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Optical Imaging Instruments and Main Science Results of Small Body Exploration: A Review

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ABSTRACT Compared with planets and their moons, small bodies retain the characteristics of their early formation. Therefore small bodies, especially Near Earth Asteroids (NEA), have become one of the most valuable targets in space exploration. This paper presents a review of the current status of small body exploration, including the science objectives, main optical imaging instruments and the main scientific results obtained from the relevant exploration missions in the past two decades. Then, it outlines and discusses future missions to small bodies by different space agencies, including those already planned and under development. Finally, it discusses the trend of optical imaging instrument development for exploring small bodies.

INDEX TERMS Small bodies, comet, asteroid, dwarf planet, optical imaging instrument.

I. INTRODUCTION

Where do we come from? Human beings have yearned to explore the vast and mysterious universe, among which the origin and early evolution history of the solar system [1], the search for life information of the solar system, the disastrous influence of small bodies on the Earth, and the comparative study of various celestial bodies in the solar system are hot issues. The category of small bodies (including asteroids, comets, dwarf planets, etc.) [2], [3], especially Near-Earth Asteroids (NEA) [4]–[7], is one of the most valuable in recent space exploration. Exploring these bodies is related to the exploration of the origin and evolution of the universe, the material structure, the origin of life and other important basic frontier science issues [8]. In 1978, the United States successfully launched the International Sun-Earth Explorers-3 (ISEE-3) spacecraft [9], which served as a prelude to the exploration of small bodies in the solar system. Through multiple means of exploration of the typical small bodies in the solar system, we can study the characteristics and space environment of each body, understand the features of the morphology, composition, internal structure of the typical small bodies in the solar system, and interpret their formation and evolution mechanism [10]–[13].

According to the existing theory of galactic evolution [14], in the early stage of galaxy formation, dust particles composed of materials including ice and organic matter continuously collided and combined during their movement around the star, and accreted in size like snowballs, forming micro planets (planetesimals). Although planetesimals had the ability to gather surrounding materials faster through the gravitational effect when their diameter increased to about 1km, most of them collided with each other and smashed, while a few surviving micro planets continued to grow larger and gradually evolve into stars and satellites in the galaxy.

This study contains a review of optical imaging instruments and the main science results obtained in the past two decades of small bodies exploration, starting from the sample return of the JAXA (Japan Aerospace Exploration Agency) Hayabusa mission [15]–[25] with asteroid (25143) Itokawa in 2003 and ending with the sample return of asteroid (101955) Bennu by the NASA (National Aeronautics and Space Administration) OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer) mission [26]–[37] in 2016. Future missions [38]–[40] already approved and under development by the various space agencies are also outlined at the end of this work.

The rest of the paper is structured as follows. Section II describes the science objectives of small bodies exploration.

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Section III introduces the missions, optical imaging instruments, and science results of small bodies exploration. Future missions were introduced in Section IV. Finally, this paper comes to conclusions and discussion in Section V.

II. SCIENCE OBJECTIVES

The specific contents of small bodies exploration include:

- Determine the orbit parameters, rotation parameters, shape, size and thermal radiation of small bodies.
- Obtain background information about asteroid samples by exploring the appearance, surface material composition, internal structure, near-space environment, possible water and organic matter of small bodies.
- Carry out laboratory analysis and research on asteroid return samples, to determine the physical properties, chemical and mineral composition, isotopic composition and structure of asteroid samples; to determine and study the age of asteroid samples; to carry out comparative research with meteorites, to establish the relationship between return samples and meteorites, surface observation and remote sensing in situ analysis data.

Exploration missions can acquire data that can drive the following scientific research.

A) Reveal the characteristics and evolution mechanism of typical small bodies in the solar system

The formation mechanism, collision history and spatial orbital distribution of small bodies are important topics in planetary science. Small body exploration can provide all-round near-range observation data (geological, spectral, albedo and reflectance, mass spectrometry, etc.), so that researchers can understand small bodies more clearly, and then uncover the mystery of the origin of the solar system.

B) Gather material and information relevant to the origin of life in the early stage of solar system formation

Obtain and analyze information about the initial stages of the solar system's formation, explore and reveal the formation and evolution history of the solar system; carry out a comprehensive study of possible water, various organic matters and minerals in asteroids and comets, all of which provides important evidence for the origin of life. At present, most of the meteorites collected probably come from S-type, C-type and M-type asteroids [41]. But many types of asteroids are not represented among the meteorites. In particular, the main-belt comets (MBCs) are a special kind of small body, which are expected to provide new clues for researchers. Asteroids and comets contain organic components, which can provide a new way to study the origin of life on Earth. Sample return and remote sensing of C-type asteroids and comets is of great significance to the study of the origin of life.

C) Understand the interaction between solar wind and small bodies

Explore the propagation and evolution of solar wind in interplanetary space, study the solar weathering of asteroids and the formation and evolution of cometary atmosphere and ionosphere in the main belt, and understand the spatial distribution characteristics and dynamic changes of dust in small bodies.

D) Prepare to harvest natural resources from space in the future

It is easier to transport water from small bodies to space stations than from Earth, which can save a lot of energy. In addition to water, asteroids also contain other rare metal and mineral resources, which can be exploited and utilized for human beings.

III. RECENT MISSIONS, OPTICAL IMAGING INSTRUMENTS, AND SCIENCE RESULTS

A. A BRIEF HISTORY OF SMALL BODY EXPLORATION

As of 2021, human beings have carried out 20 missions [42]–[71] of remote sensing exploration, in-situ exploration and sample return for dwarf planets, comets and asteroids (excluding moons such as Phobos and Deimos) by flyby, orbit, landing, impact and sampling return. The exploration history is shown in Table 1.

It can be seen from Table 1 that after entering the 21st century, with the improvement of the overall capability of deep space exploration and the progress of science instrument technology, the exploration mission of small bodies in the solar system has shifted from the original flyby exploration to the orbit exploration/landing exploration/sample return. The total number of missions launched after 2000 is 9, of which 8 are successful or in progress, and 6 are orbit exploration/landing exploration/impact/sampling return missions (Hayabusa [15]–[25], Rosetta/Philae [72]–[81], Deep Impact (EPOXI) [82]–[88], Dawn [89]–[104], Hayabusa 2 [105]–[113], OSIRIS-REx [26]–[37], [114]).

It can be seen from the instrument configuration that the optical imaging instrument is the main science instrument of the above six exploration missions. The reasons are as follows: the direct driving force of small bodies exploration is to know the global topography of small bodies within a short period of time, including the characteristics of volume, shape, rotation period and orbit. Although the traditional ground observation can obtain the basic orbit parameters and some physical characteristics, it is difficult to achieve high resolution from the ground due to the influence of the atmosphere and so on. Therefore, in-situ imaging at close range is still the main way to explore and fully understand the characteristics of small bodies and carry out remote sensing exploration, such as orbit exploration and landing exploration.

We describe the optical imaging instruments on board the above six exploration missions and the science results they achieved in the following sub-sections. This summary represents an up-to-date portrait of our knowledge about small bodies coming from in-situ studies. Table 2 displays the parameters of the main optical imaging instruments on board the above six exploration missions.

B. HAYABUSA

Japan launched Hayabusa asteroid probe on May 9, 2003, and successfully landed in the Muses sea of asteroid (25143)

TABLE 1. All launch attempts for small bodies exploration (1978-2019).

	Launch date	Spacecraft	Objectives	Exploring mode	Nation/Agency	Outcome[1]
1	1978-08-12	ISEE-3	Comet Giacobini-Zinner	Flyby	NASA	S
2	1984-12-15	Vega 1	Comet Halley	Flyby	USSR[2]	S
3	1984-12-21	Vega 2	Comet Halley	Flyby	USSR	S
4	1985-01-07	Sakigake	Comet Halley	Flyby	JAXA	S
5	1985-07-02	Giotto	Comet Halley	Flyby	ESA[3]	S
6	1985-08-18	Suisei	Comet Halley	Flyby	JAXA	S
7	1989-10-18	Galileo	Asteroid Gaspra Asteroid Ida	Flyby	NASA	S
8	1996-02-17	NEAR Shoemaker[4]	Asteroid Mathilde Asteroid Eros	Flyby Orbit/Landing	NASA	S
9	1997-10-15	Cassini	Asteroid Masursky	Flyby	NASA	S
10	1998-10-24	Deep Space 1	Asteroid Braille Comet Borrelly	Flyby	NASA	S
11	1999-02-07	Stardust	Comet Wild 2 Asteroid Borrelly	Sample return/Flyby Flyby	NASA	S
12	2002-07-03	CONTOUR[5]	Comet Encke Comet Schwassmann-Wachmann-3 Comet d'Arrest	Flyby	NASA	F
13	2003-05-09	Hayabusa	Asteroid Itokawa	Station-Keeping/Sample return	JAXA	S
14	2004-03-02	Rosetta/Philae	Comet Churyumov-Gerasimenko Asteroid Steins Asteroid Lutetia	Orbit/Landing Flyby Flyby	ESA	S
15	2005-01-12	Deep Impact	Comet Tempel 1 Comet Hartley 2	Impact Flyby	NASA	S
16	2006 -01-19	New Horizons	Dwarf planet Pluto Asteroid 132524 APL Kuiper Belt object Arrokoth	Flyby	NASA	IP
17	2007-09-27	Dawn	Asteroid Vesta Dwarf planet Ceres	Orbit	NASA	S
18	2010-10-01	Chang'e-2	Asteroid Toutatis	Flyby	CNSA[6]	S
19	2014 -12-03	Hayabusa 2	Asteroid Ryugu	Station-Keeping/Landing/Sample return	JAXA	IP
20	2016-09-08	OSIRIS-REx	Asteroid Bennu	Orbit/Touch-and-Go/Sample return	NASA	IP

1. F = failure, IP = in progress, S = success.
2. USSR: Union of Soviet Socialist Republics.
3. ESA: European Space Agency.
4. NEAR: Near Earth Asteroid Rendezvous.
5. CONTOUR: Comet Nucleus Tour.
6. CNSA: China National Space Administration.

Itokawa on November 19, 2005 [17], [19]. On June 13, 2010, Hayabusa returned the surface samples (about 1500 rock particles) collected from Itokawa to Earth. Hayabusa is the first probe to land on a celestial body outside the Earth-Moon system and return to Earth successfully. Samples taken from Itokawa are of great reference value for the study of the mystery of the formation of the solar system.

The primary scientific objective of the Hayabusa mission was to collect surface samples of material from Itokawa and return them to Earth for analysis. As a technical demonstration mission, the Hayabusa mission focused on the key technologies needed for future large-scale sampling return missions, as well as new scientific observation and research. Other scientific objectives of the mission included detailed studies of Itokawa's shape, size, spin state, topography, color, composition, density, photometric and polarimetric properties, interior and evolution history. In order to achieve the above scientific objective, it was necessary to carry an optical imaging instrument. The main optical imaging instrument carried by Hayabusa was the Optical Navigation Cameras (ONC) [16], which consisted of one telescopic camera (T) and two wide-angle cameras (W1, W2). The Optical Navigation Camera Telescope (ONC-T), a refractive telescope camera head, was referred to as the AMICA when used for scientific observations, as shown in Figure 1. AMICA was used for both science and optical navigation purposes. It was a simple refractor telescope consisting of five lenses, each of which was cosmic-radiation-resistant and anti-reflection-coated. Just in front of the first lens, the designers placed a quartz optical parallel

TABLE 2. Parameters of the main optical imaging instruments.

Mission	**Hayabusa**	**Rosetta/Philae**	**Deep Impact**	**Dawn**	**Hayabusa 2**	**OSIRIS-REx**	**OSIRIS-REx**
Camera	AMICA[1]	NAC[2]	HRI[3]	FC[4]	ONC-T[5]	MapCam[6]	PolyCam[7]
Focal length (mm)	120	717.4	10500	150	120	125	629
F number	8	8	35	7.5	8	3.3	3.15
Field-of-view (°)	5.7×5.7	2.20×2.22	0.118×0.118	5.5×5.5	6.27×6.27	4×4	0.82×0.82
Spectral response (nm)	360-1050	250-1000	320-1050	400-1050	390-950	400-900	400-900
Filters	8	16	9	8	8	8	-
Chip size	1024×1000	2048×2048	1024×1024	1024×1024	1024×1024	1024×1024	1024×1024
Chip type	back-illuminated CCD[8]	back-illuminated UV-enhanced[9] CCD	CCD	CCD	CCD	CCD	CCD
Pixel size (um)	12	13.5	21	14	13	8.5	8.5
Resolution	2m@20km	0.372m@20km	1.4m@700km	1.87m@20km	2.17m@20km	1.36m@20km	0.27m@20km
A/D conversion (bits)	12	14	14	14	12	14	14

1. AMICA: Asteroid Multi-band Imaging CAmera.
2. NAC: Narrow Angle Camera.
3. HRI: High-Resolution Instrument.
4. FC: Framing Camera.
5. ONC-T: Optical Navigation Camera Telescope.
6. MapCam: Mapping Camera.
7. PolyCam: Polyfunctional Camera.
8. CCD: Charge-Coupled Device.
9. UV: Ultra-Violet.

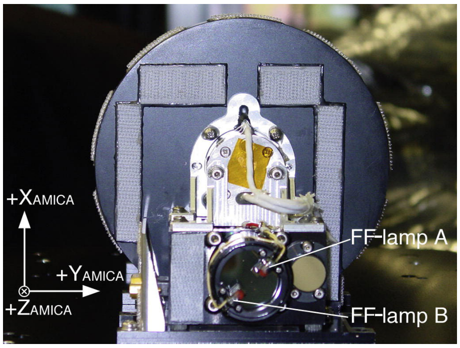

FIGURE 1. AMICA front view. *Image credit*: [16].

window for radiation protection [15]. The focal length of AMICA was 120 mm, and the pixel resolution was 2 m when at altitude of 20 km. Table 2 displays AMICA's parameters. It realized 7 spectral and panchromatic imaging capabilities by using an eight-position filter wheel. Ref. [15], [16] provides the AMICA filter transmittances and the system spectral efficiency.

During the station-keeping [113] period, AMICA obtained about 1500 high-resolution images. The mission team made many scientific and engineering achievements in carrying out relevant scientific research based on the above image data. Examples follow:

(1) Three-dimensional topography of Itokawa. Based on the high-resolution images [19] taken by AMICA, the three-dimensional topography [21] and related physical parameters [17], [21] of Itokawa were obtained, as shown in Figure 2.

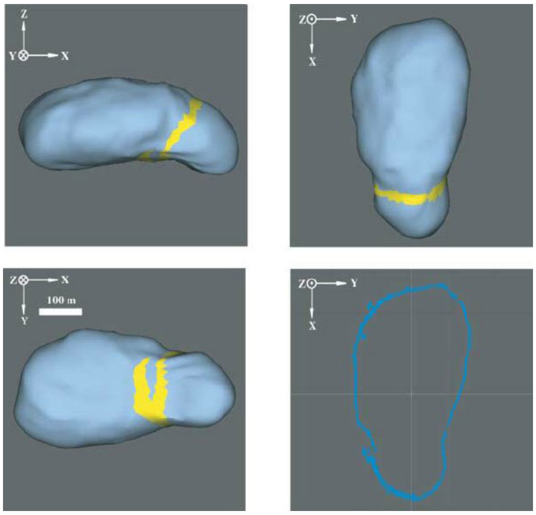

FIGURE 2. Three views of Itokawa's shape model and a detailed cross section along the equator. *Image credit*: [21].

(2) Morphological and geological discoveries about Itokawa. From images taken by AMICA, it can be seen that the surface of Itokawa is covered with huge boulders [17], [21], [22], [24], and naked surfaces not covered by regolith, as shown in Figure 3.

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[1] https://www.isas.jaxa.jp/e/snews/2005/1102.shtml

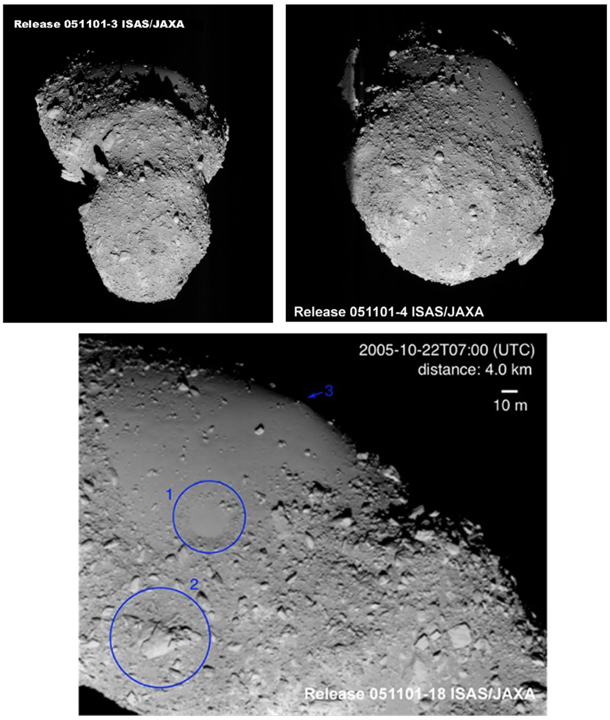

FIGURE 3. **The surface of Itokawa is covered with huge boulders and exposed surface. *Image credit*: ISAS/JAXA[1].**

(3) High-resolution observation of Itokawa surface. Figure 4 shows the image of the landing area (Muses sea) of Hayabusa; the resolution of figures (c) and (d) is 6-8 mm/pix [22]. Based on the high-resolution image taken by AMICA, it can be seen that the Muse sea is relatively smooth as a whole, and there is a high density of granular gravel with diameters from several millimeters to several centimeters [24].

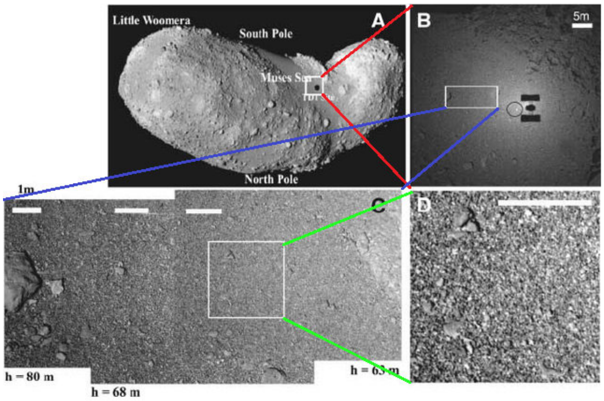

FIGURE 4. **Location of the Muses sea smooth terrain. *Image credit*: [22].**

(4) Gravity model of Itokawa.

(5) Mass and density estimate for Itokawa.

(6) Optical navigation technology. The main engineering achievement of ONC was to verify the optical navigation technology and realize the precise navigation of spacecraft. If ‘‘hybrid navigation using optical and radiometric observations’’ (simply referred to as ‘‘Optical Navigation’’) technology is adopted, asteroids can be found and located in the early stage when the distance is millions of kilometers. Optical navigation technology was later applied to the Hayabusa 2 mission, as shown in Figure 5.

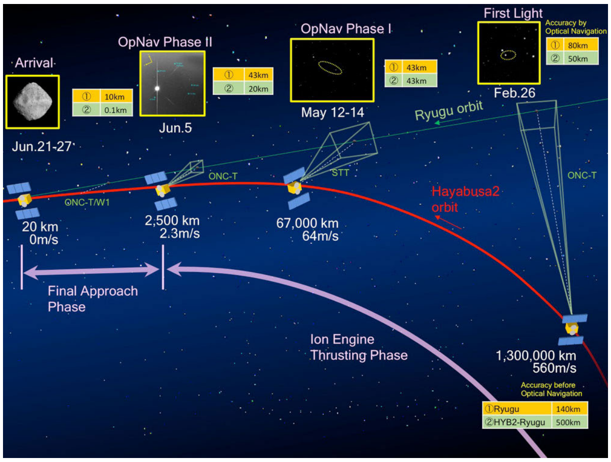

FIGURE 5. **Progression of the estimation accuracy for the orbits of the spacecraft and asteroid made using optical navigation. *Image credit*: JAXA[2].**

C. ROSETTA AND PHILAE

ESA launched the Rosetta probe [74], [115]–[118] on March 2, 2004, to explore the mystery of the origin of the solar system 4.6 billion years ago, and whether comets provided the Earth with the water and organic materials necessary for the birth of life. Rosetta flew by the asteroid (2867) Steins [119]–[124] and (21) Lutetia [125]–[135] on September 5, 2008 and July 10, 2010, respectively, and released the Philae probe [136]–[138] on November 12, 2014 to successfully land on the surface of 67P/Churyumov-Gerasimenko.

In order to achieve the above scientific goals, an optical imaging instrument was essential. Rosetta's main optical imaging instrument was OSIRIS (Optical Spectroscopic and Infrared Remote Imaging System), which comprises a high resolution NAC (Narrow Angle Camera) unit and a WAC (Wide Angle Camera) unit accompanied by three electronics boxes [75]. Figure 6 shows the NAC, whose high spatial resolution allowed an initial detection of the nucleus and survey of its structure and rotation from relatively great distances, an investigate of the mineralogy of the surface, and a survey of the dust ejection processes [75]. Table 2 displays the parameters of NAC. A flat-field, TMA (Three-Mirror Anastigmat) system was adopted for the NAC. It realized 11 spectral and panchromatic imaging capabilities by using two eight-position filter wheels placed in front of the CCD.

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[2] https://www.hayabusa2.jaxa.jp/en/topics/20180828eb/index.html

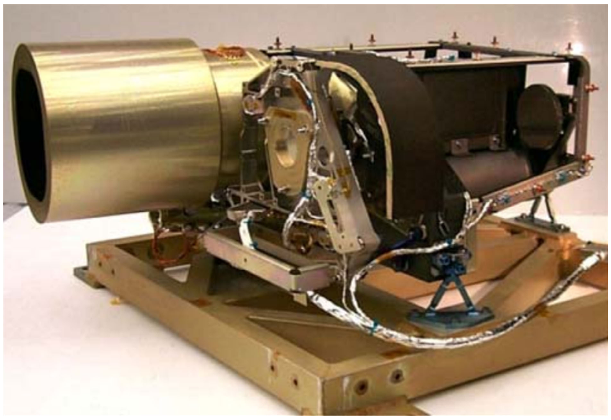

FIGURE 6. **The OSIRIS narrow angle camera.** ***Image credit***: **ESA/Rosetta/MPS for OSIRIS team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA/ [75].**

During the orbit period, OSIRIS obtained a large number of high-resolution images. The mission team made many scientific achievements based on the image data. Examples follow:

(1) Geological analysis of Steins and Lutetia.

The mission team identified a landslide, which supports a YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) origin for Steins' unusual diamond shape [120], [123]. As Figure 7 shows, detailed analysis of the data obtained by Rosetta confirmed that Lutetia is one of the best-characterised asteroids and as such adds significantly to our understanding of the different types of asteroids as well as helping to solve the puzzle of how the solar system formed and evolved [128].

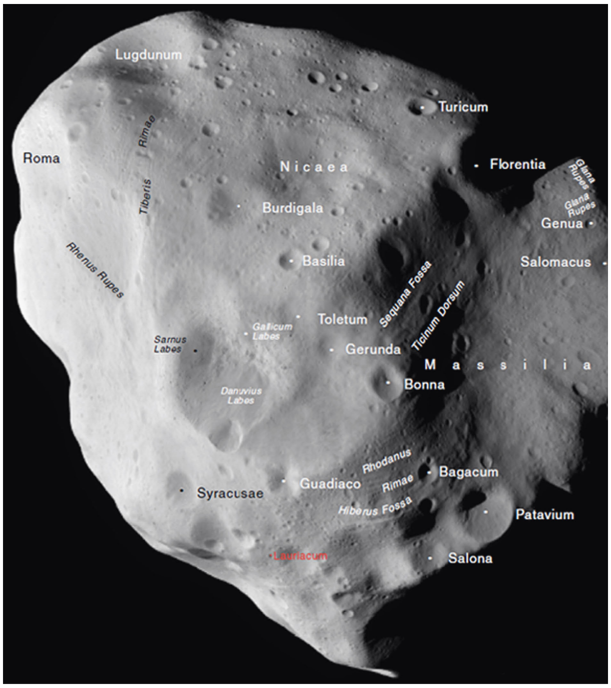

FIGURE 7. **Road map of Lutetia.** ***Image credit***: **ESA/Rosetta/MPS for OSIRIS team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA/ [128].**

(2) Three-dimensional topography of 67P. Based on the high-resolution images taken by OSIRIS, the three-dimensional topography and related physical parameters of 67P were obtained [126], [139]–[143]. Figure 8 shows a shape model of 67P generated by OSIRIS NAC images.

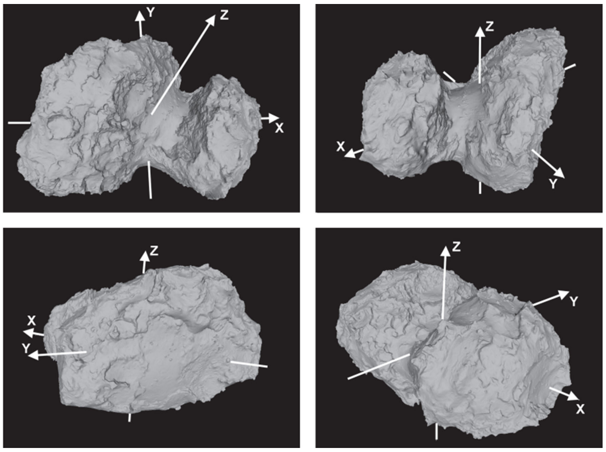

FIGURE 8. **Shape model of 67P.** ***Image credit***: **[139].**

(3) Cometary activity of 67P. Figure 9 shows cometary activity at 67P. Researchers have studied the composition and characteristics of the coma. Cometary dust particles are related to the interstellar dust particle swarm. In the early stages of the solar system, these dust particle swarms are considered to have grown into larger and larger particle clusters. To understand how comets form, scientists need to understand the structure of the smallest particles and how they form [76], [78], [80], [144]–[146].

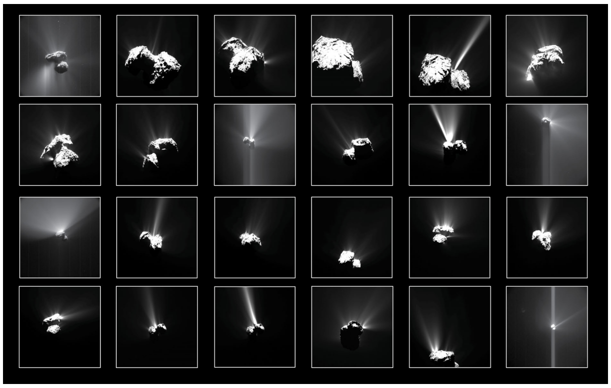

FIGURE 9. **The brightest outbursts seen at 67P by OSIRIS NAC and navigation camera between July and September 2015.** ***Image credit***: **OSIRIS: ESA/Rosetta/MPS for OSIRIS team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; Navigation Camera: ESA/Rosetta/NavCam[3].**

(4) High-resolution observation of 67P surface and geological analysis. The shape and surface characteristics of comets play an important role in their activities, seasonal evolution, dust transport and influence on the gas density

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[3] https://sci.esa.int/web/rosetta/-/58319-comet-outbursts

observed in comets. Researchers have made a detailed study on the surface of cometary nucleus, classified the surface features and regions [77], [79].

As shown in Figure 10, NAC captured this detailed view of 67P on 2 September 2016 from a distance of just 2.1 km from the comet's surface, giving a resolution of just under 4 cm/pixel at the centre of the image. It imaged part of the Nut and Serquet regions on the comet's smaller lobe which displayed a mix of fine dust and boulders.

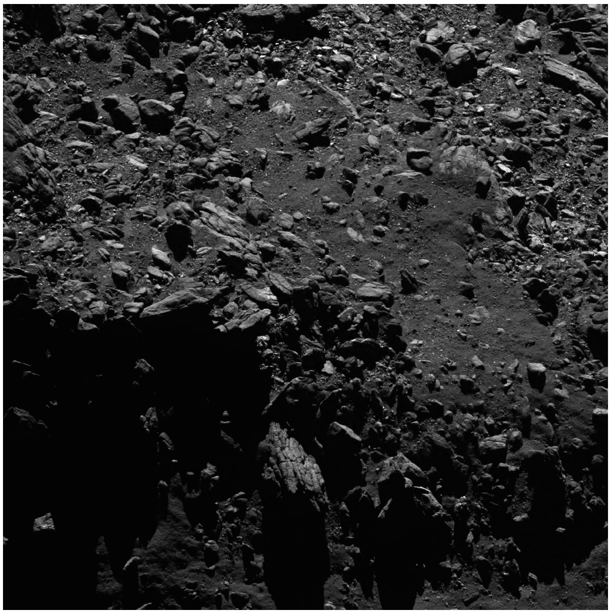

FIGURE 10. **Detailed view of 67P. *Image credit*: ESA/Rosetta/MPS for OSIRIS team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA[4].**

The data from Rosetta largely confirmed our view of cometary activity. Based on the data from the Rosetta mission, our understanding of the formation of comets, Earth and other planets is different. For example, fractures of an irregular pattern are observed on the edges of scarps. Bases of fractured scarps display debris and talus deposits, indicating an ongoing process of mass wasting. Such mass wasting events should be the primary process by which cometary materials are being fragmented [10].

D. DEEP IMPACT (EPOXI)

Deep Impact [83]–[85] was launched by USA on January 12, 2005 to study the internal components of comets by deploying impact detectors. The impactor successfully hit the nucleus of 9P/Tempel 1 on July 4 of the same year. Deep Impact flew by comet Hartley 2 [147] on November 4, 2010.

The Deep Impact mission was designed to help answer basic questions about comets, such as the composition of cometary nuclei, the location of cometary formation, and so on. By observing the impact, astronomers hoped to determine observe the difference between the nucleus and the outer layer of the comet, so as to explore the process of comets formation. In order to achieve the above scientific goals, Deep Impact carried three optical instruments: a HRI (High-Resolution Instrument), a MRI (Medium-Resolution Instrument) and an ITS (Impactor Targeting Sensor) [84], as shown in Figure 11. The HRI pixel resolution was 1.4 m at a range of 700 km. The parameters of HRI can be seen from Table 2. It has realized 7 spectral and panchromatic imaging capabilities by using a nine-position filter wheel. Ref. [84] provides the HRI filter transmittances.

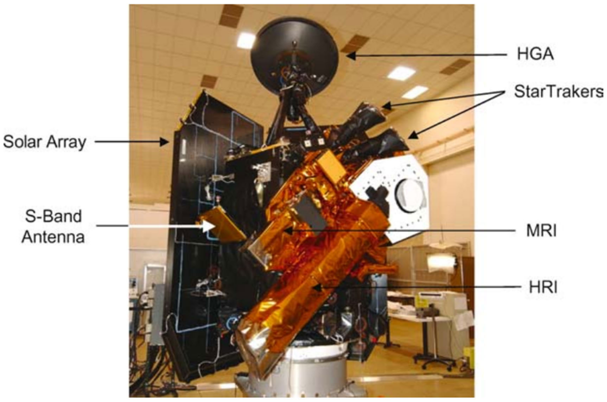

FIGURE 11. **Deep impact spacecraft. *Image credit*: [148].**

During the orbit period, three optical instruments of Deep Impact acquired about 500000 images. The mission team made many scientific achievements based on the image data. They are:

(1) Confirmed the cometary material composition.

(2) Determined that a comet's surface layer is very porous.

(3) Discovered that hyperactive comets are driven by carbon dioxide [86].

(4) Observed the impact event. About 4,500 images were obtained by the three optical instruments. As shown in Figure 12, this spectacular image of comet 9P was taken 67 seconds after impact.

(5) Photometric investigations of extrasolar planets.

E. DAWN

USA launched the Dawn probe [89], [90] on September 27, 2007, and it successfully entered orbit around (4) Vesta and (1) Ceres on July 16, 2011 and March 7, 2015, respectively. It was the first spacecraft to explore small bodies in the main belt, and also the first spacecraft to orbit dwarf planets.

Dawn's primary scientific objective was to investigate in detail the two largest protoplanets that have remained intact since their formation. Vesta is rocky, while dwarf planet Ceres is icy. They each followed a very different evolutionary path and both were influenced by various evolutionary processes in the solar system in the first few million years. Their in-situ exploration will help astronomers to understand more about the origin of the solar system and the formation of planets.

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[4] https://sci.esa.int/web/rosetta/-/60438-comet-67p-on-2-september-2016-from-21-km-osiris-nac

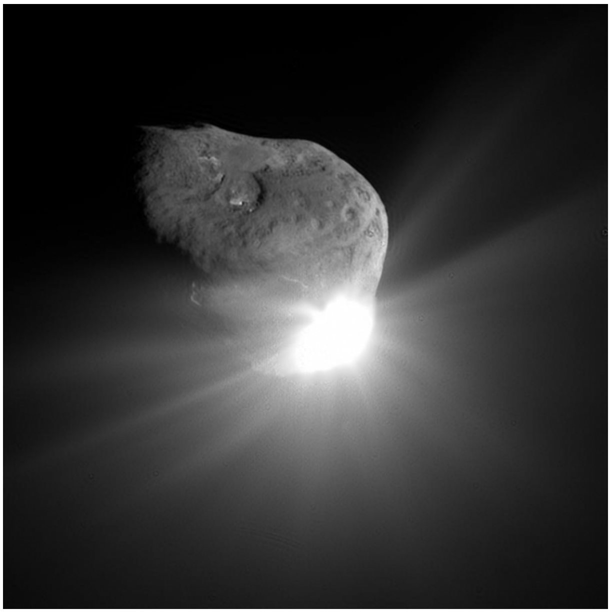

FIGURE 12. **Tempel alive with light. *Image credit*: NASA/JPL-Caltech/UMD[5].**

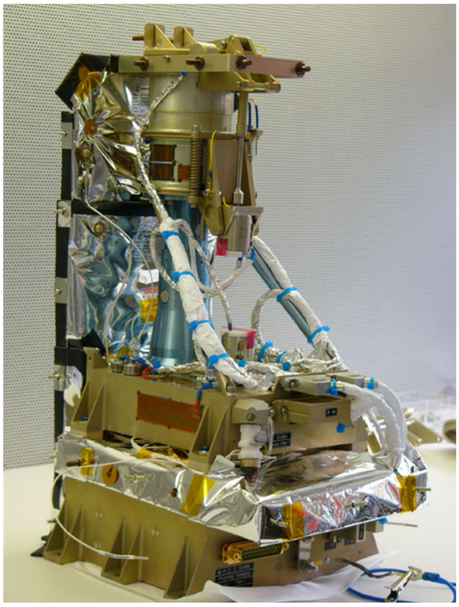

FIGURE 13. **Framing camera of dawn. *Image credit*: [92].**

Dawn carried three kinds of scientific instruments: two FCs (Framing Camera), a VIR (Visible and Infrared Mapping Spectrometer) and a GRaND (Gamma Ray and Neutron Spectrometer).

FC is shown in Figure 13. Its focal length was 150 mm, and its pixel resolution was 1.87 m at a range of 20 km. The parameters of FC can be seen from Table 2. FC has realized 7 spectral and panchromatic imaging capabilities by using an eight-position filter wheel. Ref. [92] provides the transmission profiles of the FC filters.

During the orbit period, Dawn obtained more than 167GB worth of scientific data. The mission team made many scientific achievements based on the image data. They include:

(1) Global mapping and geological analysis of Vesta. FC image data reveal a novel and diverse primitive planet.

- Vesta is more closely related to the terrestrial planets (including Earth) than to typical asteroids. Like planets, it has a dense core [91], surrounded by a mantle and a crust [149], [150].
- Vesta has a crater more than 400 miles in diameter [96], [151]–[153]. In the center is a mountain more than twice the height of Mount Everest.
- Vesta has a network of more than 90 chasms - some with dimensions rivaling those of the Grand Canyon - that are scars from two giant impacts hundreds of miles away.
- Vesta is the source of more meteorites on Earth than Mars or the moon [150].

Dawn found many surprises, such as an olivine-bearing mantle exposed near the south-pole, a weakly or un-weathered surface that has been relatively recently resurfaced, and a very thin layer of surficial volatiles derived from interaction with the solar wind [91]. Vesta is unique among main-belt asteroids. Its surface is basaltic, implying that it has experienced a planetary scale differentiation that produced a crust and mantle and possibly a core [91]. The formation of Vesta's crust and mantle occurred in the first ∼30 My of solar system history, well before larger terrestrial planets formed [149]. Vesta may thus represent the type of proto-planet that was heated and differentiated early in solar system evolution and was subsequently accreted into the terrestrial planets [150]. Observations from the Dawn mission hold the promise of revolutionizing our understanding of Vesta, and by extension, the nature of collisional, melting and differentiation processes in the nascent solar system [150].

(2) Global mapping and geological analysis of Ceres. Based on the Dawn data, scientists obtained the basic data of the shape, average density, surface morphology, mineralogical distribution and composition, regional gravity, topography, crater distribution, etc [101]–[104].

(3) New discoveries in comparative planetology.

- Through the exploration of the large impact basin (Rheasilvia) at Vesta's south pole, combined with the existing meteorite data, it is confirmed that Vesta is the parent of the HED meteorites [94], [95], [151], [153]–[155]. Scientists believe that about 6% of all meteorites found on Earth were caused by this ancient impact.
- Dawn also found hydrated and carbon rich material on Vesta's surface supplied by impactors, a result that was unexpected based on pre-Dawn telescopic observations. Localized dark and bright materials were found on Vesta's surface [95], as shown in Figure 14.

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[5] https://www.nasa.gov/mission_pages/deepimpact/multimedia/pia02137.html

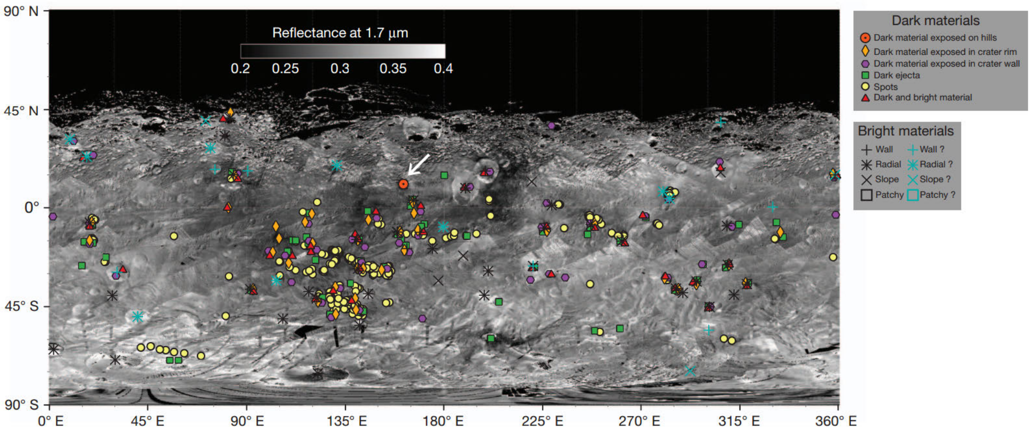

FIGURE 14. **Locations of dark and bright material.** ***Image credit*****: [95].**

- Surprisingly, cratered terrain and gullies have been found in several young craters, which are interpreted as evidence of volatile release and instantaneous water flow. Since Vesta's volatile components are depleted, these hydrated substances may be exogenous.
- The spectral characteristics of the fresh impact crater were studied by combining data from VIR and FC [94].

(4) Discovered probable sublimation of water ice in Ceres.

F. HAYABUSA 2

JAXA's Hayabusa 2 mission is a successor of Hayabusa [109]. It was launched by an H-IIA rocket in December 3, 2014. Hayabusa 2 arrived at the C-type asteroid (162173) Ryugu in 2018, and returned the collected samples to Earth in December 2020.

Similarly to Hayabusa, the main optical imaging instrument carried by Hayabusa 2 is ONC [109], [110]. The focal length of ONC-T (Fig. 15) is 120 mm, and the pixel resolution is 2.17 m when at a range of 20 km. The parameters of ONC-T can be seen from Table 2. Ref. [110] provide the transmittance spectra of the band-pass filter installed on the wheel in ONC-T.

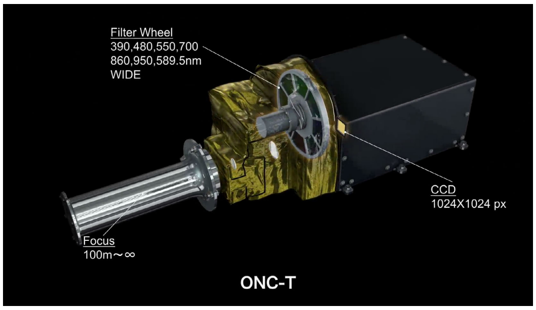

FIGURE 15. **ONC-T of Hayabusa 2.** ***Image credit*****: JAXA[6].**

The Hayabusa 2 mission is still in progress, and the mission team has achieved the following scientific results based on the image data:

(1) Determined the basic parameters of Ryugu. Based on the high-resolution images taken by Hayabusa 2's optical instruments, the shape, mass, color, slope and other basic data of Ryugu were obtained [105].

Based on images obtained by optical cameras, researchers use photogrammetry and other related technologies to carry out three-dimensional mapping of small bodies, combined with the position, attitude, time and other information of the probe platform, to generate three-dimensional shape models of small bodies. In the actual mission, Stereophotoclinometry (SPC) [124], [140], [156]–[158] and Structure from Motion (SfM) [105], [159], [160] methods can be used to build the preliminary global shape model by using the lower resolution image acquired at long distance. On this basis, the global model can be divided into several small square digital terrain models, covering all light surface areas. Each small area model, with the approach of distance, further uses the obtained high-resolution image, comprehensively considers the observation geometry parameters of each image, registers the projection pixel values corresponding to the same area observed on multiple images, and establishes a high-resolution shape model. Finally, the high-resolution global terrain model of small bodies is constructed by integrating all the small area terrain. Table 3 shows the three-dimensional reconstruction methods used in different small bodies exploration missions. Figure 16 shows the three-dimensional shape model of Ryugu generated from the image obtained by Hayabusa 2's ONC-T; the left is generated by the SPC method, and the right is generated by the SfM method. Compared with the model based on the observation data of ground-based telescope (Fig. 17), the resolution has been improved significantly.

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[6] https://www.hayabusa2.jaxa.jp/galleries/othermovie/pages/Hayabusa2_mission_E.html

TABLE 3. Three-dimensional reconstruction methods used in different small bodies exploration missions.

Mission	Hayabusa	Hayabusa 2	OSIRIS-REx
Asteroid	Itokawa	Ryugu	Bennu
Camera	AMICA	ONC-T	OCAMS[1]
Number of images	212	214	2164
Image resolution	0.3∼0.7m	0.5∼0.7m	0.32∼2.0m
Methods	SfM integrated limb profiles [124], [161]	SPC SfM	SPC
Model accuracy	Volume uncertainty: 5% Resolution: 1m	Volume uncertainty: 1.3% Resolution: 1m	Resolution: 0.8m

1. OCAMS: OSIRIS-REx Camera Suite.

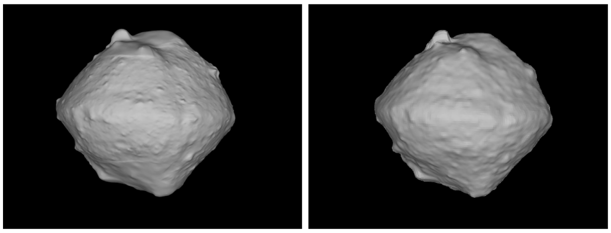

FIGURE 16. Shape model of Ryugu. *Image credit*: University of Aizu, Kobe University, JAXA and collaborators[7].

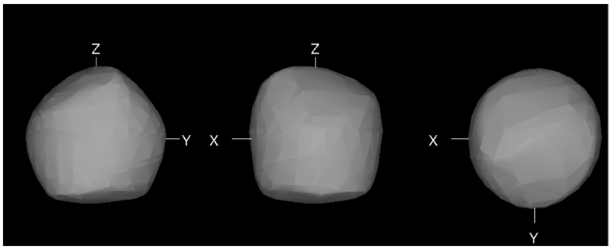

FIGURE 17. The formally best-fit shape model of Ryugu for pole direction (340°, −40°). *Image credit*: [162].

From the global three-dimensional topography, the volume of the asteroid can be obtained by integrating the volume of triangle surface and polyhedron, and the mass of the asteroid can be obtained from the measurement results of radio scientific instruments. At that point, the density of the asteroid can be calculated. Its bulk density, 1.19 ± 0.02 g/cm^3, indicates a high-porosity (>50%) interior [105].

(2) High-resolution observation of Ryugu surface. By analyzing the high-resolution images obtained by ONC-T, the mission team also determined the appropriate sample collection points.

In low orbit, the resolution image of centimeter level or even millimeter level can be obtained, and the high-resolution (centimeter level) and high-precision digital terrain model can be generated. Based on the above high-resolution image and digital terrain model, the factors such as slope, roughness and stone distribution in the possible touchdown area can be analyzed, which will provide reliable guidance to find the best touchdown point. The correlation analysis of the selection of the touchdown area of Hayabusa 2 is shown in Figure 18.

G. OSIRIS-REx

On September 8, 2016, USA launched the OSIRIS-REx probe, targeting the asteroid (101955) Bennu. It will be the first mission launched by USA to bring samples back from an asteroid. The OSIRIS-REx mission will give scientists more information about how the early solar system formed and about how life began. It will also help scientists better understand asteroids that could impact Earth in the future. In order to achieve the above scientific objective, the main optical imaging instrument carried by OSIRIS-REx is OCAMS (OSIRIS-REx Camera Suite), which is fitted with three cameras: MapCam (Mapping Camera), PolyCam (Polyfunctional Camera) and SamCam (Sample Acquisition Verification Camera) [28], as shown in Figure 19. The MapCam's pixel resolution is 1.36 m at a range of 20 km, and its other parameters can be seen from Table 2. MapCam has realized 6 spectral and panchromatic imaging capabilities by using an eight-position filter wheel. Ref. [28] provides the MapCam filter transmittances. The PolyCam's pixel resolution is 0.27 m at a range of 20 km, and its other parameters can be seen from Table 2.

At present, the OSIRIS-REx mission is still in progress, and the mission team has made some scientific achievements based on the image data, including:

(1) Determined the basic parameters of Bennu. Based on the high-resolution image taken by MapCam and PolyCam, the shape, mass, color, three-dimensional topography and other basic data of Bennu were obtained [31]–[37], [114]. Figure 20 shows the global digital terrain model of Bennu generated from OCAMS imaging, the model has a resolution of ∼0.8 m per facet [34]. Compared with the model obtained from ground-based radar [27], [163], the resolution was significantly improved.

(2) High-resolution observation of Bennu's surface.

(3) Observation of particle ejection events from the surface of Bennu.

(4) Successful Acquisition of Sample from the Surface of Bennu.

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[7] https://www.hayabusa2.jaxa.jp/topics/20180711bje/index_e.html

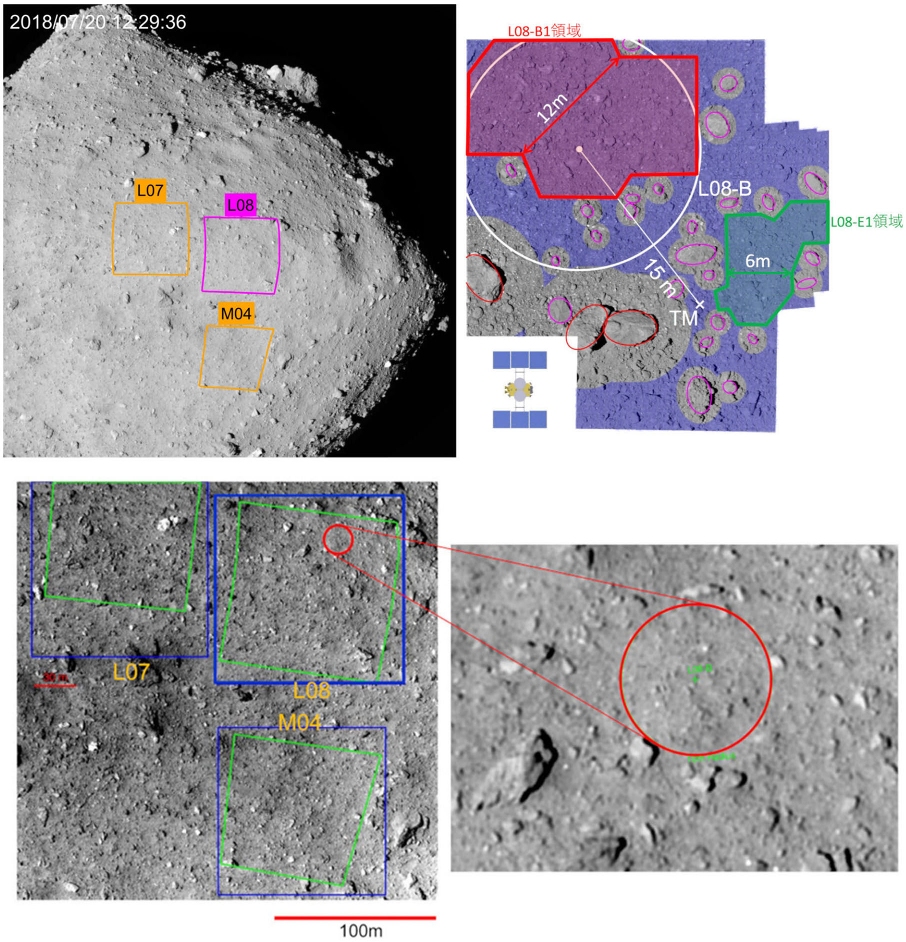

FIGURE 18. Selection of the touchdown area. *Image credit*: JAXA, University of Tokyo and collaborators[8].

IV. FUTURE MISSIONS TO SMALL BODIES AND RELATED OPTICAL IMAGING INSTRUMENTS

A. LUCY MISSION-ANIMATIONS OF JUPITER's TROJANS

Lucy will launch in 2021 and will have encounters from 2025 to 2033. It will visit (52246) Donaldjohanson (Main belt, C-type) on April 20, 2025, (3548) Eurybates (Lagrangian point L_4, C-type) on August 12, 2027, (15094) Polymele (Lagrangian point L_4, P-type) on September 15, 2027, (11351) Leucus (Lagrangian point L_4, D-type) on April 18, 2028, (21900) Orus (Lagrangian point L_4, D-type) in November 11, 2028, and the Patroclus/Menoetius binary (Lagrangian point L_5, P-types) in March 2, 2033 [38].

B. ZhengHe-CHINA's FUTURE ASTEROID MISSION

China will launch in the forthcoming years a sample return mission called ZhengHe, to NEA 469219 Kamo'oalewa (provisional designation 2016HO3) and Main-Belt Comet (MBC) 133P/Elst-Pizarro [40]. 2016HO3, which was discovered on April 27, 2016 by B. Gibson, T. Goggia, N. Primak, A. Schultz and M. Willman observing with the 1.8-m Ritchey-Chretien telescope of the Pan-STARRS Project, is the fifth quasi-satellite of our planet. Its semimajor axis $a = 1.0012$ AU, absolute magnitude $H = 24.1$, suggested a diameter in the range 26-115 m for an assumed albedo in the range 0.60-0.03. Its current quasi-satellite episode started nearly 100 years ago and it will end in about 300 years from now. Among the known Earth quasi-satellites, it is the closest to our planet and as such, a potentially accessible target for future in-situ study [164]. 133P is the first recognized main-belt comet, but we still know little about its nucleus. Its absolute magnitude of the nucleus is 15.7, its albedo is 0.05±0.02, and its size is estimated to be about 3.6km×5.4km. In terms of albedo, 133P is similar to other Themis family asteroids, C-type asteroids, and other comet nuclei [165]–[168].

The Chang Zheng 3B rocket will be launched at Xichang Satellite Launch Center. The mission will carry out orbital exploration of NEA 2016HO3. Then it will attempt to perform a touch-and-go of the asteroid's surface and collect a sample. After that, it will return to the nearby Earth to release the return capsule and the asteroid samples. This process will

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[8] https://www.hayabusa2.jaxa.jp/en/topics/20190220e_TDPoint/

[9] https://www.nasa.gov/image-feature/ocams-instrument-suite

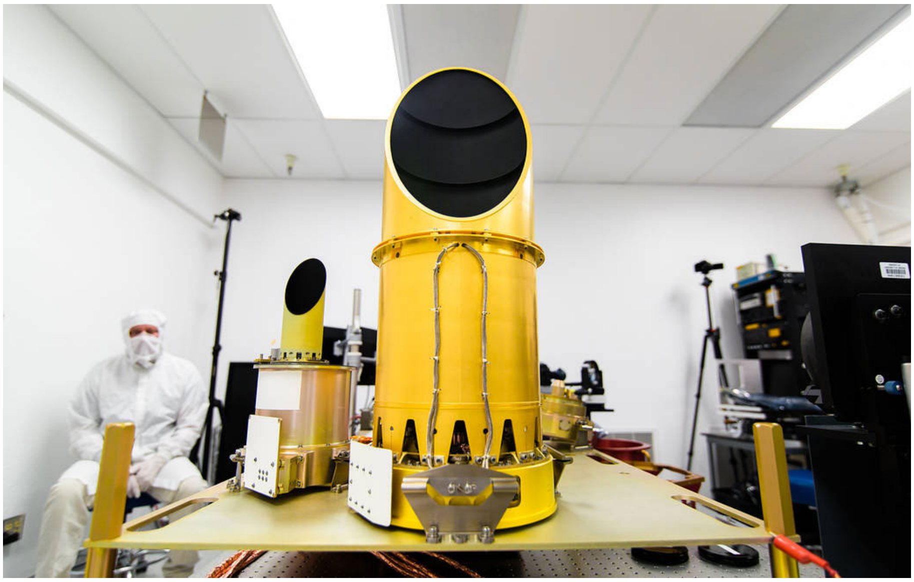

FIGURE 19. PolyCam (center), MapCam (left), and SamCam (right) make up the OSIRIS-REx camera suite. *Image credit*: University of Arizona/Symeon Platts[9].

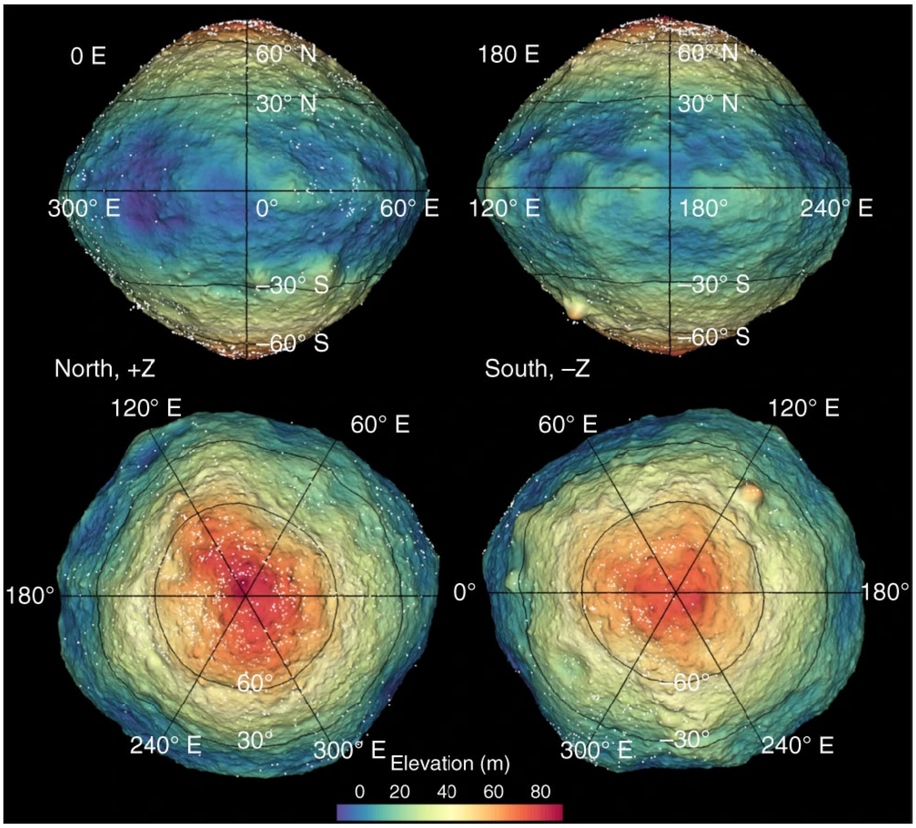

FIGURE 20. The global digital terrain model of Bennu. *Image credit*: [34].

be completed in about three years. After that, it will travel to the asteroid belt for about 7 years, and carry out orbital exploration of MBC 133P.

The science objectives of the ZhengHe mission are as follows:

- Determine the orbit parameters, rotation parameters, shape size and thermal radiation of 2016HO3 and 133P.
- Explore the appearance, surface material composition, internal structure and near-space environment of 2016HO3 in order to return samples.

TABLE 4. **Parameters of the main optical imaging instruments.**

Mission	Camera	Focal length (mm)	Field-of-view (°)	Spectral response (nm)	Resolution	A/D conversion (bits)
Lucy	MVIC[1]	450	-	380-920	-	-
Lucy	L'LORRI[2]	2620	0.292×0.292	450-850	0.28m@20km	-
ZhengHe	Mid Field Color Camera	-	-	wider than 450-760	better than 2m@20km	≥8
Psyche	Multispectral Imager	-	-	-	-	-
Milani	VIS	32.3	10×10	-	-	-
LICIACube	LEIA	220	2.91×2.91	-	0.50m@20km	-
LICIACube	LUKE	70.55	7.07×7.07	400-900	1.56m@20km	-
Castalia	MBCCAM-v	150	5.5×5.5	380-1100	1.90m@20km	16

1. MVIC: Multispectral Visible Imaging Camera.
2. L'LORRI: LOng Range Reconnaissance Imager.

- Explore the appearance, surface material composition, internal structure, near-space environment, possible water and organic matter of 133P.
- Carry out laboratory analysis and research on 2016HO3 returned samples, chemical and mineral composition, isotopic composition and structure; determine and study the age of asteroid samples; carry out comparative research with meteorites and establish the relationship between return samples and meteorites, and conduct surface observation and remote sensing in situ analysis data.

In order to achieve the above science objectives, eight science instruments will carry out remote sensing exploration, in-situ exploration and sampling return for the target asteroid by flyby, orbit, and touch-and-go sample return. The objective of the Mid Field Color Camera is global imaging of 2016HO3 and 133P, and obtaining the features of shape, size, surface morphology, rotation period and orbit.

C. PSYCHE-NASA's 14th DISCOVERY MISSION

The Psyche mission was chosen by NASA at the same time as Lucy for the agency's Discovery Program. This mission will investigate what is likely an exposed planetary metallic core, the asteroid (16) Psyche [169], [170]. The Psyche mission is scheduled to launch in summer 2022 and to be captured at the asteroid Psyche in 2026 [38], [170].

D. ASTEROID IMPACT & DEFLECTION ASSESSMENT (AIDA) MISSION

The AIDA mission is an international cooperation between NASA and ESA [171]–[173] to study near Earth object kinetic impact deflection. It includes the Double Asteroid Redirection Test (DART) mission [174]–[176] and the Hera mission (the original version called Asteroid Impact Mission (AIM)) [177]–[179]. DART mission will be the first demonstration of the kinetic impactor technique to change the motion of an asteroid in space. Schematic of the DART mission shows the impact on the moonlet of asteroid (65803) Didymos [180]–[182] (Fig. 21).

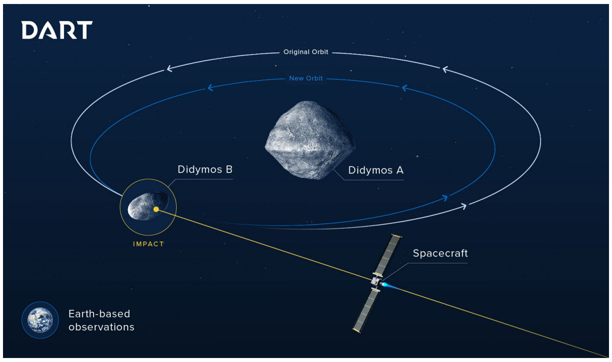

FIGURE 21. **Schematic of the DART mission. *Image credit*: NASA/Johns Hopkins APL**[10]**.**

Hera will investigate the smallest asteroid visited so far therefore providing a unique opportunity to shed light on the role cohesion and Van der Waals forces may play in the formation and resulting internal structure of such small bodies [178]. The baseline payload of the Hera mission includes an Asteroid Framing Camera (AFC) and a miniaturized LIght Detection And Ranging (LIDAR) instrument [178]. The AFC is a flight spare of the Dawn mission camera (Fig. 13).

Hera will carry with it two 6U (6 unit) CubeSats - Milani [183], [184] and Juventas [185]–[187]. The main payload aboard Milani is the ASPECT (Asteroid Spectral Imager) hyperspectral camera [188]. The payload has three channels, which are the Visible (VIS), the Near-Infrared (NIR), and the Short Wavelength Infrared (SWIR) [183]. Juventas will carry a camera and a low-frequency radar (JuRa) [187], for determining the internal structure of Dimorphos. It will operate for 3-6 months near the asteroid. At the end of its mission, it will attempt a landing on the surface of Dimorphos to obtain close-up data.

Light Italian Cubesat for Imaging of Asteroids (LICIACube) mission [189], [190] will be part of the DART mission. The LICIACube instrument is composed by LEIA (Liciacube Explorer Imaging for Asteroid), a narrow FoV camera, and LUKE (Liciacube Unit Key Explorer), a wide

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[10] https://www.esa.int/ESA_Multimedia/Images/2018/06/DART_impact

FoV imager with an RGB Bayer pattern filter, that will collect and transmit to Earth several unique images of the effects of the DART impact on the asteroid, such as the formation and the development of the plume potentially determined by the impact [189].

E. OTHERS

At the time of writing only a few scientific publication has been released, and little news about the Castalia mission [191], the Miniaturised Asteroid Remote Geophysical Observer (M-ARGO) mission [192] and the Near Earth Asteroid Scout (NEA-Scout) mission [193], [194] is coming from the web.

Table 4 displays the parameters of the main optical imaging instruments on board the above future missions.

V. CONCLUSION AND DISCUSSION

In this paper, we summarized the current situation of small body exploration, including the science objectives, main optical imaging instruments and the main science results obtained in the past two decades, starting from the Hayabusa mission to the OSIRIS-REx mission. For orbital exploration of small bodies in the solar system, the ground resolution and the selection of the working spectrum band are the key factors to realize the creative scientific discovery. At present, with the improvement of the overall ability in the field of deep space exploration, especially the improvement of the TT&C (Telemetry, Tracking and Control) ability and the progress of scientific instruments technology, the optical imaging instruments for the detection of small bodies in the solar system show the following trends:

- Based on the requirements of scientific research on image resolution, the image data acquired by optical imaging instruments should meet the resolution requirements from meter level to millimeter level. With the improvement of the TT&C ability, the resolution is focused on 2m@20km, and the resolution of the acquired image covers the range of tens of meters to millimeters with the difference of orbital height. The focal length is gradually concentrated in 120-150 mm, which is suitable for transmission optical system.
- Based on the importance of surface high-resolution observation for scientific research, optical imaging instruments pay attention to the combination of panchromatic imaging and multispectral imaging. And the selection of imaging detector spectrum band matches the characteristics of the detection target.
- Based on Eight Color Asteroid Survey [195], in order to establish the relationship between the ground observation data and the remote sensing/in-situ detection data, optical imaging instruments need to have the ability of wide-band imaging, and the ability of near ultraviolet and near-infrared spectrum imaging.
- Due to the low albedo and wide range of variation of the detection target, and in order to obtain the image data with rich texture details in a wider range of solar height angle, optical imaging instruments need to have the characteristics of high quantum efficiency and high dynamic range. Therefore, large pixel, high quantum efficiency imaging detectors are used, and the A/D conversions are generally 12-14 bits.
- Due to the relative velocity of the detector and target is relatively low, the area array imaging detector becomes the main choice.
- The trend of multi-functional integration, the combination of scientific application and engineering application.

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