REPORT

PLANETARY SCIENCE

Localized aliphatic organic material on the surface of Ceres

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Organic compounds occur in some chondritic meteorites, and their signatures on solar system bodies have been sought for decades. Spectral signatures of organics have not been unambiguously identified on the surfaces of asteroids, whereas they have been detected on cometary nuclei. Data returned by the Visible and InfraRed Mapping Spectrometer on board the Dawn spacecraft show a clear detection of an organic absorption feature at 3.4 micrometers on dwarf planet Ceres. This signature is characteristic of aliphatic organic matter and is mainly localized on a broad region of ~1000 square kilometers close to the ~50-kilometer Ernutet crater. The combined presence on Ceres of ammonia-bearing hydrated minerals, water ice, carbonates, salts, and organic material indicates a very complex chemical environment, suggesting favorable environments to prebiotic chemistry.

ignatures of organics on solar system bodies have been sought for decades (1). The 3.3to 3.6- μ m spectral region is considered diagnostic for the presence of organics because it contains absorptions from chemical groups such as CH, NH, OH, and CO₃. Indeed, the detection of a 3.2- to 3.6- μ m band has been extensively reported in laboratory samples containing organic material (2–4), but absorption bands at these wavelengths have been observed remotely for only a few solar system objects, such as com-

et 67P/Churyumov-Gerasimenko (5), and mainbelt asteroids 24 Themis (6, 7) and 65 Cybele (8), where weak absorptions have been reported. Weak organic bands have also been reported for Phoebe, Iapetus, and Enceladus (9–11). Groundand space-based observations of Ceres exhibit a broad absorption feature in the 3.3- to 3.6- μ m region (12, 13), and ammoniated phyllosilicates and carbonates have been identified as the main components responsible for this absorption observed on Ceres (12). Ground-based spectral observations of Ceres at global scale have found no unambiguous evidence for the presence of organics, although spatially resolved observations show local variations, such as around Occator crater, where bright materials exhibit a strong, complex absorption spectrum that has been shown to be dominated by carbonates with the likely addition of a nonidentified component (*14*).

We examined a broad region of ~1000 km² close to Ernutet crater [latitude ~53°N, longitude 45.5°E, diameter 53.4 km, Kait reference system (15)]. This region exhibits a prominent 3.3- to 3.6- μ m band (Fig. 1), distinct from the surrounding region as well as the bright material around Occator crater. We used the Visible and InfraRed Mapping Spectrometer (VIR) (16) on board the Dawn spacecraft to observe the Ernutet region from a maximum altitude of 4300 km over the mean surface of Ceres down to a minimum altitude of 385 km.

The pronounced difference in the 3.3- to 3.6- μ m region between the surface around Ernunet crater and regions further away (Fig. 1) indicates the presence of additional absorbing species in the latter. These species are able to produce a distinctive absorption (at 3.4 μ m) without appreciably affecting the remaining parts of the spectrum. The main candidates for this band are materials

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Α В OH NH, Organic mm Reflectance normalized at 2 µm Reflectance Normalized at 2.6 80 60 0.8 0.6 Ernutet organic rich Non organic rich 0.4 Occator bright material Organic rich Non organic rich 1.5 2 2.5 3.5 4 3 3.5 4 1 Wavelength (µm) Wavelength (µm)

Fig. 1. Spectra of organic-rich areas compared with nonorganic-rich areas. (**A**) Spectra of the organic-rich area in Ernutet (blue; average of 7 pixels, equivalent to ~2 km², taken from area b in Fig. 4), of a background area from a region at ~100 km southeast of Ernutet (gray; average of 25 pixels, equivalent to ~6 km², taken at 45°N, 65°E in Fig. 4), and of Occator central dome (red spectrum at 20°N, 240°E) normalized at 2 μ m for comparison. (**B**) Examples of organic-rich pixels (blue lines; equivalent to ~0.5 km², taken from area a in Fig. 4) and nonorganic-rich pixels (black lines; equivalent to ~0.5 km², taken from a region at ~100 km southeast of Ernutet (areas), equivalent to ~0.5 km², taken from a region at a mean absolute deviation of the calibration uncertainties along the 256 samples.



Fig. 2. Spectra of organic-rich pixels. Spectra of organic-rich pixels (OR-1 to OR-4, 450 m/pixel taken from area a in Fig. 4) compared with (**A**) methyl (CH₃) and methylene (CH₂) functional groups, (**B**) terrestrial hydrocarbons, and (**C**) IOM in carbonaceous chondrites. The spectra are offset for clarity.

containing C–H bonds, including a variety of organic materials, such as hydrogenated amorphous carbon and complex residues produced by the irradiation of different ices (*17–19*). All these species are broadly described as "organics," and we will use the term "organic-rich" (OR) to describe the spectrum and the area showing this band.

Among different pixels of the OR area, the band exhibits small variations due to noise, mixing with nonorganic materials, and/or small intrinsic differences in the nature of the organics (Fig. 1B). Nevertheless, the 3.3- to 3.6-µm band is well defined with an asymmetric shape and several subfeatures near 3.38 to 3.39 µm, 3.40 to 3.42 µm, and 3.49 to 3.50 µm, suggesting that this complex absorption feature is actually composed of several bands (Fig. 2). These absorptions are characteristic of the symmetric and antisymmetric stretching frequencies of methyl (CH₃) and methylene (CH₂) functional groups, typical of aliphatic hydrocarbons (2). Ceres' 3.2to 3.6-µm band shows marked similarities with the organic bands of terrestrial hydrocarbons such as asphaltite and kerite (Fig. 2B), which are considered to be analogs for asteroidal and cometary organics (3).

The organic materials in carbonaceous chondrites include macromolecular material and a variety of insoluble organic matter (IOM), as well as soluble organic matter (SOM) (20–22). CI, CR, and CM chondrites contain up to 4 weight % (wt %) organic matter, mainly in the form of kerogenlike IOM (2). The IOM consists of large clusters of aromatic rings; SOM includes molecules of prebiotic interest such as amino acids, nucleobases, sugars, and monocarboxylic acids (3). SOM is particularly abundant in the CR carbonaceous chondrites, where N-containing amino acids and amines are predominant (23).



A comparison with IOM extracted from different carbonaceous chondrites (Fig. 2C) shows an overall agreement between IOM and Ceres OR, even though Ceres OR seems to have less-defined subfeatures within the broad band.

The identification of the precise nature of the organic material is challenging. The shape of the band and the lack of a clear 3.3-µm feature allow us to eliminate aromatic species as main carriers of the features on Ceres, whereas hydrogenated sp³ carbon can be identified from the antisymmetric and symmetric stretching modes of methyl and methylene functional groups. Thus, we can exclude organics with a high content of aromatic carbon (like anthraxolites) in favor of hydrocarbons rich in aliphatic carbon (like asphaltite and kerite). However, a further discrimination among different aliphatic-rich organics is difficult. Furthermore, we used a nonlinear mixing algorithm (24) and found a good match with an intimate mixture of ~4 to 9% of aliphatic hydrocarbons (table S1). The specific value of the abundance of organics depends on the spectral end-member, i.e., kerite or asphaltite (25), used in the fitting procedure. Although the best fit is achieved with 5% of kerite, asphaltite also provides a good result (Fig. 3). Therefore, we cannot clearly identify the specific aliphatic compound present on Ceres. In addition, IOM materials are very good spectral analogs of Ceres OR, but the available laboratory spectra of IOM lack absolute reflectance and thus cannot be used for the fitting procedure.

The large OR area associated with part of Ernutet crater (Fig. 4) shows an enhancement of the 3.4-um band, but the intensity of the band is highly variable. The strongest band strength is found on the floor of Ernutet and on the southern rim and proximal ejecta (Fig. 4, area a), whereas another large area with well-defined absorptions covers the northwest portion of the crater rim and extends in the proximal ejecta (Fig. 4, area b). In addition, several smaller OR areas occur a few kilometers west and east of the crater (Fig. 4, areas c to f). Area c has been observed at spatial resolutions of ~450 and ~100 m/pixel; the data taken at ~100 m/pixel (fig. S2) show a deep, well-structured band, whereas the ~450-m/pixel data show a weaker and less-defined band. Similarly, data of area f, taken at ~450 m/pixel, show an organic band with lesser intensity, indicating that organic material is present but probably more spatially diluted.

OR areas near Ernutet crater also exhibit other differences from the average Ceres surface. Variations in the carbonate band depth at 3.9 μm indicate an enhancement in carbonate (Fig. 4, area a), in particular in correspondence of the southern crater rim and ejecta, whereas the northwest OR area (Fig. 4, area b) does not show any clear carbonate enhancement. The distribution of the 3.07- μm band depth (Fig. 4C), associated with ammoniated species, shows an increase correlated with the broad areas a and b in Ernutet.

The search for unambiguous signatures of organics elsewhere on the surface relied on data acquired at a nominal resolution of ~450 m/pixel (surface coverage of 68.3% from 68°S to 65°N). We searched for coherent OR areas larger than three adjacent pixels, so smaller occurrences would not be detected by our survey. Nevertheless, we found one additional very small area for which spectra are compatible with detectible organic material in Inamahari crater (latitude 10°N, longitude 89°E, at ~400-km distance from Ernutet), shown as spectrum G in fig. S2.

Disentangling the contributions of different components in this spectral region at the global scale requires detailed analysis. Spectral-fitting models of the average Ceres spectrum did not require organics, using a minimum number of end-members to fit the spectrum (*12*), and the inclusion of organics in the model does not change the quality of the fit if the organics are limited to <1% (fig. S3). Thus, we cannot exclude the possibility that organics are widespread at abundances of <1% on Ceres' surface.

The large concentration of organic materials in the Ernutet region has two possible origins: delivery of organics from an impactor or an intrinsic origin, associated with processes on Ceres



Fig. 4. Distribution of the organics, carbonates, and ammoniated phyllosilicates. (**A**) Distribution of the 3.4-µm band depth. (**B**) Distribution of the 3.9-µm band depth. (**C**) Distribution of the 3.1-µm band depth. Band depths are calculated according to (30) and cylindrically projected on framing camera (FC) clear filter mosaic. Letters a to f indicate OR areas as discussed in text. The data used to compute the maps are listed in table S2. [FC mosaic photo credit: NASA/Jet Propulsion Laboratory–California Institute of Technology/University of California, Los Angeles/Max Planck Institute for Solar System Research/German Aerospace Center/Institut für Datentechnik und Kommunikationsnetze]

(endogenous material). Although laboratory spectra of carbonaceous chondrites often exhibit organic bands, the relative depth of their 3.4-µm band is weaker than their phyllosilicate 2.7-µm band (4), whereas at Ernutet the 3.4-um band dominates the spectrum. A complication is that organic bands in carbonaceous chondrites are strongly influenced by terrestrial contamination. It is also difficult to see how a CM or CI carbonaceous-chondrite impactor could result in the inferred high concentration of organics on Ceres, because impact mixing distributes the projectile within a diluted matrix of target material. A cometary impactor, instead, could be a more concentrated source of organic matter. The percentage of organic matter in comets is, however, not fully constrained, and the only example of a clear organic signature on a cometary surface, 67P/Churyumov-Gerasimenko (5), shows an absorption band very different from that observed on Ceres (fig. S4).

On average, interplanetary dust particles, many of which are probably cometary, are enriched in organic matter relative to carbonaceous chondrites, with carbon abundances averaging ~13 wt % (26). However, laboratory experiments on the stability of the C-H bond spectral signature show that aliphatic C-H is instable. According to (27), the aliphatic C-H band is lost within ~200 years at ~370 K. At ~770 K, aliphatic C-H disappears within approximately 90 s. An impactor striking at a velocity of ~20 km/s and an angle of 45° is thoroughly heated above 500 K, whereas ~70% of its volume is heated above 750 K (28). Jupiter family comets have an average impact speed with main-belt asteroids of ~10 km/s, and although the impactor peak temperature is lower than 750 K, it could be high enough to considerably suppress the organic signature. Thus, although it cannot be excluded that part of an organic cometary material could survive the impact, we expect the organic signature to be strongly reduced and, when mixed with the original Ceres material, the organic signature should be even more subdued, making its recognition very difficult. Thus, it seems unlikely that a chondritic or cometary impactor can explain the observed organic signature.

The geological settings of the organic-rich areas provide additional information. The Ernutet area is heavily cratered and appears to be ancient [it is adjacent to the heavily cratered terrains (29)], as many large craters are subdued. The Ernutet crater, however, exhibits relatively fresh rims, but the distribution and character of the OR areas are not associated with any single crater. The largest concentration appears to drape discontinuously across the southwest floor and rim of Ernutet crater and onto an older, highly degraded crater. Other OR areas are scattered independently to the northwest.

The organic-rich area appears to be admixed with additional carbonate and ammoniated-species concentrations, at least close to the main location (Fig. 4). As carbonates and ammoniated phyllosilicates are clearly Ceres' endogenous material (12, 14, 30), this Ceres-like mineralogy would add difficult constraints for delivery by an impactor of different composition. Alternatively, because Ceres shows clear signatures of pervasive hydrothermal activity and aqueous alteration (12, 14, 30, 31), the OR areas may be the result of internal processes, which is also supported by the concentration of carbonate and ammoniated species in the same Ernutet area. The difficulty of an endogenous origin for the observed OR regions on Ceres, however, is identifying a viable method for transporting such material from the interior to the surface in the pattern observed.

Some of the organic compounds in carbonaceous chondrites may be the result of hydrothermal processing within the meteorite parent bodies (19), although exotic stable isotope ratios also indicate the possible formation of organic precursors in interstellar space (32). Organic matter is most abundant in those carbonaceous chondrites that display the greatest amount of inorganic aqueous alteration products as phyllosilicates and carbonates (33). Clay minerals are known to adsorb organic species and actively participate as catalysts in their syntheses and reactions (33, 34). In this sense, we expect that Ceres is a perfect world to develop substantial indigenous organic material formed by hydrothermal alteration, given the widespread presence of other hydrothermal products.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/355/6326/719/suppl/DC1 Materials and Methods Supplementary Text Figs. S1 to S4 Tables S1 and S2

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Editor's Summary

Organic compounds detected on Ceres

Water and organic molecules were delivered to the early Earth by the impacts of comets and asteroids. De Sanctis *et al.* examined infrared spectra taken by the Dawn spacecraft as it orbited Ceres, the largest object in the asteroid belt (see the Perspective by Küppers). In some small patches on the surface, they detected absorption bands characteristic of aliphatic organic compounds. The authors ruled out an external origin, such as an impact, suggesting that the material must have formed on Ceres. Together with other compounds detected previously, this supports the existence of a complex prebiotic chemistry at some point in Ceres' history.

Science, this issue p. 719; see also p. 692

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