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Modeling Thermal Transport and Emission of Particle Ensembles

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Abstract

Since 2004, Cassini's Composite Infra-Red Spectrometer (CIRS) has taken over a million spectra of Saturn's main rings. Almost all spectra are well fit with a Planck function and scalar multiplier, producing a database of effective temperature and emissivity that vary with location, illumination and viewing geometry. Use of this data to extract information about the rings has been complicated by the many parameters influencing the emission, and by computational difficulties. Here we present a new method for addressing two of the basic computational hurdles in producing verifiable models of Saturn's ring emission.

1. Introduction

The data from the CIRS instrument surprised investigators with the degree to which observed temperature and emissivity varied with location, illumination, and viewing geometry. Aside from variation with radius and Hour Angle, temperature is seen to vary with solar elevation, phase angle, Saturn season, and the observer's elevation and azimuth [2]. The scalar multiplier to the Planck function has been shown to be a complicated product involving the filling factors of temperatures within the instrument field of view, the total opacity, and any emissivity effects [9].

Initial analyses of the Cassini data built on historical approaches explaining temperature variation as due to the thermal response of individual particles [3]. In extending these models it was also realized that the optical thickness of the rings played an important role. The further discovery that the optical thickness of the rings is not a simple function of elevation drove efforts to been made to model the emission of, e.g., plateaus [1] and wake structures [5][4].

A complete thermal forcing model must take into account the temporal variation of radiation forcing that individual ring particles see as they orbit Saturn, as mediated by particle self shading and emission. Such models have been built which account for the temporal forcing of particles with self shading and emission [7] [8],but they suffer from deficiencies. In the face of a multiplicity of parameters– i.e., particle size distribution, vertical distribution and spatial correlation function, spin distribution and orientation, thermal conductivity, thermal inertia, albedo and volume filling factor– inverse modelling is out of the question, and even forward modelling is difficult.

2. Current Models

The fundamental computational difficulties are the radiative transport in the medium and conduction of heat within the particles. The integral equation approach to classical radiative transfer allows for fast solutions of the visible and thermal radiation field within an ensemble, but is not applicable to discrete particulate media where significant shading occurs. Ray tracing is accurate, but for calculating interior light fields for the many different configurations necessary to support sensitivity analyses, is slow.

All of the extant models reduce the 3-d computation to 1-d, under assumptions that the thermal skin depth is small. Credible treatment of the response of a rotating particle to arbitrary forcing requires a 3-d numerical solution, but becomes prohibitive when computation for a ring involves an ensemble of particles.

Extant models start with an assumed ring structure and hone parameter values until consistency is found with the data. But the models are not unique, leaving open the question of what other models might fit the data. Answering that question is made difficult by the fact that sensitivity analyses compute very slowly. Further, the models represent particle distributions with endmember particles [6][7], contributing to a phenomenological gap in extending from observed ring properties to particle properties.

3. A New Model

The model to be presented here borrows from work in computer graphics and chip design to computate the radiation field, with the main benefit that it allows one to evaluate radiation coupling between particles very quickly. A second feature is that the model embodies a shift in focus from individual particle response to the collective, such that individual particles mayb be treated statistically as circuit elements.

A ring section is modeled as a number of layers, each of which consists in a "checkerboard" in which flat particles fill random locations. The number of particles in each layer is chosen to be consistent with a total opacity, and each particle is broken down into a grid of sub-facets. Thermal coupling and the multiple scattered light field are effected via a radiosity computation [10], which computes the integrated solid angle of every facet as seen by every other facet. These coupling matrices grow quite large. The close particles are more influential, and at some distance one may just replace the exact calculations with a mean light field. The number of neighbors exactly calculated relates to the density of the block near-diagonal sparse coupling matrix.

Initial results from this system, with illumination from a point source and where the conductive transport of the slabs is solved straightfowardly using 1-d computations, duplicate the gross features observed in ring emission, such as variation of temperature with phase, illumination, and viewing angles. We examine how the thermal response of the ensemble is only loosely connected with the thermal inertia of the individual particles, in a way that is mediated by the geometrical arrangement. Generalization to the light field that would be seen from Saturn and the Sun by such an orbiting ring section is straightforward.

The general effect of an absorbing particle on the radiation field within the medium is to low-filter any variations and induce a phase-lagged directionally dependent signal due to particle spin [7]. This model allows the particles to be assigned semi-random filter functions, with a response computed from look-up tables. The collective emission is evaluated in a similar way to how the response of microchips is modeled in the design phase.

4. Summary and Conclusions

The CIRS instrument aboard the Cassini spacecraft has provided a data set of unprecedented quality for emission from Saturn's main rings. Models of the thermal transport are currently computationally constrained, and have enough free parameters that they may be run until the results agree with observation. This does provide a check on consistency of some models. However, if thermal modeling of Saturn's rings is to provide more than a consistency check, for instance, if it is to be used to constrain A-Ring wake parameters or lifetimes, or draw tenable conclusions about heat transport through the B-Ring, then basic computational difficulties must be addressed. The chief numerical difficulties seem to be in calculating the ensemble behavior of particles and performing sensitivity analyses in which particle thermal properties and spin states are altered. The "checkerboard model" presented in this paper is a tool aimed at getting a better physical understanding of these effects.

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