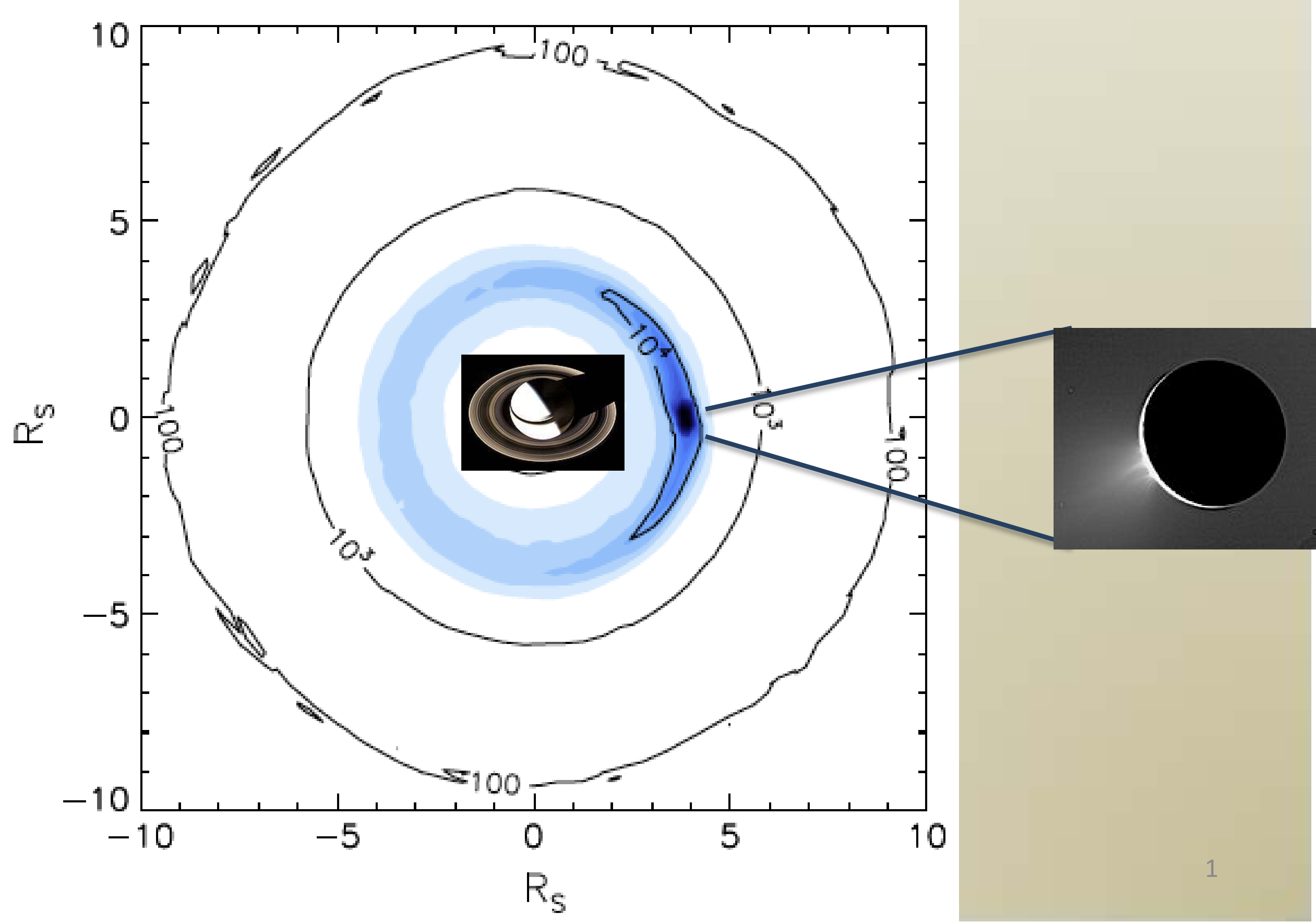
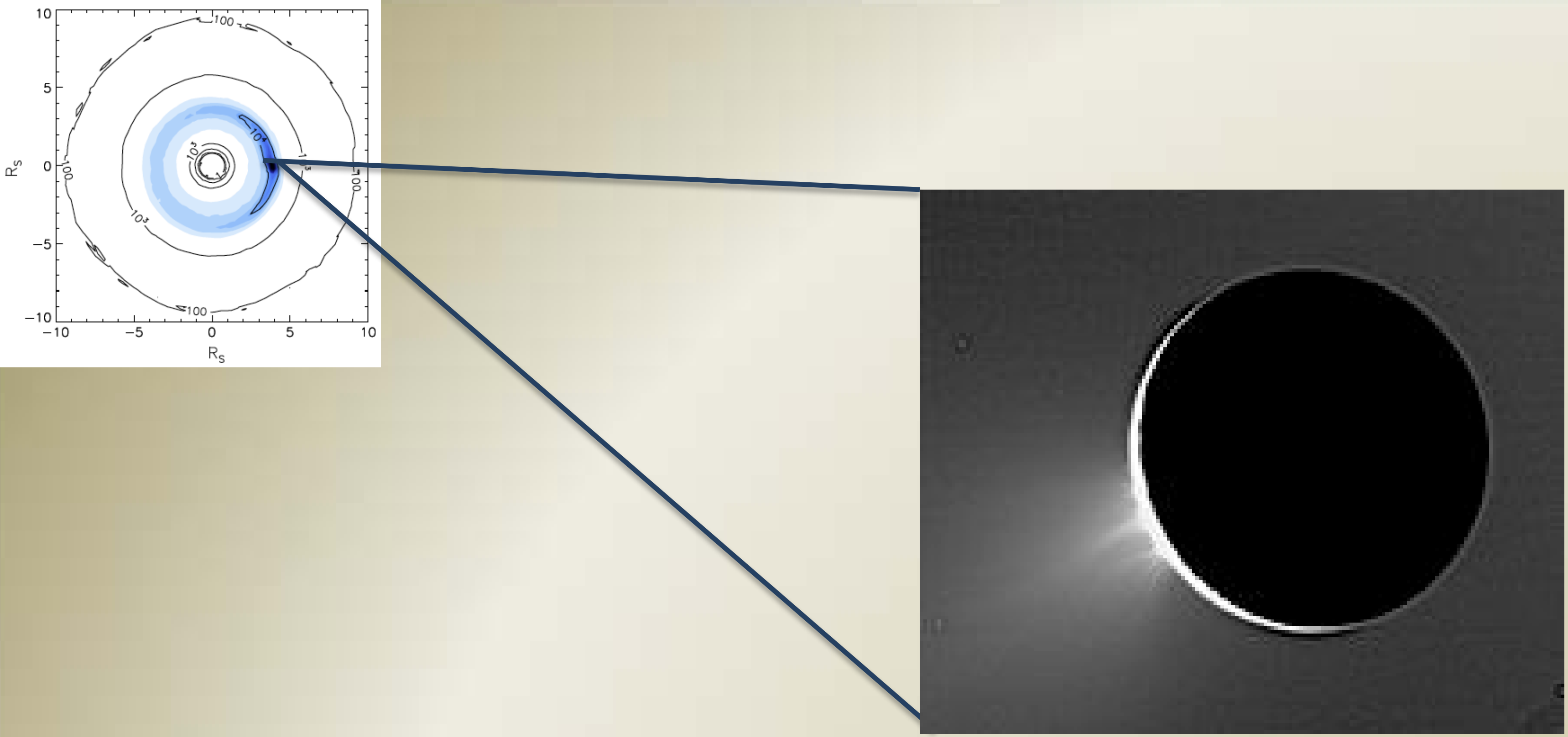
The Enceladus Torus: Saturn’s Vaporous Ring

T. A. Cassidy



Top-down view of water vapor ejected from Enceladus

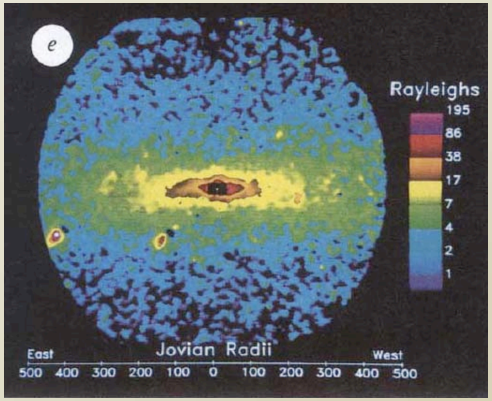


Initial torus formation is simple enough: Enceladus' high-speed jets (Hansen et al., 2008) eject water vapor with escape speed, into Saturn orbit. (similar to how E-ring is formed)

Most of this talk will be about what happens to the vapor as it orbits Saturn.

Enceladus’ torus is one of several in the solar system

- Io torus: mostly ionized, a “plasma torus” made of S and O ions.



Neutral Na orbiting Jupiter

- Europa: indirectly detected H/H_2 torus
- H in the Saturn system, some of it from Titan

Outline of talk:

- History of the Enceladus torus

- New modeling results and a comparison to data

  Our explanation for why the torus is so broad

- Comparison to Saturn’s solid rings

  Why are they so confined and orderly?

- Implications for whole Saturn system

  torus material ends up everywhere

Discovered in early 90’s:

This was actually the second torus discovered in the Saturn system. Broadfoot et al. (1981) discovered the Titan H torus…which turned out not to be a torus at all:

Shemansky et al. (1985) showed that the H came from Saturn’s upper atmosphere.

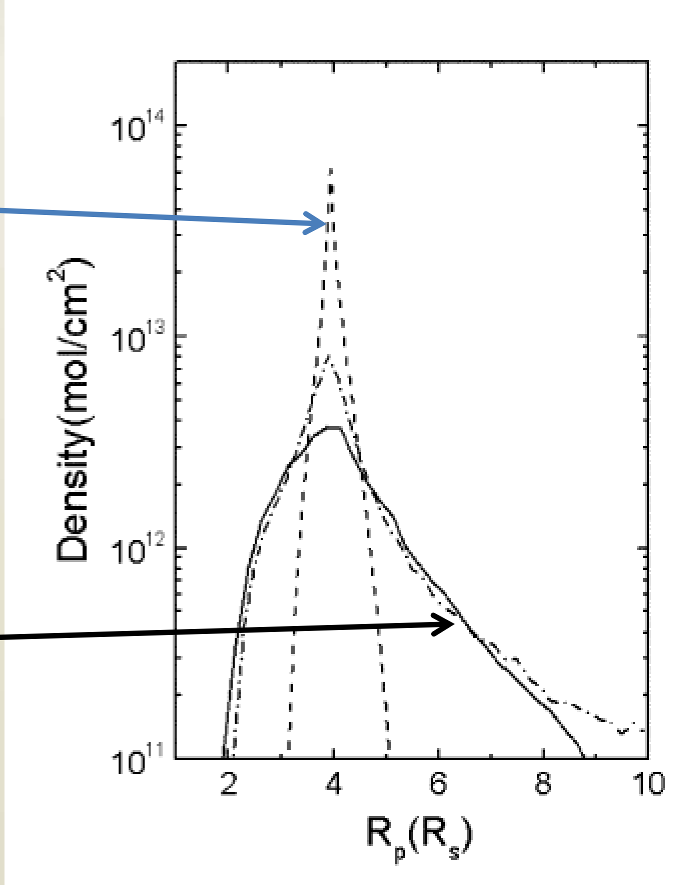
Shemansky and Hall (1992) predicted that there should be large quantities of neutrals to explain the unexpectedly cold electrons in Saturn’s magnetosphere.

OH (along with H_2O and O) were the probable neutrals, based on the likely presence of freshly-produced water ions. Shemansky et al. (1993) discovered OH orbiting Saturn in 1993.

Subsequent modeling

H_2O ejected from Enceladus forms narrow torus

Observed OH (HST, 1992-1996) Assumed to come from H_2O



Johnson et al. (2006)

requires spreading

The two spreading processes

Thought to be the only important spreading processes as of 2007

1) Dissociation:

(included in previous models)

UV photons (and electrons) split H_2O

$\mathbf{H_2O} + \nu \rightarrow H + \mathbf{OH} + K.E.$

$\mathbf{OH} + \nu \rightarrow H + \mathbf{O} + K.E.$

This produces the **OH** and **O** from H_2O

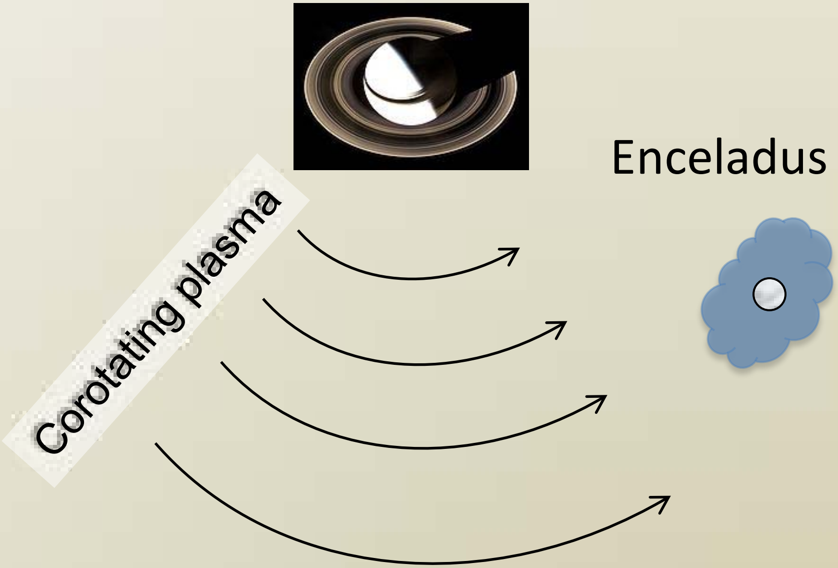
2) Charge exchange:

(included in previous models)

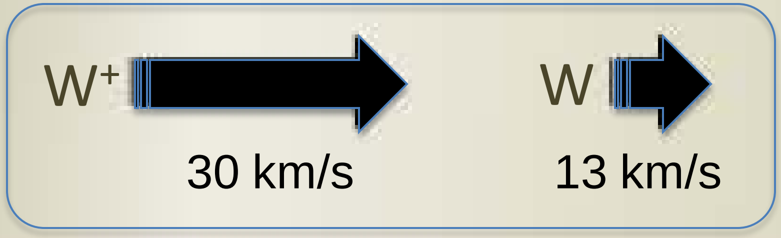
Fast-moving ion is neutralized (and thus freed from the magnetic field)

$W + W^+ \rightarrow W^+ + W$

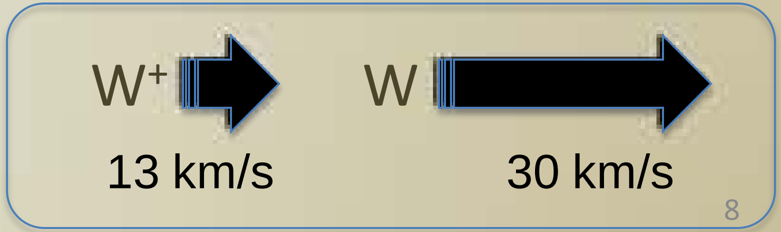
Also: ion/neutral collisions without charge exchange



Before charge exchange

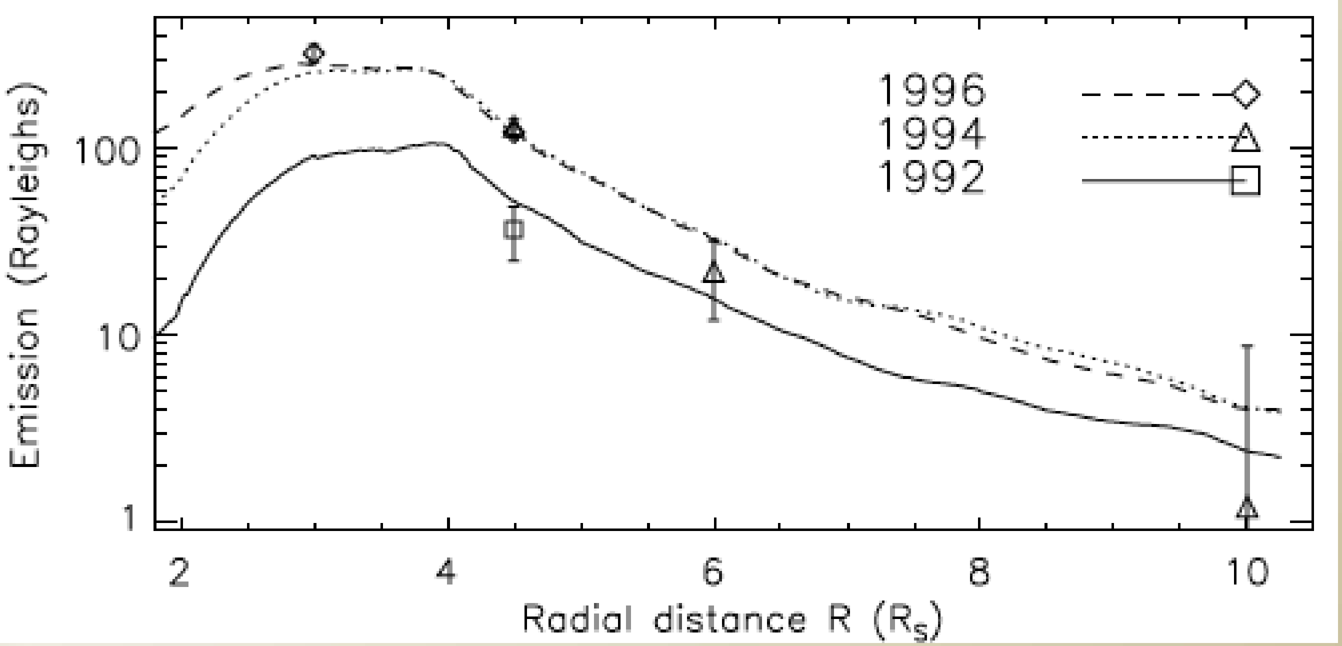


After



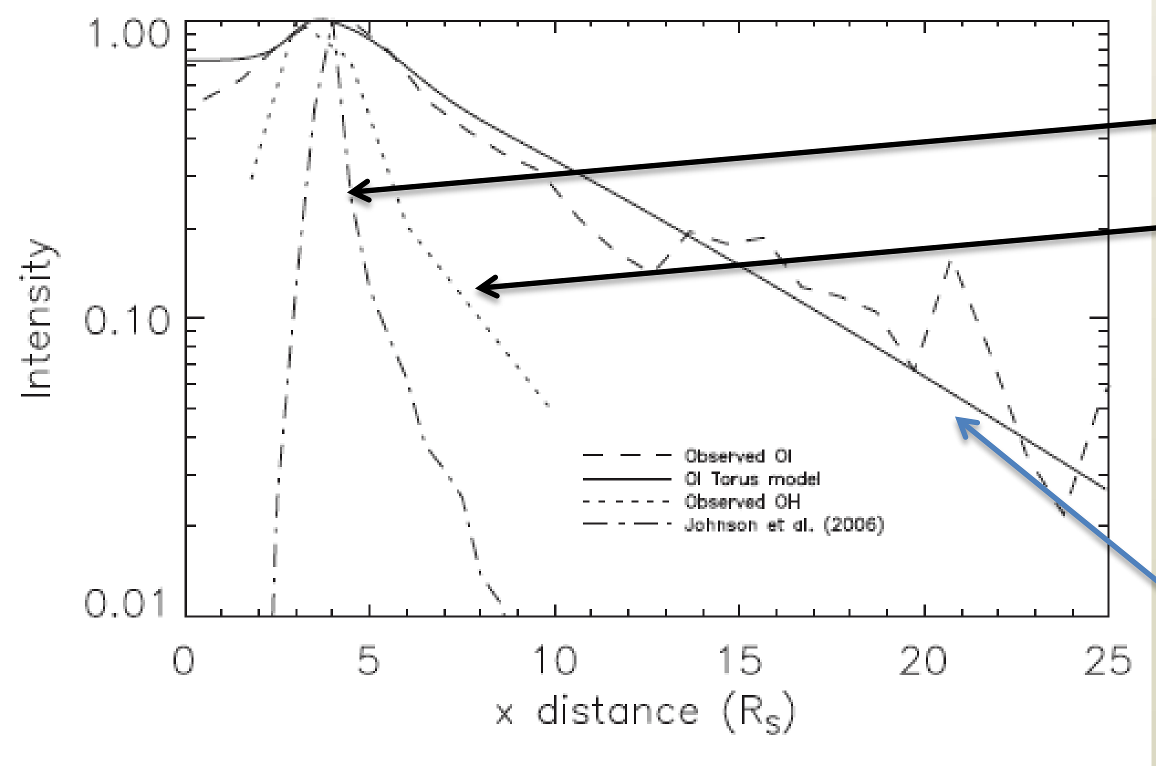
Problem solved

Models (Jurac et al., Johnson et al.) seemed to explain the data. Jurac et al. even estimated the source rate (~10^{28} s^{-1}) that agreed with later Cassini measurements.



Jurac and Richardson, 2005

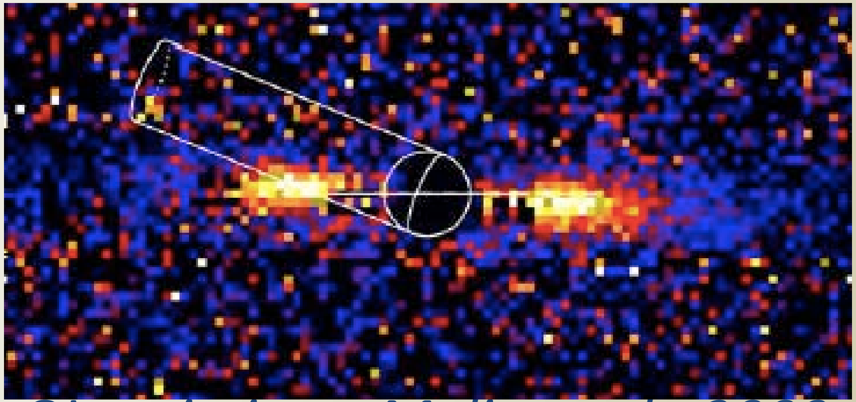
But the cloud is broader than we thought (2009):



OH, previous interpretation

Revised OH, based on careful treatment of fluorescence

Even broader O cloud (Cassini UVIS)

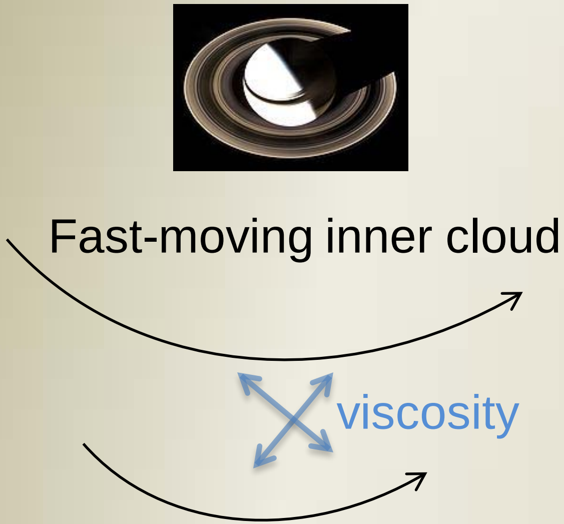


OI *emissions, Melin et al., 2009*

Luckily, Farmer (2009) proposed another spreading process:

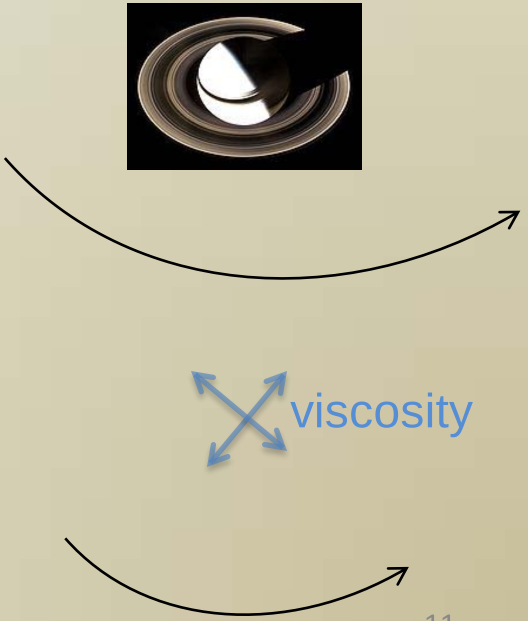
Neutral/neutral collisions:
Other modelers had underestimated the collision cross sections

Collisions between molecules provides viscosity:

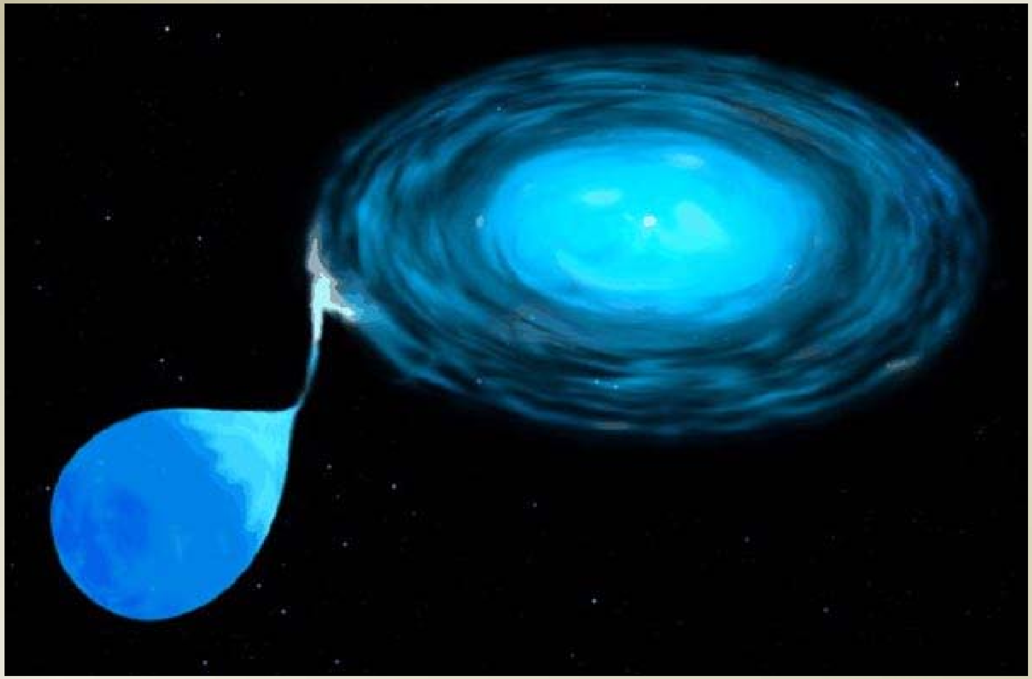


Slow-moving outer cloud

Viscosity transfers momentum:
Outer cloud speeds up and inner cloud slows down



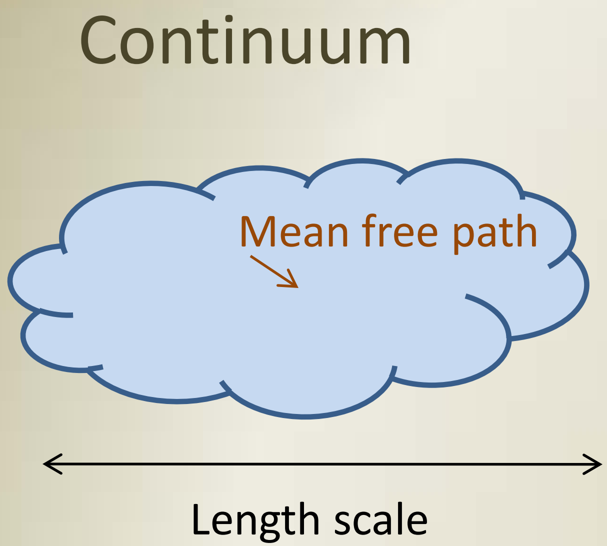
The result is analogous to an astrophysical accretion disk:

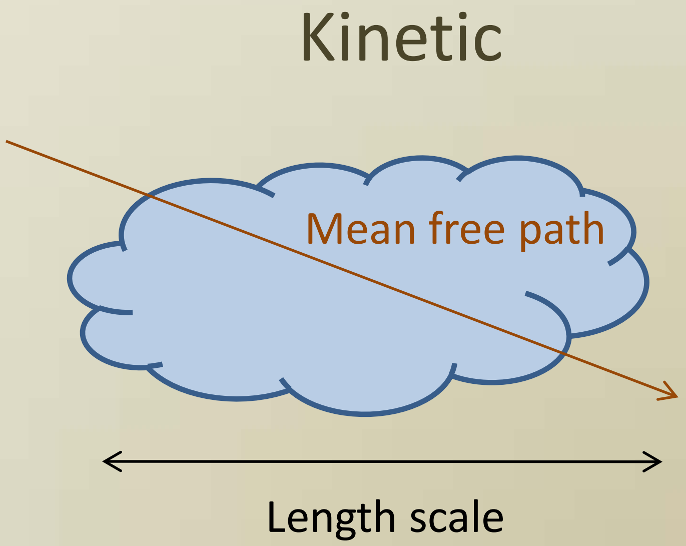


most of the cloud moves inward, but to do this, it needs to lose angular momentum. This angular momentum is *transported outwards* by expelling a fraction of the gas outward with high energy, producing the extended neutral torus.

But collisions are extremely rare
(~1 per orbit)

And Farmer treated the torus a fluid





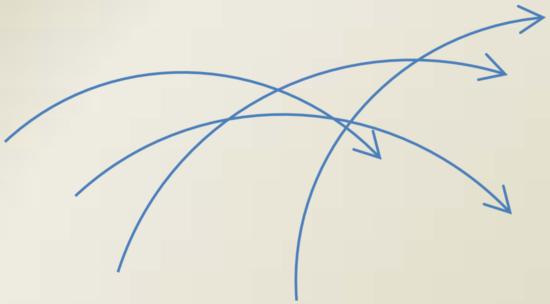
We needed a “kinetic” model

We used a DSMC model:
Direct **S**imulation **M**onte **C**arlo

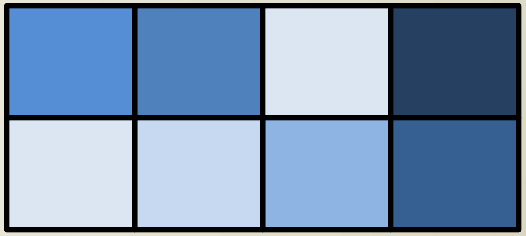
Direct Simulation: means that we model the gas as a collection of molecules, rather than a fluid.

Instead of fluid properties, like viscosity or heat conductivity, DSMC requires molecular collision details.

Eject “test particles” and follow their trajectories under the influence of Saturn’s gravity



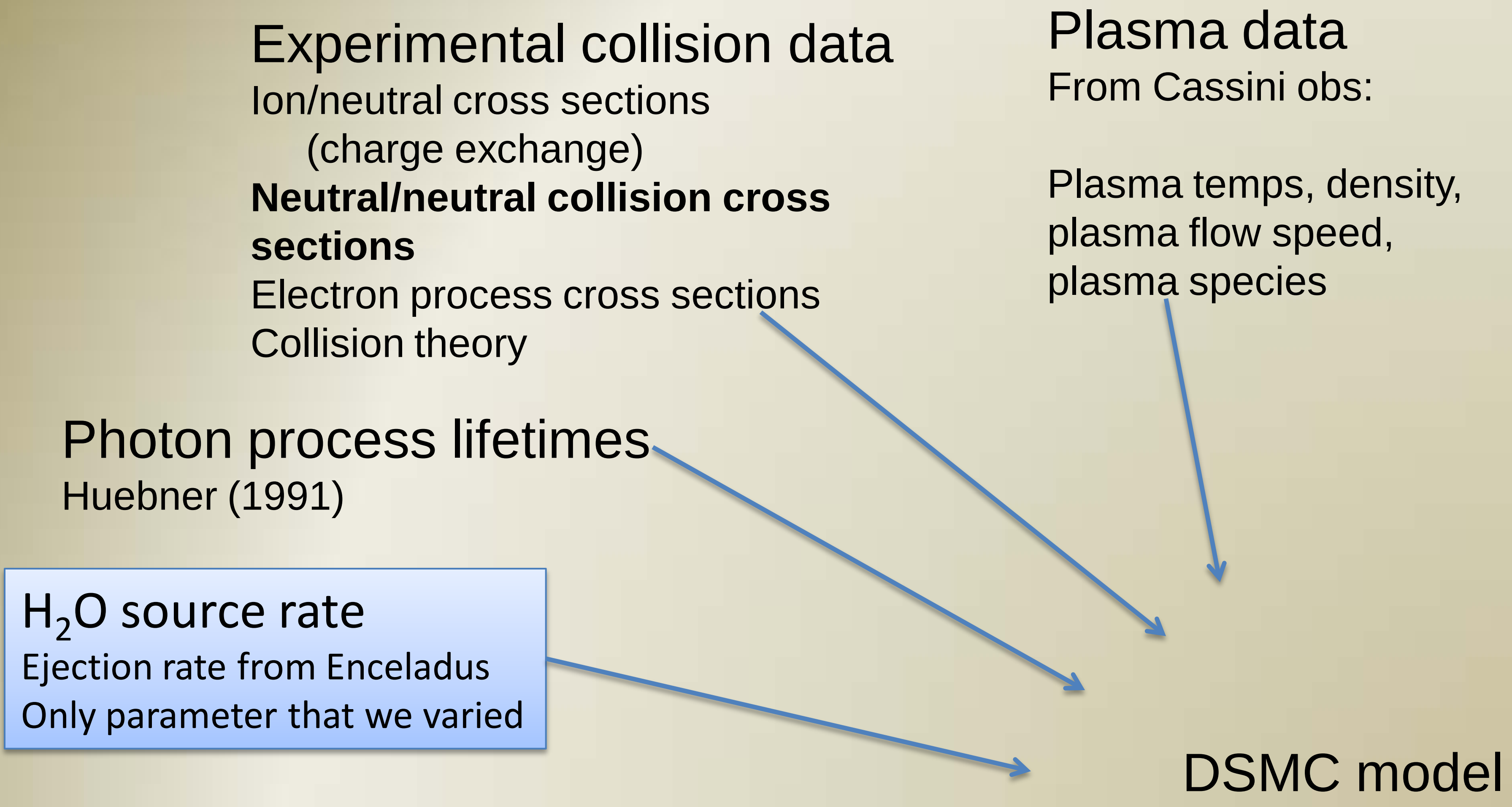
Calculate densities from trajectories



Use densities to calculate collision probabilities

Iterate

We combined these three processes in a model:



Experimental collision data

Ion/neutral cross sections
(charge exchange)
Neutral/neutral collision cross sections
Electron process cross sections
Collision theory

Plasma data

From Cassini obs:

Plasma temps, density,
plasma flow speed,
plasma species

Photon process lifetimes

Huebner (1991)

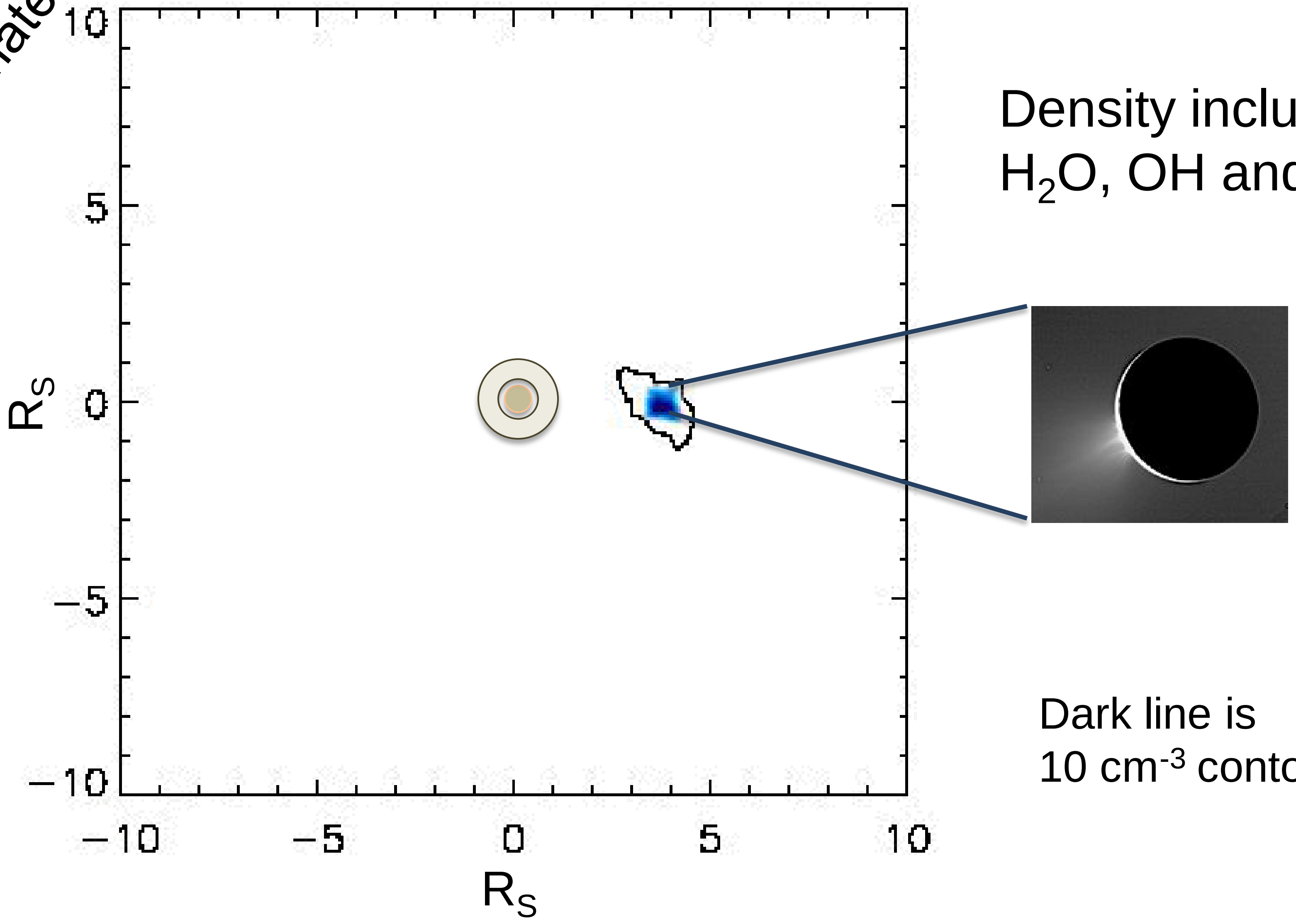
H_2O source rate

Ejection rate from Enceladus
Only parameter that we varied

DSMC model

Modeled Equatorial Density

Animated .gif

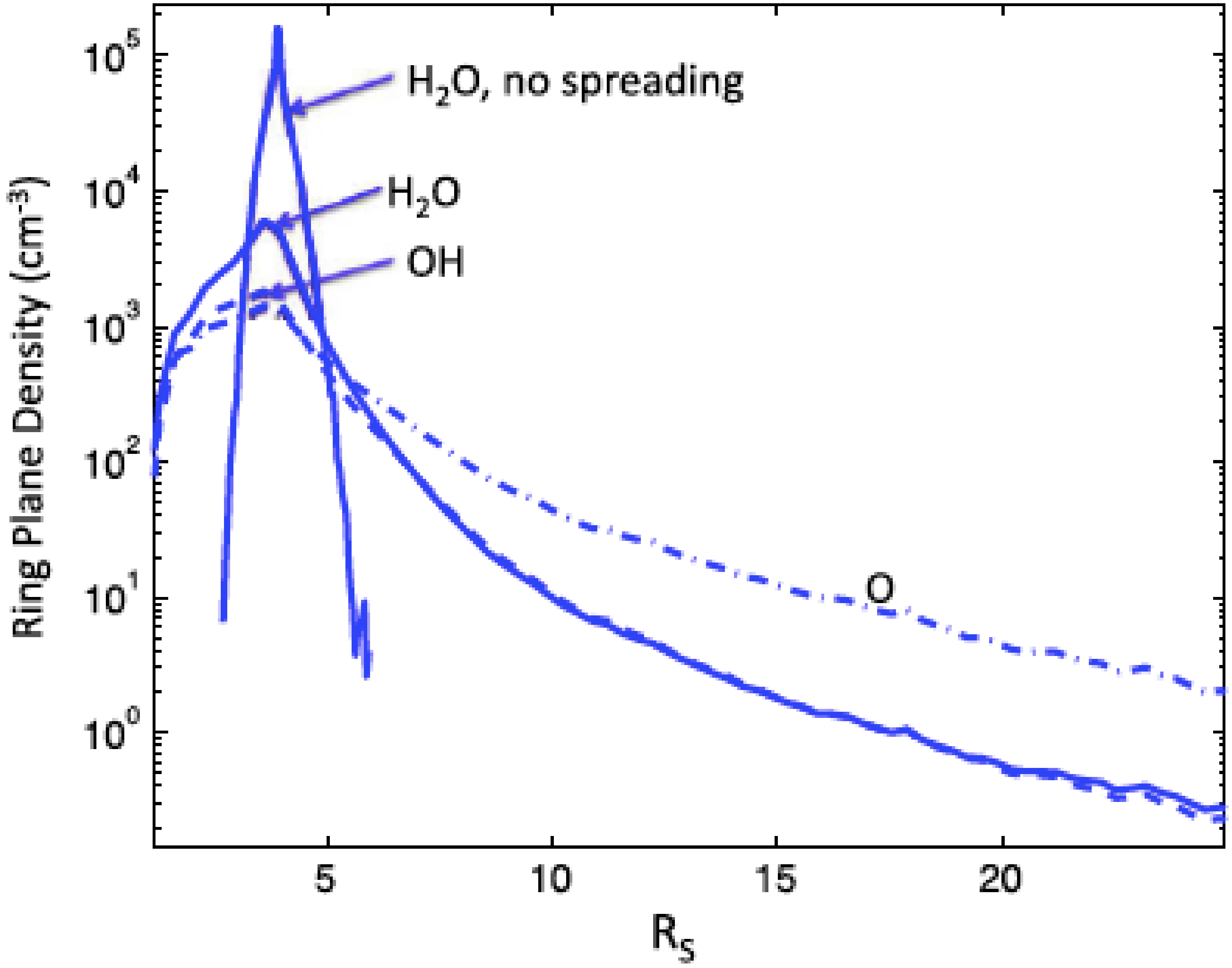


Density includes H_2O, OH and O

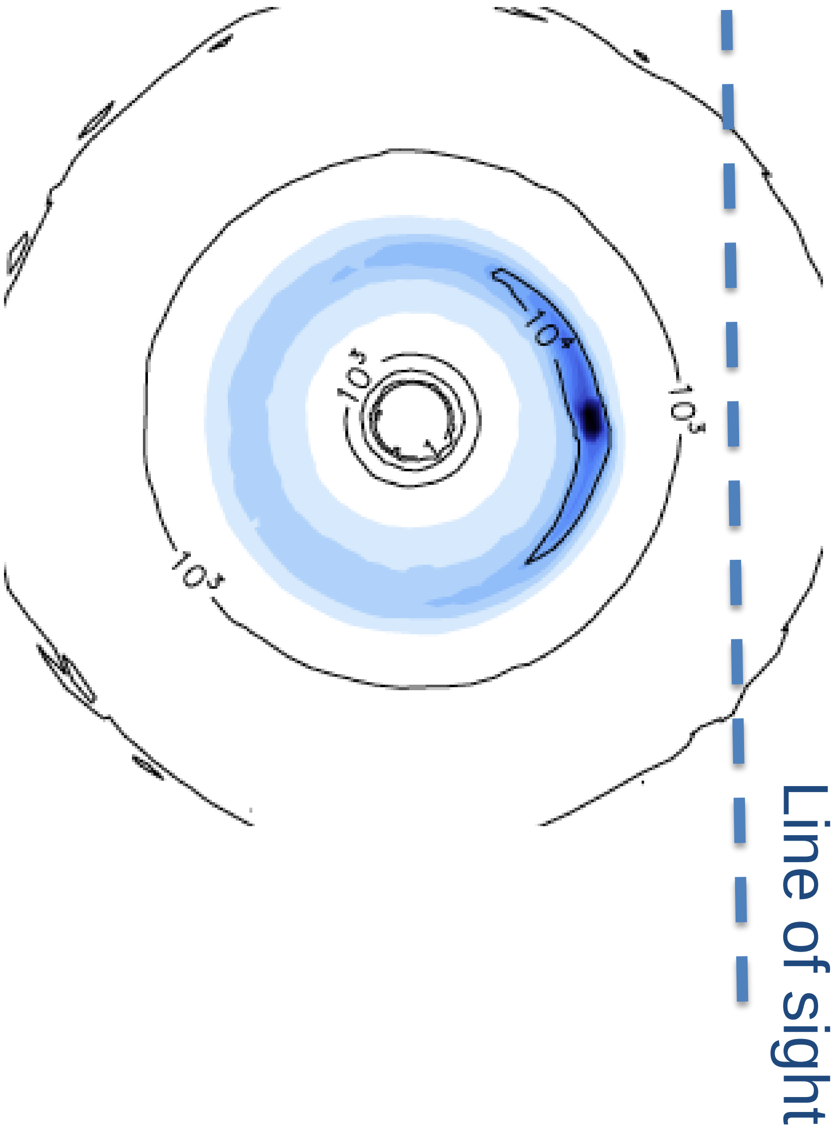
Dark line is 10 cm^{-3} contour

~3 months modeled time

Model Results



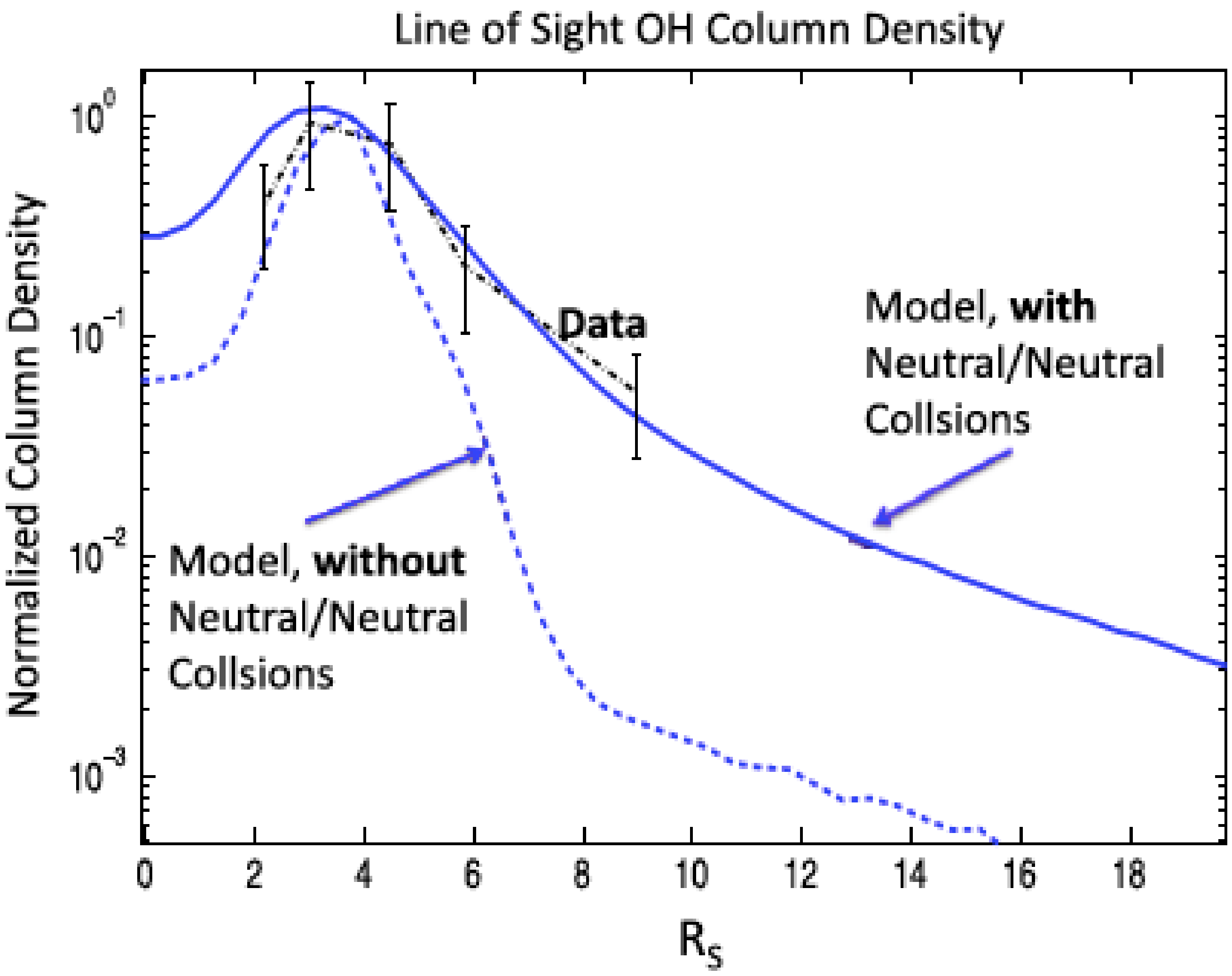
Compare results with Melin et al. (2009)



O and OH observed via fluorescence of solar UV light

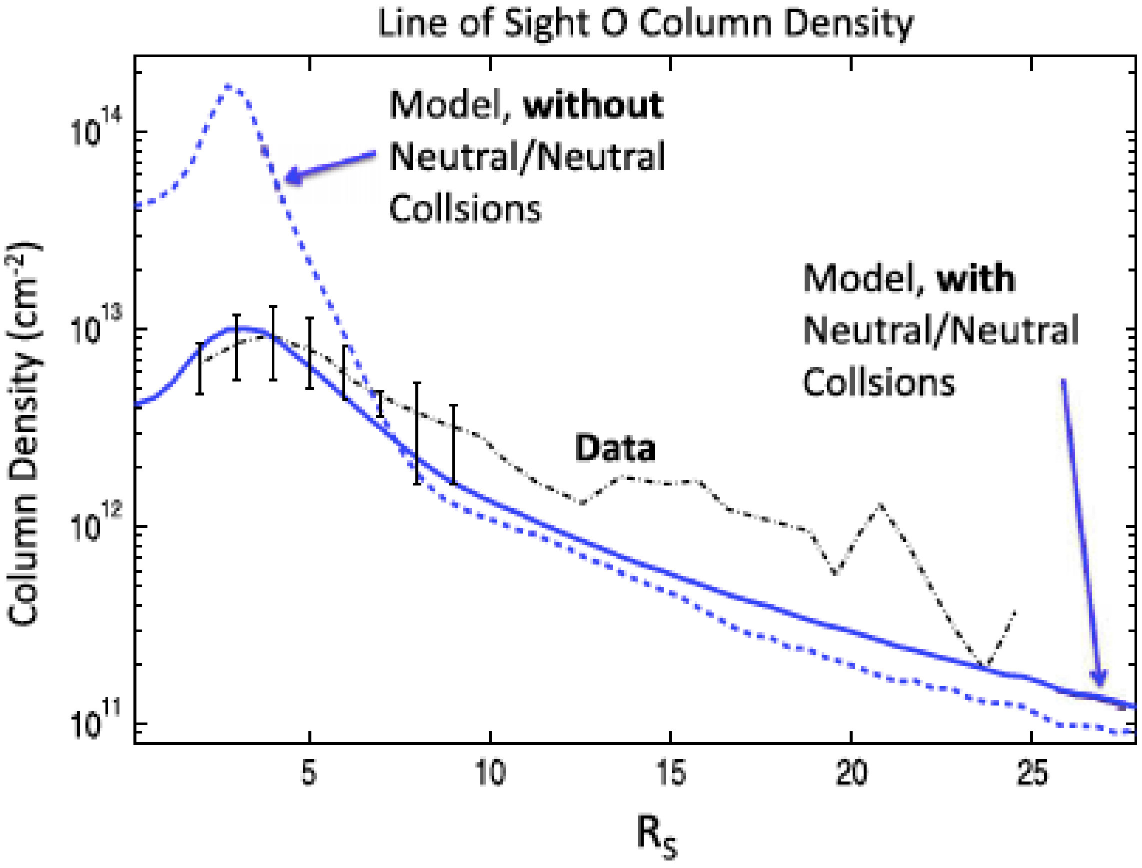
O: 130.4 nm
OH: ~308.5 nm

OH
Measured by HST
Observations from the early to mid 90s



Atomic O
Measured by Cassini UVIS

UVIS can't measure the OH, unfortunately

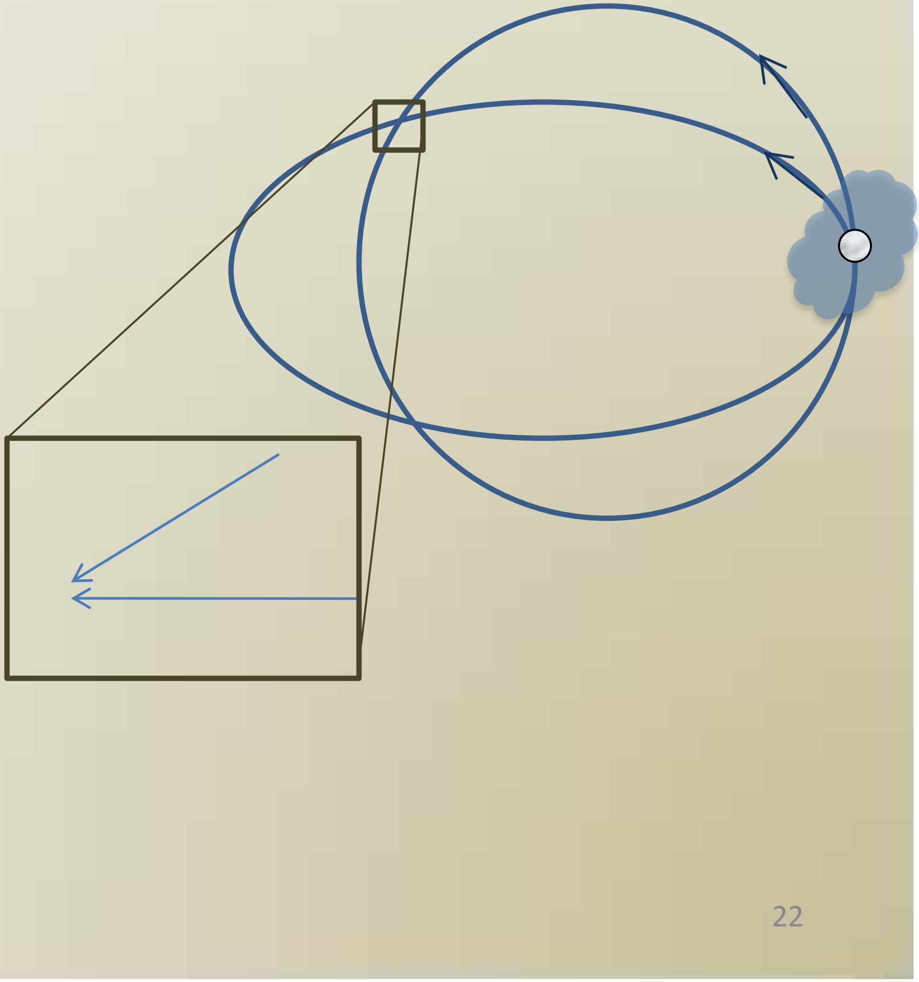


Conclusion: our one free parameter is the H_2O source rate. We found that we need about 10^{28} H_2O s^{-1}.

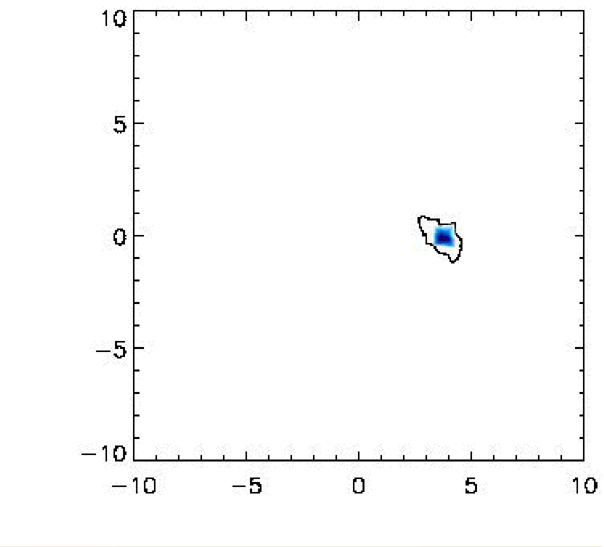
How can collisions in a sparse, cold gas spread the cloud?

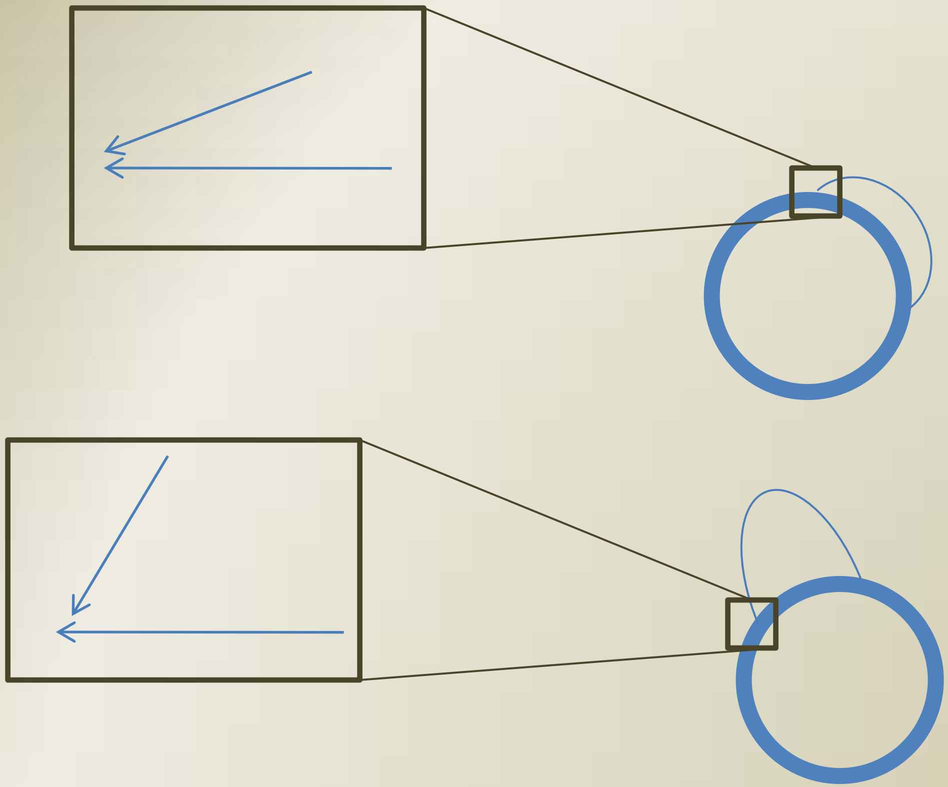
Molecules start with *slight* variety of eccentricities and inclinations—results in particles with nearly identical orbital speeds travelling in slightly different directions.

Results in high relative velocity ~eccentricity x circular orbit speed



As the simulation continues, eccentricity increases, which increases relative speeds



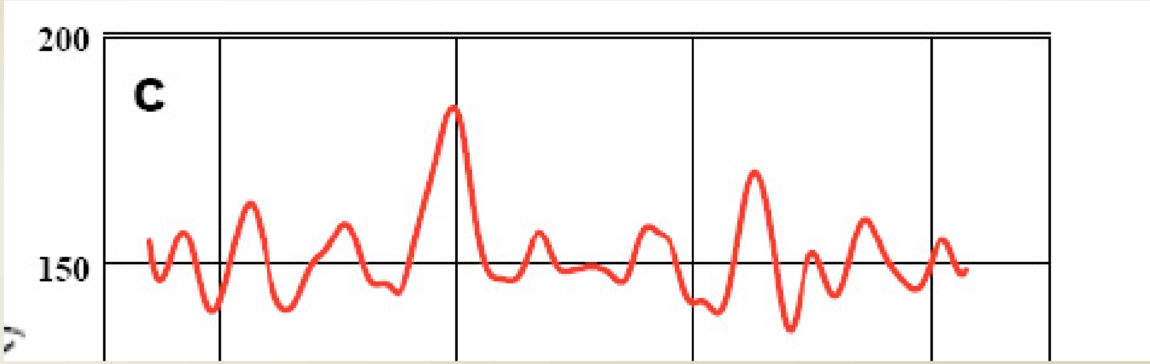


Most of the collisions happen near Enceladus’ orbit, the thickest part of the cloud. This is completely different than the fluid viscous spreading concept.

What about H_2O measurements?

•Cassini can detect H_2O near the plumes themselves, of course.

•Maser emission



Pogrebenko et al., 2009

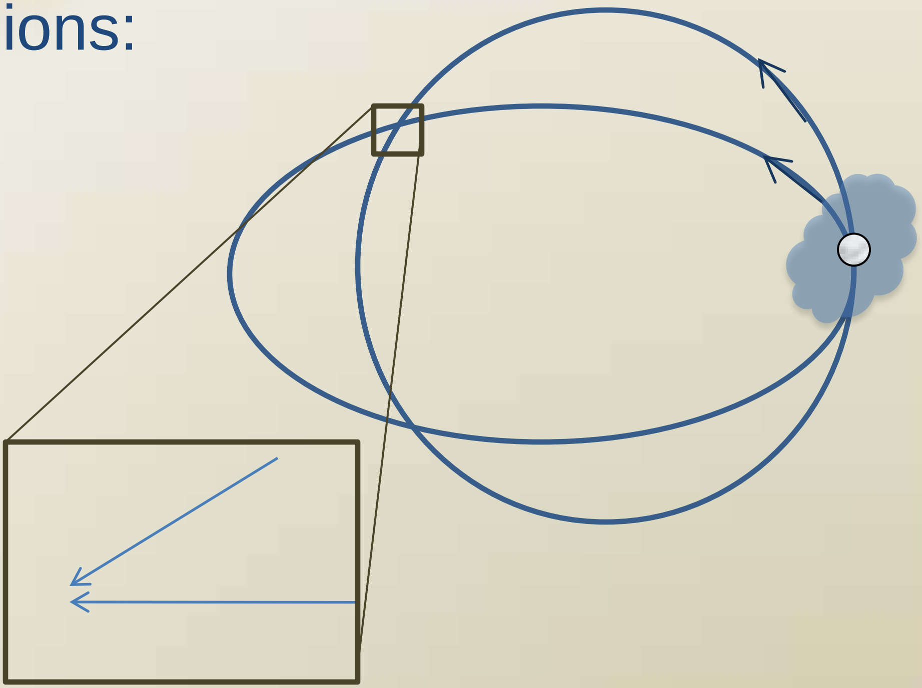
We’re checking this out with the Green Bank Telescope

Why are Saturn’s main rings so orderly?

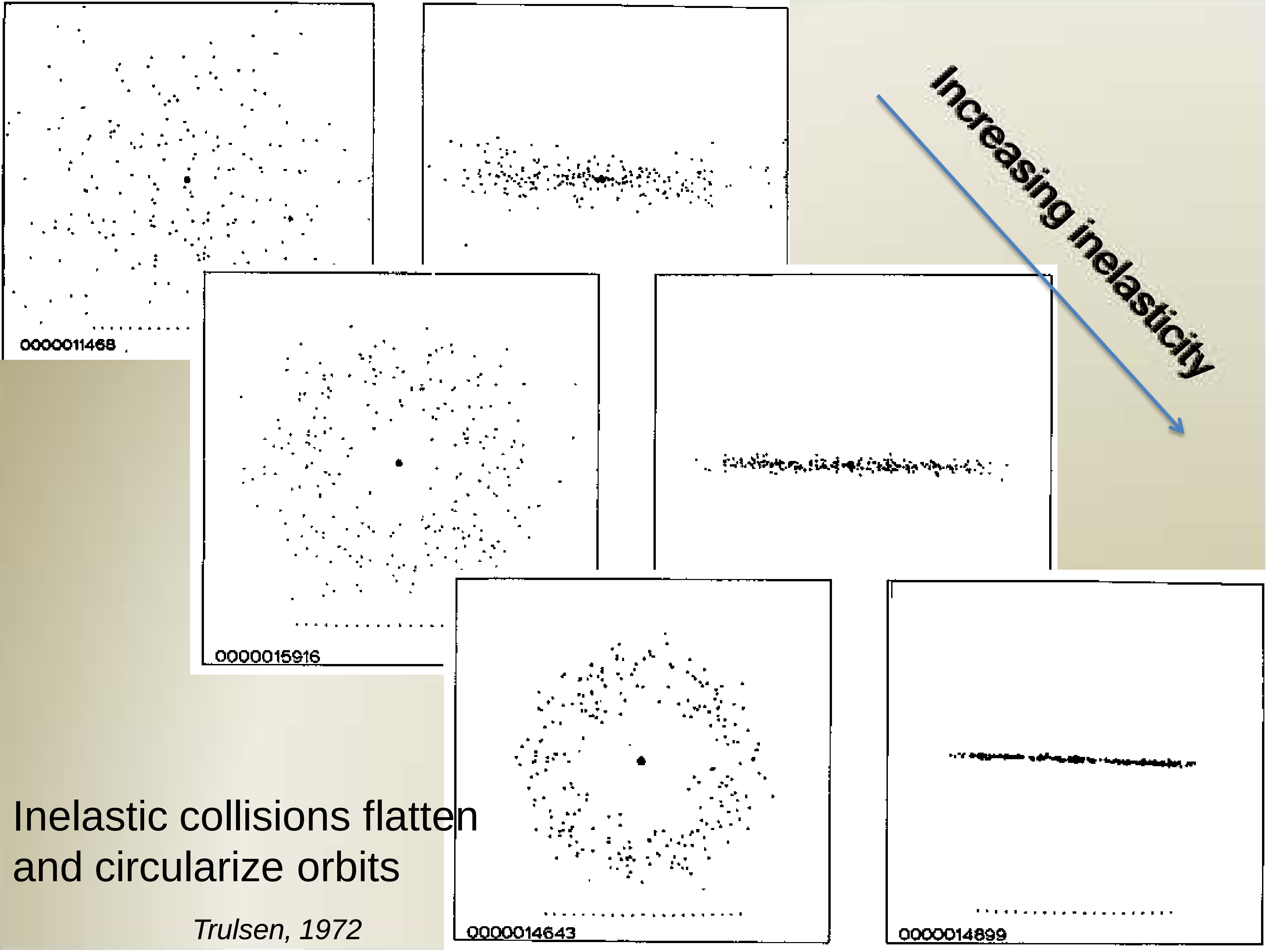
They’re also composed of orbiting, colliding particles.

Well, there are many complicated processes that govern the rings, but the fundamental reason is…

Ring particles have inelastic collisions:



Unlike our elastic collisions, the ring particles' relative speeds cancel out. Inelastic collisions serve instead to remove energy from the system and to dampen eccentricity.



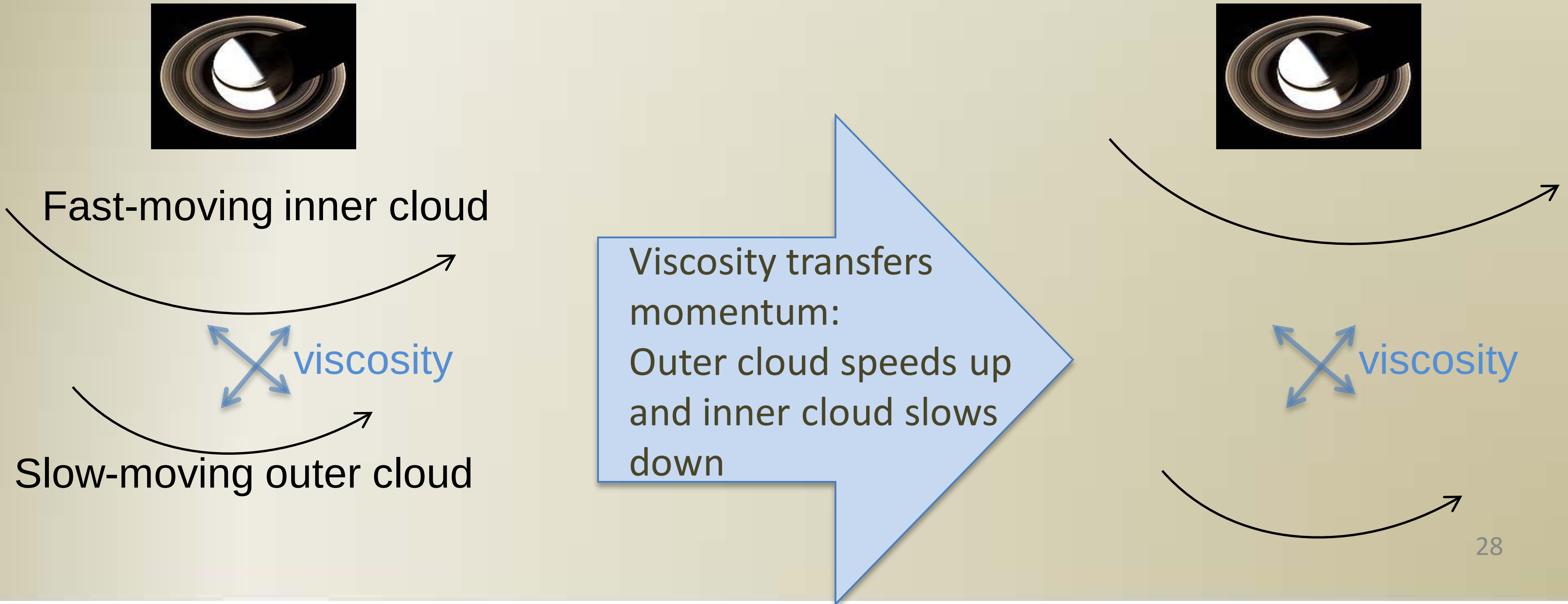
Increasing inelasticity

Inelastic collisions flatten and circularize orbits

Trulsen, 1972

Rings *are* still slowly spreading, due to their viscosity

Collision speeds are much lower, though, several mm s^{-1} compared to several km s^{-1} for our modeled cloud.



Fast-moving inner cloud

viscosity

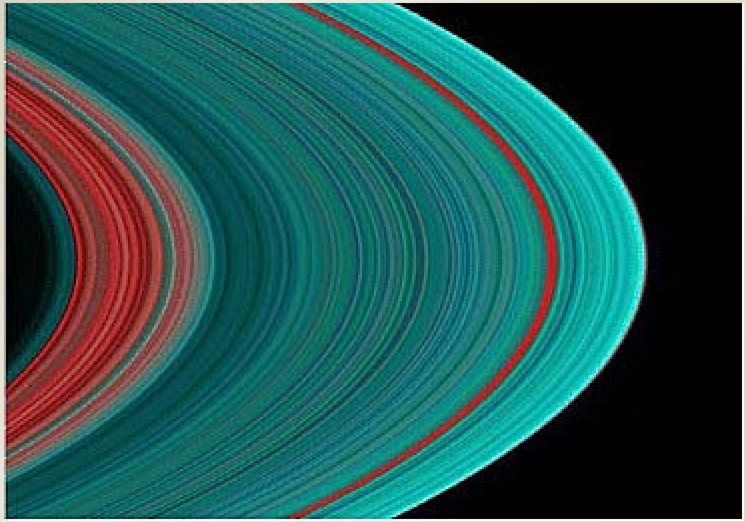
Slow-moving outer cloud

Viscosity transfers momentum:
Outer cloud speeds up and inner cloud slows down

viscosity

Implications

Redistributed water products affect the whole Saturn system:



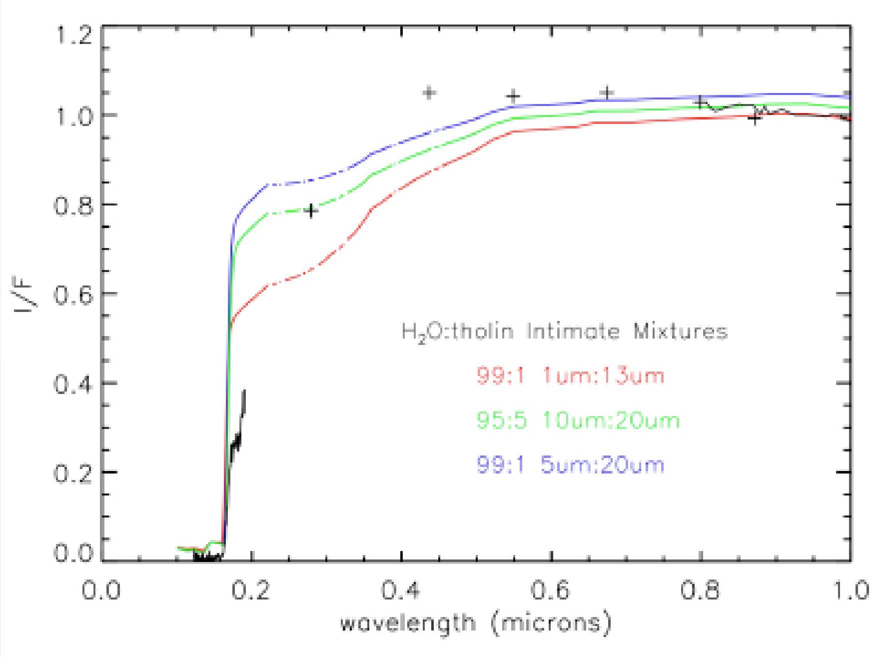
The relatively pure water ice at the edge of the main rings may be due to water from Enceladus (Jurac and Richardson, 2007)

We predict that the main rings are the single largest sink for Enceladus' H_2O

The major icy moons are embedded in the Enceladus torus, they each receive large fluxes of H_2O, OH and O.

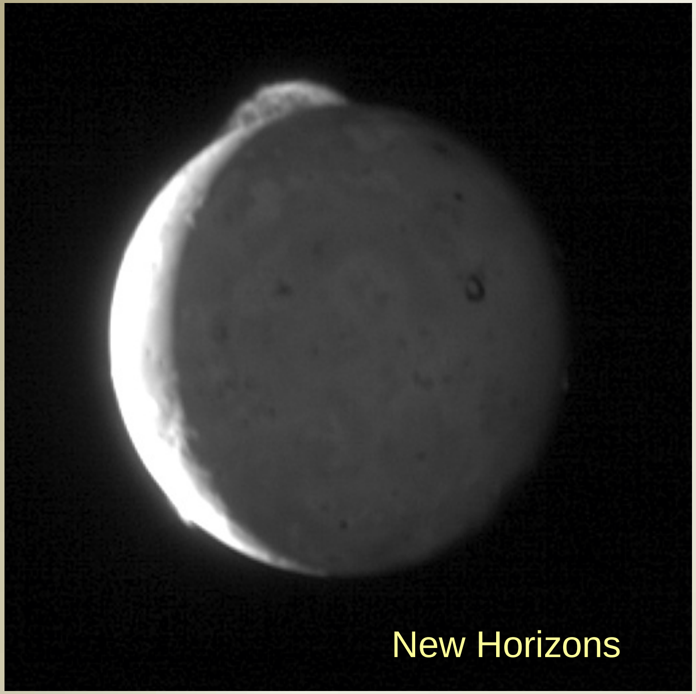
Along with Enceladus' H_2O, we predict that these moons should be coated by the other species detected in the plume. In particular, NH_3 (~1% of plume).

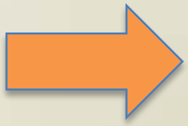
Several monolayers of plume material coat Mimas and Tethys per year.

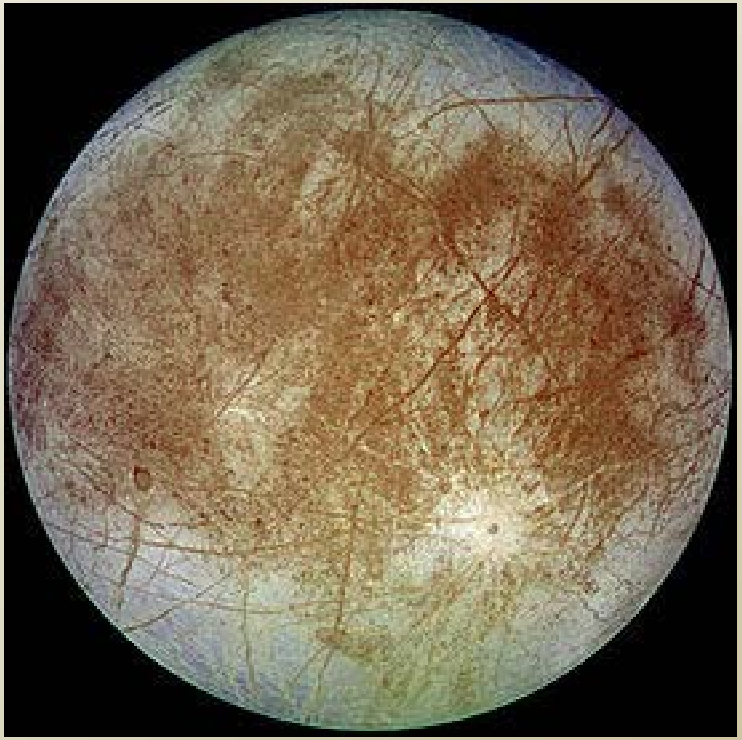


Hendrix et al., 2010

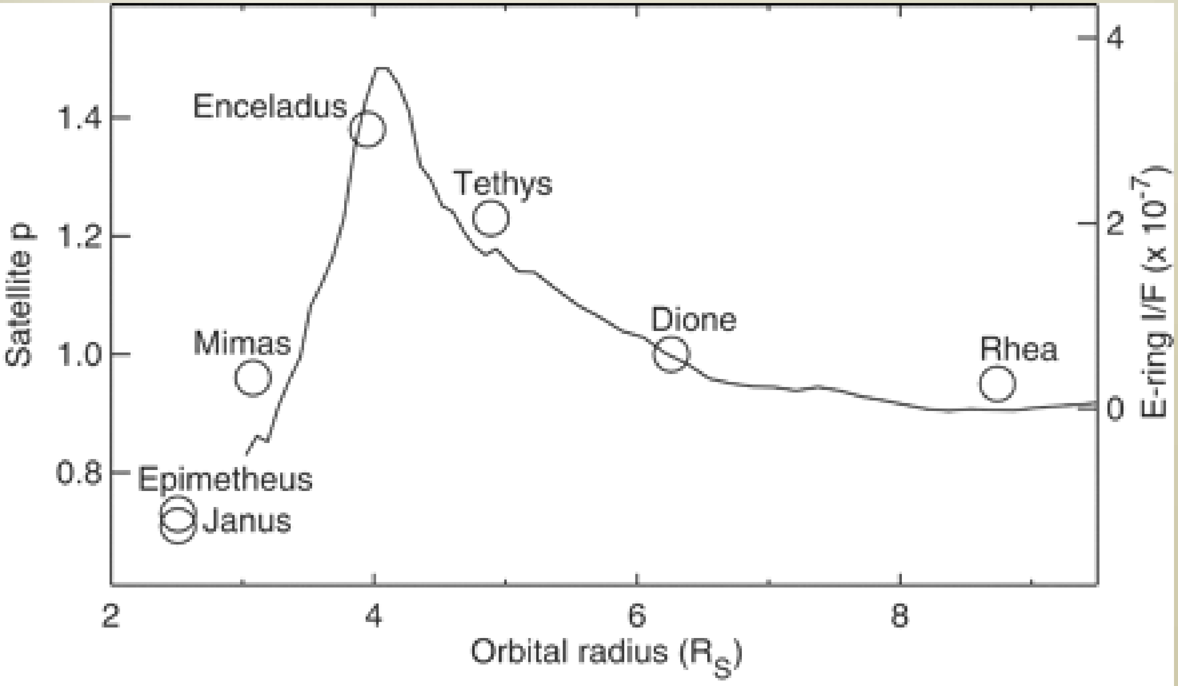
Perhaps analogous to Io and the Jupiter system







E-ring also delivers material, but is mostly responsible for breaking up surface.



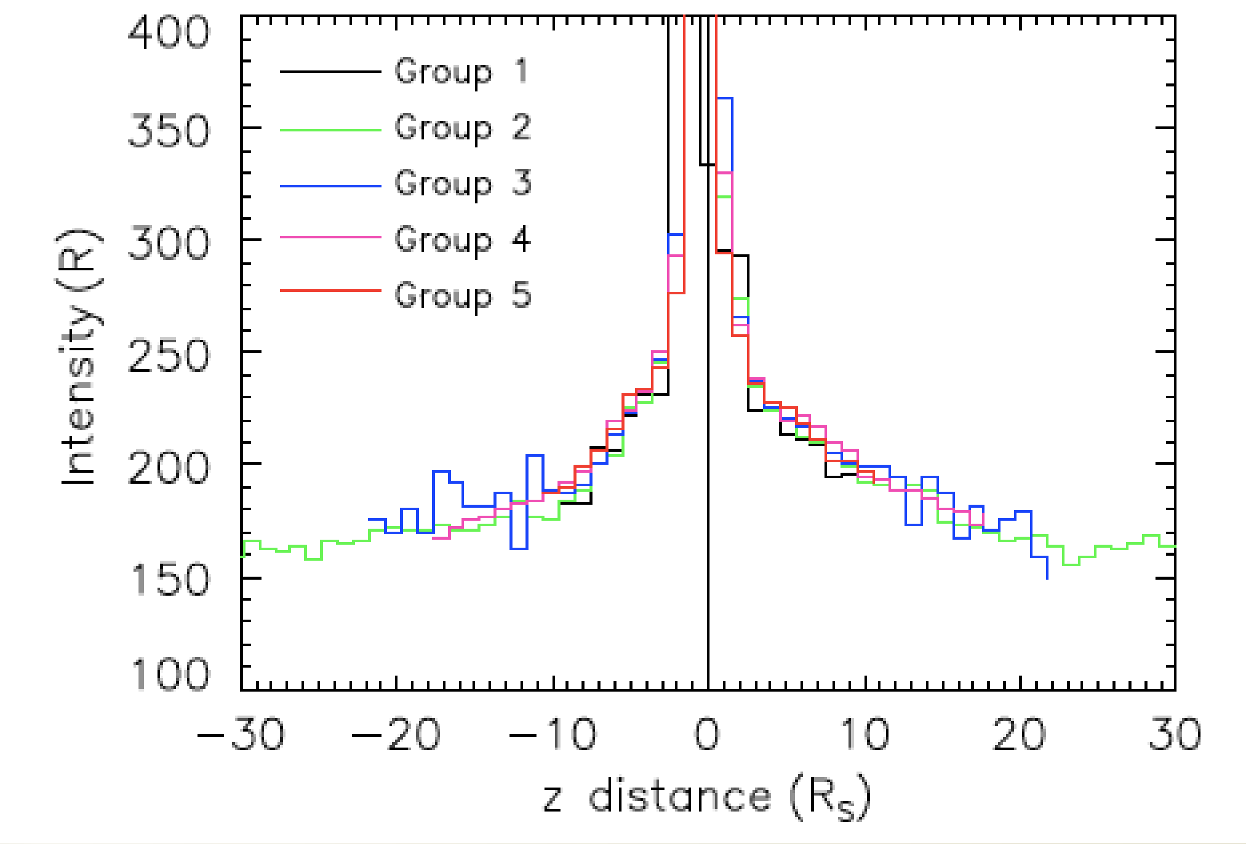
Verbiscer et al., 2007

We estimate that the neutral cloud is the dominant source of O for Titan's upper atmosphere, exceeding comet and ion bombardment. A source of O needed to explain presence of CO, CO_2 and H_2O. (compare fluxes to Sittler et al., 2009)

Major contributor of O to Saturn's upper atmosphere. The "ring atmosphere" of O_2 also contributes (Tseng et al., 2009).

H torus

Reflected Lyman alpha



Melin et al., 2009

Conclusions

- Enceladus’ plume is redistributed throughout Saturn system by neutral/neutral collisions

- Elasticity of collisions is critical for the spreading to occur

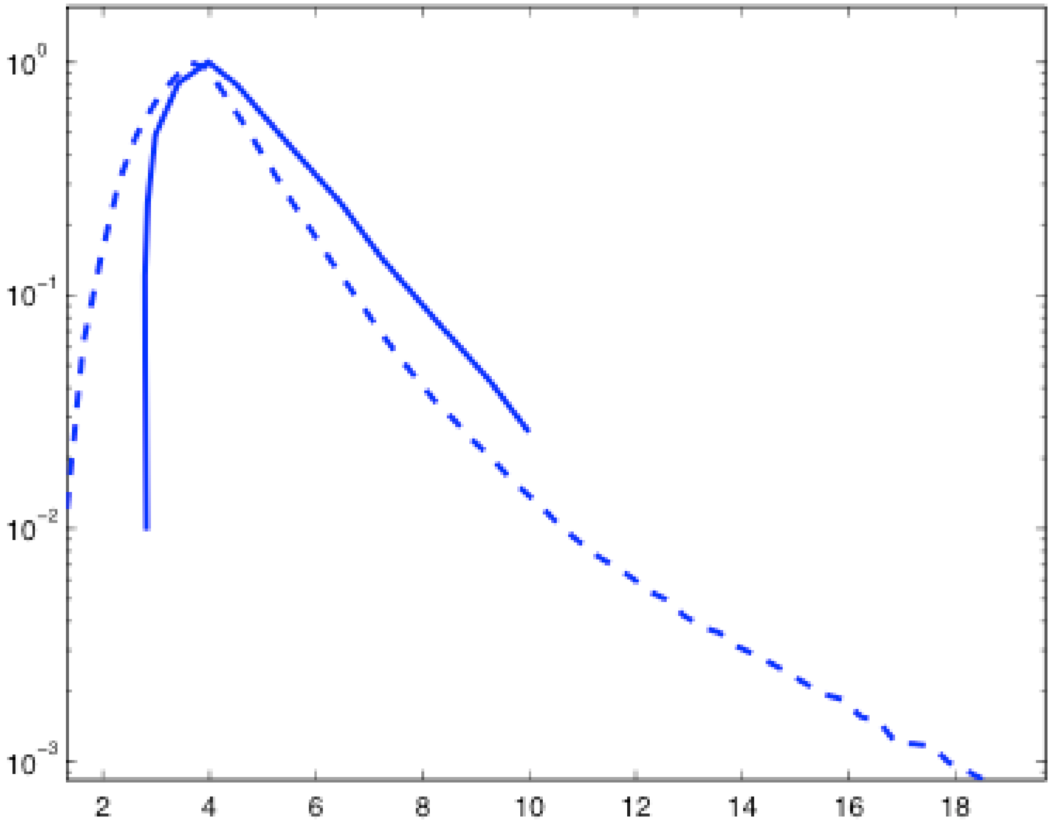
- The torus delivers large quantities of material to every object between, and including, Saturn and Titan

Extra slides

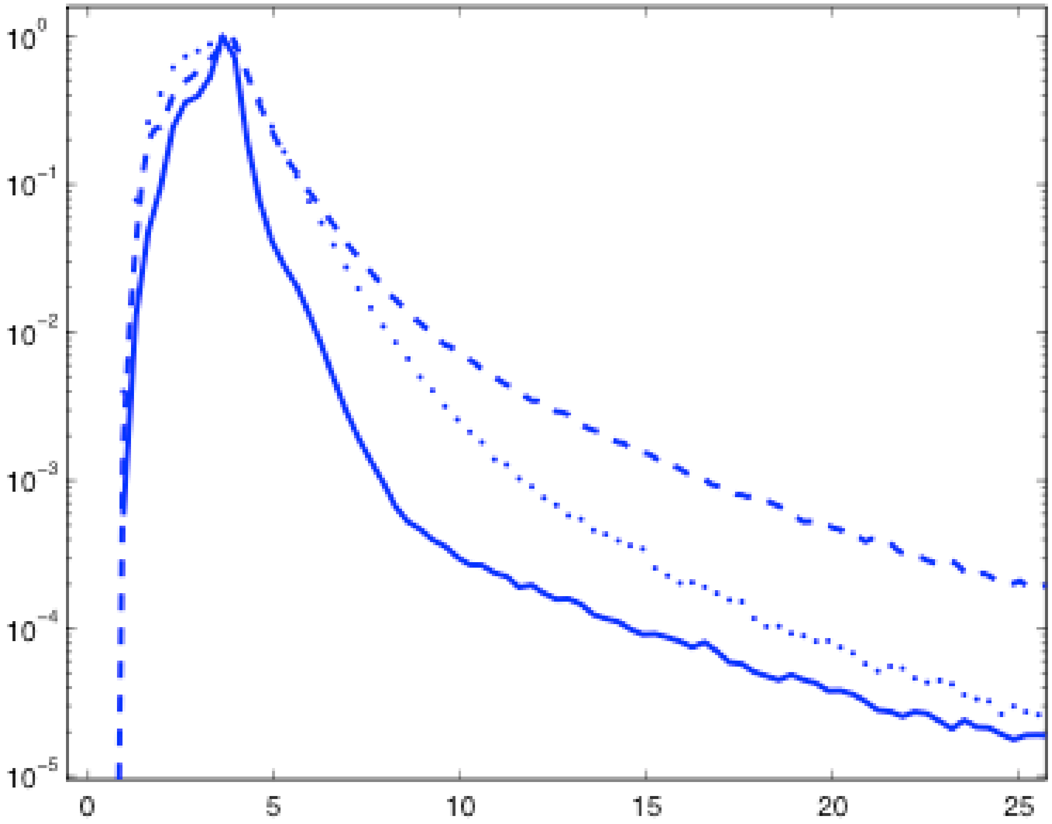
Boltzmann equation:

$$f\left(\mathbf{x}+\frac{\mathbf{p}}{m}dt,\mathbf{p}+\mathbf{F}dt,t+dt\right)d\mathbf{x}\,d\mathbf{p}-f(\mathbf{x},\mathbf{p},t)d\mathbf{x}\,d\mathbf{p}=\left.\frac{\partial f(\mathbf{x},\mathbf{p},t)}{\partial t}\right|_{\mathrm{coll}}d\mathbf{x}\,d\mathbf{p}\,dt$$

We used a DSMC model:
Direct **S**imulation **M**onte **C**arlo



10^0
10^{-1}
10^{-2}
10^{-3}
2
4
6
8
10
12
14
16
18


10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
5
10
15
20
25