INWARD RADIAL DRIFT OF MATERIAL FROM ANGULAR MOMENTUM LOSS DUE TO BALLISTIC TRANSPORT IN SATURN'S RINGS: IMPLICATIONS FOR OBSERVED MASS LOSS RATES AND REMAINING RING LIFETIME.

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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 [2-3], and the total ring mass [4]. These three factors taken together constrain the ring age to be no more than ~ 200 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., 5]. However, the contribution needed to account for the ring rain phenomenon is considerably less than the total measured mass influx of 4800 – 45000 kg s^{-1} [6] requiring additional mechanism(s).

Recall that micrometeoroid bombardment 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. We [7] demonstrate that BT 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. We then discuss the ramifications of this feature as it pertains to the evolution and remaining lifetime of the rings.

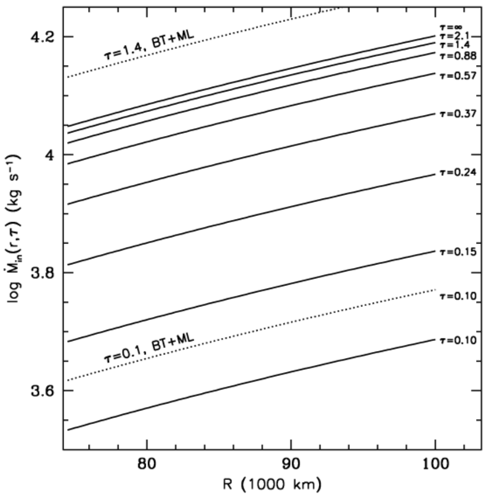

Fig. 1. Log of mass inflow rates due to BT only (solid curves) and additionally mass loading (dotted) curves for C and B ring optical depths.

Mass Inflow Rates due to BT: BT models are mostly concerned with how ring structure can be produced near edges [8-9] or instabilities [10-11], 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 [7]. 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 from the full BT equations [see 10] the inflow rate for a uniform ring:

$$\dot{M}_{in} = 8\pi x_b r^2 PR \; + 4\pi r^2 \dot{\sigma}_{im} \qquad (1)$$

where P and 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 $\dot{\sigma}_{im}$ is the impact rate on the rings. The first term is due to BT's exchange of ejecta mass between different ring regions, and the second is due to mass loading from direct deposition of micrometeoroids. Both R and $\dot{\sigma}_{im}$ depend on the 2-sided flat plate micrometeoroid flux at infinity [1], but R also depends on the impact ejecta yield, Y which we assume here to be 10^4. Figure 1 shows this mass inflow rate plotted for a range of τ. In particular, the characteristic background optical depths for the C ring are $\tau = 0.1$, whereas $\tau > 1$ for the B ring. We find that the inflow rate can indeed match the observed rates, though the C ring can only match the lower bound of the observed rate. However, reasonable choices of parameters (e.g., $Y = 10^5$, a value required to maintain the inner B ring edge may be more suitable [12]). The B ring may provide sufficient material to account for replenishment for the C ring, and loss via the ring rain phenomenon. How efficient this process can be will require detailed BT modeling.

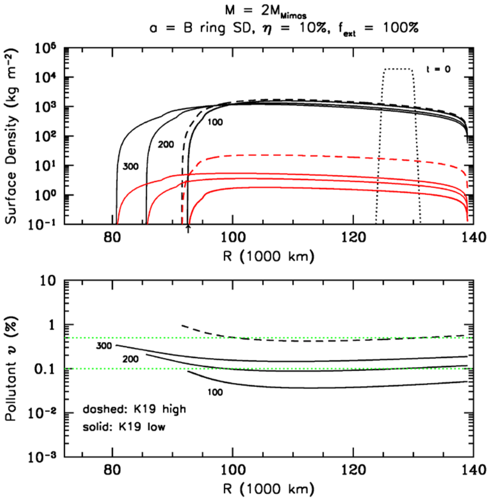

Fig. 2. Model for the combined viscous and pollution evolution of an initial 2 Mimas mass annulus due to direct deposition only. Plotted (top) are the total surface mass density (black) and pollutant (red) for different times as indicated in Myrs, and (bottom) the mean volume fraction of pollutants υ. The A and B rings are observed to have υ ≃ 0.1-0.5% (as indicated by the green dashed lines). The lower bound of the measured flux gives the solid curves, and the upper bound gives the dashed curves [1]. The new flux is consistent with polluting the ring to its current state in the allotted time. The current ring mass in these models is from 0.8 – 1 Mimas depending on model and time, with mass being lost to outside the A ring [15].

Implications for Ring Evolution: [13] recently presented models of the long term viscous evolution and pollution of a massive ring over the age of the solar system under the influence of direct deposition of micrometeoroids using the old [14], and new [1] measured flux and showed that the rings would be too polluted if they were primordial. New work [15] shows that the final pollution state is fairly independent of initial ring mass, while the final mass is asymptotic as well (consistent with [16]). This is partly because rings are at low mass for most of their history.

Given the low ring mass, measured flux, and volume mass fractions, it was shown that the current polluted state of the rings can be matched by assuming they were formed much more recently, at most a few hundred Myr ago. Figure 2 shows one such model where the rings begin as a 2 Mimas mass annulus of pure ice and are allowed to evolve viscously for 100 – 300 Myr (see figure caption), assuming that only 10% of the micrometeoroids remain as absorbing material (effective pollutant). However, what is missing from these models is the mass inflow rates imposed by BT which may cause more rapid evolution at low mass. Figure 3 (red curves) represents a first attempt at including both effects, here shown for a massive (100 Mimas mass ring). Most early evolutionary curves lie on top of each other, but after 100 Myr the mass flux from BT starts to overwhelm viscosity and the disk "shrinks". By 700 Myr, the disk mass is 0.01 Mimas.

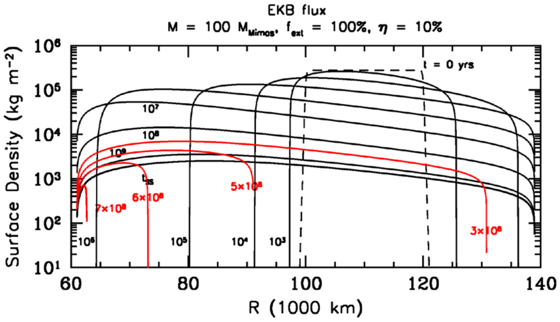

Fig. 3. Comparison of viscous evolution of a massive initial ring over time without (black) and with (red) BT and mass loading.

Conclusions: Our derived mass rates suggest that the remaining life time of Saturn's rings ~50 – 500 Myr, in agreement with [5] and [6]. Thus Saturn's rings are not only young, but ephemeral. These mass rates, due to BT and mass loading, carry with them the caveat that they are only valid away from steep edges, so a more careful treatment is required. However, these simulations imply that rings that are subject to BT, barring any mechanism to contain the ring, will cause any substantial ring to evolve until a time where BT is ineffective at angular momentum and mass transport, perhaps similar to sparse and very dark ring systems such as those of Uranus and Neptune.

References: [1] Kempf et al. (2019) *in prep.* [2] Zhang et al. (2017a) *Icarus, 281,* 297. [3] Zhang et al. (2017b), *Icarus*, *294*, 14. [4] Iess (2018), *20th EGU Assembly*, Vienna, 10770. [5] O'Donoghue et al. (2013) *Nature, 496*, 193. [6] Waite Jr. et al. (2018), *Science*, *362*, aat2382. [7] Durisen and Estrada (2019), *in prep*. [8] Durisen et al. (1992) *Icarus, 100*, 364. [9] Estrada et al. (2015), *Icarus*, *252*, 415. [10] Durisen (1995), *Icarus*, *115*, 66. [11] Latter et al. (2014), *MNRAS*, *441*, 2773. [12] Estrada et al. (2018), in *Planetary Ring Systems*, Cambridge U. Press. [13] Estrada et al. (2017), *Cassini Symposium*, *LASP*. [14] Cuzzi and Estrada (1998), *Icarus*, *132*, 1. [15] Estrada and Charnoz (2019), *in prep*. [16] Salmon et al. (2010), *Icarus*, *209*, 771.