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Modeling Temperatures and Spectral Properties of Phobos and Deimos from CRISM and OMEGA Data

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Abstract

The spectral radiances of Phobos and Deimos measured by the CRISM and OMEGA instruments are composed of both reflected solar and thermally emitted contributions. Thermal emission is controlled by surface temperature, and becomes increasingly important at longer wavelengths (> 2.5µm). Here we present a method to estimate surface temperatures using pairs of spectra from locations with the same emissivity but different temperatures. Knowing the surface temperature allows us to model the reflected and emitted contributions to the total radiance, retrieve spectral reflectance, and interpret important mineralogical information.

1. Introduction

The unusually low densities of Phobos (1.87 ± 0.06 g/cm^3) and Deimos (1.54 ± 0.23 g/cm^3) have led to speculation that the two moons are either highly porous or contain a large amount water ice [6]. Surface water ice would cause an absorption feature around 3µm, but there is no evidence such a feature exists in the spectra from Phobos or Deimos [5,8]. However, reflectance measurements at wavelengths >2.5µm are complicated by increasing thermal emission contributions, so the thermal properties of the moons must be well understood in order to interpret radiance spectra beyond 2.5 µm.

2. Observations

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) aboard the Mars Reconnaissance Orbiter has recently acquired three hyperspectral images each of Phobos and Deimos between 0.362 – 3.92 µm [7]. The three Deimos images were obtained at a spatial resolution of 1.2 km/pixel and phase angle of ~22˚. The three Phobos images have a resolution of 350 m/pixel and phase angle of ~41˚.

The Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (OMEGA) instrument on Mars Express has also made observations of Phobos, acquiring six hyperspectral images covering 0.35 – 5.1µm and two from 0.35 – 1µm only [1]. The spatial resolution of these observations ranges from 2.2 km/pixel to 100 m/pixel and the phase angles range from 47.2˚ to 95˚

3. Temperature Models

The total radiance recorded by CRISM and OMEGA at each wavelength is a function of lighting and viewing geometry, temperature of the observed body, and reflectance and emissivity of the surface. It may be expressed as:

$$L_\lambda = S_0(\lambda)\cdot \rho(i,e,g,\lambda) + B(T,\lambda)\cdot \varepsilon(\lambda) \qquad (1)$$

where L_λ is the spectral radiance measured by the spectrometer at each wavelength, S_0 is the solar irradiance at Phobos or Deimos, ρ is the surface reflectance for given incidence, emission, and phase angles, B is the characteristic Planck function at a given temperature, and ε is the emissivity.

To first order, we assume the moons are Lambertian surfaces in thermal equilibrium. Kirchhoff's Law is valid in this situation, and we can reduce the number of unknowns in the system with the relation:

$$\rho(i,e,g,\lambda) = A(\lambda)=1-\varepsilon(\lambda) \qquad (2)$$

where A is the Lambert albedo.

The incidence angle at each pixel is computed from knowledge of the spacecraft orientation and sun position at the time of the observation along with shape models of the moons [9]. The surface temperatures and corresponding characteristic Planck functions are found by selecting a pair of spectra taken from locations that have the same emissivities but different surface temperatures. Since the spectral pairs have the same emissivity, it is possible to solve for the emissivity of one in terms of the temperature at that spot and then substitute this into the second, allowing us to find the pair of temperatures that create the best-fit model spectral radiance for both observations.

The CRISM and OMEGA Phobos and Deimos spectra exhibit a wide range of curvature at wavelengths >3.0µm, implying the observations cover an area with a large variation in surface temperatures. Our spectral pairs can therefore come from nearby pixels that have different temperatures and are assumed to have the same spectral properties (CRISM and OMEGA) or from a single point observed at two different times (OMEGA only).

4. Results and Discussion

The ultimate goal of this work is to estimate surface temperatures and use them to model the solar and thermal contributions to the total radiance and retrieve spectral reflectance values. We have estimated the maximum surface temperatures for CRISM data of Phobos using the methodology described above. Figure 1 shows the pair of spectra that were input into our model, along with the Planck functions for the calculated best-fit temperatures of 350K and 341K. We found the temperatures that create the best fit by running the MPFIT function in IDL [4]. MPFIT searches for the parameters that minimize the χ^2 function given a set of input guesses. MPFIT converges to the same temperatures for a range of realistic inputs, but initial temperature guesses that are too high or low lead MPFIT to converge on physically unrealistic temperatures associated with different local minima in the χ^2 function.

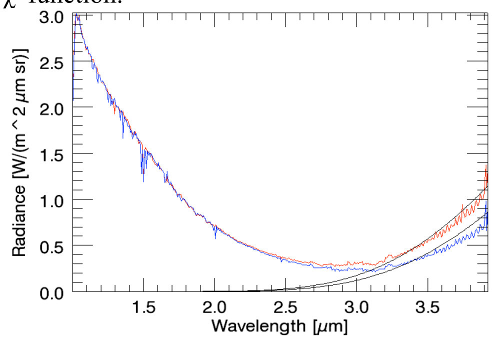

Figure 1: Model input spectrum from 3x3 regions on Phobos centred at 311,128 (red) and 311, 125 (blue). Black lines are Planck functions for T = 350K (top) and T = 341K (bottom)

Figure 2 shows an example of the resulting modeled spectral radiance (red) compared to the original CRISM spectral radiance (black).

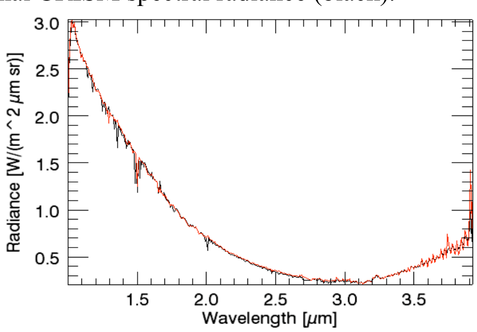

Figure 2: Modeled spectral radiance. The black spectrum is a 3x3 CRISM spectral radiance from Phobos centred at (311,125) and the red is our modeled spectral radiance

The highest temperatures in each observation occur in the regions that receive the most solar irradiance, i.e. those with the lowest incidence angles. By examining these regions, we estimate the maximum temperature in the Phobos CRISM image is ~350K. This temperature estimate and associated emissivity values at 4µm are in agreement with previously reported results [3]. Other studies report slightly lower temperatures [2], but those results are based on data that were collected when Phobos had greater heliocentric distances and was therefore presumably cooler.

Our model had difficultly reproducing spectra taken from areas with high incidence angles. This is likely because our assumption of a Lambertian scattering surface breaks down at extreme observation geometries. We were also unable to accurately model the Deimos reflectance spectrum, possibly because of the large variation in local incidence angle covered by a single pixel. We will study these areas by solving for the Hapke function parameters for reflectance and emission, which provide a more realistic model for material properties.

This methodology will also be extended to OMEGA observations, and the combined OMEGA-CRISM set will provide a range of maximum temperature values for different heliocentric distances. Additionally, spectra from the same points in the CRISM and OMEGA data can be directly compared once differences in temperature are accounted for. Finally, we will use a Hapke model and our surface temperature estimates to fully model the system and analyze the reflected component for mineralogical and compositional information.

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