

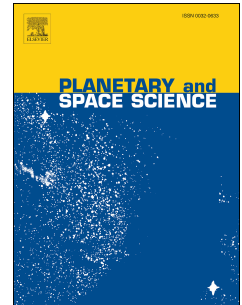


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Thermal inertia of Occator's faculae on Ceres

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# Thermal inertia of Occator's faculae on Ceres

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## Key points

- The thermal inertia of Occator's faculae on Ceres has been derived using spatially resolved, high resolution VIR data from the Dawn mission.
- In the central part of the Cerealia facula a higher thermal inertia (up to about  $60 \text{ Jm}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ ) with respect to the surrounding regions, corresponding to a thermal anomaly, has been derived.

## 23 Abstract

24 Thermal inertia is a key information to quantify the physical status of a planetary surface; it can be  
25 retrieved by comparison between theoretical and observed temperature diurnal profiles. We have  
26 calculated the surface temperature for a set of locations on Ceres' surface with a thermophysical  
27 model that provides temperature as a function of thermal conductivity and roughness, and we have  
28 determined the values of those parameters for which the best fit with the observed data is obtained.  
29 The observed temperatures have been retrieved from spatially-resolved data from the Dawn  
30 mission. In our previous work [Rognini *et al.*, 2019], we have found that the average thermal inertia  
31 for the overall surface of Ceres is low (from 1-15 to  $60 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ ), as expected according to the  
32 general trend observed in the Solar System for atmosphere-less bodies, while the thermal inertia of  
33 the very bright faculae found in the floor of the Occator crater could not be well defined. Using  
34 more recently acquired VIR high resolution data we find that the central part of the Cerealia facula  
35 displays a thermal anomaly ( $\sim 10 \text{ K}$  above the average) compatible with a higher thermal inertia  
36 with respect to the surrounding regions, while the Vinalia facula does not display any consequently  
37 could have a grain size comparable with the Ceres' surface average.

38 **Keywords:** thermal inertia, thermophysical model, Ceres, facula

## 39 1. Introduction and background

40 The dwarf planet Ceres is the largest and most massive body in the Main Asteroid Belt. Its size  
41 (mean diameter 939 km) suggests that it has experienced many of the processes typical of planet  
42 formation and evolution; its planet-like nature and its survival from the early stages of the Solar  
43 System make it an important object for understanding the planetary evolution.

44 The NASA Dawn mission [Russell *et al.*, 2011] was launched in 2007 with the goal of studying  
45 Vesta and Ceres, two of the largest bodies of the Main Belt. The Visible and InfraRed (VIR)

mapping spectrometer [De Sanctis *et al.*, 2011] onboard the Dawn spacecraft operates in the overall spectral range 0.25-5.1  $\mu\text{m}$ , with an Instantaneous Field of View (IFOV) of 250  $\mu\text{rad/pixel}$ , and a spectral sampling of 1.8 nm/band in the 0.25-1.0 visual range and 9.8 nm/band in the 1-5  $\mu\text{m}$  infrared range. VIR was designed to provide mineralogical mapping of Vesta and Ceres. Its data are stored as hyperspectral images or “cubes”, i.e. bidimensional images of the surface at varying wavelength.

Dawn began orbiting Ceres in March 2015. This phase of the mission was divided in different sub-phases, characterized by different altitudes and related VIR pixel resolution (**Tab. 1**): Rotational Characterization orbit (RC3), Survey, High Altitude Mapping Orbit (HAMO), Low Altitude Mapping Orbit (LAMO) for the nominal mission, plus Extended Mission phases 1 and 2 (XM1 and XM2, with the second extended mission phase following an elliptical orbit). While the primary scientific objective of VIR was to determine and map the surface mineralogy, the long-wavelength component of the infrared spectra in the range  $4.5 \mu\text{m} < \lambda < 5.1 \mu\text{m}$  can be used to retrieve the surface temperature; the retrieval is applied separately on each pixel unaffected by detector saturation. The VIR instrument can sense temperatures within the uppermost surface layer as thick as tens of microns; in the sampled spectral range the temperature is a non-linear function of radiance, with a larger weight of the hottest sub-pixel features, so the obtained value is representative of the subpixel regions at higher temperatures modulated by their effective areas. Temperature values retrieved in this way show an accuracy better than 3 K above 180 K, and better than 1 K above 210 K, while values below 180 K have increasingly worse accuracy. The lower limit of temperatures sensed by the instrument is dictated by the in-flight instrumental noise, varying over time depending on a number of parameters, most notably the spectrometer's temperature.

Thermal inertia is defined as:

$$TI = \sqrt{k\rho c} \quad (\text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}) \quad (1)$$

71 where  $k$  is the thermal conductivity,  $\rho$  the density and  $c$  the specific heat; it is a fundamental  
 72 parameter that controls the surface temperature variations of atmosphere-less bodies, and measures  
 73 the velocity of penetration of the thermal wave controlling the surface temperature. The daily  
 74 temperature curve of an airless body (i.e., the profile of surface temperature of a given location as a  
 75 function of the local solar time (LST)), from which thermal inertia can be estimated [e.g.,  
 76 *Neugebauer et al.*, 1971; *Audouard et al.*, 2014; *Delbo et al.*, 2015]), is strongly dependent on the  
 77 physical and thermal properties of the uppermost surface layer, as thick as few centimeters.  
 78 Therefore, the derivation of thermal inertia provides an insight into the structure and physical  
 79 properties of that surface, giving indications on the type (e.g., dust, regolith or rock) and the  
 80 physical structure of the surface material [*Harris and Lagerros*, 2002].

81 In a previous work [*Rognini et al.*, 2019], we modeled VIR data acquired during the Survey and  
 82 HAMO mission phases with an average spatial resolution of 1.1 km/pixel and 0.38 km/pixel,  
 83 respectively. We derived the average thermal inertia of Ceres and of two specific locations: the  
 84 crater Haulani and the crater Occator. The average thermal inertia of Ceres turned out to be  
 85 relatively low ( $\sim 60 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ ), which confirms previous independent estimations and is  
 86 compatible with the trend of the thermal inertia as function of diameter found for the airless bodies  
 87 of the Main Asteroid Belt [*Delbo and Tanga*, 2008]. Crater Haulani revealed a higher than the  
 88 average thermal inertia in its central mountainous ridge (up to  $130\text{-}140 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ ),  
 89 corresponding to the most distinct thermal signature on the entire surface of Ceres (Tosi et al.,  
 90 2018a), which is probably due to the compactness of that particular geologic feature. Conversely,  
 91 crater Occator, as seen at spatial resolution as high as 0.38 km/pixel, could hardly display any  
 92 thermal signature, and its surface temperatures could be fitted by theoretical diurnal temperature  
 93 profiles associated with a broad range of thermal inertia values.

94 In this work, we follow up our analysis on the bright spots (“faculae”) located in crater Occator by  
 95 using VIR data acquired during the final, elliptical XM2 phase mission at much higher pixel

96 resolution (9-11 m/pixel). Occator is a 92-km wide crater, centered at 19.7°N 239.6°E. Occator's  
 97 facula cluster is formed by a very bright spot located in the center of the crater (*Cerealia Facula*),  
 98 and a secondary group of bright spots in the eastern floor, named *Vinalia Facula*. In particular,  
 99 *Cerealia Facula* is the brightest material unit on Ceres with an average visual normal albedo of  
 100 about 0.6 at a resolution of 1.3 km per pixel (several times Ceres's average) [Schröder *et al.*, 2017;  
 101 Longobardo *et al.*, 2017a]. The spectral slope indicates that the crater interior is younger than the  
 102 crater walls, and the white material of the faculae is likely even younger: age estimations give  $34 \pm$   
 103  $2$  Ma [Nathues *et al.*, 2015] for Occator and  $6.9 \pm 0.9$  Ma for the floor material [Nathues *et al.*,  
 104 2016]. Mass deposits originate from the wall of the crater and extend to the floor for 10-20 km, and  
 105 are covered, at SW and NE, by floor material that extends from the center. The features of these  
 106 morphological structures, the presence of fractures and their orientation and age, the central  
 107 depression all suggest post impact processes such as hydrothermal processes, evaporation and  
 108 emplacement of flow materials [Jaumann *et al.*, 2017]. The spectra of the faculae suggest a  
 109 composition of a mixture of anhydrous sodium carbonate or natrite ( $\text{Na}_2\text{CO}_3$ ) and ammonium  
 110 chloride ( $\text{NH}_4\text{Cl}$ ) or ammonium bicarbonate ( $\text{NH}_4\text{HCO}_3$ ) [Raponi *et al.*, 2019; De Sanctis *et al.*,  
 111 2016; Carrozzo *et al.*, 2018; Palomba *et al.*, 2019]. The faculae probably originated from a  
 112 relatively recent crystallization of brines that made their way from a subsurface liquid reservoir up  
 113 to the surface [De Sanctis *et al.*, 2016; Stein *et al.*, 2017]. VIR data of the Occator crater acquired  
 114 on 11, 13, 23 and 24 June 2018, despite their sparse coverage and non-optimal signal-to-noise ratio,  
 115 first revealed that the central part of the *Cerealia* facula is about 10 K cooler than the surrounding  
 116 areas, while *Vinalia* facula has no thermal contrast compared to the rest of the eastern floor [Tosi *et*  
 117 *al.*, 2018b].

118

| Mission phase | Starting date | End date | Altitude<br>(km) | Pixel resolution (m) |
|---------------|---------------|----------|------------------|----------------------|
|               |               |          |                  |                      |

|        |      |                   |                   |               |           |
|--------|------|-------------------|-------------------|---------------|-----------|
| RC3    |      | April 23, 2015    | May 9, 2015       | 13,522-13,637 | 3380-3409 |
| SURVEY |      | June 6, 2015      | June 30, 2015     | 4380-4423     | 1095-1106 |
| HAMO   |      | August 17, 2015   | October 23, 2015  | 1450-1475     | 363-369   |
| LAMO   |      | December 16, 2015 | September 2, 2016 | 355-403       | 89-101    |
| XM1    | XMO1 | 19 Jun 2016       | 2 Sep 2016        | 378           | 95        |
|        | XMO2 | 10 Oct 2016       | 04 Nov 2016       | 1522          | 380       |
|        | XMO3 | 21 Jan 2017       | 17 Feb 2017       | 7738          | 1930      |
|        | XMO4 | 29 Apr 2017       | 24 May 2017       | 19457         | 4860      |
| XM2    |      | May 21, 2018      | July 15, 2018     | 29-2662       | 7-665     |

**Table 1.** Characteristics of the mission phases of Dawn around Ceres. Data from XM2, i.e. the last mission phase, have been used in this work.

## 2. Thermophysical analysis of the Occator faculae

### 2.1 Temperature retrieval method

The method used to derive surface temperatures and spectral emissivity from VIR data is described in details in the Appendix of *Tosi et al.* (2014). It was originally applied to VIR data acquired at Vesta, and subsequently adapted to VIR data acquired at Ceres (Tosi et al., 2018a, 2019a) and to Rosetta/VIRTIS data acquired at the comet 67P/Churyumov-Gerasimenko (Tosi et al., 2019b). Briefly, a synthetic radiance spectrum is computed by summing the solar contribution and the thermal contribution, with emissivity and temperature defined by their respective first guesses. The Kirchhoff's law is used to relate reflectance with emissivity. This is a two-step process: in the first step, spectral emissivity and temperature providing the best fit with the measured spectral radiance within the instrumental error in the 4.5–5.1  $\mu\text{m}$  range (where thermal emission is predominant on most of the dayside) are iteratively and simultaneously computed in a cycle, until convergence around stable values is achieved. In the second step, the scalar value of the surface temperature is retained and a second Bayesian retrieval is performed by considering a broader spectral range

starting 0.5  $\mu\text{m}$  shortward of the crossover point to compute the spectral emissivity up to the upper bound of VIR sensitivity (5.1  $\mu\text{m}$ ). Formal errors on the unknown quantities, related to random variations of the signal, are also a standard output of the Bayesian algorithm: each temperature image of Ceres can be associated to an image of the formal errors on the retrieved values, and similarly, for each wavelength where emissivity is retrieved, there is an associated uncertainty. VIR is not sensitive to physical temperatures on the nightside of Ceres, where the signal from the target is considerably low. In VIR data acquired at Ceres, uncertainties increase with decreasing surface temperature, and 170–180 K is the typical minimum temperature value that can still be retrieved while keeping uncertainties  $< 30$  K (typical uncertainties are  $< 1$  K for temperature values  $> 200$  K).

## 2.2 The Thermophysical Model

The determination of the thermal inertia from measured temperatures requires a thermophysical model [e.g. *Rozitis et al., 2011, Delbo et al., 2015*]. We have used the one-dimensional model described in *Capria et al. (2014)* and *Rognini et al. (2019)*, that solves the heat conduction equation and provides the temperature as a function of thermal conductivity, albedo, emissivity, density, and specific heat. The details of the code are reported in the above-mentioned papers; we here briefly recall its main points.

The model is applied to a detailed shape model of Ceres in order to take into account the instantaneous illumination [*Raymond et al., 2011; Preusker et al., 2016*]. The code solves with a finite-differences scheme the 1D heat transport equation in all the layers into which the internal radius has been subdivided:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) \quad (1)$$

where  $\rho$  is the density,  $c$  the specific heat,  $T$  the temperature,  $t$  the time,  $x$  the depth and  $k$  is the thermal conductivity. The surface boundary condition is:

$$\frac{S(1-A)\mu}{r^2} = X\sigma T^4 + k \frac{\partial T}{\partial x} \quad (2)$$

159

160 where  $S$  is the solar constant,  $A$  is the Bond albedo,  $\mu$  is the cosine of the solar incidence angle,  $r$  is  
 161 the heliocentric distance in AU,  $\sigma$  is the Stefan-Boltzmann constant, and  $X = (1 - \varepsilon\xi)\varepsilon$  is a  
 162 “roughness parameter” where  $\varepsilon$  is the emissivity and  $\xi$  is the sub-pixel roughness.  $\xi$  is a measure of  
 163 the surface irregularity at a scale smaller than the shape model and larger than the thermal skin  
 164 depth; it can be interpreted, for example, as the percentage of cratered terrain with respect to flat  
 165 terrain [Müller and Lagerros, 1998; Keihm et al., 2012]. Flat surfaces will have  $\xi$  values close to 0,  
 166 while very irregular surfaces will have values approaching unity; moreover, high values of  $\xi$  will  
 167 increase the computed surface temperature, while low values will have an opposite effect. We used  
 168 an albedo map that has been calculated by conversion of a reflectance map at 1.2  $\mu\text{m}$  [Ciarniello et  
 169 al., 2017], this being a good proxy for the reflectance at 0.55  $\mu\text{m}$  (the peak of the solar spectrum),  
 170 with differences of a few % [Longobardo et al., 2019]. It should be noted that, while the bolometric  
 171 Bond albedo of Ceres at 0.55  $\mu\text{m}$  is  $0.037 \pm 0.002$  on average [Li et al., 2019], Occator bright spots  
 172 have a Bond albedo rising up to  $0.24 \pm 0.01$  through the Dawn Framing Camera clear filter [Li et  
 173 al., 2016], i.e.  $\sim 6.5$  times the Ceres average.

174 The model is applied to a given location specified by planetocentric coordinates (latitude and  
 175 longitude) referred to a digital shape model of Ceres [Preusker et al., 2016]. The corresponding  
 176 illumination conditions at any step within a given time interval are derived through SPICE-based  
 177 software and navigational databases, the so-called “SPICE kernels” [Acton, 1996], keeping into  
 178 account the position of Ceres along its orbit and that of the Dawn spacecraft. Time interval and  
 179 steps are optimized so as to stabilize the results of the computation.

180 We assume that the surface of Ceres is covered by a layer of particulate material (regolith), ranging  
 181 from very fine dust to incoherent rocky debris, with density increasing with depth. The formulae for  
 182 density and thermal conductivity are based on the properties of the particulate material, which have

been derived from ground and spacecraft observations, lunar in-situ measurements and returned samples [Capria et al., 2014; Vasavada and Paige, 1999; Vasavada et al., 2012]. Surface density ranges from 1200 to 1350 kg/m<sup>3</sup> (fine dust and regolith, respectively, see **Tab. 2**) at the surface and increases with depth, while thermal conductivity has the form:

$$k(T) = k_{cond} + k_{rad}T^3 \quad (3)$$

where  $k_{cond}$  is the conductive term (that takes into account the conductive heat transfer across the particles) and  $k_{rad}$  is the radiative term (that takes into account the radiative heat transfer, sensible at high temperatures). For  $k_{cond}$  and  $k_{rad}$  we apply the expressions used in Rognini et al. (2019), where more details can be found. Laboratory experiments show that the thermal conductivity only depends on the physical structure of the soil and not on composition [Opeil et al., 2012]. Three kinds of particulate material have been assumed in this work: fine dust, dust, fine regolith, with the corresponding density profiles (**Tab. 2**). By assuming these materials type, typical total thermal conductivity values (**Eq. 3**) range from about 10<sup>-5</sup> to 0.001 W m<sup>-1</sup> K<sup>-1</sup> (for fine dust and fine regolith, respectively); the lower value is probably unrealistic for our work, and represents a theoretical lower limit in the range we are looking for.

The specific heat for the points located inside the faculae has been set to 1060 J kg<sup>-1</sup> K<sup>-1</sup>, which corresponds to the specific heat of sodium carbonate, i.e. the main constituent of the bright faculae. For the points outside the faculae we used a temperature-dependent specific heat derived from a fit of experimental measurements of materials compatible with Ceres surface [Biele et al. 2014]:

$$c(T) = a_0 + a_1(T - T_0) + a_2(T - T_0)^2 + a_3(T - T_0)^3 \quad (\text{J kg}^{-1} \text{K}^{-1}) \quad (4)$$

where  $T_0 = 250$  K,  $a_0 = 633$  J kg<sup>-1</sup> K<sup>-1</sup>,  $a_1 = 2.513$  J kg<sup>-1</sup> K<sup>-2</sup>,  $a_2 = -0.0022$  J kg<sup>-1</sup> K<sup>-3</sup>,  $a_3 = -2.8 \times 10^{-6}$  J kg<sup>-1</sup> K<sup>-4</sup>.

On a real planetary surface, the derivation of thermal inertia is complicated by the presence of small-scale surface roughness, which cannot be detected even in the highest resolution optical

imagery, but should be taken into account to properly model the measured heat flow. In this regard, the problem is degenerate to some extent, because different combinations of parameters, particularly thermal conductivity and surface roughness, in principle might lead to the same value of thermal inertia.

## 2.2 Derivation of the Thermal Inertia of Cerealia and Vinalia faculae

In order to perform the analysis of the thermal properties of the surface of the Occator faculae we used the procedure already applied to determine the average thermal inertia of Ceres (see *Rognini et al.*, 2019 for a detailed description), while the VIR data used in this work come from the XM2 mission phase (**Tab. 1**). The areas selected and analyzed are reported in **Fig. 1** and **Fig. 2**: the magenta square represents the central part of Cerealia facula, while the cyan square and circle respectively indicate the portion of Occator's floor west of Cerealia facula and the border of the facula itself (**Tab. 3**).

For each VIR pixel, the retrieved temperature value represents the average temperature measured on a resolution cell defined by the instantaneous ground footprint as observed at a given time. For each pixel, a complete set of geometric information, including planetocentric latitude and longitude, and illumination and observation angles, are available. The retrieved temperature values are affected by the illumination geometry, while our thermophysical code, for each surface element approximated by a triangular plate ("facet"), calculates the temperature at zero emission angle (i.e, the local normal to the surface element). To reduce the differences between theoretical and observed temperature values, we then discarded all VIR observations with an emission angle greater than 30°, and uncertainties associated with retrieved temperature values greater than 5 K. For every given area, a set of locations (3-5 points) has been selected in such a way as to cover the area as best as possible, and for every selected location within a given area, we calculated theoretical temperature profiles by assuming varying pairs of  $k$  and  $\xi$  values. The set of theoretical curves is

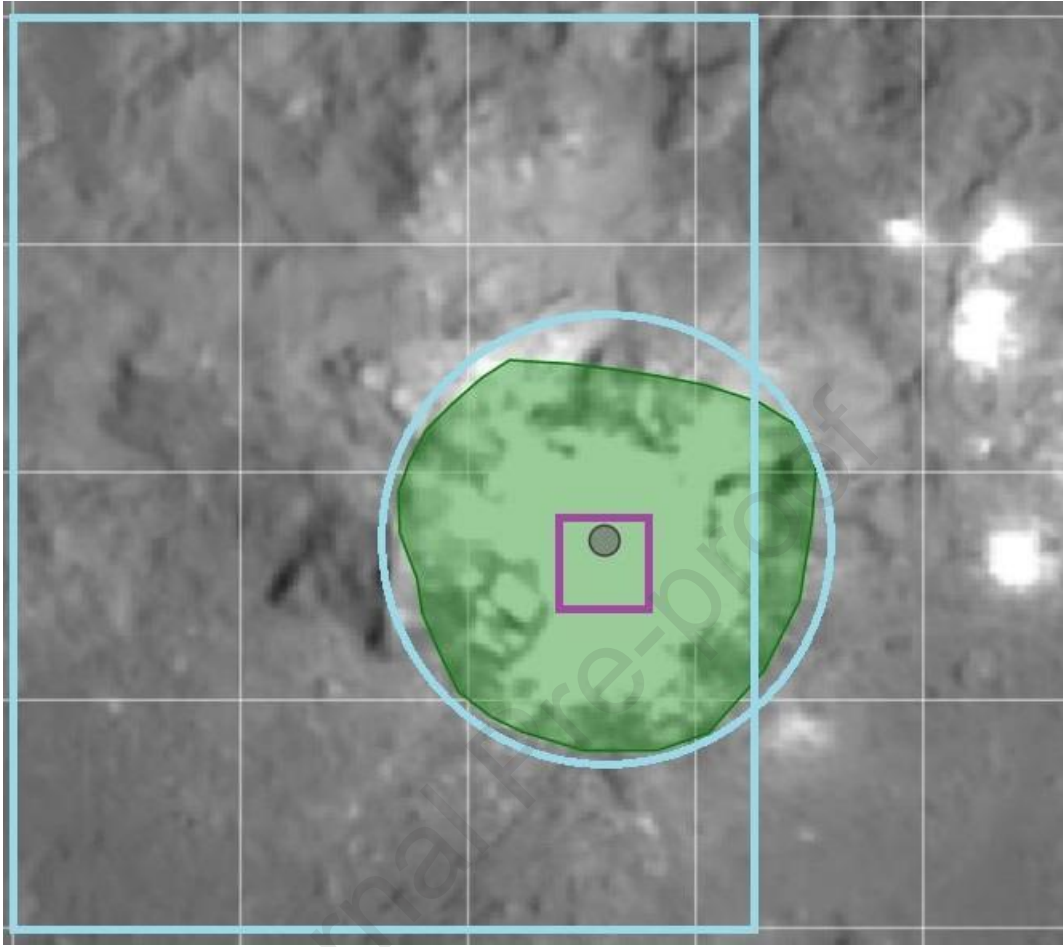
then compared with the observed temperature data using a chi-square function defined in Rognini et al. (2019), that has to be minimized (for every class of material) as a function of  $\xi$ ; a thermal inertia value is subsequently derived from thermal conductivity, density and specific heat capacity (Eq. 1). This procedure is based on the fundamental hypothesis that, if for given values of the input parameters the theoretical temperatures match the measured ones within the associated uncertainties, then the input parameters are retained because they are realistic. More precisely, because of the degeneration in roughness-thermal inertia, we identify a range of roughness and thermal conductivities that are candidate “real” values, as they match the observations.

| <b>Material</b> | <b>Minimum<br/>density (kg/m<sup>3</sup>)</b> | <b>Maximum<br/>density (kg/m<sup>3</sup>)</b> |
|-----------------|-----------------------------------------------|-----------------------------------------------|
| Fine dust       | 1200                                          | 1800                                          |
| Dust            | 1320                                          | 1930                                          |
| Fine regolith   | 1350                                          | 1950                                          |

**Table 2.** Ranges of density values (in kg/m<sup>3</sup>) for the materials considered in this work.

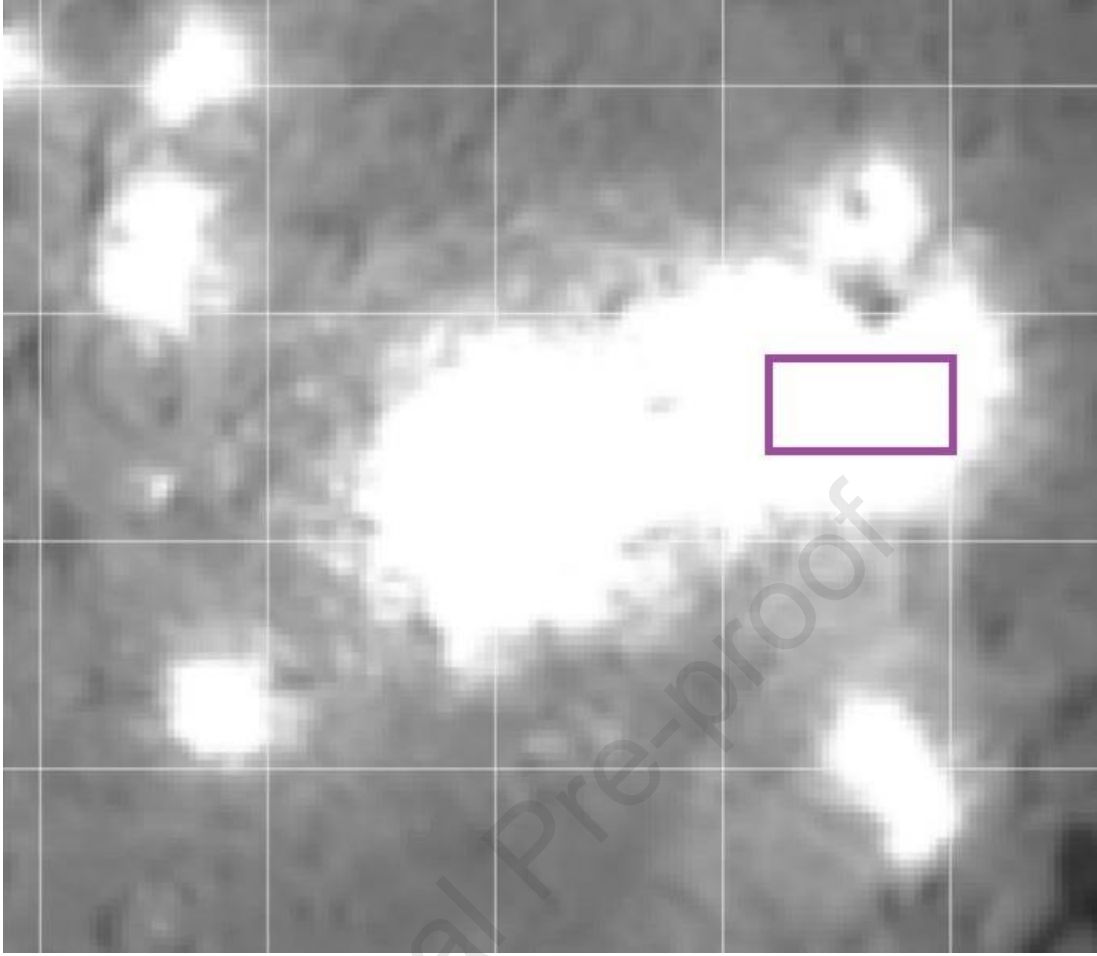
| <b>Area</b>     | <b>Location (longitude-latitude)</b>             |
|-----------------|--------------------------------------------------|
| Cerealia        | [239.4°, 239.8°] × [19.4°, 19.8°]                |
| Vinalia         | [242.6°, 243°] × [20.2°, 20.4°]                  |
| Around Cerealia | [237°, 240.5°] × [18°, 22°] (outside the Z area) |

242 **Table 3.** The areas considered in this work.  $Z$  is an area defined by  $(lon - 239.6^\circ)^2 + (lat - 19.7)^\circ \leq 1$ .



243

244 **Figure 1.** Selected areas for the Cerealia facula and the surrounding regions (see **Tab. 3**). The square and circle  
 245 drawn in cyan refer to the area selected around Cerealia, while the magenta square identifies the area selected in the  
 246 central part of Cerealia. The area bordered by the cyan circle and the cyan square is the “ $Z$ ” area indicated in Tab. 3.



**Figure 2.** The magenta rectangle surrounds the area selected in Vinalia facula (see **Tab. 3**).

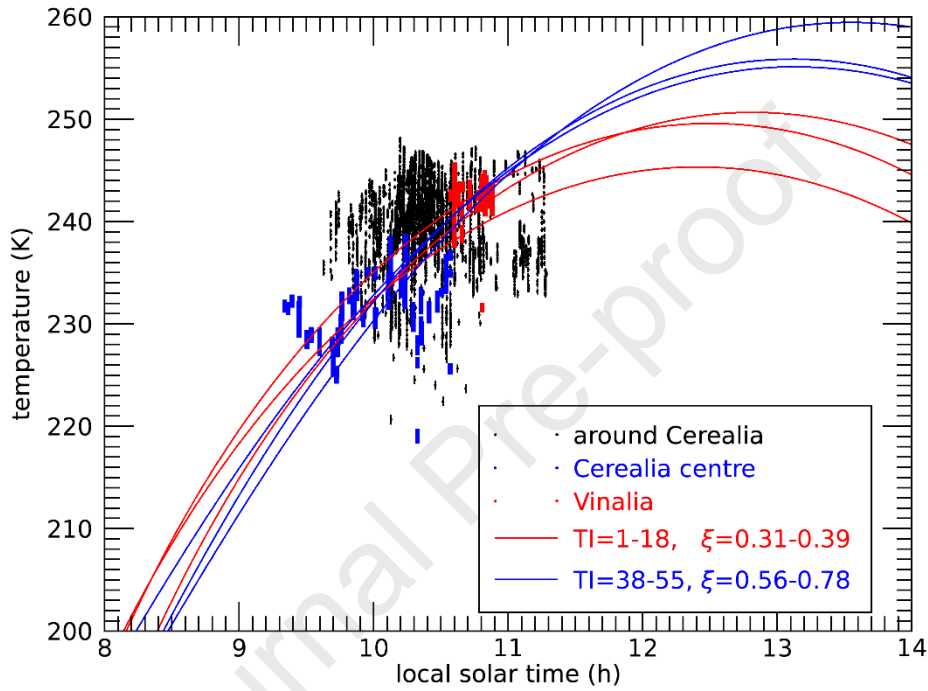
### 3. Results and Discussion

The results of our analysis are summarized in **Fig. 3**, which shows measured data and modeled diurnal temperature profiles for the central part of Cerealia, a selected region within Vinalia, and a larger area surrounding Cerealia (**Tab. 3**). The temperatures in the central part of Cerealia are lower with respect to those in the surrounding regions, while Vinalia facula does not display any thermal signature. This could indicate a higher thermal inertia only for the inner region of Cerealia facula. A different sub-pixel roughness would also be possible, as explained in subsection 2.2.

Theoretical temperature curves calculated by assuming the material defined as “fine dust”, with corresponding thermal inertia up to about  $20 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ , and  $\xi \approx 0.3 - 0.4$ , fit the observations of both Cerealia and Vinalia faculae; a similar result is obtained by assuming the material defined as

260 “dust”, with thermal inertia up to  $55 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$  and  $\xi \approx 0.6 - 0.8$ . The curves differ between  
 261 them only after 11 h LST, when no observed temperature is available, which precludes the  
 262 possibility to discriminate the most plausible solutions.

263



264

265 **Figure 3.** Comparison between observed (points) and theoretical (lines) temperatures in the areas analyzed in this work.  
 266 The selected areas are reported in **Tab. 3**. For the theoretical temperatures, the corresponding  
 267  $\xi$  values and the resulting thermal inertia are also shown.

268

269 When considering diurnal temperature profiles, the maximum daytime temperature value moves  
 270 from local noon to the local afternoon with increasing thermal inertia, thus the position of this  
 271 maximum in principle could further constrain the thermal inertia value. However, due to operational  
 272 constraints of the Dawn mission, the coverage in terms of local solar time is very limited (typically  
 273 less than 3 hours in the local morning between 9 and 11.5 h LST, see **Fig. 3**), which precludes this  
 274 possibility.

275 Effects of unresolved surface roughness are important in modeling thermophysical properties of  
 276 airless bodies. Our model uses the known values of Bond albedo and takes into account the small-  
 277 scale surface roughness with a simple  $\xi$  parameter, rather than considering a variable density of  
 278 nearly hemispherical concavities at sub-pixel scale, distributed randomly across the surface; the  
 279 complexity required to implement this approach in our model goes beyond the scope of the article.

280 To some extent, the thermal conductivity is temperature dependent, and so is the thermal inertia  
 281 (**Eq. 1**). When the regolith grains are small, the radiative heat transfer is dominant, particularly at  
 282 high temperatures, because the surface contact between grains is small, and the solid-state heat  
 283 conduction (transfer by phonons) is less efficient. In this case, the thermal conductivity tends to be  
 284 small and is very sensitive to the temperature itself, because the radiative heat transfer is  
 285 proportional to  $T^3$ . If the grain size increases then the transfer by phonons becomes dominant, and  
 286 the conductivity value increases and is less sensitive to the temperature [Hale & Hapke, 2002].

287 In our previous work [Rognini *et al.*, 2019], we found that the surface temperature of the bright  
 288 spots in crater Occator as seen at a resolution of 0.38 km/pixel could be compatible with both low  
 289 ( $1\text{--}17 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ ) and high (up to about  $140 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ ) thermal inertia. Much higher  
 290 resolution VIR data were needed to highlight a temperature difference in Cerealia facula, which  
 291 however only shows up in its central part, while Vinalia does not show any thermal contrast at  
 292 spatial scales ranging from meters to kilometers. Longobardo *et al.* (2017) found that the phase  
 293 curve of the faculae has the same steepness of the average of Ceres despite their larger albedo. They  
 294 proposed that this could be due to a mixing of bright and dark material (similar to what happens on  
 295 Vesta) or a larger grain size and/or a larger roughness. Cerealia facula could have higher thermal  
 296 inertia with respect to the surrounding regions due to its lower temperature; this hypothesis would  
 297 agree with the conclusions of Longobardo *et al.* (2017) regarding the larger grain size, because if  
 298 the grain size increases then thermal inertia increases. A higher roughness value with respect to  
 299 Ceres' average ( $\xi \approx 0.2 - 0.3$ , Rognini *et al.* 2019) is also required in order to fit the temperatures

in this area. The Vinalia data could also be fitted by the high thermal inertia curves, but the fact that no thermal anomaly has been detected in this area suggests that a lower thermal inertia solution, together with a lower roughness value (magenta curve in the **Fig. 3**), appears to be more likely in this case. However, spectral unmixing carried out by *Raponi et al.* (2017) suggests that the grain size of the surface regolith in the faculae could be smaller or anyway compatible with the average grain size of the surface of Ceres; this conclusion would agree with a low thermal inertia solution, especially for Vinalia. Anyway, the roughness value required in order to fit the Vinalia temperatures is higher with respect to the Ceres' average, and this could agree also with the high roughness values suggested by *Longobardo et al.* (2017). The high roughness value could be explained by the young age of Occator: the surface of the faculae has not yet been smoothed because not enough time has passed, and some surface irregularity could still be present today. Moreover, the brines that have reached the surface from the interior are not evenly distributed. *Nathues et al.* (2017) have found that Occator's bright dome formation likely took place over a long period of time, instead than forming in a single event; this different formation could explain the observed differences between the faculae. Unlike Cerealia facula, Vinalia facula is composed of a mixture of carbonate and dark materials (*Palomba et al.*, 2019); the dark component, with a different composition and physical structure with respect to the bright one, could be the reason of a thermal inertia more similar to the average one of the Ceres' surface.

## 5. Conclusions

We have analyzed the temperature data of the faculae in the Occator crater by using the new high resolution VIR data, acquired in the Extended Mission 2 phase (XM2). The central part of the Cerealia facula displays a thermal anomaly ( $\sim 10$  K above the average) compatible with a higher thermal inertia with respect to the surrounding regions; lower values of thermal inertia would also be possible, but because of the temperature anomaly the higher value is the preferred interpretation. This can be supported by other results that seems to suggest larger grain sizes of the surface

regolith. The Vinalia facula does not display a thermal anomaly, and this is consistent with other studies that could indicate a grain size comparable with the Ceres' surface average. The faculae have different history formation and bright/dark material ratio, and this could explain the differences.

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- New high resolution data revealed a thermal anomaly in the center of Cerealia facula
- Higher thermal inertia may be an indicator of higher grain size or cementation
- Faculae are not homogeneous, different evolutionary history may be possible

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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