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Supplementary Materials for

Dawn arrives at Ceres: Exploration of a small, volatile-rich world

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Supplementary Materials

Identification of Energetic Electrons by GRaND

Dawn's Gamma Ray and Neutron Detector (GRaND) consists of a large-volume bismuth germanate (BGO) scintillator surrounded by an anticoincidence shield (ACS). The BGO scintillator is an efficient gamma ray spectrometer. The ACS, which consists of four sensors, serves the dual purpose of identifying cosmic rays and removing them from the particle count and neutron detector. Strong bursts in counts reported here were recorded by the outboard (+Z) "phosphor sandwich" (phoswich), an ACS sensor that points towards the center of Ceres during science data acquisition. The phoswich consists of optically coupled lithium-loaded glass and boron-loaded plastic scintillators. All of the scintillators on GRaND are read out by photomultiplier tubes. See (29) for a detailed description of the instrument.

The broad peak in the time series for the outboard phoswich and BGO scintillator (from 18-21 June, Fig. 4 & Fig. S1) includes contributions from solar protons with sufficient energy to induce nuclear reactions in spacecraft materials. During this period, we observed an increase in the intensity of reaction gamma rays at 4.4-, 6.1-, and 6.9/7.1-MeV, corresponding to the first excited level of ^{12}C , the second excited level of ^{16}O , and third/fourth levels of ^{16}O , respectively (Fig. S2). The gamma rays are likely produced by inelastic scattering of protons with C and O in the outer layers of the spacecraft and instrument housing. Protons below about 4 MeV cannot excite these levels, nor can they penetrate GRaND's housing. Since the rapid bursts seen in the phoswich do not appear in the BGO time series, they are not the result of changes in the flux of energetic ions. Electrons are the only viable alternative. The sensitive side of the detector was toward Ceres when these rapid bursts were seen. After June 21, the intensity of the gamma ray

peaks was consistent with excitation by galactic cosmic rays, as observed during quiet Sun conditions (Fig. S2) (29).

The distribution of energy deposited in the phoswich by the spike-producing particles ranges from equivalent energies deposited by an electron of 20 keV (the lower energy detection threshold) to about 100 keV (Fig. S3). The contribution from the spikes was determined by subtracting the pulse height spectrum measured during a quiet time from a period of intense bursts (marked W1 and W2 in Fig. S1). The energy scale is set by the approximate location of the 93 keV ^{10}B (n,α) reaction peak in the phoswich pulse height spectrum, observed in December 2015, when Dawn reached its low altitude orbit.

Electrons with kinetic energies greater than about 2 MeV can penetrate GRaND's housing, depositing energy in the phoswich; however, bremsstrahlung photons made by these electrons can reach the BGO scintillator. Consequently, given the absence of bursts in the BGO time series, it is unlikely that MeV electrons cause these. Electrons with somewhat lower energies can make bremsstrahlung photons that can reach the housing. These photons would be fully absorbed in the phoswich and structural materials. As such, the maximum observed electron equivalent energy deposition of 100 keV is a reasonable upper bound for the kinetic energy of the incident electrons produced by the bursts.

The MESSENGER gamma ray and neutron spectrometer (MGRNS) observed hundreds of energetic electron bursts while in orbit around Mercury (35). The detection mechanism was determined to be production of bremsstrahlung photons by the interaction of swift electrons with the sensor housing materials. Because the GRaND and MGRNS use similar sensor technology, the same mechanism is valid for GRaND.

The trajectory of the Dawn spacecraft in longitude and latitude in a Ceres centered coordinate system oriented toward the Sun is shown in Figure S4. Symbols along the trajectory show the locations of the bursts. Shapes of the symbols indicate the orbit on which the event occurred. Symbol size indicates strength. The superposition of the bursts of electrons on the three orbits indicates the source of electrons was present for an entire week, much longer than the duration of the solar proton event. The formation of a temporary bow shock in the solar wind flow past Ceres can explain the continuous electron acceleration.

Model Used for Cerean Bow Shock

A single fluid ideal magnetohydrodynamic (MHD) model is used to simulate the mass-loading around Ceres (36). While other codes might treat the problem in greater detail, the MHD code has been used by the authors in similar problems and they are familiar with the code. Such a bow shock would arise when the atmospheric density and resultant ionization rate is sufficiently high. Typical values of the solar wind expected at Ceres based on spherical expansion of the solar wind observed on average at 1AU are given in Table S1.

Table S1. Solar wind parameters applied to the upstream solar wind at Ceres. The total ionization rate is estimated for water group neutrals to ionize via photoionization, while proton and electron impact ionization may substantially enhance this value during solar energetic particle events. The charge exchange rate is estimated for water group ion reactions (37).

Parameters	Value Used
SW Number density, n_i	1.3 cm^{-3}
Velocity, u_{sw}	500 km/s
Interplanetary magnetic field, B	1.54 nT
Solar wind plasma temperature, T	10^5 K
Ionization rate, per molecule	$2 \times 10^{-7} \text{ s}^{-1}$
Ion-neutral charge exchange rate	$2 \times 10^{15} \text{ m}^3 \text{ s}^{-1}$

To simulate this interaction with the solar wind we assume that the cerean atmosphere is solely H₂O molecules. Neither water group species nor neutral cloud shape are expected to change the location of the bow shock. Gravity on Ceres is substantial so a constant outflow flux of $Q = 90 \text{ kg/s}$ with a scale height of $H = 4 R_C$ (Ceres radii) is used to simulate a spherically symmetric gas halo around Ceres. This is 15 times the Herschel Space Observatory observation and assumes that the solar proton event has released adsorbed H₂O from the surface. The neutral density at a distance r from the center of Ceres is $n = Q \exp(-r/H) / 4\pi u r^2$ where $u = 0.36 \text{ km/s}$ is a constant expansion of the cloud corresponding to a surface temperature of 180 K. The surface of Ceres is treated as an absorbing boundary where the plasma is absorbed by the surface and no induction is assumed. The modeled bow shock is shown in 2D projections in Figure S5. The shock is approximately $2 R_C$ from the subsolar Ceres surface. Possible interplanetary magnetic field orientations are shown as straight lines that intersect the strongest burst locations and are tangent to the bow shock surface.

Since the solar wind electrons can be accelerated to high energies at the point of tangency of the solar wind magnetic field with the bow shock, we examine in Figure S5 the magnetic field geometry that would provide tangent field lines starting at the Dawn spacecraft at the locations for which strong energetic electron bursts were seen. The events seen by the +Z detector were all observed on the dawn side of the planet in the southern hemisphere. The figure shows that the same direction of the interplanetary magnetic field could provide this tangency on all four days. For spacecraft locations behind Ceres (as seen from the Sun) or in the northern hemisphere, it would be unlikely for the magnetic field, which has an Archimedean spiral direction so that it approaches Ceres on average about 75° from the solar direction on the morning side, to be tangent to the shock surface. The southern morning segment of the orbit is the segment where

tangency is most likely. The outboard phoswich detector on Dawn was continuously pointed in the Ceres direction throughout this period.

An alternate way of deflecting the solar wind at Ceres is if Ceres became magnetized. This could occur if a magnetic cloud were present in the solar wind, such as the magnetic clouds that accompany a coronal mass ejection. When this magnetic cloud reached Ceres, it could induce electric currents inside Ceres if Ceres were sufficiently electrically conducting in its interior. This magnetic field would continue to build up as long as the magnetic cloud existed at Ceres and would begin to decay at the same rate as it built up after the magnetic cloud passed. This scenario notionally could produce a transient magnetosphere and bow shock such as our simulation produced above.

In order to test this second bow shock production mechanism, we use a different simulation because we now must treat the interior of Ceres and not the region outside of Ceres. We numerically calculate the magnetic diffusion into Ceres, assuming that an electrically conducting shield is present inside the dwarf planet. This hypothesis is consistent with Dawn observations that suggest the interior of Ceres contains brines, but we need to determine whether a strong enough and permanent enough effect can be produced by this scenario.

Magnetic diffusion is governed by the equation

$$\nabla^2 \mathbf{A} = \mu \sigma d\mathbf{A} / dt \quad (\text{S1})$$

where \mathbf{A} is the magnetic vector potential. We model a cylindrical domain with a 10 Ceres radii (R_C) height and a 10 R_C of the cross section. Ceres is at the center of this volume. We then apply a uniform magnetic field along the cylinder at its outer boundary, and the magnetic field everywhere in the model including inside Ceres is calculated in 3D using finite element modeling using FlexPDE software (38).

We assume that the conducting shell in Ceres is a thin sphere beginning at the planetary surface and extending into Ceres some depth. The values of the electrical conductivity used are: inside Ceres but outside the conducting shell 0.01 s/m; in the shell, 25 s/m, outside Ceres, 0. The magnetic permeability is $4\pi \times 10^{-7}$ at all points. Twenty-five $\text{s}\cdot\text{m}^{-1}$ is close to the maximum for a saturated NaCl solution and is as high as we would expect a natural brine to possess (39).

The calculation of the magnetic field vectors began with the application of the external uniform field for a period of 25d at which point the field had completely diffused into the planet. Between $t = 0$ (on day 25) and $t = 0.01\text{d}$, the external uniform field was linearly brought to zero, allowing the magnetic field inside the planet to gradually diffuse outward. Figure S6 shows the decay of the surface magnetic field magnitude at the pole of this induced dipole for shell thicknesses of 2%, 4%, 6%, 8%, and 10% of a Ceres radius.

The results shown in Figure S6 indicate that the thicker the shell, the longer the decay time is. However, the half-life of a field ranges from only 0.5 to 1.5 days. Furthermore, we used a conductivity of 25 s/m, as high as what we would expect for a naturally occurring brine layer. Hence we do not feel that magnetic induction from a coronal mass injection is the answer to the production of a bow shock at Ceres. A transient bow shock produced by a transient sputtered atmosphere or even the steady-state atmosphere at Ceres is a more likely scenario.

Methods

The Dawn spacecraft (41) carries a communication system operating at 7.180 GHz (uplink) and 8.35 GHz (downlink) that enables radiometric measurements of the velocity of the spacecraft relative to the Earth-based Deep Space Network. These data are used in the gravity investigation to obtain the mass of the bodies orbited and the distribution of that mass (42). The

cameras on-board the spacecraft are also used to perform optical navigation that complements the radiometric tracking. The combination of these two techniques provides a very accurate measurement of the gravitation field and its harmonic structure as reported herein.

Two techniques are used to define the shape of the body, Stereophotogrammetry and Stereophotoclinometry (43). Stereophotogrammetry uses landmarks imaged from differing directions (at least three) to build a three-dimensional model of the surface.

Stereophotoclinometry uses gradations in brightness to deduce slopes on the surface using several different directions of illumination to deduce the three-dimensional shape. These two techniques are both used and compared. The differences between them allow improvements to be developed that increase the accuracy of the technique. These techniques enable calculation of the average density of the body, the rotation axis of the body, and to compare that rotation axis with the orbital pole determined originally from telescopic observations. This allows the calculation of the obliquity, the angle between the rotation axis and orbital pole. This angle determines the seasonal dependence of the illumination on the body's surface.

Supplementary Figures

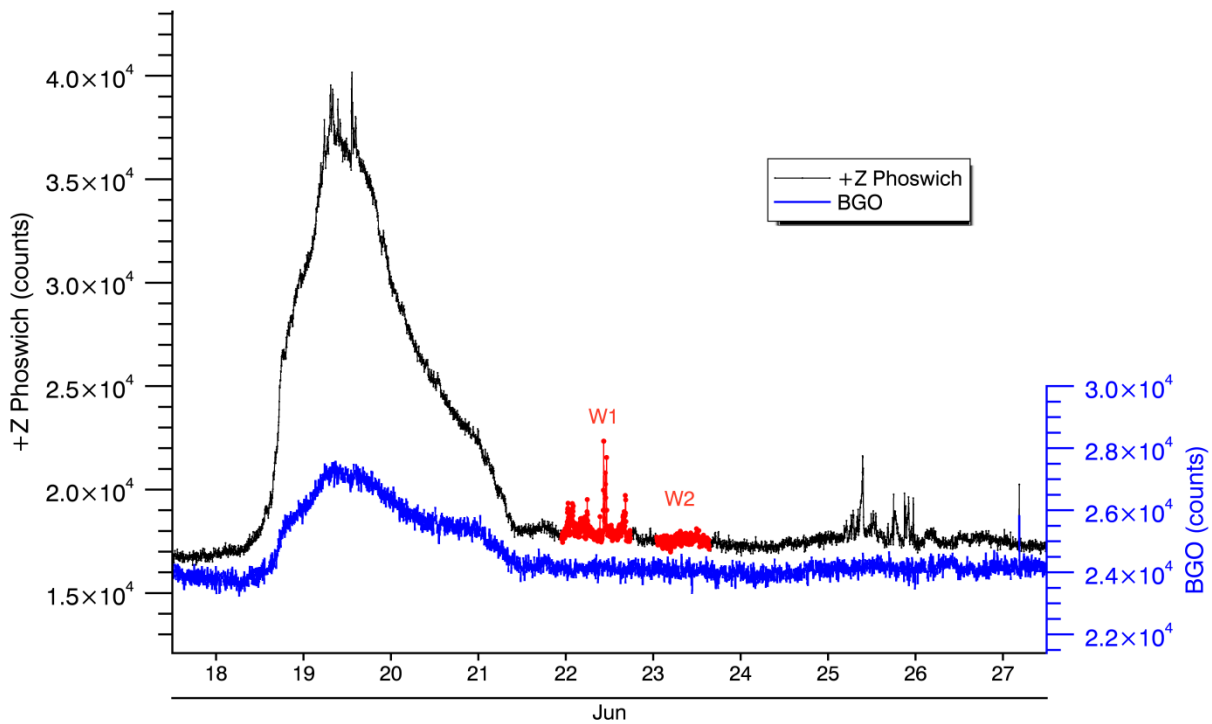


Figure S1. Time series of gross counts for the +Z phoswich and BGO scintillator. The counting time for each measurement was 210s. Time windows used to determine the pulse height spectrum of energetic electrons (W1 and W2) are marked in red. The spurious event on the 27th, which occurred at about 0429:39 6/27/2015 (UTC spacecraft event time) is likely a gamma ray burst (GRB 150627A) detected by the Fermi Gamma-ray Burst Monitor at 0423:24 6/27/2015 (UTC trigger time) (33). Long-duration, intense gamma ray bursts can cause spikes in the +Z phoswich time series. Four of these were observed during Ceres orbit through Survey.

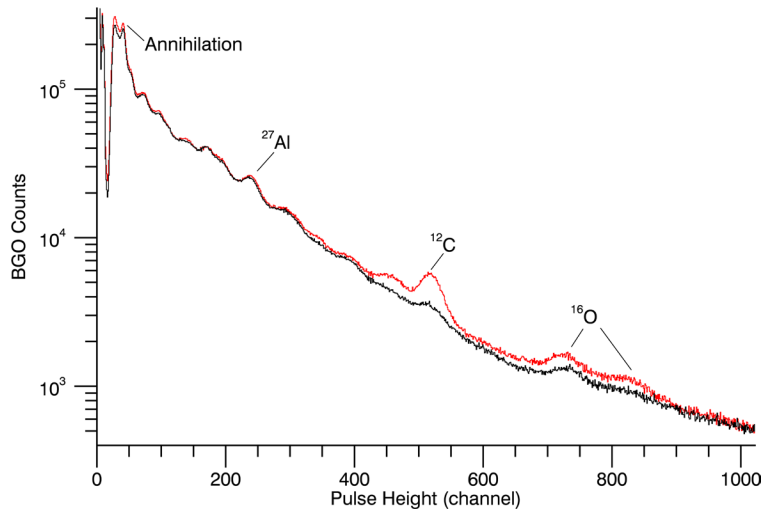


Figure S2. Peak scintillator spectrum. The spectrum measured by the BGO scintillator during three days spanning the broad peak (noon-noon, June 18-21) is shown in red. The spectrum acquired during the quiet period that followed (noon-noon June 22-25) is shown in black. Reaction gamma rays are indicated by the residual isotope.

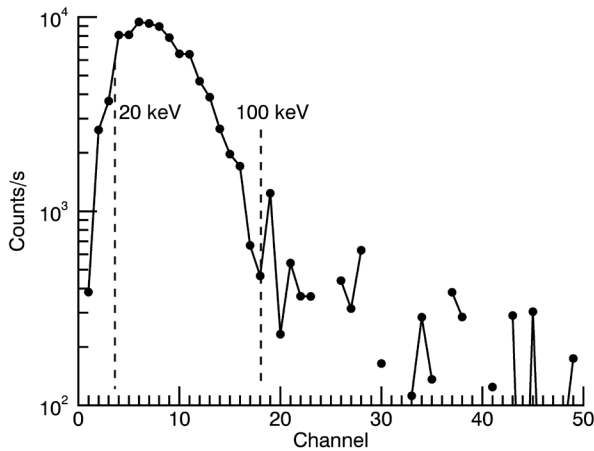


Figure S3. Histogram of energy deposition during the bursts. The data were obtained by subtracting the phoswich pulse height spectrum during a quiet period (W2) from the spectrum observed during a period with bursts (W1). The time series of gross counts above channel 20 does not contain bursts. Consequently, the spectrum for W2 was scaled (by 1.34) to zero the

counts above channel 20. The vertical lines indicate the approximate range for energy deposition.

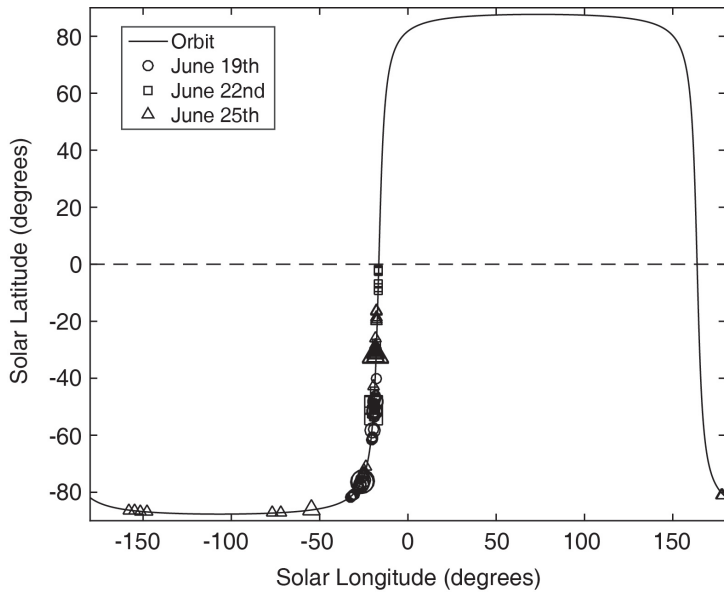


Figure S4. The trajectory of the Dawn spacecraft during the bursts. The trajectory is given in solar longitude and latitude for the three orbits on which bursts occurred, showing the location of the bursts along the trajectory. These occurred when the spacecraft was in its 4900 km circular orbit. Symbol sizes reflect event intensities.

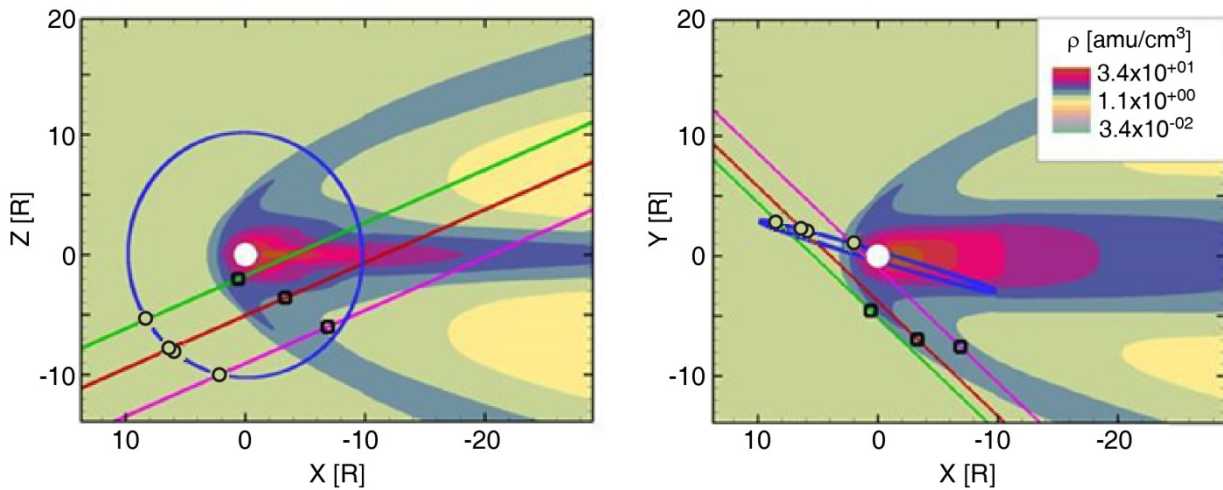


Figure S5. Modeled shock surface in two planes. The left-hand panel (view from dusk) shows the cross section of the simulated interaction in the plane containing the solar wind flow and the

Ceres rotation axis. Locations at which strong electron bursts were observed on the three orbits over a week period are shown with open circles. The right-hand panel (view from above the north pole) shows the orthogonal X-Y projection. The solid lines show a possible field orientation that would be close to tangency with the postulated Ceres bow shock. Black squares indicate near tangent intersections with the shock surface. Other orientations that might also be tangent to the shock on the three orbits appear to be less likely than these, given the usual Archimedean spiral orientation of the solar wind magnetic field.

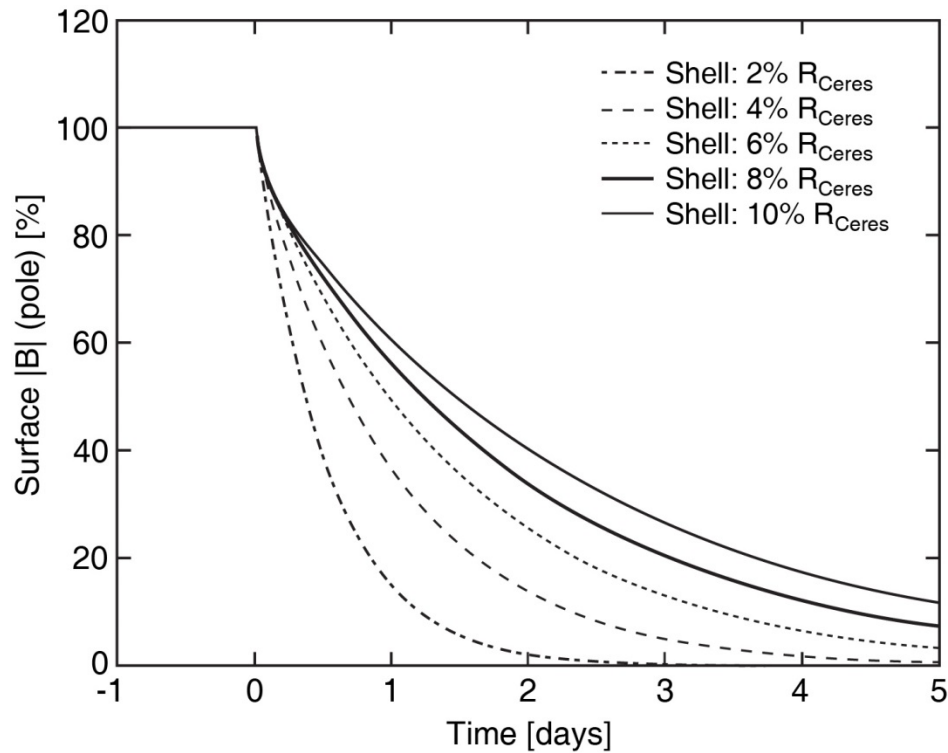


Figure S6. Magnetostatic solution of the demagnetization of an electrically conducting shield after uniform magnetization. For bodies the size of Ceres and electrical conductivities of naturally occurring brines, the decay is too rapid to explain a week-long appearance of a planetary bow shock after a passage of an interplanetary coronal mass ejection.

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