Physical properties of near-Earth asteroids from thermal infrared observations and thermal modeling

MARCO DELBÖ1,2* AND ALAN W. HARRIS2

1INAF, Osservatorio Astronomico di Torino, Strada Osservatorio 20, 10025 Pino Torinese (TO), Italy
2DLR Institute of Space Sensor Technology and Planetary Exploration, Rutherfordstrasse 2, D-12489 Berlin, Germany
*Correspondence author's e-mail address: delbo@to.astro.it

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Abstract—We review the physical principles on which asteroid thermal models are based and their application in the derivation of asteroid sizes and albedos. In particular, the use of simple thermal models to derive reliable diameters and albedos of near-Earth asteroids is discussed.

INTRODUCTION

The current rate of discovery of near-Earth asteroids (NEAs) is far outstripping progress in their physical characterization. Over 1500 NEAs have been discovered to date, but <50 have reliably determined albedos and diameters. On discovery the only physical information available for a NEA is its absolute magnitude, H. Since albedos can lie anywhere in the range 0.05–0.5, an object having an absolute magnitude H = 18 may have a diameter anywhere in the range 0.5 to 1.5 km.

Simultaneous measurements of the asteroid flux in the visible and in the thermal infrared (from 5 to 20 µm, where the thermal emission peak lies), combined with a suitable thermal model, allow both the diameter and the albedo to be determined.

Information on the albedo and size distributions of NEAs is a vital prerequisite for attempts to investigate their physical nature, mineralogy, taxonomy, and origins. Furthermore, accurate albedo and size distributions for NEAs are the key to an accurate assessment of the impact hazard and the optimization of survey strategies.

RADIOMETRY OF ASTEROIDS: BASIC PRINCIPLES

The energy balance at the surface of an asteroid, illuminated by the Sun, can be summarized as:

\[ \frac{S_\odot}{r^2} s = F_r = F_e \]  \hspace{1cm} (1)

where \( S_\odot \) is the solar constant, \( r \) is the heliocentric distance in astronomical units and \( s \) is the projected area. \( F_r \) is the total emitted radiation in all directions and \( F_e \) is the total reflected solar radiation in all directions (Lagerros, 1996). Radiation that is not reflected is absorbed by the surface and has to be balanced by thermal emission. If it were possible to measure \( F_r \) and \( F_e \) directly, finding an exact solution for \( s \) would be trivial. Unfortunately, this is not the case; it is clearly impractical to measure the total radiation emitted in all directions from the asteroid. Typically, the asteroid can be observed only over a limited range of directions, or solar phase angles. Thus it is necessary to calculate the total emitted radiation, \( F_e \), by means of an asteroid thermal model. Each surface element can be considered to behave like a black body (or gray body with an emissivity \( e \)) at a temperature \( T \), emitting radiation according to the Stephan–Boltzmann law \( (F_e = e\sigma T^4) \), the spectrum of which is described by the Planck radiation formula:

\[ B(\lambda, T) = \frac{2\pi c^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \]  \hspace{1cm} (2)

where \( B(\lambda, T) \) has units of flux density (e.g., W m\(^{-2}\) µm\(^{-1}\)). \( F_e \) in Eq. (1) can be obtained by integrating the contribution of all the surface elements. Since \( S_\odot \) is a physical constant and \( r \) can be obtained from knowledge of the object's orbit, assuming \( F_r \) can be derived \( \text{via} \) optical observations, it is possible to determine \( s \) and thus the size of the asteroid. Furthermore, since the reflected radiation is proportional to both asteroid size and albedo, \( A \),

\[ F_r = \frac{AS_\odot}{r^2} s \]  \hspace{1cm} (3)

the albedo of the asteroid can also be derived. In this case \( A \) is the bolometric Bond albedo, which refers to the total scattered
solar energy in all directions and at all wavelengths ratioed to the incident energy. The above is the basis of the radiometric method of asteroid diameter and albedo determination. Radiometric diameters have been derived and discussed by several authors (Morrison, 1977a,b; Hansen, 1977; Brown and Morrison, 1984; Spencer et al., 1989), but the largest catalog of radiometric diameters and albedos of asteroids to date is the infrared astronomical satellite minor planet survey (IMPS) (Tedesco, 1992).

ASTEROID SURFACE TEMPERATURES

The temperature of a surface element of an asteroid is a function of distance from the Sun, albedo, emissivity, and angle of inclination to the solar direction. A dark object absorbs more solar radiation than a brighter one, which results in a higher equilibrium temperature. The total incoming energy incident on a surface element of area $dS$ is:

$$dU_i = \frac{S_\odot}{r^2} \mu dS$$

(4)

where $\mu$ is the direction cosine of the normal to the surface with respect to the solar direction. Energy that is not reflected is absorbed by the asteroid surface:

$$dU_s = dU_i (1 - A)$$

(5)

and has to be balanced by thermal emission. The energy emitted by a surface $dS$ with emissivity $\varepsilon$ at a temperature $T$ is:

$$dU_e = \sigma \varepsilon T^4 dS$$

(6)

where $\sigma$ is the Stefan–Boltzmann's constant. Assuming that each element of the surface is in instantaneous equilibrium with solar radiation, conservation of energy implies that $dU_b = dU_e$, which can be expressed by the following equation for a surface element at the subsolar point ($\mu = 1$):

$$\frac{S_\odot (1 - A)}{r^2} dS = \sigma \varepsilon T(0)^4 dS$$

(7)

This expression can be used to derive the value of $T(0)$, the maximum (sub-solar) temperature, as a function of heliocentric distance, $r$, and Bond albedo, $A$ (see Fig. 1).

THE STANDARD THERMAL MODEL AND THE DERIVATION OF DIAMETERS AND ALBEDOS OF ASTEROIDS

The vast majority of asteroid diameters and albedos, including those in the IRAS minor planet survey (Tedesco, 1992), have been derived by means of the standard thermal model (STM). The basis of the STM is the assumption of a spherical shape and instantaneous equilibrium between

![Figure 1: Plot of temperature vs. heliocentric distance for a sunward-facing asteroid surface element in thermal equilibrium with insolation. The following parameters have been assumed: $A = 0.0393$ (corresponding to $p_r = 0.1$; $G = 0.15$; see Eq. (11)), emissivity = 0.9, and solar constant = 1373 W m$^{-2}$.](image)
insolation and thermal emission for each point on the surface. The direction cosine can be written as \( \mu = \cos(\Omega) \), where \( \Omega \) is the angular distance from the sub-solar point; therefore the surface temperature distribution is simply a function of the distance from the sub-solar point and is equal to zero beyond the terminator (\( \Omega > 90^\circ \)). The temperature can be written as:

\[
T(\Omega) = T(0)[\cos(\Omega)]^{1/4}
\]  
(8)

where \( T(0) \), the maximum (sub-solar) temperature, is given by Eq. (7):

\[
T(0) = \left( \frac{(1 - A)S_\odot}{r^2 \varepsilon \sigma} \right)^{1/4}
\]  
(9)

Furthermore, taking into account Wien's Displacements Law: \( \lambda_{\text{peak}} T = 2898 \), where \( \lambda_{\text{peak}} \) is expressed in micrometers and \( T \) in degrees Kelvin, it is possible to derive the wavelength of the maximum of the asteroid thermal emission as a function of its solar distance and albedo. Figure 2 shows the temperature distribution on the surface of an STM-like asteroid. The Sun, and thus the sub-solar point, are on the \( y \) axis. (Note that Eq. (9) is not exactly correct in the framework of the STM: the "refined"

STM of Lebofsky et al. (1986) includes a correction to \( T(0) \) via a "beaming" parameter, \( \eta \)—see "Infrared Beaming and the \( \eta \) Parameter"). Knowledge of the surface temperature distribution allows the observable thermal infrared flux of the asteroid at a given wavelength and geocentric distance, \( \Delta \), to be calculated by integrating the contribution from each surface element:

\[
F_\lambda = \frac{\varepsilon D^2}{\Delta^2} \frac{\pi h c^2}{\lambda^5} \int_0^{\pi/2} \frac{1}{\exp \left( \frac{hc}{\lambda k T(\Omega)} \right) - 1} \cos \Omega \sin \Omega \, d\Omega
\]  
(10)

The Bond albedo, \( A \) in Eq. (9), can be derived from the geometric visual albedo \( p_v \), which is defined as the ratio of the visual brightness of a planetary body observed at zero phase angle to that of a perfectly diffusing "Lambertian" disk of the same radius and at the same distance as the body. The geometric albedo, \( p_v \), is a measurable and widely quoted parameter. The relationship between the Bond albedo, \( A \), and \( p_v \) is

\[
A \approx A_v = q p_v
\]  
(11)

The phase integral \( q \) is 0.290 + 0.684 \( G \), following the description of the standard \( H, G \) magnitude system of Bowell

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**Fig. 2.** The surface temperature distribution of a STM-like asteroid. The Sun is on the \( y \) axis. The highest temperatures are denoted by white and the lowest by black. No thermal radiation is emitted on the dark side of the asteroid and the temperature falls smoothly to zero at the terminator.
et al. (1989), in which $H$ is the absolute magnitude and $G$ is the slope parameter. $H$ is defined as the mean $V$-band magnitude of an asteroid referred to a heliocentric and geocentric distance of 1.0 AU and zero solar phase angle (opposition). This abstract definition does not detract from the usefulness of $H$ for comparing the absolute brightnesses of asteroids. $D$, $H$, and $p_v$ are related via (e.g., Fowler and Chillemi, 1992):

$$D = \frac{1329}{\sqrt{p_v}} 10^{-H/5} \quad (12)$$

The above set of equations can be used to derive the diameter and albedo of an asteroid. In practice, the thermal infrared flux, $F_\lambda$, at a given wavelength is measured and the $H$ value is derived from optical photometry in the $V$-band. An initial guess is made for $p_v$ and by means of Eq. (10) an initial estimate for $D$ is obtained. This value of $D$ is inserted into Eq. (12) to obtain an improved estimate of $p_v$. This iterative procedure is continued until sufficiently stable values of $D$ and $p_v$ emerge.

To allow the STM to be used at non-zero solar phase angles, $\alpha$, Lebofsky et al. (1986) adopted an empirical phase correction, $\beta_E$, of 0.01 mag/deg to the infrared flux, that is:

$$F_\lambda(\alpha) = F_\lambda(0) \times 10^{(1-\beta_E|\alpha|)/2.5} \quad (13)$$

See Harris and Lagerros (2002) for further details and references.

Infrared Beaming and the $\eta$ Parameter

Does this simple model reproduce asteroid diameters and albedos to an acceptable accuracy? It turns out that diameters are overestimated unless a correction is incorporated for an effect known as "infrared beaming". The beaming effect causes the apparent color temperature of a rough surface to increase, with respect to a smooth one, when the surface is viewed at a small solar phase angle (for more details and references on the beaming effect see Harris and Lagerros, 2002). To account for this, the sub-solar temperature in Eq. (9) is increased by a factor $\eta^{-1/4}$ (i.e., Eq. (9)) has to be replaced by:

$$T(0) = \left[ \frac{(1-A)S_\odot}{r^2 \eta \epsilon \sigma} \right]^{1/4} \quad (14)$$

(see Lebofsky and Spencer, 1989, and references therein).

The value of $\eta$ in the "refined" STM of Lebofsky et al. (1986), the basis of the IMPS, is 0.756; this value was determined empirically to give the correct occultation diameters of 1 Ceres and 2 Pallas from photometric measurements at 10 µm. Comparisons of STM-derived diameters with those obtained from occultation observations are discussed by Tedesco (1994) and Harris and Lagerros (2002).

NEAR-EARTH ASTEROIDS

Problems arise in the application of the STM to NEAs, which are relatively small and often irregularly shaped, may lack the dusty insulating regolith (which reduces the surface thermal inertia) characteristic of larger bodies, and are often observed at large solar phase angles. For these reasons the assumptions inherent in the STM are not generally valid in the case of NEAs. In general, the STM appears to underestimate the diameters and over estimate the albedos of NEAs (Harris and Lagerros, 2002). Lebofsky et al. (1978) proposed an alternative fast-rotating/high-thermal-inertia thermal model that gives results for some NEAs that are in better agreement with diameters and albedos estimated by other means (e.g., from radar observations or spectral class).

High Thermal Inertia and the Fast Rotating Model

Consider a surface element of a body with a high thermal inertia: this element behaves like a capacitor or sink for the solar energy, and thus its temperature is not only a function of albedo and heliocentric distance but depends also on its previous thermal history. With the Sun in the equatorial plane, the higher the thermal inertia the smoother the temperature distribution with respect to longitude. For a very high thermal inertia and rotation rate the surface element has no time to cool down on the night side: its temperature remains constant through day and night (i.e., it is independent of longitude). The effect of thermal inertia is coupled to rotation rate. An asteroid rotating slowly with high thermal inertia displays a similar temperature distribution to one rotating very rapidly but with a lower thermal inertia. The corresponding model for a spherical asteroid rotating with the Sun in its equatorial plane is called the fast rotating model (FRM) or "isothermal-latitude" model.

Consider an elementary surface strip around the equator of the spherical asteroid. The conservation of energy requires that the solar energy absorbed by the strip on the day side is re-emitted as thermal radiation around its entire circumference:

$$\frac{(1-A)S_\odot}{r^2} 2R^2 d\theta = 2\pi R^2 d\theta (\epsilon \sigma T^4) \quad (15)$$

where $R$ is the radius of the asteroid and $d\theta$ is the width of the strip. Equation (15) yields the following expression for the equatorial temperature, $T(0)$:

$$T(0) = \left[ \frac{(1-A)S_\odot}{r^2 \pi \epsilon \sigma} \right]^{1/4} \quad (16)$$
which is the same as Eq. (14) for the STM with \( \eta \) replaced by \( \pi \). Furthermore, the dependence of the temperature on latitude, \( \theta \) is given by Eq. (17) with \( \Omega \) replaced by \( \theta \):

\[
T(\theta) = T(0)(\cos \theta)^{1/4}
\]

Figure 3 shows the temperature distribution on the surface of a FRM-like asteroid. The Sun is in the \( x-y \) plane and the asteroid spin axis is coincident with the \( z \) axis. The expression for the observable flux at a given wavelength in this case is:

\[
F_\lambda = \frac{2\pi D^2}{\Delta^2} \frac{h c^2}{k^5} \int_0^{\pi/2} \frac{1}{\exp \left( \frac{h c}{\lambda k T(\theta)} \right) - 1} \cos^2 \theta d\theta
\]

Note that due to the longitude-independent temperature distribution of the FRM, the observed infrared flux does not vary with solar phase angle.

**The Near-Earth Asteroid Thermal Model**

In general, neither the STM nor the FRM provide good fits to the measured spectral energy distributions of NEAs; measured thermal-flux continua are normally intermediate to those of the STM and FRM. Figure 4 shows a comparison of the spectral energy distributions from the STM (continuous line) and the FRM (dashed line) of a synthetic asteroid at 1 AU from the Sun, at 0.1 AU from the Earth and with a solar phase angle of zero. Its geometric albedo is 0.15 and its diameter has been set to 2 km in the case of the STM and to 5 km for the FRM to give similar flux values from the two models. These parameters, and the resulting flux values, are similar to those for large NEAs, although lower fluxes would result with non-zero phase angles in the case of the STM.

The near-Earth asteroid thermal model (NEATM), proposed by Harris (1998), incorporates a freely variable \( \eta \) which is adjusted to produce the best fit to the spectral data. The NEATM is based on the same temperature distribution as the STM, but in the case of NEATM the model temperature distribution is modified, by changing \( \eta \), to force consistency with the observed apparent color temperature of the asteroid, which depends on thermal inertia, surface roughness and spin vector orientation. Furthermore, the NEATM phase correction is also different to that of the STM. The empirical phase coefficient (of 0.01 mag/deg) used with the STM has been derived and tested for solar phase angles no greater than 30°. NEAs, however, are often observed at much higher phase angles. For example, Mottola *et al.* (1997) report thermal infrared observations of the NEA 6489 Golevka.
This different treatment of the phase-angle effect produces similar results to the STM at small phase angles but, other parameters being equal, results in larger diameters and lower albedos at large phase angles. It should be emphasized that fitting thermal models to observed thermal continua of asteroids requires high-quality spectrophotometric data. When observing asteroids in the thermal infrared "chopping" and "nodding" techniques are necessary to subtract the background to high precision. As a rule-of-thumb, the relative uncertainty in N-band data is ~5% and in M- and Q-band data ~10%. NEATM requires good wavelength sampling of the thermal continuum (i.e., four or five filter measurements over the range 5 to 20 μm). If only one or two filter measurements closely spaced in wavelength are available, the derivation of  η via spectral fitting is not possible. In such cases a default value of η can be used (e.g., 1.2; Harris, 1998). For further details and a discussion about the application of the STM, FRM and NEATM to NEAs, see Harris (1998) and Harris and Lagerros (2002).

Near-Earth Asteroids: The Effect of Shape

Accurate modeling of the observed thermal emission from an irregularly shaped asteroid at a high phase angle (e.g., 90°) is a complex task that requires knowledge of parameters such as thermal inertia, surface roughness, and rotation vector, beside shape. Relatively simple models, based on spherical geometry, are designed to give good estimates of albedo and size when, as in most cases, the above parameters are unknown. However, the accuracy of these models with data taken at high phase angles remains largely untested. The case of NEA 6489 Golevka is particularly interesting: Mottola et al. (1997) attempted to derive its size and albedo from a single 10 μm photometric measurement using versions of the STM and FRM modified to take into account the extreme geometry at the time of the thermal infrared observation: the object was almost pole-on and the solar phase angle was ~90°. Both the modified STM and FRM give results that are about a factor of 2 smaller than the radar diameter obtained by Hudson et al. (2000). The explanation for the inconsistency probably lies in the effect of shadowing and the extreme geometry at the time of the observation. The availability of the three-dimensional radar shape model enables such effects to be explored numerically. A first step is to assign temperatures to surface elements as a function of absorbed solar energy taking into account the effects of shadowing. The comparison between the radar-derived model of Golevka and a simple sphere is given in Fig. 5. For a brief introduction to thermophysical modeling including the effects of shape, and further references, see Harris and Lagerros (2002).

CONCLUDING REMARKS

Several observing programs dedicated to radiometric studies of NEAs have been carried out since the 1970s. Recently, the development of large telescopes and powerful mid-infrared
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FIG. 5. (a) Three-dimensional shape model of the NEA 6489 Golevka derived from the radar observations described by Hudson et al. (2000). The temperature distribution (see text) was obtained by illuminating the model from the $y$ axis assuming instantaneous thermal equilibrium (zero thermal inertia). The observer is on the $x$ axis perpendicular to the page (phase angle = 90°). The rotation axis at the time of the Mottola et al. (1997) infrared observations was almost coincident with the viewing direction (i.e., the asteroid was viewed almost pole-on). (b) A STM-like temperature distribution calculated for the same geometry as in (a). It is clear that a larger number of warm facets are visible than in (a). The thermal infrared flux that an observer would see in this case is higher than in the case of the irregular Golevka shape model.

Cameras and spectrographs has opened up the possibility of studying the small-size tail of the NEA size distribution. A fascinating outcome is that in a number of cases the albedos derived for NEAs do not fall in the ranges expected from the taxonomic system developed for Main Belt asteroids. Albedo is an important parameter in the derivation of the size distribution of the NEA population from the results of NEA discovery programs. There appears to be a lack of dark ($p_r < 0.1$) objects among NEAs compared to the Main Belt population. It is not yet clear whether this result is due to observational selection effects as discussed by Luu and Jewitt (1989), inadequacies in the thermal models, or reflects a real difference in the surface characteristics of NEAs. Radar is a powerful means of investigating the surface properties of NEAs. The circular polarization ratio SC/OC is a measure of the surface roughness on the radar wavelength scale. Comparing the distribution of estimates of the SC/OC ratio for large Main Belt and near-Earth asteroids, Ostro et al. (2002) argue that the surfaces of NEAs and Main Belt asteroids probably differ in fractional rock coverage. Binzel et al. (2002) provide an up-to-date review of the physical properties of NEAs. They argue that the physical properties of NEAs may be representative of asteroids in the Main Belt of similar size, but may differ significantly from the larger Main Belt asteroids.

Thermal infrared spectrophotometry is a powerful means of investigating the physical properties and mineralogy of NEAs but the reliability and limitations of simple thermal models applied to NEAs, especially when observed at large phase angles, requires further study.

The close approaches of NEAs, such as 1998 WT24 in 2001 November–December, offer opportunities to test thermal models over a very wide range of phase angle (i.e., 10–90°), and provide a basis for improving the accuracy of NEA albedo and diameter determination. In particular, such studies will allow the dependence of the beaming parameter, $\eta$, on phase angle to be characterized. Radar observations constrain the size and shape of these objects, thereby providing "ground-truth" data for checking the reliability of thermal models at large solar phase angles. In recent years the rate of discovery of NEAs has improved dramatically and efforts to physically characterize the NEA population have been unable to keep pace due to insufficient allocation of resources and observing opportunities. About 1900 NEAs have been discovered to date but radiometric data are available for only ~50 objects, while good-quality multi-wavelength spectrophotometry, necessary for reliable spectral fitting, is available for no more than 30 objects. On the basis of our experience, rule-of-thumb, practical $V$-magnitude limits for obtaining good-quality thermal infrared data of NEAs are $V = 16.5$ for a 4 m class telescope and $V = 18$ for a 10 m class telescope. The space infrared telescope facility (SIRTF) is predicted to have a sensitivity limit at 20 $\mu$m, 2 orders of magnitude below that of the largest groundbased infrared facilities at 20 $\mu$m.

It is clear that a great deal of work remains to be done.

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REFERENCES


APPENDIX

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<td>$F_r$</td>
<td>Reflected flux in all directions</td>
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<tr>
<td>$F_\lambda$</td>
<td>Emitted thermal infrared flux in all directions at a given wavelength ($\lambda$)</td>
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