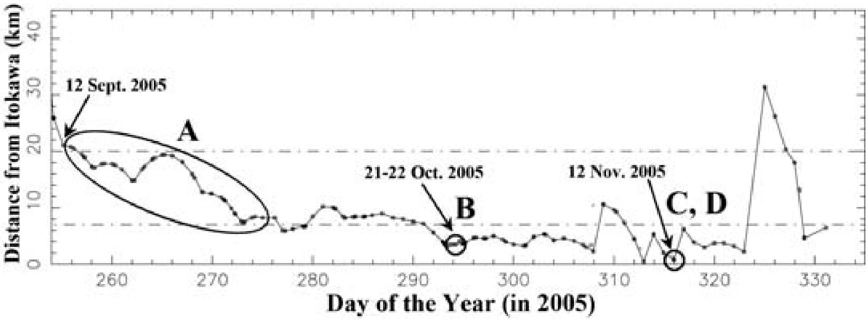

Figure 17. Variation of distance between Hayabusa and Itokawa and the periods when the mass estimations ware carried out. The circles marked by "A" to "D" indicate the periods when the mass of Itokawa was estimated. The distance data in November 2005 (after DOY of 307) does not represent actual changes especially when Hayabusa was far from Itokawa, because the data points are not dense enough. The distance data were based on the range measurement from the Earth.

much closer. However at the beginning of October 2005 (just after the period "A" in Figure 17), one of the reaction wheels had a trouble and stopped functioning. Hayabusa has three reaction wheels, and one of them broke down before arriving at the asteroid. The attitude control did not have serious problems with two reaction wheels. However, by the break down of the second reaction wheel, we had to use the chemical thrusters to control the attitude of Hayabusa. When chemical thrusters are used, small acceleration is generated in its orbital motion. This makes very difficult to estimate the mass of Itokawa. In order to get the proper orbital data to estimate the mass, we intentionally stopped the attitude control for two days, and let Hayabusa move without the artificial force. This period is October 21 and 22, which is shown by "B" in Figure 17. Using the data of LIDAR and the navigation camera in addition to the range and Doppler, the mass of Itokawa was estimated with an error of 5%.

When Hayabusa came quite near to Itokawa, the gravitational attraction by Itokawa became much stronger than the solar radiation pressure. As we mentioned in Chapter 2, Hayabusa made approaches to Itokawa five times in November 2005. By using the data (mainly LIDAR and navigation cameras) of the third descent (Nov. 12), two independent mass estimations were carried out. They are "C" and "D" in Figure 17. Each mass estimation was done by using the data of a short period. The parts of the orbit used for the mass estimation here are so close to the asteroid that the mass distribution (shape of the asteroid) was taken into account assuming that the density of asteroid is homogeneous. (In the analysis of "A" and "B", the asteroid is treated as a point mass.) The error of the mass estimation of "C" and "D" is 5 or 6%.

The mass estimations of Itokawa are summarized in Table 2, where the estimated values are shown in GM (G is the gravitational constant and M is the mass of Itokawa). In order to compare the results shown in Table 2, the error range of each estimate is plotted in Figure 18. From this figure, we can say that the estimated mass is consistent within each other.

Taking the weighted mean of these results, the final value of GM is $(2.34 \pm 0.07) \times 10^{-9}$ (km^3/s^2), which is converted to the mass of Itokawa as $(3.51 \pm 0.105) \times 10^{10}$ (kg). According to the shape modeling team, the volume of Itokawa was estimated as $(1.84 \pm 0.092) \times 10^7$ (m^3). Thus the density of Itokawa is calculated as 1.9 ± 0.13 (g/cm^3). This value of density is quite important to understand the nature of Itokawa. These

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Table 2. Results of Mass Estimation of Asteroid Itokawa

Phase	Period	Data Type*	Distance from Itokawa	Model of Itokawa	GM 10^{-9}km^3/s^2	Error
A	Sep. 12 – Oct. 2	R, Dop	20 – 7 km	point mass	2.34	15%
B	Oct. 21 – 22	R, Dop, Opt, LI	3.5 km	point mass	2.29	5%
C	Nov. 12	LI, Opt	1427 – 825 m	polyhedron	2.39	5%
D	Nov. 12	Opt, LI	800 – 100 m	polyhedron	2.36	6%

*R: Range, Dop: Doppler, LI: LIDAR, Opt: Optical images

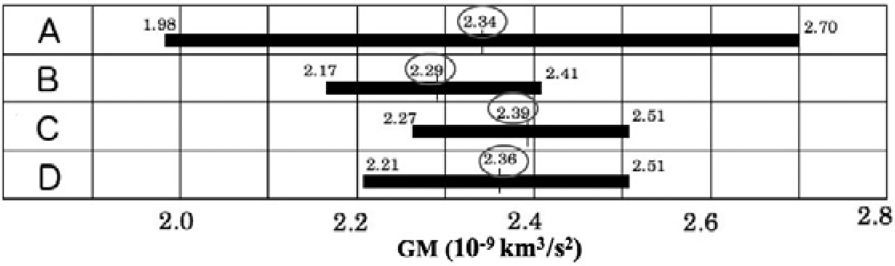

Figure 18. Estimated GM values with the error range. The values of GM and error in Table 2 are shown graphically. The dark lines indicate the range of estimated GM for each phase of the orbit.

results of the mass and the density were taken as the first reference for the basic physical characteristics of Itokawa, which was mentioned in chapter 3.2.

4. Summary

Now we know that the density of Itokawa is 1.9 g/cm^3, and the surface material is probably LL-chondrite. A macro-porosity equal to 40% was calculated. This means that there is large vacant space inside of Itokawa. Therefore, we concluded that Itokawa is a rubble pile object. A possible formation scenario is as follows (Figure 19) : (a) The parent body was disrupted by impact. (b) A portion of fragments coagulated each other forming two objects, which were forming a contact binary. (c) These two bodies were merged into one and became Itokawa.

For the first time, we saw a very small asteroid from its vicinity. This tiny asteroid was very different from what was expected. We can say that we saw more basic and original elements that created larger asteroids and planets.

The Hayabusa mission is still going on. Although the probability that some surface materials are inside the capsule is small, we have not gave up. The operation of the spacecraft is rather difficult because we can use only the ion engines, but we will try to bring it back to the Earth in June 2010. From the point of the engineering of Hayabusa, the only thing that we have not yet tried is the capsule reentry.

At the same time, we are planning post-Hayabusa missions. One is what we call "Haybusa-2." Hayabusa-2 is almost the copy of Hayabusa, but the target asteroid is a C-type NEO. The target asteroid is tentatively 1999 JU3. Since Hayabusa-2 is a copy mission of Hayabusa, we can save the time for development. The possible launch window is November 2010 (backup window is November 2011). It will arrive at the asteroid in 2013 and it will come back to the Earth in 2015 or 2016. The other mission is what we call "Hayabusa-Mk2," where we will develop a totally new spacecraft. Especially the

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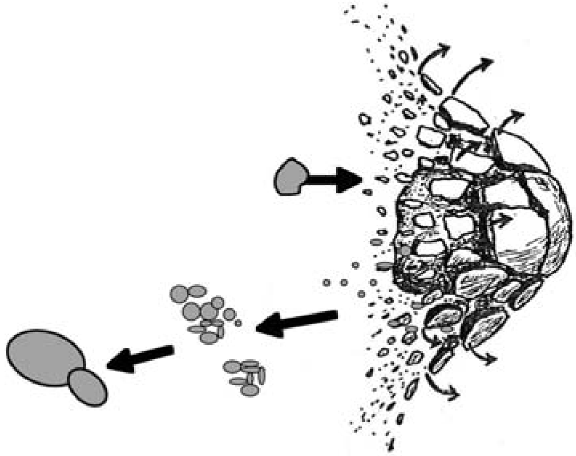

Figure 19. Possible origin of Itokawa.

sampling method will be significantly changed. The target object is not selected yet, but it will be much more primitive object.

Space missions to small solar system bodies are quite important to understand the origin and evolution of the solar system. Also it will be important to know the origin of life. We hope that many exciting missions will be carried out with international collaborations.

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We think that the Hayabusa mission was successful because many people joined forces to overcome many difficulties. Especially here we would like to express our appreciation to the navigators in Jet Propulsion Laboratory and the operators of Deep Space Network for their excellent assistance. Also we acknowledge LINEAR team, who kindly accepted the proposal of the name of Itokawa.

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