

Ammonium-bearing phyllosilicate grains detected in Ryugu and Bennu samples via infrared spectroscopy

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Understanding the nature of nitrogen reservoirs in primitive small bodies is fundamental for tracing the evolution of volatiles in the early Solar System and their contribution to prebiotic chemistry. Here we report the identification, via infrared spectroscopy, of ammonium (NH_4^+)-bearing phyllosilicates inclusions in samples returned from carbonaceous asteroids Ryugu and Bennu. Typically hundreds of micrometers in size, they exhibit highly similar near-infrared spectral profiles in both collections, pointing to a generic formation process across this class of primitive objects. This process implies a chemical path that likely starts with highly soluble ammonium salts trapped in ices and mixed with anhydrous silicates, as detected on comet 67 P/Churyumov-Gerasimenko, and ends with ammoniated phyllosilicates, and a few less soluble ammonium salts such as the Hydrated Ammonium Magnesium Phosphorus-rich grains found in Ryugu and Bennu. These second-generation ammonium-bearing species were thus able to contribute efficiently to the delivery of nitrogen to terrestrial planets.

Nitrogen (N) is a key component of volatile species and prebiotic compounds in the Solar System. Its distribution in planetary bodies provides clues about their formation and transport. N-bearing compounds exist in various forms, such as ammonia (NH_3) ice, nitride minerals, ammonium salts, ammoniated phyllosilicates, various N-rich organic compounds found in extraterrestrial materials, etc. (e.g.,

refs. 1–9). In particular, the distribution and speciation of the ammonium ion (NH_4^+) and its associated compounds (salts and phyllosilicates) are crucial, as ammonium represents more stable, less volatile carriers of nitrogen from the outer to the inner Solar System^{2,10}. NH_4^+ -bearing compounds exhibit a $\sim 3.1\ \mu\text{m}$ (ν_3 stretching mode) and a $\sim 7\ \mu\text{m}$ (ν_4 bending mode) band in the infrared (e.g. refs. 11–13). While the

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-3.1 μm band is indicative of the presence of N-H-rich material, the -7 μm feature is diagnostic of the NH_4^+ ion.

On comet 67P, ammonium salts have been detected by mass spectrometry in the coma^{3,4} and a broad -3.2 μm infrared absorption in the spectrum of the surface has been attributed to them². Ceres infrared spectrum exhibits an absorption band around 3.06 μm , which is interpreted as ammonium interlayered in the phyllosilicates (e.g., refs. 5,6). Observations also suggest that several other primitive asteroids have similar infrared features, raising the question of the presence and distribution of NH_4^+ -bearing compounds on these Solar System bodies and their potential role in delivering ammonium-rich species to the inner Solar System^{14–18}.

Millimeter to centimeter scale near-infrared (NIR) spectroscopy of the Ryugu sample returned by the JAXA Hayabusa2 mission revealed a weak -3.06 μm absorption^{19,20}, indicating the presence of NH-bearing compounds. This finding was followed by the identification of hydrated ammonium-magnesium-phosphorus-rich (HAMP) salts, first in Ryugu samples and then in Bennu samples returned by the OSIRIS-Rex mission^{21,22}. In the NIR range, HAMP grains are mainly characterized by a particularly strong and wide 3 μm H_2O absorption band, which tends to obscure the N-H stretching band of their ammonium content.

Distinct from the spectral profile of the HAMP salts, one rare Ryugu grain, a few hundreds-of- μm in size, showed strikingly strong -3.06 μm , suggesting localized NH enrichment (hereafter referred to as the NH-rich grains), and a 2.72 μm feature related to the presence of phyllosilicates¹⁹. Similar grains were later detected in Bennu samples²². These observations suggest the existence of another distinct reservoir for NH-bearing material in the returned sample. However, their nature, abundance, distribution, and relationships to the other components, such as phyllosilicates and organics, remained poorly constrained.

This study reports a systematic spectroscopic survey of these poorly constrained NH-rich materials across both Ryugu (~5.4 g) and a subset of Bennu (~0.6 g) samples stored at the JAXA curation center. We use a combined near-infrared (NIR) and mid-infrared (MIR) spectroscopic characterization at a tens-of-micrometers scale to identify their chemical speciation. In particular, the same NIR hyperspectral microscope (MicrOmega) was used on both samples' collections, enabling a direct comparison and unique cross-analysis. Critically, this survey was performed while the samples were kept in their preservation chambers, ensuring they were protected from terrestrial atmospheric interaction throughout the entire analytical process. Our results allow us to determine and compare the characteristics of these NH-rich materials between Ryugu and Bennu samples, ultimately inferring their origin and the implications for the transport of volatile phases within the solar system.

Results

Near-IR spectra with MicrOmega

As of September 2025, we identified in the MicrOmega dataset (22.5 μm of spatial resolution), 13 regions of interest (ROIs) in Ryugu samples that display absorptions at -3.1 μm (NH stretching mode) and -2.7 μm (OH stretching mode of Mg-rich phyllosilicates, Figs. 1, s1). An identical approach to Bennu samples resulted in the detection of 12 ROIs (Figs. 1 and s1).

Their size ranges from -100 μm (Fig. 1a, m) to several hundreds of μm (Fig. 1e, g, and j) with smaller grains/areas potentially present but approaching our detection limit (1–2 pixels, -22–45 μm). They also show various morphologies: rounded (Fig. 1a), elongated with sub-regions (Fig. 1e), vein-like (Fig. 1j), and patchy-shape (Fig. 1g). Noticeably, all these NH-rich ROIs are much brighter than the matrix. They typically display a 5–10% reflectance factor at 2.5 μm , with some up to 15% depending on geometry (Fig. 1, 2nd column), compared to 2–3% for the matrices^{19,22}. In comparison, the typical reflectance factor values for HAMP-like grains and carbonates are 10–20% and 5–15%, respectively²².

The NH stretching band observed on the ROIs' average spectra generally shows an asymmetric shape, which can be roughly decomposed into two Gaussian curves with a strong peak at -3.04 μm and another weaker one at -3.10 μm (Fig. s2). The band minimum of the whole NH band varies from -3.04 to -3.08 μm , and its relative depth ranges from -5% to -25%. ROIs from Ryugu chamber C and Bennu tend to show a stronger and shorter-wavelength NH band (-7–25% and 3.04–3.05 μm) compared to ROIs from Ryugu chamber A (6–15% and 3.05–3.09 μm) (Fig. s3a). The shift observed in the Ryugu Chamber A samples is primarily due to a change in the relative band strengths of the two sub-peaks, rather than a uniform shift of both sub-peaks (Fig. s4). The spectral slope (1.0–2.5 μm) varies both with geometry (different orientation) (Figure s5a) and between ROIs (Figure s5b). While most continua range from weakly positive to flat, a few ROIs display a negative slope (Fig. s5b). Importantly, no significant organic bands related to C-H stretching modes are detected at -3.4–3.5 μm in these NH-rich ROIs.

The OH stretching band of the phyllosilicate is nearly ubiquitous across the samples, but its depth over the NH-rich ROIs is much stronger than on the matrix: respectively 35–60% for Ryugu and 30–50% for Bennu, compared to only 5–20% on the matrix^{19,22,23}. Le Pivert-Jolivet et al.²³ systematically studied the OH peak positions for Ryugu mm-size grains, showing that most are located between 2.715 and 2.725 μm . Pilorget et al.²², also reported that the OH peak position for the Bennu bulk sample at the cm-scale is $2.717 \pm 0.005 \mu\text{m}$. The average peak position of all NH-rich ROIs (2.712–2.719 μm , Fig. s3b) is comparable to matrix-rich material of Ryugu and Bennu samples, but falls on the slightly shorter wavelength side of the distribution^{19,22,23}. A robust positive correlation can be observed between the -2.7 and -3.1 μm depth for ROIs from Bennu (Fig. s3c) and Ryugu Chamber C, whereas Ryugu Chamber A ROIs display deeper OH bands but weaker uncorrelated NH features. The 2.7 μm OH band can be roughly decomposed into three Gaussian curves that peak at -2.71, -2.76, and -2.85 μm (Fig. s6b), with no clear differences between Bennu, Ryugu Chamber A, and Ryugu Chamber C. The most intense component at -2.71 μm is typically associated with Mg-OH stretching^{23,24}. The features at longer wavelengths (-2.76 and -2.85 μm) reflect a more diverse cationic environment, including the Fe-OH stretching and potentially the influence of hydrogen bonding. Compared to matrix typical spectra, NH-rich ROIs have more prominent second sub-peaks around 2.76 μm (-3600 cm^{-1}); thus, making the OH band broader on its right-wing (Fig. s7). In addition, most of the ROIs exhibit a weak 2.32 μm feature (Fig. 1), corresponding to the combination mode of OH stretching and Mg-OH bending²⁵.

These ROIs are less frequent than other minor phases (similar size scale, a few hundreds of microns) detected with MicrOmega, such as carbonates (-700 detections in Ryugu up to June 2024 and -90 in Bennu up to November 2024²⁶) and HAMP grains (a few tens of detections with comparable area sizes in both Ryugu and Bennu samples^{19,22}). Noticeably, NH-rich ROIs in this study do not show a strong and wide 3 μm water absorption like HAMP grains.

Mid-IR spectra

Complementary mid-IR spectra with spot size -70 μm were measured on a few ROIs of Bennu samples without any atmospheric exposure. In addition to the -2.7 and -3.06 μm features already observed with MicrOmega, we could identify the systematic presence of a -6.1 μm (-1640 cm^{-1}) band attributed to H_2O bending mode, a -7 μm (-1430 cm^{-1}) band attributed to the ν_4 out-of-plane bending mode of NH_4^+ , as well as a pronounced -10 μm (-1025 cm^{-1}) band corresponding to Si-O stretching vibrations of phyllosilicates (Fig. 2). Weaker bands at -3.28 μm (-3049 cm^{-1}), and -3.54 μm (-2825 cm^{-1}) are also present for the spectra that show the highest quality. They are tentatively attributed to $\nu_2 + \nu_4$ asymmetric stretching and $2\nu_4$ bending modes of NH_4^+ , respectively¹². The Si-O band positions of the NH-rich areas are

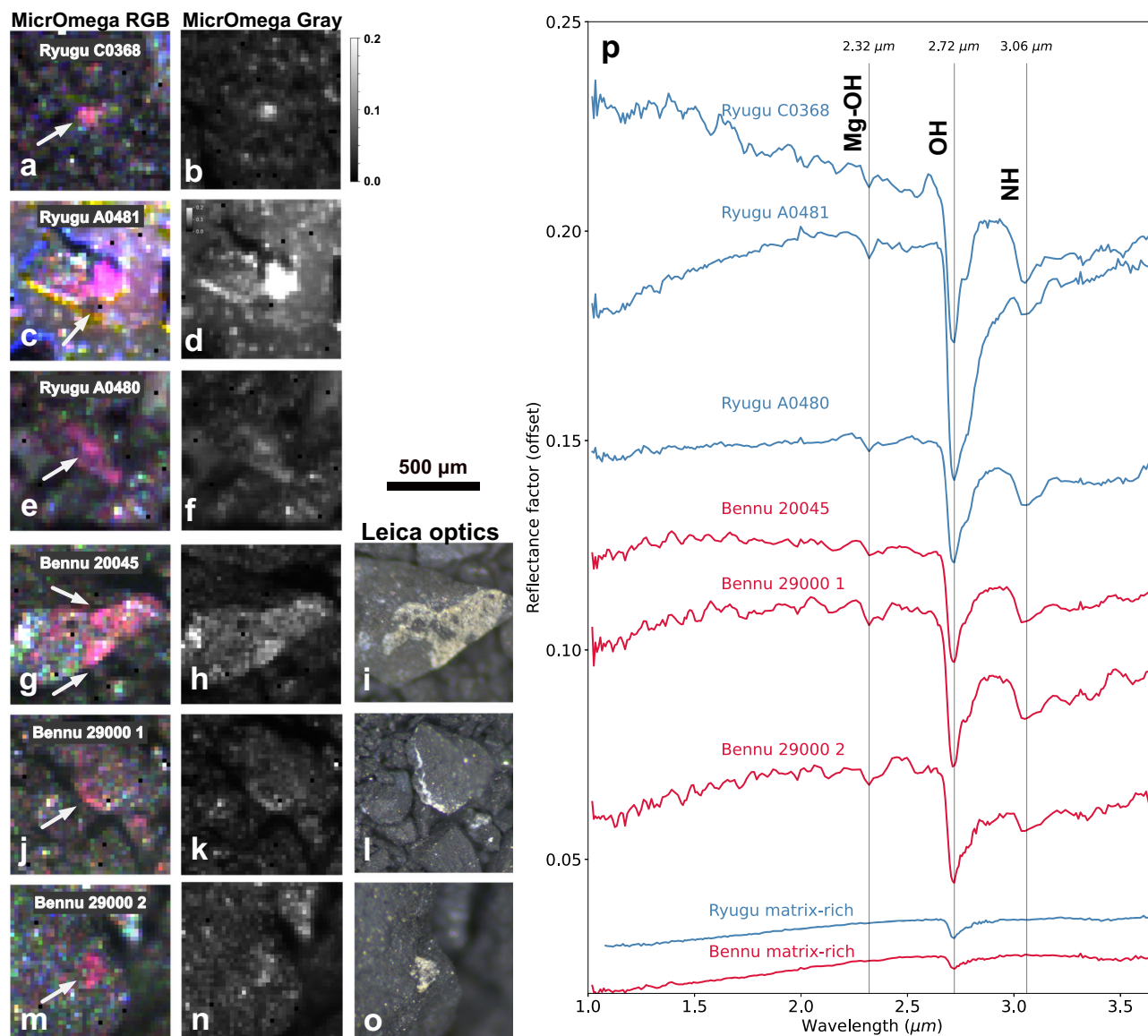


Fig. 1 | Examples of images and corresponding average MicroOmega spectra of the NH-rich regions of interest (ROIs) detected in Ryugu and Benu samples. The first column (MicroOmega RGB) (a–m) shows RGB images of the ROIs measured by MicroOmega, with $R = 2.01 \mu\text{m}$, $G = 2.71 \mu\text{m}$, $B = 3.45 \mu\text{m}$. The second column (MicroOmega Gray) (b–n) shows grayscale images of the average reflectance factor (REFF) values between 2.0 and 2.5 μm , with scale bars ranging from 0.0 to 0.2. The third column (Leica optics) (i–o) shows the optical images acquired with a Leica microscope implemented for Benu samples only. White arrows indicate the ROIs.

All the subfigures share the same scale bar. Panel p (right) shows the average spectra corresponding to the example ROIs on the left, compared to the matrix-rich material spectra of Ryugu and Benu. All the spectra are shown in REFF with offset applied but without stretching. The number of pixels averaged for Ryugu C0368, A0481, A0480, Benu 20045, 29000-1, 29000-2 ROI spectra displayed in (p) is 27, 105, 95, 239, 34, 56, respectively. Mg–OH, OH, and NH are the positions of the corresponding vibration modes.

systematically located in the shorter wavelength range (centered at $9.71 \mu\text{m}$ ($1030 \pm 10 \text{ cm}^{-1}$)) of the matrix phyllosilicates band positions (the majority centered at $9.80 \mu\text{m}$ ($-1020 \pm 20 \text{ cm}^{-1}$)) (Figs. 3 and s8). A positive correlation is observed between the areas of the $-2.7 \mu\text{m}$ (-3682 cm^{-1} , OH mode), the $-3.1 \mu\text{m}$ (-3268 cm^{-1} , NH mode) and the $-7 \mu\text{m}$ (-1430 cm^{-1} , NH_4^+ bending mode) bands (Figs. 3 and s8).

Noticeably, at the scale of the NH-rich ROIs, the $-2.7 \mu\text{m}$ (-3682 cm^{-1}) and $-3.06 \mu\text{m}$ (-3268 cm^{-1}) features show a good positive correlation, both with MicroOmega (Fig. s3c) (excluding Ryugu Chamber A) and MIR observations (Fig. 3c). But at the scale of MicroOmega pixel size ($\sim 22 \mu\text{m}$), we can observe that in some ROIs, the pixels corresponding to NH maximum band depth are slightly spatially shifted or more localized than the pixels that correspond to the OH maximum band depth, implying some spatial variability in the NH-enrichment.

Importantly, our results show that there is no spatial correlation with the spatial distribution of the $3.4 \mu\text{m}$ band (when there is one) corresponding to the C–H vibration mode and/or carbonates (Fig. s9).

Discussion

Based on the MicroOmega measurements, the NH-rich ROIs in both Ryugu and Benu samples exhibit striking physical and spectral similarities. Physical features are characterized by a relatively large size (on the order of hundreds of micrometers) and are visually brighter than the surrounding matrix, while displaying various morphologies. Spectrally, the strong $3.06 \mu\text{m}$ NH band is spatially correlated with a strong $2.72 \mu\text{m}$ OH absorption band, and crucially, its highly similar shape and position for the NH band strongly suggests that these ROIs contain the same NH-rich species.

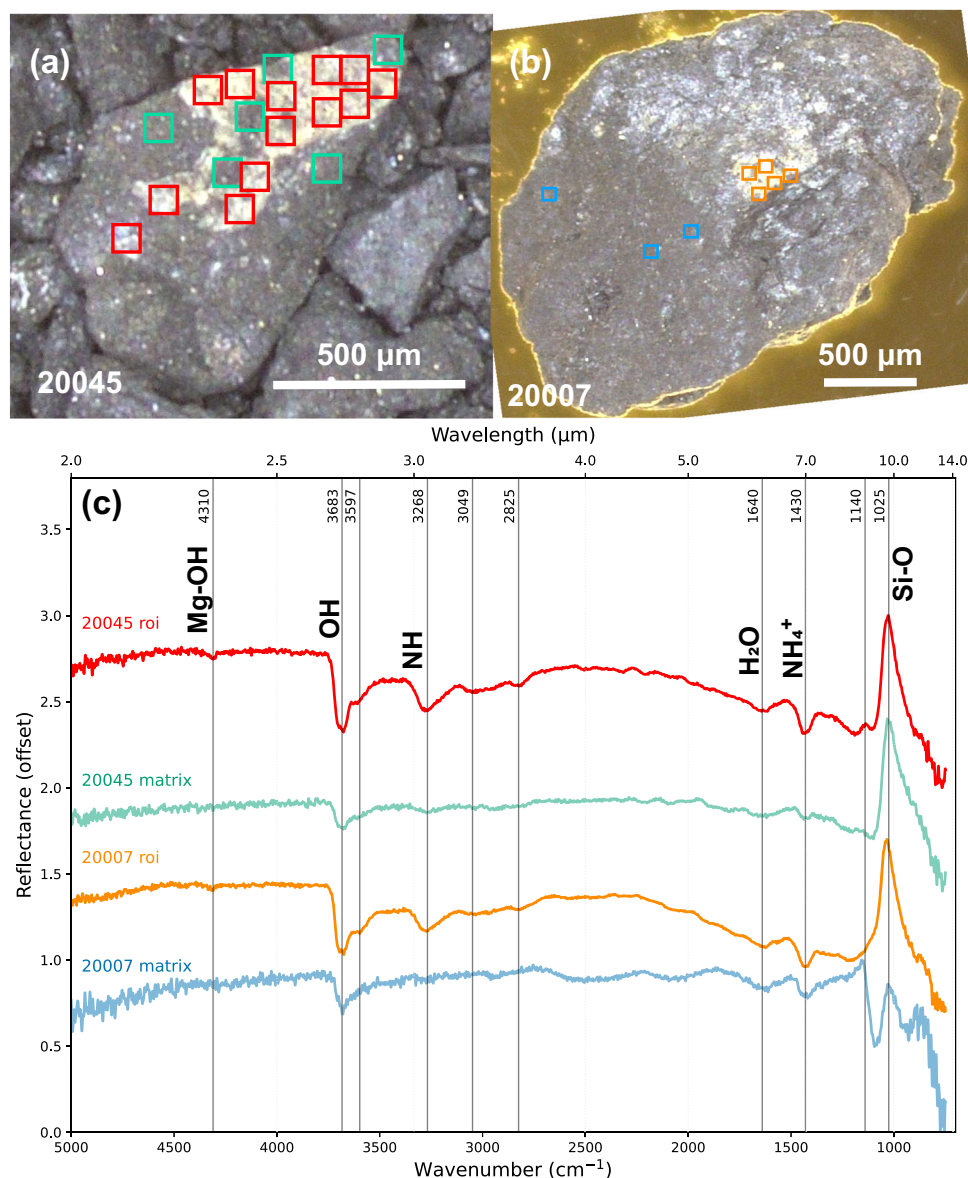


Fig. 2 | Typical Leica microscopic images and MIR spectra of the NH-rich regions of interests (ROIs). **a, b** are Leica images of ORX-20045 (aggregate) and ORX-20007 (grain) Benu samples, respectively, and the surrounding areas were

measured by an FTIR spectrometer. In **a** and **b**, the spot sizes for each ROI and matrix measurement are $\sim 70\ \mu\text{m}$. The corresponding spectra in **(c)** are an average of all identically colored square spots from **(a)** and **(b)**.

The $3.06\ \mu\text{m}$ band appears to decompose into two small sub-peaks in the NH-rich ROIs. This NH signature in the Benu ROIs is precisely constrained by the additional MIR spectral data. The strong positive correlation between the NH_4^+ ν_4 out-of-plane bending band ($\sim 7\ \mu\text{m}$) and the NH stretching band ($\sim 3.06\ \mu\text{m}$) and their intensities is consistent with NH_4^+ being the major contributor to the NH stretching band. This deduction rules out NH bearing organic functional groups, namely amines (R-NH_2), amides (R-CO-NH_2), and free ammonia (NH_3) as primary sources of the N-H stretching signature detected by MicrOmega²⁷. While the ν_1 symmetric mode ($\sim 3.29\ \mu\text{m}$) of free NH_4^+ is infrared inactive, its ν_3 stretching mode ($2.99\text{--}3.23\ \mu\text{m}$) is triply degenerate. When incorporated into solid crystalline matrices, such as ammonium salts or phyllosilicate interlayers (e.g., refs. 28–30), the reduced local symmetry causes this ν_3 band to split into multiple components, which may account for the observed dual sub-peaks at $3.06\ \mu\text{m}$.

Therefore, the combined spectroscopic evidence indicates that the NH-rich ROIs in both Benu and Ryugu are, in fact, ammonium-rich regions and contain the same ammonium (NH_4^+)-bearing species.

We further constrain the (NH_4^+)-bearing matter chemical composition by examining its potential link with organic compounds. Organic matter is ubiquitous in both Ryugu and Benu samples, with a shallow $3.4\ \mu\text{m}$ CH band^{19,20,22,31} of the bulk sample. The absence of clear or systematic C-H absorption for NH-rich ROIs around $3.4\ \mu\text{m}$ (in both MicrOmega and MIR data) suggests that organic compounds are absent or present only in trace amounts around the ammonium moieties. Furthermore, the absence of infrared bands corresponding to the fundamental stretching modes of carboxylate (RCOO^- , $\sim 6.25\text{--}6.50$ and $7.25\text{--}7.4\ \mu\text{m}$), or cyanide (CN^- , $4.5\text{--}4.8\ \mu\text{m}$), or cyanate (OCN^- , $\sim 4.6\ \mu\text{m}$) moieties, discards the possibility of the NH_4^+ signature being primarily attributed to the corresponding organic salts suggested for comet 67P².

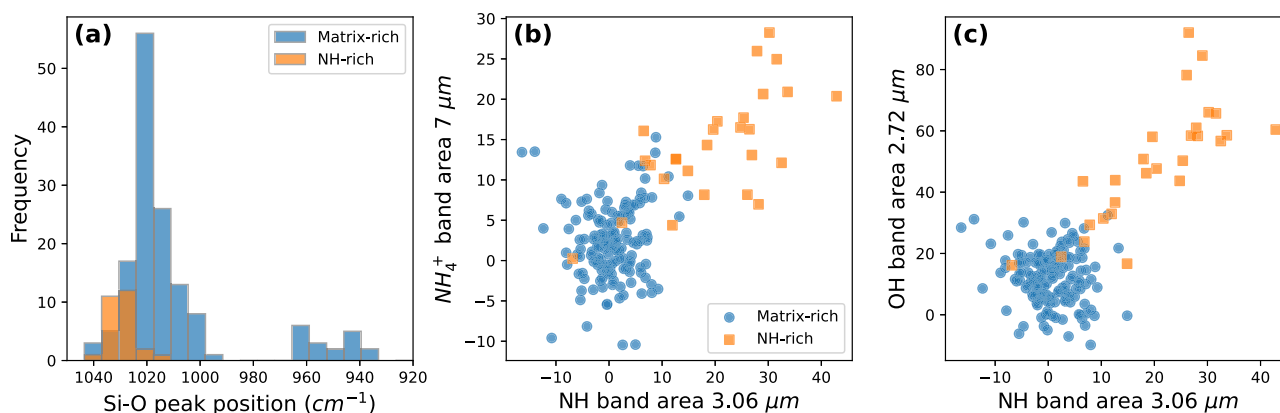


Fig. 3 | Spectral parameters extracted from MIR spectra of the NH-rich and matrix-rich grains. a Histogram of Si–O peak position with a polynomial fitting (7 degree, Fig. s15) between 930 and 1080 cm^{-1} . **b** scatter plot of NH band area at 3.06 μm and NH_4^+ band area at 7 μm . **c** Scatter plot of NH area at 3.06 μm and OH

area at 2.72 μm . Each spot in **(b)** and **(c)** is one single MIR measurement on the sample; some of them are within the same region of interest/grain but different sub-areas.

Given the systematic presence of the strong O–H absorption at $\sim 2.7 \mu\text{m}$ and the Si–O band at $10 \mu\text{m}$ (indicative of Mg-rich phyllosilicate), the candidates are then narrowed to inorganic ammonium salts intimately mixed with phyllosilicates, or ammoniated phyllosilicates.

To constrain the identity of NH_4^+ potential counterion(s) (if the compound is a salt), we systematically compare our data with the spectra of specific ammonium salts (Fig. s10, Table s1). We first exclude ammonium hydrosulfide (NH_4SH), also identified in 67P coma^{3,4}, as its $3 \mu\text{m}$ absorption band shape is different, and the characteristic S–H stretching at $5.3 \mu\text{m}$ (1890 cm^{-1}) is absent in the MIR spectra (Fig. s10). Ammonium carbonates (e.g., $(\text{NH}_4)_2\text{CO}_3$)¹², previously considered for Ceres bright facula³², are excluded by the absence of characteristic CO_3^{2-} bands at 3.4, 3.9, and its strong reststrahlen band near $7 \mu\text{m}$ ¹². Similarly, P–O stretching bands are not observed between 8.3 and $11 \mu\text{m}$ ³³, excluding ammonium phosphates, pyrophosphates, etc., and the HAMP grains detected in Ryugu and Bennu samples^{21,22}. Candidate counterions without signatures in the mid-infrared (MIR) range, like chloride ion (Cl^-) and the corresponding ammonium chloride (NH_4Cl)¹², also do not match the spectra because the positions and shapes of the ammonium stretching and bending bands ($3\text{--}3.5$ and $6.9 \mu\text{m}$) clearly differ from those of the NH-rich ROIs (Fig. s10). The other halides, with F^- , Br^- , and I^- as counterions, will behave spectrally similarly to NH_4Cl ^{2,34}, and are unlikely candidates given their significantly lower bulk abundances expected in Cl-like material compared to chlorine³⁵, and the relatively large spatial scale of the observed NH-rich ROIs. Sulfate (SO_4^{2-}) might contribute to the little peak around $9.6 \mu\text{m}$ (1040 cm^{-1}) (Fig. 2), but this peak is not systematically present, indicating that SO_4^{2-} cannot be the major counterion. Additionally, the ν_3 band for ammonium sulfate is generally more blue-shifted ($\sim 3.0 \mu\text{m}$)¹², making it less likely a candidate.

Then, based on these comparisons and arguments, ammonium salts cannot be the main carriers of the ammonium-rich ROIs detected by MicrOmega.

Ammoniated phyllosilicates exhibit characteristic additional absorption bands at ~ 3.06 , ~ 3.3 , ~ 3.5 , and $\sim 7 \mu\text{m}$ compared to non-ammoniated ones^{11–13,36}. These features align well with the NH-rich ROI spectra, and ammoniated phyllosilicates are the best fit to explain the spectral signatures characterizing the ammonium-rich ROIs. Furthermore, the strong correlation between the OH ($2.7 \mu\text{m}$) and NH ($3.06 \mu\text{m}$) bands, observed by both MicrOmega and MIR, provides evidence for a close physical association between NH_4^+ and the phyllosilicate, and strongly suggests the interlayer incorporation of NH_4^+ . Further analysis of the host phyllosilicate phase reveals subtle but

systematic differences compared to the bulk matrix. The OH band in the NH-rich ROIs is notably asymmetric with a wider right shoulder compared to the matrix (Fig. s7). This widening could be caused by hydrogen bonding interactions between NH_4^+ , residual H_2O , and the hydroxyl groups within the phyllosilicate interlayers as invoked for ammoniated-phyllosilicates³⁷. Similarly, the Si–O band of the NH-rich ROIs is centered at $\sim 1030 \pm 10 \text{ cm}^{-1}$, which represents a slight shift toward the shorter wavelength (higher wavenumber) compared to the bulk matrix materials ($\sim 1020 \pm 20 \text{ cm}^{-1}$ (Figs. 3 and s8)), and the band is usually sharp and narrow (Fig. 2). The NH-rich ROIs exhibit an OH band minimum centered at ~ 2.715 with a variability of $\pm 0.003 \mu\text{m}$ across the surveyed ROIs (ranging from 2.712 to $2.719 \mu\text{m}$). While this position is nearly identical to the bulk matrix signature of both Ryugu and Bennu samples, indicating a similar structure and mixture of saponites and serpentines with a globally similar Mg/Fe ratio, there is a subtle shift toward the shorter wavelength end for the ammonium-rich ROIs. This subtle shift either suggests a slight structural difference or a slightly higher Mg/Fe ratio. These systematic differences indicate that the phyllosilicates of the NH-rich ROIs have slight structural differences compared to the typical phyllosilicate mixture of the matrix. Thus, either the interlayer structure is simply affected by the presence of NH_4^+ species and displays a somewhat different signature, or the phyllosilicates hosting ammonium in their interlayers are the result of a slightly different process of alteration that resulted in a somewhat different phyllosilicate mixture and structure than the rest of the matrix. In any case, matrix materials of Ryugu and Bennu samples are dominated by intergrown Mg-rich saponite and serpentine-like material^{38,39}, which the spatial resolution of the IR instruments used here cannot distinguish. However, among these two phyllosilicate types, saponite-like material is the only one that can effectively incorporate NH_4^+ into the interlayers of its structure.

Although a $6 \mu\text{m}$ band for the water molecule is present in the FTIR spectra of the ROIs, the absence of a strong, wider absorption near $3 \mu\text{m}$, suggests limited interlayer H_2O . To form ammoniated phyllosilicates, the initial formation process would require NH_4^+ -containing fluid (most likely water) to be absorbed and retained within the interlayer, suggesting that both H_2O and NH_4^+ should be readily detectable in this region. However, our spectroscopic analysis contradicts this expectation: we observe no correlation between H_2O ($6 \mu\text{m}$) and NH_4^+ ($3.06 \mu\text{m}$) or H_2O and Si–O (Fig. s8). In fact, the H_2O signal in the $6 \mu\text{m}$ area is roughly at the same level of intensity as that of the matrix-rich materials (Fig. s8). This observation may be explained by studies showing that NH_4^+ can establish several hydrogen bonds with oxygen atoms in the phyllosilicate layers⁴⁰, which reduces the

swelling ability and H₂O retention, leading to smaller layer spacing in ammoniated smectite^{13,41}.

In conclusion, the spectral evidence discards organic matter and organic and inorganic salts as the main species responsible for the ammonium signatures we are reporting here, and strongly supports structural integration of ammonium species in phyllosilicate interlayers as the main contributor to these infrared signatures.

The high albedo of the ammonium-rich ROIs (2–4× brighter than the host matrix) suggests a localized change in composition and/or physical state. This brightness may result from a lower abundance of opaque phases (e.g., magnetite or complex organics) or a reduction in effective grain size, both of which increase spectral reflectance. It is thus either the particular structure of the ammonium-bearing phyllosilicates or their potential mixture with less opaque phases that would explain their particular brightness.

Ammonium-rich ROIs in Ryugu Chamber A exhibit slightly different N–H band positions and depths compared to Chamber C. One possible explanation is space weathering since they were sampled at different depths; however, no similar trend is observed for the O–H band of ammonium-rich ROIs between Chambers A and C²³, possibly reflecting different sensitivities of the hydroxyl moiety and ammonium to space weathering. Another possibility is that Chamber A and C samples contain slight differences in the ammonium-bearing phase, but this cannot be confirmed due to the lack of MIR data. On the other hand, the band depth difference for the 3.06 μm band between Chamber A (surface material, shallow) and Chamber C (subsurface material, deeper) in Ryugu data might reflect their divergent evolution history. Processes such as space weathering or thermal cycling could have induced the loss of some of the ammonium or modified the structure of the NH₄-bearing phase.

Strong near-IR spectral similarities regarding Ryugu and Benu samples were also observed for the phyllosilicate-rich matrix, carbonates, and HAMP-type phosphates^{22,26}, supporting the idea of similar (though not identical) alteration and evolution processes on their parent bodies. The ammonium-rich phyllosilicate phase is 6 times more frequently detected and exhibits larger band depths in Benu samples than in Ryugu. Indeed, the total detected NH-rich ROI area across all sample categories (bulk, sub-bulk, and grains; Table s2) are comparable: $\sim 8.0 \times 10^2$ pixels (~ 0.40 mm²) in Ryugu versus $\sim 8.5 \times 10^2$ pixels (~ 0.43 mm²) in Benu. However, Ryugu has substantially more measurement areas (96 dishes with ~ 61 equivalent dish area coverage) compared to Benu (14 dishes with ~ 8 equivalent dish area). The number of detected NH-rich pixels is similar (~ 500 pixels or 0.258 mm² in Ryugu versus ~ 410 pixels or 0.208 mm² in Benu). Furthermore, in the average spectra of all NH-rich ROIs (Fig. s7), after normalizing the OH band depth at 2.7 μm, the NH band at 3.06 μm is deeper for the Benu samples than for the Ryugu ones. Both pieces of evidence suggest that while the total bulk N abundance may be generally similar⁴², the ammoniated phyllosilicates are clearly more abundant in Benu than Ryugu samples.

Liquid extraction of Ryugu grains allowed to find a small amount of NH₄⁺ (up to 0.18 μmol/g) in the water-soluble fraction, a concentration significantly lower than that in the Orgueil meteorite (33.54 μmol/g)⁴³. Glavin et al.⁴² further confirmed this disparity, reporting that free ammonia was much higher in Benu (13.6 μmol/g) than in Ryugu. The efficiency of hot water extraction of NH₄⁺ interlayered within saponite structures is uncertain, making the relative contribution from salts and phyllosilicate phases challenging to estimate, thus precluding a direct comparison with our observations. However, both results may indicate that Benu's parent material may have originally accreted a larger abundance of ammonia and/or ammonium in its ice phase.

The identification of NH₄⁺-bearing phyllosilicate provides compelling evidence for a second inorganic ammonium reservoir in both Ryugu and Benu, complementing the first, the HAMP-like grains,

previously reported²¹. This result also supports studies suggesting multiple distinct nitrogen reservoirs in Ryugu, where nitrogen is partitioned between N-bearing organic matter and inorganic phases like salts or minerals⁴⁴. The spectra of the NH-rich Regions of Interest (ROIs) exhibit striking similarities to remote-sensing data from Ceres and Hygiea¹⁶ across the 2.5–3.5 μm spectral range (Fig. 4). Specifically, they share key features at 2.7 μm (OH) and 3.06 μm (NH). This spectral resemblance is notable, despite the significant differences in scale (micrometer-scale ROIs versus global, kilometer-scale features) and abundance (minor, highly localized components versus material ubiquitous across the surface)⁴⁵. Crucially, the 3.06 μm NH band is nearly identical for Ceres, Hygiea, and the NH-rich ROIs (measured by both MicrOmega and MIR) (Fig. s11b), which strongly suggests the presence of similar NH-rich components. Despite this strong match, minor variations exist. Upon continuum removal, the 2.7 μm OH band in Ceres' spectrum is slightly shifted to a longer wavelength compared to the NH-rich ROIs (Fig. s11a). Furthermore, neither Ceres nor Hygiea displays a clear band around 2.3 μm. These minor differences suggest a slight variation in the nature of the phyllosilicate. Previous laboratory studies attempting to reproduce the Ceres spectrum using ammonium-bearing phyllosilicates often faced a major challenge: the presence of interlayer absorbed water, which produces a deep and wide 3 μm water absorption feature. While recent work (e.g., ref. 37) has shown that heating in a vacuum can remove this interlayer water, replicating the exact band shape around 3 μm remains difficult. Despite the minor variations that suggest a slight difference in the nature of phyllosilicates, the exceptional spectral match still suggests the possibility of a common or closely related formation process.

The detection of a growing number of spectrally Ceres-like and 67P-like small bodies in the main asteroid belt (e.g., refs. 14,15,46) and among the satellites of Jupiter and Saturn (e.g., ref. 18) suggests that Ceres and 67P are not exceptional cases. This implies a wide distribution of ammonium-bearing compounds in the solar system. Some asteroids, exhibiting only the sharp 2.7 μm absorption, but lacking the 3.06 μm band, were previously thought to have formed within the NH₃ snow line¹⁵. No strong 3.06 μm absorption was remotely observed on Ryugu (e.g., ref. 47), Benu (e.g., ref. 48), or their potential parent body, the Polana family⁴⁹. However, the returned samples from both Ryugu and Benu revealed small, yet significant, quantities of ammonium-bearing phyllosilicate. This crucial result indicates that these asteroids, presumed to be devoid of ammonium-bearing material, may in fact harbor it in trace amounts. This strongly suggests a far more ubiquitous distribution of ammonium compounds throughout the Solar System than remote spectral data alone can reveal. Notably, together with HAMP material, NH₄⁺-bearing phyllosilicates could constitute one major contributor of ammonium in the CI chondrites⁵⁰, though their perseverance through exposure to the terrestrial environment still remains unexplored.

The formation of ammoniated phyllosilicates and ammonium salts (like the HAMP grains) via aqueous alteration provides a robust mechanism for the long-term storage and delivery of nitrogen. Ammonium salts are considered a significant nitrogen reservoir for comets, such as 67P, and likely other small celestial icy bodies 67P^{2–4}. Their lower volatility compared to pure ammonia (NH₃) allows them to be incorporated into C-type asteroids during their formation in the outer Solar System. Upon the onset of aqueous alteration, these initial (first-generation) ammonium salts, which are typically highly soluble, readily dissolve, releasing ammonium ions (NH₄⁺). These mobile NH₄⁺ ions can then participate in forming a new generation of more stable ammonium compounds, such as less soluble secondary ammonium salts (e.g., those HAMP grains detailed in refs. 21,22) and ammoniated phyllosilicates, or be converted to NH₃ and lost if the pH is alkaline. For secondary salts to persist, they must either have low solubility or have formed late during the dehydration phase of the parent body. These more stable compounds could then be transported into the inner Solar

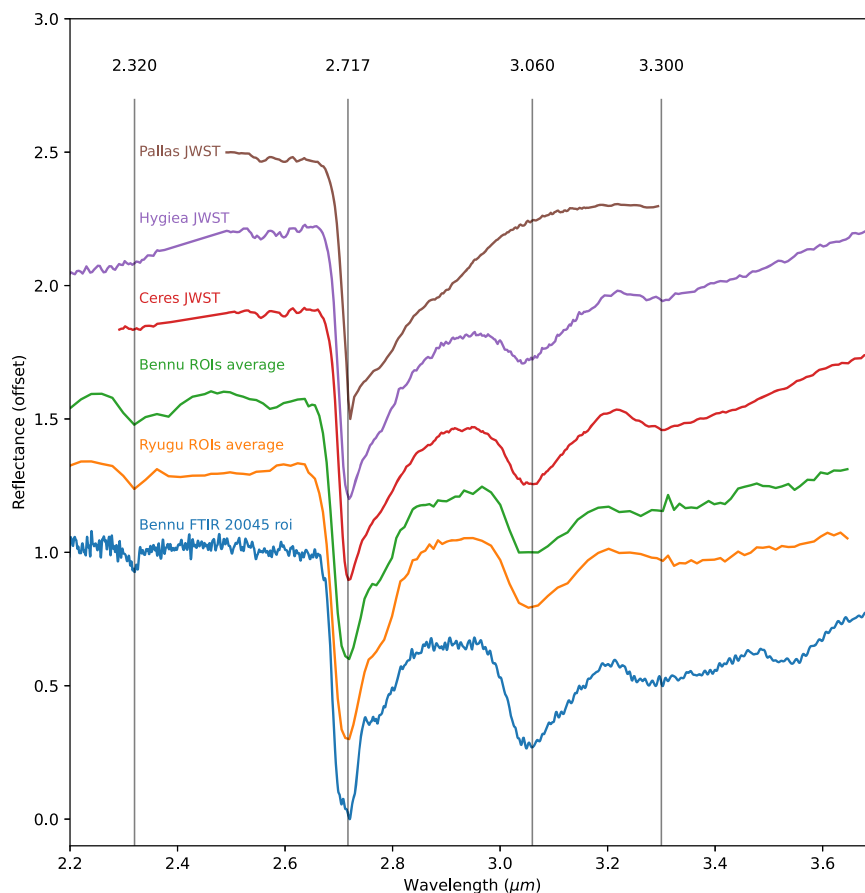


Fig. 4 | Comparison of the spectra of the NH-rich regions of interests (ROIs) with Ceres, Hygiea, and Pallas data observed by the James Webb Space Telescope (JWST)¹⁶. “Benu FTIR 20045 roi” is the FTIR average spectrum of several spots for the NH-rich ROI in the aggregate sample ORX-20045. “Benu ROIs

average” and “Ryugu ROIs average” are the average MicroOmega spectra for all the Benu and Ryugu NH-rich ROIs, respectively. All the spectra are first stretched to be 1 at 2.5 μm and 0 at 2.72 μm , then shifted with different offsets for clarity.

System, providing a vital mechanism for delivering essential volatile elements (nitrogen and hydrogen) to the terrestrial planets, potentially influencing the early chemical inventory necessary for the development of life.

Methods

Samples

Both Ryugu and Benu sample collections are stored and measured under a controlled environment (N_2 purged) to avoid terrestrial contamination and alteration^{31,51}. From 2021 to May 2024, MicroOmega has measured almost half (in weight) of the Ryugu returned samples (~5.4 g) in the form of aggregates (~54 for Chamber A and ~42 for Chamber C, small subsets extracted from the 6 bulks) and individual (mm-sized) grains (>500). Thanks to an agreement between NASA and JAXA, ~0.6 g of Benu samples was also delivered to the Extraterrestrial Sample Curation Center (ESCuC) at JAXA for comparative studies. From September 2024 to September 2025, MicroOmega measured all the 5 bulk samples (~0.6 g), 14 aggregates, and ~110 individual (mm-sized) grains.

MicroOmega

MicroOmega is an infrared hyperspectral microscope developed at the Institut d'Astrophysique Spatiale (Orsay, France)⁵², and is now installed inside the Hayabusa2 Curation Facility at JAXA ESCuC (Extraterrestrial Samples Curation Center). It covers the spectral range 0.99–3.65 μm with a pixel size of $\sim 22.5 \times 22.5 \mu\text{m}^2$, and a total field of view covering $\sim 5 \times 5 \text{ mm}^2$. At the time of measurement, all the samples had never been exposed to the terrestrial atmosphere, so they are pristine in this

respect. Also, considering that the Ryugu samples do not contain a lot of water^{23,53}, and were not exposed to terrestrial atmosphere, the 3.06 μm feature is not hidden or biased by the wide, strong 3 μm absorption by H_2O . The sample holder is mounted on a stage with 3 moving axes and one rotational axis, so that to adjust the region of interest to the field of view in terms of position and focus, and to rotate the sample to vary the viewing geometry. All the samples were measured with an incidence angle of 35° and a viewing angle of 0° . MicroOmega uses an acousto-optic tunable filter (AOTF) as a dispersive system, with a full width at half maximum of $\sim 20 \text{ cm}^{-1}$ and minimum sampling steps of $\sim 2 \text{ cm}^{-1}$. The spectral accuracy is evaluated to be better than 5 nm. Radiometric calibration was performed first at the Institut d'Astrophysique Spatiale and then periodically within the Curation Facility, using two reference targets: Spectralon 99% and Infragold from Labsphere⁵⁴.

Visible microscopy and mid-IR spectrometry

For Benu samples, MicroOmega data were combined with images from a LEICA visible microscope and mid-IR spectral data obtained by a micro-FTIR spectrometer JASCO IRT-5200/VIR-200 (single pixel, $\sim 50\text{--}100 \mu\text{m}$ FOV, spectral range 2–13 μm), both present within the curation facility. Regarding the micro-FTIR spectrometer, the spectral resolution is 4 cm^{-1} with sampling 1 cm^{-1} . The geometry of the measurement is 0° incident and 0° viewing. Sample data is calibrated with a gold mirror from Labsphere. Samples are simply transferred from one instrument to another without leaving the N_2 -purged curation chambers.

Spectral index extraction for NH-rich ROIs with MicrOmega data

We use the average spectrum of the grain (Fig. s12) from the first NH-rich detection in ref. 19 as a reference spectrum. We perform a continuum removal by dividing the spectrum in the 2.5–3.2 μm range to suppress noise influence originating from the dark region. Subsequently, the similarities (covariance) between the reference spectrum and the spectrum of each pixel are calculated. Then we select the enriched regions with high similarity (strong 3.06 and 2.7 μm bands) and check for consistency at different orientations to increase the confidence. We have three confidence levels: Level 1 for low similarities without confirmation in different orientations, Level 2 for high similarities without confirmation in different orientations or low similarities with confirmation in different orientations, and Level 3 for high similarities with confirmation in different orientations. Here, the threshold is $\geq 5 \times 10^{-5}$ for similarities and ≥ 2 for orientations.

Reference spectra of Ryugu and Bennu bulk samples

To show the differences between the usual matrix-rich material spectra and those of the NH-rich ROIs, we used the bulk measurement for Ryugu and Bennu sample^{19,22} (Fig. s13).

2.72 and 3.06 μm band fitting methods

To quantitatively understand the band parameters, such as band position and depth, of 2.7 and 3.06 μm absorptions, we have done a 3-gaussian peaks fitting. We first get the continuum with ConvexHull methods from the Python package `scipy.spatial` at two wavelength regions, 2.55–3.0 and 2.95–3.25 μm . Here, we divide the spectrum by the continuum to have a better understanding of the relative band depth. Then we convert wavelength to wavenumber space and used 3-gaussian peaks to fit the curves:

$$f(x) = \sum_{i=1}^3 a_i \exp\left(-\frac{(x - \mu_i)^2}{2\sigma_i^2}\right), \quad (1)$$

where a_i , μ_i , σ_i represents the amplitude, mean (center), and standard deviation (width) of the gaussian peak, respectively. We chose a 3-gaussian fitting for the band at 2.72 μm and 2-gaussian for the band at 3.06 μm as the minimum for an acceptable fitting. We used the `curve_fit` method on the Python packages `scipy.optimize` to do the fitting. This fitting methods for OH band is slightly different from the one used in ref. 23, but the comparison between the two methods showed that they agree with each other within 2 nm difference.

Consistency between MicrOmega and MIR data in the overlapping region

The spectral range between 2 and 3.64 μm constitutes an overlapping region between the MicrOmega and MIR measurements. Figure s14 displays a comparative analysis of the NH-rich Regions of Interest (ROIs) derived from both instruments. Following a two-point normalization (where the spectra are set to unity at 2.5 μm and zero at 2.72 μm to match the OH absorption band depth), the resulting spectral shapes show excellent agreement.

Spectral parameter extraction methods for MIR spectrum

To isolate specific absorption features, the linear continuum was removed across several wavenumber space (in cm^{-1}) (Fig. s15): [4255, 4385] for Mg-OH ($\sim 2.3 \mu\text{m}$), [3448, 3846] for OH- ($\sim 2.7 \mu\text{m}$), [3100, 3400] for NH- ($\sim 3.06 \mu\text{m}$), [1550, 1750] for H_2O ($\sim 6.10 \mu\text{m}$), and [1360, 1500] for NH_4^+ ($\sim 7.0 \mu\text{m}$). For each region, the two endpoints of the linear continuum are defined by averaging the values of 5 surrounding data points. The Si-O peak was subsequently extracted by applying a 7th-degree (Fig. s16) polynomial fitting to the region between 930 and 1080 cm^{-1} .

Data availability

Images and source data are provided in the Source Data file. IR spectral data of the ROIs will also be available in the catalog of Ryugu and Bennu samples (<https://darts.isas.jaxa.jp/app/curation/ryugu/>, <https://darts.isas.jaxa.jp/app/curation/bennu/>). Other data and images on the Ryugu and Bennu samples are available at the same address. Source data are provided with this paper.

References

- Bockelée-Morvan, D. & Biver, N. The composition of cometary ices. *Philos. Trans. R. Soc. A*. **375**, 20160252 (2017).
- Poch, O. et al. Ammonium salts are a reservoir of nitrogen on a cometary nucleus and possibly on some asteroids. *Science* **367**, eaaw7462 (2020).
- Altwegg, K. et al. Evidence of ammonium salts in comet 67P as explanation for the nitrogen depletion in cometary comae. *Nat. Astron.* **4**, 533–540 (2020).
- Altwegg, K. et al. Abundant ammonium hydrosulphide embedded in cometary dust grains. *Mon. Not. R. Astron. Soc.* **516**, 3900–3910 (2022).
- King, T. V. V., Clark, R. N., Calvin, W. M., Sherman, D. M. & Brown, R. H. Evidence for ammonium-bearing minerals on Ceres. *Science* **255**, 1551–1553 (1992).
- De Sanctis, M. C. et al. Ammoniated phyllosilicates with a likely outer Solar System origin on (1) Ceres. *Nature* **528**, 241–244 (2015).
- Glavin, D. P. et al. The origin and evolution of organic matter in carbonaceous chondrites and links to their parent bodies. In *Primitive Meteorites and Asteroids*. 205–271 <https://doi.org/10.1016/B978-0-12-813325-5.00003-3> (Elsevier, 2018).
- Smith, L. R. et al. Rare phosphides and nitrides in igneous clasts within aqueously altered chondrites. *Planet. Sci. J.* **6**, 122 (2025).
- Chan, Q. H. S. et al. Organic matter in extraterrestrial water-bearing salt crystals. *Sci. Adv.* **4**, eaao3521 (2018).
- Singh, S. K. et al. Origin of ammoniated phyllosilicates on dwarf planet Ceres and asteroids. *Nat. Commun.* **12**, 2690 (2021).
- Bishop, J. L., Banin, A., Mancinelli, R. L. & Klovstad, M. R. Detection of soluble and fixed NH_4^+ in clay minerals by DTA and IR reflectance spectroscopy: a potential tool for planetary surface exploration. *Planet. Space Sci.* **50**, 11–19 (2002).
- Berg, B. L. et al. Reflectance spectroscopy (0.35–8 μm) of ammonium-bearing minerals and qualitative comparison to Ceres-like asteroids. *Icarus* **265**, 218–237 (2016).
- Ehlmann, B. L. et al. Ambient and cold-temperature infrared spectra and XRD patterns of ammoniated phyllosilicates and carbonaceous chondrite meteorites relevant to Ceres and other solar system bodies. *Meteor. Planet. Sci.* **53**, 1884–1901 (2018).
- Takir, D. & Emery, J. P. Outer Main Belt asteroids: identification and distribution of four 3- μm spectral groups. *Icarus* **219**, 641–654 (2012).
- Rivkin, A. S. et al. The nature of low-albedo small bodies from 3 μm spectroscopy: one group that formed within the ammonia snow line and one that formed beyond it. *Planet. Sci. J.* **3**, 153 (2022).
- Rivkin, A. S. et al. Observations and quantitative compositional analysis of Ceres, Pallas, and Hygiea using JWST/NIRSpec. *Planet. Sci. J.* **6**, 9 (2025).
- Kurokawa, H. et al. Distant formation and differentiation of outer main belt asteroids and carbonaceous chondrite parent bodies. *AGU Adv.* **3**, e2021AV000568 (2022).
- Sharkey, B. N. L. et al. JWST reveals varied origins between Jupiter's irregular satellites. *Planet. Sci. J.* **6**, 242 (2025).
- Pilorget, C. et al. First compositional analysis of Ryugu samples by the MicrOmega hyperspectral microscope. *Nat. Astron.* **6**, 221–225 (2022).
- Yada, T. et al. Preliminary analysis of the Hayabusa2 samples returned from C-type asteroid Ryugu. *Nat. Astron.* **6**, 214–220 (2022).

21. Pilorget, C. et al. Phosphorus-rich grains in Ryugu samples with major biochemical potential. *Nat. Astron.* **8**, 1529–1535 (2024).
22. Pilorget, C. et al. Bennu and Ryugu constituents from samples IR analyses and potential source of terrestrial planets' ingredients. *Nat. Commun.* **16**, 9532 (2025).
23. Le Pivert-Jolivet, T. et al. Space weathering record and pristine state of Ryugu samples from MicrOmega spectral analysis. *Nat. Astron.* **7**, 1445–1453 (2023).
24. Potin, S. et al. Style and intensity of hydration among C-complex asteroids: a comparison to desiccated carbonaceous chondrites. *Icarus* **348**, 113826 (2020).
25. Clark, R. N., King, T. V. V., Klejwa, M., Swayze, G. A. & Vergo, N. High spectral resolution reflectance spectroscopy of minerals. *J. Geophys. Res.* **95**, 12653 (1990).
26. Mahlke, M. et al. Tracing Water's Reach: Carbonate Mineralogy of Ryugu and Bennu as Seen by MicrOmega. <https://meetingorganizer.copernicus.org/EPSC-DPS2025/EPSC-DPS2025-1228.html>. <https://doi.org/10.5194/epsc-dps2025-1228> (2025).
27. Silverstein, R. M. & Bassler, G. C. *Spectrometric Identification of Organic Compounds* (ACS Publications, 1962).
28. Pironon, J., Pelletier, M., de Donato, P. & Mosser-Ruck, R. Characterization of smectite and illite by FTIR spectroscopy of interlayer NH₄⁺ cations. *Clay Miner.* **38**, 201–211 (2003).
29. Petit, S., Righi, D. & Madejová, J. Infrared spectroscopy of NH₄⁺-bearing and saturated clay minerals: a review of the study of layer charge. *Appl. Clay Sci.* **34**, 22–30 (2006).
30. Sergeeva, A. V. et al. Spectroscopy of ammonium occupying symmetry-inappropriate positions in crystal structures of salts. *J. Appl. Spectrosc.* **91**, 550–562 (2024).
31. Fukai, R. et al. Nondestructive analysis of Bennu samples toward comparative studies with Ryugu samples. *Meteorit. Planet. Sci.* **61**, 3–16 (2026).
32. De Sanctis, M. C. et al. Bright carbonate deposits as evidence of aqueous alteration on (1) Ceres. *Nature* **536**, 54–57 (2016).
33. Lane, M. D., Dyar, M. D. & Bishop, J. L. Spectra of phosphate minerals as obtained by visible-near infrared reflectance, thermal infrared emission, and Mössbauer laboratory analyses. In *38th Lunar and Planetary Science Conference LPI contribution no. 1338 p. 2210* (2007).
34. Bovey, L. F. H. The infrared absorption and reflection spectra of the ammonium halides. *J. Opt. Soc. Am.* **41**, 836 (1951).
35. Lodders, K. & Fegley, B. Solar system abundances and condensation temperatures of the halogens fluorine, chlorine, bromine, and iodine. *Geochemistry* **83**, 125957 (2023).
36. Ferrari, M. et al. Reflectance spectroscopy of ammonium-bearing phyllosilicates. *Icarus* **321**, 522–530 (2019).
37. De Angelis, S. et al. High-temperature VIS–IR spectroscopy of NH₄-phyllosilicates. *JGR Planets* **126**, e2020JE006696 (2021).
38. Ito, M. et al. A pristine record of outer Solar System materials from asteroid Ryugu's returned sample. *Nat. Astron.* **6**, 1163–1171 (2022).
39. Lauretta, D. S. et al. Asteroid (101955) Bennu in the laboratory: properties of the sample collected by OSIRIS-REx. *Meteorit. Planet. Sci.* **59**, 2453–2486 (2024).
40. Díaz, M. *Etude des interactions cations compensateurs/feuilles dans les argiles: contribution à la connaissance des mécanismes de rétention sélective* (Université d'Orléans, 1999).
41. Gautier, M., Muller, F., Le Forestier, L., Beny, J.-M. & Guegan, R. NH₄-smectite: characterization, hydration properties and hydro mechanical behaviour. *Appl. Clay Sci.* **49**, 247–254 (2010).
42. Glavin, D. P. et al. Abundant ammonia and nitrogen-rich soluble organic matter in samples from asteroid (101955) Bennu. *Nat. Astron.* <https://doi.org/10.1038/s41550-024-02472-9> (2025).
43. Yoshimura, T. et al. Chemical evolution of primordial salts and organic sulfur molecules in the asteroid 162173 Ryugu. *Nat. Commun.* **14**, 5284 (2023).
44. Hashizume, K. et al. The Earth atmosphere-like bulk nitrogen isotope composition obtained by stepwise combustion analyses of Ryugu return samples. *Meteorit. Planet. Sci.* **59**, 2117–2133 (2024).
45. Ammannito, E. et al. Distribution of phyllosilicates on the surface of Ceres. *Science* **353**, eaf4279 (2016).
46. Rivkin, A. S., Howell, E. S. & Emery, J. P. Infrared spectroscopy of large, low-Albedo Asteroids: are Ceres and Themis archetypes or outliers? *J. Geophys. Res.: Planets* **124**, 1393–1409 (2019).
47. Kitazato, K. et al. The surface composition of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy. *Science* eaa7432 <https://doi.org/10.1126/science.aav7432> (2019).
48. Simon, A. A. et al. Widespread carbon-bearing materials on near-Earth asteroid (101955) Bennu. *Science* **370**, eabc3522 (2020).
49. Arredondo, A. et al. JWST spectroscopy of (142) Polana: connection to NEAs (101955) Bennu and (162173) Ryugu. *Planet. Sci. J.* **6**, 195 (2025).
50. Laize-Général, L. et al. Nitrogen in the Orgueil meteorite: abundant ammonium among other reservoirs of variable isotopic compositions. *Geochim. Cosmochim. Acta* **387**, 111–129 (2024).
51. Yada, T. et al. A curation for uncontaminated Hayabusa2-returned samples in the extraterrestrial curation center of JAXA: from the beginning to present day. *Earth Planets Space* **75**, 170 (2023).
52. Riu, L., Bibring, J.-P., Pilorget, C., Poulet, F. & Hamm, V. The on-ground calibration performances of the hyperspectral microscope MicrOmega for the Hayabusa-2 mission. *Planet. Space Sci.* **152**, 31–44 (2018).
53. Yokoyama, T. et al. Samples returned from the asteroid Ryugu are similar to Ivuna-type carbonaceous meteorites. *Science* eabn7850 <https://doi.org/10.1126/science.abn7850> (2022).
54. Riu, L. et al. Calibration and performances of the MicrOmega instrument for the characterization of asteroid Ryugu returned samples. *Rev. Sci. Instrum.* **93**, 054503 (2022).

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Author contributions

T.O., K.H., R.F., M.N., T.Y., K.Y., C.P., J.-P.B., and V.H. conceived and designed the experiments and the workflow. T.O., K.H., R.F., M.A., Y.E., S.K., A.Mi, K.N., M.N., R.Sa., R.Shi., R.T., T.U., T.Y., and K.Y. led the curation activities at ESCuC. K.H., D.L., L.N., L.R., R.She., C.L., M.M., Y.E., S.K., A.Mi., F.P., K.N., R.Sa., R.Shi., R.T., K.Y., C.P., J.-P.B., and V.H. performed the measurements. T.J., D.B., C.P., D.L., K.H., M.M., L.N., T.L.P.-J., J.-P.B., R.She., A.A., R.B., C.L., F.P., Z.Di., Z.Dj., V.H., Y.L., and L.R., contributed to data processing, analysis, and interpretation. T.J., D.B., C.P., D.L., K.H., M.M., L.N., T.L.P.-J., J.-P.B., R.She., A.A., R.B., C.L., F.P., T.O., R.F., T.U., M.A., Z.Di., Z.Dj., Y.E., V.H., S.K., Y.L., A.Mi., A.M.-S., K.N., M.N., L.R., R.Sa., R.Shi., R.T., T.Y., and K.Y. were involved in the discussions of the results and the preparation of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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