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TITLE: Effects of Meteoroid Erosion in Planetary Rings

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Introduction

This grant supported continuing studies of the effects of ballistic transport on the evolution of Saturn's rings. Ballistic transport, as used in this context, refers to the net transport of mass and angular momentum caused by the exchange of meteoroid impact ejecta between neighboring ring regions (Ip 1983, 1984, Morfill *et al.* 1983, Lissauer 1984, Durisen 1984a,b). The characteristic time scale associated with this process is the gross erosion time t_g, the time it would take a ring region to be completed eroded if all impact ejecta were lost. This time scale is estimated to be about 10^5 to 10^6 years for a ring region with normal optical depth $\tau \sim 1$. Earlier work by myself and collaborators developed the physical theory and simulation techniques to model this process (Durisen *et al.* 1989, Cuzzi and Durisen 1990). Detailed simulations, supported in part by this grant, have demonstrated that ballistic transport can produce observed structures in Saturn's rings, especially at and near the inner edges of the A and B Rings (Durisen *et al.* 1992, 1996). The structures of interest in the real rings are illustrated in Figures 1 and 2. Most of these structures were previously unexplained. The computational results plus analytic treatments place useful constraints on fundamental ring properties, including the indication of a relatively young ring age $\leq 10^8$ years (see reviews by Nicholson and Dones 1991, Esposito 1993, Cuzzi 1995, and Porco 1995). This grant also supported development of the faster computational algorithms necessary to permit longer evolutions. Resulting simplications in the ballistic transport equations permitted an analytic linear stability analysis (Durisen 1995), which has provided considerable insight into ballistic transport processes and applications to Saturn's rings. All these accomplishments are described in more detail below.

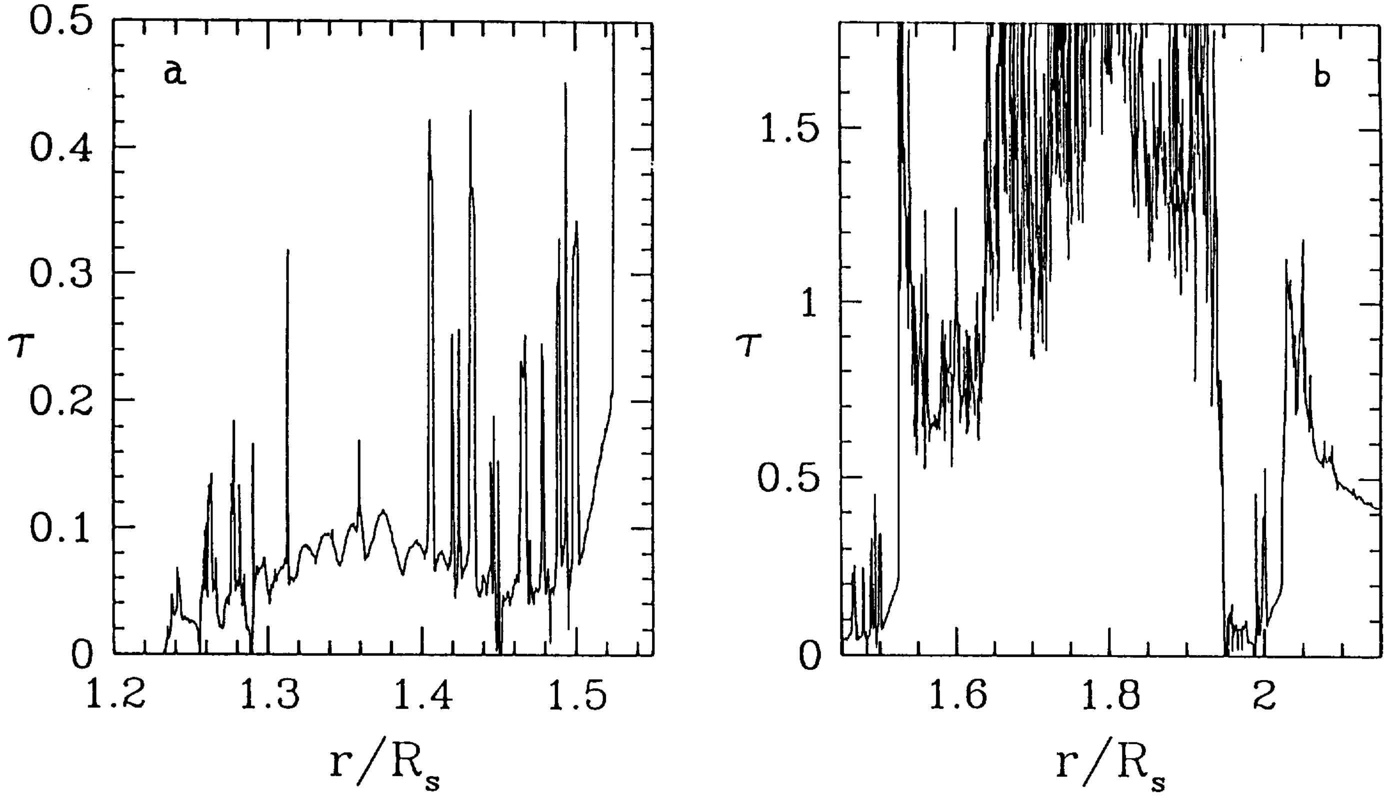

Figure 1: Voyager ISS scans of ring normal optical depth as a function of ring radius. Part (a) shows the C-ring. Part (b) shows the outer C-ring to inner A-ring. $R_s = 60{,}300$ km is the equatorial radius of Saturn.

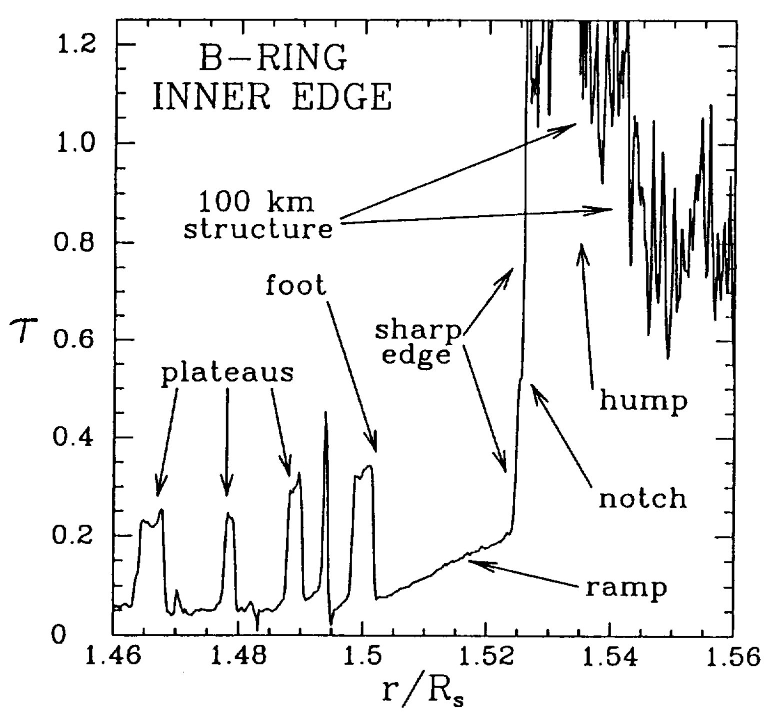

Figure 2: Detail near the inner B-ring edge from the same data as in Figure 1.

Publications and Activities

Publications. The following papers were supported entirely or in part by this grant.

1.) R.H. Durisen, P.W. Bode, J.N. Cuzzi, S.E. Cederbloom, and B.W. Murphy 1992, "Ballistic Transport in Planetary Rings due to Particle Erosion Mechanisms. II. Theoretical Models for Saturn's A and B Ring Inner Edges," *Icarus,* **100**, 364-393.

2.) R.H. Durisen 1995, "An Instability in Planetary Rings due to Ballistic Transport," *Icarus*, **115**, 66-85.

3.) R.H. Durisen, P.W. Bode, S.G. Dyck, J.N. Cuzzi, J.D. Dull, and J.C. White II 1996, "Ballistic Transport in Planetary Ring Systems due to Particle Erosion Mechanisms. III. Torques and Mass Loading due to Meteoroid Impacts," *Icarus*, in press.

Personnel. The P.I. received summer salary from this grant for three years (1992-4). Over the four year funding period, contributions to this research were made by Indiana University graduate students P.W. Bode, J.D. Dull, and R. Tripoli and by Professor J.C. White at Middle Tennessee State University at a total level of about one to two Person Months per year. The P.I.'s NASA-Ames collaborator J.N. Cuzzi directed parallel efforts on the evolution of ring color due to meteoroid pollutants and on refinements to our understanding of meteoroid impact physics.

Other Activities. Current funds were used to support annual week-long visits by the P.I. to NASA-Ames for consultations with collaborator J.N. Cuzzi and his colleagues. The P.I. also attended a Cassini Project Ring Hazard Workshop at NASA-Ames in January, 1996. Important work on the linear stability analysis and fast code development was accomplished during three visits to the Max-Planck-Institute for Extraterrestrial Physics in Garching (near Munich), Germany: from January to July, 1992 as a Fulbright Scholar and in Summer, 1993 and May, 1994 as a visiting scientist.

Accomplishments

Inner-Edge Studies. The numerical algorithms described in Durisen *et al.* (1989) were used in Durisen *et al.* (1992, 1996) to produce simulations of ballistic transport evolution in Saturn's B Ring inner-edge region using the Cuzzi-Durisen (1990) characterization of meteoroid impact ejecta. Figure 3 shows several calculations from Durisen *et al.* (1992) performed with different assumptions about the total mass yield Y (= ejected mass/meteoroid mass) for hypervelocity impacts. A comparison of Figures 2 and 3 illustrate that ballistic transport can: a) maintain the sharp inner edge against viscous spreading, b) produce a ramp-like structure on the low-τ side and c) produce the 100 km structure in the inner B Ring. There are no other viable mechanisms proposed for these structures. As a result, Figure 3 has been reproduced in two recent review articles (Cuzzi 1995 and Porco 1995). Durisen *et al.* (1992) considered only ballistic transport due to ejecta exchanges. Durisen *et al.* (1996) included the additional effects of mass and angular momentum deposition by the meteoroids themselves. This produces overall inward drifts important over time scales of a few x 10^8 years, especially in the C Ring, but has little effect on ballistic transport features near inner edges.

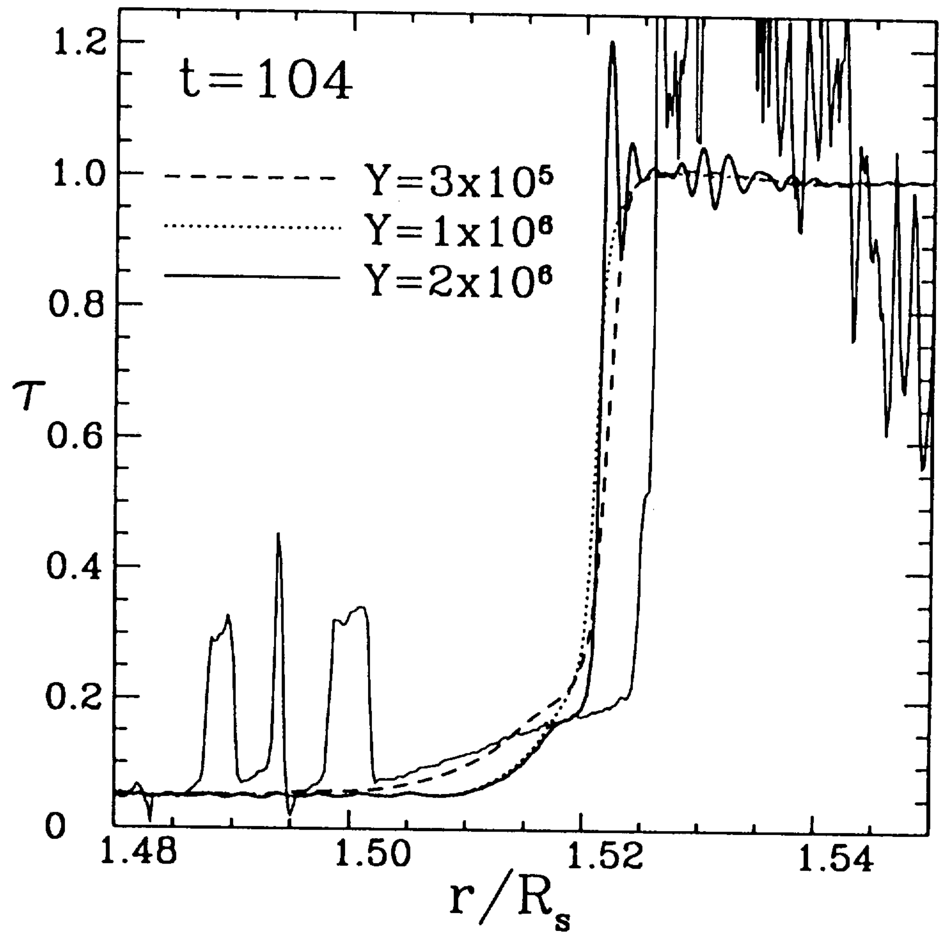

Figure 3: The optical depth profiles at the end of three ballistic transport simulations lasting 104 t_g. Y is the impact ejecta yield. The thin line is the optical depth profile for the real rings as given Figures 1 and 2. The calculation with the highest yield provides the best fit to the scale-length of the inner-edge and the 100 km structure (Horn and Cuzzi 1996).

Fast Code Development. The longest simulations in Durisen *et al.* (1992, 1996) were stopped at about 100 t_g due to the extreme computational expense of these calculations. Estimates based on extrapolations from these endpoints indicated that ballistic transport features would not become as fully developed as they appear to be in Saturn's rings until more like 500-1,000 t_g. An important aspect of research under this grant has been the development of faster algorithms for modeling ballistic transport. The old code was computational expensive primarily because evaluation of the net mass and angular momentum exchange involves triple integrals over the ejecta speed and direction distributions at every radial bin every time step. The principal speed up (by almost two orders of magnitude) is obtained by reducing the impact ejecta loss and gain integrals from triple integrals over ejecta speed and direction to single integrals. This requires an ejecta velocity distribution in which angles, speed, optical depth τ, and distance from Saturn r are separable so that some of the integrals can be done once-and-for-all at the beginning of the calculation, leaving only single integrals to be done at each radial bin each time step.

Unfortunately, the Cuzzi-Durisen (1990) ejecta yield and velocity distribution functions, their eqs. 40 to 46, combine all the variables in a complex, inseparable form. The simplications of the loss and gain integrals during slow code development had the important side benefit of facilitating linear stability analyses (Durisen 1995). These in turn provided the analytic understanding needed to guide our attempts to fit the Cuzzi-Durisen distribution more accurately in a separable form. We had to characterize the τ and r dependencies of the ejecta yield, the prograde/retrograde ejecta asymmetry (with respect to ring particle orbit motion), and the prograde/retrograde probabilities of ejecta absorption where they reintersect the ring plane. As our test case, we chose the B Ring inner-edge simulation illustrated in Figure 10 of Durisen *et al.* (1992). Successive improvements to our Cuzzi-Durisen fits were implemented until fast and slow code results at an evolutionary time of 35 t_g were practically indistinguishable. Figure 4 shows that the subsequent extension of both the fast and slow calculations to about 100 t_g indicates continued agreement. The fast code calculation required only about three hours on an HP 735 workstation, while the old slow code calculation required tens of cpu hours on a Cray Y/MP. As shown in Figure 5, the new fast code is being used to study the development of ballistic transport structures over much longer times.

Linear Stability. As already mentioned, simplications to the ejecta loss and gain integrals made possible a linear stability analysis similar to that in Goertz and Morfill (1988). This enabled us to understand one of the principal phenomena seen in ballistic transport calculations, the formation and propagation of undulatory structure. Good agreement is obtained between the analytic results and the simulations. It seems likely that instability driven by ballistic transport is the likely explanation for the 100 km structure seen in the inner B Ring (Horn and Cuzzi 1996).

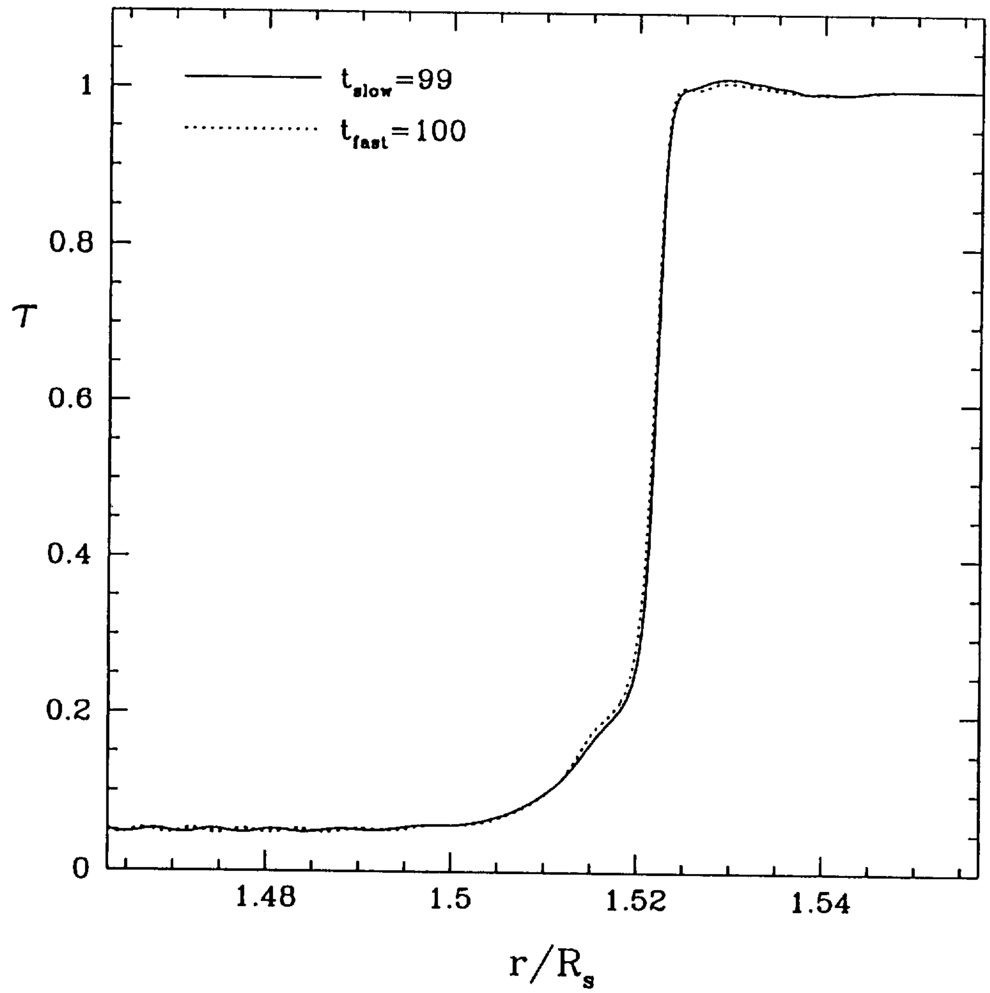

Figure 4. Comparison between results from the new fast code and the old slow code for the $Y = 3 \times 10^5$ calculation shown in Figure 3. The fast code algorithms appear to do a good job of reproducing the old code results. Time is given in t_g units.

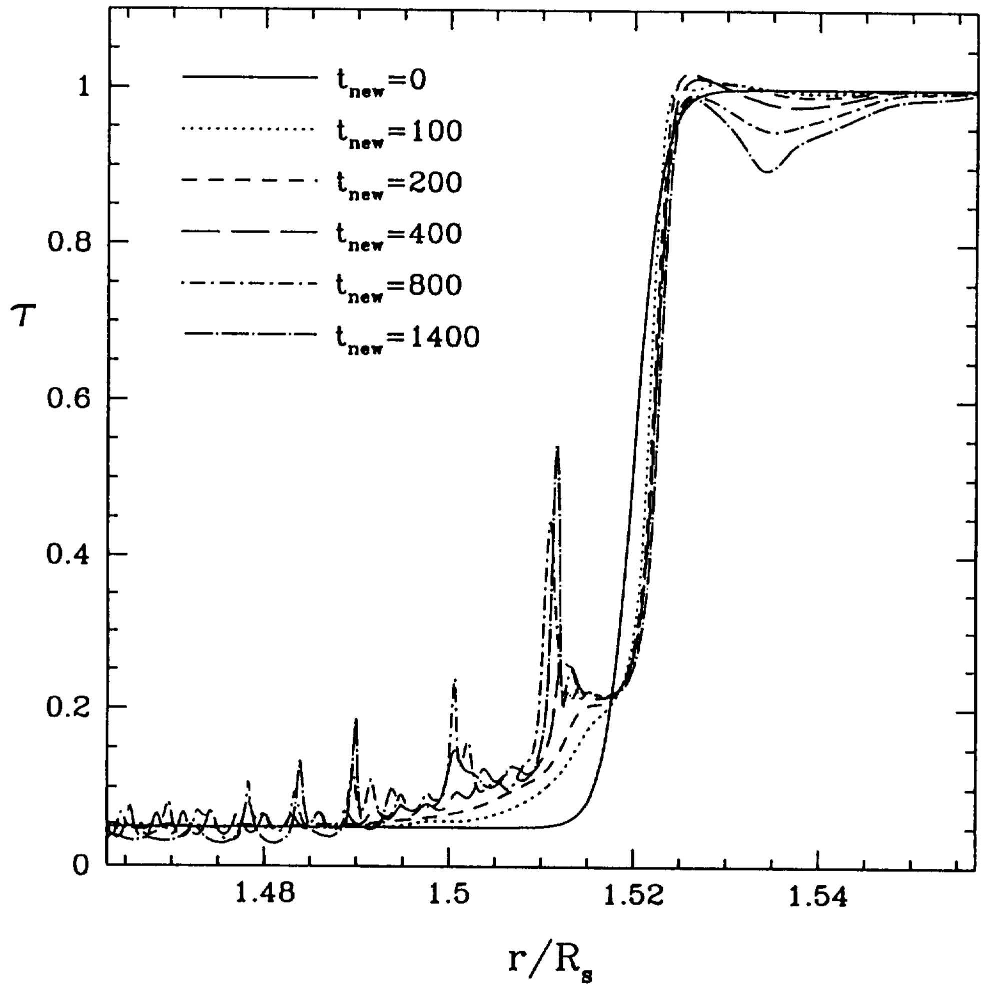

Figure 5: Extension of the fast code calculation in Figure 4 to 1,400 t_g .

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