Structure and Dynamics of Saturn’s Rings

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Saturn Equinox 2009

- Oblique lighting exposed vertical ring structure and embedded objects
- Rings were the coldest ever
- Images inspired new occultation and spectral analysis
- Steady progress and new discoveries continue: More complex, time variable
Mimas Casts a Long Shadow at Equinox
This is a picture taken directly above these camels in the desert in Saudi Arabia during sunset. It is considered one of the best pictures of the year by National Geographic. Look closely, the camels are the little white lines in the picture. The black you see are just the shadows!! Enlarge the picture
Aggregates form at outer B ring edge
Sub-km structure seen in wavelet analysis varies with longitude

- Wavelet analysis from multiple UVIS occultations is co-added to give a significance estimate.
- For the B ring edge, the significance of features with sizes 200-2000m shows maxima at 90 and 270 degrees ahead of Mimas.
- For density waves, significance correlated to resonance torque from the perturbing moon.
Epoch is 2008-001T01:25:26.8219, mean motion n=381.9944522

Wavelet WWZ value (=probability)
“Spikes” in A-ring outer edge (Spitale and Porco 2009) suggest embedded satellites there as well.
‘Straw’ seen between density wave crests
Figure 1: Density waves in the A ring of Saturn. (left) The waves as seen in the Cassini Narrow Angle Camera. Imagery provides a two-dimensional view of the rings, but with spatial resolution no better than a kilometer per pixel. (right) The same region as seen in a stellar occultation observed by the Cassini UVIS High Speed Photometer, which offers up to sub-meter resolution. These data are binned by a factor of 100.
Janus 5:4 occulting alpha Virgo, rev 8 (egress)

Sharp peak breaking wave regularity
ISS imagery

Janus 4:3

UVIS HSP optical depth

Radial Distance - 125350km [km]

UVIS HSP counts

I/F * 10^3

100px
Solitary wave propagating through A ring?
Daphnis Edge Wake
Clumps Form
Ring Edge Shears and Separates
Cassini UVIS Occultation across Keeler Gap
(for qualitative optical depth invert vertical axis)

Del_Per_R36: OEG Keeler

width = 1.7km
-7deg trailing moon

gap feature

Keeler gap
Feature Distribution Keeler Gap (Daphnis)

Grey background: Ring and Simple wakes regime [Showalter et al. (1986)]
Orange cross: Detected Feature
Figure 3: Five gaps (marked by the shaded rectangles) in the unbinned ζ Centauri R60 occultation. The horizontal red line gives the median-smoothed optical depth of the region and each identified gap is labeled with its $dr$. 
Predator-Prey model of Moon-triggered Accretion?
Predator-Prey Equations for Ring Clumping

\[ M = \int n(m) m^2 \, dm \;/\; <M>; \]

\[ V_{rel}^2 = \int n(m) V_{rel}^2 \, dm \;/\; N \]

\[ \frac{dM}{dt} = \frac{M}{T_{acc}} - \frac{V_{rel}^2}{v_{th}^2} \frac{M}{T_{coll}} \]

[accretion] [fragmentation/erosion]

\[ \frac{dV_{rel}^2}{dt} = -(1-\varepsilon^2) \frac{V_{rel}^2}{T_{coll}} + \left(\frac{M}{M_0}\right)^2 \frac{V_{esc}^2}{T_{stir}} \]

[dissipation] [gravitational stirring]

- \( A_0 \cos(\omega t) \) [forcing by streamline crowding]

Not included: Separate evolution for small and large particles; Tidal forces.
Why this simplified model?

• N-body simulations can’t include all the relevant physics and consider long azimuthal and time scales
• Predator-Prey model gives some useful intuition about equilibrium points, stability, and asymptotic behavior
• Provide direction for more detailed models and key observations
Strength regime, the particles have reached equilibrium, Sigma forcing.
What have we learned?

• Moon-forced streamline crowding can cause temporary aggregates, out of phase with the moon
• Disk instability is needed to produce clumps on the orbital time scale
• Perturbations by Pan and Daphnis may grow large enough through disk instability to tear apart lanes in the nearby rings
Post-Equinox View

• Cassini Equinox observations show Saturn’s rings as a complex geophysical system, incompletely modeled as a single-phase fluid: clumps evident; particles segregate by size; viscosity depends on shear; shear reverses in perturbed regions; rings are far from equilibrium in perturbed regions

• Self-gravity causes wakes, viscosity, overstability and local aggregate growth

• Larger fragments: seeds for growth
Ring dynamics and history implications

• Moon-triggered clumping at perturbed regions in Saturn’s rings creates both high velocity dispersion and large aggregates at these distances, explaining both small and large particles observed there.

• A simple ecological model can give us some insight

• This confirms the triple architecture of ring particles: a broad size distribution of particles; aggregates into temporary rubble piles; coated by a regolith of dust..

• Cassini results show the rings are much younger than the Solar System, but they may replicate processes in planet formation
Backup Slides
Are Saturn’s Rings Young or Old?

• Voyager found active processes and short lifetimes: we concluded the rings were created recently.
• Because it is highly unlikely a comet or moon as big as Mimas was shattered recently to produce Saturn’s rings, we ask: Are we very fortunate?
• Cassini observations show a range of ages, some even shorter!
• Esposito et al. (1983) considered the Voyager mass estimate a lower limit
• Conversely, density waves in the B ring show less massive rings (Hedman and Nicholson 2016)
• Cassini confirms earlier dust estimates. Because meteoritic dust pollutes rings: Less massive rings must be very young: tens of millions of years
Why are Saturn’s rings so active and dynamic?

1. Granular material: Particle-to-particle collisions dominate; *Kinetic,* not *fluid* description needed; Stresses are strikingly inhomogeneous; Fluctuations large compared to equilibrium.

2. Strongly forced by resonances: Non-linear response to moon forcing; Thresholds lead to persistent states.

**Pred-Prey Model:**

\[
\frac{dM}{dt} = \frac{M}{T_{\text{acc}}} \frac{V_{\text{rel}}^2}{V_{\text{th}}(M_0)} \frac{M^\alpha M_0^{1-\alpha}}{T_{\text{coll}}^\beta \left( \frac{\rho_0}{\rho_1} \right)^{\beta/3}}
\]

\[
\frac{dV_{\text{rel}}^2}{dt} = -\frac{V_{\text{rel}}^2(1-e^2)}{T_{\text{coll}}} + \frac{V_{\text{esc}}^2(M_0)}{T_{\text{strir}}} \left( \frac{M}{M_0} \right)^2 \left( \frac{2\pi B V_{\text{th}}^2}{T_{\text{syn}}} \cos \left( \frac{2\pi t}{T_{\text{syn}}} \right) \right)
\]
Saturn’s B ring is the brightest and most opaque
Conclusions

- Ring structure shows clumping in perturbed regions: Moon forcing triggers aggregation. Lewis & Stewart simulations show streamline crowding and reduction of the velocity dispersion downstream from the satellite.
- The structure forms rapidly, on orbital time scales, out of phase with the moon, and is reduced at the next moon passage (shown by wavelet analysis, straw, gaps, statistics).
- A simple two parameter model for the aggregate mass and velocity dispersion captures the key parts of the dynamics. This ‘Predator-Prey’ model allows ecological analogies, and can be directly related to the pendulum and the Duffing ‘Moon-beam’ oscillator, both well-studied non-linear systems.
- This model shows the fixed points, their stability and the phase plane response from driving the system. Cell-to-cell mapping techniques transform the trajectories to a Markov process.
Conclusions (2)

- Stochastic collisions lead to larger, compacted, longer-lived aggregates.
- The Predator-Prey model can be adjusted to Goldreich’s ‘Two-Group’ model by specifically defining the small and large particles as the ring particles and the clumps.
- In this approximation, we can calculate the fixed points and the growth rates in the driven system: We find that growth by aggregation is too slow to explain the excess structure observed in between density wave crests.
- Gravitational disk instability can act on orbital time scales; We use Toomre’s stability parameter $Q$ to estimate the growth rate for clumps.
- We can achieve rapid growth by reducing the increasing the surface mass density, decreasing the velocity dispersion or decreasing the shear. This last is like ‘swing amplification’.
Conclusions (3)

• We can identify the fixed points with self-gravity wakes and those of the longer-lived clumps with the Equinox objects, straw and the larger kittens.

• Disk instability is a violent one: as the wavelength of the disturbance shrinks to zero, the growth rate grows without limit – a cold, zero-thickness disk disintegrates on small scales in an arbitrarily short time (Binney and Tremaine, 2008, p495). This can explain the gaps ripped open at the edges of the Encke and Keeler gaps (Albers 2012).

• The ring clumpiness means that we underestimate the ring mass and viscosity, both dominated by the aggregations, which have a different physical nature, like a phase change in a fluid (Tremaine 2003): this could give a different dispersion relation for density waves, leading to an underestimate of the ring mass from density wave analysis.

• A larger ring mass means that Saturn’s rings could be ancient.
Region 1:
- 2006 Janus wave overlaps the 2002 Epimetheus wave, "stirring" the ring region and forming the solitary wave

Region 2:
- This solitary wave propagates faster than the density wave group velocity

Region 3:
- Group velocity propagation of wave perturbations

Region 4:
- Wave perturbations from 2002 waves form
Rare accretion can renew rings

- Solid aggregates are persistent, like the absorbing states in a Markov chain
- Even low transition probabilities can populate these states
- These aggregates
  - shield their interiors from meteoritic dust pollution
  - release pristine material when disrupted by an external impact