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Article

Brief History of Lunar and Asteroidal Remote Sensing and Discoveries with Their Returned Samples

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Abstract: History of remote sensing studies of the Moon and asteroids changed when lunar samples were returned by the Apollo 11 mission and many meteorites were discovered on Antarctica starting in 1969. Discovery of the isotopic similarity between lunar and terrestrial materials led us to the giant-impact model to form the Moon. In addition, the existence and nature of space weathering were also discovered in 1993 by analyzing the Apollo samples. Another change occurred in 2010 when the Hayabusa spacecraft returned particles of asteroid Itokawa that proved the identity between many S-type asteroids and ordinary chondrites and the existence of space weathering similar to the Moon. The second sample return from asteroids occurred in 2020 when the Hayabusa2 spacecraft returned samples of C-type asteroid Ryugu. In spite of some expectations, it was a pristine CI1 chondrite material that was free from terrestrial contaminations suffered by known CI1 chondrite meteorites. Sample return missions drastically improved the accuracy of our knowledge on the raw materials of solar system planets and will surely keep revealing the secrets behind the birth of this special planet Earth. This part of history also teaches us that scientists should proclaim the truth against denial or persecution by others.

Keywords: remote sensing, sample return, Moon, asteroids, Apollo 11, Hayabusa, Hayabusa2, OSIRIS-REx

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1. Introduction

Our very existence highly relies on the special characteristics of planet Earth, and discovering the origin and evolution of the Earth requires studying the Solar System as a whole, which falls into the field of planetary science. Planetary science has been mostly developed through remote sensing of planets and satellites by ground-based, airborne, and space telescopes, and spacecraft missions. Atmospheric compositions of planets are relatively easy to investigate through such remote sensing. However, in order to fully understand the reason why our Earth-Moon system has its current configuration including the sizes, dynamics, and compositions, we really need to study solid samples of planetary bodies. For that purpose, meteorites and interplanetary dust particles (IDPs) were in the past the only such samples available of solid planetary materials although they were somewhat altered by the terrestrial environment. In 1969, the Apollo 11 mission returned the first lunar rocks and regolith materials as the first recovery of pristine extraterrestrial solid materials, the Japanese Antarctic Research Expedition (JARE) discovered nine distinct meteorites concentrated at the foot of Yamato Mountain Range [1], and two large carbonaceous chondrites (CCs), Murchison and Allende, fell in Australia and Mexico, respectively [2]. These events allowed researchers to examine many detailed aspects of solar system formation such as elemental, isotopic, and mineral abundances, physical characteristics such as density and porosity, and alteration such as heating, shock, and space weathering. In this brief paper, the history of lunar and asteroidal remote sensing and discoveries from their returned samples are reviewed.

2. Moon

Throughout history, the Moon has been the target of imagination, observation, studies, and exploration. However, the origin and evolution of the Moon had not been clear until after Apollo missions returned samples in 1969-1972, which led researchers to form and confirm the giant-impact hypothesis for forming the Moon [3].

2.1. Lunar remote sensing

Galileo Galilei started observing and sketching the Moon in 1609 [4]. He provided not only evidence that the lunar surface is rough but also how it could be derived even from naked-eye observation that the entire sun-lit surface is illuminated instead of just a longitudinal line which would specularly reflect sunlight if the surface were totally smooth [5]. This was an example of thought experiments he also used in concluding both heavy and light objects fall at the same speed [6]. Albert Einstein also employed thought experiments in deriving special and general relativity theories. Geniuses like them could obtain much more truth from limited facts than ordinary people.

Since then, there were many telescopic observations and spacecraft missions to study the Moon before the first crewed landing by the Apollo 11 mission. While many researchers were lost in identifying the surface composition of the Moon, Bruce Hapke correctly predicted the presence of silicate minerals and space weathering by simulating solar wind with H^+ ions irradiated on basalt powders that altered their photometric, polarimetric, and spectroscopic properties to resemble those of the lunar surface [7, 8]. Unfortunately, his idea of space weathering was not well accepted by the science community at that time, and he redirected his research efforts toward developing a spectrophotometric model, which is now well-known as Hapke's model [9]. A bad thing can indeed end up being a good thing.

2.2. Moon-forming hypotheses

There were four main hypotheses for how the Moon was formed [10]:

a) Capture: The Moon was captured by the Earth's gravity as it passed nearby.
b) Accretion: The Moon was created along with Earth at its formation.
c) Fission: The Earth had been spinning so fast that some material broke away to form the Moon.
d) Giant impact: A Mars-size planet hit a proto-Earth, and the debris from this impact formed the Moon.

The accretion and fission hypotheses could not easily explain the difference between the Earth's spin axis and the Moon's orbital axis, the capture hypothesis could result in the Earth and the Moon having totally different compositions, while the giant-impact hypothesis predicted high compositional similarity between the Earth and the Moon. Therefore, finding the compositional difference or similarity between the Earth and the Moon was the key to narrow down the origin of the Moon between the capture and the giant impact hypotheses. Remote sensing alone could not achieve this goal because it would take isotopic analysis of solid materials to validate the common origin of two planetary bodies.

2.3. Apollo sample analyses

When the samples returned by the Apollo 11 and subsequent missions were analyzed, their oxygen isotopic compositions were identical to terrestrial materials within analytical errors [11], which added support to the giant-impact hypothesis. In addition, when a high-voltage transmission electron microscope (TEM) was utilized to examine submicroscopic-scale composition of Apollo lunar soil particles, nanophase metallic iron ($npFe^0$) particles were found within a thin (100-200 nm) amorphous vapor coating layer [12], confirming the existence of space weathering as Bruce Hapke predicted [8]. The lunar surface became darker and redder through space weathering by solar wind implantation and micrometeorite bombardments over a long period of time. Discovering the products of space weathering ($npFe^0$) took 26 years after Apollo 11 samples were returned since the analytical techniques had to be developed.

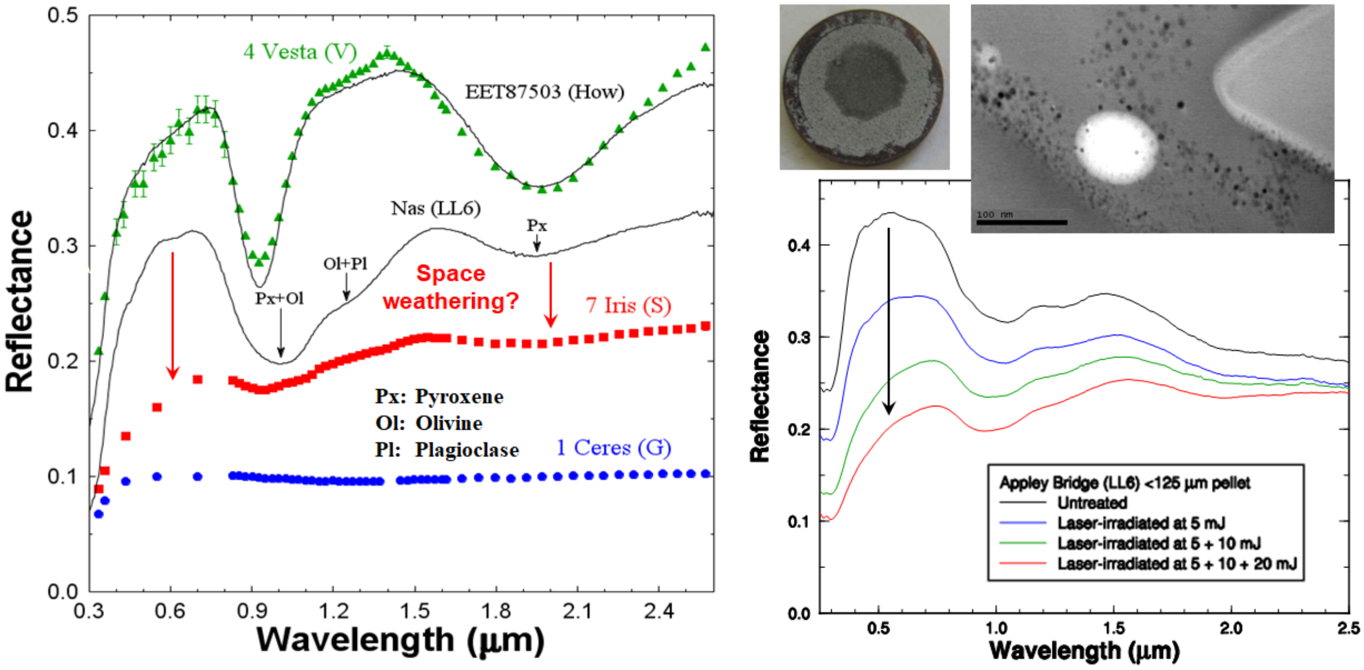
This is an excellent example of the fact that sample return missions allow discoveries by not only the present-day scientists and their techniques but also the future more knowledgeable scientists with more advanced techniques.

3. Asteroids

Around the same time when Apollo 11 samples were first analyzed, asteroid 4 Vesta was spectroscopically identified as similar to a basaltic achondrite meteorite [13]. This was a confirmation that meteorites could be samples of asteroids and gave hope to identify their parent bodies among asteroids through reflectance spectroscopy. However, very few more pairs of asteroids and meteorites turned out to show spectral matches.

3.1. S-type asteroids and ordinary chondrite controversy

As shown in Fig. 1 (a), asteroid 4 Vesta had been the only asteroid whose reflectance spectrum matched with meteorites for a long time since 1970. The main problem was the spectral mismatch between the most common ordinary chondrite meteorites and the most abundant S-type asteroids in the inner main belt. Ordinary chondrites include the H, L, and LL classes in the order of high to low iron content, and the spectral mismatch is demonstrated in Fig. 1 (a) with the Näs LL6 chondrite (black solid line) and asteroid 7 Iris (red filled squares) as examples. If the lunar-type space weathering is occurring on the S-type asteroids, ordinary chondrites could change their spectra to the S-asteroid spectra. However, there had been no npFe^0 particles or any other type of clear space weathering products discovered in our ordinary chondrite meteorite collections, although, a npFe^0–rich rim was found the Kapoeta howardite meteorite [14] which likely came from a V-type asteroid as possible evidence of space weathering. Therefore, almost no meteoriticist had believed in asteroidal space weathering.



(a) **(b)**

Figure 1. (a) Comparison of visible to near-infrared reflectance spectra of asteroids and meteorites, where telescopic asteroid spectra are shown in colored markers, and laboratory meteorite spectra are shown in black solid lines, and asteroid and meteorite classes are indicated in parentheses. Note that 1 Ceres is now classified as a dwarf plane; (b) Pulse-laser irradiation on a powder pellet sample of Appley Bridge LL6 chondrite meteorite at various accumulated amounts of energy.

3.2. Pulse-laser irradiation experiments to simulate space weathering

In 1999, a successful space-weathering simulation was performed using pulse-laser irradiation of pressed powder pellet samples of olivine and pyroxene (which are the main mineral components of ordinary chondrites) in vacuum [15]. As shown in Fig. 1b, as the laser energy was increased, the ordinary chondrite spectrum became darker and redder to resemble those of S-type asteroids, and $npFe^0$ particles were discovered in the amorphous vapor coating layer as in the case of Apollo soil particles. This was the first proof that ordinary chondrites could change their reflectance spectra into the S-type asteroid spectra in the similar space environment to that of the Moon in terms of having no atmosphere and residing in the inner solar system. Using these artificially space-weathered olivine and pyroxene spectra, two asteroid spectra were nearly perfectly fit to demonstrate the existence of space weathering on those asteroids [16].

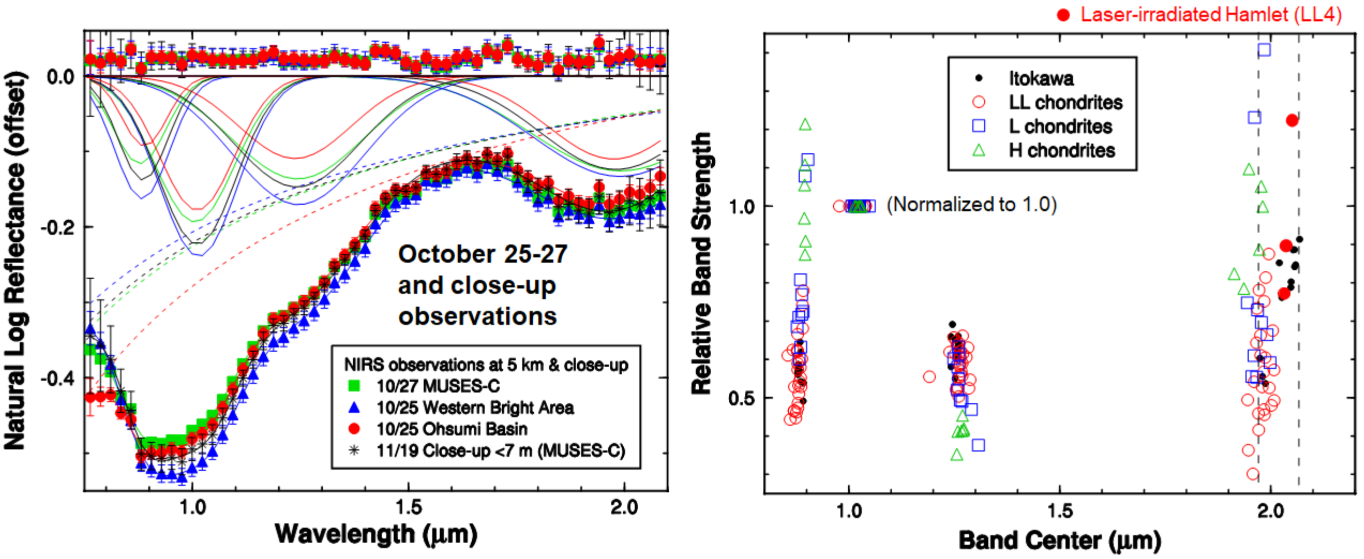
However, in the same manner as happened to Bruce Hapke's H^+ ion implantation experiments, many researchers either neglected or attacked the above results by Japanese scientists, even to the level of rejecting the author's abstract submitted to the 30th Lunar and Planetary Science Conference (LPSC) in 1999 with obviously nonsense reasons such as "the wavelength of the pulse laser was not written" because it was common knowledge that YAG laser had a wavelength of 1064 nm.

3.3. Hayabusa mission returned samples of S-type asteroid 25143 Itokawa

In 2005, the Japanese Hayabusa spacecraft rendezvoused with S-type asteroid Itokawa [17], and despite having many accidents and challenges, miraculously returned its sample-laden capsule to the Earth in 2010. During the rendezvous phase, the Near-Infrared Spectrometer (NIRS) onboard the Hayabusa spacecraft measured reflectance spectra (0.75-2.1 μm) on many spots of Itokawa's surface [18].

Shown in Fig. 2 are modified Gaussian model (MGM) [19] fittings of four representative spots, and Gaussian band center and relative band strength values of a larger number of spots, plotted along with those of ordinary chondrites including the Hamlet LL4 chondrite pellet irradiated with a pulse laser. In Fig. 2 (a), it is clear that all four spectra share almost the same Gaussian band center values with different band strengths and continuum background spectra (broken curves). The continuum slopes indicate increasing degrees of space weathering in the order of Western Bright Area (blue filled triangles), MUSES-C Regio (green filled squares), and Ohsumi Basin (red filled circles). The close-up spectrum (black asterisk) close to the MUSES-C Regio spectrum (red filled square) corresponds to about a 1 cm size footprint, which signifies that the surface is highly homogenous down to the cm scale, consistent with ordinary chondrite lithology. In Fig. 2 (b), it is evident that Itokawa spectra (black filled circles) are most similar to those of LL chondrites (red open circles) and more spectra are similar to laser-irradiated LL chondrite spots (red filled circles).

These results indicates that Itokawa is made of LL-chondrite materials and its surface is space-weathered in various degrees, consistent with another study employing Hapke's space-weathering model [20]. Analyses of mostly tiny (~0.1 mm) particles returned from Itokawa revealed these rendezvous phase remote-sensing results were correct [21, 22].



(a) (b)

Figure 2. (a) Modified Gaussian model (MGM) fittings of four select reflectance spectra of asteroid Itokawa spots taken by the Near-Infrared Spectrometer (NIRS) onboard the Hayabusa spacecraft; (b) Gaussian band center vs relative band strength of a larger number of Itokawa spectra (black filled circles) plotted along with those of ordinary (H, L, and LL) chondrites including a Hamlet LL4 chondrite pellet irradiated with pulse laser (red filled circles).

3.4. Hayabusa2 mission returned samples of C-type asteroid 162173 Ryugu

In 2019, the Japanese Hayabusa2 spacecraft landed twice on C-type asteroid Ryugu, and returned its samples to Earth in 2020. During the rendezvous phase, the Near-Infrared Spectrometer (NIRS3) onboard the Hayabusa2 spacecraft measured reflectance spectra (1.8-3.2 µm) of the surface spots to detect hydration features near 2.7 µm, indicating that Ryugu's surface was made of partially dehydrated CI chondrite or shocked CM chondrite material [23]. However, returned Ryugu samples (5.4 g in total) turned out to be pure CI chondrite materials, totally free of terrestrial contamination, heating, or significant shock [24]. Also, by comparing the 2.7 µm hydroxyl absorption band position between the returned sample and the NIRS3 data of Ryugu, a 6 nm shift was detected that is evidence of space weathering by solar wind [25].

The reason why the remote-sensing based prediction was incorrect is that the unheated CI chondrite samples in our collections were all contaminated with terrestrial materials and altered (oxidized) by the Earth's atmosphere, forming secondary minerals. We simply never knew what the true, pure CI chondrite spectrum should look like. This situation is illustrated in Fig. 3. Alais CI1 chondrite in our collection shows a much brighter spectrum with features such as UV and broad 3 µm band which are absent in Ryugu sample spectra. On the other hand, Ivuna CI1 chondrite heated at 500°C shows a much closer spectrum to Ryugu spectra. The probable explanation is that CI1 chondrites in our collection contain terrestrial contamination including iron hydroxides, and moderate heating them in vacuum could remove them although too much heating would totally dehydrate saponite and serpentine, erasing the 2.7 µm band. Samples of another C-type asteroid 101955 Bennu were returned by NASA OSIRIS-REx mission, and their detailed analyses are now being undertaken to find any similarity or difference from Ryugu samples.

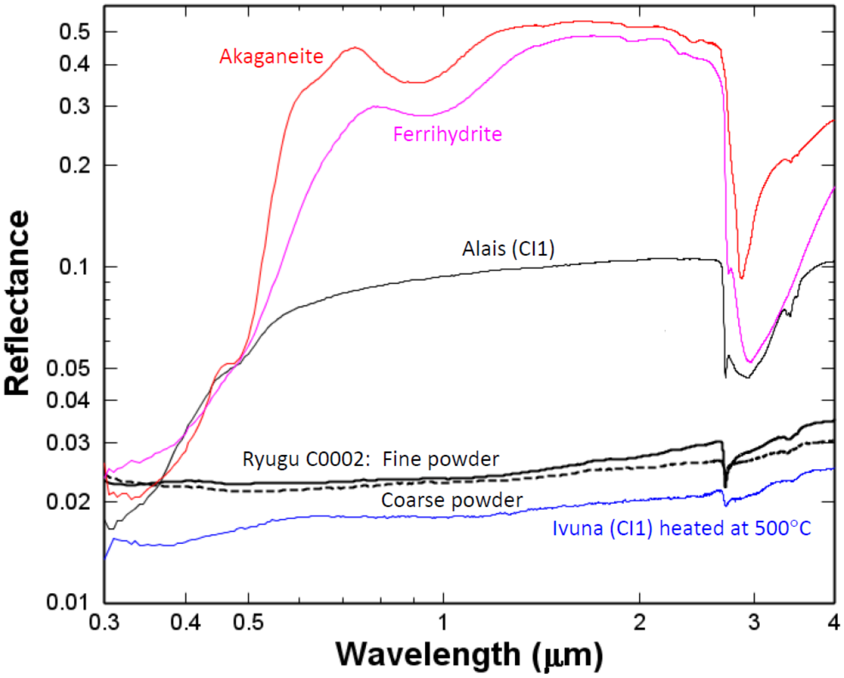


Figure 3. Visible to near-infrared reflectance spectra (0.3-4 μm) of fine and coarse powder samples of asteroid Ryugu [24], powder samples of Ivuna (CI1) meteorite heated at 500°C, of Alais (CI1) meteorite, ferrihydrite, and akaganeite, which are all taken from the RELAB database [26].

4. Summary

Lunar sample returns by the Apollo missions revealed the origin of the Moon and the existence of space weathering of airless bodies. S-type asteroid Itokawa sample return by the Hayabusa mission proved that space weathering altered asteroid surfaces with ordinary chondrites hidden among S-type asteroids, and the Hayabusa2 mission provided a lesson and a reminder that our CI chondrites (and undoubtedly others) are terrestrially contaminated or altered. In order to correctly integrate our knowledge of the Moon, asteroids, and lunar and meteorite samples, space weathering and terrestrial weathering must be evaluated and removed. Along with expanding remote-sensing studies, sample return missions should give us trustable key elements for revealing the secrets of the birth of the special planet Earth where intellectual life emerged and developed science. Another important lesson is that even the world greatest scientists are imperfect, having prejudice against different opinions, etc. We must be obedient to the facts and humbly pursue the truth with unbiased reasoning and imaginations.

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References

1. Yoshida, M. Discovery of the Yamato Meteorites in 1969. *Polar Science 3*, 272-284 (2010).
2. Zolensky, M., Russel, S. and Brearley, A. The fall of the Murchison meteorite. *Meteoritics & Planetary Science 56*, 8-10 (2021).
3. Wikipedia: Giant-impact hypothesis. https:// https://en.wikipedia.org/wiki/Giant-impact_hypothesis (accessed on 11 January 2024).
4. Righini, A. The telescope in the making, the Galileo first telescopic observations. *Proceedings of the International Astronomical Union 6*, 27-32 (2010).

5. Galilei, G. *Dialogue Concerning the Two Chief World Systems* (1632).
6. Galilei, G. *Discourses and Mathematical Demonstrations Relating to Two New Sciences* (1638).
7. Hapke, B. Optical properties of the Moon's surface. In *The Nature of the Lunar Surface* (Johns Hopkins Univ. Press, 1966).
8. Hapke, B. The composition of the lunar surface inferred from optical properties. *Science 159*, 76-79 (1968).
9. Hapke, B. Bidirectional reflectance spectroscopy: 1. Theory. *Journal of Geophysical Research 86*, 3039-3054 (1981).
10. Lotzof, K. How did the Moon form? https://www.nhm.ac.uk/discover/how-did-the-moon-form.html (accessed on 11 January 2024).
11. O'Neil, J. and Adami, L. Oxygen isotope analyses of selected Apollo 11 materials. In Proceedings of the Apollo 11 Lunar Science Conference, 2, Houston, TX, USA (5-8 January, 1970).
12. Keller, L. and McKay, D. Discovery of vapor deposits in the lunar regolith. *Science 261*, 1305-1307 (1993).
13. McCord, T. et al. Asteroid Vesta: Spectral reflectivity and compositional implications. *Science 168*, 1445-1447 (1970).
14. Noble, S., Keller, L. and Pieters, C. Evidence of space weathering in regolith breccias II: Asteroidal regolith breccias. *Meteoritics & Planetary Science 45*, 2007-2015 (2010).
15. Yamada, M. et al. Simulation of space weathering of planet-forming materials: Nanosecond pulse laser irradiation and proton implantation on olivine and pyroxene samples. *Earth Planets Space 51*, 1255-1265 (1999).
16. Hiroi, T. and Sasaki, S. Importance of space weathering simulation products in compositional modeling of asteroids: 349 Dembowska and 446 Aeternitas as examples. *Meteoritics and Planetary Sciences 36*, 1587-1596 (2001).
17. Fujiwara, A. et al. Hayabusa at asteroid Itokawa. *Science 312*, 1327-1353 (2006).
18. Abe, M. et al. Near-infrared spectral results of asteroid Itokawa from the Hayabusa spacecraft. *Science 312*, 1334-1338 (2006).
19. Sunshine, J., Pieters, C. and Pratt, S. Deconvolution of mineral absorption bands: An improved approach. *Journal of Geophysical Research 95*, 6955-6966 (1990).
20. Hiroi, T. et al. Developing space weathering on the asteroid 25143 Itokawa. *Nature 443*, 56-58 (2006).
21. Nakamura, T. et al. Itokawa dust particles: A direct link between S-type asteroids and ordinary chondrites. *Science 333*, 1113-1116 (2011).
22. Noguchi, T. et al. Incipient space weathering observed on the surface of Itokawa dust particles. *Science 333*, 1121-1125 (2011).
23. Kitazato, K. et al. The surface composition of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy. *Science 364*, 272-275 (2019).
24. Yokoyama, T. et al. Samples returned from the asteroid Ryugu are similar to Ivuna-type carbonaceous meteorites. *Science 379*, eabn7850 (2023).
25. Hiroi, T. et al. Evidence of global space weathering by solar wind on asteroid 162173 Ryugu. *Icarus 406*, 115755 (2023).
26. Reflectance Experiment Laboratory (RELAB). https://sites.brown.edu/relab/ (accessed on 13 January 2024).