Invited Articles

# 隼太空船返航之旅

阿部新助
國立中央大學天文研究所
32001 桃園縣中壢市中大路 300 號, 臺灣

## 摘要

2003年以M-V火箭發射升空後，日本宇宙航空研究開發機構的「隼」小行星採樣返還任務，經歷7年的各種困難，終於成功地降落在糸川小行星表面，採集岩石(塵土)樣本，並將樣本送返地球。隼太空船於2010年6月13日結束任務，包括太空船主體和樣本返還艙在午夜時分重返地球大氣，在澳洲沙漠Woomera Prohibited Area上空裂解，造就一場非常明亮的火球秀。太空船主體在大氣中完全瓦解，返還艙則正常進入大氣，並著陸在離原本預定地點約500公尺遠處。這篇論文便是針對太空船和返還艙在高速重返大氣過程中所做的光譜觀測初步分析結果。

# Hayabusa back to the Earth

Shinsuke Abe
Institute of Astronomy, National Central University (IANCU)
300 Jhongda Road, Jhongli, Taoyuan, 32001, Taiwan

## Abstract

For about seven years since its launch by an M-V Launch Vehicle in May 2003, the Hayabusa asteroid sample return mission of the Japan Aerospace Exploration Agency (JAXA) successfully completed a great achievement by landing on the asteroid (25143) Itokawa, gathering rocks (dusts) there, and returning to the Earth with them while overcoming various troubles. Hayabusa ended on June 13, 2010, with the planned atmospheric reentry of the main spacecraft and its capsule. Both capsule and spacecraft reentered the atmosphere during mid-night, showing fragmented bright fireballs in the sky over the Woomera Prohibited Area in the Australian desert. The main spacecraft disintegrated in the atmosphere, and the capsule reentered nominally and landed approximately 500 m from its targeted landing point. This paper reports on the preliminary result of our spectroscopic observation of a hypervelocity reentered spacecraft and its released capsule.

關鍵字(Keywords): 流星(Meteor)、小行星(Asteroid)、光譜(Spectroscopy)、隼太空船返還艙(Hayabusa reentry capsule)

## 1. Introduction

Hayabusa, the third engineering space missions of JAXA/ISAS (Japan Aerospace eXploration Agency/Institute of Space and Astronautical Sciences) has several engineering technologies to verify in space: highly fuel efficient 'ion engine', an 'automatic navigation system' to approach the asteroid by spacecraft self-control, 'sampling under microgravity'. Hayabusa was launched on May 9, 2003. On September 12, 2005, Hayabusa arrived at the asteroid 25143 Itokawa. The rendezvous with an asteroid after a long flight with continuous acceleration using ion engines was the first success of its kind in the world. With remote scientific observations and terrain measurement mostly completed in September and October 2005. In November, Hayabusa conducted three descent operations and two touchdowns on the asteroid Itokawa. Asteroid gravity, ~$10^{-5}$ G, were measured directly by the spacecraft motion during the decent, leaded to a density of (1.95±0.14) g/cm$^3$ and a bulk porosity of ~40%, which was similar to angular sands, showing that Itokawa is the first rubble-pile body rather than a single monolithic asteroid among S-class asteroids (Abe et al. 2006, Fujiwara et al. 2006, Fig.1). Finally, the spacecraft performed a landing on Itokawa. The samples ejected from the surface or floating near the surface of the asteroid were collected through an extending sampler horn on the bottom of the spacecraft. Then the dust particles might have reached and trapped in a canister of the capsule. Once the collection process was completed, the hatch of the canister was closed to secure the potentially collected samples. Due to the lost of the communication Hayabusa started orbit transfer to return to the Earth in April 2007. On June 13, 2010, after 7 years space travel, Hayabusa spacecraft backed to the Earth with asteroid samples. We observed the Hayabusa's flash as an artificial fireball.

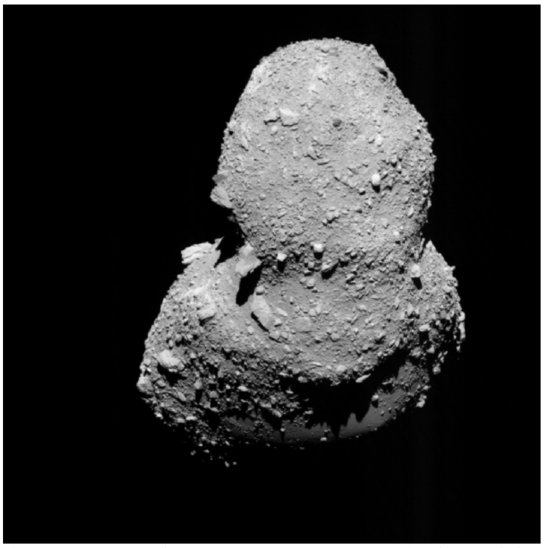

Fig. 1: 25143 Itokawa (535 x 294 x 209m) observed by AMICA onbord camera of Hayabusa spacecraft. (Credit: JAXA)

## 2. Meteor phenomena

Meteor is a luminous phenomenon that is generated when a meteoroid enters into the Earth's atmosphere and can be observed by visual, photographic, or radar methods. These meteors form between approximately 130 and 70 km altitude. In other words, the terrestrial upper atmosphere is a natural detector of meteoroids. The smallest meteoroid size that is able to produce a meteor is roughly estimated to 0.01 mm, depending on the velocity. Typical meteors are associated with meteoroid sizes between 0.01 mm and 20 cm in diameter, which corresponds to the mass range $10^{-9}$ – $10^{-4}$ g, ejected from solar system small bodies such comets and asteroids. In fact, there is no cut-off toward large sizes. A meteor brighter than approximately -2 magnitude is called a 'fireball'. A ‘meteorite’ is a meteoroid recovered on the Earth’s surface. The geocentric entry speed of the meteoroid varies from 11 to 72 km s/ due to Earth’s motion.

Spectroscopic observations of meteors reveal not only chemical composition of the cometary meteoroids but also emission processes of hyper-velocity impacts in the atmosphere, which are difficult to reproduce in laboratory experiments at present. For example, Leonid meteoroids which correspond to cometary grains from the comet 55P/Tempel-Tuttle have produced the best meteor shower for its high incident velocity at ~72 km/s among known annual meteor showers and bright flux of its meteors as ~10,000 /hr. Of particular interest is the question whether meteoroids could have delivered organics and water to the early Earth. It is hypothesized that Leonid meteors are large aggregates that might include precursors to the interplanetary dust particles (IDPs) and survival of meteoritic compounds through the atmospheric entry is feasible even if its high velocity ablation.

The mass loss due to severe ablation causes a practical upper velocity limit of about 30 km/s for the occurrence of a meteorite fall. A meteoroid larger than ~20 cm (for a velocity of 15 km/s) is able to survive the ablation in the atmosphere because there is not enough time to ablate the entire meteoroid mass, before the body slows down to a critical ablation limit of ~3 km/s. We can distinguish the following three phases of the meteoroid entry: 'sputtering (preheating)', 'ablation' and 'dark flight' (Fig. 2). It shows the importance of the ablation process for producing the observed luminosity.

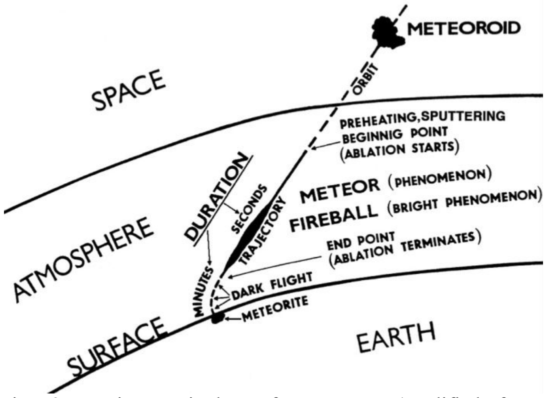


Fig. 2: Basic terminology for meteors (modified from Ceplecha et al. 1998). A phenomena of a meteorite fall is indicated as three regimes, sputtering/preheating (400-120 km), ablation (120-20 km), and dark flight (<20 km).

In order to understand the chemical and physical processes of the ablation, Hayabusa's reentry directly from the interplanetary space with the velocity of ~12 km/s is a golden opportunities for an artificial fireball spectroscopy test, because materials, mass, shape, velocity, and entering angle are all known for Hayabusa reentry, on the other natural meteors have large uncertainties of these parameters. Examples of fireball spectra in visible and near-ultraviolet wavelength are shown in Fig. 3(a)(b).

The meteor phenomena is overviewed in 'Meteoroids and Meteors; Observations and Connection to Parent Bodies' (Abe, 2009).

## 3. Hayabusa reentry and its spectrum

On June 13, 2010, HAYABUSA separated its capsule at 10:51 (UT) and reentered the atmosphere to complete its mission operation at 13:51 (UT) by reentering the atmosphere and delivering its sample return capsule safely to the Earth. The

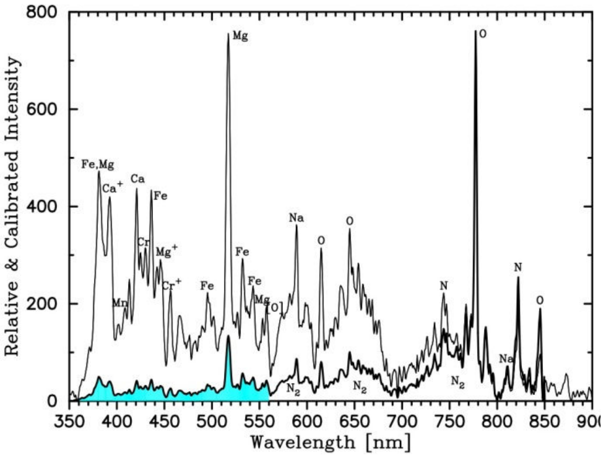


Fig. 3(a): Visible spectrum of a Leonid meteor observed by II-HDTV system on November 18, 1999 (Abe et al. 2000). The thin line is the observed spectrum and lower bold line is the spectrum after sensitivity calibration. Meteor emission originates from a mixture of atoms and molecules ablated from the meteoroid itself (blue rectangle), Fe, Mg, Na, and Ca as well as the surrounding air plasma, O, N, and N2. The atmospheric emissions are particularly prominent for high-speed meteor showers such as Leonids, Perseids and Orionids.

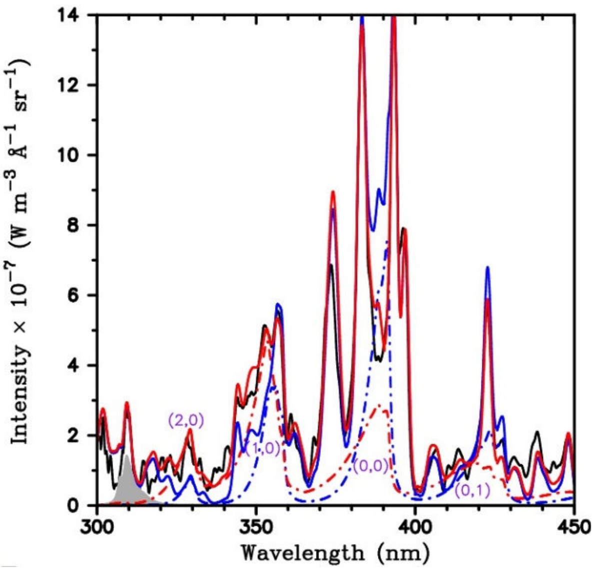


Fig. 3(b): Near-ultraviolet spectrum of a -5 magnitude fireball of Leonids (Abe et al. 2005). Observed spectrum (blackline) compared with synthetic spectrum considering atoms and molecules of $N_2^+$ (1-) with a temperature of 10,000 K (redline) and 4400 K (blueline). The dash-dotted lines indicate $N_2^+$ (1-) at the appropriate temperature. The gray area near 310 nm shows OH A-X bands. Hayabusa reentry provided us with a good opportunity for comparing with meteor spectrum in visible and near-ultraviolet wavelength regions.

spacecraft and capsule reentered over South Australia, with the main spacecraft disintergrating in the atmosphere and the capsule landing in the Woomera Prohibited Area (WPA). Fig. 4 is the final image obtained from Hayabusa spacecraft

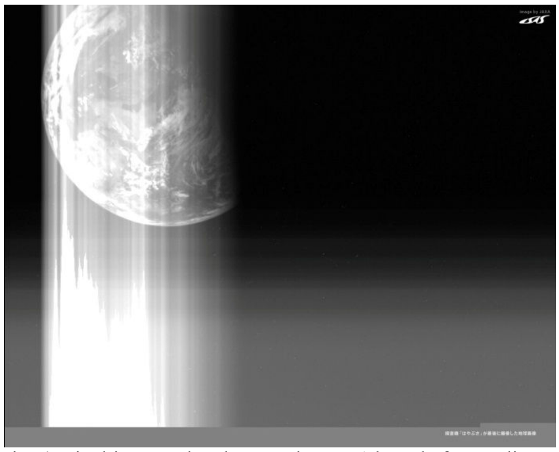

Fig. 4: Final image taken by Hayabusa, ~1 hour before ending its mission. This image was taken by Hayabusa onboard camera after releasing the capsule.


Fig. 5: Reentry fireball of the Hayabusa spacecraft and the capsule. This photographic observation was carried out using Nikon D40x with a fisheye lens (f=10.5mm/F2.8) with the exposure time of 3 minutes.

after releasing the capsule. Fig. 5 is a photographic image of the atmospheric reentry taken by my camera, which occurred around 13:51 UTC (23:21 in local Australian time). The capsule as seen by a point bright fireball was roughly 2 km ahead of Hayabusa spacecraft, while the spacecraft burst into many fragments in the upper atmosphere (Fig. 5). The estimated peak brightness of the capsule was about -6 mag. and that of fragmented spacecraft was about -13 mag., which correspond to Venus and double full moon brightness, respectively. In order to measure the trajectory and estimate the landing point (as a backup in case of failure of beacon signal), triangulation observation from 2 stations were

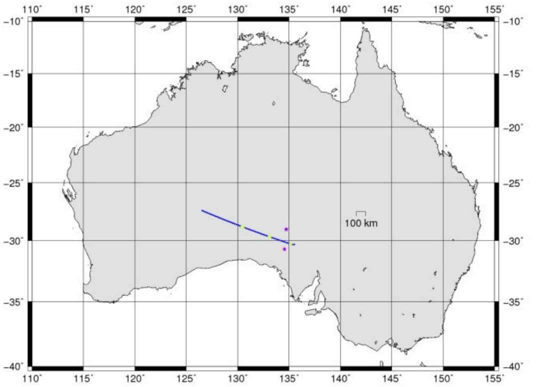


Fig. 6: Trajectory of the reentry capsule in Australia. The line from west to east represents the projected trajectory from the height of 200 km to 31 km. Three yarrow marked in the line are 111 km (beginning height), 65 km (peak brightness), and 33 km (terminal height). Observational station at GOS3: Tarcoola (south) and GOS4: Coober Pedy (north) are shown as stars.

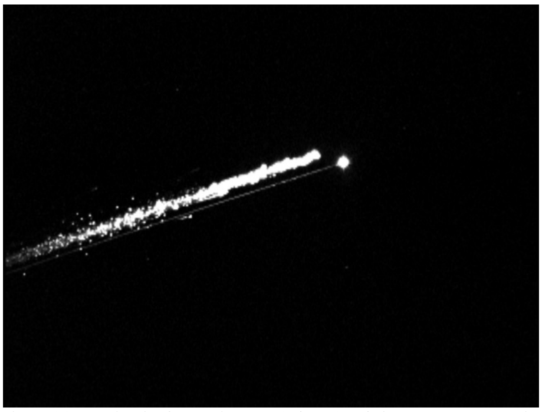

Fig. 7(a): A single frame image (1/30 s) of the reentry capsule (the right front) and fragmented Hayabusa spacecraft are captured by Watec video system. The size of the capsule is 40 cm in diameter, 17 kg in weight. The capsule is covered with front and rear heat-shields made by carbon phenolic ablator.

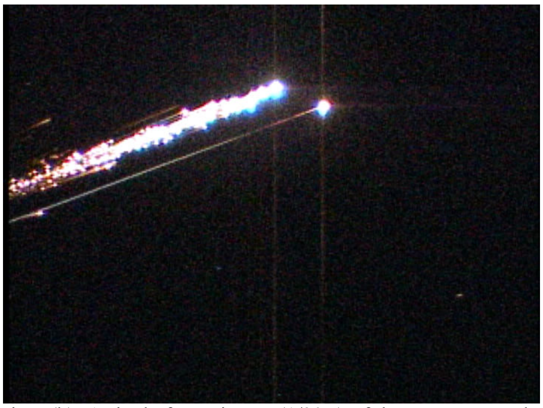

Fig. 7(b): A single frame image (1/30 s) of the reentry capsule (the right front) and fragmented Hayabusa spacecraft are captured by NC-R550a, EMCCD color TC.

coordinated at Tarcoola (134.55858 E, -30.699114 S) and Coober Pedy (134.719172 E, -29.032811 S) (Fig. 6). The capsule was recovered approximately 500 m from its targeted landing point, which means that the predicted trajectory of the reentry was almost perfect match with the result. The position (velocity) difference between the nominal and estimated trajectories measured by low resolution TV camera is approximately 2 km (200 m/s) averaged over the measurement span (Shoemaker et al. 2010). According to the nominal trajectory and the observing time, each event corresponding time, altitude and ground-velocity is summarized in Table. 1. From the analysis of Watec and NC-R550a TV cameras, the beginning height, peak brightness, and the terminal height were ~111km, ~65 km, and ~33 km, respectively

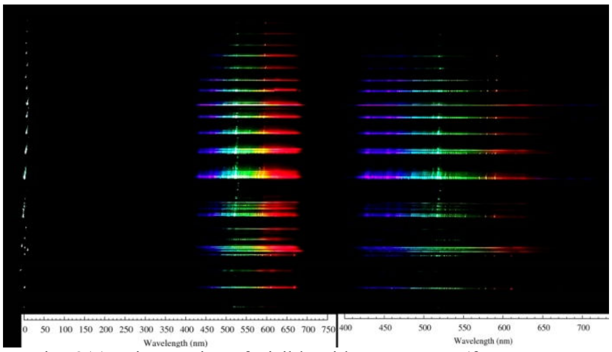


Fig. 8(a): Time series of visible video spectrum (from top to down). The spacecraft and the capsule are on the left as 0th order image. The diffraction direction is from left to right. The 1st and 2nd order spectra are middle and right part in this image.

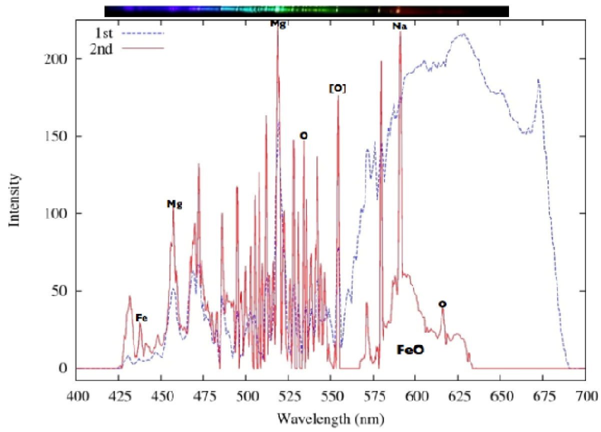


Fig. 8(b): 1st and 2nd order spectrum of the Hayabusa reentry. The wavelength was estimated by the grating's diffraction equation and appropriate atomic lines such as Na and O. Sensitivity is not calibrated in this plot.

(Fig. 6). Near-ultraviolet spectrograph image intensified high-definition TV camera (UV-II-HDTV) and visible spectrograph digital camera (EOS-5DMKII with f=80mm/F5.6 lens) were carried out for spectroscopy. Since the length of the capsule's trajectory was much larger than camera's field of view, the reentry capsule was tracked manually using our optical tracking system with a small monochromatic CCTV camera (Watec WAT 100N with f=25mm/F0.95 lens; Fig. 7(a)). The NC-R550a color TV with a 13x wide angle zoom (F1.5) system which used an Electron Multiplying CCD (EM-CCD) technology also observed the reentry (Fig. 7(b)). Our movies and images are providing via NEC Corporation[a] and JAXA digital archive[b]. Here we show a preliminary result of a visible spectrum obtained by the digital camera (EOS-5DMKII) with a grating spectrograph, which was operated as video recording mode (Fig. 8(a)). The wavelength range between 420-700 nm in 1st and 2nd order spectra were obtained. It seems that some species such as Na and O are originated from the Earthly atoms. Surprisingly, oxygen forbidden [O] (557.7 nm) was detected. The abundant Mg, Fe and many unknown atomic lines are probably owing to the spacecraft body and a rest of chemical fuels. We will identify these time series of unknown lines with considering excitation temperature, chemical reactions and the spacecraft/fuel components. These valuable data will provide us more information on the ablation mechanism in the upper atmosphere and the fragmentation processes. Our data will also provide to be very useful in getting the knowledge of Earth impacts of meteorites and small asteroids.

[a] http://www.nec.co.jp/ad/hayabusa/comeback/
[b] http://jda.jaxa.jp/index_e.html

**Table 1.** Trajectory of Hayabusa reentry capsule

| Time (s) | Time (UT) | Height (km) | v (km/s) | Events |
|---|---|---|---|---|
| 0.0 | 13:51:12.22 | 200.0 | 11.7 | at 200 km |
| 38.0 | 13:51:50 | 111.6 | 11.7 | beginning by Watec |
| 41.0 | 13:51:53 | 105.3 | 11.7 | beginning by NC-R550a |
| 43.6 | 13:51:55.82 | 100.0 | 11.7 | at 100 km |
| 60.0 | 13:52:12 | 68.6 | 11.6 | first explosion |
| 62.0 | 13:52:14 | 65.1 | 11.4 | peak brightness of S/C |
| 69.0 | 13:52:19 | 56.7 | 10.7 | last explosion |
| 95.0 | 13:52:47 | 33.8 | 1.6 | ending by NC-R550a |
| 98.0 | 13:52:50 | 33.0 | 1.3 | ending by Watec |

Note: Watec CCTV camera with 25mm lens and EMCCD camera (NC-R550a, GOTO INC.) were used for imaging observation. v is an atmospheric velocity relative to the ground. At the altitude of 200 km, v=11.65186 km/s corresponds to the geocentric velocity of 12.03644 km/s.

## Acknowledgement

I would thank to all of the JAXA personnel who organized and participated in the recovery operations, especially Jun-ichiro Kawaguchi, Hitoshi Kuninaka, and Tetsuya Yamada. We are also grateful to all of the GOS team members, especially Kazuhisa Fujita (JAXA) who is the chief coordinator of the ground-based observation, Yoshihiro Kakinami (NCU), Ohmi Iiyama (Osaka Science Museum), Masaharu Suzuki (GOTO INC.), NEC Corporation, Michael Shoemaker (Kyushu University) and other members at JAXA, The Nippon Meteor Society, NAOJ, Kochi University of Technology, Kanazawa University and

Nagoya University who assisted in observing at GOS3 and GOS4 stations. SA is supported by the JAXA and the National Science Council of Taiwan (NSC 97-2112-M-008 -014-MY3).

## References

Abe, S., Yano, H., Ebizuka, N., and Watanabe J., 2000, *Earth, Moon, and Planets*, 82/83, 369

Abe, S., Ebizuka, N., Yano, H., Watanabe, J., and Borovicka, J., 2005, *ApJL*, 618, 141

Abe, S. et al., 2006, *Science*, 312, 5778, 1344

Abe, S. 2009, *Lect. Notes Phys.*, 758, 129-166 in Small Bodies in Planetary Systems, Ed. I. Mann, A.M. Nakamura and T. Mukai

Ceplecha, Z. Borovicka, J. Elford, W.G., Revelle, D.O., Hawkes, R.L., Porubcan, V. and Simek, M., 1998, *Space Science Reviews*, 84, 3/4, 327

Fujiwara, A. et al, 2006, *Science*, 312, 5778, 1330

Shoemaker, M.A., van der Ha, J.C., K. Fujita, and Abe, S., 2010, *Journal of Spacecraft and Rockets*, submitted.