AN IMPROVED MODEL FOR MODELING THE COUPLED STRUCTURAL AND COMPOSITIONAL EVOLUTION OF SATURN'S RINGS DUE TO METEOROID BOMBARDMENT.
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Abstract: We report on the development of a new code for modeling the structural and pollution evolution of Saturn's rings, in tandem, due to the ballistic transport of micrometeorite impact ejecta. Previous studies were restricted to the study of the exchange of mass and angular momentum, and material properties separately, but provided a solid framework for future development that could be advanced once we achieved a better understanding of key ring physical properties such as opacity, and improved processing power became available. Our result is a robust code capable of modeling both structural and compositional changes over time on both local and global scales. We will discuss these improvements, as well as applications, and present our most recent results. This new code is being used with new Radiative Transfer codes that were developed in parallel, along with a suite of available Cassini data to help to better constrain the ring's non-icy constituents, and ring age.

Introduction: Because the rings have a huge surface area-to-mass ratio, they are particularly susceptible to modification due to extrinsic meteoroid bombardment. Meteoroid impacts on the rings can produce a large amount of particulate ejecta (in addition to significant amounts of gas and plasma, e.g., see [1]). with the vast majority of the dust and debris produced from these collisions being ejected at speeds much less than the velocity needed to escape the rings. As a result, a copious exchange of ejecta between different ring regions can occur, which over time can lead to the structural and compositional evolution of the rings on a global scale. This process by which the rings evolve subsequent to meteoroid bombardment is referred to as "ballistic transport" of impact ejecta [2-6].

Impact ejecta from a given micrometeorite impact on an icy ring particle are thrown predominantly in the prograde orbital direction [7] and carry not only mass, but angular momentum to other regions within the rings which typically have larger angular momentum. This leads to a net drift of material inward where ejecta preferentially land. Ring structure (optical depth τ and surface density σ) can have an effect on the material drift rate, because the ejecta absorption probability is a weak function of τ, and its angular momentum depends linearly on σ [7,8]. These properties can have an effect on how the rings evolve compositionally. For example, ring particles tend to be smaller in low τ regions, so that lower surface density regions are more quickly altered compositionally (e.g., darkened) relative to higher surface density regions because the mass fraction of "polluting" material relative to the overall local mass surface density will be higher in low surface density regions, for a given micrometeoroid flux [6].

Durisen and colleagues developed the first rigorous dynamical code to model ring evolution due to meteoroid bombardment and ballistic transport [9,10], and found that the influence of these processes on the rings could explain certain aspects of ring structure such as the fairly abrupt inner edges

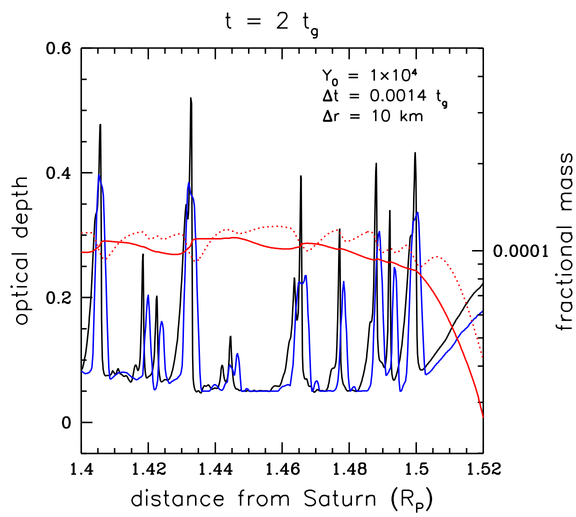

Figure 1: Evolution of the C ring plateaus using constant opacity. <u>blue curve:</u> Initial (real) optical depth. <u>black curve:</u> BT simulation. <u>Red curves:</u> Fractional mass of extrinsic pollutant. Sharpening of features is due to BT. The spiky look of the simulations may mean that viscosity and/or particle properties in plateaus are inapropriate. For comparison, the fractional mass in the case of no structural evolution (dotted curve) as was done in [8] is shown.

of the A and B rings, including the very similar "ramp" features which connect them to the Cassini division and C ring, respectively [10-12] given evolutionary times of $\sim 10^8$ years (see [6] for a review of this body of work). Subsequently, [8] developed a "pollution transport model" to model the evolution of ring *composition* that consisted of a dynamical code (that held the structure fixed in time) that calculated how the non-icy constituents build up over time and how these impurities are redistributed over the rings (*i.e.*, only the *fractional* amounts of non-icy constituents are allowed to vary with time), and a radiative transfer calculation that used the dynamical code results to see how ring particle composition was manifested in ring particle albedo and color. With these numerical tools, [8] found that they could simultaneously explain both the C ring/Cassini division versus A ring/B ring albedo and color dichotomy *and* the form and shape of the radial color variation across the C ring/B ring transition on a similar timescale as derived by Durisen and colleagues on the basis of purely structural evolution.

These previous modeling efforts remain compelling; however, the structural models [9-12] at the time suffered most from a lack of understanding of key physical properties of the rings such as ring opacity, optical depth, surface density, and viscosity, not to mention a lack of the proper computng power necessary to carry out broad and detailed simulations in a timely manner. The former has seen great improvement thanks to recent and ongoing analyses of available data from the Cassini mission, while the latter has improved to the point where global, long-term evolution models have become tractable. On the other hand, the pollution transport models [8] suffered most from not allowing the structure of the rings to evolve simultaneously (thus eliminating, e.g., the ability to model transient features), as well as a limited amount of relevant data and incomplete understanding of ring spectral properties such as ring particle albedo which requires more sophisticated models and comprehensive data sets to derive, which are now available.

Structural and Compositional Model and Applications: Our new code remains largely based on the original works of [7-12]. We will discuss the implementation of some of the new improvements to the code including optical depth and mass density relations, as well as more up-to-date viscosity models, properties which affect the form of the ejecta distribution, and the role and model for disruptive impacts which can affects the model's response to ejecta deposition.

In addition, we will discuss the simulations we will conduct of evolving ring stucture and pollution transport, which include sharp inner ring boundaries, constraining the currently unknown surface density in the middle and outer B ring to provide an alternate means of estimating the ring mass and age, and small scale structure and transient features. As an example, in Fig. 1, we show a simulation of the structural and compositional evolution of the C ring plateaus over 2 "gross erosion" times t_g ($\sim 2.5 \times 10^6$ years) using a constant ring opacity κ, and a viscosity due only to particle collisions [13]. A gross erosion time is the time it would take for a ring of some surface density to be eroded completely away if no material returned to the ring.

Even over this short time, the C ring plateaus *migrate* (and evolve) inwards due to mass and angular momentum transport. Structures alter because different parts of the rings are drifting at different rates (due to underlying structure). Prograde-ejecta-dominated ballistic transport sharpens the outer edges of plateaus because faster drifting material (in the non-plateau regions) is piling up at the edge of the more slowly drifting plateau region. Yet the observed C ring plateaus are not so sharply peaked, suggesting that they are maintained that way in some manner. Given that particle properties appear to be different in and out of the plateaus [14], we suspect that a suitable combination of viscosity, opacity, and (retrograde) disruptive impact ejecta, which can lead to *outward* drift of material, may help to explain these structures.

We further note that the observed compositional trends across the plateaus also appear to correlate with optical depth. In Fig. 1, the evolving structure model tends to smear out the compositional differences (solid red curve) more quickly than the non-evolving model (dotted red curve). Furthermore, the trend in composition across the plateaus are opposite for the two cases. Interestingly, it is concluded in [6] that if the rings are much older than previously thought, the C ring has likely been regenerated several times. This would further suggest that much of the structure we now see is the result of processes with timescales considerably shorter than the ring's turnover time ($\sim 10^7 - 10^8$ years). Most of the structure in the C ring remains poorly understood. It is the hope that new detailed simulations may shed some light on some of the currently unexplained, observed structure.

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