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Combined structural and compositional evolution of planetary rings due to micrometeoroid impacts and ballistic transport

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ABSTRACT

We introduce improved numerical techniques for simulating the structural and compositional evolution of planetary rings due to micrometeoroid bombardment and subsequent ballistic transport of impact ejecta. Our current, robust code is capable of modeling structural changes and pollution transport simultaneously over long times on both local and global scales. In this paper, we describe the methodology based on the original structural code of Durisen et al. (Durisen, R.H. et al. [1989]. Icarus 80, 136–166) and on the pollution transport code of Cuzzi and Estrada (Cuzzi, J.N., Estrada, P.R. [1998]. Icarus 132, 1–35). We provide demonstrative simulations to compare with, and extend upon previous work, as well as examples of how ballistic transport can maintain the observed structure in Saturn's rings using available Cassini occultation optical depth data. In particular, we explicitly verify the claim that the inner B (and presumably A) ring edge can be maintained over long periods of time due to an ejecta distribution that is heavily biased in the prograde direction through a balance between the sharpening effects of ballistic transport and the broadening effects of viscosity. We also see that a "ramp"-like feature forms over time just inside that edge. However, it does not remain linear for the duration of the runs presented here unless a less steep ejecta velocity distribution is adopted. We also model the C ring plateaus and find that their outer edges can be maintained at their observed sharpness for long periods due to ballistic transport. We hypothesize that the addition of a significant component of a retrograde-biased ejecta distribution may help explain the linearity of the ramp and could provide a mechanism for maintaining the sharpness of C ring plateau inner edges. This component would arise for the subset of micrometeoroid impacts which are destructive rather than merely cratering. Such a distribution will be introduced in future work.

1. Introduction

The rings' huge surface area-to-mass ratio ensures that they are particularly susceptible to the effects of extrinsic meteoroid bombardment. Until recently, the mass of Saturn's rings was thought to be comparable to a Mimas mass (although see Charnoz et al., 2009). Based on this value, the area-to-mass ratio for Saturn's rings exceeds that of Mimas[1] by $\gtrsim 10^4$. A consequence of this is that hypervelocity micrometeoroid impacts on the rings, depending on parameters, would likely erode them on timescales much shorter than the age of the Solar System, if all the ejecta escaped (Durisen et al., 1989). More realistically, these impacts produce a large amount of particulate ejecta, the vast majority of which are 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 occurs which leads to changes in ring structure and composition on both local and global scales (Durisen et al., 1989; Cuzzi and Estrada, 1998; Charnoz et al., 2009). This process, by which the rings evolve subsequent to meteoroid bombardment, is referred to as "ballistic transport" of impact ejecta (Ip, 1983; Durisen, 1984a,b; Lissauer, 1984).

In a series of papers, Durisen and colleagues (Durisen et al., 1989, 1992, 1996) developed the first rigorous dynamical code to model ring structural evolution due to meteoroid bombardment and ballistic transport. They found that the influence of these processes on the rings could explain certain aspects of ring structure such as the fairly abrupt inner edges of the A and B rings, and

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[1] For purpose of this illustration, all the mass is assumed to be in the B ring where the optical depth $\tau \geqslant 1$. The mass of Mimas is $\sim 4 \times 10^{22}$ g.

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the very similar "ramp" features which connect them to the Cassini division and C ring (see Fig. 1) respectively. These structures imply evolutionary times of $\gtrsim 100$ "gross erosion" times, where the gross erosion time t_G (see Table 1 for a list of parameters) is defined as the time a reference ring annulus of surface density σ would disappear due to loss of ejected material if nothing returned (see below, and Section 2.2.1). In a complementary study, Cuzzi and Estrada (1998, hereafter CE98), developed a model for the evolution of composition while assuming constant structure. They calculated how the abundance of both intrinsic and extrinsic non-icy materials evolves over time as icy rings are bombarded by largely cometary material, and how these impurities are redistributed over the rings. CE98 found that they could simultaneously explain the albedo and color dichotomy between the C ring/Cassini division material versus the A ring/B ring material *and* the radial variation of color across the C ring/B ring transition in a time scale similar to that on which Durisen and colleagues explained structural evolution.

Two key quantities in ballistic transport are the impact yield Y and the impacting micrometeoroid flux $\dot{\sigma}_{\rm im}$. Both Y and $\dot{\sigma}_{\rm im}$ (see Table 1 and Section 2) are essential for providing more accurate age-dating of specific ring features, as well as the overall age of the rings themselves. The yield of a single impact, Y, which is defined as the ratio of ejecta mass to impactor mass, can be quite large depending on several factors (e.g., see Durisen, 1984b). The gross erosion time is expressed in terms of these quantities $t_G = \sigma / Y \dot{\sigma}_{\rm im}$; this definition serves as a handy reference, but in fact most ejecta are not lost (see Section 2.2.1). Moreover, this definition is appropriate for cratering impacts, but does not straightforwardly generalize to disruptive impacts.

The ejecta velocity distribution resulting from an impact depends on the hardness of the target and the angle of impact (Cuzzi and Durisen, 1990 hereafter CD90). If the target is powdery, yields can be in excess of $\sim 10^5 - 10^6$ for cratering (non-disruptive) impacts at normal incidence (e.g., Burns et al., 1984), while micrometeor-sized particles impacting into hard or granular surfaces can have yields as small as $\sim 10^3$ (Vedder, 1972). The ejecta velocities for the bulk material from cratering impacts tend to range from ~ 1–10 m s^{-1}, much less than the local orbital velocity within the rings (tens of kilometers per second). This means that, regardless of whether impacts are cratering or disruptive, the net mass gain or loss from the rings due to micrometeoroid bombardment is small compared to its redistribution from place to place. The net gain or loss needs to be considered only for very long exposure times (Charnoz et al., 2009) or regions where tiny charged ejecta can be swept into the planet (Northrop and Connerney, 1987).

Earlier estimates of the current micrometeoroid flux at Saturn vary significantly (e.g., Morfill et al., 1983; CE98; Landgraf et al., 2000), but all suggest that the rings could be impacted by close to their own mass (for the Mimas mass estimate) over the age of the Solar System. These estimates are largely based on the meteoroid mass fluxes measured by the Pioneer and Ulysses spacecraft between 5 and 10 AU (see, CE98, Fig. 17). Some hope for improving this estimate had recently surfaced from Galileo measurements of the flux at Jupiter. Sremčevíc et al. (2005) used an indirect technique to provide an estimate of the mass flux that may be off by at most a factor of 2–3 (larger) compared to previous estimates and is comparable to that estimated by CE98 (see Section 2.2.1). However, some recent measurements of the mass flux at Saturn suggest that the flux may be considerably lower – perhaps an order of magnitude – than previously thought (Kempf et al., 2013 AGU), making t_G longer than what we generally assume in this work.

In a frame rotating at orbital velocity, the ejecta mass from an extrinsic micrometeoroid impact that is not disruptive is thrown

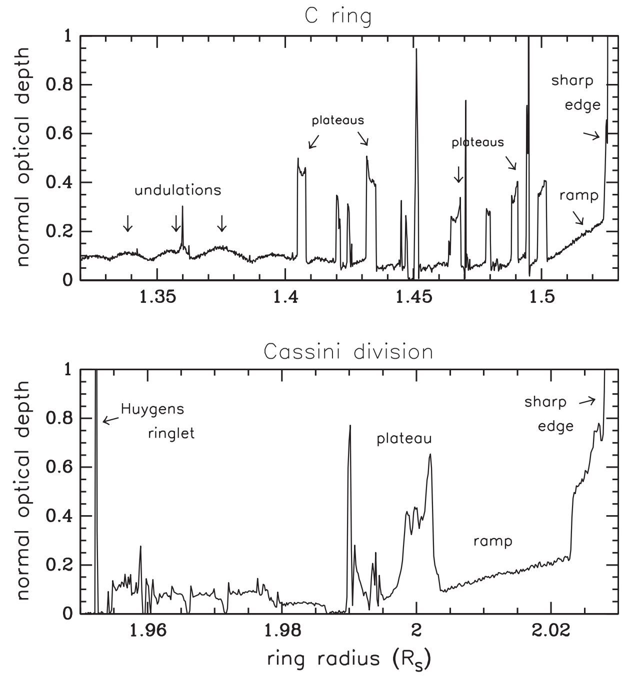

Fig. 1. The optical depth profile from the UVIS Cassini α-Arae occultation (Colwell et al., 2009) as a function of radius from Saturn in planetary radii. *Top panel:* Much of the structure in the C ring has long remained a mystery; however, there is evidence to suggest ballistic transport is at work, particularly with the inner B ring edge (at 1.525 R_S) sharpness and its associated ramp, and the outer (and inner) edges of plateaus. The radial drift due to ballistic transport can lead to a pile up of material at plateau edges, which may be characterized by the sloped tops of the plateaus. The reversal of the slopes of plateau peaks about the Maxwell ringlet at ~ 1.45 R_S may be indicative of impacts that change in nature to fragmenting from cratering across the region. *Bottom panel:* The Cassini division and inner A ring displays some of the same properties as the C/inner B ring. A similar ramp connects to the sharp inner A ring edge at 2.025 R_S. Even though the radial scales in the plots are different, the ramp width is roughly the same in both cases.

predominantly in the prograde orbital direction. This result arises naturally from the tendency of projectiles to arrive with velocity vectors that are retrograde in the orbital sense, as azimuthally averaged over the rings (CD90). That is, the combination of the orbital motion of ring particles and the motion of Saturn through the micrometeoroid flux leads to a "headwind" of material that increases both the number of impacts on the leading faces of ring particles and the impacting velocities (see also Latter et al., 2012). In addition to mass, ejecta carry away with them angular momentum. Since most of the ejecta from a non-disruptive (cratering) impact are prograde, they tend to reimpact the rings at outer locations. Prograde ejecta are launched from their original radial location with more angular momentum than their parent ring particle, but less angular momentum than ring particles they may impact on their next ring crossing at some outer radius. The net result is to decrease angular momentum at the secondary impact location, leading to radial inward drift.

On the other hand, an impact that leads to complete disruption of a target ring particle into several fragments would likely produce the opposite effect because the fragment velocities are biased in the same direction as that of the impactor, resulting in a retrograde distribution (relative to Keplerian) with lower ejecta velocities than their prograde counterparts (Nakamura and Fujiwara, 1991; Paolicchi et al., 1989). In either case, the structure of the rings (i.e., optical depth τ and surface density σ) will have an effect on the rate of material drift. This is because the probability of ejecta absorption, which determines the actual ejecta mass that is reabsorbed by the rings instead of merely passing through them,