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Evolution of Saturn's Rings due to Combined Viscous Spreading and Micrometeoroid Bombardment

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1. Introduction

Over its more than twelve year tenure, the Cassini mission provided key measurements that are important for determining the absolute age of Saturn's rings. These include the extrinsic micrometeoroid flux at Saturn [1], the volume fraction of non-icy pollutants in the rings [e.g., 2], and the total ring mass [3]. These three factors taken together constrain the ring age to be no more than a few 100 Myr [1]. The Cassini Grand Finale also provided a suite of observations that demonstrate that the rings are losing mass to the planet at a surprising rate. Some of the mass flux falls as "ring rain" at higher latitudes consistent with the H_3^+ infrared emission pattern thought to be produced by an influx of charged water products from the rings [e.g., 4]. However, the contribution needed to account for the ring rain phenomenon is considerably less than the total equatorial measured mass influx of 4800 – 45000 kg s^{-1} [5] requiring additional mechanism(s).

Recall that micrometeoroid bombardment (MB) not only leads to pollution of the rings over time (as well as a catalyst for ring rain), but also to exchange of mass and angular momentum throughout the rings due to ballistic transport (BT) of their predominantly prograde impact ejecta. As a result of this fundamental feature of BT, the rings act like an accretion disk with outward angular momentum transport leading to a steady inward drift of material to the planet. Here for the first time we quantify this radial drift rate in the context of a quasi-steady uniform ring using an accretion disk analog.

2. Viscous Evolution and MB

We have first modeled the long term viscous evolution and pollution of massive ring over the age of the Solar System and found that, for a persistent flux a the value measured by Cassini [1], the rings always end up much darker if they were ancient or primordial, regardless of their initial mass. This is because the rings spend almost all their lifetime at low mass. Instead, we find that models in which the rings start at $\sim 1-4$ Mimas masses, ~ 100 Myr ago can always match the current volume fraction of non-icy material if the rings started as pure ice (e.g., Figure 1.).

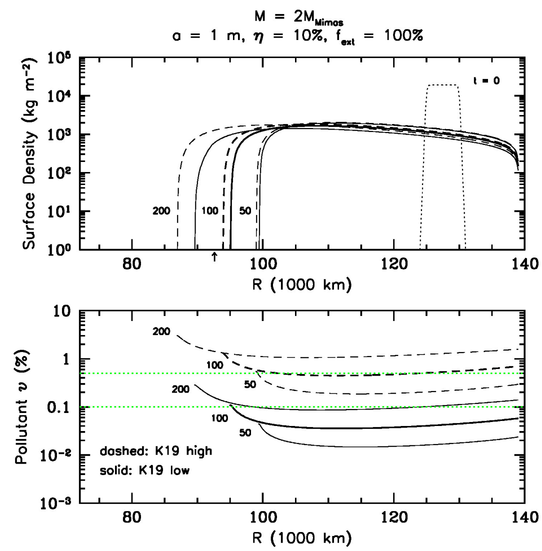

Figure 1: Initial 2 Mimas mass annulus (dotted) evolving due to viscosity alone, and subject to MB at the Cassini measured lower (solid) and upper (dashed) bounds for the flux. Top panel: surface density Σ at $100-300$ Myr. Bottom panel: volume fraction of pollutant. The green dashed lines mark the range of measured non-icy fraction in the A and B rings [2].

3. Effect of Including ML and BT

BT models are mostly concerned with how ring structure can be produced near edges or instabilities [see 6], normally a complicated process. Here, we are more concerned with a fundamental feature of BT, namely that because micrometeoroid impact ejecta are mostly prograde, a BT active disks acts like an accretion disk.

Using an accretion disk analogy, we have explored a model for a quasi-steady uniform ring (constant surface density Σ and optical depth τ) to derive the mass inflow rate due to BT and mass loading (ML):

$$\dot{M}_{\rm bt} + \dot{M}_{\rm load} = 8\pi x_b r^2 \mathscr{P}\mathscr{R} + 4\pi r^2 \dot{\sigma}_{\rm im}, \quad (1)$$

where $\mathscr{P}$ and $\mathscr{R}$ are the optical depth-dependent absorption probability and local ejecta mass emission rate, $x_b = 10^{-4}$ is the characteristic ejecta velocity-to-orbital speed ratio, r is radial distance from Saturn, and $\dot{\sigma}_{\rm im}$ is the impact rate on the rings [6]. Both $\mathscr{R}$ and $\mathscr{P}$ depend on the 2-sided flat plate micrometeoroid flux at infinity [1], but $\mathscr{R}$ also depends on the impact ejecta yield, Y whose plausible range is $10^4 - 10^5$. We will show that BT and ML can lead to an overall inward flux of material on the order of $\gtrsim 10^3 - 10^4$ kg s^{-1} in rough agreement with the total rate of ring material observed falling into Saturn during the Cassini Grand Finale.

4. Implications for Ring Evolution

When we include the effects of ML and BT in the simulations (Figure 2), we find much more rapid evolution of the disk than by viscosity alone (Fig. 1), even as the ring is polluted roughly at the same rate. Quite notably, we see that a consequence of ML (and also BT) is that the inner lower optical depth foot of the ring annulus leads to the formation of a "C ring", because as it turns out, the induced inward radial drifts of material due to ML and BT increase asymptotically to maximum values as τ decreases (even as the mass inflow rates become negligible). We will discuss the full implications of this characteristic in detail, and how we expect more detailed, full BT calculations would refine this result.

5. Summary and Conclusions

We find that if the micrometeoroid flux was constant at least at its current measured value [1] then the rings would appear consistent with being only $\sim$ 100 Myr old, and likely had an initial mass of $\sim 1 - 4$ Mimas masses. Moreover, our analysis implies a remaining lifetime of $\sim 8 - 200$ Myr, suggesting the rings may not only be young, but ephemeral as well. Some caveats will be discussed. We also find that the formation of lower optical depth C ring from an initially optically thick annulus is a natural consequence of MB.

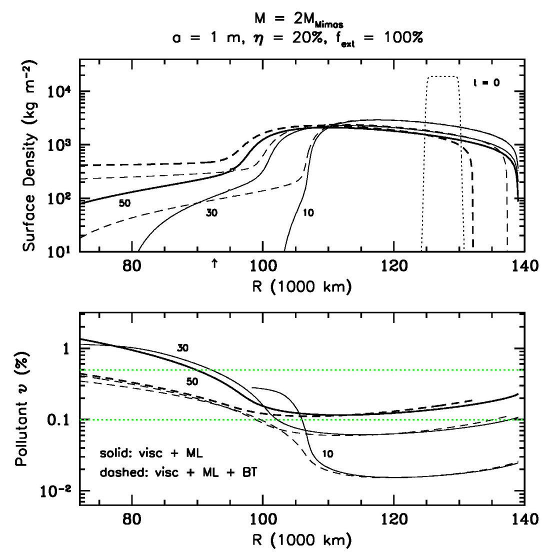

Figure 2: Initial 2 Mimas mass annulus (dotted) evolving due to viscosity and ML (solid), and also ML and BT (dashed) for $Y = 10^4$, using the logarithmic mean of [1]. Note (a) the much more rapid evolutionary times, and (b) the formation of a "C ring".

Acknowledgements

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