Tides, Roche Radius, and Rings
Why the oblong shape?

Saturn’s Satellite Mimas, R~200-km
What determines Tidal Height?
Tides

• Tides are due to **differential** gravitational forces on a body.
  - Consider the Earth and Moon: the gravitational force on the Moon due to Earth is stronger on the near side than on the far side.
  - This **net difference** in force will cause the body to stretch along the line between the bodies.
What force is exerted on body $M_1$, by the tidal bulges raised on body $M_2$?
Tides Result from Every Perturber

- Spring Tide
- Neap Tide
- Lunar Tide
- Mean Sea Level
- Solar Tide
- Combined Tide
Roche limit

Estimate the Roche limit for two equal-mass particles, just touching and with their centres separated by a distance $dr$. If these particles are a distance $r$ away from a much larger mass $M$, at what distance (the Roche limit) will tidal forces overwhelm the gravitational force holding them together?
Roche limit

- The tidal force gets very large as the distance between objects decreases.

\[ a_T \approx \frac{2GM_p}{r^3} R_s \]

- At a critical distance, the tidal forces will exceed the gravitational force holding the satellite together, and it will be torn apart.

- Use Astronomy Workshop to calc H/R.
Observed Tidal Disruption

- Fragment chain discovered in 1993
- Orbit determination showed it was a known comet that encountered Jupiter inside the Roche radius in 1992.
- It later returned to impact Jupiter in 1994
- First observed tidal disruption / collision
- Animation of SL-9 Jupiter Impact
The rings of Uranus are thin, narrow, and dark compared to other planetary ring systems. There are also embedded moonlets in the rings.

Jupiter's “gossamer” ring - very faint.

Saturn's massive ring system. It is a true particle disk.

Rings of Neptune show thin ringlets, and ring arcs.
How was material delivered inside the Roche limit?
Ring locations – Ice Giants

Uranus

- Puck
- Belinda
- Rosalind
- Juliet
- Portia
- Cressida
- Desdemona
- Bianca
- Ophelia
- Cordelia

1986 U2R

Synchronous radius

Roche limit (p=1)

Neptune

- Proteus
- Galatea
- Larissa
- Despina
- Naiad
- Naiad
- Thalassa
- Galle
- Adams
- Arago
- Lassell
- Le Verrier

Roche limits
• Ring features (gaps, edges) due primarily to embedded satellites or orbital resonances with distant satellites.
• In densest regions, ring particles collide with one another every few orbits (~hours).
• Extend out to Roche limit: these are swarms of debris which cannot coalesce to form a moon.
• For Jupiter and Saturn, small moonlets are associated with the outer ring edges, near the Roche limit.
Thickness of Rings

• Saturn’s rings are very thin: only a few tens of metres thick (270,000 km in diameter)
• Why?
Shepherding satellites

• Narrow rings can be maintained by gravitational action of small moons in or between rings.

Two small moons (Prometheus inside and Pandora outside) on either side of Saturn’s narrow F ring

Two shepherding moons straddling the brightest ring around Uranus
Shepherding moons: Pandora

- Pandora is a shepherding moon of Saturn’s F ring.
- Craters on Pandora appear to be covered over by some sort of material, providing a smooth appearance. Curious grooves and ridges also appear to cross the surface of the small moon.
Moons in Gaps

- Gap moons have the opposite effect: clearing a gap in the ring structure
Rings of Uranus

- several distinct rings, mostly narrow
- dark, sooty particles
- some banded structure
- only tens of metres thick
- mass \( \sim \frac{1}{4000} \) Saturn’s system
Rings of Jupiter

Jupiter has two ring systems, likely produced by material ejected from moons following meteorite impacts.
How do Rings Originate?

• Saturn's rings appear to be made of mostly ice

• The mass of the system is at least that of R~=200-km Mimas

• The ice appears 'clean' – not contaminated by dirt (at least at the surface).

• What does this imply about when rings formed?

• How was material delivered to the rings (i.e. The region interior to the Roche limit)?
SPH simulation showing the tidal removal of ice from a differentiated, Titan-mass satellite.
Ring Origin Scenario #2
Catastrophic Disruption of a Satellite
Ring Origin Scenario 3
Tidal Disruption of a Centaur

NB: “Disruptive” scenarios for Saturn’s rings do not necessarily imply recent origin.
Disintegrative Capture

Origin of the Moon:
Öpik 1972
Wood and Mitler 1974
Wood 1986

Tidal disruption of stars by black holes:
Lacy et al. 1982
Evans and Kochanek 1982

Fig. 11. An idealized example of disintegrative capture. A planetesimal at the top of the figure is tidally disrupted during passage at parabolic velocity through Earth’s Roche zone. The subsequent trajectories of material from ten parallel slabs in the original planetesimal (inset, upper left) are followed. Debris from slabs 1–5 (farthest from Earth) is returned to heliocentric orbits; debris from slabs 6–10 is captured in geocentric orbits. In the case of encounters at greater than the parabolic velocity, a smaller number of slabs, those that pass closest to Earth, are lost in Earth’s gravitational pull.
\[ v = (2v_0^2 + v_\infty^2)^{1/2} \]

where \( v_0^2 = \frac{GM_s}{q} \)

Need \( D > q \frac{v_\infty^2}{v_0^2} \) to capture debris.

For \( q = R_s = 60,000 \) km, \( v_0 = 25 \) km/s,

\[ D > 100 \text{ km (} v_\infty / 1 \text{ km/s)}^2 \]

Mass of rings \( \sim \) mass of Mimas or larger

(Stewart et al., this session) \( \rightarrow \)

Ring parent body must have \( D > 400 \) km
The largest known Saturn-crossers have diameters < 200 km, but larger escapees from the Kuiper belt/scattered disk are likely to visit from time to time.
Numerical Model

N-body code based upon the code.

Code treats interloper as a strengthless rubble pile comprised of uniform, frictionless spheres (‘gumballs’).

Forces considered:

- Gravitational attraction by Saturn
- Self-gravity of gumballs
- Simple model for collisions between gumballs
## Inputs for Models

<table>
<thead>
<tr>
<th></th>
<th>Range (km/s)</th>
<th>This Talk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encounter velocity ($v_\infty$, km/s)</td>
<td>0-6</td>
<td>0-3</td>
</tr>
<tr>
<td>Size of interloper (D, km)</td>
<td>140-3000</td>
<td>1000</td>
</tr>
<tr>
<td>Internal density of interlopers ($\rho$, g/cm$^3$)</td>
<td>0.5-2.5</td>
<td>0.6</td>
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<tr>
<td>Closest approach distance to Saturn (Saturn radii)</td>
<td>1-2</td>
<td>1.1-1.3</td>
</tr>
<tr>
<td>Shape</td>
<td>Ellipsoids</td>
<td>Spheres</td>
</tr>
</tbody>
</table>

*Note: The range values for this talk are not explicitly stated; they are inferred from the table.*
Distribution of $v_\infty$ for Centaurs at Saturn

Zahnle et al. (2003), based on models of Levison and Duncan (1997)
Pericenter Distance: 1.1 $R_s$

$y$-Distance from Saturn Center ($R_s$)

$x$-Distance from Saturn Center ($R_b$)
Do Rings Exist Only Around Giant Planets?

- No!
- Rings have been found around TransNeptunian Objects (TNOs) Chariklo (discovered in 2014) and Chiron (maybe).
- Oct 11, 2017 Rings were discovered around Haumea, a large dwarf planet in the Kuiper Belt.
- Earth once had rings
- Mars may have rings in the future!
Challenges observing properties of minor planets

• Can not resolve their size with telescope (don’t know their size – only brightness in sky).

• If the orbit is known precisely (i.e., the observations of high precision have been done for a long time) then we can predict when minor planets will occult, or pass in front of stars.

• We know the speed of the planet across the sky from its orbit

• We measure the time that the planet blocks the star (at several places on the globe)

• Can then fit a size and shape model to the minor body.

• Sometimes interesting things are found…..
Detection by Occultation! (Eclipse)

Chariklo ring system.

Chariklo ring system.

Fits to the Danish ring events.

Ring Origins

• Ring origins are still being studied (i.e., we don't have a single theory that explains it all yet).

• Data from Cassini spacecraft has provided a treasure trove of information about Saturn's rings (and constraining how they may have formed and evolved).

• Tidal Forces are the fundamental reason why rings exist and that ring particles do not collide and accumulate into a larger moonlet.