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Forward Modelling of Asteroid Density for Planetary Defense

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Abstract

Density is one of the key inputs to asteroid threat assessment risk models [1], [2]. Similarly, the related physical property macroporosity, is critical to evaluating the likely performance of mitigation missions [3]. Unfortunately, measuring the density of asteroids is difficult. The number of density and macroporosity measurements available for asteroids is extremely limited and these measurements often have substantial uncertainties. Nonetheless, planetary defense requires models of the distribution of asteroid density / macroporosity and the ability to infer the density / macroporosity of individual objects.

We present two approaches for forward modelling of asteroid density. The first uses Bayesian methods to infer an asteroid's (or group of asteroids') density from the available density measurements of other asteroids. The second method combines measured meteorite densities with a physically motivated macroporosity distribution. We will compare the outcomes of the two models and discuss pros and cons of the two approaches.

1. Hierarchical Bayesian Model

A Hierarchical Bayesian Model is used to probabilistically forecast densities, masses, and porosities of asteroids. The model is conditioned on available asteroid density measurements (e.g. [4], [5]) and includes the effects of observational errors and intrinsic scatter. The model is implemented in Stan, a Markov Chain Monte Carlo software package utilizing a Hamiltonian sampler. The model can be used to forecast the mass, density, and porosity (and the related uncertainties) of an asteroid of a specified size and taxonomic complex. A density distribution of a group of asteroids can be forecast by specifying the independent properties (e.g. size, taxonomy) of the members of the group.

2. Meteorite Derived Model

Our alternate model is based on the available measurements of meteorite density (e.g. [6], [7], [8]), a mapping between asteroid taxonomy and meteorite class, and a physically motivated macroporosity distribution. The mapping between asteroid taxonomy and meteorite class was derived from a literature survey (c.f. [9], [10]). For each taxonomic class, a distribution of base densities was derived from the measured densities of the related meteorites. The base density is subsequently modified by a physically motivated macroporosity distribution. As with the hierarchical Bayesian model, given a size and taxonomic class, the mass, density and porosity (and their associated uncertainties) can be inferred for a specific asteroid. The density distribution of any group of asteroids can be generated given the relative contribution of each taxonomic class.

3. Discussion

Both the hierarchical Bayesian model and the meteorite driven model have their advantages and disadvantages. The hierarchical Bayesian model relies upon measurements of asteroid densities – which are difficult to obtain. Whereas the meteorite driven model relies upon a chain of inference from taxonomic type to meteorite class as well as a macroporosity distribution based on limited data. Nonetheless, both of these models can be useful in various situations. We will illustrate the use of both models in different situations.

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