SPECTRAL EVIDENCE FOR HALITE IN THE FACULAE ON CERES AS OBSERVED BY THE DAWN VIR SPECTROMETER.
M. S. Bramble[1] and K. P. Hand[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA (michael.s.bramble@jpl.nasa.gov).

Introduction: The high albedo 'bright spots' or faculae on the surface of Ceres have revealed a history of aqueous processes. Analyses of spectral data from the Visible and Infrared (VIR) spectrometer [1] aboard the Dawn spacecraft have suggested the composition of the faculae is consistent with a large abundance of sodium carbonates [2,3], with lesser aluminum phyllosilicates, ammonium chloride, and ammonium carbonate [3,4]. Recent VIR analysis in conjunction with new laboratory analyses of frozen brines has identified hydrohalite ($NaCl \cdot 2H_2O$) at Cerealia facula on the basis of two absorption features near 3.2 µm [5,6]. At the pressures and temperatures at the surface of Ceres, hydrohalite is unstable and will dehydrate on the order of tens of years [6,7].

While the mineral halite (NaCl) is generally featureless at visible and near-infrared wavelengths, when halite is exposed to a radiation environment of high energy particles it develops diagnostic spectral features. These spectral features are color centers resulting from the trapping of electrons in halogen vacancies and appear at 450 nm and 720 nm corresponding to F and M centers [8–10]. These color centers are spectrally broad and allow for robust identification of halite if present, increasing the confidence in previous identifications of hydrohalite.

We report here on our investigation of the VIR visible-wavelength data set for evidence of radiation-formed color centers. We begin our analyses at Cerealia facula where hydrohalite was previously discovered. We then extend our analyses to other locales using the available high spatial resolution data, and finally extend globally using all the available data. We perform radiative transfer and unmixing models to quantify the presence and abundance of mineral phases. We show that the surface of Ceres may bear evidence for the non-hydrous halite and that there may be evidence of the formation of halite-bearing lag deposits.

Methods: VIR data from the (extended) Low Altitude Mapping Orbit (LAMO) phase as well as High Altitude Mapping Orbit (HAMO) and Survey data were investigated to provide high spatial resolution data for in-depth analyses of particular facula, such as Cerealia facula, but also provide the spatial coverage for global-scale analyses. Level 1B VIR visible data were calibrated into reflectance data following standard processing pipelines [11–14]. A Hapke [15] radiative transfer model was applied to convert both VIR and laboratory reflectance data to single-scattering albedo (SSA) using the viewing geometry and reflectance values. A suite of laboratory endmember SSA spectra were used to unmix the VIR SSA data cubes into the fractional component of each endmember at each pixel.

Results: Examination of the VIR visible detector data of Cerealia facula exhibits a unique spectral curvature near 500 nm, as reported by Rousseau et al. [13]. Comparing visible detector data of Cerealia facula to the modal mixtures modeled by De Sanctis et al. [6] (**Figure 1**) demonstrates that these mixtures do not account for the spectral curvature. Substituting a modest

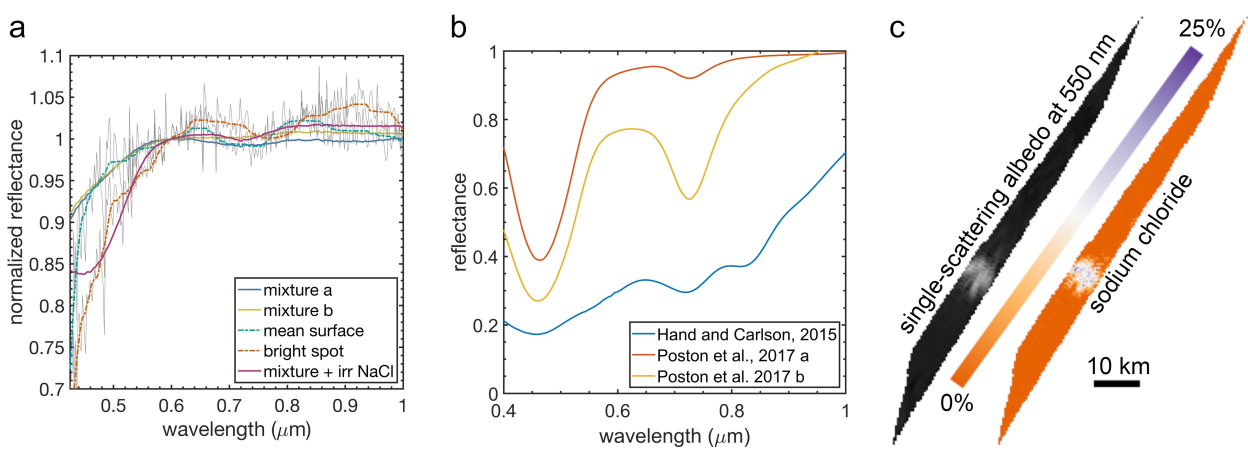

Figure 1: (a) Comparison of visible spectra of the dark mean surface of Ceres to that of a facula "bright spot". These spectra are compared to two numerical mixtures "a" and "b" from [6] and to a third mixture that uses irradiated NaCl as a substitute. (b) Laboratory spectra of irradiated NaCl showing color center formation at 450 nm and 720 nm. (c) VIR image 524703945 of Cerealia facula (also the source of (a) spectra) displayed with the spectral model results for irradiated NaCl.

amount of irradiated NaCl into the modeled mixtures exhibit spectra that match the observed spectral curvature at Cerealia facula. This observation motivated our spectral modeling.

Spectral modeling of extended LAMO VIR visible detector observations of Cerealia facula favors the presence of irradiated NaCl. Modeled spectral fraction values for irradiated NaCl for pixels covering the facula range from 5 to 35%, with the highest values concentrated in the northwest of the faculae and with elevated values also occurring to the south and east of Cerealia tholus. HAMO observations also identify irradiated NaCl at Vinalia faculae at similar abundances as Cerealia facula (**Figure 2a**).

Spectral modeling of the HAMO and Survey observations allow for a significant proportion of the surface of Ceres to be investigated for the presence and abundance of irradiated NaCl. Using these data, the second most prominent location for irradiated NaCl signatures is Ahuna mons. There 8% to 13% fraction of irradiated NaCl is modeled with the main concentration located at the northeast flank (**Figure 2b**). Several craters across the surface of Ceres also have modeled spectral fractions for irradiated NaCl, typically correlating with surface faculae, in the ~5–10% range. These craters include Oxo, Dantu, Ernutet, and Hulani.

Discussion and Implications: Using the global data set, we searched for latitude trends in the positive model results for irradiated NaCl as a proxy to probe the source of the radiation. The non-zero model results for irradiated NaCl a function of latitude does not appear to have a relationship to the latitudinal position of the pixel on the surface (**Figure 3**). The main trend this data appears to show is the relationship between modeled irradiated NaCl and surface processes allowing for the deposition and concentration of NaCl on the surface, such as cratering. This would suggest a globally homogeneous contribution from galactic cosmic rays as opposed to solar UV flux as a source for color center formation, though of course there are many competing factors.

Whether it was emplaced as halite, or emplaced as hydrohalite and subsequently dehydrated, our observations suggest there are more extensive sodium chloride-bearing salt deposits on the surface of Ceres than previously identified. These observations suggest that endogenous halite salts may have been emplaced on the surface throughout time and space from subsurface liquid water environments.

Acknowledgments: All Dawn data used in this study are publicly available and archived in the Planetary Data System. Laboratory spectral data were utilized from the Reflectance Experiment Laboratory (RELAB). This research utilized the Integrated Software for Imagers and Spectrometers (ISIS) provided by the United States Geological Survey.

References: [1] De Sanctis M. et al. (2011) *SSR, 163,* 329–369. [2] De Sanctis M. et al. (2016) *Nature, 536,* 54–57. [3] Carrozzo F. G. et al. (2018) *Science Advances, 4,* e1701645. [4] Raponi A. et al. (2019) *Icarus, 320,* 83–96. [5] Thomas E. C. et al. (2019) *Icarus, 320,* 150–158. [6] De Sanctis M. et al. (2020) *Nature Astronomy, 4,* 786–793. [7] Zolotov M. Y. (2017) *Icarus, 296,* 289–304. [8] Seitz F. (1946) *Reviews of Modern Physics, 18,* 384. [9] Hand K. and Carlson R. (2015) *GRL, 42,* 3174–3178. [10] Poston M. J. et al. (2017) *JGR, 122,* 2644–2654. [11] Kaplan H. H. et al. (2018) *GRL, 45,* 5274–5282. [12] Rousseau B. et al. (2019) *RSI, 90,* 123110. [13] Rousseau B. et al. (2020) *A&A, 642,* A74. [14] Carrozzo F. G. et al. (2016) *RSI, 87,* 124501. [15] Hapke B. (1981) *JGR, 86,* 3039–3054.

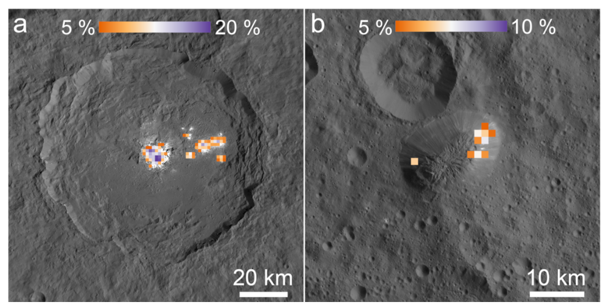

Figure 2: Framing Camera views of (a) Occator crater and (b) Ahuna mons with maps of the unmixed irradiated NaCl endmember modeled using the HAMO data set overlain.

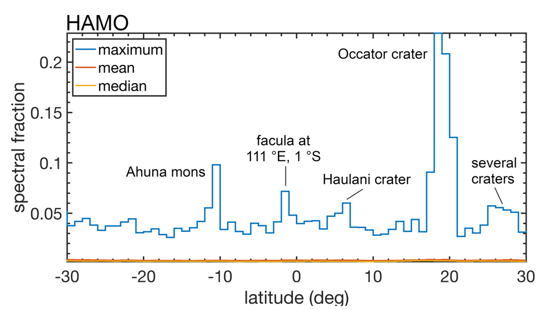

Figure 3: Variations in irradiated NaCl spectral fraction value statistics for 1° latitude bins using the HAMO data set. Notable surface features correlating with excursions in the data are highlighted.