

[E] 口頭発表 | セッション記号 P (宇宙惑星科学) : P-PS 惑星科学

■ 2021年6月6日(日) 15:30 ~ 17:00 | 会場 Ch.04 Zoom会場04

### [P-PS04] 太陽系小天体：はやぶさ2等の宇宙ミッションからの新展開

コンビーナ:岡田 達明(宇宙航空研究開発機構宇宙科学研究所)、中本 泰史(東京工業大学)、黒田 大介(京都大学)、座長:岡田 達明(宇宙航空研究開発機構宇宙科学研究所)、中本 泰史(東京工業大学)、YACHEN YANG(Center for Space and Remote Sensing Research)

小惑星、彗星、衛星、惑星間塵など太陽系小天体は、われわれの太陽系の起源と進化の謎を理解するため、また人類を含む生命の誕生をもたらした材料物質を供給源として、きわめて重要である。小天体は地球上や周回軌道からの望遠鏡や現地訪問する探査機による観測的研究によって多くの新発見がなされてきた。隕石や宇宙塵に加えてサンプルリターンによる帰還試料の分析的研究によって太陽系史の新たな描像が加わった。それらの結果と数値シミュレーションを組み合わせた理論的研究や実験的研究によって検証され、また新たな視点が形成されている。本セッションでは、太陽系小天体に関するあらゆる方法論での最新の科学的成果の報告や、新規の方法論の提案を歓迎する。特に「はやぶさ2」での観測結果や帰還試料の分析結果、MMX、Destiny+、Hera、Comet Interceptor、Hayabusa2延長ミッションなど将来のミッションでの期待される成果や準備状況などについての報告を期待する。

15:30 ~ 15:50

[PPS04-19] 小惑星リュウグウとベヌーの外来物質から示唆される衝突史

★招待講演

\*巽 瑛理<sup>1,2</sup>、杉本 知穂<sup>2</sup>、杉田 精司<sup>2</sup>、Popescu Marcel<sup>4</sup>、Campins Humberto<sup>11</sup>、de León Julia<sup>3</sup>、Amy Simon<sup>5</sup>、Kaplan Hannah<sup>6</sup>、長 勇一郎<sup>2</sup>、諸田 智克<sup>2</sup>、本田 理恵<sup>7</sup>、亀田 真吾<sup>8</sup>、横田 康弘<sup>3</sup>、湯本 航生<sup>2</sup>、青木 美波<sup>2</sup>、DellaGiustina Daniella<sup>10</sup>、Golish Dathon<sup>10</sup>、Licandro Javier<sup>1</sup>、Rizos Juan Luis<sup>1</sup>、廣井 孝弘<sup>12</sup>、Domingue Deborah<sup>13</sup>、Michel Patrick<sup>14</sup>、Lauretta Dante<sup>10</sup>、山田 学<sup>15</sup>、坂谷 尚哉<sup>8</sup>、神山 徹<sup>9</sup>、本田 親寿<sup>16</sup>、早川 雅彦<sup>3</sup>、松岡 萌<sup>3</sup>、鈴木 秀彦<sup>17</sup>、小川 和律<sup>3</sup>、澤田 弘崇<sup>3</sup> (1.カナリア天文学物理学研究所、2.東京大学、3.宇宙科学研究所、4.ルーマニア天文研究所、5.NASAゴダード宇宙飛行センター、6.サウスウエスト研究所、7.高知大学、8.立教大学、9.産業総合研究所、10.アリゾナ大学、11.セントラルフロリダ大学、12.ブラウン大学、13.惑星科学研究所、14.コートダジュール天文台、15.千葉工業大学、16.会津大学、17.明治大学)

15:50 ~ 16:10

[PPS04-20] The ESA Hera mission: rendezvous with a binary asteroid, planetary defense and science

★Invited Papers

\*Patrick Michel<sup>1</sup>、Michael Kueppers<sup>2</sup>、Alan Fitzsimmons<sup>3</sup>、Simon F. Green<sup>4</sup>、Monica Lazzarin<sup>5</sup>、Stephan Ulamec<sup>6</sup>、Ian Carnelli<sup>7</sup>、Paolo Martino<sup>7</sup> (1.Universite Côte D'Azur, Observatoire De La Côte D'Azur, CNRS, Laboratoire Lagrange、2.ESA-European Space Astronomy Centre、3.Queen's University Belfast、4.The Open University、5.Padova University、6.DLR RB-MUSC、7.ESA-ESTEC)

16:10 ~ 16:25

[PPS04-21] Hayabusa2 Extended Mission to rendezvous with Asteroid 1998 KY26: Investigations of an extremely small fast rotator for planetary defense

\*Masatoshi Hirabayashi<sup>1</sup>、Y. Mimasu<sup>2</sup>、N. Sakatani<sup>3</sup>、S. Watanabe<sup>4</sup>、Y. Tsuda<sup>2</sup>、T. Saiki<sup>2</sup>、S. Kikuchi<sup>2</sup>、T. Kouyama<sup>5</sup>、M. Yoshikawa<sup>2</sup>、S. Tanaka<sup>2</sup>、S. Nakazawa<sup>2</sup>、Y. Takei<sup>2</sup>、F. Terui<sup>2</sup>、H. Takeuchi<sup>2</sup>、A. Fujii<sup>2</sup>、T. Iwata<sup>2</sup>、K. Tsumura<sup>6</sup>、S. Matsuura<sup>7</sup>、Y. Shimaki<sup>2</sup>、S. Urakawa<sup>8</sup>、Y. Ishibashi<sup>9</sup>、S. Hasegawa<sup>2</sup>、M. Ishiguro<sup>10</sup>、D. Kuroda<sup>11</sup>、S. Okumura<sup>8</sup>、S. Sugita<sup>12</sup>、T. Okada<sup>2</sup>、S. Kameda<sup>3</sup>、S. Kamata<sup>13</sup>、A. Higuchi<sup>14</sup>、H. Senshu<sup>15</sup>、H. Noda<sup>16</sup>、K. Matsumoto<sup>16</sup>、R. Suetsugu<sup>17</sup>、T. Hirai<sup>15</sup>、K. Kitazato<sup>18</sup> (1.Auburn University、2.Japan Aerospace Exploration Agency、3.Rikkyo University、4.Nagoya University、5.National Institute of Advanced Industrial Science and Technology、6.Tokyo City University、7.Kwansei Gakuin University、8.Japan Spaceguard Association、9.Hosei University、10.Seoul National University、11.Kyoto University、12.University of Tokyo、13.Hokkaido University、14.University of Occupational and Environmental Health、15.Chiba Institute of Technology、16.National Astronomical Observatory of Japan、17.National Institute of Technology、18.University of Aizu)

16:25 ~ 16:40

**[PPS04-22] Tomo-e Gozenカメラを用いた微小地球接近小惑星の高時間分解撮像観測**

\*紅山 仁<sup>1</sup>、酒向 重行<sup>1</sup>、大澤 亮<sup>1</sup>、瀧田 怜<sup>1</sup>、小林 尚人<sup>1</sup>、奥村 真一郎<sup>2</sup>、浦川 聖太郎<sup>2</sup>、臼井 文彦<sup>3</sup>、吉田 二美<sup>4,5</sup>、吉川 真<sup>3</sup> (1.東京大学大学院理学系研究科附属 天文学教育研究センター、2.日本スペースガード協会、3.宇宙航空研究開発機構宇宙科学研究所、4.産業医科大学、5.千葉工業大学惑星探査研究センター)

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16:40 ~ 16:55

**[PPS04-23] すばる望遠鏡Hyper Suprime-Cam で得たメインベルト小惑星のカラーとサイズ分布**

\*前田 夏穂<sup>1</sup>、寺居 剛<sup>2</sup>、大槻 圭史<sup>1</sup>、吉田 二美<sup>3,4</sup>、石原 昂将<sup>1,2,5</sup>、出山 拓門<sup>1,6</sup> (1.神戸大学大学院理学研究科、2.国立天文台、3.千葉工業大学、4.産業医科大学、5.総合研究大学院大学、6.株式会社NTTデータMSE)

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16:55 ~ 17:00

**[PPS04-24] Discussion**

## 小惑星リュウグウとベヌーの外来物質から示唆される衝突史

### Impact histories inferred from exogenic boulders on asteroids Ryugu and Bennu

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Rubble-pile asteroids, such as (162173) Ryugu and (101955) Bennu, are formed as a result of catastrophic disruption of a parent body and re-accumulation of the fragments by self-gravity (Michel and Ballouz et al. 2020). Therefore, reaccumulated rubble piles could include mixtures of materials from both the parent body and its catastrophic impactor, as they did in the case of 2008 TC<sub>3</sub> and the Almahata Sitta meteorites (Jenniskens et al. 2009). Indeed, six unusually bright, basaltic, meter-scale boulders were recently identified on Bennu's dark surface (DellaGiustina et al. 2021), and their close spectral matches to the Howardite-Eucrite-Diogenite (HED) meteorites and Vesta family members indicate that they originated from asteroid (4) Vesta. In parallel, bright exogenic anhydrous-silicate-rich materials were found on Ryugu (Tatsumi et al. 2021). The bright boulders on Ryugu are consistent with ordinary chondrite meteorites, based on their albedo and the weak or even absent absorption band at 2 μm. These exogenous materials on the surfaces of rubble-pile asteroids could be a key to constraining their specific impact conditions and collisional evolution.

In this study, we report further study of the visible spectrophotometry and morphology of exogenic boulders on Ryugu and Bennu using two multi-band cameras: the telescopic Optical Navigation Camera (ONC-T) onboard the Hayabusa2 spacecraft, and MapCam onboard the Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft, respectively.

For Ryugu, we first detected objects with peak reflectance brighter by a factor of  $>1.5$  than the surrounding area. Tatsumi et al. (2021) found two spectral groups among the bright boulders: S-type with an absorption near  $1 \mu\text{m}$  and C/X-type with a flat spectrum. That study found 6 S-types and 15 C/X-types, and here we report the additional finding of two S-types and  $\sim 70$  C/X-types. We found that S-type bright boulders follow two parallel trends consistent with space weathering of ordinary chondrites. Fragments from projectiles suggest that Ryugu may not have formed directly from the original parent body, i.e., it is from a second or higher generation of collisional descendants (Sugimoto et al. in revision).

For Bennu, we directly surveyed the absorption near  $1 \mu\text{m}$ , which is indicative of anhydrous silicates. We propose 77 objects of exogenic origin including 6 boulders previously reported by DellaGiustina et al. (2021). We find that proposed exogenic objects follow two mixing trends with respect to the average spectrum of Bennu (Tatsumi and Popescu et al. submitted). One trend can be explained by mixing with HEDs, as discussed in DellaGiustina et al. (2021), and the other trend can be explained by mixing with another, of olivine-rich composition. Near-infrared spectra also support the possibility of multiple compositions among exogenic objects on Bennu. Le Corre et al. (submitted) also reached to the similar conclusion with a different methodology. Thus, similar to Ryugu, Bennu could represent a second or higher generation collisional fragment.

Using high-resolution images, we found that more than half of the exogenic objects that we identified on Bennu have breccia-like or inclusion-like morphologies. We do not observe a correlation between morphology and spectral shape.

Direct comparison of reflectance spectra of exogenic materials between Ryugu and Bennu suggests a compositional difference. Furthermore, the number density of exogenic objects  $> 0.5 \text{ m}$  on Bennu is  $\sim 40$  times that on Ryugu (Tatsumi and Popescu et al. submitted). Bennu exhibits much more contamination from exogenic materials than Ryugu, which likely reflects differences in impact conditions, such as impact velocity and impactor size.

Michel and Ballouz et al. (2020) Nat. Commun. 11, 2655

Jenniskins et al. (2009) Nature 458, 485-488.

DellaGiustina et al. (2021) Nat. Astron. 5, 31-38.

Tatsumi et al. (2021) Nat. Astron. 5, 39-45.

Sugimoto et al. (in revision) Icarus.

Tatsumi and Popescu et al. (submitted) MNRAS.

Le Corre et al. (submitted) PSJ.

キーワード：小惑星、はやぶさ2、オシリスレックス、リュウグウ、ベヌー

Keywords: Asteroids, Hayabusa2, OSIRIS-REx, Ryugu, Bennu

## The ESA Hera mission: rendezvous with a binary asteroid, planetary defense and science

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The Hera mission is in Phase C for launch in 2024 in the ESA Space Safety Programme. Hera will contribute to the first deflection test of an asteroid, in the framework of the international Asteroid Impact and Deflection Assessment (AIDA) collaboration, supported by NASA and ESA

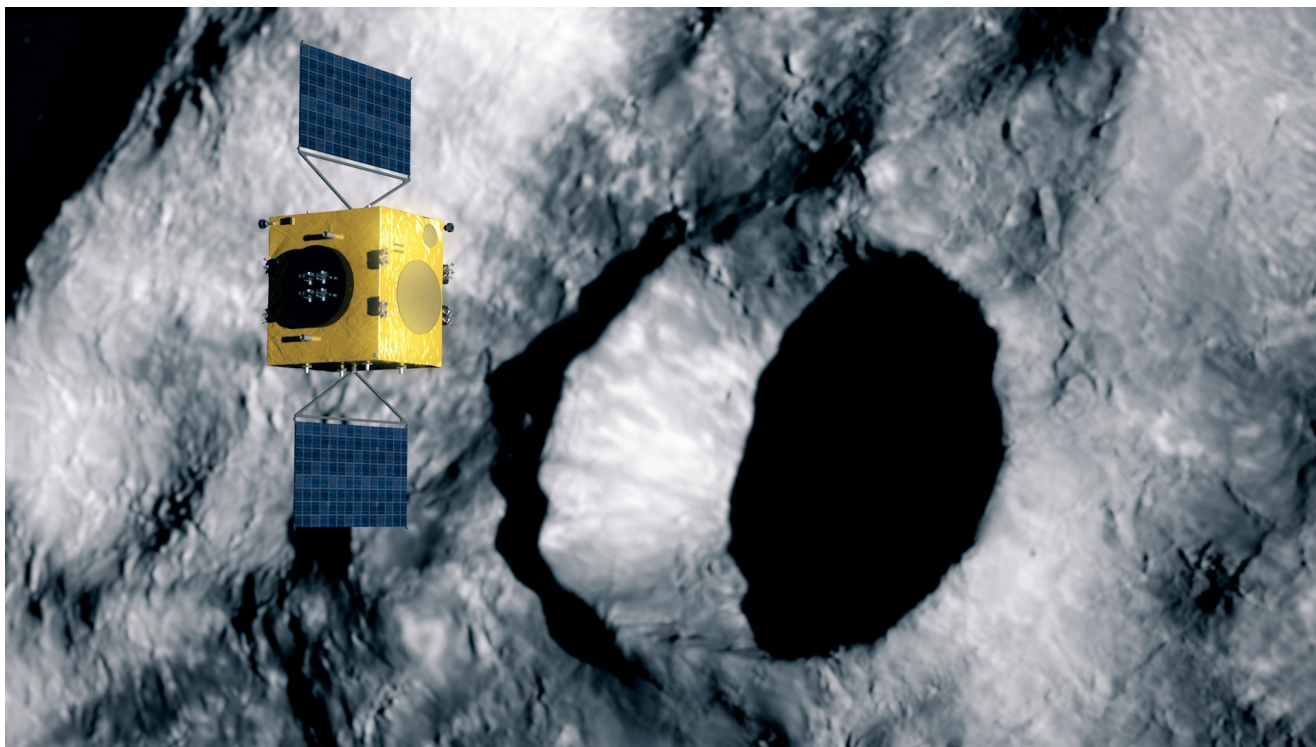
Hera will rendezvous for the first time with a binary asteroid, (65803) Didymos, and take particular emphasis on its secondary, Dimorphos, of only 160 m in diameter. So far, no mission has visited such a small rock in space. Moreover, for the first time, internal and subsurface properties will be directly measured. As a crucial contribution to planetary defense, Hera will perform the measurements necessary to understand the effect of the NASA DART impact on Didymos' secondary in 2022, in particular its mass, its internal structure, the direct determination of the momentum transfer and the detailed characterization of the crater left by DART.

How do binaries form? What does a 160 m-size rock in space look like? What is the surface composition? What are its internal properties? What are the surface structure and regolith mobility on both Didymos and Dimorphos? What are the surface geophysical properties of two objects of different size and surface gravity, which probably formed from the same material? And what will be the size and the morphology of the crater left by DART, which will provide the first impact experiment at full asteroid scale using an impact speed close to the average speed between asteroids? What will be the exact momentum transferred by DART, which needs the precise measurement of the mass of the target by Hera? These questions and many others will be addressed by Hera as a natural outcome of its investigations focused on planetary defense.

The measurements performed by Hera will thus provide unique information on many current issues in asteroid science and therefore, the scientific legacy of the Hera mission will extend far beyond the core aims of planetary defense. Hera is, thus, the main European contribution to the current international asteroid exploration era.

Acknowledgement: Funding support from ESA and from the European Union's Horizon 2020 research and innovation programme under grant agreement No 870377 (project NEO-MAPP) is acknowledged.

Keywords: Asteroids, Binary Asteroids, Impact Physics, Planetary defense, Cubesat, Space mission



## Hayabusa2 Extended Mission to rendezvous with Asteroid 1998 KY26: Investigations of an extremely small fast rotator for planetary defense

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Hayabusa2, led by the Japan Aerospace Exploration Agency (JAXA), brought material samples from asteroid Ryugu back to Earth. On December 6, 2020, the Hayabusa2 team successfully collected the re-entry capsule, while the spacecraft departed from Earth, again. As of January 2021, the spacecraft is reported to have no critical issues.

Based on the spacecraft's healthy condition and remaining fuel, the Hayabusa2 extended mission development team has evaluated the feasibility of an additional mission. Here, we introduce an extended mission in which the spacecraft will explore Asteroid 1998 KY26, a ~30 m - ~40 m in diameter asteroid rotating at a spin period of ~10 m, after a ~10-year cruise phase. Rendezvous operations are planned to detail the physical properties and surrounding environments of this target, one of the smallest elements of small planetary bodies.

In the planned mission schedule, the spacecraft will rendezvous with 1998 KY26 in late 2031. During this cruise phase, the spacecraft may fly by 2001 CC21 in middle 2026. It will approach the asteroid at high speed (~5 km/sec) during the flyby, and thus sophisticated guidance, navigation, and control technologies will be necessary. We also plan to conduct long-term monitoring of the zodiacal light and the transits of exoplanets. After two Earth swing-by operations in late 2027 and early 2028, the spacecraft will arrive at the target asteroid. The planned trajectory will need an additional delta-V of 1.09 km/sec, given the 2,900-sec Isp. The distance from the sun is ~1 AU when the spacecraft arrives at this asteroid.

There are key challenges that need to be resolved in Planetary Defense.

Extremely small bodies (especially smaller than 100 m in diameter) are the most common in the solar system and may have a high probability to influence our societies. Ground- and space-based-telescopes still have technical difficulties in observing these asteroids. Therefore, the physical properties of these objects are poorly understood. Successful planetary defense strategies strongly depend on the physical conditions of asteroids. Extremely small asteroids, which may be the largest pieces within rubble pile asteroid elements, will strongly constrain these conditions.

Given the planned observations, the Hayabusa2 extended mission will significantly contribute to advancing science and engineering knowledge about Planetary Defense by exploring an extremely small body.

Finally, we note that the Hayabusa2 extended mission was approved by the science-engineering space exploration mission assessment committee in Japan, which evaluated the scientific and engineering significance of the mission, and is currently waiting for official approval by the government for budgeting. Also, this abstract is also presented at the Planetary Defense Conference in 2021.

Keywords: Asteroids, Planetary defense, Space exploration mission

# Tomo-e Gozenカメラを用いた微小地球接近小惑星の高時間分解撮像観測

## Highly Time-Resolved Photometric Observations of Tiny Near Earth Objects with the Tomo-e Gozen Camera

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近日点距離が1.3 au未満である地球接近小惑星 (Near Earth Objects, NEO) の多くは火星-木星間のメインベルトから軌道進化した天体であると考えられている。その軌道進化過程においては太陽や惑星の重力に加え、太陽の輻射に起因して小惑星の軌道や自転状態が変化する非重力効果が重要となる。非重力効果の一つであるYORP効果は微小天体 (直径100 m 以下) に強く作用し、軌道進化のタイムスケールに比べて短いタイムスケールで自転周期を変化させる。高速自転する小惑星には強い遠心力が働くため、YORP効果により自転加速され、構造を維持できなくなる臨界自転周期に達した天体は変形や自転破壊を経験する。このことからYORP効果が強く働く微小NEOの自転周期を用いることで、微小天体の強度を推定することができる。近年、大型サーベイ計画により年間2,000から3,000天体のNEOが発見されており、分以下の自転周期をもつ高速自転NEOが見つかりつつある。各観測装置で推定可能な自転周期は露光間のオーバーヘッド時間に依存するため、分以下の高速自転小惑星の周期を正確に推定するためには高時間分解撮像観測が必要である。これまで得られている小惑星の自転周期は多種多様な装置を用いた観測から推定されているが、全ての観測装置が高速自転を検出できるとは限らない。特に検出が難しい高速自転周期の分布が真の小惑星の自転周期分布を反映しているかどうかは明らかではない。

我々は東京大学木曾観測所105 cmシュミット望遠鏡に搭載されたTomo-e Gozenカメラを用いた2 fps観測により、推定直径3-86 m の37天体の微小NEOの高時間分解光度曲線を取得した。計22天体の微小NEOの自転周期を推定し、この中には自転周期20秒以下の超高速自転小惑星が5天体存在した。本研究で観測したNEOの最短自転周期は約11秒であり、2 fpsの高時間分解観測を行っても秒オーダーで高速自転する小惑星は検出されなかった。微小NEOの系統的な高速観測により高速自転する微小NEOの欠如を示したのは本研究が初めてである。本発表では高速観測を行うことで明らかになった微小NEOの直径-自転周期分布に対し、YORP自転加速を考慮した解釈を行う。微小NEOの直径-自転周期分布は微小NEOの強度が典型的な隕石に比べ小さい、微小NEOは最近地球近傍で生成した天体であり十分な自転加速を経験していない、という二つにより説明することができる。

キーワード：小惑星、地球接近小惑星、太陽系、光度曲線、YOPR効果

Keywords: asteroid, near earth objects, solar system, light curve, YORP effect

## すばる望遠鏡Hyper Suprime-Cam で得たメインベルト小惑星のカラーとサイズ分布

### Color and size distributions of main belt asteroids obtained by the Subaru/Hyper Suprime-Cam

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S-type and C-type asteroids are two of the most major types in the main asteroid belt (e.g., DeMeo & Carry 2014). S-type asteroids are thought to have a stony composition, while C-type asteroids are characterized by carbonaceous composition and hydrous minerals (e.g., DeMeo et al. 2015; Usui et al. 2019). Although S-type asteroids and C-type asteroids are thought to have different compositions and origins in this way, their evolution paths are still not well understood.

The size distribution of a population of asteroids strongly reflects the process of their collisional evolution (e.g., Bottke et al. 2015). In the collision equilibrium, the size distribution is primarily determined by the size dependence of impact strength (O'Brien & Greenberg 2003). Therefore, by comparing size distributions of asteroids with different spectral types, we can obtain information about the relation between their type and their impact strength. This is essential information to reveal their collisional evolution. Although some previous observational works studied size distributions of asteroids with different spectral types (Ivezić et al. 2001; Yoshida & Nakamura 2007), the understanding is still far from complete.

In this work, we performed a survey observation of small main-belt asteroids with the wide-field camera, Hyper Suprime-Cam installed on the 8.2 m Subaru Telescope. Using data acquired with two types of filters, *g*-band (0.40-0.55  $\mu\text{m}$  wavelength) and *r*-band (0.55-0.70  $\mu\text{m}$  wavelength), we measured *g-r* color for 3459 main-belt asteroids detected in 14 deg<sup>2</sup> of the sky. From the asteroids we obtained above, we selected a statistical sample consisting of 1814 asteroids with absolute magnitude brighter than 20.3 mag to remove a detection bias. We classified them into two groups, i.e., reddish “S-like” asteroids and bluish “C-like” asteroids based on the boundary color derived from the previous survey data (The fourth release of Sloan Digital Sky Survey Moving Object Catalog, Ivezić et al. 2010). We converted the absolute magnitude of each sample into a diameter assuming an albedo of 0.21 for S-like and 0.07 for C-like asteroids, respectively, which are the mean values of the S- and C-type main-belt asteroids measured by the infrared astronomical satellite AKARI (Usui et al. 2013). We found that the shapes of the size distributions of the S-like and C-like samples agree well with each other within statistical errors for the diameter range from 0.4 km to 1.5 km. The similarity between the size distributions of the S-like and C-like asteroids indicates that their size dependences of impact strength are also similar at least in the size range from several hundred meters to several kilometers. Namely, the impact strength of asteroids in this

size range is likely to be dominated by any other factors rather than their compositions. On the other hand, spin periods of most asteroids in this size range have an upper limit of 2.2 hours, the so-called “spin-barrier” (e.g., Chang et al. 2015). This is interpreted as showing that the asteroids in this size range are rubble-piles, i.e., they consist of numerous pieces of components held together by their self-gravity. The similarity of the size distributions between the S-like and C-like asteroids seems to support the view that most of them have a rubble-pile structure. Also, Itokawa and Ryugu, which were explored by Hayabusa/Hayabusa2, are both several hundred meters in diameter and are considered to have a rubble-pile structure (Fujiwara et al. 2006; Watanabe et al. 2019). Our result is also consistent with this view.

キーワード：小惑星、サーベイ、サイズ分布

Keywords: asteroids, survey, size distributions

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[E] 口頭発表 | セッション記号 P (宇宙惑星科学) | P-PS 惑星科学

## [P-PS04] 太陽系小天体：はやぶさ 2 等の宇宙ミッションからの新展開

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2021年6月6日(日) 15:30 ~ 17:00 Ch.04 (Zoom会場04)

小惑星、彗星、衛星、惑星間塵など太陽系小天体は、われわれの太陽系の起源と進化の謎を理解するため、また人類を含む生命の誕生をもたらした材料物質を供給源として、きわめて重要である。小天体は地球上や周回軌道からの望遠鏡や現地訪問する探査機による観測的研究によって多くの新発見がなされてきた。隕石や宇宙塵に加えてサンプルリターンによる帰還試料の分析的研究によって太陽系史の新たな描像が加わった。それらの結果と数値シミュレーションを組み合わせた理論的研究や実験的研究によって検証され、また新たな視点が形成されている。本セッションでは、太陽系小天体に関するあらゆる方法論での最新の科学的成果の報告や、新規の方法論の提案を歓迎する。特に「はやぶさ 2」での観測結果や帰還試料の分析結果、MMX、Destiny+、Hera、Comet Interceptor、Hayabusa2延長ミッションなど将来のミッションでの期待される成果や準備状況などについての報告を期待する。

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16:55 ~ 17:00

## [PPS04-24]Discussion