ASTEROIDS

The surface composition of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy

K. Kitazato[1]*, R. E. Milliken[2], T. Iwata[3,4], M. Abe[3,4], M. Ohtake[3,4], S. Matsuura[5], T. Arai[6], Y. Nakauchi[3], T. Nakamura[7], M. Matsuoka[3], H. Senshu[8], N. Hirata[1], T. Hiroi[2], C. Pilorget[9], R. Brunetto[9], F. Poulet[9], L. Riu[3], J.-P. Bibring[9], D. Takir[10], D. L. Domingue[11], F. Vilas[11], M. A. Barucci[12], D. Perna[13,12], E. Palomba[14], A. Galiano[14], K. Tsumura[7,15], T. Osawa[16], M. Komatsu[4], A. Nakato[3], T. Arai[8], N. Takato[17,4], T. Matsunaga[18], Y. Takagi[19], K. Matsumoto[17,4], T. Kouyama[20], Y. Yokota[3,21], E. Tatsumi[22], N. Sakatani[3], Y. Yamamoto[3,4], T. Okada[3,22], S. Sugita[22], R. Honda[21], T. Morota[23], S. Kameda[24], H. Sawada[3], C. Honda[1], M. Yamada[8], H. Suzuki[25], K. Yoshioka[22], M. Hayakawa[3], K. Ogawa[26], Y. Cho[22], K. Shirai[3], Y. Shimaki[3], N. Hirata[26], A. Yamaguchi[27,4], N. Ogawa[3], F. Terui[3], T. Yamaguchi[28], Y. Takei[3], T. Saiki[3], S. Nakazawa[3], S. Tanaka[3,4], M. Yoshikawa[3,4], S. Watanabe[23,3], Y. Tsuda[3,4]

The near-Earth asteroid 162173 Ryugu, the target of the Hayabusa2 sample-return mission, is thought to be a primitive carbonaceous object. We report reflectance spectra of Ryugu's surface acquired with the Near-Infrared Spectrometer (NIRS3) on Hayabusa2, to provide direct measurements of the surface composition and geological context for the returned samples. A weak, narrow absorption feature centered at 2.72 micrometers was detected across the entire observed surface, indicating that hydroxyl (OH)–bearing minerals are ubiquitous there. The intensity of the OH feature and low albedo are similar to thermally and/or shock-metamorphosed carbonaceous chondrite meteorites. There are few variations in the OH-band position, which is consistent with Ryugu being a compositionally homogeneous rubble-pile object generated from impact fragments of an undifferentiated aqueously altered parent body.

Scientific knowledge of extraterrestrial materials collected by sample-return missions is enhanced if these materials can be analyzed in the broader context of their parent body. In June 2018, the Japanese Aerospace Exploration Agency (JAXA) spacecraft and sample-return mission Hayabusa2 (*1*) arrived at the near-Earth target asteroid 162173 Ryugu. A mapping campaign with the onboard remote-sensing instruments was performed to provide context for sample collection. Before arrival, ground- and space-based telescopic measurements indicated that the surface of Ryugu was consistent with that of a low-albedo C-type (assumed to be carbon-bearing) asteroid (*2*, *3*). Carbonaceous chondrite meteorites that exhibit evidence of chemical alteration by water, such as CM and CI type, have been proposed as possible compositional analogs for Ryugu (*4*–*7*). However, the lack of spectral data in the 3-μm region, where OH stretching and H_2O bending vibrational modes occur, has precluded definitive compositional identification. We report results of near-infrared (NIR) reflectance observations of Ryugu by the Near-Infrared Spectrometer (NIRS3) on the Hayabusa2 spacecraft.

NIRS3 is a point spectrometer with a 0.1° field of view that takes continuous point-target spectra over the effective wavelength range from 1.8 to 3.2 μm (*8*). On 21 June 2018, NIRS3 began observing Ryugu from a distance of 70 km. On 11 and 19 July, NIRS3 operated in a scanning mode, in which slews of the spacecraft were combined with the rotational motion of the asteroid, to acquire near-global coverage at a surface spatial resolution of 40 and 20 m, respectively. During a descent close to the surface on 6 to 7 August, NIRS3 continuously acquired spectra down to 1 km altitude, corresponding to a spatial resolution of 2 m. By the time of sampling-site selection on 17 August, NIRS3 had acquired >69,000 spectra of Ryugu's surface. These data can be used to constrain surface composition at sampling locations and across the asteroid as a whole (*9*).

All reflectance spectra of Ryugu exhibit thermally emitted radiation at wavelengths longer than 2.1 to 2.4 μm (Fig. 1A). Daytime surface temperatures of Ryugu were estimated from the intensity of the thermal component; they range from 330 to 370 K when the asteroid was located at a heliocentric distance of 1.01 astronomical units (Fig. 2, C and D). The temperature estimated from each spectrum was used to model and subtract the contribution due to thermal emission from the total observed radiance, thus isolating the surface-reflected sunlight (*9*). After conversion from radiance to reflectance, the thermally corrected spectra of Ryugu exhibit several common features. There is a very low reflectance factor ("reflectance" hereafter) value across nearly the entire body. The reflectance has been corrected to a standard viewing geometry (incidence angle, 30°; emission angle, 0°; phase angle, 30°) using the radiative transfer theory of Hapke (*9*, *10*). The globally averaged reflectance at 2.0 μm is 0.017 ± 0.002, which is consistent with values at visible wavelengths observed by the Hayabusa2 Optical Navigation Camera Telescope (ONC-T) (*11*) (fig. S3). Reflectance values vary within 15% across the entire observed surface, excluding regions in shadow (Fig. 2, A and B). Brighter surfaces are primarily observed along the equatorial ridge and crater rims and for individual boulders, again similar to visible-wavelength images. The spectra commonly exhibit a weak positive spectral slope (0.2 to 0.6% μm^{-1}) between 2.0 and 2.5 μm.

All spectra of Ryugu exhibit a weak, narrow absorption feature centered at 2.72 μm (Fig. 1B) and absorption intensity values that range from 7 to 10% of the spectral continuum. The 2.72-μm feature is observable even in the radiance data of Ryugu, and its veracity was confirmed by searching for a similar feature in NIRS3 calibration observations of the Moon, where it was found to be lacking (*9*). The absolute band depth of this feature in processed reflectance data is dependent on the thermal correction. The intensity of the 2.72-μm feature exhibits a positive correlation with estimated surface temperatures (fig. S5), which indicates that uncertainties in the radiometric calibration and/or thermal emission component could be responsible for the observed variations in the band depth of this feature. When normalized by the observed temperature trend, the intensity of the 2.72-μm feature exhibits no clear correlation with topographic or morphologic features (Fig. 2, E and F).

Ryugu is darker than other objects visited by spacecraft, including the nucleus of comet 67P/Churyumov-Gerasimenko (*11*–*13*). It is also darker than many laboratory reflectance spectra of carbonaceous chondrite meteorites, which are thought to be derived from C-type or similar asteroids (*14*). Meteorite samples have reflectance

[1]The University of Aizu, Fukushima, Japan. [2]Brown University, Providence, RI, USA. [3]Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan. [4]The Graduate University for Advanced Studies (SOKENDAI), Kanagawa, Japan. [5]Kwansei Gakuin University, Hyogo, Japan. [6]Ashikaga University, Tochigi, Japan. [7]Tohoku University, Sendai, Japan. [8]Chiba Institute of Technology, Chiba, Japan. [9]Institut d'Astrophysique Spatial, Université Paris-Sud, Orsay, France. [10]Astromaterials Research and Exploration Science, NASA Johnson Space Center, Houston, TX, USA. [11]Planetary Science Institute, Tucson, AZ, USA. [12]Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, Meudon, France. [13]Osservatorio Astronomico di Roma, Istituto Nazionale di Astrofisica (INAF), Monte Porzio Catone, Italy. [14]Istituto di Astrofisica e Planetologia Spaziali, INAF, Roma, Italy. [15]Tokyo City University, Tokyo, Japan. [16]Japan Atomic Energy Agency, Ibaraki, Japan. [17]National Astronomical Observatory of Japan, Tokyo, Japan. [18]National Institute for Environmental Studies, Ibaraki, Japan. [19]Aichi Toho University, Nagoya, Japan. [20]National Institute of Advanced Industrial Science and Technology, Tokyo, Japan. [21]Kochi University, Kochi, Japan. [22]The University of Tokyo, Tokyo, Japan. [23]Nagoya University, Nagoya, Japan. [24]Rikkyo University, Tokyo, Japan. [25]Meiji University, Tokyo, Japan. [26]Kobe University, Kobe, Japan. [27]National Institute of Polar Research, Tokyo, Japan. [28]Mitsubishi Electric Corporation, Kanagawa, Japan.
***Corresponding author. Email: kitazato@u-aizu.ac.jp**

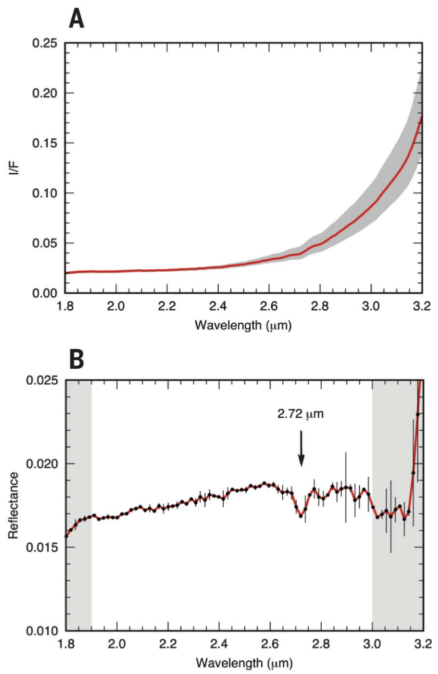

Fig. 1. NIRS3 near-infrared spectra of Ryugu. (**A**) Reflectance spectra, including thermal emission. The range of variation in spectra acquired from the equatorial scan on 10 July 2018 is shown (gray) along with the average spectrum (red). *I/F* is the measured radiance divided by the solar flux. (**B**) Example of a thermally corrected spectrum (observation date and time: 10 July 2018 06:02:22 UTC). Error bars are calculated based on the uncertainties in the element-to-element radiometric calibration (*9*). Shaded areas indicate regions with large calibration residuals. The absorption band indicated by the arrow at 2.72 μm is due to OH.

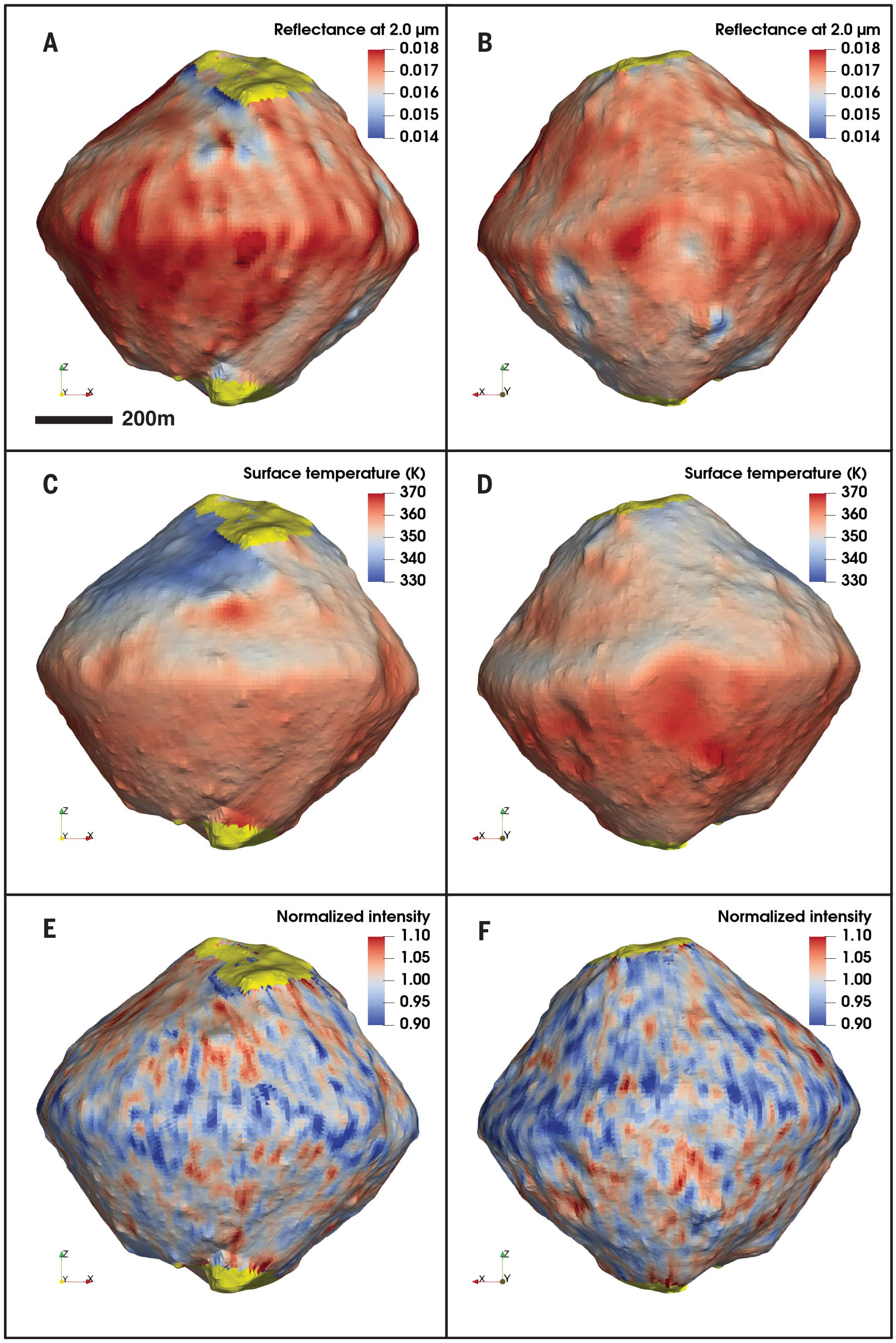

Fig. 2. NIRS3 spectral features projected onto the shape model of Ryugu. The left- and right-side views correspond to the western and eastern hemispheres, respectively. Yellow-shaded areas represent regions that were not observed. (**A** and **B**) Reflectance factor at 2.0 μm, corrected to a standard viewing geometry (*9*). (**C** and **D**) Surface temperature (K) derived from the thermal emission component. (**E** and **F**) Normalized intensity of the 2.72-μm feature. The *z* and *x* arrows indicate Ryugu's rotation axis and zero-longitude definition, respectively. [Ryugu shape model is taken from (*25*)]

values as dark as 0.03 to 0.10 at 2.0 μm wavelength (*15*–*17*), in part because they contain Fe-bearing phyllosilicates, opaque minerals (magnetite and Fe sulfides), and organic carbon, yet the surface of Ryugu is darker still. Such a low and relatively homogeneous albedo indicates the presence of a highly absorbing component dispersed throughout the surface materials of the asteroid, though we cannot specifically determine its composition and origin. Possible explanations include high abundances of carbon, opaque minerals (e.g., magnetite), and/or products of shock-induced metamorphism (e.g., dark glassy components).

The detection of an absorption feature at 2.72 μm indicates the presence of OH attached to a cation, which the position of the reflectance minimum indicates is most likely Mg. The band position is similar to Mg-OH features observed in Mg-rich phyllosilicates, such as serpentine and saponite, which are known to be present in aqueously altered CI and CM chondrites (*18*, *19*). It is also similar to OH features observed in spectra of the dwarf planet Ceres and some C-complex main-belt asteroids, which have been interpreted as evidence for Mg-rich phyllosilicates (*20*, *21*). Our spectra indicate that the OH band position does not vary across the surface of Ryugu within the ~18-nm spectral sampling of the instrument (fig. S7), suggesting a relatively homogeneous phyllosilicate cation composition.

No other absorption features are detected in the 3-μm region in addition to the 2.72-μm feature. Spectra of some C-complex main-belt asteroids

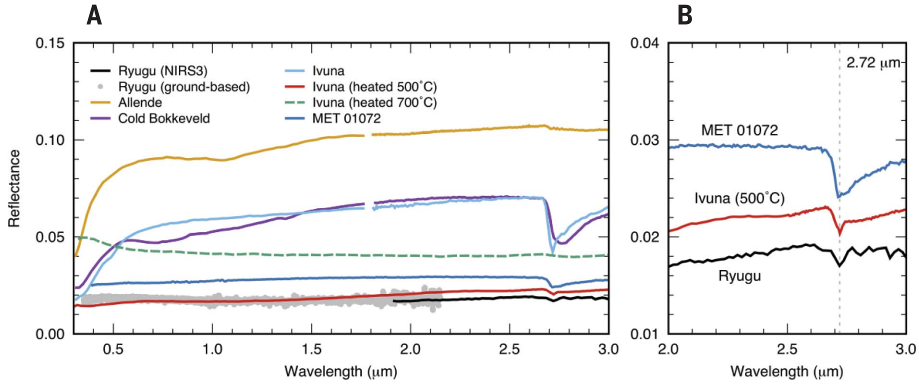

Fig. 3. Comparison of Ryugu with meteorite spectra. (**A**) Globally averaged NIRS3 spectrum of Ryugu compared with laboratory spectra of meteorite samples: Ivuna (CI1), Cold Bokkeveld (CM2), MET 01072 (shocked CM2), and Allende (CV3). Details and references for the meteorite spectra are listed in table S1. A ground-based visible and NIR spectrum of Ryugu (*6*) is also plotted. (**B**) Enlargement of the NIRS3 wavelength range in (A).

have been found to exhibit absorption features that may be attributable to H_2O frost (*22*, *23*), H_2O-bearing minerals (*24*), or NH_4-bearing phyllosilicates (*20*, *21*) in the NIRS3 wavelength range. A decrease in reflectance values at 3 µm can be produced in the NIRS3 data by overestimating the surface temperatures during thermal correction, and it is also possible to mask a weak 3-µm feature if the thermal contribution is underestimated. Nevertheless, a 3-µm feature is expected to be detectable in the radiance data if it were similar to that found on other asteroids.

There are no published meteorite samples whose reflectance spectra perfectly match those of Ryugu at visible to NIR wavelengths. However, spectra of thermally metamorphosed CI chondrites and shocked CM chondrites are similar, in brightness and shape, to those of Ryugu at NIR wavelengths. Laboratory spectra of samples taken from the Ivuna meteorite (classified as CI1) heated to 500°C and from MET 01072 (classified as shocked CM2) are darker than unaltered carbonaceous chondrites, flat, and yet retain a weak 2.72-µm feature (Fig. 3). These meteorite data suggest that thermal alteration processes, such as partial dehydration and decomposition of hydrated minerals induced by static or shock heating, can act to darken hydrated carbonaceous chondrites. Such processes are consistent with current interpretations of Ryugu's formation history (*11*). The low bulk density (~1.2 g cm^{-3}) of Ryugu suggests that it is a rubble-pile asteroid formed by a collisional event with a parent body (*25*), thus it is likely to have experienced shock and postshock heating that could lead to darkening, dehydration, and dehydroxylation. However, it is also possible that the weak OH absorption occurs because the degree of aqueous alteration on Ryugu was never extensive, perhaps owing to low water-to-rock ratios or slow and/or incomplete hydration reactions on the parent body.

Alternatively, it has been suggested that Ryugu's orbit might have had shorter perihelion distances in the past, a characteristic that would have increased radiative heating from the Sun (*26*) and altered the mineralogy of the uppermost surface. Similarly, the surface of Ryugu has experienced solar-wind irradiation and micrometeorite impacts (space weathering), which can alter surface composition and spectral properties. Laboratory experiments suggest that space weathering can destroy OH bonds, causing the reduction or disappearance of a 2.72-µm feature (*27*), a process that may explain the uniformly weak OH signature observed in NIRS3 data. These processes—solar radiative heating and space weathering—represent near-surface phenomena that continue to operate on Ryugu today, whereas the other interpretations for the apparent low-hydration state represent inherent chemical and mineralogical attributes of the asteroid resulting from its early geological history.

Reflectance spectra of Ryugu differ from the heated Ivuna and MET 01072 meteorite samples at visible wavelengths (Fig. 3). This may be due to effects of space weathering or physical properties that could preferentially affect shorter wavelengths. Laboratory experiments show that reflectance spectra of some ion-irradiated CI and CM chondrites tend to increase in brightness at visible wavelengths (*27*). Moreover, there are differences in particle size and, likely, porosity between the meteorite samples and Ryugu's surface materials. For CM chondrite–like materials, an increase in the average particle size of a powdered sample results in spectra with more-positive slope and lower reflectance values, as well as an increase in band depth values of diagnostic absorption bands (*28*). With increasing porosity, overall reflectance decreases (*28*). Despite these differences, hydrated carbonaceous chondrites that have been metamorphosed by thermal and/or shock processes are the best available spectral matches to the NIRS3 data, so Ryugu may be analogous in composition.

Another possible spectral analog is the interplanetary dust particle (IDP). IDPs are known to be darker than CV meteorite samples and have featureless reflectance spectra between 0.4 and 1.0 µm (*29*). However, no published reflectance spectra of IDPs span the NIRS3 wavelength range and therefore a direct comparison cannot be made. In this scenario, and if the spectral properties observed by NIRS3 are indicative of the bulk asteroid, then Ryugu may consist of carbon-rich, partially hydrated, possibly comet-like material that is darker than common aqueously altered carbonaceous chondrites. If Ryugu is indeed such a carbon-rich body, then nonlinear masking effects induced by carbonaceous material (*30*) may result in an underestimation of the relative abundance of phyllosilicates and the degree of aqueous alteration based on the apparent weak 2.72-µm feature.

REFERENCES AND NOTES

1. Y. Tsuda, M. Yoshikawa, M. Abe, H. Minamino, S. Nakazawa, *Acta Astronaut.* **91**, 356–362 (2013).
2. R. P. Binzel, A. W. Harris, S. J. Bus, T. H. Burbine, *Icarus* **151**, 139–149 (2001).
3. H. Campins *et al.*, *Astron. Astrophys.* **503**, L17–L20 (2009).
4. F. Vilas, *Astron. J.* **135**, 1101–1105 (2008).
5. N. A. Moskovitz *et al.*, *Icarus* **224**, 24–31 (2013).
6. D. Perna *et al.*, *Astron. Astrophys.* **599**, L1 (2017).
7. L. Le Corre *et al.*, *Mon. Not. R. Astron. Soc.* **475**, 614–623 (2018).
8. T. Iwata *et al.*, *Space Sci. Rev.* **208**, 317–337 (2017).
9. Materials and methods are available as supplementary materials.
10. B. Hapke, *Theory of Reflectance and Emittance Spectroscopy* (Cambridge Univ. Press, 1993).
11. S. Sugita *et al.*, *Science* **364**, eaaw0422 (2019).
12. S. Fornasier *et al.*, *Astron. Astrophys.* **583**, A30 (2015).
13. M. Ciarniello *et al.*, *Astron. Astrophys.* **583**, A31 (2015).
14. T. H. Burbine, T. J. McCoy, A. Meibom, B. Gladman, K. Keil, in *Asteroids III*, W. F. Bottke Jr., A. Cellino, P. Paolicchi, R. P. Binzel, Eds. (Univ. of Arizona Press, 2002), pp. 653–667.
15. E. A. Cloutis *et al.*, *Icarus* **212**, 180–209 (2011).
16. E. A. Cloutis, P. Hudon, T. Hiroi, M. J. Gaffey, P. Mann, *Icarus* **216**, 309–346 (2011).
17. E. A. Cloutis, P. Hudon, T. Hiroi, M. J. Gaffey, P. Mann, *Icarus* **221**, 984–1001 (2012).
18. P. Beck *et al.*, *Geochim. Cosmochim. Acta* **74**, 4881–4892 (2010).
19. D. Takir *et al.*, *Meteorit. Planet. Sci.* **48**, 1618–1637 (2013).
20. M. C. De Sanctis *et al.*, *Nature* **528**, 241–244 (2015).
21. F. Usui, S. Hasegawa, T. Ootsubo, T. Onaka, *Publ. Astron. Soc. Jpn.* **71**, psy125 (2018).
22. H. Campins *et al.*, *Nature* **464**, 1320–1321 (2010).
23. A. S. Rivkin, J. P. Emery, *Nature* **464**, 1322–1323 (2010).
24. D. Takir, J. P. Emery, *Icarus* **219**, 641–654 (2012).
25. S. Watanabe *et al.*, *Science* **364**, 268–272 (2019).
26. P. Michel, M. Delbo, *Icarus* **209**, 520–534 (2010).
27. C. Lantz *et al.*, *Icarus* **285**, 43–57 (2017).
28. E. A. Cloutis *et al.*, *Icarus* **305**, 203–224 (2018).
29. J. P. Bradley, L. P. Keller, D. E. Brownlee, K. L. Thomas, *Meteorit. Planet. Sci.* **31**, 394–402 (1996).
30. R. N. Clark, *J. Geophys. Res.* **88**, 10635–10644 (1983).

ACKNOWLEDGMENTS

We thank the Hayabusa2 engineering teams for their efforts in making the mission successful and enhancing science operations, in particular T. Masuda, S. Yasuda, K. Matsushima, and T. Ohshima. We also thank H. Murao, Y. Sakata, and K. Taguchi for the development of NIRS3. T.N. thanks M. Takahashi for help with the meteorite analysis. **Funding:** The NIRS3 instrument was funded and coordinated by JAXA and built by Meisei Electric, Genesia, and Hamamatsu Photonics. K.K. and the Japanese coauthors acknowledge support from JAXA and the Hayabusa2 project. The French coauthors acknowledge support from CNES. The Italian coauthors acknowledge support from ASI. D.T. and D.L.D. have been supported by the NASA Hayabusa2 Participating Scientist Program (NNX17AL02G, NNX16AL34G). M.A., T.N., N.H., T.Ok., T.Mo., and S.W. have been supported by Grant-in-Aid for Scientific Research from JSPS (16H04044,

17H06459, 17K05639). Y.N., M.M., E.T., N.S., and S.S. have been supported by the JSPS Core-to-Core Program (17H01175). The work of T.H. is funded by NASA's Emerging Worlds Program (NNX17AK46G). The work of D.P. is funded by the European Union's H2020 program (664931). **Author contributions:** K.K. led the operation and calibration of NIRS3, analyzed the data, and wrote the manuscript. R.E.M. contributed to the calibration and data analysis and assisted in the writing of the manuscript. T.I. led the development of NIRS3. M.A., M.O., S.M., Ta.A., Y.N., and K.T. contributed to the development and operation of NIRS3. T.N., M.M., and T.H. provided information about laboratory spectra of meteorites. H.Se., C.P., R.B., F.P., and L.R. contributed to the data analysis. D.T., D.L.D., M.A.B., D.P., E.P., and A.G. participated in the interpretation of the data. All authors discussed the results and commented on the manuscript. **Competing interests:** Y.Ya. is also affiliated with Tokyo Metropolitan University. **Data and materials availability:** The NIRS3 calibrated data are available through the JAXA Data Archives and Transmission System at https://darts.isas.jaxa.jp/pub/hayabusa2/nirs3_bundle/browse/.

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/364/6437/272/suppl/DC1
Materials and Methods
Figs. S1 to S7
Table S1
References (*31*–*39*)

26 October 2018; accepted 7 March 2019
Published online 19 March 2019
10.1126/science.aav7432

The surface composition of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy

K. Kitazato, R. E. Milliken, T. Iwata, M. Abe, M. Ohtake, S. Matsuura, T. Arai, Y. Nakauchi, T. Nakamura, M. Matsuoka, H. Senshu, N. Hirata, T. Hiroi, C. Pilorget, R. Brunetto, F. Poulet, L. Riu, J.-P. Bibring, D. Takir, D. L. Domingue, F. Vilas, M. A. Barucci, D. Perna, E. Palomba, A. Galiano, K. Tsumura, T. Osawa, M. Komatsu, A. Nakato, T. Arai, N. Takato, T. Matsunaga, Y. Takagi, K. Matsumoto, T. Kouyama, Y. Yokota, E. Tatsumi, N. Sakatani, Y. Yamamoto, T. Okada, S. Sugita, R. Honda, T. Morota, S. Kameda, H. Sawada, C. Honda, M. Yamada, H. Suzuki, K. Yoshioka, M. Hayakawa, K. Ogawa, Y. Cho, K. Shirai, Y. Shimaki, N. Hirata, A. Yamaguchi, N. Ogawa, F. Terui, T. Yamaguchi, Y. Takei, T. Saiki, S. Nakazawa, S. Tanaka, M. Yoshikawa, S. Watanabe and Y. Tsuda

Science **364** (6437), 272-275.
DOI: 10.1126/science.aav7432originally published online March 19, 2019

Hayabusa2 at the asteroid Ryugu

Asteroids fall to Earth in the form of meteorites, but these provide little information about their origins. The Japanese mission Hayabusa2 is designed to collect samples directly from the surface of an asteroid and return them to Earth for laboratory analysis. Three papers in this issue describe the Hayabusa2 team's study of the near-Earth carbonaceous asteroid 162173 Ryugu, at which the spacecraft arrived in June 2018 (see the Perspective by Wurm). Watanabe *et al.* measured the asteroid's mass, shape, and density, showing that it is a "rubble pile" of loose rocks, formed into a spinning-top shape during a prior period of rapid spin. They also identified suitable landing sites for sample collection. Kitazato *et al.* used near-infrared spectroscopy to find ubiquitous hydrated minerals on the surface and compared Ryugu with known types of carbonaceous meteorite. Sugita *et al.* describe Ryugu's geological features and surface colors and combined results from all three papers to constrain the asteroid's formation process. Ryugu probably formed by reaccumulation of rubble ejected by impact from a larger asteroid. These results provide necessary context to understand the samples collected by Hayabusa2, which are expected to arrive on Earth in December 2020.

Science, this issue p. 268, p. 272, p. 252; see also p. 230

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.