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Characterizing asteroids multiply-observed at infrared wavelengths

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ABSTRACT

We report Markov chain Monte Carlo fits of the thermophysical model of Wright (Wright, E.L. [2007]. Astrophysics e-prints arXiv:astro-ph/0703058) to the fluxes of 10 asteroids which have been observed by both WISE and NEOWISE. This model is especially useful when one has observations of an asteroid at multiple epochs, as it takes advantage of the views of different local times and latitudes to determine the spin axis and the thermal parameter. Many of the asteroids NEOWISE observes will have already been imaged by WISE, so this proof of concept shows there is an opportunity to use a rotating cratered thermophysical model to determine surface thermal properties of a large number of asteroids.

1. Introduction

Thermophysical asteroid models have been in use for decades, and they have gradually improved in their completeness. The effects of thermal inertia in causing a time delay from local noon in the temperature maximum have long been taken into account (Peterson, 1976). The peaking of emission near zero observational phase angle (‘beaming’) was accounted for later in the Standard Thermal Model (STM) by calculating the emission at zero phase and then applying a linear correction factor for other phases. A beaming correction factor was then applied to account for the fact that beaming reduces reradiated energy; the STM is from Lebofsky et al. (1986). The beaming correction had also been used in Jones and Morrison (1974) and Morrison and Lebofsky (1979). Harris (1998) improved the effectiveness of the STM with his Near Earth Asteroid Thermal Model (NEATM) by letting this correction factor be a free parameter, and adjusting it to match the observed color temperature when multiple thermally-dominated wavelengths are available. However, both of these are empirical models that account for a variety of phenomena and parameters using only the beaming parameter.

Hansen (1977) did not use a beaming model and instead considered an asteroid as covered in craters, so that at non-zero phase angle there is increased shadowing of the visible portion of the asteroid over what would be observed from a smooth surface. This dampening of flux at non-zero phase can be interpreted as a peak at zero phase. Spencer (1990) adds to this model the consideration of light reflecting off different parts of craters, as well as an iterative numerical process to model heat conduction. Lagerros (1996) combines the effects of both thermal inertia and cratering in his model, and calculates a correction factor based on a comparison between a smooth surface and one with craters, though a more detailed discussion as to the effects of different sorts of surface roughness is given in Lagerros (1998). Delbo’ et al. (2007) includes surface roughness by considering the mean slope of the surface of the asteroid, rather than assuming any sort of crater geometry. Hanuš et al. (2015) uses optical photometric data to investigate shape models of the asteroid before applying a thermophysical model using infrared data.

Wright (2007) takes the surface cratering into account explicitly in his Spherical, Cratered, Rotating, Energy-conserving Asteroid Model (SCREAM, name assigned here for ease of reference) by including the local effects of this geometry in the power balance calculations of the temperature distribution over the surface of the asteroid. As a result energy is entirely conserved, and the model can include the effects of the reflection of solar light and the absorption of blackbody radiation caused by the mutual visibility of different parts of a crater, in addition to considering vertical heat conduction. Other asteroid thermophysical models that take all of these into account include those of Müller (2007), Rozitis and Green (2011), and Leyrat et al. (2012).

The Wide-field Infrared Survey Explorer (WISE) mission has provided a veritable treasure trove of information on the infrared sky (Wright et al., 2010). This includes asteroids, of which over 160,000 have now been observed. The NEOWISE project allowed individual exposures from WISE to be publicly archived and

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searched for moving objects, to enable the discovery of new asteroids and comets (Mainzer et al., 2011a).

The NEATM makes it possible to quickly perform thermal modeling of asteroids and has already been used on WISE data (e.g. Mainzer et al., 2011c). While the SCREAM is much more computationally intensive, it has the potential to allow additional parameters beyond diameter, albedo, and beaming to be determined, such as spin axis and thermal inertia. Parameters such as thermal inertia and spin axis can be more narrowly constrained when observations of an asteroid are available at multiple epochs. In cases when multiple viewing geometries are available, the NEATM can converge to different beaming factors at each epoch (though this can also result just from asphericity or different viewing geometries). Multiple epochs of observation are very advantageous in the SCREAM, as the differing phase angle gives views of different local times and/or latitudes of the asteroid, which allows one to characterize the asteroid spin axis in order to explain the phase-varying flux.

With the recent reactivation of the WISE telescope for the restarted NEOWISE mission, many asteroids are now being reobserved at different phase angles (Mainzer et al., 2014). This new mission thus gives us an opportunity to characterize these asteroids using the SCREAM, with which we can jointly fit all the data to explain the phase-varying flux. As a proof of concept, we here report Markov chain Monte Carlo fits of the SCREAM to 10 asteroids which have already been reimaged by the NEOWISE mission.

2. Data

Candidates for analysis were found by querying the Minor Planet Center[1] (MPC) for all WISE and NEOWISE observations of asteroids, and then searching through the output for asteroids which were seen by both. Then the Infrared Science Archive's[2] moving object search feature was used to find flux data for each of the asteroids. After throwing away temporal outliers (>1 day from other observations), the data were binned into time series from different observational epochs, and then the interquartile mean (or mid-average) of each epoch was taken as the new data point. Since our asteroids all have prograde orbits with periods $\gtrsim 1$ yr, no meaningful intra-bin trends were seen in the observational epochs, which were of length $\lesssim 10$ days. A new uncertainty for each data point was calculated as:

$$\sigma_{f,i} = \sqrt{\frac{C^2}{N/2}\sum_{j=N/4+1}^{3N/4}\sigma_j^2 + \left(\frac{0.1\ln(10)}{2.5}f_i\right)^2} \quad (1)$$

where there are N sorted observations being mid-averaged with uncertainty σ_j, and their mid-average flux value is f_i. The first term is the standard combination of independent uncertainties applied to the second and third quartiles of the data, but the correction factor $C \simeq 0.77$ accounts for the extra information from the data points we discarded and was found via Gaussian error modeling.[3] The second term is the equivalent of 0.1 magnitudes, and was added to account for the magnitude of the approximations made in our model which are detailed in Section 3, especially the discretization of the craters.

A summary of the data used can be found in Table 1.

[1] http://www.minorplanetcenter.net/.

[2] https://ceres.ipac.caltech.edu/frontpage/.

[3] Pseudocode:

```
do M times
  take N samples from a unit normal distribution
  calculate the standard deviation of the combined second and third quartiles
calculate the average standard deviation
divide by the standard deviation of N/2 samples from a unit normal distribution
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of $1/\sqrt{N/2}$This calculation produces $C \simeq 0.77$, indicating that the data in the first and fourth quadrants which are thrown out are nonetheless adding information to our statistic and so need to be accounted for.

When many high-accuracy observations of an asteroid over its rotational period are available, one may use a technique called 'lightcurve inversion' to deduce both the shape and rotational characteristics of the asteroid (Kaasalainen et al., 2001). However, in our relatively low S/N regime this method is not so useful. By binning our data over entire observational epochs, we average over the periodic flux variations due to the asphericity of the asteroid and solve for an 'effective diameter'. Our interquartile mean provides us with statistically robust data at each viewing geometry. As a test, we did perform fits for 2 of our asteroids using all the observations separately, without binning, and the results were found to agree well with the results found using our binning process. For more on the assumption of sphericity in our model, see Section 5.

In our modeling we used Keplerian orbital parameters from the MPC, and found the absolute magnitudes of the asteroids using the JPL Horizons web interface[4] which were assigned an uncertainty of 0.3 magnitudes, as was done in Mainzer et al. (2011a,c).

3. Methods

Markov chain Monte Carlo (MCMC) methods sample probability distributions by constructing a Markov chain in state space which converges on the desired equilibrium distribution. A discussion of the mathematics behind the algorithm is beyond the scope of this paper (see MacKay, 2003), but the method is often used in astronomy to sample posterior probability distributions of free parameters in a model given some data. It is useful to think of a Markov chain as a biased random walk, where the bias is such that the 'walker's' steps converge to the desired probability distribution. Here, this is accomplished by defining a likelihood function using the familiar χ^2 statistic which has as its equilibrium distribution the likelihood of a given parameter vector Ξ being the 'true' parameter vector. We define:

$$L[\Xi] = \kappa e^{-\frac{1}{2}\chi^2[\Xi]} \quad (2)$$

$$\chi^2 = \sum_i \left(\frac{f_{data,i} - f_{model,i}[\Xi, t_i]}{\sigma_{f,i}}\right)^2 \quad (3)$$

where i indexes the data points, each of which has a flux $f_{data,i}$, an uncertainty on that flux $\sigma_{f,i}$, and a time of observation t_i. κ is a normalization constant which may be ignored for our purposes since MCMC methods evaluate only $L[\Xi_1]/L[\Xi_2]$ to determine the acceptance or rejection of the next parameter vector. We have assumed a diagonal covariance matrix on the data in our χ^2 equation for simplicity, which should be a good approximation. We used the *emcee* package for our MCMC analysis (Foreman-Mackey et al., 2013). *emcee* provides an 'ensemble sampler' which is affine-invariant and utilizes a large number of 'walkers' to efficiently explore and sample parameter space, while employing parallelization to reduce the computational time needed for sampling. Affine-invariance ensures that the performance of our MCMC is not affected by correlations between our parameters causing anisotropic probability distributions (Goodman and Weare, 2010).

Our thermophysical model has five free parameters:

- φ – The RA of the spin axis of the asteroid.
- θ – The Dec of the spin axis of the asteroid.
- Θ_1 – The dimensionless thermal parameter of Spencer et al. (1989) computed at a distance of 1 AU.

[4] http://ssd.jpl.nasa.gov/?horizons.