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An aqueously altered carbon-rich Ceres

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Supplementary Information

An aqueously altered carbon-rich Ceres

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Chondrite Type	Reference	Note
CI: Carbonaceous Ivuna	Ref. 54	The normalized spectrum has been scaled to value of the measured CI (MP-TXH-018) at 1.7 μm
CM: Carbonaceous MET00639	Ref. 54	The normalized spectrum has been scaled to value of the measured CM (MB-TXH-056) at 1.7 μm
CM: Carbonaceous LAP02277	Ref. 54	The normalized spectrum has been scaled to value of the measured CM (MB-TXH-056) at 1.7 μm
CR: Carbonaceous Renazzo	RELAB Spectrum MB-TXH-058 /NCMB58	PI: T. Hiroi, Brown University.
OC: Ordinary Chondrite	RELAB Spectrum MA-ATB-052 /BMR1MA052	Laser-Irradiated L5, PI: A.T. Basilevsky, Vernadsky Institute.

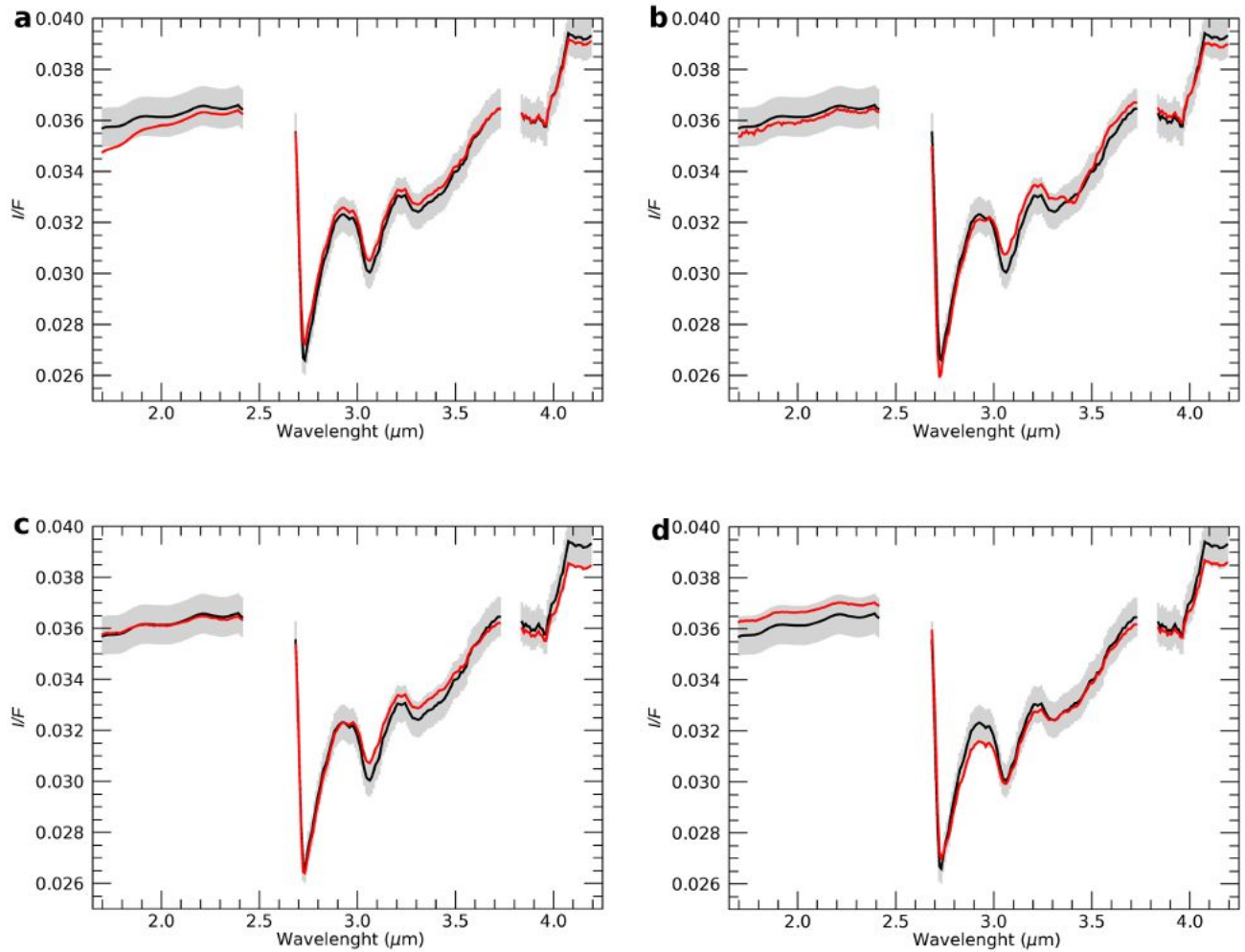
Supplementary Table 1 | Chondrite spectra used in this work. Notice the OC sample has been laser irradiated to remove terrestrial water contamination. While this procedure can somewhat alter the optical properties of the sample, this is the only dehydrated OC available.

Mineral	Type	Sample ID
Antigorite	Mg-phyllosilicate	AT-TXH-007
Dolomite	Mg-Ca-carbonate	CB-EAC-003
NH ₄ -montmorillonite	NH ₄ -phyllosilicate	JB-JLB-189
NH ₄ -annite	NH ₄ -phyllosilicate	AA-A1S-002
Magnetite	Dark material	MG-EAC-002

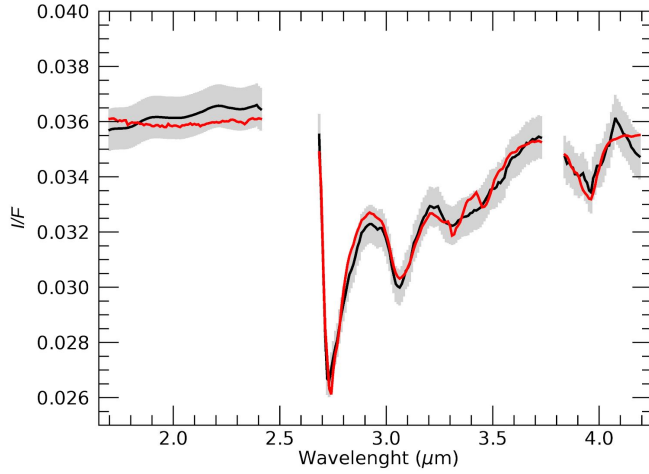
Supplementary Table 2 | End-members used in calculating optical constants of the mineral types. Spectra are taken from the RELAB spectral database. Optical constants of amorphous carbon used in the mixtures (main text) are from ref. 55 (ACH2 sample).

Name	Formula	Grain density (g/cm ³)	Notes
NH ₄ -annite	NH ₄ Fe ₃ AlSi ₃ O ₁₀ (OH) ₂	3.33	Assume NH ₄ replaces K
NH ₄ -montmorillonite	Ref. 56	2.35	Densities range from 2 to 3 g/cm ³ . Adopted density from http://webmineral.com
Dolomite	CaMg(CO ₃) ₂	2.85	
Antigorite	Mg _{2.25} Fe _{0.75} (Si ₂ O ₅)(OH) ₄	2.61	http://webmineral.com/
Amorphous carbon	CH _{0.6}	2.0	
Magnetite	Fe ₃ O ₄	5.175	

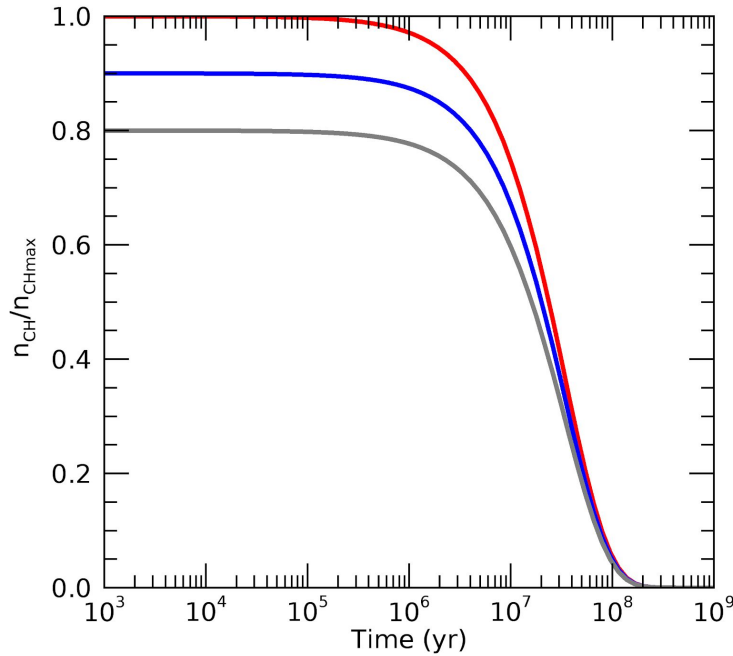
Supplementary Table 3 | Mineral empirical formulae and grain densities. Except where indicated, mineral structural formulae and densities are from ref. 57.



Supplementary Figure 1 | Ceres' spectral mixing with meteoritic contaminants. The panels show the average spectrum of Ceres (black line), and the modeled mixtures (red lines) corresponding to the upper allowable limit of chondritic abundance. Gray bands indicate on the average spectrum correspond to 1- σ calibration uncertainties. Results are 7 % OC (a), 20 % CI (b), 8 % CM (c), and 8 % CR (d). All mixtures are in vol.%. These percentages have been estimated by requiring the model spectra to be contained within the 1- σ errors bars of the average Ceres. Using a less stringent criteria, such as overall probability of 5 % based on the chi-squared of the differences, will only increase these probabilities by a few unit percents. Details on the chondrites used in the models are shown in Supplementary Table 1.



Supplementary Figure 2 | Spectral mixing with CM meteorites. As in Fig. 2b, but now with CM meteorites. The mixture contains: 50 % CM (LAP02277), 22 % amorphous carbon, 2.5 % magnetite, 3.5 % antigorite, 5.5 % dolomite, 6.5 % NH_4 -montmorillonite, 10 % NH_4 -annite. All mixtures are in vol.%. Grain size of 25 μm is derived by the best fit routine (grain size is assumed the same for all species).



Supplementary Figure 3 | C-H decay through time at Ceres. Computed number of C-H bonds over time due to solar proton and UV flux at Ceres for various starting number of C-H bonds (see Methods).