

Research Article

Thermal Modeling of Oxia Planum: Thermophysical Characterization of the Dark Resistant Unit (DRU) in the Germania Lacus

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The aim of this work is to characterize, from a thermophysical perspective, the dark resistant unit (DRU) characterizing Germania Lacus in the Oxia Planum Region, providing new insights to constrain the nature of the materials which compose this unit. We investigated the temperature distribution of the DRU by adopting common values of the thermophysical parameters of the basalt and by exploring several values of porosity. As an additional case, we also explore a composition made of pebbles. The numerical model developed here represents a follow-up of the work recently published by Formisano et al. 2021, and it takes into account a large-scale topography of the site and assumes a diurnal temperature profile for the atmosphere rather than a constant value (unlike Formisano et al. 2021). Comparisons with Mars Pathfinder and Viking data as well as numerical models are also reported. The methodology described here could be useful to characterize as well other sites on Mars' surface with available small-scale topographic data.

1. Introduction

Oxia Planum is the selected landing site for the mission Rosalind Franklin planned to land on Mars on 2030. Rosalind Franklin is part of the European Space Agency (ESA) program ExoMars whose principal target is to search for traces of present or past life on Mars [1]. The 150 by 15 km landing site is located at a latitude of 18°N at the margin of Chryse Planitia basin. The major geologic characteristics of the landing area of Rosalind Franklin are that it is ancient [2] and morphological and compositional orbital observations suggest a paleoenvironment where water played a key role [3, 4].

Oxia Planum's thermophysical and compositional characteristics are a matter of debate since in the literature, we find several estimates of thermal inertia for a variety of its terrains. Based on the observations of the planetary brightness temperature of the Mars Global Surveyor (MGS), the Thermal Emission Spectrometer (TES) provides a value of thermal inertia between 300 and 400 thermal inertia units (TIUs $(J \cdot m^{-2} \cdot K^{-1} \cdot s^{-1/2})$ hereafter) [5]. In [6], the terrain of Oxia Planum is interpreted as consisting of dark fines, with some coarse sand and duricrust, but very little dust, with grain sizes below 3 mm: in this case, the estimated value of thermal inertia is around 260 TIU. Quantin-Nataf [4], however, showed an extensive distribution of clay-bearing terrains, whose thermal inertia is in the range 550–650 TIU, while Gary-Bicas and Rogers [7] characterized the clay unit with a thermal inertia around 370–380 TIU, by using the Thermal Emission Imaging System (THEMIS) data.

The rover of the ExoMars mission is equipped with a drilling system able to penetrate the Mars surface down to 2 meters to search for astrobiological signatures. Attached to the drill system is the Mars Multispectral Imager for Subsurface (MA_MISS), which will generate hyperspectral images [8–11], providing information about the mineralogy, oxidation state, and hydration state of the sample before the extraction and crushing [1].

This work represents a follow-up of Formisano et al. [12] with several improvements. We focused on a portion (1 km²)

of Germania Lacus (18.2°N, 335.5°E), characterized by variable topography, allowing the possibility to investigate with our modeling the effects of indirect light in regions not directly hit by sunlight. Germania Lacus lies in geological unit 3 identified by Gary-Bicas and Rogers [7]. Accordingly, Gary-Bicas and Rogers [7] identified the mean thermal inertia of this unit to be 368 TIU. However, this region is also characterized by the presence of a dark resistant unit (DRU-the site here investigated), which is different from a mechanical point of view from the clay-bearing unit (which largely characterizes Oxia Planum). The DRU probably consists of lava (possibly basalts) or pebbles, with thermal inertia that could differ with respect to the mean thermal inertia of Oxia Planum. For this reason, in this work, we modeled the DRU with the typical thermophysical parameters of basalts. Moreover, here we adopted a temperature profile for the atmosphere rather than a fixed value (as done in [12]), exploring different values of the optical depth.

The paper is structured as follows: in Section 2, we report the numerical modeling used; in Section 3, the numerical results and testing of the model in comparison with literature models are presented; finally, Section 4 contains the summary and conclusions.

2. Numerical Model

Planetary surface temperature is controlled by the energy balance at the surface. The surface temperature is influenced both by its interaction with the atmosphere and by the heat transferred downwards into the subsurface. As pointed out by Paton et al. [13], the dominant mechanisms in the atmosphere are the absorption and emission of radiation, while convection is nearly negligible due to the low density of the Martian atmosphere. The heat transferred downwards, instead, depends on the thermal characteristics of the materials in the subsurface. Modeling the temperature of the atmosphere is not trivial: physical exchange processes between the lower layers of the atmosphere and the surface often are treated in a simplified way, by applying, for example, appropriate boundary conditions. The interaction between the surface and atmosphere implies a well-defined knowledge (based on in situ observations and modeling efforts) of the properties of the atmosphere, such as pressure and temperature, whose both daily and seasonal variations are more pronounced than on Earth [14]. In the literature, we can find specific works on the modeling of the Martian atmosphere, for example, [15-17]. A specific model of the atmospheric temperature is beyond the scope of this work, so we will adopt a diurnal atmospheric temperature profile from the model of KRC numerical thermal model [18]. The KRC model solves only for one-layer grey body atmosphere with two-stream Delta-Eddington approximations with no height variability. We extracted diurnal atmospheric temperature variability profile from Kieffer [18] by using a tool "WebPlotDigitizer." This profile has been used in the boundary conditions of our modeling.

The surface temperature is calculated according to the following equation (e.g., [12, 19–21]):

$$S_c(1-a)\cos(z) + Q_{SH} = -K\overrightarrow{n}\cdot\overrightarrow{\nabla}T + \varepsilon\sigma T^4, \qquad (1)$$

where S_c is the solar constant (scaled by the heliocentric distance), a is the albedo, z is the incidence angle, Q_{SH} is the self-heating, K is the thermal conductivity, T is the temperature, ε is the emissivity, and σ is the Stefan–Boltzmann constant. As in [12, 19, 21], we use the software COMSOL Multiphysics for our numerical analysis. The atmospheric temperature enters the last term of the equation (1), in particular in the "Diffuse Surface" included in the "Surface-to-Surface Radiation" node in COMSOL.

The illumination conditions are calculated according to the algorithm discussed, for example, in [21, 22]: the components of the normal vector of each facet of the mesh covering the shape model are multiplied by a specific rotation matrix. This approach is similar to that used in [23, 24], where the Sun is considered an "external radiation point source" at a fixed position in the object-fixed reference frame. As in [21], the surface is considered as a grey body, emitting IR radiation (after absorbing the solar irradiation) with an emissivity of 0.97, similar to [23]. In addition to the direct illumination by the Sun, we also take into account indirect illumination, i.e., the mutual radiative interaction of the various surface elements, the socalled self-heating (Q_{SH}).

In the subsurface, the temperature is calculated according to the classic heat conduction equation:

$$\rho c_p \frac{\partial T}{\partial t} = K \overrightarrow{\nabla} \cdot (\overrightarrow{\nabla} T), \qquad (2)$$

where *t* is the time, ρ is the density, and c_p is the specific heat. The heat conduction equation does not contain the convection term, due to the small temperature gradients involved that can be considered negligible, as well as the characteristic depth of the shape model under study.

On the lateral and bottom sides of our geometry, we imposed a condition of zero heat flux. In [12], we considered a fixed value of 150 K for the atmosphere, while here we adopted a diurnally variable temperature profile taken from the KRC thermal model [18]. The assumption of the profile of Kieffer [18] is affected by a small error, since the diurnal temperature profile from the KRC thermal model [18] was run with a solar longitude of 100° while our simulations refer to the aphelion: this assumption, however, does not change significantly our results. The initial temperature of Oxia is fixed to 180 K (close to the black-body temperature), and no bottom heat flux is considered. However, we observed that the initial value of temperature does not affect the numerical results. Insolation on Mars' surface is composed of the direct beam and the diffuse component. Scattering and absorption from the top of the atmosphere to the surface affect the direct beam. In order to take into account the attenuation of the solar incidence by the atmosphere, we adopt the approach of Appelbaum and Flood [25], by reducing the solar incidence by a factor proportional to the optical depth of the atmosphere according to Beer's law:

$$I_{\rm sun} = I_0 \exp\left(-\frac{\tau}{m(z)}\right),\tag{3}$$

where I_0 is the solar incidence with no attenuation (i.e., at the top of the atmosphere), τ is the optical depth, and m(z) is the air mass determined by the zenith angle z. We neglect the diffuse component of the atmosphere. For a zenith angle less than 70°, we can approximate the air mass as

$$\frac{1}{m(z)} \simeq \frac{1}{\cos(z)}.$$
(4)

Using equation (4), we can rewrite equation (3) in this form:

$$I_{\rm sun} = I_0 \exp\left(-\frac{\tau}{\cos\left(z\right)}\right). \tag{5}$$

In Figure 1, we show the influence of the optical depth on the solar irradiance at different sun zenith angles on a flat surface, according to [25]. Large values of optical depth correspond to dust storms and lead to very low insulation.

We model a 2×0.6 km portion of Germania Lacus where the morphology and imagery [3] show evidence for the contact between the elevated DRU and the lower unit, showing evidence for the presence of clay (see right panel of Figure 2).

The area is dominated by terrains which are more resistant to erosion than the surroundings. Two viable interpretations are that this dark resistant unit (DRU) could be a basalt deposit or a sedimentary conglomerate unit commonly found in delta river environments.

We selected this area for our modeling because we can estimate the effects of the variable topography on the surface temperature: it is indicated by the blue rectangle in Figure 2 (left panel). Starting from a Tagged Image File Format (TIFF) of the site of interest, we created the DEM (digital elevation model) file to import in COMSOL, by using the tool "DEMto3D" included in the free software QGIS. However, before importing the 3D file in COMSOL, we used the software MESHLAB to remove possible irregular regions or applying smoothing to portion of regions, exporting a stereolithography file (.stl) and after we imported the file in COMSOL. The geometry adopted in our numerical model is covered by a triangular mesh (87225 elements) and a mesh volume at 0.04481 km³. The mesh is selected automatically by the software COMSOL Multiphysics, which chooses the appropriate mesh on the basis of the equations to solve and the geometry involved. We characterized the DRU with the typical parameters of basalt, assuming a porosity-dependent thermal conductivity. We assumed a value of 2700 kg·m⁻³ for density and a specific heat of 800 J·Kg·K⁻¹ [27]. The thermal conductivity is considered as a function of the porosity through a simple relation [28]:

$$K = K_{\text{bas}}(1 - \phi), \tag{6}$$

where ϕ is the porosity and K_{bas} is a reference value for the thermal conductivity, assumed equal to 2.7 W·m⁻¹· K^{-1} from [29], which presented empirical data for the thermal conductivity of basalt in the temperature range of 224–289 K. In this range, according to [29], the thermal conductivity ranges from 2.71 to 2.63 W·m⁻¹· K^{-1} , so we can reasonably use 2.7 W·m⁻¹· K^{-1} since our expected



FIGURE 1: Effect of the optical depth on the solar irradiance for several values of zenith angle, according to [25]. The surface considered is horizontal, and the solar longitude is 90°. A value of $\tau = 3$ indicates a dust storm, even if at solar longitude 90°, is not expected.

temperatures are in that temperature range. We assumed a low albedo, which could characterize the dark resistant unit: 0.1 [30]. Here, we considered two values of porosity: 0.1 and 0.5. In the case of basalt composition, the thermal inertia of the DRU ranges from 1350 to 2430 TIU, much higher values compared to the mean value characterizing the geological unit to which DRU belongs. We also performed numerical simulations by considering DRU characterized by a pebble composition. In the case of the composition made of pebbles, the corresponding thermal inertia is 505 TIU, a value close to the highest value provided by Gary-Bicas and Rogers [7] for geological unit 3. In fact, in this scenario, the thermal conductivity is very low (0.4 W·m⁻¹· K^{-1} , [31]). Pebbles, in our modeling, are essentially basalt but with texture and porosity different. The values adopted for the density and the thermal conductivity are compatible with the estimations of Fountain and West [32] in which the authors estimated the thermal conductivity of particulate basalt as a function of density in simulated Martian environments.

We recall that the thermal inertia measures the reaction of a body to the temperature variations, and it is defined as

$$I = \sqrt{K\rho c_p}.$$
(7)

Clearly, the thermal inertia is linked to the subsurface conduction and heat storage as well as to the surface temperature via the skin depth, defined as

$$\delta = \frac{I}{\rho c_p} \sqrt{\frac{P}{\pi}},\tag{8}$$



FIGURE 2: Left panel: portion of Germania Lacus topography at 18.2° N and 335.5° E. The image is produced by the HiRISE data, instrument onboard MRO [26]. Right panel: geometry adopted in our modeling (area of $2 \text{ km} \times 0.6 \text{ km}$). On the surface, we selected five "probes" on which we calculated the surface temperature: two points on the left crater ("crater 1A" and "crater 1B"), two points on the right crater ("crater 2A" and "crater 2B"), and a point on the flat region ("Flat").

where *P* is the rotational period of the body. The skin depth measures the ability of penetration of the heat wave, or alternatively, is the depth to which the amplitude of the thermal wave is attenuated by a factor 1/e. In the scenarios we explored, the skin depth will be of the order of tens of centimeters. Moreover, we also varied the optical depth (τ) of the atmosphere, exploring two cases: 0.1 and 0.5. In Table 1, we report the main thermophysical parameters used in our simulations. As in [12], the heliocentric distance explored is the aphelion, when the Northern Hemisphere is in summer. In Table 2, we summarize all the cases explored with the corresponding thermal inertia.

2.1. Numerical Test. In order to validate our model, we carried out several numerical tests. Here we report in particular the comparison with the data provided by the Mars Pathfinder (MPF, hereafter), taken from https://mars.nasa. gov/MPF/science/weather.html, and the comparison with the KRC thermal model reported in [18]. These numerical tests are performed for a horizontal surface.

2.1.1. Comparison with Mars Path Finder and Viking Data. MPF's location is at about 19°N, with an estimated thermal inertia of 387 TIU [5]. The solar longitude at MPF's location on Mars was $L_s = 162.5^\circ$, at a distance of 1.54 AU from the Sun. MPF sensors estimated the temperature at three heights above the surface: 25 cm, 50 cm, and 1 m. For our comparison, we adopted a thermal conductivity of 0.0936 W·m· K^{-1} , a density of 2000 kg·m⁻³, and a specific heat of 800 J·kg· K^{-1} . The albedo was set to 0.19, the surface emissivity to 0.95, and the optical depth at 0.5 [33]. In Figure 3, we report the comparison with the MPF data at 25 cm above the surface (black dots) and our numerical modeling (red line) along a Martian day. Even if the comparison is not completely accurate since MPF data

TABLE 1: Thermophysical parameters adopted in this work.

| Parameter | Symbol | Value | Reference |
|-----------------------------|------------------|--|------------|
| Distance | d | 1.67 AU (aphelion) | This study |
| Initial temperature | T_0 | 180 K | This study |
| Specific heat | Cp | $800 \text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ | [27] |
| Basalt density | $\rho_{\rm bas}$ | 2700 kg m^{-3} | [27] |
| Pebble density | $\rho_{\rm peb}$ | $800 \text{ kg} \text{ m}^{-3}$ | [34] |
| Basalt thermal conductivity | $K_{\rm bas}$ | $2.7 \mathrm{Wm^{-1}K^{-1}}$ | [29] |
| Pebble thermal conductivity | $K_{\rm peb}$ | $0.4Wm^{-1}K^{-1}$ | [31] |
| Optical depth | τ | 0.1 - 1 | This study |
| Albedo | а | 0.10 | [30] |
| Emissivity | ε | 0.95 | This study |
| Latitude | ϕ | 18°N | [4] |

refer to the temperature of the atmosphere immediate to the surface (while we modeled the surface temperature), the agreement with the MPF data is very good. For the sake of completeness, in Figure 3, we also included the Viking data (blue plot) corresponding to the same period of observation of MPF: the difference both with respect to our model and the MPF data lies in the fact that the single Viking temperature sensor is located about at 1.5 meters above the ground, where the temperature is reasonably lower.

2.1.2. Comparison with KRC Model. Here, we compared our numerical solutions with the KRC one-layer atmosphere numerical model [18]. The calculations are performed for the Viking Lander 1 site (22°N) at $L_s = 100^\circ$ and for albedo equal to 0.25, thermal inertia equal to 270 TIU, and optical depth equal to 0.3. From Figure 4, it is clear that there is

| | Scenario | Porosity | Thermal conductivity | Density | Optical depth | Thermal inertia |
|---------|----------|----------|----------------------|---------|---------------|-----------------|
| | M0 | 0.1 | 2.43 | 2430 | 0.1 | 2174 |
| | M1 | 0.1 | 2.43 | 2430 | 0.5 | 2174 |
| Basalt | | | | | | |
| | M2 | 0.5 | 1.35 | 1350 | 0.1 | 1271 |
| | M3 | 0.5 | 1.35 | 1350 | 0.5 | 1271 |
| Pebbles | | | | | | |
| | M4 | 0.0 | 0.4 | 800 | 0.1 | 505 |
| | M5 | 0.0 | 0.4 | 800 | 0.5 | 505 |

TABLE 2: Scenarios developed in this work.

Density is expressed in $kg \cdot m^{-3}$, thermal conductivity is expressed in $Wm^{-1} \cdot K^{-1}$, and thermal inertia is expressed in TIU.



FIGURE 3: Comparison of our numerical prediction (red plot) with Mars Pathfinder (black points) and Viking data (blue plot). Temperatures refer to the landing site of Mars Pathfinder (19.28°N) at $L_S = 162.5^\circ$, I = 387 TIU, and a = 0.19.



FIGURE 4: Comparison between our numerical model (red line) and KRC model (black line). The temperatures refer to the Viking Lander 1 landing site $(22^{\circ}N)$ at $L_s = 100^{\circ}$, with a = 0.25 and TI = 270 TIU.

a very good agreement between our model (red line) and the KRC model (black line).

3. Results: Surface/Subsurface Temperature Profiles

In this section, we report the numerical results of our simulations. We start to discuss the case characterized by a basaltic composition and thus a thermal inertia of between \approx 1300 TIU and \approx 2200 TIU, depending on the porosity assumed. Subsequently, we discuss the hypothesis of a dark unit composed of pebbles and thus a thermal inertia of \approx 500 TIU. In both cases, we also explored the influence of the variation of the optical depth, assuming two values: 0.1 and 0.5. We report the surface temperatures, in all the cases explored, of the selected points (see Figure 2) and, as an example, the entire surface temperature map for the "pebbles" case (with $\tau = 0.1$), over a Martian day. A comparison between the two compositions will be carried out, in particular comparing the surface temperature of the "Flat" point.

3.1. Basalt Case. In the scenario in which DRU is dominated by a basalt composition, we explored the dependence of the porosity on the thermal conductivity, exploring two different values of porosity: 0.1 and 0.5.

3.1.1. Porosity of 0.1: M0 and M1 Cases. From Figure 5(a), we can observe that, in the case of optical depth $\tau = 0.1$ (case M0), the maximum value reached is around 225 K for the point "crater 1A," while for the other points, the maximum is around 220 K. The minimum temperature is around 205 K for all the points, except for the point "crater 1B," a few degrees colder. Increasing the optical depth ($\tau = 0.5$ (case M1)), we obtain a significant decrease in temperature (see Figure 5(b)), with the maximum temperature around 200 K for most of the points selected and a minimum temperature around 195 K, except for the point "crater 1B" (190 K). In these two cases (M0 and M1), the thermal inertia is very high and consequently the oscillations of the surface temperature are confined to a small range (about 20 K).

3.1.2. Porosity of 0.5: M2 and M3 Cases. Increasing the porosity to 0.5 leads to a decrease in the efficiency of heat transmission, since the thermal conductivity is reduced to $1.35 \text{ W} \cdot \text{m}^{-1} \cdot K^{-1}$ and consequently the thermal inertia is 1271 TIU. With $\tau = 0.1$ (case M3), the oscillations of the surface temperature for all probes points are in the range of 200-235 K (see Figure 6), a range larger than the previous cases (M0 and M1) due to lower values of thermal inertia. With optical depth $\tau = 0.5$, we obtain values of maximum temperature around 205 K for all the probe points (see Figure 6(b)), and the minimum temperature decreases as far as 185 K.

3.2. Pebbles Case. We can assume that DRU is not made of a compact material but rather than composed of pebbles, which may is a test to see if the thermophysical

characterization of this site could be completely different from the cases discussed so far. Here, we assumed no porosity for the pebbles, but the thermal conductivity is lower than a basaltic composition. Consequently, the calculated thermal inertia is approximately 505 TIU, a value compatible with the extreme values of the range of thermal inertia of geological unit 3 including the DRU [7].

3.2.1. M4 and M5 Cases. In case of optical depth $\tau = 0.1$ (case M4), the maximum temperatures are around 250 K for all the selected points, while the minimum temperatures are between 190 and 195 K (see Figure 7(a)). The oscillations in this case are larger than the basaltic composition, in a range of about 60 K, since the thermal inertia is lower. Increasing the optical depth ($\tau = 0.5$ (case M5)), the maximum temperatures are around 210K for all the points while the minimum temperature obtained is the lowest of all the explored scenarios (see Figure 7(b)), i.e., 170 K. The optical depth value of 0.1 is the most likely value for the heliocentric distance considered in this work. In fact, high values of optical depth are only expected in case of dust storm conditions, unlikely at the explored solar longitude of 71° for this work. Storms are generally associated with solar longitudes in the range of $210^{\circ} < L_s < 300^{\circ}$. In Figure 8, we present the entire surface temperature maps for the pebbles case $\tau = 0.1$ (case M4), during a Martian day, at some selected times. We observe how in some ridges of the craters the surface temperature is the hottest with respect to the floor of the crater. This may be due to a contribution of the indirect light or so-called "self-heating" effects. This contribution will be discussed in more detail in the next subsection. The choice to show the temperature maps of the pebbles case (M4) is due to the fact that thermal inertia value in this case is compatible with the estimation of THEMIS [7].

3.3. Comparison between "Basalt" and "Pebbles" Cases. Finally, we report a comparison between the scenarios characterized by basalt and pebbles composition. The point for which we carried out a comparison is the "Flat" point. In Figure 9, we report the M0, M2, and M4 cases, all characterized by optical depth $\tau = 0.1$, with variable porosities and compositions. We note that the increase in the maximum temperature is notable in the pebbles case (M4) with respect to the basalt cases (M0 and M2), and it is due to the reduced thermal inertia in M4 case. The difference in the maximum temperature, between M0 and M4 cases, is about 50 K.

3.3.1. Self-Heating Influence. In this section, we evaluate the influence of the indirect light, the so-called self-heating between the facets of our geometry, in the temperature estimation. Self-heating is computed through the hemicube method, implemented in the COMSOL Multiphysics software. As a test case, we adopted the case characterized by a basalt composition and optical depth equal to 0.1: we ran a simulation without self-heating, with the same physical parameters, and we compared the numerical



FIGURE 5: Surface temperature for the selected points of Figure 2 for M0 (a) and M1 (b) cases. Thermal inertia in this case is equal to 2174 TIU.



FIGURE 6: Surface temperature for the selected points of Figure 2 for M2 (a) and M3 (b) cases. Thermal inertia in this case is equal to 1271 TIU.



FIGURE 7: Surface temperature for the selected points of Figure 2 for M4 (a) and M5 (b) cases. Thermal inertia in this case is equal to 505 TIU.



FIGURE 8: Example of surface temperature maps for M4 case at selected times: the frames cover a whole rotation. The plot on the right hand side refers to the "Flat" point.



FIGURE 9: "Flat point" temperatures for M0 and M2 cases (basalt composition) and M4 case (pebbles composition).

outcomes. In Figure 10, we report the difference in temperature (case with self-heating versus case without selfheating) at specific moments during the Martian day. We observe that in some areas, especially the rims of the two craters of our selected area, the increase in temperature is at about 5–7 K. This means that the self-heating cannot be neglected in the energy budget computation of a planetary surface, and it must be included into a numerical modeling when topography is not completely flat and for regions with no direct sunlight.



FIGURE 10: Self-heating effects in M4 case. Difference in temperature between the case with self-heating and without self-heating at four different moments during the Martian day.

4. Summary and Conclusions

In this work, we provided the distribution of temperature of the dark resistant unit (DRU), located at Germania Lacus, a region of Oxia Planum. This work could be considered a follow-up of the paper [12] with several improvements. Here we considered a large-scale topography (a region of about 1 km²) and a diurnal atmospheric temperature profile, rather than a constant value. We emphasize that the estimation of the atmospheric temperature requires more precise and accurate modeling, but this is beyond the scope of this work. The presence of the atmosphere is mimicked by attenuating the solar flux through Beer's law, and we used diurnal atmospheric temperature profiles computed by the KRC model [18] as radiation boundary conditions which are valid for the heliocentric distance we considered. We explored two compositions: basaltic rock and pebbles, which may reasonably characterize the dark resistant unit in Oxia Planum. In order to see the effects of the atmospheric density on the total energy budget, we explored also two different values of optical depth: $\tau = 0.1$, corresponding to quasi-zero absorption of solar energy by the atmosphere, and $\tau = 0.5$, which corresponds to a high absorption by the atmosphere. In the case of a basaltic composition (M0 to M3 cases), temperatures ranged from about 200 K to 225 K for an optical depth τ = 0.1 and from about 185 K to 205 K for an optical depth $\tau = 0.5$. With a composition made of basaltic

rock, the corresponding thermal inertia is more than 1000 TIU, a value which is significantly higher in contrast to estimation of the region using THEMIS data [7]. For this reason, we consider a composition made up of pebbles as the most plausible, since in this case the thermal inertia is about 500 TIU and compatible with the values suggested by THEMIS [7]. In this scenario, with an optical depth $\tau = 0.1$, the surface temperature ranges from about 190 K to 250 K. Probably, a value of $\tau = 0.5$ is not expected at the heliocentric distance considered in this work; we regardless explored the dependence of the optical depth on the surface temperatures. These simulations could help to constrain the nature of the dark resistant unit when temperature data of the selected area will be available. The methodology we described in this work can be applied to other Mars' regions of interest, providing temperature distribution surface maps and subsurface temperature profiles, with greater accuracy than 1D and 2D thermal models given that this work takes topographical effects into account in a 3D framework.

Data Availability

Data will be available in a public github directory.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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