Icarus 000 (2017) 1–17

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

SHERMAN, a shape-based thermophysical model. I. Model description and validation

Christopher Magri[a,*], Ellen S. Howell[b,c], Ronald J. Vervack, Jr.[d], Michael C. Nolan[b,c], Yanga R. Fernández[e], Sean E. Marshall[f,b], Jenna L. Crowell[e]

[a] University of Maine at Farmington, 173 High St – Preble Hall, Farmington, ME 04938, USA
[b] Arecibo Observatory, Arecibo, PR 00612, USA
[c] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[d] Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, USA
[e] Department of Physics, University of Central Florida, Orlando, FL 32828, USA
[f] Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

ARTICLE INFO

Article history:
Received 29 January 2017
Revised 11 November 2017
Accepted 20 November 2017
Available online xxx

Keywords:
Asteroids, surfaces
Infrared observations
Spectroscopy

ABSTRACT

SHERMAN, a new thermophysical modeling package designed for analyzing near-infrared spectra of asteroids and other solid bodies, is presented. The model's features, the methods it uses to solve for surface and subsurface temperatures, and the synthetic data it outputs are described. A set of validation tests demonstrates that SHERMAN produces accurate output in a variety of special cases for which correct results can be derived from theory. These cases include a family of solutions to the heat equation for which thermal inertia can have any value and thermophysical properties can vary with depth and with temperature. An appendix describes a new approximation method for estimating surface temperatures within spherical-section craters, more suitable for modeling infrared beaming at short wavelengths than the standard method.

© 2017 Elsevier Inc. All rights reserved.

1. Introduction

Measuring and analyzing thermal emission is an important means of characterizing solid bodies in the solar system. For example, one can compare an asteroid's brightness in scattered visible light vs. emitted infrared light to estimate the object's diameter and albedo. It may also be possible to determine the asteroid's thermal inertia, with a low value implying porous regolith and a high value indicating exposed bedrock. Disk-resolved observations of the Moon have even permitted investigators to constrain subsurface density variations and the relative importance of conductive vs. radiative heat transport (Vasavada et al., 2012; Hayne et al., 2017).

Many thermal observations, especially those produced by spacecraft-based infrared surveys, are of objects about which little is known, and thus simple thermal models that make major assumptions – a spherical target, equatorial illumination, instantaneous equilibrium between insolation and emission – may be the best that one can do. But some targets have well-constrained shapes and spin states, for example if they have been analyzed via radar or via lightcurve inversion. Thus there is a need for more sophisticated thermophysical models that can take this information into account, explicitly modeling heat flow into and out of each surface element as the target rotates and orbits the Sun.

In the past dozen years a number of new thermophysical models, in addition to ours, have appeared in the literature (Delbo, 2004; Mueller, 2007; Statler, 2009; Leyrat et al., 2011; Rozitis and Green, 2011; Nugent, 2013; Emery et al., 2014; Hanuš et al., 2015; for a review see Delbo et al., 2015). These models are generally based on the work of Spencer (1990), and especially on the extensive theoretical treatment of Lagerros (1996a,b, 1997, 1998), in which Lagerros goes into detail about the physics of various effects that determine just how much thermal radiation an asteroid will emit at different wavelengths. These model codes explicitly include subsurface heat conduction, and in many cases can model infrared beaming, for example by placing an ensemble of spherical-section craters on the surface. But even these more complex models tend to include some simplifying assumptions, such as Lambertian optical scattering, graybody reflectance, uniform surface properties, and depth- and temperature-independent thermophysical properties.

* Corresponding author.
E-mail address: magri@maine.edu (C. Magri).

https://doi.org/10.1016/j.icarus.2017.11.025
0019-1035/© 2017 Elsevier Inc. All rights reserved.

In the following sections we describe SHERMAN[1], a shape-based thermophysical model that uses the shape, spin, and orbital characteristics of near-Earth asteroids (NEAs) in order to explore their thermal properties. SHERMAN can waive any or all of the simplifying assumptions listed above, making it both powerful and flexible. The program is based on the radar fitting code SHAPE, written by Hudson (1994) and further enhanced by Magri et al. (2007, 2011). It was designed for modeling disk-integrated spectra in the 1–5 µm region but can handle data, in either absolute or relative flux units, covering any wavelength range.

Section 2 presents the equations solved by SHERMAN and recasts them in terms of dimensionless variables. Section 3 outlines the numerical methods that the program uses to achieve a valid temperature solution at all times over the entire surface, and lists the forms of output produced for comparison with actual data. Section 4 then describes a number of tests used to validate SHERMAN for special cases where the correct results can be derived from theory. Section 5 concludes the paper with a brief discussion. A companion paper (Howell et al., 2017) demonstrates SHERMAN's capabilities by using it to analyze a contact binary NEA, 8567 (1996 HW1), for which thermal spectra and optical photometry are combined with an existing shape/spin model based on radar and lightcurve observations (Magri et al., 2011).

2. Equations and variables

Given a model with an arbitrary shape, realized (approximated) as a polyhedral solid comprised of triangular facets, SHERMAN solves the one-dimensional heat equation for each facet to obtain temperature as a function of time and of depth:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c}\frac{\partial}{\partial z}\left(\kappa\,\frac{\partial T}{\partial z}\right) \tag{1}$$

where t is time, z is depth, T is temperature, ρ is density, c is specific heat, and κ is thermal conductivity. We allow ρ to vary with depth and c to vary with temperature. We treat κ as the sum of a solid component and a radiative component, each of which can vary with both depth and temperature (with the radiative component always varying as T^3). The user actually specifies ρ, c, and thermal inertia $\Gamma \equiv \sqrt{\rho\, c\, \kappa}$ rather than ρ, c, and κ.

SHERMAN solves the heat equation over a user-specified time interval that typically covers 10–20 rotations, long enough that the model can "forget" the initial conditions. The user inputs the model's spin state and photometric properties and provides ephemerides for the target and the Sun, so that SHERMAN can work out each facet's insolation (see Section 3.2.1) and viewing geometry as time progresses. There are no restrictions on the spin state; for example, non-principal-axis rotation is allowed. All photometric and thermal properties are permitted to vary across the surface.

The boundary condition at the model's maximum depth $z_{\max}$ is

$$-\left(\kappa\,\frac{\partial T}{\partial z}\right)\Bigg|_{z=z_{\max}} = -F \tag{2}$$

where F is the upward secular heat flux due to internal ("geothermal") processes. The boundary condition at the surface is

$$\epsilon\,\sigma\,T_0^4 - \left(\kappa\,\frac{\partial T}{\partial z}\right)\Bigg|_{z=0} = S \tag{3}$$

where T_0 is surface temperature, ϵ is IR emissivity, σ is the Stefan–Boltzmann constant, and S is insolation. For a model with concavities, S includes not only absorbed sunlight but also absorbed thermal radiation (mutual heating) if the user chooses to model the latter effect.

We now switch to dimensionless variables, doing so separately for each facet if the model's properties vary from facet to facet. Such variables have typical values of order unity, thus reducing problems involving finite numerical precision (e.g., underflow and overflow). They also are more directly tied to the underlying thermal physics: for example, the temperature changes occurring during a given time interval depend on the ratio of that interval to the rotation period.

First we compute the mean absorbed optical flux at normal incidence, $\langle S_{opt,\perp}\rangle$, averaged over time in case the Sun-target distance varies. From this we obtain subsolar temperature T_{ss} by equating

$$\langle S_{opt,\perp}\rangle = \epsilon\,\sigma\,T_{ss}^4 \tag{4}$$

Next we normalize density by dividing by surface density ρ_0. We normalize specific heat by dividing by c_{ss}, its value when $T = T_{ss}$. We normalize thermal conductivity by dividing by $\kappa_{0,\,ss}$, its value at the surface when $T = T_{ss}$. For notational convenience we will continue to use symbols ρ, c, and κ for the dimensionless versions of these quantities.

Dimensionless time τ is t multiplied by angular rotation frequency ω. Dimensionless depth ζ is z/Z where thermal skin depth Z is evaluated at the surface for $T = T_{ss}$:

$$Z = \sqrt{\frac{\kappa_{0,ss}}{\rho_0\, c_{ss}\,\omega}} \tag{5}$$

Dimensionless temperature u is T/T_{ss}. Dimensionless insolation s and dimensionless upward secular heat flux f are obtained by dividing S and F, respectively, by $\epsilon\,\sigma\,T_{ss}^4$.

We now can rewrite the heat equation (1) and boundary conditions (2) and (3) using dimensionless variables:

$$\frac{\partial u}{\partial \tau} = \frac{1}{\rho c}\frac{\partial}{\partial \zeta}\left(\kappa\,\frac{\partial u}{\partial \zeta}\right) \tag{6}$$

$$-\Theta\left(\kappa\,\frac{\partial u}{\partial \zeta}\right)\Bigg|_{\zeta=\zeta_{\max}} = -f \tag{7}$$

$$u_0^4 - \Theta\left(\kappa\,\frac{\partial u}{\partial \zeta}\right)\Bigg|_{\zeta=0} = s \tag{8}$$

where we assume that $\zeta_{\max} \gg 1$. Here u_0 is normalized surface temperature, whereas dimensionless thermal parameter Θ is a constant defined as

$$\Theta \equiv \frac{\Gamma_{0,ss}\sqrt{\omega}}{\epsilon\,\sigma\,T_{ss}^3} \tag{9}$$

where $\Gamma_{0,ss}$ is the thermal inertia at the surface for $T = T_{ss}$. The larger Θ is, the more effectively heat conduction moderates surface temperatures. For instance, Howell et al. (2017) find a best-fit thermal inertia of 70 J m^{-2} K^{-1} s$^{-1/2}$ for 8567 (1996 HW1) (hereafter referred to as HW1), from which it follows that $\Theta \sim 0.4$: this value, somewhat below unity, implies that the influence of heat conduction is noticeable but not large.

The following sections assume normalized variables unless explicitly stated otherwise.

3. Numerical methods

3.1. Discretization

SHERMAN uses discrete time steps and depth layers to solve the heat equation via finite differencing. The typical time step corresponds to a quarter-degree of rotation. The numerical truncation error is first-order in this time increment when the explicit or

[1] Not an acronym, but fondly recalling Mr. Peabody's able assistant (Jay Ward Productions)

Download English Version:

https://daneshyari.com/en/article/8134440

Download Persian Version:

https://daneshyari.com/article/8134440

Daneshyari.com