Compositional Variability on the Surface of 1 Ceres Revealed through GRaND Measurements of High-Energy Gamma Rays. David J. Lawrence[1], Patrick N. Peplowski[1], Andrew W. Beck[1], William C. Feldman[2], Thomas H. Prettyman[2], Chris T. Russell[3], Michael J. Toplis[4], Jack T. Wilson[1], Eleonora Ammannito[5,6], Julie C. Castillo-Rogez[7], M. C. DeSanctis[6], Scott C. Mest[2], Adrian Neesemann[8]; [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA (David.J.Lawrence@jhuapl.edu); [2]Planetary Science Institute, Tucson, AZ, USA; [3]Univ. California Los Angeles, Los Angeles, CA, USA; [4]L'Institut de Recherche en Astrophysique et Planétologie, Toulouse, France; [5]Agenzia Spaziale Italiana, Roma, Italy; [6]Istituto di Astrofisica e Planetologia Spaziali, Istituto Nazionale di Astrofisica, Roma, Italy; [7]Jet Propulsion Laboratory, Pasadena, CA, USA; [8]Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany.

Introduction: One of the major objectives of the Ceres portion of the Dawn mission is to measure and characterize mineralogical and elemental composition of Ceres' surface. Data from Dawn's Gamma-Ray and Neutron Detector (GRaND) shows that Ceres has large hydrogen (H) abundances in the range of 16 to 29 wt.% water equivalent H (WEH) [1]. The H data also show evidence for significant depth variation, where the high abundances near the poles are likely due to ice that is stable at or near the surface. For more equatorial regions, H enhancements are located tens of centimeters to meters below the surface [1]. Fe abundance data suggest that Ceres could have experienced ice-rock fractionation or dilution by a neutral component such as C, resulting in differences between Ceres' surface and bulk composition [1]. Dawn spectral reflectance data show that Ceres' surface contains abundant phyllosilicates and carbonates [2,3], where the concentrations of these materials vary across the surface [4]. Taken together, these observations reveal a world that is rich in water and water-bearing species, and where aqueous alteration processes played an important role in shaping the surface and the interior.

Here, we report surface composition information derived from GRaND-measured high-energy gamma-rays (HEGR). HEGRs provide a measure of average elemental composition similar to average atomic mass (<A>). When combined with other elemental composition information, HEGRs can provide unique elemental abundance maps [5,6]. At Ceres, we find that HEGRs provide hydrogen composition information complementary to that inferred from GRaND neutron data, as well as new information about non-hydrogen elemental compositions.

HEGR Measurements at Ceres: For this study, HEGRs are defined as gamma rays with energies in the range of roughly 8 to 9 MeV. These energies are above the nominal line-emission gamma-rays and form a continuum in measured planetary gamma-ray spectra. Measured HEGR count-rates are inversely correlated to Ceres hydrogen concentrations [1] (Figure 1). This result confirms a model prediction [7] that HEGRs should be inversely related to hydrogen concentrations. The minimum and maximum relative HEGR values are 0.95 and 1.05, respectively, for a dynamic range of 10%. Based on a comparison with model variations, the full measured HEGR variation corresponds to a hydrogen variation of 19 wt.% WEH, which is larger than the neutron-measured variation of 13 wt.% WEH (=29 – 16 wt.% WEH). Thus, while hydrogen can account for a majority of the observed variability in the HEGR data, there is evidence for additional source(s) of variability in the data not due to hydrogen.

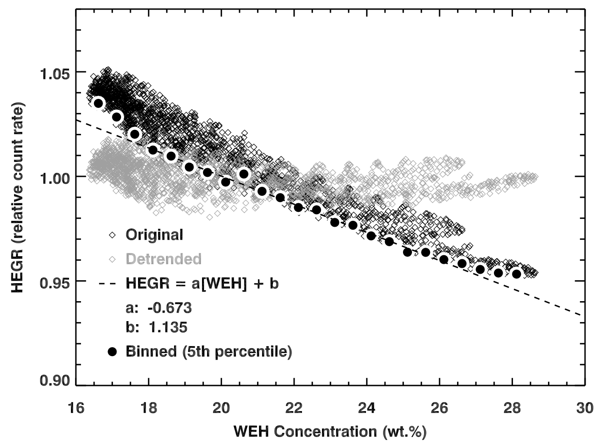

Fig. 1. HEGR count rates (black diamonds) versus WEH concentrations [1]. Large black circles show 5th percentile HEGR values in WEH bins. The dashed line shows a linear fit of the binned values for linear portion of the binned data points that range from 19 to 26 wt.%. Gray diamonds show HEGR values that have been detrended using the dashed line.

Model results suggest that if the Ceres-measured HEGR count rate is detrended with H values, then the residual variation will be related to a water-free average atomic mass, which we define as <A>*, where

$$\frac{1}{\langle A\rangle^*} = \sum_{i \neq H_2O} \frac{w_i}{A_i}.$$

The summation over elements i for weight fractions w_i and atomic masses A_i is calculated over all elements except the hydrogen and oxygen from the water fraction in the particular composition. The detrended HEGR data are shown in Figure 1 as gray diamonds; the detrended HEGR map is shown in Figure 2. Using model-based variations, the detrended HEGR map is presented in units of both relative HEGR count rate

Δ<A>*, which represents a difference in <A>* values from a mean <A>* value. The detrended HEGR map shows clear compositional variability across Ceres that is not related to hydrogen variations.

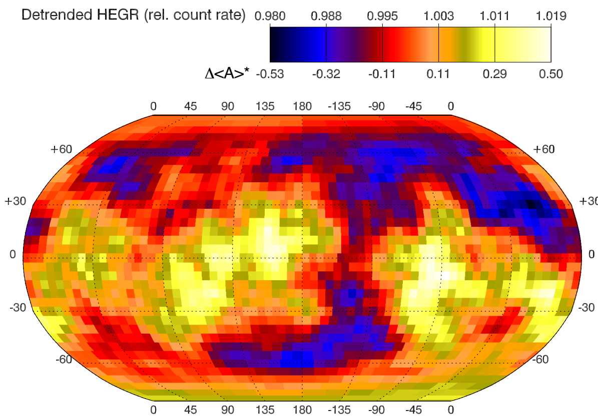

Fig. 2. Map of detrended HEGR values across Ceres' surface. The top numbers on the scale bar show relative count rate; the bottom numbers show variations in water-free average atomic mass (Δ<A>*) from the mean value..

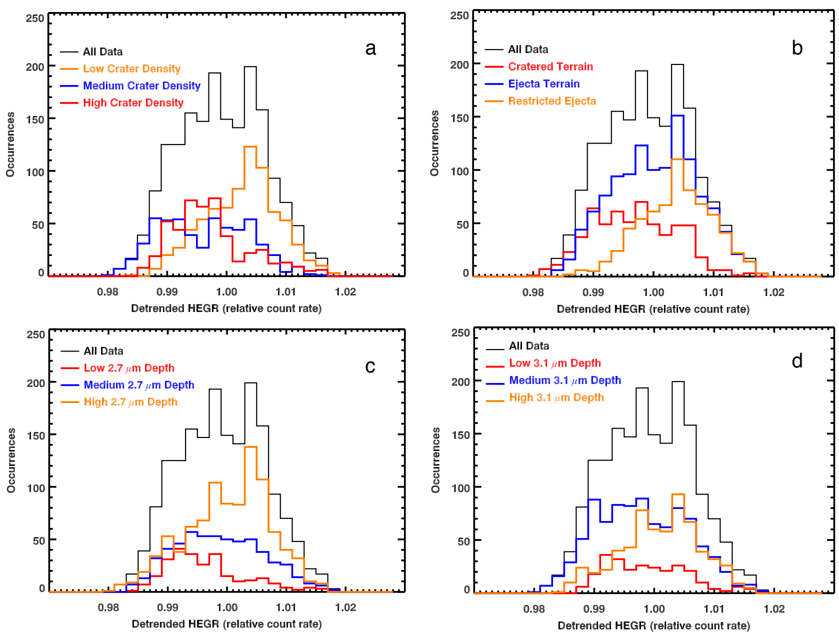

Fig. 3. Histograms of detrended HEGR data, where the HEGR data are binned based on the contours of (a) crater densities; (b) geologic map boundaries; (c) 2.7 µm VIR band depths; (d) 3.1 µm VIR band depths

The H-detrended HEGR data have been compared, with other global information derived from Dawn data, namely a map of crater density [8], a global geologic map [9], and reflectance band-depth data (2.7 and 3.1 µm) from Dawn's Visible and Infrared (VIR) spectrometer [4]. Histograms of HEGR data binned into three broad ranges of these global datasets are shown in Figure 3. The relationship between crater density and HEGR values (Fig. 3a) shows that the HEGR histogram for low crater-density regions is centered at high HEGR values, and the HEGR histogram for high crater-density regions has a centroid at relatively low HEGR values. The comparison of geologic units and HEGR values (Fig. 3b) shows that the older cratered terrains tend to have lower HEGR values, and units associated with the large craters (labeled 'Ejecta Terrain' in Fig. 3b) have higher HEGR values. When the crater units are restricted to locations closer to the large craters Dantu, Kerwan, Urvara, and Yalode (labeled 'Restricted Ejecta' in Fig. 3b), there is a larger separation of high HEGR values from lower HEGR values in cratered terrains. The comparison of VIR band depth data with HEGR values generally shows that locations with higher phyllosilicate abundances (greater band depth) tend to have higher HEGR values.

Summary: Ceres HEGR count rate variations show a good correlation with H concentrations. When the HEGR map is detrended with H, model data suggest that the detrended map correlates with water-free average atomic mass. When the H-detrended HEGR map is compared to other Dawn data, we find that locations with higher <A>* values (and possibly higher Fe concentrations) tend to be located in younger, less cratered terrains that are associated with impact ejecta of Ceres' largest craters. In some instances, these locations of higher <A>* values are also associated with higher abundances of phyllosilicates. Conversely, locations with lower <A>* values (and possibly lower Fe concentrations) are found in older, more heavily cratered terrains.

References: [1] Prettyman, T. H. et al. (2017), *Science*, 335, 6320; [2] De Sanctis, M. C. et al. (2015), *Nature*, 528, 241; [3] De Sanctis, M. C. et al. (2016), *Nature*, 536, 54. [4] Ammannito, E. et al. (2016), *Science*, 353. [5] Peplowski, P. N. and D. J. Lawrence (2013), *JGR*, 118; [6] Peplowski, P. N. et al. (2013), *Met. & Planet. Sci.*, 48, 2252; [7] Lawrence, D. J. et al. (2017), *Met. & Planet. Sci.*, submitted; [8] Hiesinger, H. et al. (2016), *Science*, 353, 10.1126/science.aaf4759; [9] Mest, S. C. (2017), *3rd Planetary Data Workshop*. Abstract #1986.