ATM: AN OPEN-SOURCE TOOL FOR ASTEROID THERMAL MODELING Joachim Moeyens[1], Nathan Myhrvold[2], Željko Ivezić[1], [1]University of Washington, 3910 15th Avenue NE, Seattle, WA 98195, USA; moeyensj@uw.edu; [2]Intellectual Ventures, Bellevue, WA 98005, USA

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Abstract: ATM is an open-source Python package designed to model asteroid flux measurements to estimate an asteroid's size, surface temperature distribution, and emissivity. A number of the most popular static asteroid thermal models (NEATM, STM, FRM) are implemented with the reflected solar light contribution and Kirchhoff's law accounted for. Priors for fitted parameters can be easily specified and the solution, including the full multi-dimensional posterior probability density function, is found using Markov Chain Monte Carlo (MCMC). We summarize recent analysis of WISE data with ATM and discuss how candidate metallic asteroids can be selected using the best-fit ATM temperature parameter and infrared albedo. Data files with ~2.5 million WISE flux measurements for ~150,000 unique asteroids and additional Minor Planet Center data are also included with the package, as well as Python Jupyter Notebooks with examples of how to select subsamples of objects, filter and process data, and use ATM to fit for the desired model parameters.

Introduction:

Asteroid thermal flux modeling aims to estimate an asteroid's size (volume-equivalent diameter, hereafter diameter) and surface temperature distribution, and sometimes other physical properties such as emissivity, from measured infrared (IR) fluxes. We have recently released [1] a new Python modeling tool, ATM (Asteroid Thermal Modeling[1]), designed to enable easy fitting of the most common thermal models (NEATM, STM, FRM) to asteroid flux measurements. Data analysis software is often a crucial component in delivering scientific results, and scientific reproducibility and transparency can be greatly enhanced by collaborative software development and code sharing. By releasing ATM we aim to increase reproducibility – a fundamental tenet of the scientific process.

Technical details about ATM are available in [1]. Here we provide a high-level overview of its functionality, summarize analysis of WISE dataset with ATM, and discuss how the results of such analysis can be used to identify candidates for metallic asteroids.

[1]See https://github.com/moeyensj/atm

ATM **functionality:**

Static or instantaneous thermal models, offer a relatively simple but effective method to estimate an asteroid's diameter. These models assume the asteroid is a non-rotating or simply rotating sphere with a well-defined surface temperature distribution which is often expressed as a function of angular distance from the subsolar point. Static thermal modeling, while simpler than thermophysical models, offers a computationally feasible method to get estimates of diameters and other properties with the bonus that they can be applied at scale.

ATM computes the model flux from an asteroid, $F_\nu^{ast}(\lambda)$, corresponding to flux detected by the observer, $F_\nu^{obs}(\lambda)$, as the sum of the emitted thermal flux, $F_\nu^{th}(\lambda)$, controlled by the asteroid's surface temperature distribution, and the portion of the incident solar flux reflected by the asteroid, $F_\nu^{ref}(\lambda)$,

$$F_\nu^{ast}(\lambda) = F_\nu^{th}(\lambda) + F_\nu^{ref}(\lambda), \quad (1)$$

where F_ν is the specific flux (flux per unit frequency, ν), and λ is wavelength.

A given model spectrum $F_\nu^{ast}(\lambda)$, corresponding to observational quantity $F_\nu^{obs}(\lambda)$, is integrated over the bandpass (assumed known hereafter) to obtain observed in-band model flux for a given instrument. Both $F_\nu^{th}(\lambda)$ and $F_\nu^{ref}(\lambda)$ depend on the relative positions of the Sun, the asteroid and the observer, the asteroid's diameter D, and the aster-

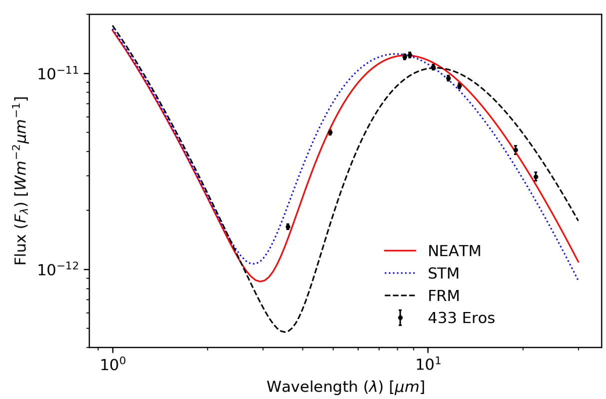

Figure 1: Physical model validation using data for 433 Eros (symbols) from [2] and models evaluated using best-fit parameters from [3]. This figure recreates Figure 1a from [3] was generated using example_1991EE&Eros.ipynb.

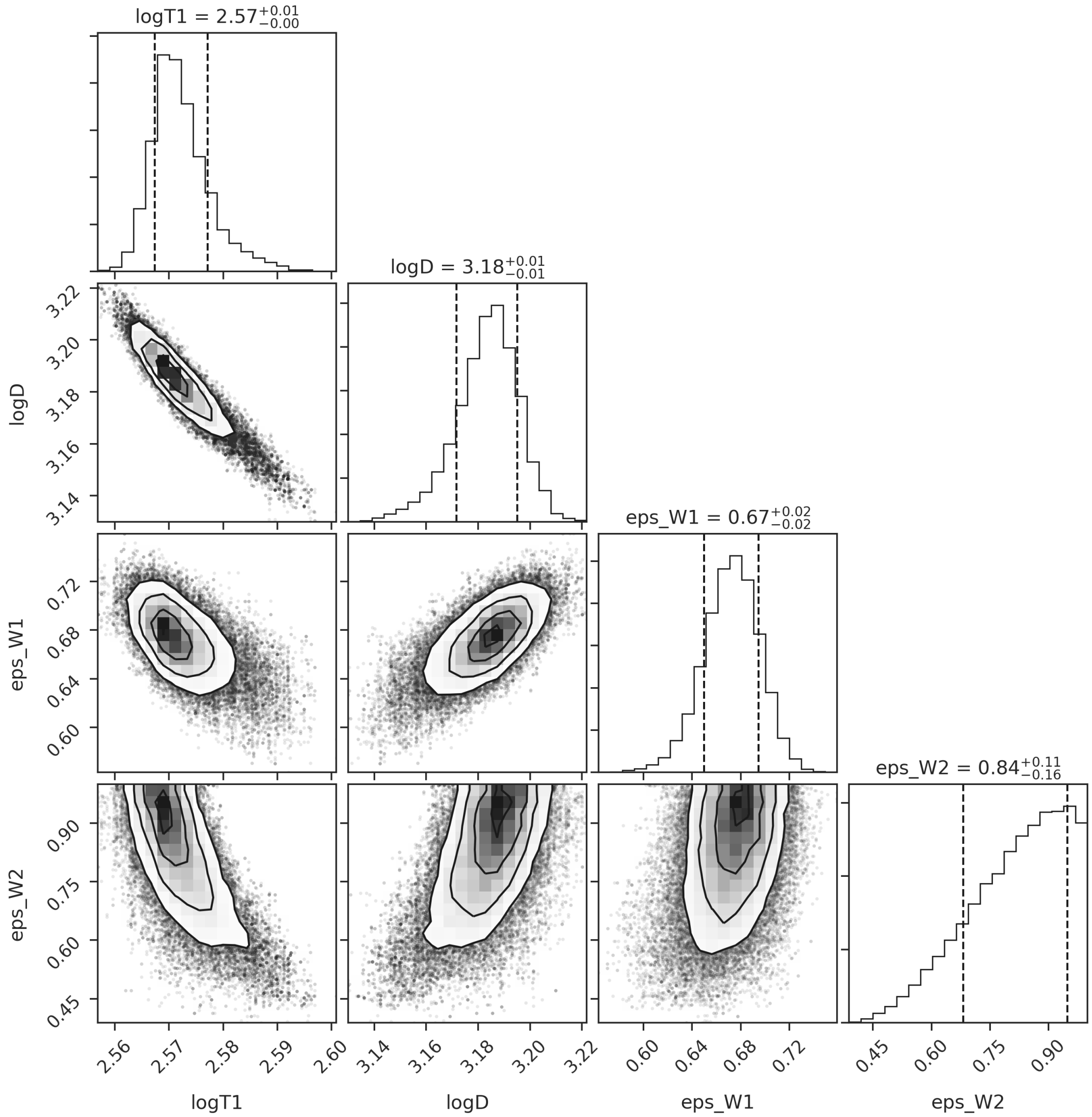

Figure 2: An example of the posterior probability density function obtained using ATM to fit a spectral energy distribution similar to that shown in Figure 1. Given four fitted parameters, the input dataset is not sufficient to meaningfully constrain emissivity in WISE W2 band. This figure was generated using single_object_54789.ipynb.

oid's emissivity, $\epsilon(\lambda)$, which controls the balance between absorbed/emitted and reflected incident flux. An example of ATM output is shown in Figure 1.

ATM also includes fitting functionality that utilizes Markov Chain Monte Carlo to maximize the Bayesian posterior probability density function, see section 2 in [1]. Figure 2 shows a posterior probability density function obtained using ATM to fit a spectral energy distribution similar to that shown in Figure 1. The choice of Bayesian priors when fitting asteroid spectral energy distributions, such as priors for emissivity, can have a significant impact on the best-fit parameters.

Finding candidate metallic asteroids with ATM and WISE data:

The largest dataset of infrared flux measurements for asteroids was recently contributed by the WISE survey [5]. A series of papers that produced static thermal models for about 164,000 asteroids was reviewed and summarized by [6]. We revisited their analysis using ATM [1] and showed that

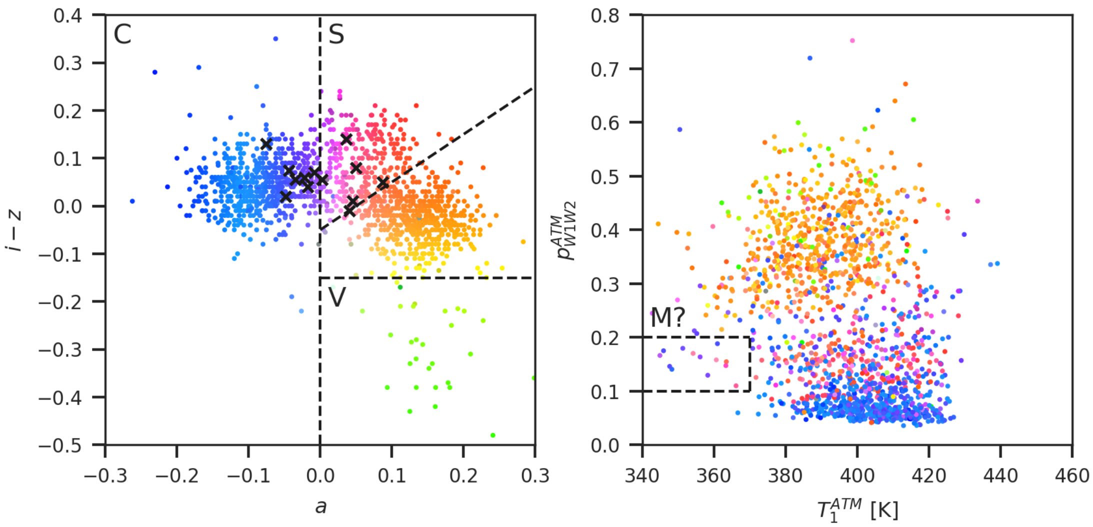

Figure 3: The colored symbols in the left panel show the a vs. $i-z$ SDSS color-color diagram for 1,574 asteroids with SDSS colors that also have WISE-based infrared albedo estimated with ATM. The symbols' color code is two-dimensional, according to a and $i-z$ colors (for algorithmic details see [4]). The same color coding is used in the right panel to visualize the correlation of optical colors and WISE-based best-fit values of infrared albedo (p_{W1W2}) and temperature parameter T_1. It is easy to discern that, for example, objects with $i-z < -0.15$ have high IR albedo, while objects with $a < 0$ have predominantly low IR albedo. The dashed lines in the right panel outline selection of 13 candidates for metallic asteroids discussed in [1]. Their distribution of optical colors is different from the color distribution for the full sample, as further visualized by showing them as crosses in the left panel. The dashed lines in the left panel outline the distribution of main taxonomic classes, as marked in the panel (C, S and V). This figure was generated using analysis_SDSS.ipynb.

ATM can match the best-fit size estimates for best-observed objects published in 2016 by the NEOWISE team with a sub-percent bias and a scatter of only 6%. Our analysis of various sources of random and systematic size uncertainties show that for the majority of over 100,000 objects with WISE-based size estimates random uncertainties (precision) are about 10%, and systematic uncertainties within the adopted model framework, such as NEATM, are in the range 10-20%. We estimate that the accuracy of WISE-based asteroid size estimates is in the range 15-20% for most objects, except for unknown errors due to an inadequate modeling framework (such as spherical asteroid approximation).

In addition to analysis of fitted objects with "typical" properties, we also selected and analyzed objects with unusual best-fit parameters. Harris and Drube [7] argued that the best-fit infrared albedo and the so-called beaming parameter can be used to select metallic asteroids (M taxonomic type). Their main argument is that objects with high radar albedo values, indicative of metallic objects, display a very narrow distribution of IR albedo (~0.2), while a larger fraction of objects with unusually high beaming parameter values are seen in the same albedo range. Therefore, objects with large values of beaming parameter and albedo values of about 0.2 are good candidates for metallic asteroids. Since WISE data are available for orders of magnitude more objects than radar observations, and metallic objects are interesting in many ways (see [7]), it was prudent to critically examine this method. As illustrated in Figure 3, SDSS data provide strong support that indeed WISE-based best-fit parameters obtained with ATM can be used to select good candidates for metallic asteroids.

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