Hayabusa Description

*Note: This document was edited on 2024-08-09 by A. Raugh to update verb tenses, remove archaic PDS3 references, correct one typo in a reference, and refresh the format for modern display and archiving.*

# Mission Overview

The Hayabusa spacecraft was successfully launched atop a Japanese M-V launch vehicle on May 9, 2003. The mission plan was to have the spacecraft briefly alight upon the surface of near-Earth asteroid 25143 Itokawa, fire pellets into the surface, collect the surface material ejecta and bring these surface samples back to Earth for intensive study. Japan's Institute of Space and Astronautical Science (ISAS) and NASA agreed to cooperate on the Hayabusa (aka MUSES-C) mission. Before launch, the mission name was MUSES-C, which stood for Mu Space Engineering Spacecraft, a space engineering spacecraft launched by a Mu rocket developed by ISAS, with C referring to it being the third in the series. Just after launch, the mission was renamed Hayabusa (Japanese for falcon).

# Science Goals

The overall science goal of the mission was to significantly advance our understanding of Earth's closest neighbors, the near-Earth asteroids. Some of these objects continue to pass closer to the Earth than the moon itself. They represent the left over building blocks of the inner solar system formation process some 4.6 billion years ago and if we wish to understand the chemical mix from which the inner planets, including Earth, formed then the study of near-Earth asteroids is key. Most objects in the inner portion of the asteroid belt have similar spectral characteristics. These asteroids, including Itokawa, are so-called S-type objects that are rich in the minerals olivine and pyroxene. By carrying out a detailed elemental composition of the surface samples, scientists will thereafter know the likely composition of existing, and newly discovered, S-type asteroids. Asteroid compositions run the gamut from carbon-rich fragile structures, to fractured silicate rock and slabs of solid iron. These objects will need to be studied to determine which among them are the most accessible to spacecraft and which are the richest in mineral wealth. Another reason for investigating near-Earth asteroids is to understand their compositions and structures to successfully deflect an object that is found on an Earth threatening trajectory.

# Technology Goals

Technology tests: Although the science return to date from the Hayabusa mission is rich, the mission's main goals were not scientific but rather the testing of four new technologies including 1.) a demonstration of the four ion engines in interplanetary space for up to 18,000 hours 2.) use of the on board camera systems to autonomously guide the spacecraft during the asteroid rendezvous 3.) a demonstration of a sample collection device for retrieval of surface materials 4.) a demonstration of the sample capsule's ability to carry out an Earth atmosphere entry direct from an interplanetary trajectory.

Although there were four ion engines onboard the Hayabusa spacecraft, up to three of them operated simultaneously. The fourth was a backup engine. These ion engines operated when xenon fuel was first ionized via a microwave device. The resulting xenon positive ions were then accelerated across a charged high voltage grid (providing the thrust) and finally a stream of electrons was used to neutralize the accelerated xenon ions. Even when all three ion engines were operating full bore, they were only capable of accelerating the spacecraft to a very modest 12 meters per second per day. The force they generated was 20,000 times less than a traditional spacecraft thruster that burns chemical fuel (e.g., hydrazine). However, while chemical thrusters operate for only a few seconds, these ion engines thrusted continuously over many months and by so doing, they were capable of pushing the spacecraft to its September 2005 rendezvous with Itokawa.

This was the first flight of a spacecraft with these advanced ion engines, the first attempt at a touch and go, autonomous landing on an asteroid's surface, and the first attempt of an asteroid surface sample return to Earth.

# Reaction Wheel Failure

To maintain spacecraft attitude, the Hayabusa spacecraft was equipped with three momentum wheels mounted in three orthogonal directions and hydrazine attitude control thrusters on the corners of the spacecraft. In late July 2005, one of the reaction wheels failed and a second wheel failed in early October 2005. That left only the z-axis reaction wheel operational for the remainder of the mission. The spacecraft made an unplanned surface landing November 20 and a planned touchdown 5 days later. Just after lifting off from the surface the second time, the hydrazine attitude fuel was exhausted as it leaked into space causing a spin up of the spacecraft. Radio contact with the spacecraft was lost on December 8, 2005 and a signal restored on January 23, 2006. With communications re-established, the cold xenon gas jets from the canted neutralizers were used to restore attitude control by firing the neutralizer gas at specific times during the spacecraft spin cycle. The high data rate was restored on February 25, 2006. After the April 25, 2006 departure from Itokawa, the Hayabusa spacecraft maintained attitude control via a careful balancing of the effects from the single operational momentum wheel, vectoring of the ion engines and the radiation pressure acting upon the solar panels. (Kuninaka, et al. 2007)

# Instruments

Using three of the four ion engines at a time, Hayabusa flew past the Earth on May 19, 2004 to boost its velocity. The spacecraft then caught up to the target asteroid in September 2005, a potato shaped near-Earth object named 25143 Itokawa, after the Japanese rocket pioneer, Hideo Itokawa (1912 - 1999). During the three month operations period (September - November), the Hayabusa science instruments were designed to undertake an intensive study of the asteroid's surface. These instruments were the science camera (AMICA); the surface hopper (MINERVA); the near infrared and x-ray spectrometers (NIRS, XRS); the Lidar altimeter (LIDAR); and the sample collection and return systems.

## AMICA

The Asteroid Multiband Imaging Camera was used to map the entire portion of the asteroid's surface that is observable in sunlight. The asteroid's size, shape, volume, and rotation characteristics were determined and a (negative) search was carried out for any neighboring satellites or dust rings that may have been closely orbiting Itokawa. Making observations with a set of colored filters (see Table 1), AMICA looked for slight differences in color over the asteroid's surface - color differences that might indicate changes in mineralogical composition. The AMICA images will also be used to determine the optical properties of the surface materials at image resolutions well below one meter, provide constraints upon the surface particle sizes, and reveal the history of impacts from other asteroids or comets. Results from the AMICA instrument are reported in Saito, et al. (2006). A description of the AMICA instrument and its calibration is provided in Shiguro, et al. (2010).

|  |  |  |
| --- | --- | --- |
| **Filter** | **Central Wavelength (nm)** | **FWHM (nm)** |
| ul | 381 | 45 |
| b | 429 | 108 |
| v | 553 | 72 |
| w | 700 | 70 |
| x | 861 | 81 |
| p | 960 | 75 |
| zs | 1008 | 66 |
| WIDE | 650 | 300 |

**Table 1**: AMICA filter bandpasses

## MINERVA

Japanese engineers developed a surface hopper that could take close up images and thermal measurements of the asteroid's surface during, and in between, 10-meter hops about the surface. About the size of a small can, the MINERVA hopper had six sun sensors (photodiodes) and an electric turntable that was designed to first orient the tiny spacecraft toward the sun thus allowing its solar panels to power it up. Once oriented properly, the thermal sensors were designed to determine Itokawa's surface temperature and then a rotating torque wheel would have spun within MINERVA causing the outside of the tiny spacecraft to counter rotate, dig into the surface and hop about 10 meters. Once a hop was complete, additional surface temperature measurements would have been made and two of the three onboard cameras would have taken very high-resolution surface images in stereo. The third camera, with a longer focal length than the other two, was designed to image the asteroid's surface while MINERVA was above the surface during mid-hop. Provided the Hayabusa spacecraft was within 20 kilometers, MINERVA's images and temperature data could have been radioed to the Hayabusa spacecraft and then relayed back to Earth. It was designed to last three asteroid days or 36 hours. MINERVA's final weight was 591 g and its diameter and height were 12 and 10 cm respectively. Its three cameras (320 x 240 px) had adjustable shutter speeds. The data rate was 9.6 Kbits/s but due to the spacecraft's slight velocity away from the asteroid, MINERVA entered into a solar orbit rather than descending to the asteroid's surface. No asteroid data were received from this instrument. A description of the MINERVA lander is reported in Yoshimitsu, et al. (1999).

## NIRS and X-Ray Spectrometers

The on board, near infrared spectrometer examined the asteroid's spectral features in the near infrared region of the spectrum. Whereas the near-infrared spectrometer relied upon meteorite analogs to identify the surface minerals of Itokawa, the x-ray spectrometer measured the elemental composition of these minerals directly. Solar x-rays excite the individual elements of the asteroid's surface minerals and the resulting x-ray spectral features were identified and measured by the on board x-ray spectrometer. Some of the expected elements include iron, silicon, manganese, calcium, aluminum and sodium. By noting the relative abundances of these elements in the asteroid's surface minerals and comparing these abundances to those measured in various types of meteorites on Earth, a link can be forged between the composition of this type of rocky asteroid and the meteorites on Earth that likely represent the collision fragments of such asteroids. Thereafter, the composition can be inferred for newly discovered asteroids that are spectrally similar to the large group of S-type asteroids like Itokawa. Results from the NIRS and X-Ray Spectrometer instruments are reported in Abe, et al. (2006), Kitazato, et al. (2008), and Okada, et al. (2006).

## LIDAR

The LIDAR instrument measured the round-trip time of flight of infrared laser pulses transmitted from the Hayabusa spacecraft to the surface of Itokawa. The instrument operated in a single autonomous mode, in which it produced ranging measurements. Surface topography estimates can be derived from these data, given appropriate corrections for the position and attitude of the spacecraft. The principal components of LIDAR were a diode-pumped, Nd:YAG laser transmitter that emitted 1.064 micrometer wavelength laser pulses, a 0.126 m diameter telescope, a silicon avalanche photodiode detector, and a time interval unit with 14 nsec resolution. During the long Home Position phase (~7km from Itokawa) of the misson, LIDAR provided measurements of the topography of Itokawa within approximately 12x4.9 m footprints. Results from the LIDAR instrument are reported in Mukai, et al. (2007).

## Sample Collection and Return to Earth

The definitive work on this asteroid's composition would be done in Earth-based laboratories after the Hayabusa spacecraft returned its precious samples in June 2010. After several weeks during which an initial mapping and reconnaissance phase was undertaken, the Hayabusa spacecraft was designed to descend to the surface of the asteroid, fire a 5 gram pellet of Tantalum into the asteroid's surface and immediately collect and store the resulting ejecta. Tantalum, a rare non-corrosive metal, was used because it is very resistant to change and any tantalum found in the collected sample would be easily identified. This sampling maneuver could be done up to three times. Because the light travel time between the asteroid and Earth was about 18 minutes at the time of the sampling, the spacecraft had to act without human intervention. As described below, there was no evidence that these pellets were successfully fired but the spacecraft did land upon the asteroid's surface so that some surface material was disturbed to an extent that allowed some of it to enter the sample collection chamber. The landing attempts are outlined in Yano, et al. (2006).

On April 25, 2007, the Hayabusa spacecraft departed from the asteroid and in June of 2010, the spacecraft approached Earth and ejected the small (40 centimeters diameter) aluminum sample return capsule. The sample container entered the Earth's atmosphere at about 12 kilometers per second, using ablative shielding to withstand the intense heat generated by atmospheric friction, and eventually parachuted down to the ground near Woomera, Australia. Eager scientists then collected the capsule and took it back to Japan so the asteroid surface samples could be carefully removed and distributed to the scientific community for study. These sample studies will be carried out using a variety of composition measuring devices in Earth based laboratories - devices that are not limited to the modest mass, volume, power, and data rates that can be accommodated by the Hayabusa spacecraft. Furthermore, as more advanced future instrumentation is developed and new hypotheses arise, archived samples from the asteroid will be available for new measurements. Preliminary ground-based sample analyses were reported by Nakamura, et al (2011), Ebihara, et al. (2011), Yurimoto, et al. (2011), Noguchi, et al. (2011), Tsuchiyama, et al. (2011), and Nagao, et al. (2011).

The instruments, with acronym and Principal Investigator (PI) or Team Leader (TL), are summarized below.

|  |  |  |
| --- | --- | --- |
| **Instrument** | **Acronym** | **PI/TL** |
| Asteroid Multiband Imaging Camera | AMICA | Tsuko Nakamura, Jun Saito |
| Near Infrared Spectrometer | NIRS | Masanao Abe |
| LIDAR | LIDAR | Tadashi Mukai |
| X-Ray Spectrometer | XRS | Manabu Kato |
| MINERVA | MINERVA | Sho Sasaki |

# Target Asteroid: 25143 Itokawa

The orbit of the Hayabusa target body, 25143 Itokawa, has a low inclination with respect to the Earth's orbital plane (1.7 deg.) so it is one of the more accessible asteroids for a spacecraft rendezvous. Fortunately, this asteroid made a close Earth approach to within six million kilometers in late March 2001 and an even closer Earth approach to within 2 million kilometers in late June 2004. Optical, infrared, and radar observations were undertaken in 2001 and 2004. The ground-based radar observations indicated that the object had a potato shape of approximate dimensions 548 x 312 x 276 meters (Ostro, et al. 2004), while ground-based optical and infrared data suggest that Itokawa was an S-type asteroid with a composition analogous to either an LL ordinary chondrite, or a primitive achondrite meteorite (Binzel, et al. 2001, Sekiguchi, et al. 2001, and Abell, et al. 2007). In either case the asteroid appeared to be largely a silicate rock with a relatively low abundance of iron. Detailed spectral observations obtained by the Hayabusa spacecraft were not able to definitively rule out either compositional interpretation (Abe, et al. 2006). The spacecraft imaging confirmed the general dimensions of the asteroid. Tables 2 and 3 provide the orbital and physical characteristics for near-Earth asteroid 25143 Itokawa as reported in Fujiwara, et al. (2006) and Demura, et al. (2006).

|  |  |
| --- | --- |
| Magnitude (Abs.): | 19.1 |
| Spectral Type: | S |
| Albedo: | 0.3 |
| Size (km): | 550 x 298 x 244 meters (bounding box) |
| Rotation Period: | 12.1 hrs |
| Temp. at Subsolar Point: | 217-445 K |

**Table 2.** Physical Characteristics of Target Body, 25143 Itokawa

from spacecraft measurements.

|  |  |
| --- | --- |
| Semi-Major Axis (AU) | 1.324 |
| Eccentricity | 0.280 |
| Inclination (deg) | 1.72 |
| Perihelion (AU) | 0.95 |
| Aphelion (AU) | 1.62 |
| Orbital Period (years) | 1.52 |

**Table 3.** Orbital Elements

# Mission Phases

## LAUNCH

Mission Phase Start Time : 2003-05-09

Mission Phase Stop Time : 2003-05-09

|  |  |  |
| --- | --- | --- |
| **Event** | **Date** | **Description** |
| Launch | 2003-05-09 | at 13 hrs, 29 min. JST, M-V launch vehicle, Kagoshima, Japan |

## CRUISE TO ASTEROID

Mission Phase Start Time : 2003-05-10

Mission Phase Stop Time : 2005-09-11

|  |  |  |
| --- | --- | --- |
| **Event** | **Date** | **Description** |
| Solar flare | 2003-11 | Solar panel efficiency degraded |
| TCM-1 | 2004-04-20 | 14 cm/s, chemical thrust |
| Trim maneuver 3 | 2004-05-12 | Trim maneuvers 0-2 were canceled |
| Earth flyby | 2004-05-19 | 06:21:40 UTC, Altitude above Earth's surface = 3725 km |
| Reaction wheel failure | 2005-07-31 | Y-axis wheel ceases to operate |

## SPACECRAFT AT GATE POSITION

Mission Phase Start Time : 2005-09-12

Mission Phase Stop Time : 2005-09-29

|  |  |  |
| --- | --- | --- |
| **Event** | **Date** | **Description** |
| Itokawa arrival | 2005-09-12 | Spacecraft 20 km from asteroid. Approach speed = 0.2 mm/s |

## SPACECRAFT NEAR HOME POSITION

Mission Phase Start Time : 2005-09-30

Mission Phase Stop Time : 2005-12-07

|  |  |  |
| --- | --- | --- |
| **Event** | **Date** | **Description** |
| Descent to Home position | 2005-09-30 | 6.8 km from surface of asteroid |
| Reaction wheel failure | 2005-10-02 | 23:08 UTC, X-axis wheel ceases to operate |
| 1st descent rehearsal | 2005-11-04 | Asteroid center-of-mass determined |
| Navigation & Guidance | 2005-11-09 | Navigation and guidance practice 1st target marker released (to space) |
| MINERVA released | 2005-11-12 | Released into solar orbit |
| Sampling attempt | 2005-11-19 | 1st (unsuccessful) sampling attempt LRF detects surface feature and attempts emergency abort. However, S/C attitude outside permitted range to tolerate departure acceleration – autonomous decision to continue descent but S/C never entered TD mode because Fan Bean Sensor detected obstacle and disabled triggering - no pellets fired into surface. Only Doppler data available. Unknown to ground controllers, S/C bounces once and sits on surface for ~30 min. before emergency abort command received from ground. |
| 2nd sampling attempt | 2005-11-25 | Fan Beam Sensor disengaged and no target marker released. Lateral S/C motion control turned off - only vertical autonomous control used. Conflicts in operations script may not have allowed pellet firings. Shooting command given but ignition switch in safe mode. Fuel leak triggered s/c safe mode with many difficulties in recovering. |

## SPACECRAFT RECOVERY OPERATIONS

Mission Phase Start Time : 2005-12-08

Mission Phase Stop Time : 2007-04-24

|  |  |  |
| --- | --- | --- |
| **Event** | **Date** | **Description** |
| Radio contact lost | 2005-12-08 | Radio contact lost possibly due to sudden leak of attitude gas causing s/c to spin. |
| Spacecraft in safe mode | 2005-12-09 |  |
| Beacon signal received | 2006-01-23 |  |
| Spacecraft responds | 2006-01-26 | Spacecraft anomaly functions begin responding |
| Low bit rate com. | 2006-02-25 | 8 bps data rate established |
|  | 2006-03-04 | 32 bps data rate established Chemical fuel expended, batteries severely degraded |
|  | 2006-03-16 | 256 bps data rate established |
| Spacecraft stabilized | 2006-05-08 | Spacecraft stabilized and pointing properly |

## CRUISE BACK TO EARTH

Mission Phase Start Time : 2007-04-25

Mission Phase Stop Time : 2010-06-12

|  |  |  |
| --- | --- | --- |
| Event | Date | Description |
| Spacecraft departs | 2007-04-25 | Ion engines started; spacecraft begins return to Earth. |

## SAMPLE CAPSULE AND HAYABUSA S/C ENTER EARTH'S ATMOSPHERE

Mission Phase Start Time : 2010-06-13

Mission Phase Stop Time : 2010-06-13

# Mission Objectives Overview

MUSES-C Science Objectives (Fujiwara, et al. 2006)

## AMICA - Asteroid Multiband Imaging Camera (Saito, et al. 2006 and Ishiguro, et al. 2010)

* Map surface morphology including surface features to 1-m resolution.
* Determine spin state, colors, size, shape, volume, and rotation characteristics.
* Search for possible asteroid satellites and dust rings.
* Establish a global map of surface features and colors.
* Reveal history of impacts from other asteroid and comet fragments.
* Determine optical parameters of regolith particles using polarization degree vs. phase curve at large phase angles.
* Map mineralogical composition of asteroid and identify rock types present.
* Determine most likely meteorite analog for composition of asteroid.

## Near-IR Spectrometer (Abe, et al 2006)

* Map mineralogical composition of asteroid and provide main evidence for rock types present on surface at scales as small as 20 m.
* Characterize surface heterogeneity.
* Together with elemental composition measurements provided by (XRS) and color imagery from camera, IR spectrometer will provide link between this asteroid and a meteorite type.

## X-Ray Spectrometer (XRS) (Okada, et al. 2006)

* Map the major elemental composition of the surface as the asteroid rotates under the spacecraft.
* Determine the major elemental composition at localized areas during asteroid approach phases.
* Measure surface composition accurately enough to establish relationship between asteroids and meteorites and identify type of meteorite to which asteroid is linked.
* Provide elemental abundance maps to investigate inhomogeneity of regolith.

## Sample Return Analysis (Yano, et al. 2006)

* Samples returned to Earth will provide a detailed and definitive elemental composition analysis of the asteroid's surface materials and hence forge an unambiguous link between the asteroid's composition and a meteorite type.

## LIDAR (Mukai, et al. 2007)

* Provide accurate shape and mass determinations for asteroid.
* Map asteroid's surface with a maximum resolution of about 1-meter.

## MINERVA (Yoshimitsu, et al. 1999)

* View the surface at high resolution, including the sampling areas
* Measure the surface gravity
* Measure the surface temperature

# References

Abe, M., T. Mukai, N. Hirata, O.S. Barnouin-Jha, A.F. Cheng, and 11 others, Near-infrared spectral results of asteroid Itokawa from the Hayabusa spacecraft, Science 312, 1334-1338, 2006.

Binzel, R.P., A.S. Rivkin, S.J. Bus, J.M. Sunshine, T.H. Burbine, MUSES-C target asteroid (25143) 1998 SF36: A reddened ordinary chondrite, Meteoritics and Planetary Science 36, 1167-1172, 2001.

Demura, H., S. Kobayashi, E. Nemoto, N. Matsumoto, M. Furuya, and 15 others, Pole and global shape of 25143 Itokawa, Science 312, 1347-1349, 2006.

Ebihara, M., S. Sekimoto, N. Shirai, Y. Hamajima, M. Yamamoto, and 17 Others, Neutron Activation Analysis of a Particle Returned from Asteroid Itokawa, Science 333, 1119-1121, 2011.

Fujiwara, A., J. Kawaguchi, D.K. Yeomans, M. Abe, T. Mukai, and 17 others, The rubble-pile asteroid Itokawa as observed by Hayabusa, Science 312, 1330-1334, 2006.

Ishiguro, M., R. Nakamura, D.J. Tholen, N. Hirata, H. Demura, and 10 others, The Hayabusa Spacecraft Asteroid Multi-band Imaging Camera (AMICA), Icarus 207, 714-731, 2010.

Kitazato, K., B.E. Clark, M. Abe, S. Abe, Y. Takagi, and 5 others, Near-infrared spectrophotometry of Asteroid 25143 Itokawa from NIRS on the Hayabusa spacecraft, Icarus 194, 137-145, 2008.

Kuninaka, Hitoshi, K. Nishiyama, Y. Shimizu, T. Yamada, H. Koizumi. Re-ignition of Microwave Discharge Ion Engines on Hayabusa for Homeward Journey. The 30th International Electric Propulsion Conference, Florence, Italy, Sept. 17-20, 2007.

Mukai, T., S. Abe, N. Hirata, R. Nakamura, O.S. Barnouin-Jha, and 11 others, An overview of the LIDAR observations of asteroid 25143 Itokawa, Advances in Space Research 40, 187-192, 2007.

Nagao, K., R. Okazaki, T. Nakamura, Y.N. Miura, T. Osawa, and 21 Others, Irradiation History of Itokawa Regolith Material Deduced from Noble Gases in the Hayabusa Samples, Science 333, 1128-1131, 2011.

Nakamura, T., T. Noguchi, M. Tanaka, M.E. Zolensky, M. Kimura, and 17 others, Itokawa Dust Particles: A Direct Link Between S-Type Asteroids and Ordinary Chondrites, Science 333, 1113-1116, 2011.

Noguchi, T., T. Nakamura, M. Kimura, M.E. Zolensky, M. Tanaka, and 13 Others, Incipient Space Weathering Observed on the Surface of Itokawa Dust Particles, Science 333, 1121-1125, 2011.

Okada, T., K. Shirai, Y. Yamamoto, T. Arai, K. Ogawa, and 2 others, X-ray fluorescence spectrometry of asteroid Itokawa by Hayabusa, Science 312, 1338-1341, 2006.

Ostro, S.J., L.A.M. Benner, M.C. Nolan, C. Magri, J.D. Giorgini, and 11 others, Radar observations of asteroid 25143 Itokawa (1998 SF36), Meteoritics and Planetary Science 39, 407-424, 2004.

Saito, J., H. Miyamoto, R. Nakamura, M. Ishiguro, T. Michikami, and 29 others, Detailed images of asteroid 25143 Itokawa from Hayabusa, Science 312, 1341-1344, 2006.

Sekiguchi, T., M. Sterzik, N. Ageorges, and O. Hainaut (2001). IAU Circular 7598, dated 2001 March 10.

Tsuchiyama, A., M. Uesugi, T. Matsushima, T. Michikami, T. Kadono, and 28 others, Three-Dimensional Structure of Hayabusa Samples: Origin and Evolution of Itokawa Regolith, Science 333, 1125-1128, 2011.

Yano, H., T. Kubota, M. Miyamoto, T. Okada, D. Scheeres, and 15 others, Touchdown of the Hayabusa spacecraft at the Muses Sea on Hayabusa, Science 312, 1350-1353, 2006.

Yoshimitsu, T., T. Kubota, I. Nakatani, T. Adachi, H. Saito, Hopping Rover 'MINERVA' for Asteroid Exploration, ESA SP-440, 83-88, 1999.

Yurimoto, H., K-I Abe, M. Abe, M. Ebihara, A. Fujimura, and 28 others, Oxygen Isotopic Compositions of Asteroidal Materials Returned from Itokawa by the Hayabusa Mission, Science 333, 1116-1119, 2011.