On the Origins of Satellites Around Gas Giant Planets

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Motivation

• Centuries old fascination. Lots of data amassed.

• Common!
  - 4 data points in 1 solar system
  - by-product of planet formation
  - extra solar giant planet satellite systems – a matter of time!

• Window into understanding the early solar system environment.
  - Composition
  - Chemistry nebula/subnebula
  - Initial conditions

• How do we get these mini-solar systems?
  - as diverse as planetary systems
  - differences
  - similarities

Is there a common framework that applies to all the satellite systems?
The Giant Planet Satellite Systems

(Mosqueira and Estrada 2003a)
Summary of Constraints

- Strong indirect evidence for a two component (subnebula) disk
  - Satellite systems are mostly compact
  - Iapetus forces a long tail
  - Irregulars?

- Most of the satellite systems are empty

- Primordial Ar in Jupiter’s atmosphere but not Titan’s

**Bulk Compositional Properties**

- Non-stochastic compositions of Ganymede, Callisto, Titan and Iapetus
- The Ganymede/Titan/Callisto moment of inertia trend

*** Tie to planet and disk formation ***
Giant Planet and Disk Formation

Main issues

- Angular momentum
- Turbulence
- Distribution of solids in the solar nebula

Ultimate Goal

A combined model for Jupiter and Saturn

(See Estrada et al. 2009)
Angular Momentum: Disk Sizes

(Lissauer et al. 1995)

Prior to opening a clean gap, planet accretes low specific ang. mom. gas from within $R_H$

Estimate of disk size

- compact disk forms consistent with numerical estimates (Machida et al. 2008; Lissauer et al. 2009)

\[
\ell \approx -\Omega \frac{\int_0^{R_H} \frac{3}{2} x^2 dx}{\int_0^{R_H} x dx} + \Omega R_H^2 \approx \frac{1}{4} \Omega R_H^2,
\]

\[
r_c \approx \frac{R_H}{48}
\]

Potentially massive disk
Specific Angular Momentum of Gas Inflow Through Giant Planet Gap

- Both 2D and 3D simulations of gas accretion through a clean gap form an extended circumplanetary disk compared with the locations of the regular satellites (D’Angelo et al. 2003; D’Angelo 2007; Ayliffe and Bate 2009; Tanigawa et al. 2012).

Extended low density tail
Turbulence in a Keplerian Disk

- The $\alpha$-prescription (where $\alpha = \nu / cH$) in the nebula
  - Traditionally is used to remove the gas disk.
  - Disks may be insufficiently ionized to sustain MRI. Presence of “dead zones” a robust result.
  - There is no evidence that $\alpha$ (typical value is $\sim 10^{-3}$) can be transplanted from the nebula around a star to the subnebula around the planet.
    - $\alpha$ is a free parameter. This can lead to fine-tuning.

Once the inflow, which drives disk evolution, wanes as the planet opens a deep, clean gas gap one would expect turbulence to decay in the absence of another driving mechanism.
Distribution of Solids at the time of Satellite Formation

- Most of the solids mass in the nebula contained within ~10 km planetesimals

- Reasons to treat planetesimals
  - Observations of comets (e.g., Chamoz and Morbidelli 2007)
  - Nice model needs many Pluto-sized planetesimals to power planet migration (LHB)
  - Asteroid belt mass problem (top-heavy size distribution)
  - Formation of cores of giant planets
  - Volatile enhancement in giant planet atmospheres
Planetesimal Processing and Delivery of Volatiles

At both Jupiter and Saturn, planetesimals processed in the giant planet envelope could incorporate volatiles in both crystalline and amorphous ice.

Trapping of volatiles occurs when the nebula is cold, passive, and optically thick.

~ 5 AU

T ~ 80 K

~ km-sized planetesimals

migration times $10^6 - 10^7$ years

~ 10 AU

~ 10 $M_\oplus$

T ~ R_H/2

~ 50 K

~ 20 AU

~ 30 AU

~ m-sized planetesimals

migration times $10^3 - 10^4$ years

T ~ 40 K

Trapping of Ar in clathrate-hydrates

T ~ 30 K

Trapping of Ar in amorphous ice

(Estrada et al. 2009)
Regular Satellite Formation

- Key Issues
  - Turbulence
  - Delivery of solids to the disk
  - Satellite survival

- Bulk constraints
  - Mass
  - Angular momentum
  - Satellite compositions
    • Solar nebula to subnebula
    • Subnebula gradients

- Galileo & Cassini constraints
  - Phoebe, Iapetus, Hyperion, Titan, Ganymede/Titan/Callisto MOI trend, inner icy moons and rings...

Combined model for Jupiter and Saturn
The SEMM and GPPC Models

• Gaseous Solids-Enhanced Minimum Mass model (Mosqueira and Estrada 2003a, b)
  - Not a “minimum mass” or local accretion model

• Gas-Poor (not gas-free) Planetesimal Capture model (Estrada and Mosqueira 2006).

• Both models are attractive because:
  - Self-consistent
  - Neither model relies on fine-tuning of the turbulence $\alpha$
  - Properly account for the angular momentum
  - Link subnebulae to outer solar nebula
  - Both treat planetesimal dynamics explicitly
Model Comparison

- **Solids-Enhanced Minimum Mass Model** (Mosqueira and Estrada 2001; Estrada 2002; Mosqueira and Estrada 2003a,b)
  
  - Turbulence decays as gas inflow wanes during tail end of planet formation.
  - Survival of satellites by gap-opening (determines $\Sigma_{\text{gas}}$).
  - Formation time for Callisto (around Jupiter) and Iapetus (around Saturn) determined by time it takes gas drag to clear the extended subnebula disk from as far as $\sim R_H/5$.
  - Compositional gradient of Galilean satellites is due to planet’s luminosity.

- **Gas-poor Model** (Ruskol 1975; Safronov et al. 1986; Estrada and Mosqueira 2006)
  
  - Relies on sustained turbulence OR some other dissipation mechanism.
  - Satellite survival due to gas disk removal (undetermined $\Sigma_{\text{gas}}$).
  - All the satellites form in a timescale set by external planetesimal feeding.
  - Impacts and Laplace resonances may explain compositional gradient of Galilean satellites.
Possibly too hot for re-condensation of CH\(_4\) and NH\(_3\).

Too hot for re-trapping of Ar.

Planetesimal Re-Processing and Delivery of Volatiles to Satellites

(Estrada et al. 2009)
SUMMARY OF SEMM INITIAL CONDITIONS

• Massive disk compared to the mass of the satellites (~10 times in gas)

• Dense inner portion containing most of the mass of gas and solids.

• Extended, low density tail out the location of the irregular satellites.

• Non-local accretion, gas-drag clearing/resonance trapping.

• Delivery of solids by ablation through the circumplanetary disk of planetesimal fragments.

(e.g., see Mosquiera and Estrada 2003a,b; Estrada et al. 2009; Johnson and Estrada 2009; Mosqueira, Chamon and Estrada 2010)
Ablation and Capture of Disk Crossers
(e.g. Podolak et al. 1988)

Delivery of Solids by Planetesimal Ablation

- At Titan and Callisto, one can ablate meter-to-kilometer-sized planetesimals (or capture).
- At Iapetus, one can ablate meter-sized icy planetesimals (e.g., Iapetus' composition).

Planetesimal size distribution following giant planet formation?
Non-homogeneous ice/rock distribution?
Explaining Iapetus’ Composition

- Assume unmixed population of planetesimal fragments
  - 1st generation of planetesimals contain $^{26}$Al
  - 70% rock, 30% ice by mass
  - 1 meter to ~10-100 km fragments

- Use N-body simulations (e.g. Charnoz and Morbidelli 2003) to calculate how much mass passes within $\sim R_H/5$

- This process can naturally account for the compositional trend we see:
  - Fractionated ice/rock population due to the collisional cascade
  - Lower density + lower velocities in the outer disk favors ice.

(Mosqueira, Estrada, and Charnoz 2010)
Ganymede/Titan/Callisto MOI Trend

• Relevant observations:
  - Ganymede (MOI = 0.311) \ Callisto (MOI = 0.358) dichotomy.
  - Titan’s moment of inertia (MOI = 0.34).
  - Dichotomy has morphed into a (Ganymede \ Titan \ Callisto) trend.
  - Major caveat: Are all three satellites in hydrostatic equilibrium?

• Geophysical issues:
  - Sources of Energy: Accretion, sinking rock, radiogenic heating.
  - Will melting lead to runaway sinking rock resulting in full differentiation (e.g., Friedson and Stevenson 1983)?
    - Observational evidence argues against this for Titan and Callisto.
  - Accretion DOES bury energy BUT how much heat is trapped by (conductive?) ice shell (if present)?
    - Hotspots (we do not model yet).
    - Collisional overturn (we do model; Squyres et al. 1988).
    - Atmosphere (we do not model yet).
Key Satellite Formation Model Parameters

- **Background temperature** (of accreting material plus background radiation):
  - Ganymede ~ 200 K
  - Titan ~ 100 K
  - Callisto ~ 100 K
  - Strong dependence of viscosity of interior with temperature.

- **Accretion timescale**:
  - Ganymede ~ $10^4$ years.
  - Titan ~ $10^5$ years.
  - Callisto ~ $10^6$ years.
  - A million years is long enough to allow heat of accretion to be radiated away.

All in the right sense to explain observed MOI trend without resorting to fine-tuning uncertain parameters.
Accretion in a Two-component Gas Disk

**Ganymede:** Embryo forms quickly due to sweep up of dust and debris. Timescale for completion controlled by time gas drag clears region of satellitesimals out to Callisto.

**Callisto:** Timescale for formation is controlled by the time it takes gas drag to clear the extended outer disk.

**Titan:** May accrete material from as far out as Iapetus. Hyperion may be a leftover satellitesimal fragment captured into resonance.
Accretion of Large Regular Satellites

- Combined model of satellite accretion and thermal evolution using ACCTHERM code.
  - Impactor size distribution
  - 80/20 burial/surface heat
  - 3-5 Myrs after CAIs

- Key Points to take away
  - Large satellites do not form undifferentiated.
  - Rocky carapace
  - Cold interior + relatively long formation times may prevent full overturn
Titan, $\tau_{ee} = 1 \times 10^5$, $\eta = 0.8$, Cl rock

- ice II
- onset of melting
- no shell (briefly)
- carapace settling

Moment of Inertia vs. time (yrs)
Conclusions

• A Solids-enhanced Minimum Mass (SEMM) model can account for:
  
  - The mass and angular momentum budgets of the regular satellites.
  
  
  - It is possible to enhance the I/R at Iapetus by ablating icy m-sized planetesimal fragments crossing the circumplanetary gas disk—as well as those of Ganymede, Titan and Callisto.
  
  - The Ganymede/Titan/Callisto trend.
  
  - Satellite survival by gap-opening.
  
  - Other constraints such as the lack of primordial Ar in Titan’s atmosphere may also fit within this framework.