CARBON ON CERES: IMPLICATIONS FOR ORIGINS AND INTERIOR EVOLUTION. T. H. Prettyman[1], N. Yamashita[1], E. Ammannito[2], J. C. Castillo-Rogez[3], B. L. Ehlmann[3,4], H. Y. McSween[5], S. Marchi[6], C. M. Pieters[7], N. Schorghofer[1], M. J. Toplis[8], C. T. Russell[9], C. A. Raymond[3], [1]Planetary Science Institute, Tucson AZ (prettyman@psi.edu), [2]Italian Space Agency, Rome, Italy, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, [4]California Institute of Technology, Pasadena, CA, [5]University of Tennessee, Knoxville, TN, [6]Southwest Research Institute, Boulder, CO, [7]Brown University, Providence, RI, [8]CNRS/IRAP, University of Toulouse, Toulouse, France, [9]University of California, Los Angeles CA.

Introduction: The NASA Dawn mission mapped the surface mineralogy and elemental composition of dwarf planet Ceres. Together with geomorphology and gravity, the compositional data acquired by Dawn provided new information about the origin and evolution of the largest body in the main asteroid belt [1]. Measurements by Dawn's Visible-to-Infrared Mapping Spectrometer (VIR) indicate that aqueous alteration assemblages, consisting of phyllosilicates, carbonates, and opaques (e.g. magnetite), are widespread on Ceres surface [2, 3]. The presence of ammoniated phyllosilicates suggests Ceres originated in the outer solar system [2]. In addition, patches of water ice were found within high-latitude craters [4] and aliphatic organic compounds were detected within a 200-km region that includes Ernutet crater [5].

The Gamma Ray and Neutron Detector (GRaND) [6, 7] measured and mapped the bulk elemental composition of Ceres' regolith (to depths of a few decimeters) within broad regions, 100s of km in scale [8]. GRaND measurements show that Ceres' regolith contains high concentrations of hydrogen, ranging from 1.8- to 3.2-wt.%. The data support the presence of a global subsurface ice table containing at least 10 wt.% water. Ice is at depths greater than sensed by GRaND near the equator. Thus, equatorial measurements are sensitive to the composition of the ice-free regolith. Equatorial regions contain higher concentrations of H and lower concentrations of Fe than the aqueously-altered carbonaceous chondrites, which are the closest analogs for Ceres' regolith [9]. Geochemical and geophysical investigations indicate ice and rock fractionated during Ceres' evolution, resulting in a chemically and physically differentiated interior [e.g. 8, 10, 11].

The concentration and chemical form of carbon provides additional constraints on Ceres origins and evolution. Furthermore, the presence of carbon in an aqueous environment makes Ceres an attractive and accessible target for studies of pre-biotic chemistry. On Ceres, carbon is in the form of carbonates and organics; however, analysis of telescopic UV spectra also suggest the presence of graphitized C [12], which can be produced by the exposure of organics on the surface to UV and ionizing radiation. Thus, organics, if endogenic in origin, may be more prevalent in the subsurface than the few patches detected by VIR [5].

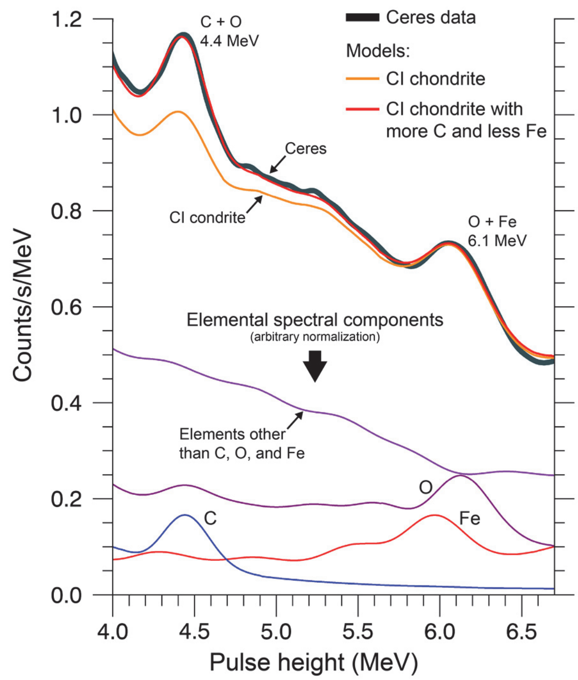

Figure 1. The average gamma ray spectrum acquired within 20 degrees of Ceres' equator is compared to models. The background from cosmic ray interactions with the spacecraft has been removed. The energy range includes contributions from O, C, and Fe, including continua and prominent gamma rays produced by fast neutron reactions with ^{16}O (6.1 MeV and 4.4 MeV), ^{12}C (4.4 MeV) and neutron capture by ^{56}Fe (5.9- and 6.0-MeV).

While GRaND cannot determine the chemical form of carbon, elemental concentrations together with optical reflectance data can constrain the abundance of chemical compounds [13]. The purpose of this study is to bound or quantify carbon concentration using data acquired by GRaND in Dawn's Low Altitude Mapping Orbit (LAMO), a circular polar orbit at an altitude of ~385 km. Improved elemental measurements are anticipated when Dawn transitions to low altitude elliptical orbits, planned for the summer of 2018. With periapsis lower than 50 km altitude, the elliptical orbits will enable high sensitivity elemental measurements of geologic units, such as the interior of Occator crater.

Analysis: Gamma ray and neutron data indicate carbon is present in concentrations similar to or greater than that of the CI chondrites (about 3.5 wt.%) [8, 14].

Fast neutron reactions with ^{12}C make gamma rays that contribute to an intense peak at 4.4 MeV (**Fig. 1**). This peak also contains unresolved contributions from neutron nonelastic reactions with ^{16}O. The reactions occur in the regolith and in the instrument/spacecraft structure, which also contains O and C. To analyze carbon, the intensity of background sources and interfering O contributions must be determined [15]. The spectrum above 4 MeV contains peaks produced by reactions with C, O and Fe (Fig. 1). Unmixing of elemental spectral components [16] can be applied to simultaneously determine their concentrations.

The background from galactic cosmic ray interactions with the spacecraft was subtracted to form a difference spectrum sensitive only to gamma rays and neutrons escaping the surface (Fig. 1, Ceres data). The response of GRaND's bismuth germanate scintillator to gamma rays and neutrons produced in Ceres' surface, including gamma production by neutron interactions with the instrument, was modeled for analog compositions, including carbonaceous meteorites and cometary dust [8]. The data are consistent with increased spectral contributions from C and decreased contributions from Fe relative to the CI chondrite spectrum (Fig. 1).

Results: The analysis of the gamma-ray spectrum indicates a range of C concentrations (7-20 wt.%), consistent with neutron counting data [8]. We are studying uncertainties in instrument/spacecraft contributions to the gamma ray spectrum, which contribute to variability in the result. Measurements of Fe and H also constrain C concentration. The elemental composition of Ceres' ice-free regolith can be modeled by the addition of a C-rich component to CI chondrites [8]. To estimate C concentrations, we blended a representative CI composition with a mixture of carbonates and organics, guided by bulk meteorite analyses [17]. The composition and concentration of the carbonaceous material was adjusted to match equatorial H and Fe concentrations measured by GRaND. The analysis suggests that the bulk regolith contains 8-14% C (**Fig. 2**).

Discussion: The elemental composition of Ceres' regolith falls between the aqueously altered carbonaceous chondrites and cometary materials (Fig. 2) [14, 18]. The presence of alteration products on the surface implies that liquid water was present within the interior, resulting in widespread serpentization, analogous to processes that occurred within the parent bodies of the CI/CM chondrites [9]. Recent modeling suggests that water-rich bodies in the main asteroid belt originated within a broad region containing the orbits of the giant planets (heliocentric distances between 4-10 AU) [19]. Comets formed in the same region; however, they are richer in volatiles than meteorites, which reflects variability in the volatile content of the solar nebula.

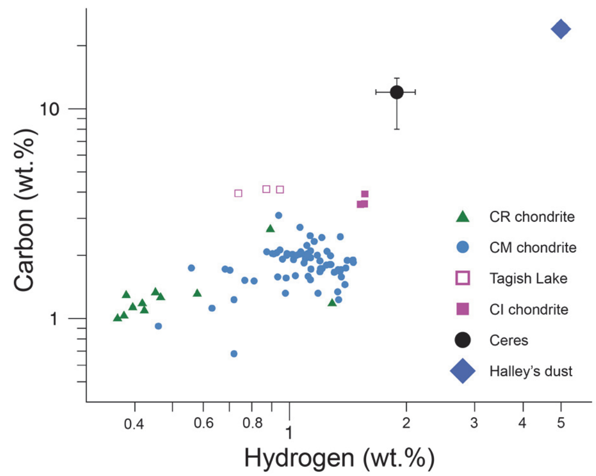

Figure 2. The range of concentrations of H and C in Ceres' ice-free regolith is compared with aqueously-altered, carbonaceous chondrites [14] and dust from comet Halley [18]. For Ceres, [H] was determined by neutron spectroscopy [8]; [C] was estimated by fitting ice-free Fe-H concentrations measured by GRaND to a model, in which a mixture of carbonates and organics was added to a representative CI chondrite. The error bar gives the variation in fitted C.

Conclusion: Similarities between the mineralogy and geochemistry of Ceres and the carbonaceous meteorites suggest that the meteorite parent bodies and Ceres formed under similar conditions from a common reservoir. Nevertheless, the elemental composition of Ceres' regolith is somewhat different than that of the CI chondrites. Super-chondritic abundances of C and H within the regolith suggest that Ceres experienced ice-rock fractionation; although, accretion from a more volatile-rich source cannot be ruled out. The elemental data are consistent with the presence of carbonates and organics within Ceres' bulk regolith.

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