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Ammonium-rich bright areas on Ceres demonstrate complex chemical activity

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The dwarf planet Ceres has been proven to be a world with an extraordinary diversity of chemical species formed in aqueous environments. Dantu crater, being one of the largest and deepest impact craters on Ceres, offers valuable insights into the geological history and composition of this enigmatic world. Its particular position, within a topographic low, can be considered a window into the composition of Ceres's subsurface. One of the intriguing aspects of Dantu is the presence of several bright areas called "faculae". These bright materials, distributed unevenly on the Cerean surface, are believed to be residua from salty fluids, likely still circulating in the subsurface and capable to extrude onto the surface, as demonstrated by the identification of fresh hydrohalite ($NaCl{\cdot}_2(H_2O)$) on the bright faculae in another exceptional crate, Occator. The detailed investigation of the Dantu's faculae reveals the presence of at least two different "populations" of bright materials, compositionally distinct even if in close geographical proximity. These faculae appear different, white and yellow, in the color images (RGB: R = 0.917 μm, G = 0.653 μm, B = 0.438 μm) taken by the Dawn camera. The spectra show that the first population -white- is mainly composed of sodium carbonate, similar to other identified bright areas on Ceres; the second one -yellow- is likely dominated by ammonium-rich components. The spectra of the yellow faculae show specific and clear bands, associated to ammonium bearing phases, but the exact species producing such spectral features are not unambiguously identified. A potential candidate is ammonium bicarbonates, but we cannot exclude other compounds and combinations of different species. Other occurrences of these yellow faculae have been identified in a few other areas, even if less numerous and with a much smaller extent with respect to the Dantu crater. The discovery of a very bright component different from the carbonates and salts previously identified increases the variety and complexity of the salty aqueous solutions on Ceres, offering tantalizing clues about the potential for habitable environments and subsurface fluid reservoirs on this dwarf planet.

The 126 km diameter Dantu crater is one of the most prominent features on Ceres' surface (Fig.1). This young complex crater (ages are 72–150 Ma from the lunar derived model, or 43–94 Ma from asteroid derived model[1]) shows a very complex geology[1,2] and strong heterogeneity in terms of mineralogy as resulting from the VIR Dawn data[2]. Dantu is centered at 24.3°N and 138.23°E, within a low-land region, interpreted as the ancient impact basin Vendimia Planitia[3]. Previous studies of the Dantu region have evidenced local enrichments in ammoniated phyllosilicates and carbonates and the presence of numerous bright areas (faculae) occurring along crater floor fractures, rim and ejecta[1,4–7]. These faculae are the most spatially extensive system of faculae outside of the Occator crater[7].

Results

Identification of Yellow Faculae

The false color mosaic of the Dantu crater (Fig. 1) clearly shows material exhibiting color and albedo variability and a sort of color dichotomy, with the central and northern part brighter and yellowish and the southern part resulting darker and bluish. A similar dichotomy has been reported in the analysis of the spectral parameters of the Dawn Visible and Infrared Mapping

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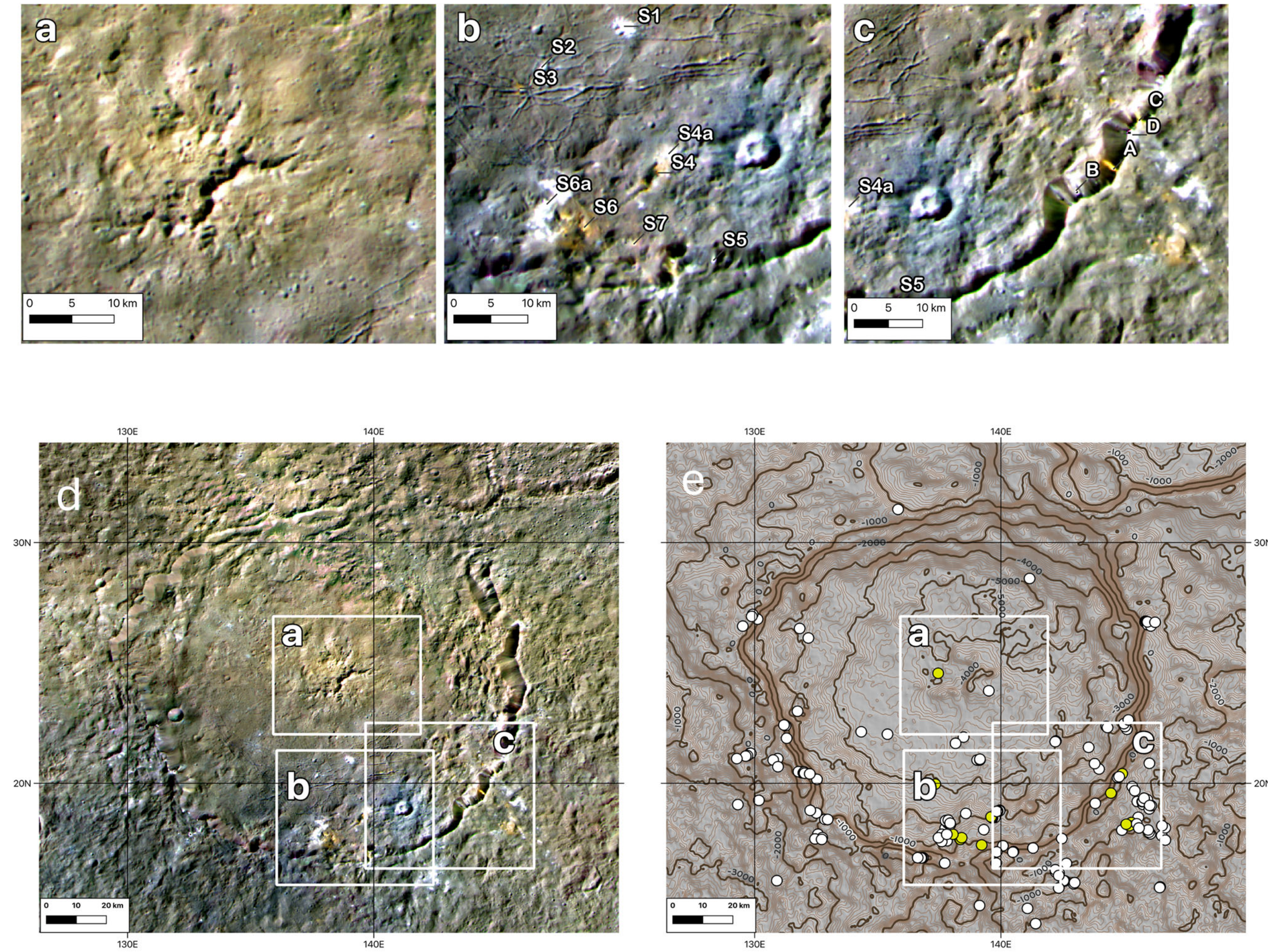

Fig. 1 | Dantu crater in colors. a Zoom in box a of Fig. 1d, showing the central peak; **b** Zoom in box b of Fig. 1d, showing white and yellow faculae on the crater floor, **c** Zoom in box c of Fig. 1d, showing the white and yellow faculae on the crater rim. **d** Framing Camera color composite (RGB: $R = 0.917$ µm, $G = 0.653$ µm, $B = 0.438$ µm); **e** Topographic map with the spatial distribution of the main bright spots (white points: white facula, yellow points: yellow facula). Text labels refer to points discussed in the text.

Spectrometer (VIR) visible channel[8,9] and Infrared channel[2,4] with the central northern part showing stronger phyllosilicate bands and steeper spectral slopes in the 400–500 nm range. Moreover, Dantu is punctuated by many bright faculae (Fig. 1a–e, Supplementary Figs. 1–4) with slightly different colors in the visible range: some faculae appear white (WF- white faculae) and some others yellow (YF-yellow faculae) in the color combination reported here. Even if the faculae are distributed everywhere, they are concentrated in the southern portion of the Dantu area (Fig. 1d). The origin of these faculae is not clear, and YF and WF are often found close to each other(Fig. 1b, c).

Previous analysis by VIR indicates that the white faculae are composed of minerals that are uncommon in our Solar System. Sodium carbonates are key components of the white faculae and different chlorides in hydrous and anhydrous forms have been identified in Cerealia facula[5,10–12]. The most prominent WF in Dantu show spectra (Fig. 2) characterized by the presence of sodium carbonate, having deep absorption bands at ~4 µm and 3.4–3.5 µm. However, carbonate is mixed with the Mg- and NH_4-phyllosilicates, because the spectra also have deep 2.73 and 3.07 µm bands (Fig. 2). Yellow faculae (YF) show different spectral properties with respect to both the WF and the background material (Fig. 2, Supplementary Fig. 4). Also, the spectra in the 1–4.3 µm range of the YF are distinct from other bright areas on the Cerean surface, including the organic-rich regions and ice-rich regions, and not seen elsewhere in previous analysis of the VIR data (Fig. 2).

The WF in Dantu (Fig. 2a, blue spectrum) share many similarities with other WF, mainly composed of sodium carbonates like those in Oxo crater (Fig. 2a, black spectrum) (Na_2CO_3 and Na-carbonate in hydrous form[5]), but differ from the Vinalia (Fig. 2a, dark grey spectrum) and Cerealia WF (Fig. 2a, light grey spectrum), in Occator, where the ammonium signature at 3.07 µm is much less intense or even absent.

The YF and WF in Dantu are unevenly distributed and associated to different morphologic context (Fig. 1, Supplementary Figs. 1–4): some appear as bright streaks on the rim and slope, associated with mass wasting material located at steep crater walls, some are within the Dantu's ejecta blanket and others on the crater floor. The central peak (Fig. 1, bottom panel a) shows yellowish colors with a couple of faculae. The southern sector of the floor (Fig. 1, bottom panel b) has an extensive set of linear to arcuate fractures. Specifically, on the crater's floor, faculae are associated to the fracture network in two elongated areas of 200 and 500 meters (Supplementary Fig. 2). Particularly interesting are the extremely bright avalanche streaks (YF and WF) on the eastern rim of Dantu (Fig. 1c labeled as A, B, C, D, Supplementary Fig. 1), showing clear signatures of sodium carbonates (spectral bands at 3.5 and 4.0 µm) in the WF and ammonium (spectral bands at 3.05–3.1 µm) in the YF (Fig. 3).

Yellow Faculae (YF) spectra

We examined all the spectra of the YF that are acquired by VIR, and even if they are slightly different, likely due to variable mixing with the background material and different states of hydration, they have common characteristics: they show several absorptions in the 1–4.3 µm range that can be better

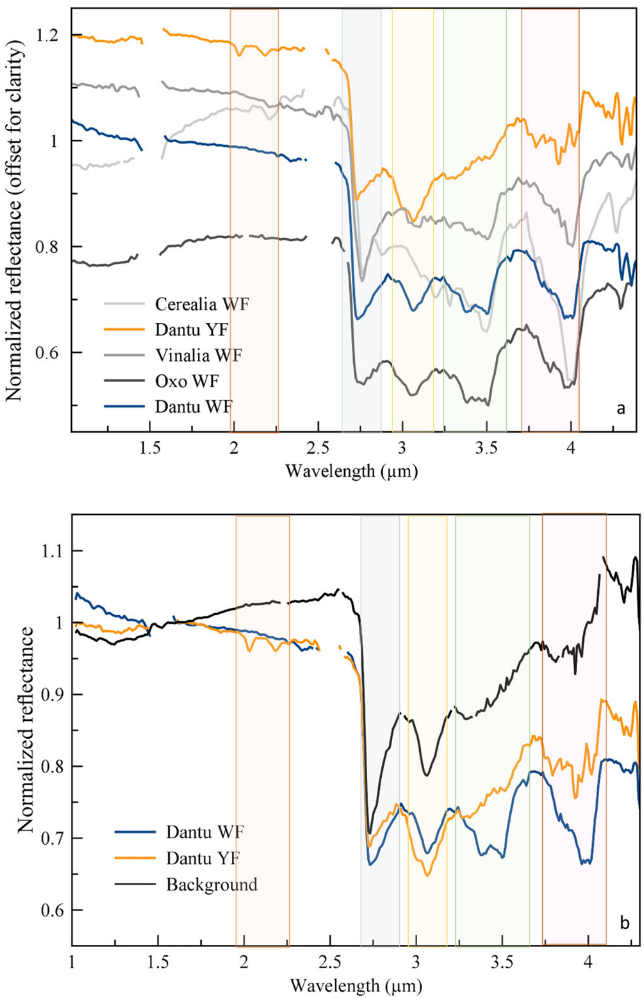

Fig. 2 | Spectra of Yellow and White Faculae. a Average spectrum of YF taken from S7-Fig. 1b compared with spectra from different WF areas on Ceres. Shaded colors identify the different absorptions. The spectra are normalized at 1.65 μm and displayed with arbitrary offsets. **b** Average spectrum of YF taken from pixels in S7-Fig. 1b compared with the spectrum of Dantu background and the WF from S1-Fig. 1b. The spectra are normalized at 1.65 μm.

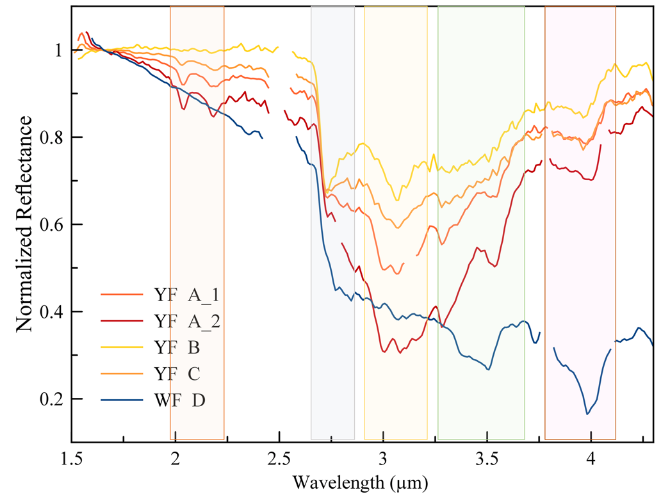

Fig. 3 | Faculae spectra on the Dantu rim. Normalized spectra at 1.65 μm of YF and WF present on the Dantu crater rim, labeled in Fig. 1c. Spectrum in A_2 is taken from YF in A, close to the rim border, A_1 in a down slope position, closer to the floor; B, C, D from the other faculae as in Fig. 1c. Shaded colors identify the different absorptions.

identified using the spectral ratio between the strongest YF and the background material (Fig. 4). In the spectral ratio we can identify minima at ~2.03 and 2.18, then at 2.99, 3.07, 3.15 and 3.18, 3.28–3.29, 3.55, 4.01 μm.

The spectra of the most prominent YF are characterized by a strong and complex absorption at ~3 μm, that extend from ~2.6 to 3.75 μm, and clear bands at 2.03 and 2.18 μm. Two small absorptions in the 2 μm range have been observed in Cerealia facula but they are different, in terms of shape, centers and intensity from those observed in Dantu YF (Supplementary Fig. 5). The bands at 2.03 and 2.18 μm (Figs. 3, 4) come together and are particularly evident when the complex band at 3 μm increases, suggesting that these absorptions are due to the same carrier(s). The trend is clear looking at Fig. 5, where the 3.07 μm band strength vs. the 2.18 and 2.03 μm band strengths are reported.

The YF spectra at ~3 μm are different from other 3 μm absorptions observed on the Cerean surface, including the broadband present in Cerealia facula and interpreted to be due to the presence of hydrohalite ($NaCl{\cdot}2H_2O$) mixed with sodium carbonate (Na_2CO_3 - natrite) and ammonium chloride (NH_4Cl)[12] (Supplementary Fig. 5). The spectral range between 2.6 and 3.15 μm shows a prominent absorption at 2.99 μm not present in Cerealia, but previously identified in some small areas in Ernutet crater, associated with organic material[13]. The spectra beyond 3.15 μm are similar to the one observed in Cerealia facula.

Looking at the 0.4-1 μm range (Supplementary Fig. 5), the YF do not show any clear feature but the overall spectral shape is different with respect to the background material. However, a change in the spectral slope at 0.405 μm can indicate the presence of an absorption. The spectral slope between 0.4 and 0.6 μm is steep and the Dantu region has been identified as the one with the steepest visible slope between 0.405 and 0.465 μm of the entire Ceres surface[9].

Suggested species in the Yellow Faculae (YF)

The absorptions at ~3.28 and 3.55 μm, seen in the YF, can be attributed to the presence of ammonium-rich species: free NH_4^+ has fundamental frequencies active in the IR[14] (ν3 = 3.18 μm and ν4 = 7.14 μm). However, multiple and partially overlapping absorption bands in the ~2.86–3.57 μm range have been associated with the *ν*3 asymmetric stretching mode, ν2 + ν4 combination, and overtone of 2ν4 of the free NH_4^+ molecule[15–17]. Absorption features in the 2.99–3.23 μm range are attributable to the *ν*3, those in the 3.23–3.33 μm to ν2 + ν4 combination, and those at ~3.57 μm are attributable to 2ν4.

Thus, the complex band extending from 2.6 μm to 3.8 μm has many features and characteristics of ammonium. In addition, overtone and combination absorption bands are expected at shorter wavelengths at ~1.08, 1.3, 1.56, 2.02, and 2.12 μm[18]. Unfortunately, the VIR spectra in the 1.5 μm region are affected by an instrumental filter and can't be used in the analysis. The absorptions at 1.08 and 1.3 μm are expected to be faint and difficult to detect.

Given the YF absorption features at 3.07, ~3.28, and 3.55 μm, associated with ammonium species, we can argue that the YF contains ammonium-rich material in large amounts.

The ubiquitous presence of the ammoniated phyllosilicates on the Cerean surface suggests the possibility that the YF are due to a large amount of those minerals. Experiments on terrestrial NH_4-phyllosilicates at different pressure-temperature conditions[19] demonstrated that NH_4^+bands at ~1.55, 2.01, 2.12, and 3.1 μm are identifiable. Moreover, removing the adsorbed terrestrial water from the ammonium-phyllosilicates in laboratory to reproduce the Ceres condition (high vacuum), the 3-μm region is characterized by the increasing separation and narrowing of OH− (~2.7 μm) and NH_4^+ (~3.1 μm) absorption bands (Supplementary Fig. 6). The exact position of the ammonium bands varies from 2.01 to 2.02, 2.11 to 2.13, and 3.03 to 3.05 μm, ~3.28 and 3.55-3.58 μm range depending on the phyllosilicate, due to the lattice and interlayer cations characterizing the mineral structure[19,20]. Looking at band positions reported for the ammonium-bearing phyllosilicates[19] we see that they do not perfectly match those

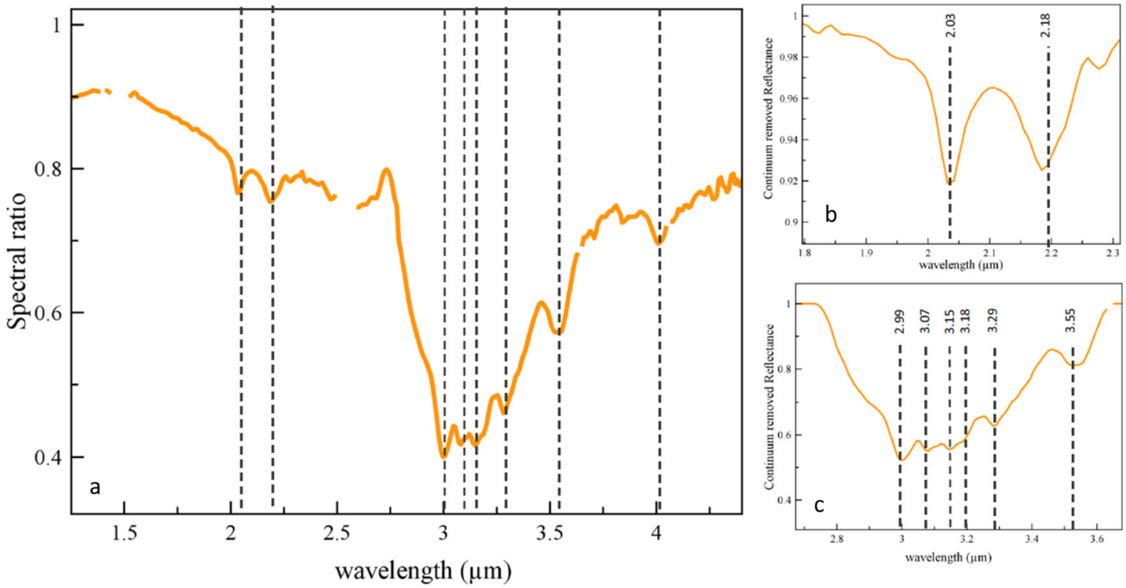

Fig. 4 | Absorptions in the Yellow faculae. a Spectral ratio between the spectrum of the YF labeled as A_2 in Fig. 3 and the average spectrum of the nearby material not containing faculae. The absorptions are highlighted. The side panels (**b, c**) are magnified views of the spectrum.

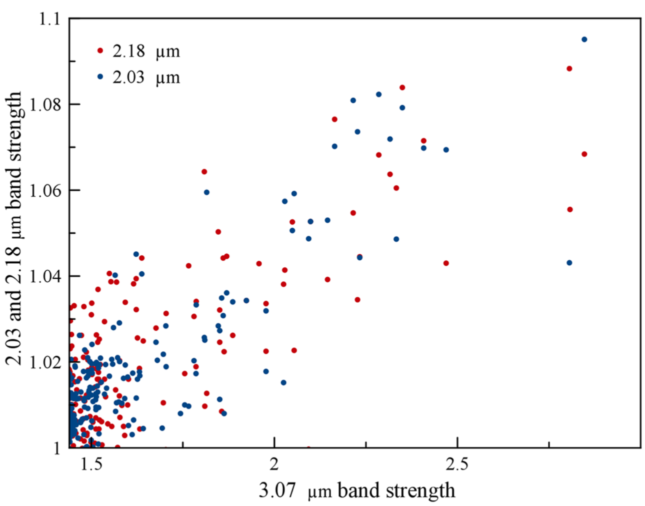

Fig. 5 | Correlation trends of the absorptions at 2.03 and 2.18 μm with the ammonium feature at 3.07 μm. Intensity of the bands at 2.03 and 2.18 μm versus the intensity of the 3.07 μm band. The intensities have been estimated from the ratio of the reflectances at 1.97 and 2.03 μm, 2.1 and 2.18 μm and 2.75 and 3.07 μm. The intensities are taken from pixels of the YF in A and C of Fig. 1c.

identified in Dantu YF (Supplementary Fig. 6). Nevertheless, we tried to fit the spectra of the YF with two representative ammonium-bearing phyllosilicates, but the results are unsuccessful (Fig. 6).

We compared the YF spectra with spectra of ammonium-rich salts, checking several species spectra available in the literature. Many of those spectra have been collected under ambient or controlled conditions[21,22] that are extremely different with respect to the condition at Ceres. Nevertheless, it is useful to compare some of them with the YF (Supplementary Fig. 7). Most of the plotted ammonium-rich species show two bands at ~2 µm, with minima ranging from ~2.02–2.06 µm to ~2.14–2.23 µm[22], both attributed NH_4 mode ν2 + ν3. Nevertheless, it must be considered that the collected spectra in the laboratory seem to show signs of hygroscopic water that can affect the band at 2.03 µm, being the H_2O ν2 + ν3 at ~ 2 µm. Also, the region at 3 µm is often affected by the presence of absorbed water and the comparison between the available laboratory spectra with the data from VIR is difficult.

The YF features at ~3.28 and 3.55 µm, as well as the band at 4.01 µm associated with sodium-rich carbonate, have been observed in some WF, such as in Cerealia Facula. Cerealia facula has been found to have spectral similarities with residua of brines made by a mixture of different salts, including Na, Cl, and NH_4[12,23]. Those brines are the results of freezing of aqueous solution obtained in the laboratory with different initial proportions of [Na+] [NH_4^+] [Cl^-] [CO_3^{2-}]. Fluids with similar composition are suggested to circulate in the Ceres interior and to extrude onto the surface[12,24] as in the Cerealia facula. We can argue that if the YF are resulting from extruding brines, their spectra should reflect the composition of the circulating fluids. We compared the spectra of the brines (called solution 1, 2 and 3 in 23) produced in the laboratory, with the greatest occurrence of YF (Supplementary Fig. 8). Both the brines and the YF have strong absorptions at ~3.28 and 3.55 µm, but the brines do not show the strong 2.99 and 3.07 µm bands of the YF and are quite different in the 2 µm region.

To better understand the components in the YF, we did an intimate mixing of the average Ceres' spectrum with many of the salts and brines here discussed (see supplementary for more details).

Using the brines previously mentioned (Fig. 7a–f), the best fit is obtained with Solution3, made of hydrohalite, ammonium chloride, and sodium carbonate ($NH_4Cl + NaCl_2H_2O + Na_2CO_3$), see Fig. 7e and extended data, that fits relatively well the spectrum beyond 3.2 µm where the signatures of the ammonium in the solutions are prominent. However, the fit is not optimal in reproducing the other features.

Using different ammonium salts, the best fit is obtained with ammonium carbonate. The fit (Fig. 7g) is better in the first part of the spectrum but fails in reproducing the ammonium feature beyond 3.2 µm. Also, the ammonium carbonate bands at ~2 µm do not fit the intensity of the YF bands. Similarly, the fits, including both the brines and salts are not fully satisfactory (Fig. 7b, d, f)

It is important to notice that the prominent absorption at 2.99 µm, corresponding to the minimum of the broadband in the spectra of the YF is not reproduced in the fits. This band has been identified in certain organic-rich areas on Ceres, but nor assigned to specific species[13].

Discussion

The YF identified in the area of Dantu crater show spectral characteristics different from the previously analyzed bright features on Ceres. The YF seem to be dominated by ammonium-rich species present in

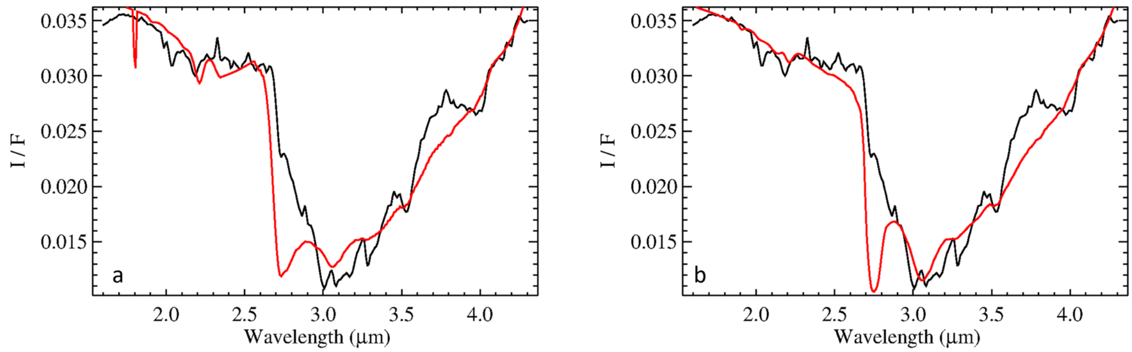

Fig. 6 | Fits of yellow faculae spectra. Best fit (red curves) obtained with: **a** ammonium-rich illite-smectite, **b** ammonium-rich montmorillonite in comparison with the spectrum of the Yellow faculae (black spectrum). The remaining fraction of the mixture is the average terrain measured from the surrounding area. See Supplementary for further details and relative abundances (Supplementary table 1).

large quantities, even if the specific carrier of the ammonium is difficult to identify.

Ammonium has been recently identified in the Ryugu samples delivered to Earth from the Haybusa-2 mission by the observation made with MicrOmega and with Fourier Transform InfraRed (FTIR) measurements[25,26] (i.e., band at 3268 cm^{-1}). Some of the Ryugu particles show clear and strong bands at about 3.06 μm, resembling the feature observed at Ceres at the global scale. Still, the 3.06 μm feature has been generally observed within the returned particles, although with varying intensities, suggesting that ammonium-rich materials are likely primary constituents of samples[26]. The presence of ammonium-bearing phyllosilicates and salts have been suggested, but also organics contain ammonium. Several different amino acids have been detected in the samples[27], likely predominantly synthesized on the Ryugu progenitor, when liquid water was present. Nevertheless, it is still unclear which species carry the ammonium in the Ryugu samples, and we cannot exclude that similar evolutionary paths were able to enrich in ammonium both Ceres and the Ryugu progenitor.

Yellow faculae have been identified elsewhere thanks to the colors of the Dawn Framing Camera[28] (Supplementary Fig. 10). Unfortunately, not all of them are covered by high-resolution VIR data, but the YF in Azacca crater (−6.6°; 218.4°) have spectra showing the characteristic absorptions at 2.03 and 2.18 μm and a broad, deep band extending from 2.6 to 3.8 μm, as the YF in Dantu (Supplementary Fig. 11). In Azacca, the YF are often found in close proximity of WF, suggesting a common mechanism for upwelling/exhumation.

The comprehension of the YF formation mechanism is not straightforward. In general, bright faculae on Ceres were found to occur in distinct geological settings, associated predominantly with impact craters but not only, as demonstrated by their presence on Ahuna Mons, recognized to be a cryovolcanic edifice[29,30]. The geomorphology of the faculae is consistent with formation via upwelling of volatile-rich materials (likely after impact-induced heating in case of craters), upwelling/excavation of heterogeneously distributed subsurface brines or their precipitation products, or a combination of both processes[7,12].

The variations in the composition of the faculae here reported indicate that their formation may be dependent on differences at the local scale in the subsurface, in terms of composition or relative abundance of the species, or presence of ice and/or brines, or thermophysical conditions that allow different faculae to form. Experiments on frozen brines, containing ammonium, sodium, carbonate, and chloride ions, demonstrated that ammonium-bearing materials are kinetically-favored products under fast-freezing conditions, while sodium salts are abundant in slow-freezing conditions[23,31]. In contrast, hydrohalite ($NaCl \cdot 2H_2O$), as detected on Occator, only forms when sodium and/or chloride were present in excess in the brine solutions. Thus, different compositions of the faculae can be due to different ionic proportions in a solution containing sodium-ammonium-chloride-carbonate but also due to the freezing rate of the solutions.

On Ceres, floor faculae occur in large, deep, and young craters that often contain crater floor fractures and pitted terrains, consistent with the upwelling and degassing of volatiles. Dantu crater, where the largest occurrence of YF are found, is settled in a low land where the global map of the NH_4-phyllosilicate shows a general enhancement of the 3.07 μm band[4]. Moreover, it is worth to note that the compositions of the peaks of complex Ceres' craters[32] show a positive correlation between the 3.07 μm band depth and crater size, thus excavation depth.

The YF have been spectrally observed by VIR in Dantu and Azacca craters, while the framing camera colors show clear YF in Gaue and Ikapati (in a 'true color' RGB display, R = 0.65 μm, G = 0.55 μm, B = 0.44 μm, Supplementary Fig. 10). All these craters have depths >3500 m and diameters >50 km, suggesting a possible correlation of YF with excavation depth. The Dawn camera also sees less definite occurrences[28] at 97E/24 N (Aristeus crater), 205E/22 S (Consus Crater), 244E/31 S, 213E/37.5 S. If the YF are the results of extruded brines which reflect the Cerean subsurface composition, we can argue that the crust has heterogeneities likely linked with the depth, having deeper layers richer in ammonium.

However, not all the large and deep craters have bright faculae and those showing faculae on the floor generally exhibit morphologically immature features, including steep crater sides and well-defined central peak/pit complexes. Ages estimation indicates that the craters with floor faculae are relatively young, with floor younger than the crater itself, suggesting that the floor faculae are due to post-impact activity.

The very bright appearance of the YF in Dantu is consistent with a recent emplacement or excavation of those materials, as a further demonstration that Ceres is somehow "active", with fluids of different composition circulating and still able to extrude onto the surface. The presence of white and yellow faculae, even if the composition of these last ones is still not fully constrained,indicates a chemical richness of Ceres subsurface, likely due to an inhomogeneous distribution of chemical elements with an enhancement of ammonium with depth. The detection of areas rich in ammonium on Ceres, likely reflecting the planet's composition at depth, suggests the existence of complex hydrothermal systems. These systems are characterized by the circulation of brines beneath the surface, providing ammonium with antifreeze properties. These brines may locally contain hydrated sodium and ammonium salts, sodium carbonates, and ammonium chloride, often associated with alteration minerals. One hypothesis proposes that the presence of such fluids is linked to local thermodynamic conditions occurring during energetic impacts, releasing sufficient heat to melt the water ice present in the subsurface and locally exposed on the surface. However, based on models of Ceres' evolutionary history[33,34], it has been suggested that cryovolcanism could be currently occurring on Ceres. Several lines of evidences, such as the fresh exposed hydrohalite and other unstable salts[12], the presence of cryovolcanic edifices[29,30] and thermal models[33–35], indicate the possibility that Ceres may host localized brine reservoirs, residua of an ancient ocean at shallow depths[35].

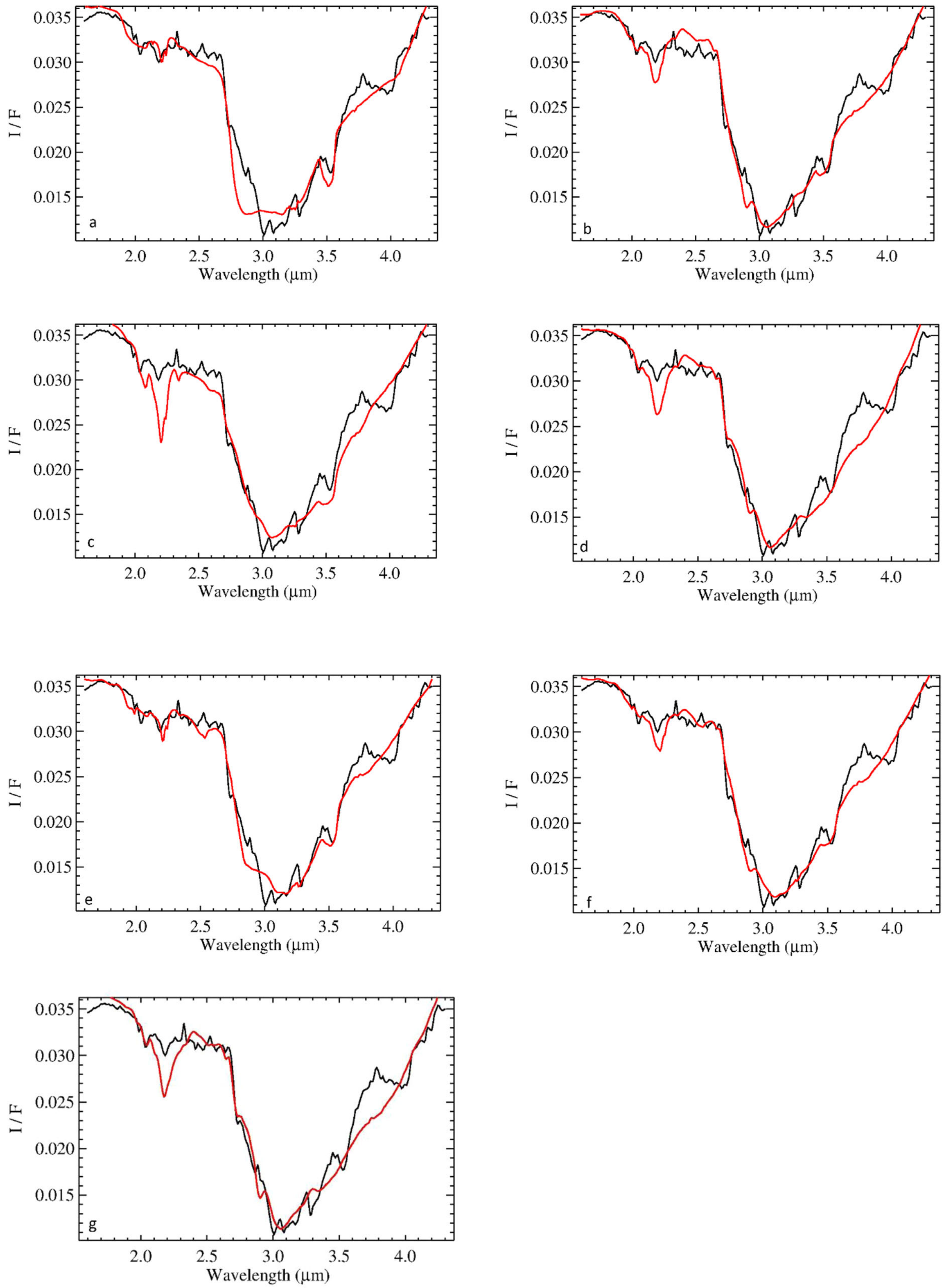

Fig. 7 | Fits of yellow faculae spectra. Best fit (red curves) obtained with: **a** solution 1, **b** solution 1 and ammonium-carbonate, **c** solution 2, **d** solution 2 and ammonium carbonate, **e** solution 3 and **f** solution 3 and ammonium carbonate, **g** ammonium carbonate in comparison with the spectrum of the Yellow faculae (black spectrum). The remaining fraction of the mixture is the average terrain measured from the surrounding area. See Supplementary for further details and relative abundances (Supplementary Fig. 9, Supplementary Table 1).

The significance of detecting new features associated with ammonium on Ceres, not only enlarge the identified species, but lies in the potential role of ammonia, acting as an antifreeze, in facilitating aqueous processes and preserving organic compounds. The presence of a variety of ammonium-rich species on Ceres, along with yet-identified organic molecules[13,36], clays and salts[4,10–12,37], highlights the potential for prebiotic chemistry and the habitability of this dwarf planet[38].

In its most fundamental form, life requires energy, liquid water, carbon, and a few essential elements. Liquid water is universally essential as a solvent for biochemical reactions, enabling the interaction of molecules crucial for life. Clay minerals are a commonly cited class of minerals to be relevant to prebiotic chemistry. In particular, Fe/Mg-clays are of interest when constraining planetary habitability, as they tend to be formed in alkaline, reducing environments that some studies propose are favorable for the transition from prebiotic to biotic activity[39]. According to geochemical modelling, the observed species on Ceres are suggested to be the result from the complete reaction between liquid water and chondritic-like material in the presence of CO_2 and NH_3, which generates alkaline conditions. Additionally, ammonia plays a crucial role in the formation of amino acids and nucleobases. In its reduced form, as ammonia, it can participate in numerous abiotic and prebiotic reactions[40]. For instance, in CR2 meteorites, the abundance of ammonia contributes to the formation of amino over hydroxyacids[41], syntheses that may be further enhanced by ammonia's ability to reduce the freezing point of water—an essential component in these processes.

Thus, this newly discovered ammonium-rich areas reinforce the astrobiological relevance of Ceres. Continued analysis and study of these ammonium-rich species and their interactions with other materials on Ceres will further deepen our understanding of this intriguing world.

Methods

Spectral modeling

To retrieve an estimation of the composition of the bright faculae we used the same method described in 10, summarized as follows.

The formulation of the quantitative spectral analysis is based on Hapke's radiative transfer model[42]. The spectral behavior of the bidirectional reflectance is a function of the composition. The absolute level of signal is also a function of the viewing geometry and the photometric parameters. Information on the viewing geometry comes from the shape model and position of the spacecraft at the time of observation. The photometric parameters are fixed[43] and define the average scattering properties of Ceres' regolith. The spectral properties are mainly affected by the single scattering albedo (SSA), and the related Ambartsumian–Chandrasekhar functions describing the multiple scattering components.

The SSA has been modeled for an intimate mixing between different minerals, which implies that the particles of the end-member materials are in contact with each other and are all involved in the scattering of a single photon. The SSA of each mineral is defined starting from their grain size and their optical constants, when available, or by reflectance measurements[44]. The average SSA is the weighted average of all components, where the weights represent the relative abundances of the minerals. The abundance has to be intended as the relative fraction of the area. However, since we assume all grains to have the same size, it is also a volume fraction in our model.

The best-fitting result is obtained by comparison of the model with the measured spectra. Free model parameters to be retrieved are: (i) Abundances of the end-members and their grain size; (ii) A multiplicative constant of the absolute level of reflectance of the model in order to account for uncertainties in the radiometric and photometric accuracies; (iii) A slope added to the model in order to better fit the measured spectrum to account for artificial slope or featureless reddish or bluish endmembers (which cannot be identified); (iv) Temperature T and beaming function[45]. The latter is free to vary in the range (0–1), and it is multiplied by the directional emissivity[46] to obtain the effective emissivity. The directional emissivity is a function of the SSA, and the emission angle.

The SSA is modeled starting from minerals, which are related to the average Ceres surface and the composition of Cerealia Facula[11,36].

Data availability

Dawn data are archived in NASA's Planetary Data System. VIR spectral data are available at https://sbn.psi.edu/pds/resource/dawn/dwncvirL1.html. The Framing camera data are available at https://sbib.psi.edu/data/PDS-Ceres/pds-ceres.html. The data used to generate the plots in this paper are available at: https://figshare.com/account/home#/projects/191586.

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Author contributions
M.C.D.S. coordinated the interpretation of the VIR data. A.F. and M.F contributed with the geological interpretation. E.A. A.R., S.D.A., M.F., F.G.C. and M.C. contributed to the data interpretation. A.R. and M.C. developed the spectral modeling of the spectra. S.D.A and M. F. did the comparison with the phyllosilicates. All authors participated in data acquisition, discussion of results and writing the manuscript.

Competing interests
The authors declare no competing interests.

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