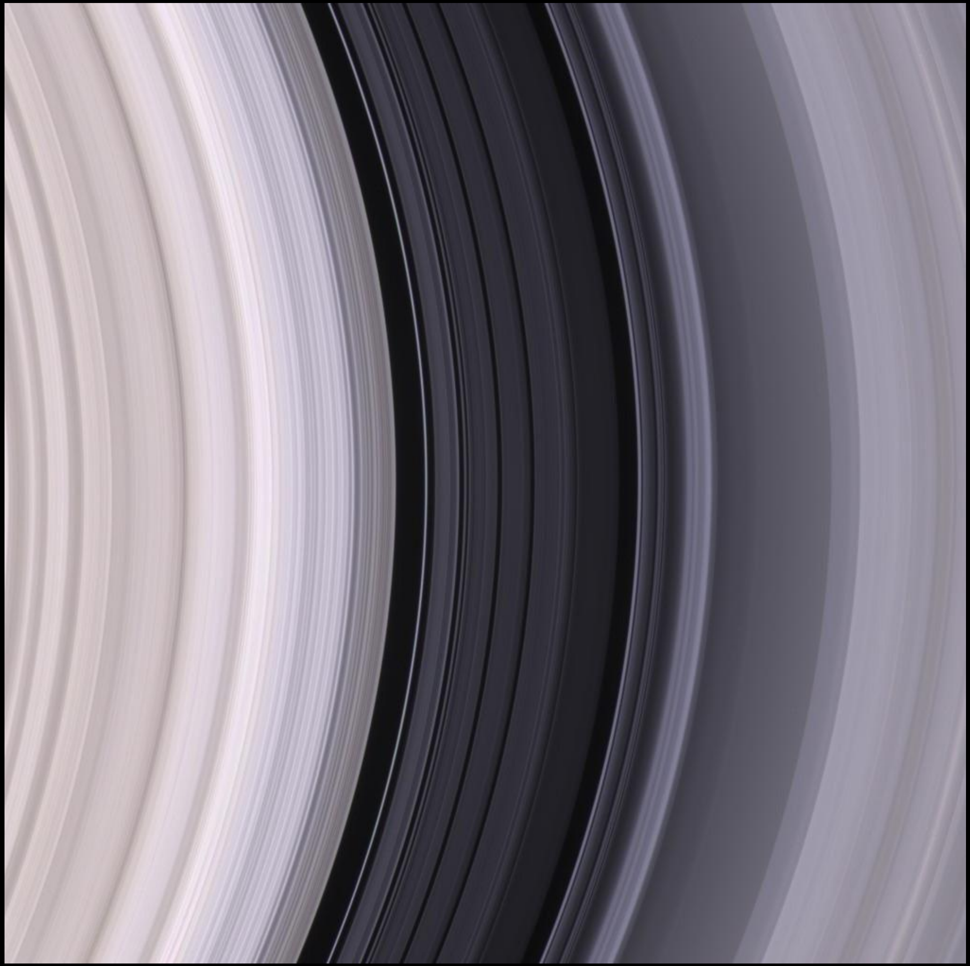
Evolution of Structure and Composition in Saturn’s Rings due to Ballistic Transport of Micrometeoroid Impact Ejecta



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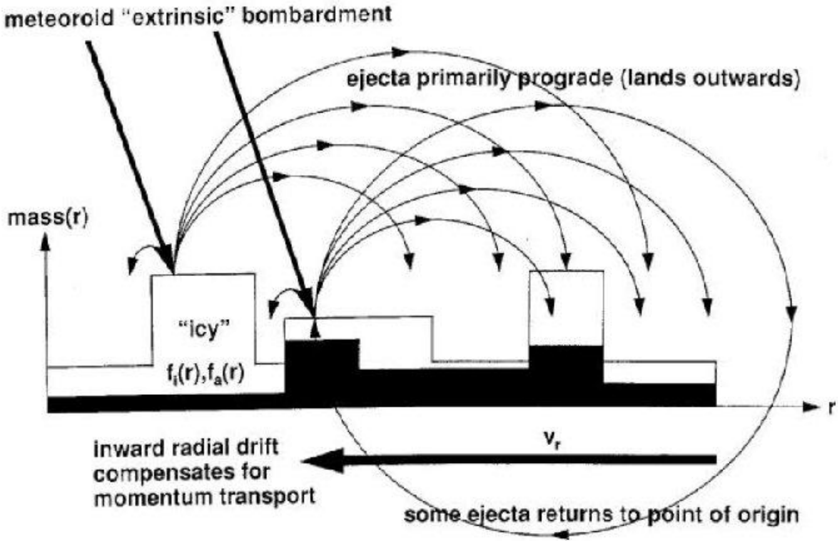
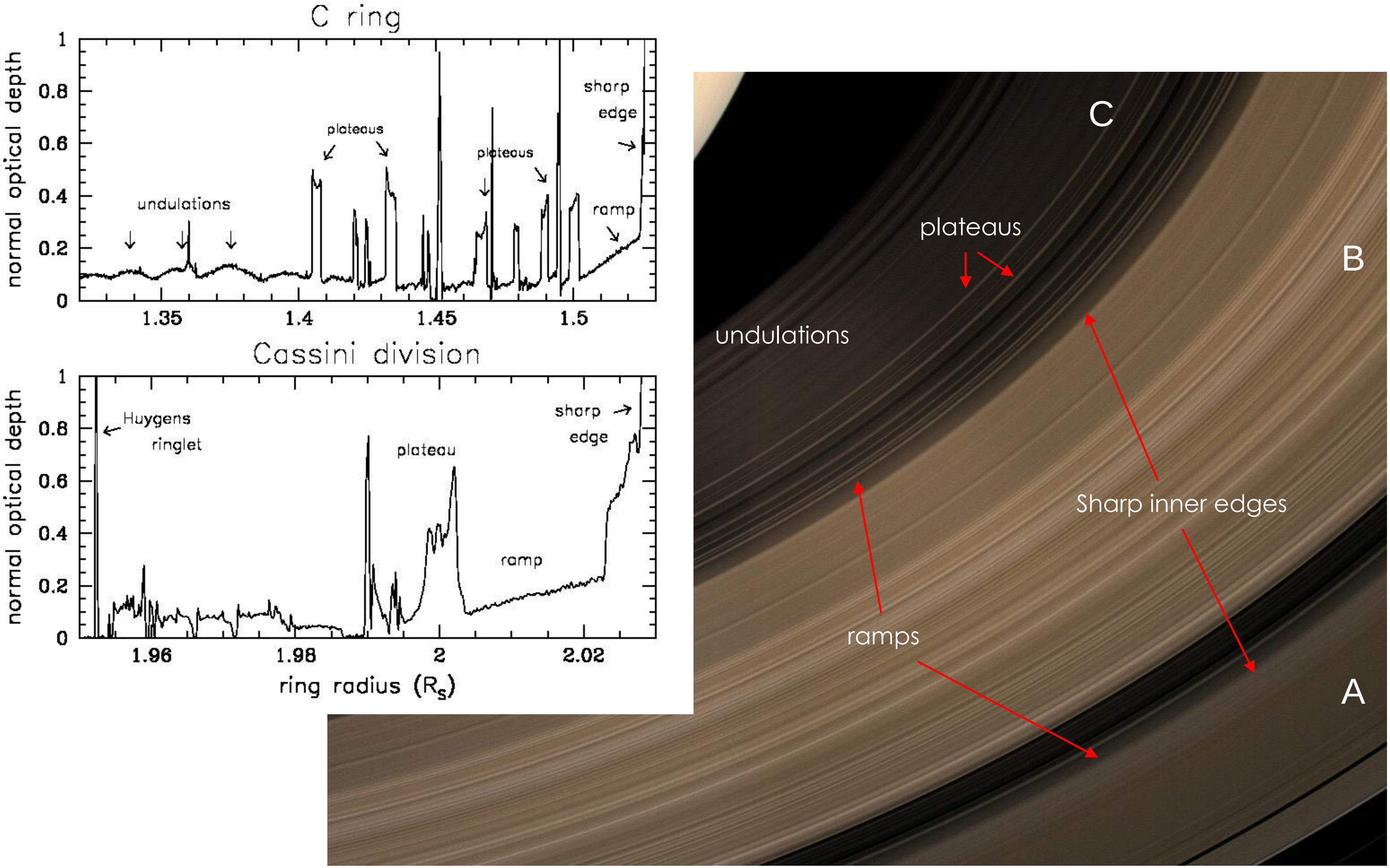
Ballistic Transport as a Process

- Rings have a “huge” ratio of area to mass.
- Particularly susceptible to effects of micro-meteoroid bombardment.
- Impacts produce a large amount of particulate ejecta.
  - Vast majority ejected at $\boldsymbol{v} \ll \boldsymbol{v}_{\mathrm{esc}}$.
  - Can have enormous yields $\boldsymbol{Y} \sim 10^3 - 10^6$



- Ejecta carry away both mass and angular momentum.
  - **Compositional Evolution**
  - **Structural Evolution**
- The process by which rings evolve subsequent to meteoroid bombardment is “Ballistic Transport” (Ip, 1983).

Structure due to BT?



Previous Studies with Ballistic Transport

- **Structural Evolution** (Durisen and colleagues,1989,1992,1996)
  - Found that BT could explain inner edges of A and B rings.
  - Similar ramp structures that connect to C ring and Cassini division.
  - Undulatory structure in inner B ring (and perhaps in C ring).
- **Compositional Evolution** (Doyle et al. 1989, Cuzzi and Estrada 1998)
  - High albedo in A and B rings inconsistent with old rings.
  - BT can explain C/CD versus A/B ring albedo and color dichotomy *and* form/shape of radial variation across B-C transition.
  - RT models suggested intrinsic material similar to “tholins”, with the extrinsic bombarding material neutral/dark in color.

Characteristics of the B-C ring boundary explained in similar time scale by both studies.

The Structural and Compositional Evolution Code

- Based on original structural code of Durisen et al. (1989), and “pollution transport” code of Cuzzi and Estrada (1998).
- Treats ring as *N* Lagrangian ringlets or annuli whose edges move due to drift velocities associated with BT, and viscosity .
- Main inputs: σ, τ, κ, a model for the viscosity ν, an impact ejecta distribution , the absorbing (non-icy) fraction of impactor f_{ext}, and a retention efficiency η.
    - Key quantities: *micrometeoroid impact flux* and *ejecta yield*.

- **Structure:** Calculates the net exchange of *mass* and *angular momentum* (both direct and indirect) between annuli over time.
- **Composition:** Calculates the changes in *mass fraction* of non-icy absorbing material due to direct and indirect (i.e. divergence) terms.
- Parallelized in radial bins.

Code Capabilities Moving Forward

- Prospects for Scientific Advancement:
  - Vastly improved data coverage.
    - 100's of occultations – help to constrain σ, τ, and κ.
    - Spectral: 8- and 15-color filter ISS, VIMS-IR, some UVIS spectral.
  - Parallelization helps to mitigate computational constraints.
    - Freedom to explore parameter space.
    - Updated viscosity models that account for the rings' wake structure (which also benefits from improved σ, τ, κ).
    - Input different ejecta distributions, and allow for radial variation.

- What we hope to help explain:
  - *Composition*: What are the rings' compositional constituents.
  - *Mass* – constrain ring surface density by matching observed brightness of features from a compositional standpoint.
  - *Age* – how long it takes to match observed features (transient and long-lived) compositionally and structurally.

The Gross Erosion Time

Fundamental time unit of BT is defined in terms of two key quantities: the impact yield *Y* and the impacting micrometeoroid flux $\dot{\boldsymbol{\sigma}}_{\mathrm{im}} \propto \dot{\boldsymbol{\sigma}}_{\infty}$

$$t_{\mathrm{G}} = \boldsymbol{\sigma} / \dot{\boldsymbol{\sigma}}_{\mathrm{ej}} \approx \boldsymbol{\sigma} / Y\dot{\boldsymbol{\sigma}}_{\mathrm{im}}$$

t_{G} is the time it would take for a ringlet of $\boldsymbol{\sigma}$ to completely erode away if no material returned. For all of our simulations we present here:

$$t_{\mathrm{G}} \approx 1.3 \times 10^{5} \left(\frac{10^{5}}{Y}\right) \left(\frac{4.5 \times 10^{-17}\,\mathrm{g\,cm^{-2}\,s^{-1}}}{\dot{\sigma}_{\mathrm{im}}}\right) \left(\frac{\sigma(\tau = 1)}{96\,\mathrm{g\,cm^{-2}}}\right) \text{ years}$$

Still remains poorly constrained – micrometeoroid flux $\dot{\boldsymbol{\sigma}}_{\infty}$

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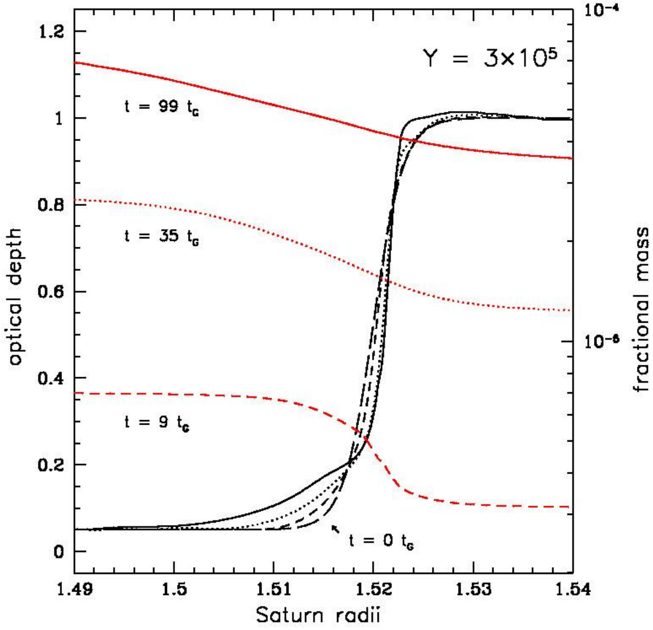
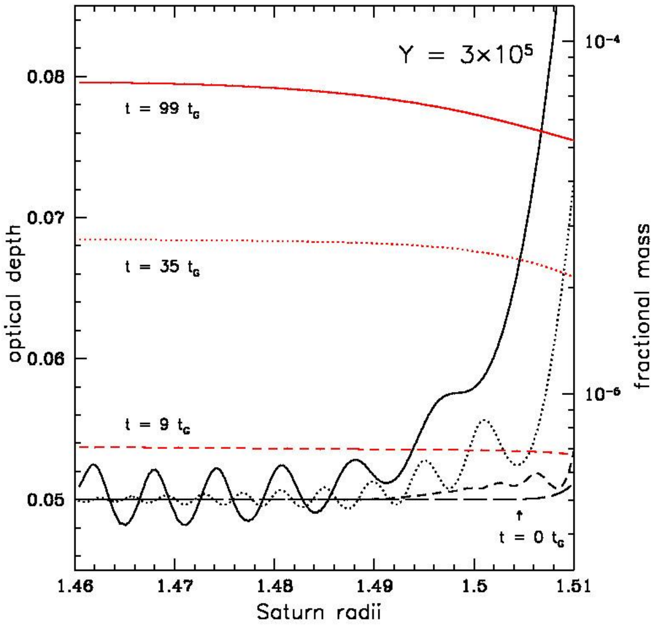
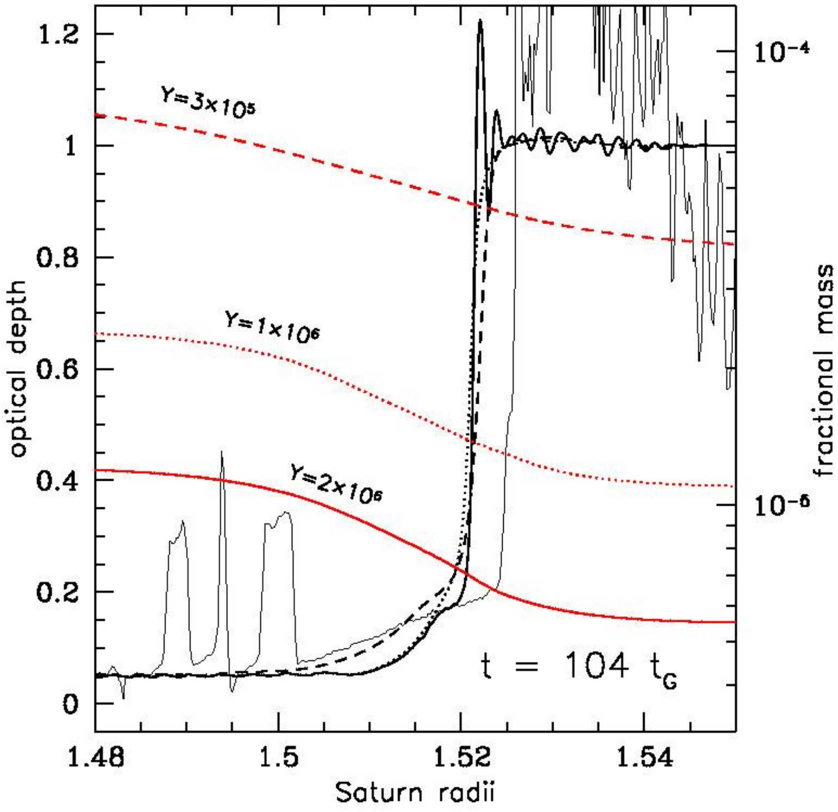
(Kempf et al., 2013, this meeting)

Sanity Check: Reproducing Results of Durisen et al. 1992







Constant opacity model - $\sigma \propto \tau$

BT sharpens and maintains inner B ring edge

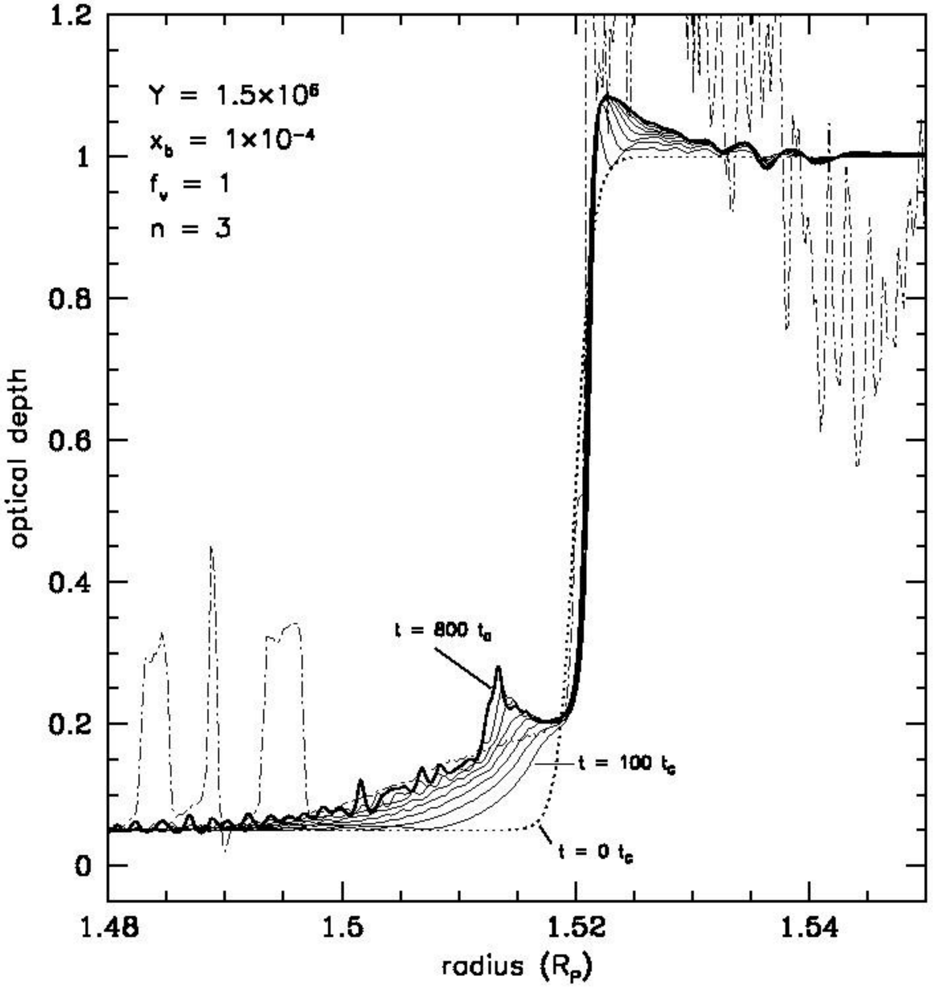
Long Term Evolution of Inner B ring Edge

Does BT in fact maintain the inner B ring edge over long time scales as implied by Durisen et al. (1992)?

- Sharpening of inner edge
  - balance between BT and viscosity.

- Inner B ring undulations
  - approaching steady-state.

- Ramp formation:
  - due to advection, not viscosity.
  - Has roughly the correct slope, but a lot of structure.
  - “Hump” may be due to BTI*



Voyager PPS imaging τ

* Ballistic transport instability (Durisen 1995; Latter et al., 2012; 2014a,b)

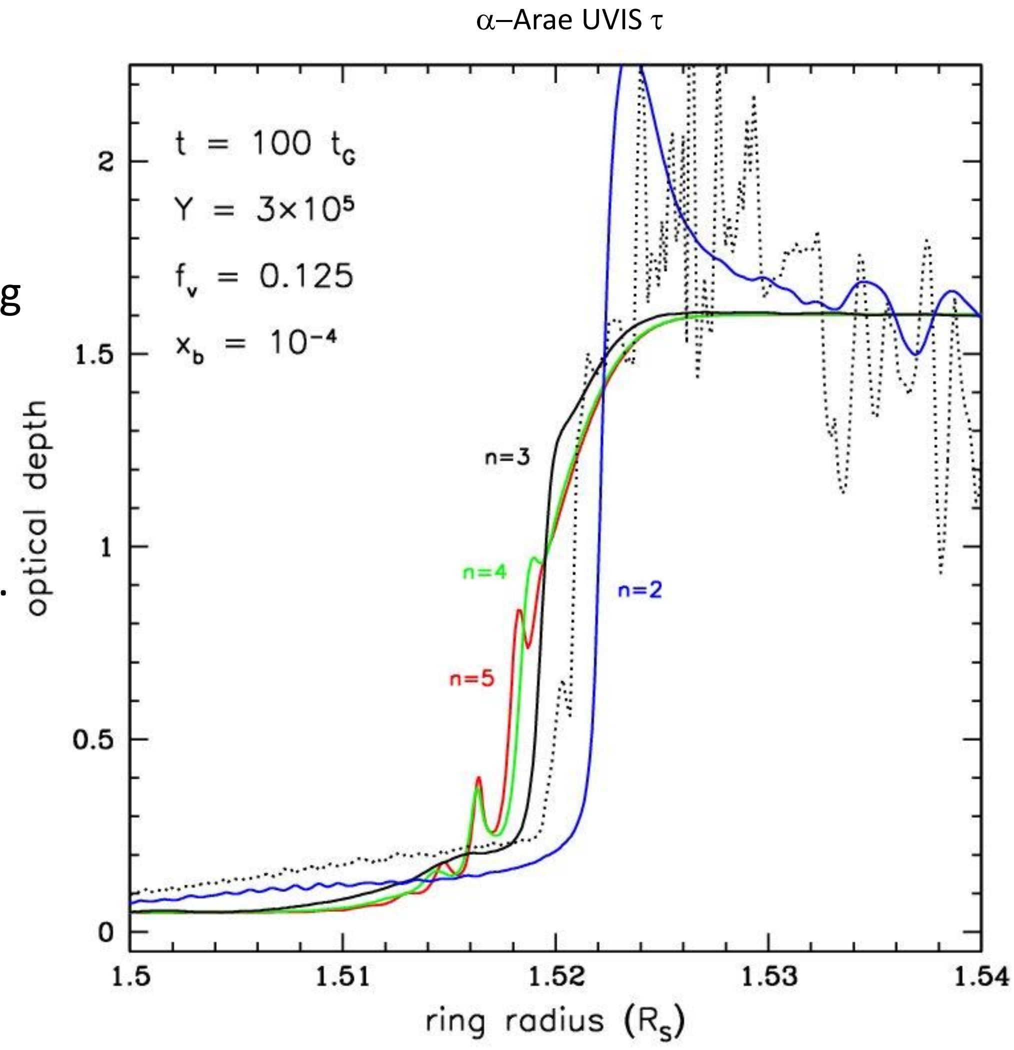
Steepness of the Ejecta Velocity Distribution

We have assumed the ejecta velocity distribution is described by a power law with index *n* = 3.

- Higher *n* values lead to gradual "spilling over" of material.
  - steeper *n* concentrates more material at smallest *x*'s.

- For higher *n* values, a "notch" appears.
  - Likely due to BTI.

- Lower *n* leads to larger and better formed ramp.
  - More ejecta at intermediate and higher *x*'s.
  - No "hump".



α–Arae UVIS τ

Strongly suggests the ejecta distribution is much more complex than what we model here.

Models for Ring Opacity: Motivation

- Cuzzi and Estrada (1998) required an opacity profile to explain the detailed shape of ring color profiles.
  - Utilized variance technique of Showalter and Nicholson (1990) to determine "largest effective particle" size.

- Heuristic model opacity in which $\boldsymbol{\kappa} \propto 1/\boldsymbol{\tau}$ that fits the CE98 opacity model range.
  - Allows us to associate certain $\boldsymbol{\tau}$ with a specific $\boldsymbol{\sigma}$.
  - Plateaus more massive, less sensitive to effects of BT.

- UVIS occultation data seems to indicate that the auto-correlation length in the C ring plateaus implies (Colwell et al., 2011: 2012):
  - Particles *smaller* in plateaus, not larger, than outside plateaus.
  - Opacity is *higher*, not lower there.

- Direct inversion of scattered Cassini RSS signal (Marouf et al. 2012):
  - Largest particles are much *larger* in plateaus than outside.
  - Narrower size distribution in plateaus.

Alternative is that viscosity is much higher in plateaus?

Effect of Kinematic Viscosity in Maintaining Structure

Models here use different values of the ejecta yield Y and the magnitude of the kinematic ν such that $Y/f_\nu = 10^5$.

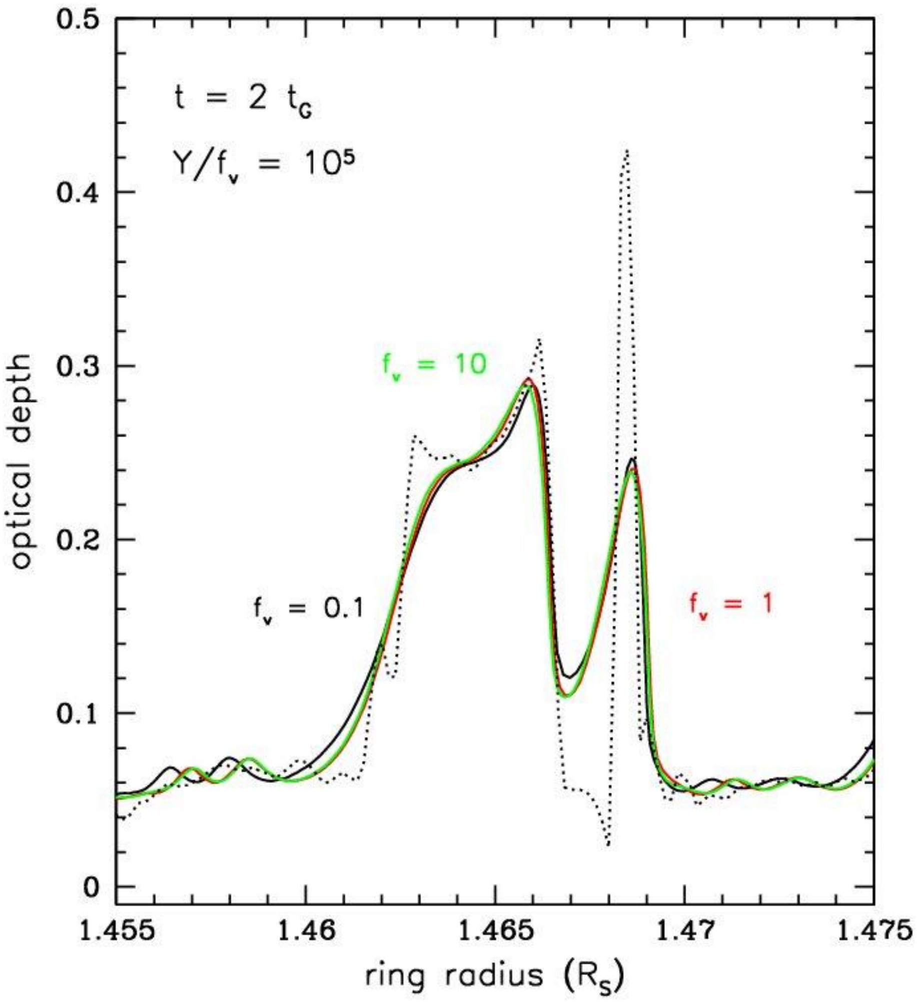
- Bulk of optical depth may be due to sizes different from fiducial ($f_\nu = 1$).

- Accounts for size distributions may be broader or narrower than we assume.

- A clear degree of scaling exists between these parameters (similar to that demonstrated by Durisen et al. 1992).

- In fact, because time variation effectively depends on t_G/t_ν, also scales with $\dot{\sigma}_\infty$.

Dotted curve: α–Arae UVIS τ



Inner edge stability requires a retrograde ejecta distribution

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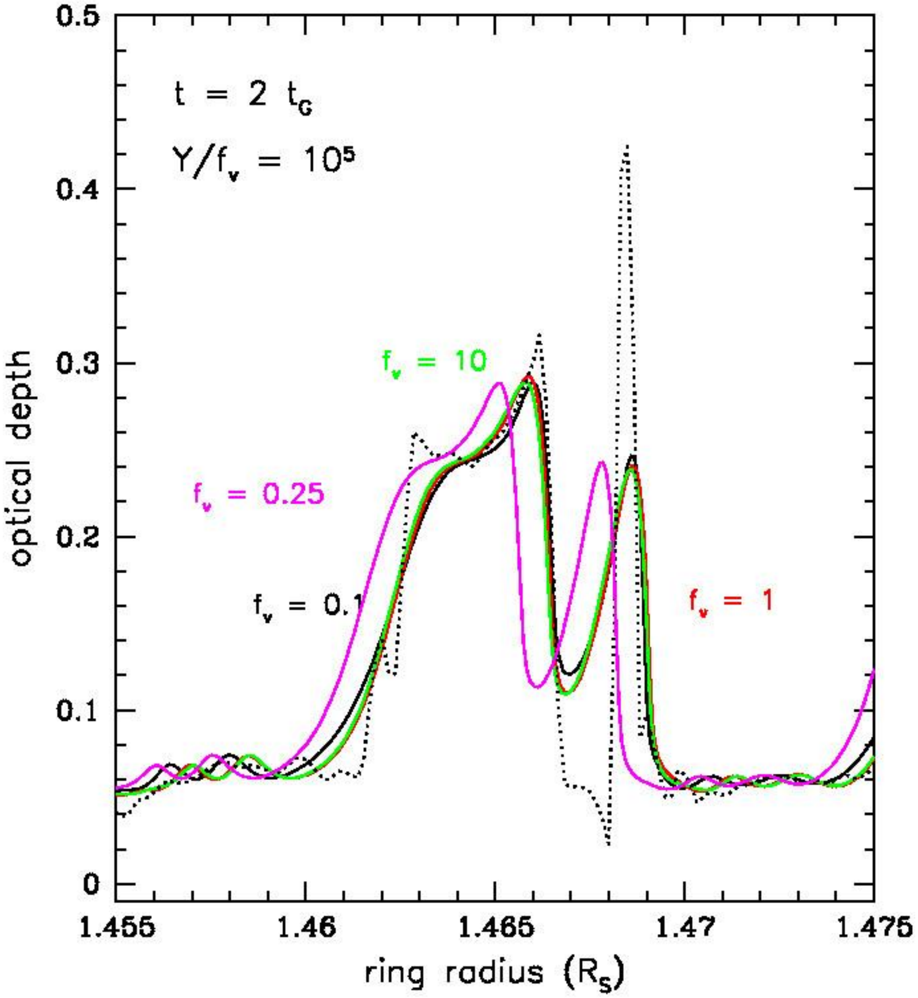

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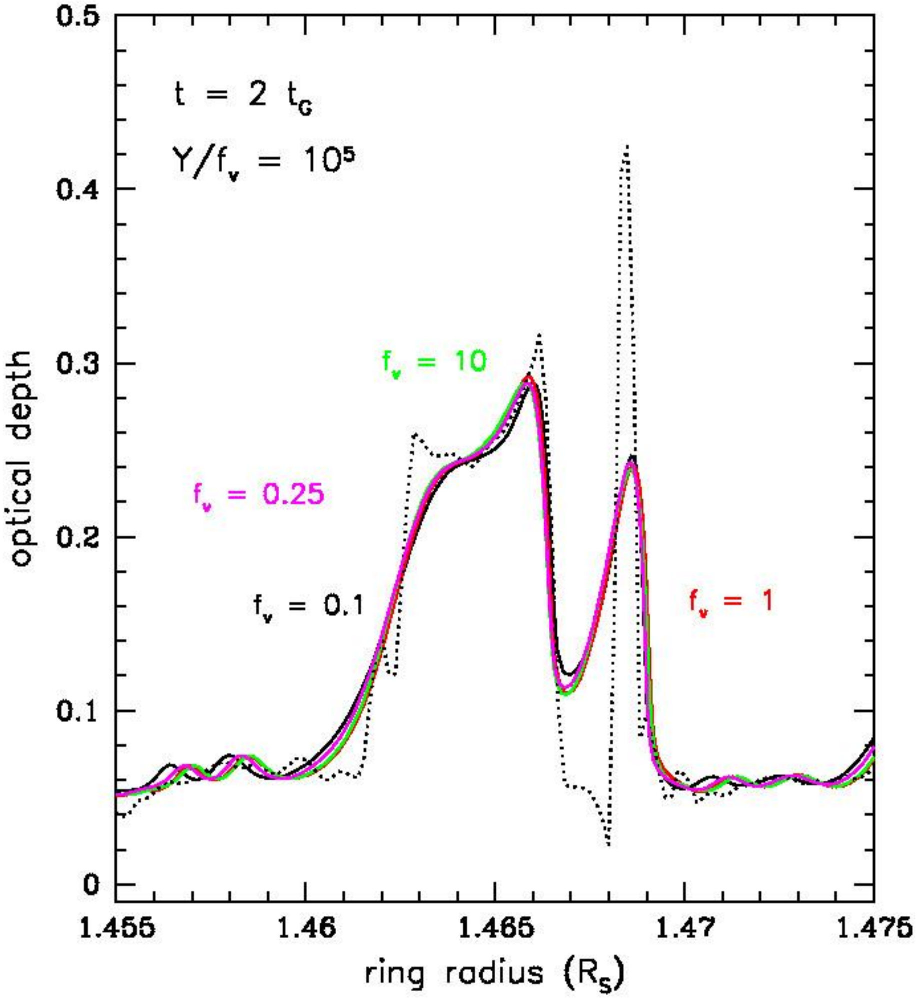

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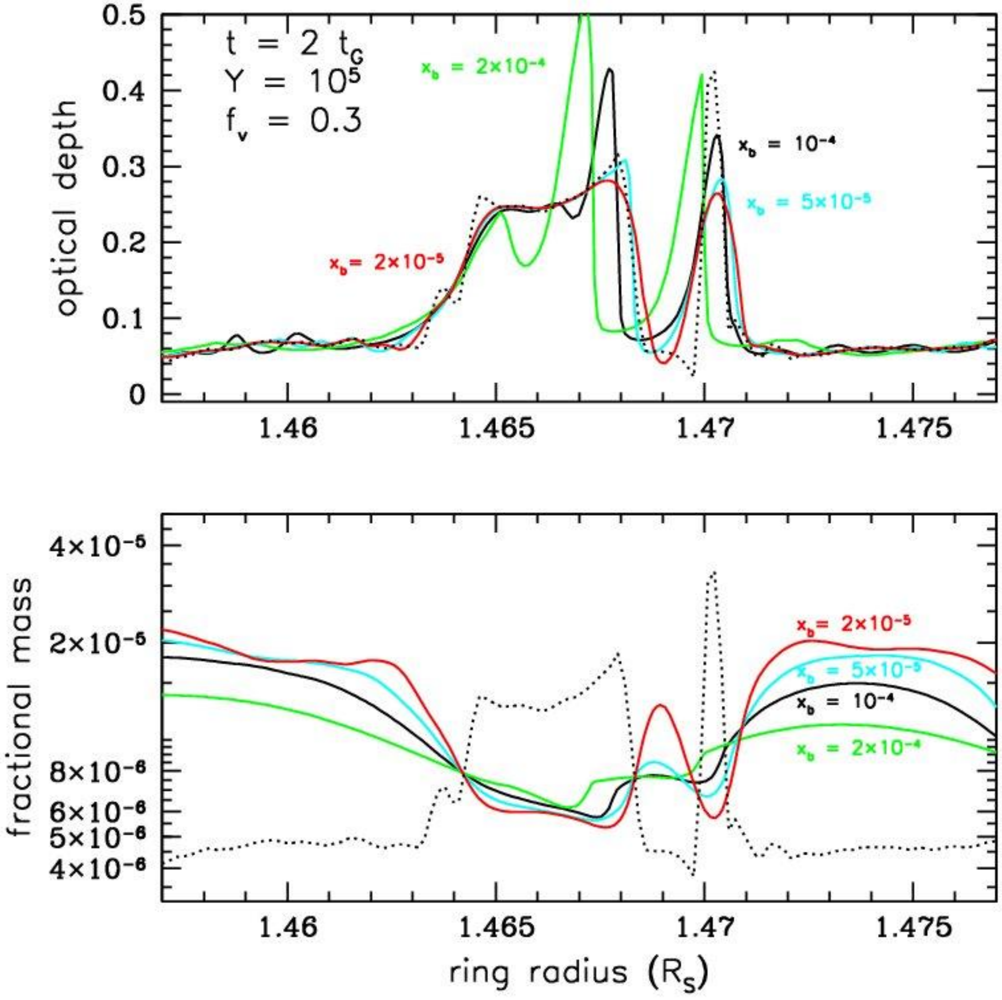
Varying the Ejecta Velocity Lower Bound x_b

Exploring the sensitivity of the structural and compositional evolution to choice of x_b for $n = 3$. Fiducial range is 2–100 m/s.

- Structure:
  - Lowering x_b has a similar "softening" effect as increasing ν.
  - Amplitude of edge, structure in plateau decreases with smaller x_b.
  - Slope of outer edge similar, but edge at different locations.

- Composition:
  - Pollution transport more localized for smaller x_b – plateaus may retain their compositional identity longer.
  - May be very important distinction for age dating young/transient features.



Conclusions

- We have confirmed that the inner B (and presumably A) ring edge, as well as ramp formation are due to BT.
- By varying the steepness of the ejecta velocity distribution, we have found that:
  - For higher *n*, notches appear as well as a gradual spillover of material from the edge as seen in some data.
  - For lower *n*, the ramp is linear (as predicted by Durisen et al. 1992) and well formed.

- We have seen structural growth that is likely due to BTI (humps and notches), but under very non-uniform conditions. BTI is clearly active in the rings in some capacity. This warrants further study.
- C ring plateau stability requires:
  - More mass in the plateaus than is predicted by constant κ.
  - Higher ν in the plateaus relative to outside plateaus for given τ.
  - ***Retrograde*** component of ejecta distribution.

Future work

- Challenge moving forward is to constrain the microphysics within the rings in order to understand how all the various effects of BT can be present at the same time.
  - e.g., C ring plateaus vs. ramp and inner B ring?

- Preliminary calculations highlight sensitivity to particle properties.
  - e.g., particle properties different inside and outside plateaus?
  - Needed to better constrain ν, Y and the ejecta distribution.

- Given sensitivity to the variation of κ, ν, Y and the form of the ejecta distribution, need to abandon the simplistic view that these properties are the same across the rings.
  - Inner B ring edge probably requires multiple ejecta distributions with different n-values at different τ's and x-values, and with both prograde and retrograde symmetries.
  - Retrograde ejecta distributions most likely play a significant role in evolving *local* ring structure.

Summary

- Prospects for significant advancement are good thanks to improvements in computational ability and new data.
- Modeling structural and compositional changes in tandem allows us to help constrain a wide array of problems, e.g.
  - C ring unexplained features, its evolution and age.
  - B ring mass and ultimately ring age.
  - Fine scale structure.
  - Similarities and differences between B and A ring inner edges.
- Evolution of the mass fractions of the various non-icy constituents can be used in radiative transfer models to constrain composition and its variation throughout the rings.
- Will continue to benefit from improvements in our understanding of key physical quantities obtained from continuing Cassini data analysis.

Plateaus with Larger Viscosity?