Chapter 4
Japanese Studies of Asteroids Following the Discovery of the Hirayama Families

Tsuko Nakamura

4.1 Introduction

As mentioned in other papers of these proceedings (Nakamura 2017; Yoshida and Nakamura 2017), in 1918 Kiyotsugu Hirayama from the University of Tokyo announced the discovery of asteroid families (Hirayama 1918). But it took quite some time before the importance of his discovery was recognized by the international astronomical community (Fig. 4.1). According to the *Astronomischer Jahresbericht*, the earliest citation of Hirayama's work on asteroid families was made in the *Russian Astronomical Journal* (Staude 1926), followed by Bobrovnikoff (1931) and Senesplada (1932), but all three only contained brief mentions of Hirayama's paper. This slow response may have been due to a lack of new asteroidal data that could be used to evaluate Hirayama's results, or to the international unrest in the period between WWI and WWII, during which interest in minor planets remained at a low level.

After WWII eminent celestial mechanicians such as Dirk Brouwer (1902–1966; Fosmire 2014), of Yale University and Adriaan van Woerkom (1915–1991) began to publish follow-up studies of Hirayama's results based on the secular perturbation theory of celestial mechanics, and they increased the number of families by identifying new ones (Van Woerkom and Brouwer 1950; Brouwer 1951). During this era, the concept of asteroid families and their theoretical origin were gradually established. Brouwer (1950) noted that

T. Nakamura (✉)
Institute for Oriental Studies, Daito-Bunka University,
Tokumaru 2-19-10, Itabashi, Tokyo 175-0083, Japan
e-mail: tsukonk@yahoo.co.jp

T. Nakamura, W. Orchiston (eds.), *The Emergence of Astrophysics in Asia*,
Historical & Cultural Astronomy, DOI 10.1007/978-3-319-62082-4_4

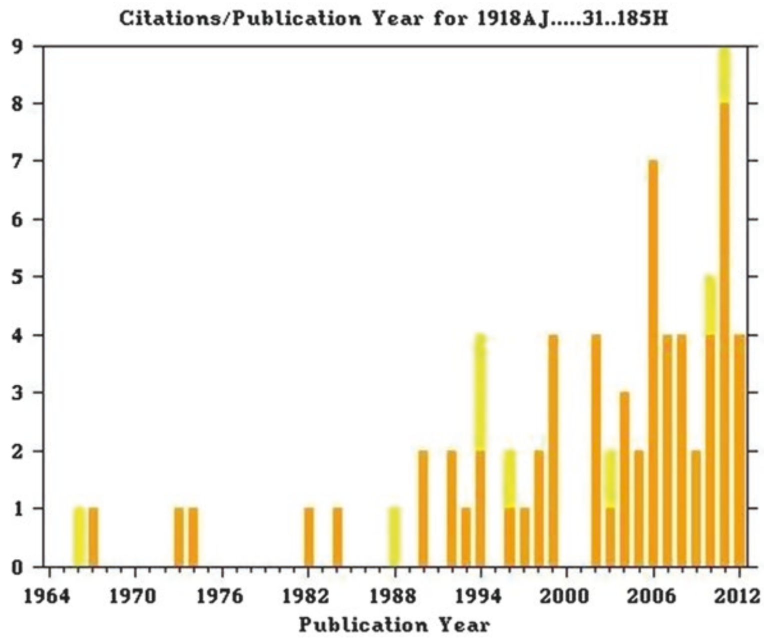

Fig. 4.1 Citation history of Hirayama's 1918 paper on asteroid families (after Astronomical Data Center, NASA). We should not forget that there have been many papers about asteroid families that do not cite Hirayama's 1918 paper (*Plot* Astronomical Data Center, NASA)

> While anyone familiar with celestial mechanics could have recognized this [importance of using the proper elements of minor planets for classifying them], Hirayama was the first to go through the rather laborious calculations.

As is currently well known, studies of asteroid families have grown into a major field in planetary sciences that can be systematically investigated using various disciplines, such as the long-term orbital evolution for Solar System small bodies (analytical/numerical); photometry; spectrophotometry; spectroscopy; radiometry; radar investigation; geology and mineralogy; laboratory impact experiments; the interrelation between asteroids and meteorites (meteoritics); space exploration using spacecraft; etc.

In this paper I provide a short overview of the development history of asteroid studies conducted in Japan since Hirayama's achievements. Through this work I conclude that Japan has produced quite a few asteroid researchers, and this is likely to be due to the influence of Hirayama's work. A similar situation also seems to be found among Italian astronomers, and it may be attributable to the tradition nurtured in Italy since Giuseppe Piazzi's discovery of the first asteroid Ceres in 1801 (Cunningham 1988, 2001).

4.2 Studies on the Dynamics of Asteroids

4.2.1 The Eros Observing Campaign to Determine the Astronomical Unit

Asteroid (433) Eros was discovered in 1898 by Carl Gustav Witt (1866–1946) in Berlin and Auguste Charlois (1864–1910) in Nice (Minor Planet Center), and soon recognized to be the first of the Mars-crossing asteroids (or more generally a member of the near-Earth asteroids). Because of the nature of Eros' orbit, this object was then regarded as the most appropriate candidate to be used to improve the value of the Astronomical Unit (the mean Earth-Sun distance). Thus, world-wide astrometric observing campaigns were conducted during the 1900–1901 and 1930–1931 oppositions, and the final results were published by Arthur Hinks (1909) and Harold Spencer Jones (1940) respectively.

Tokyo Astronomical Observatory (TAO) participated in the 1931 campaign, because photographic observations of Eros were considered to be a good project for the scientific 'first-light' of the 26-in (66-cm) Zeiss refractor that had been installed at TAO in 1929. Observed astrometric positions of Eros were reported to the Central Bureau for Astronomical Telegrams in Copenhagen.

4.2.2 Secular Perturbation Theory of Asteroids

The secular perturbation theory of celestial mechanics that Hirayama had used extensively to discover the asteroid families thereafter became part of the tradition of subsequent Japanese astronomers who studied motions and dynamics of asteroids, and adopted both analytical and numerical approaches. Takenouchi (1950) and Kozai (1953) examined the long-term behaviour of the motion of asteroid Thule, which is in the 4:3 commensurability (mean-motion resonance) with Jupiter.

Since Hirayama (1918), astronomers have proposed several improved criteria for identifying asteroid families (e.g., see references in Knezevic et al. 2002 and Bendjoya and Zappalà 2002). Among them, Yoshihide Kozai (b. 1928) tabulated 72 families using a new perturbation theory that took into account higher order and higher degree terms in the disturbing functions (Kozai 1979). The basis of the theory had been developed by Yuasa (1973) in response to Kozai's suggestion.

In an introductory part of Kozai's paper (1979) reviewing the classical linear theory of secular perturbations on which the Hirayama families are based, Kozai devotes some words to emphasize the correctness of Hirayama's approach that used the proper orbital elements for classifying family asteroids by saying:

> I would like to make clear what Hirayama did as there have been several possible misquotings of his work in subsequent papers except Brouwer's. To do this I shall quote the following sentences from three papers[1]…

[1] Kozai points out that the three papers by Arnold (1969), Lindblad and Southworth (1971) and Williams (1971) quote Hirayama as if he simply regarded groupings of asteroids seen in a space of

This suggests that the dynamical concept of Hirayama asteroid families has not been correctly understood among astronomers, even as late as the 1970s (also see Fig. 4.1): the above three papers misunderstood that Hirayama could discover the asteroid families by simply using *osculating* orbital elements, not proper ones. The long-term orbital motions of asteroids with secular perturbation methods have subsequently been investigated by Kozai's students and followers (e.g., Nakai and Kinoshita 1985; Yoshikawa 1990).

4.2.3 The Kozai Mechanism[2]

In his paper of 1962, Kozai discussed possible motions of asteroids with very large eccentricities and inclinations—such a possibility had never been considered before. By applying secular perturbation theory of an asteroid with Delaunay's canonical variables, he showed that the z-component of the angular momentum of the asteroid is conserved along its motion. Since this relation can be expressed as

$$\sqrt{\left(1-e^{2}\right)}\cos i = \text{constant} \tag{4.1}$$

(where e is the eccentricity and i is the inclination), this means that a near-circular orbit with large inclination can evolve to a very eccentric one with low inclination, and *vice versa* (see Fig. 4.2). Developments of high-speed computers and efficient numerical intergration methods since the 1980s have enabled us to perform orbital calculations of asteroids over many millions of years without accumulation of errors (e.g., Holman and Wisdom 1993). As a result, very large orbital changes in eccentricity and inclination have been confirmed not only for asteroids but also other Solar System small bodies.

We now know that the Kozai Mechanism can explain unusual orbital behavior for various kinds of celestial bodies that used to be enigmatic in the past (Fig. 4.3). Such examples are irregular motions of the outer satellites of Jupiter; the origin of Sun-grazing comets; orbital motions of Kuiper-belt objects; the existence of upper bounds of inclinations for asteroids and the outer satellites of Jupiter; curious motions of planets in extra-solar systems and multiple stellar systems, etc. (for example, see Innanen et al., 1997, Murray and Dermot 1997).

---

the *osculating* orbital elements as 'families'.

[2] It has recently been noted that Russian astronomer Michail L'vovich Lidov (1926–1993) published a Russian paper in 1961 (translated into English in 1962) including essentially the same theory as the 'Kozai mechanism' (Lidov 1961). So the Kozai mechanism is also sometimes referred to the 'Lidov and Kozai mechanism'.

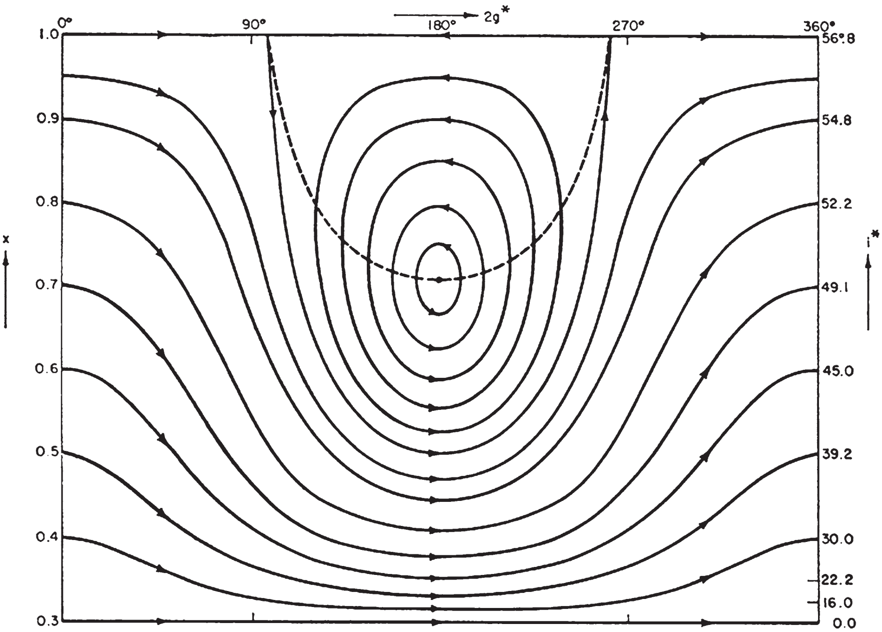

Fig. 4.2 An example of the phase diagram for large coupled variations in eccentricity and inclination due to the Kozai mechanism; the left-hand ordinate, the right-hand one, and the abscissa respectively stand for a measure of eccentricity, the inclination, and the argument of perihelion; the central part of the diagram shows the region in which the libration motion for the argument of perihelion takes place (after Kozai 1962)

4.3 Early Astrophysical Observations of Asteroids

4.3.1 Photometry

Regarding Eros mentioned above, its close approach to the Earth in 1931 inspired TAO astronomers to study the physical nature of this asteroid, looking for clues to its origin and evolution. Near the oppositions of this asteroid in 1930–1931, 1935, and 1937–1938, they recorded its light-curves by both visual and photographic means (Huruhata 1935, Kanda 1934). Since Shigeru Kanda was an experienced visual observer of variable stars, he was able to obtain reasonably good light-curves, as shown in Fig. 4.4.

As previous observations had suggested, large amplitude variations in Eros' light-curve were confirmed (Fig. 4.4), revealing the elongated shape of the asteroid.

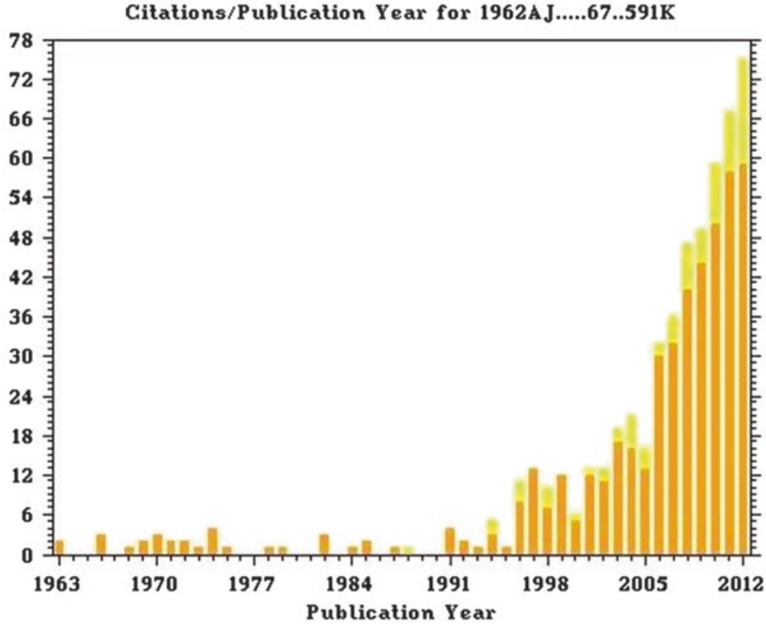

Fig. 4.3 Citation history of Kozai's paper (1962) on the Kozai mechanism (*Plot* Astronomical Data Center, NASA)

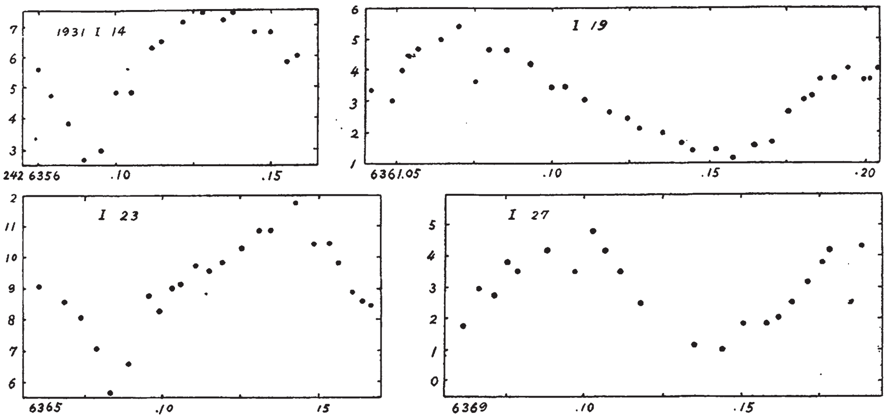

Fig. 4.4 Visual light-curves of Eros in January 1931 (after Kanda 1934)

At a later date (1968–1969), photoelectric measurements of the light variation of asteroid (15) Eunomia were used to determine its rotation period (0.2534 days, retrograde) and the pole orientation in the sky (Nakagiri and Kobayashi 1972).

4.3.2 Color Observations

It was not until in the 1930s that observations of the surface color of asteroids relative to the solar spectra were made by photographic means, but with little success, due to faintness of asteroids and subtlety of the color differences (Bobrovnikoff 1929, Recht 1935). Around 1953, a photoelectric photometer with the 1P21 photomultiplier was installed to the 65-cm Zeiss refractor at the TAO, and Masatoshi Kitamura (1926–2012) made some photometric observations of asteroids in a bid to detect a correlation between their colours and their assumed surface materials, and also to examine whether there was a correlation between asteriodal colors and their orbital elements (Kitamura 1959). He used two broad-band filters with effective wavelengths centered at 4760 and 5610 Å. In the early 1970s, when Gehrels summarised the UBV photoelectric photometry of asteroids, the number of objects listed by him was only 50 (Gehrels 1970, 1971, 1979), indicating that Kitamura's paper was one of the pioneering works in this field (Bowell and Lumme 1979).

Kitamura (1959) conducted photoelectric observations of 42 asteroids between 1953 and 1956, and he found that these asteroids did not show any color variation with rotational phase. Nor did he detect any meaningful correlation between asteroid colors and proper orbital elements.

Kitamura also measured in the laboratory the reflectance spectra of nine meteorites recovered in Japan and some rock minerals, using a standard light source operated at a color temperature near 6000 K (a solar analog). Upon comparing the laboratory results with asteroidal colors observed by him, he found that the colors of meteorites and asteroids on the whole were quite similar. It is unfortunate that Kitamura did not pursue his spectral studies of asteroids further, but he decided to change his field of research and focus on binary stars.

4.4 Impact Experiments

4.4.1 Japanese Early Experiments before WWII

In the 1920s, Professor Torahiko Terada (1878–1935) of University of Tokyo had attempted to systematize the physics of *fracturing* widely seen in natural phenomena. Soon after learning of Hirayama's discovery (1918), Terada realized that the asteroid family was a good example of his conceived new discipline. So he suggested that one of his disciples, Seitaro Suzuki (1886–1977), conduct impact experiments, in view of the fact that members of asteroid families were the products of collisional events.

Responding to his Professor's request, Suzuki began impact experiments in his laboratory and published the first result in 1921 (Yoshida 2001). The main purpose of Suzuki's experiments was to acquire clues on whether members belonging to an asteroid family were produced by a self-explosion of a large parent body or mutual

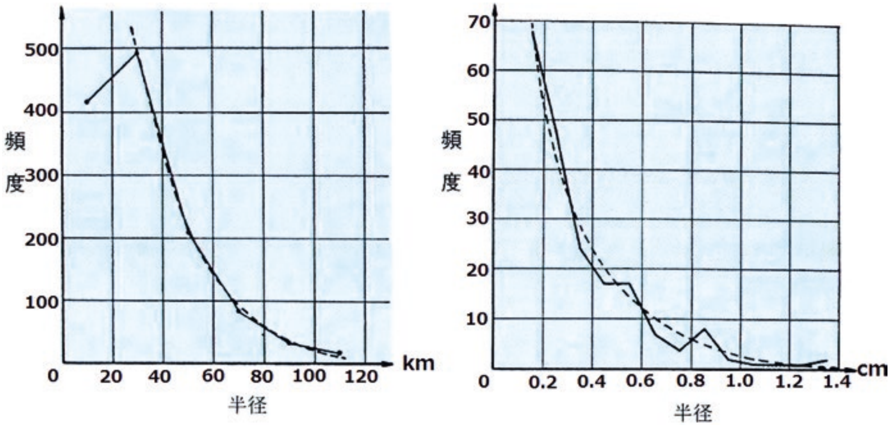

Fig. 4.5 Experiments by Suzuki and Nagashima (1938), cited in Yokoo (1997); the left hand figure is a plot of the radius (abscissa) versus number (ordinate) distribution of asteroid brightness based on data then available and assuming an average albedo for all asteroids; the right-hand figure shows the size distribution of broken fragments collected when clay balls fell freely onto a flat steel from the height of 6 m; notice the obvious similarity between the two curves

impacts between asteroids. This question about the origin of asteroid families was shared by Suzuki and Terada as well as by Hirayama, so they frequently communicated with each other.

Following the appearance of his first paper, Suzuki (1921) continued to publish further results in a series of papers that examined free-fall, head-on collisions of two small balls and gunpowder detonation. His last paper (Suzuki and Nagashima 1938) appeared in 1938—see Fig. 4.5. Not only did Suzuki collect impact fragments, but he also set up two cameras at different positions to measure the spatial velocities of each fragment. From all the obtained data, he examined the distributions of the size, shape, momentum, kinetic energy, and sometimes the spin state of collisional outcomes. However, in his quest to understand the origin of asteroid families, Suzuki never succeeded in differentiating the self-explosion hypothesis from the mutual impact one, and it is possible that Suzuki's experiments influenced Hirayama in preferring the self-explosion theory.[3]

We must admit that Suzuki's experiments were fairly primitive compared with modern laboratory experiments, in terms of collisional speeds and the time resolution of recorded photographs. Nevertheless, considering that modern high-speed impact experiments were first attempted in the US around 1970 to explain the origin

[3] Modern papers published after WWII, such as those in Sect. 4.8.2, adopt a representation of size distributions different from the one shown in Fig. 4.5. They are commonly expressed by the equation:

$$\log N = a + b \log D$$

where D is the diameter and N the cumulative number of asteroids larger than D, so that it looks like a straight line on a log-log graph.

of craters on airless celestial objects, probably in conjunction with the Apollo Lunar Mission, we may say that the collision experiments by Suzuki and his colleagues were really a pioneering and foreseeing project (Yokoo 1997).

4.4.2 Modern Impact Experiments

From 1975 Akira Fujiwara (b. 1943), as a graduate student in the Department of Physics at Kyoto University, initiated hypervelocity impact experiments under the supervision of Professor Hirokazu Hasegawa (1926–1991) who led a group to study the nature of the interplanetary dust. Fujiwara used a two-stage light-gas gun (Fig. 4.6), which had just been installed at the Department of Aviation Engineering for other purposes. This facility used not explosives but compressed light-gas to accelerate sample projectiles. The first results from his experiments were published in *Icarus,* a journal dedicated to the planetary science (Fujiwara et al. 1977).

Fujiwara and his colleagues impacted polycarbonate projectiles of mass ~ 0.4 g against targets made of basaltic rocks in sizes of about a few centimeters, with a velocity of 2.6 km/s, close to interplanetary speed. They could classify their observed impact phenomena into four typical modes: catastrophic (complete) destruction, core leaving, transition phase and cratering. They also gave an empirical formula for estimating the cumulative mass of shattered fragments and one for the maximum fragment, and attempted to apply their results to explain the origin of the two Martian satellites.

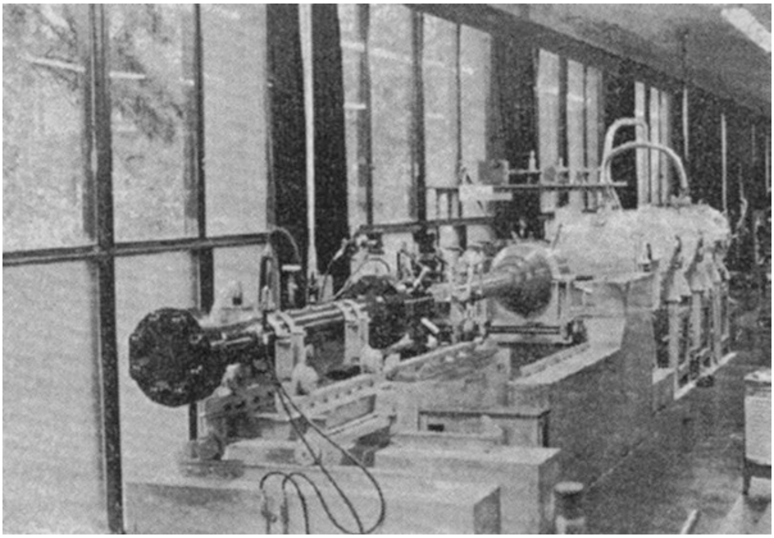

Fig. 4.6 A two-stage light-gas gun used in A. Fujiwara’s first hypervelocity impact experiments around 1975 at Kyoto University (after Fujiwara 2012)

Fujiwara's paper and his subsequent work (Fujiwara et al. 1989) subsequently received wide attention from scientists who studied asteroids, comets and satellites, and the origin of the Solar System. Stimulated by Fujiwara's activities, people in the USA, Italy and Japan started impact and explosion experiments in laboratories and outdoors, aiming to apply their results to planetary science. In Japan geophysicists from the University of Tokyo and Nagoya University carried out hyper-speed impact facilities and repeated experiments by changing collisional conditions and using different materials, e.g., rocks, metals and ice (for details see the review by Fujiwara et al. 1989). In such developing processes, they also explored scaling laws in order to link collisional outcomes to the physical nature of Solar System bodies; these scaling laws were indispensable in interpreting experimental results correctly, because sizes of projectiles in impact experiments and those of real asteroids are different by 10^5–10^6 times. Following a proposal by an Italian astronomer, Paolo Farinella (1953–2000) and others, the first Catastrophic Disruption Workshop was held at Pisa in 1985 (Davis et al. 1986), and thereafter similar conferences have continued irregularly up to the present. Now laboratory impact experiments have grown into an important field of planetary science. The main achievements thus far in this field, and relevant disciplines like numerical simulations of impact phenomena, are reviewed by Holsapple et al. (2002).

4.5 Efforts Towards the Exploration of Asteroids by Spacecraft

4.5.1 The Establishment of ISAS

The history of the Japanese spacecraft development goes back to experiments with miniature rockets led by Professor Hideo Itokawa (1912–1999). In 1955 at a laboratory of University of Tokyo, he launched for the first time so-called 'pencil rockets', less than 30 cm long. This determined a basis of the subsequent Japanese policy of developing rockets used for scientific observations. Since then it has been a tradition in Japan that solid fuel rockets are exclusively adopted for launching artificial satellites and interplanetary spacecraft for astronomical purposes.

In order to support the development of advanced rockets and encourage collaboration between engineers and scientists who were engaged in space- and geo-science, a special institute was established in 1964 at the University of Tokyo. This institute was reorganized in 1981 into a new and expanded organization, the Institute of Space and Astronautical Science (ISAS, now part of the Japan Aerospace Exploration Agency, JAXA), which was supposed to be responsible for leading space science and developing advanced technology for space exploration. From 1971 on, this institute has so far put 38 satellites and spacecraft into orbit (as of December 2016): ten for ionosphere and magnetosphere observations, three for solar observations, six for X-ray and γ-ray astronomy, two for radio and infrared astronomy, ten for Solar System science and seven for other purposes (NAOJ 2012: 167). Among these, the Hayabusa asteroid mission will be mentioned in Sect. 4.5.4 below.

4.5.2 Research on Solar System Science

From the start, ISAS worked as a hub-institute for inspiring both domestic and international cooperation from various disciplines, including planetary sciences. For Solar System research, the first Lunar and Planetary Symposium was organized in the summer of 1968, with the proceedings publishing in English, and continued every year thereafter.[4] This ISAS Symposium very much encouraged participants to make close collaborations in conducting group studies and experimental works. Also from 1979, another symposium called the Solar System Science Symposium was held annually (the proceedings published in Japanese), with emphasis on synergistic effects between planetary scientists and space engineers.

A highlight in this period was the international symposium, 75 years of Hirayama Asteroid Families, held in 1993 at ISAS in conjunction with the NAOJ, to commemorate the 75th anniversary of the discovery of asteroid families (Kozai et al. 1994). A considerable fraction of leading asteroid researchers from around the world gathered at the ISAS campus near Tokyo, and presented numerous papers on theoretical studies, observational programs and impact experiments on asteroids, and discussed the future possibility of space exploration of near-Earth asteroids. It is likely that those activities eventually led the Japanese Solar System community to propose an asteroid mission to the ISAS headquarters.

4.5.3 Radar Observations of Near-Earth Asteroids

Since the first radar detection of asteroid Icarus in 1968,[5] radar observations of asteroids have been conducted almost exclusively by the USA, using the Goldstone and Arecibo (Puerto Rico) parabola antennas. By the end of 2011 they had observed as many as 130 main-belt asteroids and about 340 near-Earth asteroids.

During 1995–1996 an international experiment was proposed to observe by radar two near-Earth asteroids, 1991 JX and Toutatis (4179) while they were on close approaches to the Earth. The 64-m ISAS antenna at Usuda and the 34-m antenna of the Communications Research Laboratory at Kashima, Japan, received the radio signals reflected from the surface of the two objects, transmitted from the Goldstone antenna at the wavelength of 3.5 cm (Koyama et al. 2001). Because this experiment was the first intercontinental astronomical radar observation, asteroid 1991 JX later

[4] It is worth noting that NASA's Lunar and Planetary Conference only started in 1970.

[5] See http://echo.jpl.nasa.gov/asteroids/PDS.asteroid.radar.history.html.

was given the permanent name Golevka (Minor Planet Center, IAU) to honor the success, this being an abbreviated combination of the names of places where the radar observatories were located, *Gol*dstone (US), *Ev*patoria (Crimia, Russia), and *Ka*shima (Japan). Although this experiment failed to generate a more advanced level of international collaboration, Japanese scientists were able to master basic techniques of planetary radar astronomy through this experience.

4.5.4 The Hayabusa Mission and Asteroid Itokawa

In May of 2003, Hayabusa (meaning falcon), the asteroid exploration spacecraft, was launched from the Uchinoura station of ISAS and successfully put into orbit to rendezvous with the near-Earth asteroid Itokawa. This was the first Japanese asteroid mission ever. The Hayabusa project had a nearly two-decades-long history before its realization: in 1985 a few ISAS engineers formed a working group to investigate an asteroid sample return mission—a very ambitious plan at that time.

For a decade the working group struggled to locate appropriate target asteriods and the practical technology needed to return the collected surface material from the asteroid to the Earth, mainly because of the limitations of the ISAS rockets then in use. However, during the first half of the 1990s a more powerful rocket, code-named the MV, became available for the Solar System exploration. Thus the asteroid sample return mission received serious consideration, and was officially approved in 1994. However, this was primarily regarded as an engineering-proof mission, rather than a scientific one. The primary aims of this mission, called MUSES-C, were fourfold:

(a) long-term test of the ion-engine propulsion system;
(b) orbital control by the Earth gravity swing-by;
(c) autonomous sample catching under micro-gravity conditions on the surface of a small asteroid; and
(d) re-entry of the sample capsule into the atmosphere of the Earth.

Each of these was a new challenge, never experienced before in the space exploration history of Japan.

In spite of the engineering nature of MUSES-C, instruments also were installed to maximize the scientific outcomes of this mission. They were a multi-band imaging camera (Fig. 4.7), a near-infrared spectrometer, a fluorescent X-ray spectrometer and a laser altimeter, some of which were indispensable for attaining engineering goals as well. A sampling mechanism was of course incorporated at the bottom of the spacecraft, which a group led by Fujiwara developed (see Sect. 4.4.2). Due to insufficient information on the orbit of a planned asteroid and the launch failure of the previous mission, the target asteroid of MUSES-C was changed twice, and the finally-selected object was asteroid 1998SF36 (25143), later named Itokawa in memory of the Japanese rocketry pioneer (Sect. 4.5.1) by the IAU after the launch of Hayabusa. Following ISAS tradition, MUSES-C was renamed Hayabusa.

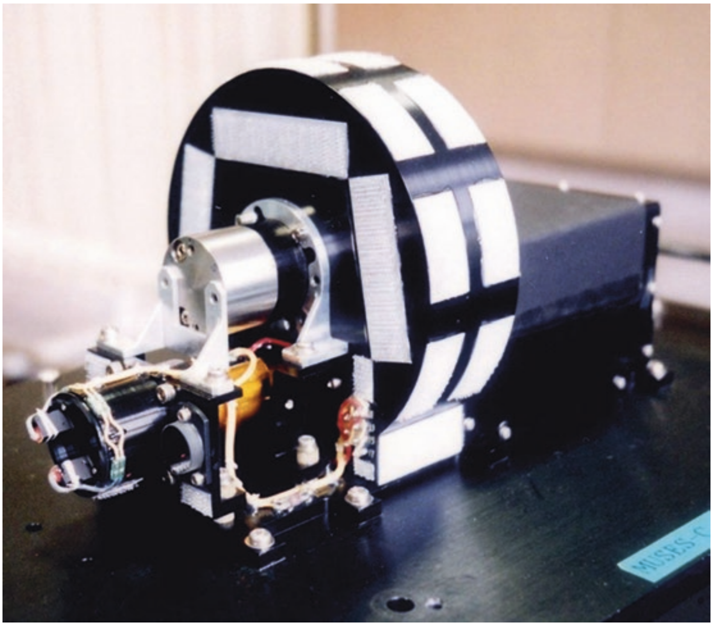

Fig. 4.7 The Asteroid Multi-band Imaging CAmera (AMICA) aboard the Hayabusa spacecraft. This camera system was designed by the author of this paper and developed by his group of astronomers (see Nakamura et al. 2001). Shown here is a photograph taken in 2001 of an AMICA engineering model, with many adhesive strain-guage plasters for stress testing. The cylinder in the middle is a filter wheel containing eight band-filters. Two small protrusions before the objective lens in the front are lamps for the flat-field calibration (*Courtesy* ISAS)

After Hayabusa's arrival at the orbit of Itokawa in September 2005, it took more than 1500 close-up images of the asteroid through several band-filters (e.g. see Fig. 4.8). Other scientific instruments also were successful in obtaining observational data. Those achievements and scientific results were reported in a special issue of the journal *Science* (e. g., Fujiwara et al. 2006; Saito et al. 2006). Hayabusa twice attempted touch-down operations for sample collecting by shooting projectiles onto Itokawa's surface, but it was not certain that the ejected surface materials were definitely stored in the sample container. On the return mission, Hayabusa encountered various fatal troubles. They were leakage of chemical propellant, resulting in the loss of attitude control; the subsequent loss of radio linkage between Hayabusa and the Earth for more than a month; heavy battery shortage; failure of two of the four ion-engines; and so on. Those at ISAS mission control made every effort to overcome these difficulties one by one, and Hayabusa finally succeeded in landing its sample capsule in the Australian desert on 13 June 2010.

The inside of the recovered capsule was scrutinized in the laboratory by means of an electron microscope, and numerous micron-sized particles found in it were identified to be ones that surely originated from Itokawa, using microanalyzers. Detailed analyses of those particles are still under way on an international collab-

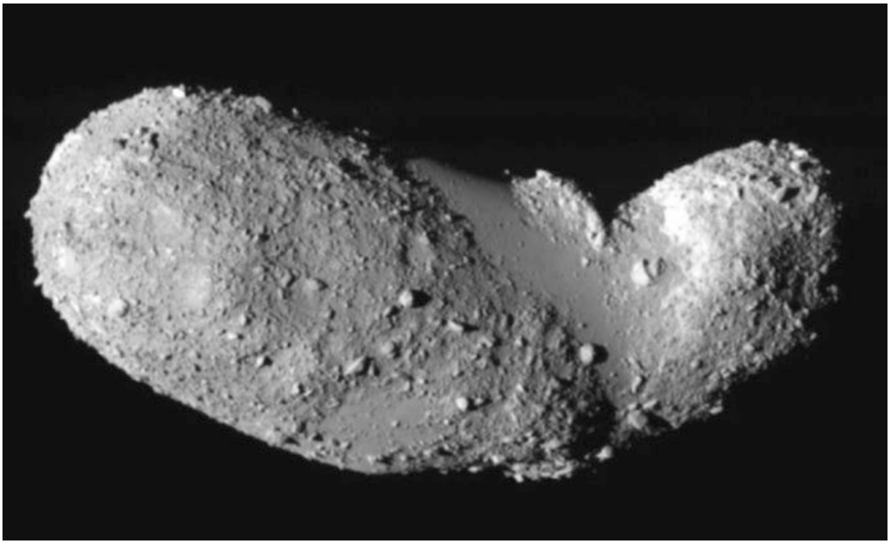

Fig. 4.8 Close-up image of asteroid Itokawa taken with the AMICA camera aboard Hayabusa spacecraft in 2005; note its unusual shape and the surface roughness (*Courtesy:* ISAS)

orative basis (e.g., Nakamura et al. 2011, and see the six papers in *Science*, Volume 333, 26 August 2011). In addition to the fact that Hayabusa's samples were the first extraterrestrial substances caught by spacecraft—except for the lunar rocks recovered during the Apollo Mission—we may safely say that scientific achievements of the Hayabusa Mission were unique, even in light of the outcomes of several asteroids missions conducted by NASA.

4.6 Antarctic Meteorites

4.6.1 The Discovery of Antarctic Meteorites

In 1959 a brilliant fireball was observed to fall at the town of Pribram near Prague, and its orbit outside the atmosphere was determined, along with many recovered meteorites. The orbit was found to be from the main asteroid belt. Since then, there have been reports of five similar meteorites, whose orbital aphelia reached the main asteroid belt or near-Earth orbits (e.g., Spurny et al. 2003). Therefore it became certain that meteorites are fragments of impacted asteroids and play a vital role in our studies of the physical nature of asteroids.

In 1957 an international scientific project called the International Geophysical Year (IGY) started, with research fields encompassing aurora and airglow, ionospheric physics, gravity, meteorology, oceanography, seismology, solar activity and cosmic rays. Studies of Antarctica were also an important target of the IGY and

Fig. 4.9 The first Antarctic meteorite discovered by Japan in 1969; this is an E3 chondrite, with many small chondrules (white spherules) in it (after Yanai et al. 1987)

several advanced countries established new research bases on the Antarctic continent.

During the half-century from Amundsen (Norway) and Scott (Britain) to the IGY only a handfull of meteorites had been collected in Antarctica, but in 1969 the Japanese Antarctic Expedition team discovered eight meteorites at the foot of the Yamato Mountains (Fig. 4.9), near where the Japanese Antarctica Research Base was located. On Earth, often it is not easy to distinguish chondrites from ordinary terrestrial rocks because of their similar appearance and surface erosion, but on the Antarctic continent most rock-like objects on the surface of the snow plains are actual meteorites and they stand out clearly (e.g., see Fig. 4.10). It was inferred that at the foot of rocky mountains like the Yamato, flowing ice grounds welled up to the surface, carrying imbedded meteorites with them.

4.6.2 The Development of Antarctic Meteoritics

The discovery of 1969 triggered systematic meteorite survey expeditions, which were first conducted by Japan from 1974, and later mainly by the Japanese, US or Japan-US international teams. In particular, the 1974–1980 expeditions around the Yamato Mountains by Japan found as many as 3600 meteorites (Yanai and Kojima 1986). As a result, the total number of meteorites discovered in the Antarctica by all nations as at the end of 1985 totaled ~7500. This amazing progress in terms of the sample number is highlighted by the fact that the total number of meteorites recorded and/or collected all over the world from ancient times through the 1960s was ~2400.

The huge collection of Antarctic meteorites and their international collaborative studies spawned the new research field of Antarctic Meteoritics (Yanai et al. 1987). Antarctic meteorites are characterized by the fact that they have suffered far less chemical erosion and environmental contamination than other terrestrial meteorites.

Fig. 4.10 A Japanese snowmobile searching for meteorites on the Yamato plain in 1974; in the foreground of the snowmobile a new meteorite is seen (after Yanai et al. 1987)

More than 80% of 7500 Antarctic meteorites were found to be ordinary chondrites (Yanai et al. 1987), which was consistent with the trend in the taxonomic-type distribution of meteorites for non-Antarctic sites. There were also several Antarctic meteorites that were inferred to have come from the Moon and Mars, due to their unusual chemical compositions. Analyses and classification of the whole Antarctic meteorite assemblage is still in progress.

4.7 The Discovery Race by Asteroid Hunters

4.7.1 The Early History of Asteroid Discoveries by TAO Astronomers

In 1896 Tokyo Astronomical Observatory at Azabu in downtown Tokyo purchased a 20-cm (8-in.) astrographic telescope from the Brashear Company of USA (Fig. 4.11). This instrument, generally called the 'Brashear Telescope', later was installed on an equatorial mounting fabricated by Warner-Swasey.[6]

On photographic plates taken with this astrograph in 1900, Shin Hirayama (1868–1945)—a different and unrelated Hirayama to the discoverer of asteroid families—

[6] The TAO Brashear telescope is sometimes called a sister telescope of the 'Bruce Telescope' of the Yerkes Observatory, since both used a twin equatorial mounting produced by Warner and Swasey (King 1979: 317).

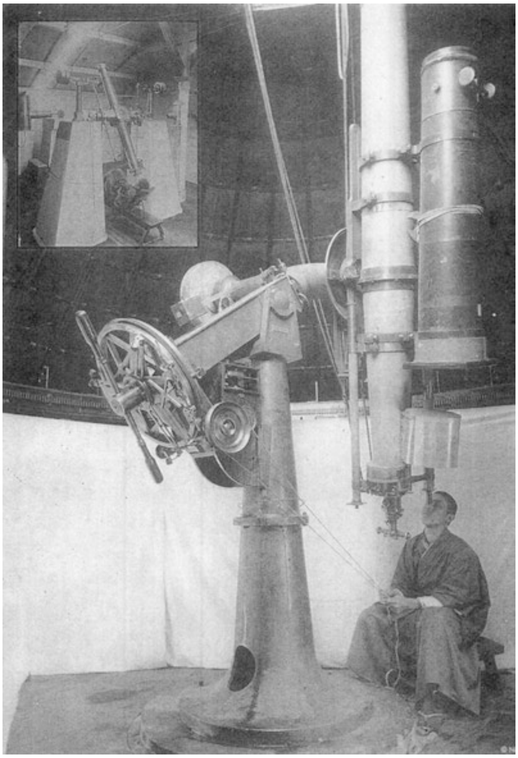

Fig. 4.11 The Brashear astrograph (the tube on the right) at the Azabu campus of TAO, co-mounted on the 20-cm Troughton & Simms equatorial telescope (*Courtesy* National Astronomical Observatory of Japan)

found two new asteroids, which were later named Tokio (498) and Nipponia (727). These were the first asteroids discovery by a Japanese astronomer.

After the transfer of TAO to Mitaka in the suburbs of Tokyo in 1924, Okuro Oikawa (1896–1970) used the Brashear telescope for much of the next 4 years for an asteroid survey. This resulted in the discovery of eight new asteroids, which received permanent designations. Along with such activities, the number of TAO astronomers increased who were expert in making orbital determinations of asteroids and comets. Soon after the end of WWII, Professor Hideo Hirose (1909–1981), who later became the Director of TAO, wrote a compendium textbook on orbital determinations for his TAO subordinates. This book played a primary role for popularizing orbit determination of asteroids and comets among Japanese amateur observers after the 1970s.

4.7.2 Systematic Asteroid Surveys

In 1950–1952 the historic Yerkes-MacDonald asteroid surveys was conducted under the leadership of Gerard Kuiper (1905–1973) (see Kuiper et al. 1958). This survey detected more than 1500 asteroids down to a photographic magnitude of about 16, and their size distributions were obtained. The Japanese astronomer Yoshio Fujita (1908–2013) participated in this project, although he was not an asteroid specialist but was an astrophysicist who researched the spectroscopic properties of low temperature stars.

The next systematic survey of faint asteroids were made in 1960 using the 1.22-m (48-in.) Schmidt telescope at the Mount Palomar (van Houten et al. 1970). The size distributions of asteroids derived from the Palomar-Leiden survey would be regarded as the standard for the next three decades (see Sect. 4.8.2 below).

In 1974 TAO founded a new branch observatory near Kiso Mountain in the central part of Honshu, the main island Japan, where a 1.05-m (41.4-in.) Schmidt telescope produced by the Nikon company was installed. This telescope was mainly intended for observational studies of distant galaxies, so it covered a sky area of 6° × 6° with a 36 cm-square photographic plate. By utilizing the wide-field merit of the Kiso Schmidt telescope, TAO astronomers H. Kosai and K. Hurukawa began an asteroid survey program in about 1976 (see Fig. 4.12). According to the Minor Planet Center of the IAU, about 90 asteroids detected by these two astronomers have thus far been assigned permanent numbers.

4.7.3 Amateur Hunters

The first non-professional discovery of an asteroid by a Japanese astronomer was made by Takeshi Urata (1947–2012) at his private observatory on 12 March 1978, and it was given a provisional designation of 1978EA in the *Minor Planet Circular* 4482. Later it was registered as a numbered asteroid 2090 with the proper name Mizuho, after his daughter.

Urata's discovery ignited subsequent discovery enthusiasm among Japanese amateur astronomers, which culminated in Takao Kobayashi's achievements. Kobayashi (b. 1961) is an engineer of Gunma prefecture working for a major electronic company, and during 1991–2002 he discovered 2373 new asteroids using a home-made telescope equipped with a CCD camera that automatically scanned the sky, detected moving objects and calculated their preliminary orbits from observed data for a night or two. Several other groups have also made contributions, thereby increasing the number of asteroid discoveries by hundreds. As a result, the numbered asteroids detected by Japanese astronomers by 2008 amounted to more than several thousands. In attaining such achievements, we must be aware of the role of the orbit calculator Shuichi Nakano, who was trained under the supervision of Brian G. Marsden (1937–2010), the then Director of the

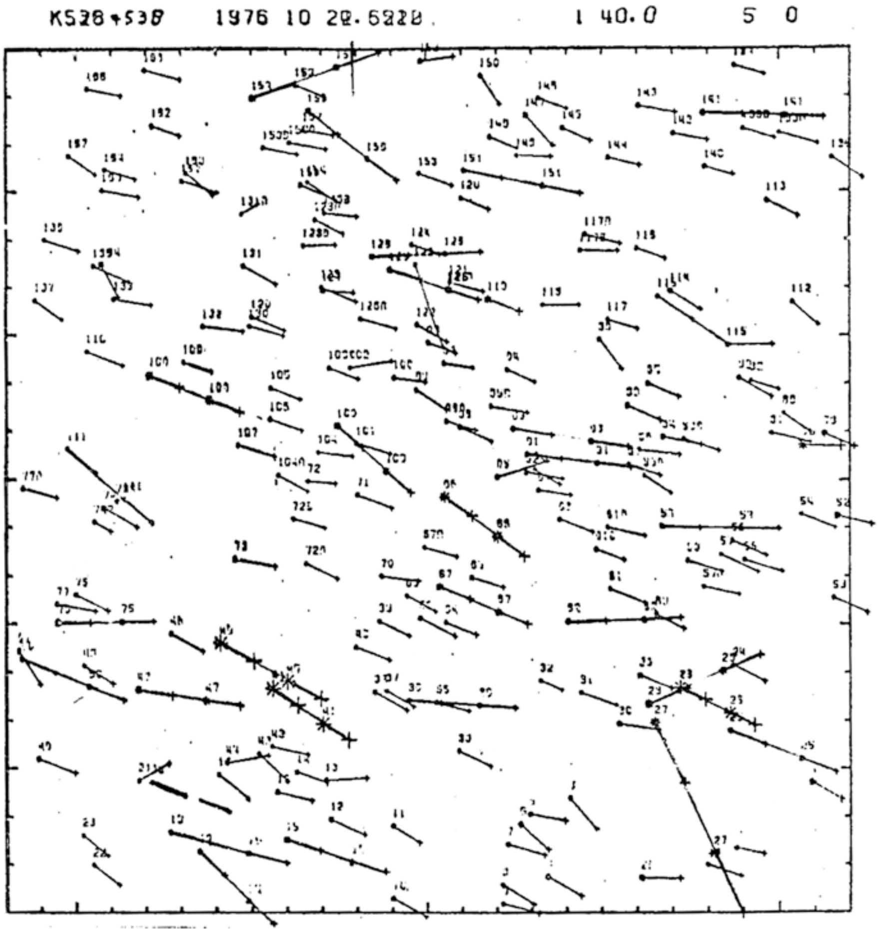

Fig. 4.12 Detected asteroids on a plate (6° × 6°) taken by the Kiso Schmidt Telescope on 29 and 31 October 1976; for each asteroid, its 2-day motion is drawn as a bar; some objects with unusual motions are likely to be near-Earth asteroids (after Kosai 1979)

Minor Planet Center (MPC) at the Smithsonian Astrophysical Observatory. After returning to Japan, Nakano set up a branch of the MPC and encouraged and organized the activities of Japanese asteroid hunters, leading to the Japanese 'Golden Age' in the asteroid discovery race.

However, several years ago the situation changed drastically, due to the advent of professional observatories dedicated to all-sky surveys such as LINEAR, Spacewatch and NEAT. Each of these has led to the discovery of thousands of new asteroids every year, and the MPC has assigned priority to discoveries by these observatories. Accordingly, the discovery rate of asteroids by amateur hunters has decreased abruptly, and many amateur astronomers have lost their enthusiasm for asteroid hunting. Some have turned their attention to other areas of astronomy, such as hunting for new nova and supernova.

4.8 Other Recent Studies

4.8.1 Space Weathering of Asteroid Surfaces

It had been understood implicitly that color and spectroscopic observations of asteroids could reveal the mineralogical and geological nature of the surface of those objects, by comparing spectroscopic measurements of meteorites in the laboratory. In particular, it is known that absorption bands in the near-infrared spectra of asteroids give the most useful diagnostics of their surface materials.

However, along with the accumulation of the spectral database of asteroids, an annoying enigma has appeared: Why are there so few asteroids in the main belt with spectral features that correspond to the laboratory-measured ones of ordinary chondrites (which is the most dominant type of meteorites recovered on Earth)? Then, as a probable solution to this question, an hypothesis of 'space weathering' was proposed. This effect explains how long-term insolation of an asteroid's surface from the solar wind and micrometeoroid bombardment substantially weakens or masks the spectral characteristics diagnostic of ordinary chondrites, microscopically caused by accumulation of nanometer-scale particles of metallic-iron on the surface of regolith grains on asteroids.

Recently, plausibility of the space weathering hypothesis was experimentally proved by the Japanese geophysicist Sho Sasaki and his group (Sasaki et al. 2001). They succeeded in producing many nanometer-sized iron particles on the surface of lunar-like rocks using strong laser emission that simulated the solar wind. Resulting samples actually reproduced commonly-observed spectral features of S-type asteroids. The experimental outcomes were later supported by physical modeling as well.

4.8.2 Detection of Very Small Asteroids, and their Significance

As the view that asteroids are shattered fragments produced by repeated hypervelocity impacts between larger asteroids has become common among planetary scientists, the importance of the size distribution of asteroids, smaller ones in particular, has been recognized. The reason is that theoretical considerations predicted that asteroids smaller than ~1 km in diameter are more or less solid (the size region ruled by the material strength), whereas larger ones are so-called 'rubble piles' (the gravity-dominant size regime), aggregates of fragments gravitationally bound to each other (Chapman 1978). It was thought that such differences in the supposed internal structure of asteroids should also be reflected in their size versus number distribution. In particular, it was of interest to know where the borderline of sizes lies separating the gravity regime from the strength one, and how different each of these size distributions is. But the most elaborate size distribution available at that time was the one obtained by the 48-in. Palomar Schmidt telescope, which only covered diameters larger than ~5 km (van Houten et al. 1970). For the study of the behaviour of main-belt asteroids smaller than 1 km (sub-km-sized asteroids), much larger telescopes were obviously needed.

The latter half of the 1990s witnessed for the first time the advent of 8-m class telescopes. However most of these gigantic telescopes were designed mainly for spectroscopy of distant galaxies and quasars, and their cameras thus had very narrow field-of-views. The Japanese 8.2-m Subaru Telescope located on Mauna Kea (Hawaii) was only exception. It was equipped with a wide-field mosaic CCD camera covering a field of view of as large as 30 arcmin × 30 arcmin. Towards the end of the 1990s Nakamura and his co-workers started an observational survey with the Subaru telescope to look into the nature of sub-km asteroids in the main belt—a research field that until then was *Terra Incognita* (Nakamura 1997).

During observations made in 2001–2002 with exposure times of just a few minutes the mosaic CCD camera at the prime focus of the Subaru telescope recorded >100 small asteroids on a single exposure (Yoshida et al. 2003). Figure 4.13 is an example of such CCD images (Dermawan et al. 2011). Since it was impossible to calculate an elliptic orbit of each asteroid from a single night's observation,

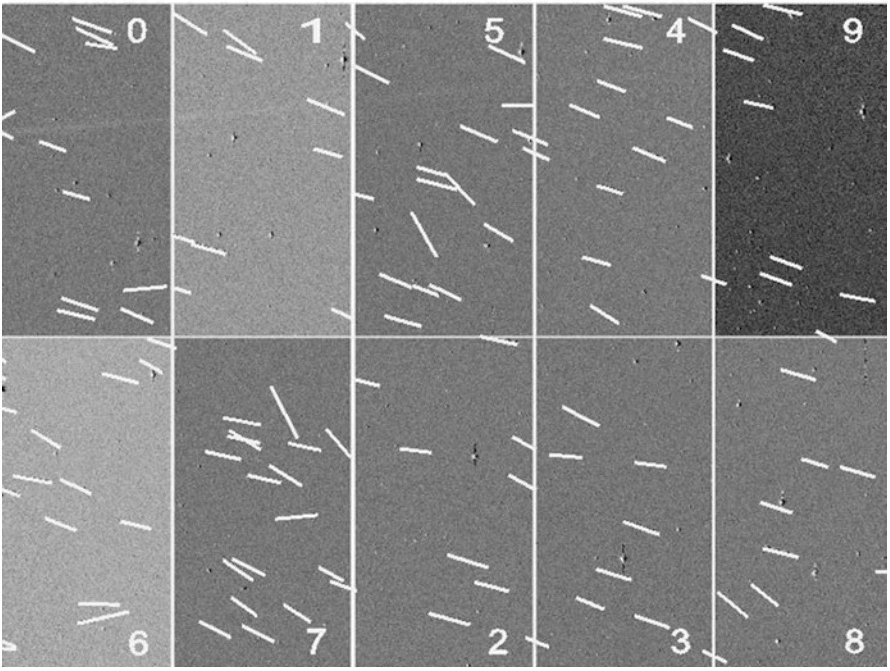

Fig. 4.13 Faint asteroids detected on 21 October 2001 in the ~30′ × 30′ field of view of the wide-field mosaic CCD camera attached to the prime focus of the 8.2-m Subaru Telescope; a single exposure time was 2 min; each white bar represents the motion of a detected asteroid made by combining eight consecutive images during about 2 h (after Dermawan et al. 2011); compare the field of view of this camera with that of the Kiso Schmidt Telescope shown in Fig. 4.12

Nakamura and Yoshida (2002) also devised a method to determine statistically a reliable size distribution of the observed asteroids from their motion vectors during several hours on a single night.

As a result of this Subaru survey, Nakamura and his collaborators found out that the number of sub-km asteroids is twice to three times more depleted than the estimate extrapolated from the size distribution obtained by the Palomar-Leiden survey. They attribute likely causes of the depletion to the following two possibilities:

1. Smaller asteroids are incorporated into chinks between fragmentary components of large rubble-pile asteroids, resulting in a seeming depletion;
2. Smaller asteroids were selectively removed from their orbits in the main asteroid belt by the Yarkovsky effect (Bottke et al. 2002b). This is a repulsive force caused by anisotropic thermal photons re-emitted from the irregular surface of an asteroid illuminated by the Sun, and its reality has already been demonstrated in accurate orbit determination of some small asteroids (Bottke et al. 2002b).

Other important insights into small asteroids revealed for the first time by this Subaru survey are as follows:

(a) The relative abundance of S-like sub-km asteroids (rocky) and C-like ones (carbonaceous) was examined. It has been shown that the heliocentric distribution of S-like objects was almost flat throughout the entire main belt, while the number of C-like asteroids increases with the heliocentric distance (Yoshida and Nakamura 2007).
(b) The size distributions of L4 and L5 Trojan asteroids of Jupiter were investigated down to the sizes <1 km in diameter (*D*), in which a similar depletion of the number for smaller members was seen as in the case of small main-belt asteroids. The number asymmetry between L4 and L5 Trojans clearly increases towards smaller ones (Yoshida and Nakamura 2005).
(c) About 70 reliable light-curves of main-belt asteroids with $0.2\ \text{km} < D < 2\ \text{km}$ were obtained from observations on a single night. From their periodogram analysis, spin periods and shapes of those objects were estimated. Nearly half of them were found to be so-called 'fast rotators' having a spin period of <2.2 h (the limiting period for rubble-pile objects to be spin-stable), and the majority of them had spherical shapes (Dermawan et al. 2011).

The last-mentioned finding was an unexpected one, because ground-based and spacecraft observations of near-Earth asteroids had suggested a contrary trend (e.g., Fujiwara et al. 2006).

4.9 Summary and Conclusion

Here we summarize asteroid studies performed by the Japanese between the 1920s to the 2000s, after the discovery of asteroid families by Hirayama (1918). Reviewed fields covered celestial mechanics, spectral comparison of observed asteroids with laboratory measurements of meteorites, the discovery of and systematic research on an enormous number of Antarctic meteorites, asteroid exploration using spacecraft as a powerful means of planetary science, hypervelocity laboratory impact experiments started in the 1970s, and the statistics of very small main-belt asteroids with 8-m class telescopes. We emphasize that collision experiments in the laboratory had already been done in Japan as early as half a century prior to modern impact experiments, to interpret the origin of the asteroid family.

From those historical achievements, it is concluded that one of the main motives for current activities in asteroid studies by Japanese astronomers could be attributed more or less to the discovery of asteroid families by Kiyotsugu Hirayama. Hopefully, this influence and tradition will continue to work as an incentive to advance the study of asteroids further at least in the near future.

References

Arnold, J.R. (1969). Asteroid families and “jet streams”. *Astronomical Journal,* 74, 1235–1242.

Bendjoya, P., & Zappalà, V. (2002). Asteroid family identification. In W.F. Bottke et al., 2002a, pp. 613–618.

Bobrovnikoff, N.T. (1929). The spectra of minor planets. *Lick Observatory Bulletin,* 407, 18–27.

Bobrovnikoff, N.T. (1931). The origin of asteroids. *Publications of the Astronomical Society of the Pacific,* 43, 324–333.

Bottke, W.F. Jr., Cellino, A., Paolicchi, P., & Binzel, R.L. (Eds.), (2002a). *Asteroids III*. Tucson: University of Arizona Press.

Bottke, W.F. Jr., Vokrouhlický, D., Rubincam, D.P., & Broz, M. (2002b). The effect of Yarkovsky thermal forces on the dynamical evolution of asteroids and meteoroids. In W.F. Bottke et al, 2002a, pp. 395–408.

Bowell, E., & Lumme, K. (1979). Colorimetry and magnitudes of asteroids. In T. Gehrels, pp. 132–169.

Brouwer, D. (1950). Families of minor planets and related distributional problems. *Astronomical Journal,* 55, 162–163.

Brouwer, D. (1951). Secular variations of the orbital elements of minor planets. *Astronomical Journal,* 56, 9–32.

Chapman, C.R. (1978). Asteroid collisions, craters, regolith, and lifetimes. In D. Morrison, & W.C. Wells (Eds.), *Asteroids: An Exploration Assessment* (pp. 145–160). Washington: NASA (Conference Publication 2053).

Cunningham, C.J. (1988). *Introduction to Asteroids*. Richmond: Willmann-Bell.

Cunningham, C.J. (2001). *The First Asteroid: Ceres 1801–2001*. Surfside: Star Lab Press.

Davis, D.R., Farinella, P., Paolicchi, P., & Zappalà, V. (1986). *Catastrophic Disruption of Asteroids and Satellites. Proceedings of the International Workshop, Pisa, Italy, July 30-August 2, 1985*. Società Astronomia Italiana (Memorie, 57, No. 1).

Dermawan, B., Nakamura, T., & Yoshida, F. (2011). Subaru lightcurve observations of sub-km-sized Main-Belt asteroids. *Publications of the Astronomical Society of Japan,* 63, S555–S576.

Fosmire, M. (2014). Brouwer, Dirk. In T. Hockey et al., pp. 320–321.

Fujiwara, A. (2012). From retrospect of impact experiments to spacecraft Hayabusa and toward future. *Nihon Wakusei Kagaku Kaishi* (*Journal of the Japan Planetary Society*), 21, 168–174. (in Japanese).

Fujiwara, A., Kamimoto, G., & Tsukamoto, A. (1977). Destruction of basaltic bodies by high-velocity impact. *Icarus,* 31, 277–288.

Fujiwara, A., Cerroni, P., Davis, D., Ryan, E., & di Martino, M. (1989). Experiments and scaling laws for catastrophic collisions. In R.P. Binzel et al. (Eds.). *Asteroids II,* pp. 240–265. Tucson: University of Arizona Press.

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

Gehrels, T. (1970). Photometry of asteroids. In A. Dollfus (Ed.), *Surfaces and Interiors of Planets and Satellites,* pp 317–375. New York: Academic.

Gehrels, T. (Ed.), (1971). *Physical Studies of Minor Planets*. Washington: NASA (SP-267).

Gehrels, T. (Ed.), (1979). *Asteroids*. Tucson: University of Arizona Press.

Hirayama, K. (1918). Groups of asteroids probably of common origin. *Astronomical Journal,* 31, 185–188.

Hinks, A.R. (1909). Solar Parallax Papers No. 7: The general solution from the photographic right ascensions of Eros, at the opposition of 1900. *Monthly Notices of the Royal Astronomical Society,* 69, 544–567.

Hockey, T. et al. (Eds.), (2014). *Biographical Encyclopedia of Astronomers. 2nd Edition*. New York: Springer.

Holman, M.J., & Wisdom, J. (1993). Dynamical stability in the outer Solar System and the delivery of short period comets. *Astronomical Journal,* 105, 1987–1999.

Holsapple, K, Giblin, I., Housen, K., Nakamura, A., & Ryan, E. (2002). Asteroid impacts: laboratory experiments and scaling laws. In W.F. Bottke et al, 2002a, pp. 443–462.

Huruhata, M. (1935). Photometric observations of Eros. *Astronomische Nachrichten,* 257, 9.

Innanen, K.A., Zeng, J.Q., Mikkola, S., & Valtonen, M.J. (1997). The Kozai mechanism and the stability of planetary orbits in binary star systems. *Astronomical Journal,* 113, 1915–1919.

Jones, H.S. (1940). On the suitability of Eros for the accurate determination of the solar parallax. *Monthly Notices of the Royal Astronomical Society*, 100, 422–434.

Kanda, S. (1934). Brightness observations of asteroid Eros in 1930–31. *Tokyo Astronomical Observatory Report,* 2(6), 107–127. (in Japanese).

King, H.C. (1979). *The History of the Telescope*. New York: Dover.

Kitamura, M. (1959). A photometric study of colors of asteroids and meteorites. *Publications of the Astronomical Society of Japan,* 11, 79–89.

Knezevic, Z., Lemaître, A., & Milani, A. (2002). The determination of asteroid proper elements. In W.F. Bottke et al, 2002a, pp. 603–612.

Kosai, H. (1979). Status report of asteroid survey project by the Kiso Schmidt telescope. *Proceedings of the First Solar System Symposium,* pp. 22–27. Tokyo: The Institute of Space and Aeronautical Science (in Japanese).

Koyama, Y., Nakajima, J., Sekido, M., Yoshikawa, M., Nakamura, A.M., and 5 coauthors (2001). Radar observations of Near Earth Asteroids 6489 Golevka and 4197 (1982 TA). *Review of the Communications Research Laboratory,* 47, 145–155.

Kozai, Y. (1953). Preliminary studies on the motion of asteroid Thule (279) (II). *Publications of the Astronomical Society of Japan,* 4, 172–179.

Kozai, Y. (1962). Secular perturbations of asteroids with high inclination and eccentricity. *Astronomical Journal,* 67, 591–598.

Kozai, Y. (1979). The dynamical evolution of the Hirayama family. In T. Gehrels, pp. 334–358.

Kozai, Y., Binzel, R.P., & Hirayama, T. (Eds.), (1994). *Seventy-five Years of Hirayama Asteroid Families: The Role of Collisions in the Solar System History*. San Francisco: Astronomical Society of the Pacific.

Kuiper, G.P., Fujita, Y., Gehrels, T., Groeneveld, I., Kent, J., van Biesbroeck, G., & van Houten, C.J. (1958). Survey of asteroids. *Astrophysical Journal Supplement,* 3, 289–427.

Lidov, M.L. (1961). The evolution of orbits of artificial satellites of planets under the action of gravitational perturbations of external bodies. *Planetary and Space Science,* 9, 719–759. (in Russian).

Lindblad, B.A., & Southworth, R.B. (1971). A study of asteroid families and streams by computer techniques. In T. Gehrels, pp. 337–352.

Murray, C., & Dermott, S. (1997). *Solar System Dynamics*. Cambridge: Cambridge University Press.
Nakagiri, M., & Kobayashi, N. (1972). Rotation of the minor planet (15) Eunomia. *Tokyo Astronomical Observatory Report*, 15, 710–732. (in Japanese).
Nakai, H., & Kinoshita, H. (1985). Secular perturbations of asteroids in secular resonance. *Celestial Mechanics*, 36, 391–407.
Nakamura, T., Noguchi, T., Tanaka, M., Zolensky, M.E., Kimura, M., and 17 coauthors (2011). Itokawa dust particles: a direct link between S-type asteroids and ordinary chondrites. *Science, 333,* 1113–1116.
Nakamura, T. (1997). An observation plan of sub-km-sized asteroids with the Subaru telescope. In H. Kinoshita, & H. Nakai (Eds.), *Proceedings of the 29th Symposium on Celestial Mechanics,* pp. 274–279. Tokyo: National Astronomical Observatory of Japan. (in Japanese).
Nakamura, T., (2014). Japanese studies of asteroids after the discovery of Hirayama families. *Asian Journal of Physics*, 23(1&2), 189–208.
Nakamura, T. (2017). The development of astronomy and emergence of astrophysics in Japan. In T. Nakamura, & W. Orchiston.
Nakamura, T.., & Orchiston, W. (Eds.), (2017). *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe*. Cham: Springer.
Nakamura, T., & Yoshida, F. (2002). Statistical method for deriving spatial and size distributions of sub-km Main-Belt asteroids from their sky motions. *Publications of the Astronomical Society of Japan,* 54, 1079–1089.
Nakamura, T., Nakamura, A.M., Tholen, D.J., and 5 coauthors (2001). Multi-band imaging camera and its sciences for the Japanese near-Earth asteroid mission MUSES-C. *Earth Planets Space*, 53, 1047–1063.
National Astronomical Observatory of Japan (2012). *Rika Nenpyo* (*Chronological Science Tables*). Tokyo: NAOJ.
Recht, A.W. (1935). Note on the color indices of asteroids. *Astronomical Journal,* 44, 104.
Saito, J., Miyamoto, H., Nakamura, R., Ishiguro, M., Michikami, T., Nakamura, T., and 28 coauthors (2006). Detailed images of Asteroid 25143 Itokawa from Hayabusa. *Science,* 312, 1341–1344.
Sasaki, S., Nakamura, K., Hamabe, Y., Kurahashi, E., & Hiroi, T. (2001). Production of iron nanoparticles by laser irradiation in a simulation of lunar-like space weathering. *Nature,* 410, 555–557.
Senesplada, E.G. (1932). Familias de asteroids. *Boletin de la Astronomico Observatorio de Madrid,* 1(2).
Spurny, P., Oberst, J., & Heinlein, D. (2003). Photographic observations of Neuschwanstein, a second meteorite from the orbit of the Pibram chondrite. *Nature,* 423, 151–152.
Staude, N. (1926). La classification des asteroids. *Russian Astronomical Journal,* 2, 45–53.
Suzuki, S. (1921). On the number of the pieces of the plates broken by a blow. *Proceedings of the Physico-Mathematical Society of Japan, 3rd Series,* 3, 168–174.
Suzuki, S., & Nagashima, H. (1938). On the distribution of mass, velocity and momentum, and energy of the broken pieces of exploded bodies. *Proceedings of the Physico-Mathematical Society of Japan, 3rd Series,* 20, 517–539.
Takenouchi, T. (1950). The long periodic term of Thule. *Publications of the Astronomical Society of Japan,* 1, 159–162.
Van Woerkom, A.A.J., & Brouwer, D. (1950). *Astronomical Papers American Ephemeris*, Vol. 13, Part II.
van Houten, C.J., van Houten-Groeneveld, I., Herget, P., & Gehrels, T. (1970). The Palomar-Leiden survey of faint minor planets. *Astronomy & Astrophysics Supplement Series,* 2(5), 339–388.
Williams, J.G. (1971). Proper elements, families, and belt boundaries. In T. Gehrels, pp. 177–181.
Yanai, K., & Kojima, H. (1986). Over 5600 Japanese collection of Antarctic meteorites. *Lunar and Planetary Institute Technical Report*, 86–01, Houston, Lunar and Planetary Institute.
Yanai, K., Takeda, H., & Shimoyama, A. (eds.) (1987). *Nankyoku Inseki (Antarctic Meteorites).* Tokyo: National Institute of Polar Research. (in Japanese).

Yokoo, H. (1997). Early experiments on collisional-breaking to test theories on the origin of Hirayama Family of asteroids by Seitaro Suzuki (1887–1977) in 1938. *Tenmon Geppou (The Astronomical Herald),* 90, 273–276 (in Japanese, Abstract in English).

Yoshida, F., & Nakamura, T. (2005). Size distribution of faint Jovian Trojan L4 asteroids. *Astronomical Journal,* 130, 2900–2911.

Yoshida, F., & Nakamura, T. (2007). Subaru main belt asteroid survey (SMBAS): size and color distributions of small main-belt asteroids. *Planetary and Space Science,* 55, 1113–1125.

Yoshida, F., Nakamura, T., Watanabe, J.-I., Kinoshita, D., Yamamoto, N., & Fuse, T. (2003). Size and spatial distributions of sub-km Main-Belt Asteroids. *Publications of the Astronomical Society of Japan,* 55, 701–715.

Yoshida, S. (2001). Kiyotsugu Hirayama and Seitaro Suzuki: Suzuki's destruction experiments in laboratory with astronomical interest. *Kagakusi Kenkyu (Journal of History of Science, Japan*), 129–139 (in Japanese, abstract in English).

Yoshida, S., & Nakamura, T. (2017). Hirayama Kiyotsugu: discoverer of asteroid families. In T. Nakamura, & W. Orchiston.

Yoshikawa, M. (1990). Motions of asteroids at the Kirkwood gaps. I - On the 3:1 resonance with Jupiter. *Icarus,* 87, 78–102.

Yuasa, M. (1973). Theory of secular perturbations of asteroids including terms of higher order and higher degree. *Publications of the Astronomical Society of Japan*, 25, 399–445.