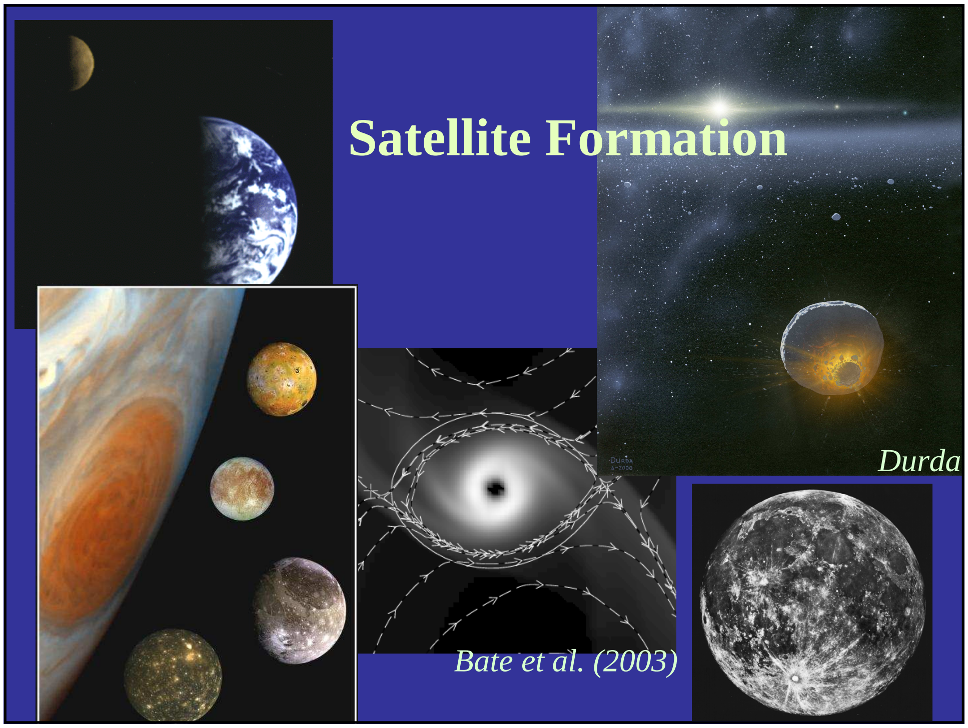
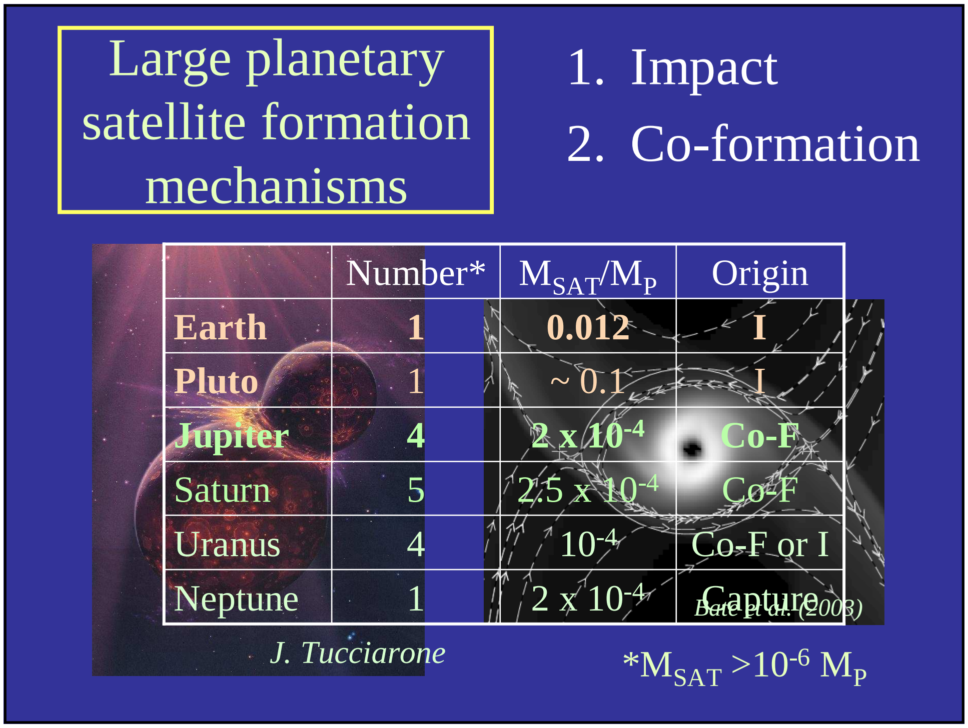


Satellite Formation

Durda

Bate et al. (2003)



Large planetary satellite formation mechanisms

1. Impact
2. Co-formation

	Number*	M_{SAT}/M_P	Origin
Earth	**1**	**0.012**	**I**
Pluto	1	~ 0.1	I
Jupiter	**4**	**2×10^{-4}**	**Co-F**
Saturn	5	2.5×10^{-4}	Co-F
Uranus	4	10^{-4}	Co-F or I
Neptune	1	2×10^{-4}	Capture

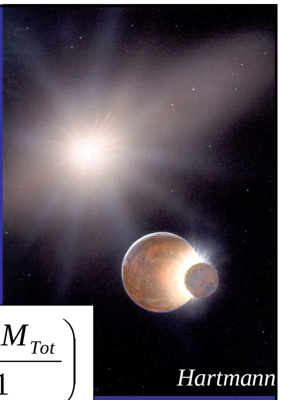
Bate et al. (2003)

J. Tucciarone

$*M_{SAT} > 10^{-6}\ M_P$

Lunar origin via giant impact

(Hartmann & Davis 1975; Cameron & Ward 1976)



Constraints:

1) Earth-Moon angular momentum

$$\frac{L_{Imp}}{L_{\oplus-M}} \approx 1.3\ b \left(\frac{M_{Tot}}{M_{\oplus}}\right)^{5/3} \left(\frac{v_{imp}}{10\text{ km/sec}}\right) \left(\frac{M_{imp}/M_{Tot}}{0.1}\right)$$

$b \equiv$ normalized impact parameter = $\sin \xi$

$b = 0,1$ head-on vs. grazing

$v_{imp} \equiv$ impact velocity; $M_{imp} \equiv$ impactor mass

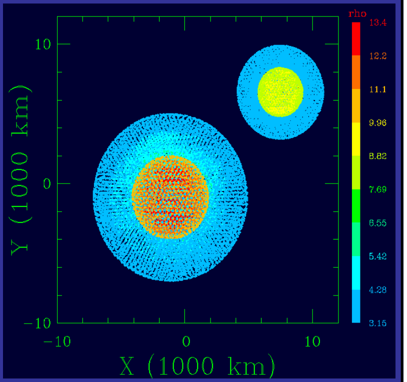
2) Iron depleted disk

3) Sufficient orbiting mass/angular momentum

Example lunar-forming impact *(from Canup 2004)*

SPH *(e.g., Benz et al. 1986)*

- M-ANEOS equation of state *(Melosh 2000; E. Pierazzo)*
- N ~ 60,000 particles total (impactor + target)



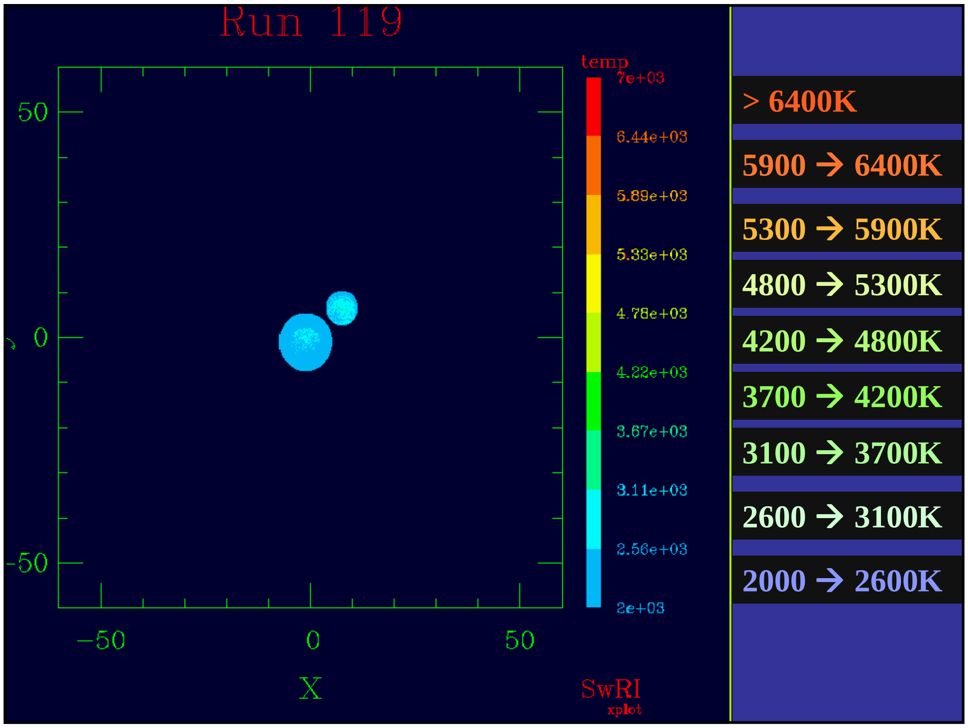
Typical initial smoothing lengths: ~300-km

Lunar mass: ~ *few* × 10^3 particles

- Total mass ~ $1M_{\oplus}$, Ang. Mom. ~ $L_{\oplus\text{-}M}$

→ impact at end of Earth's accretion

- Impactor: 0.13 Earth masses (1.2 Mars masses)
- b ~ 0.7 (45 degree impact angle); $v_{imp} = v_{esc}$



> 6400K

5900 → 6400K

5300 → 5900K

4800 → 5300K

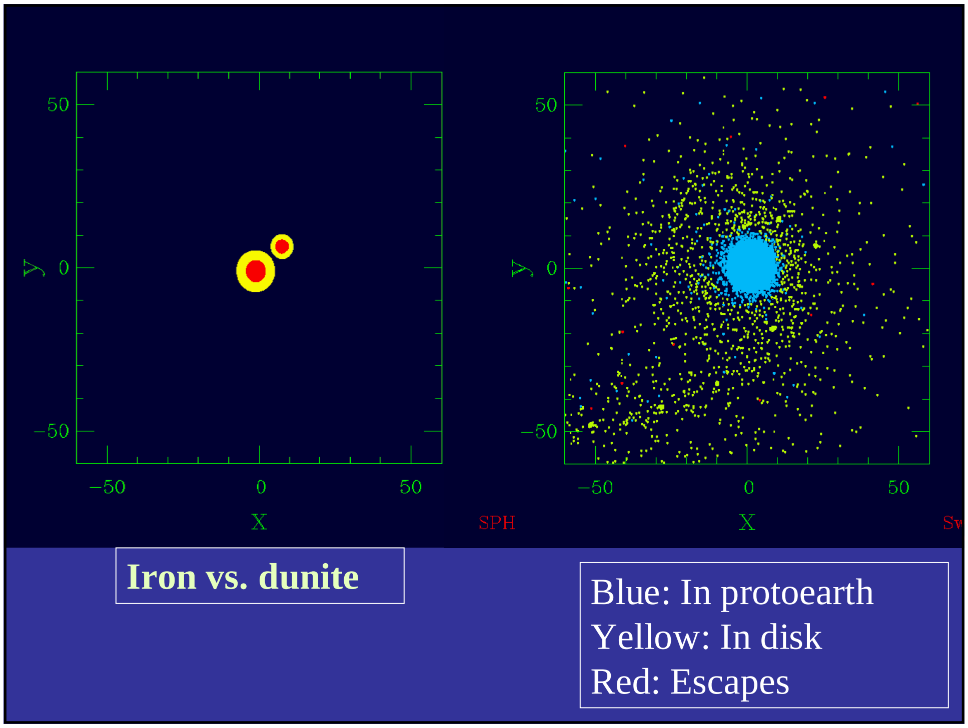
4200 → 4800K

3700 → 4200K

3100 → 3700K

2600 → 3100K

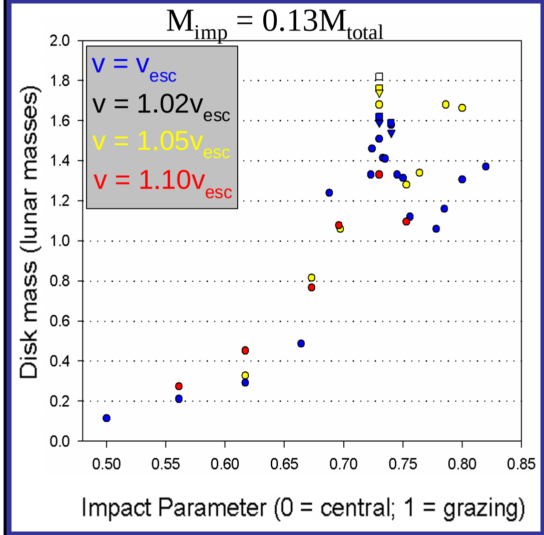
2000 → 2600K



Iron vs. dunite

Blue: In protoearth
Yellow: In disk
Red: Escapes

General trends in impact outcome



- ➢Oblique, low-velocity impacts yield orbiting material

  $b > 0.7$, $v < 1.2v_{esc}$

- ➢Fraction of colliding mass placed into orbit generally increases as:
  - b increases
  - Relative size of impactor to target increases

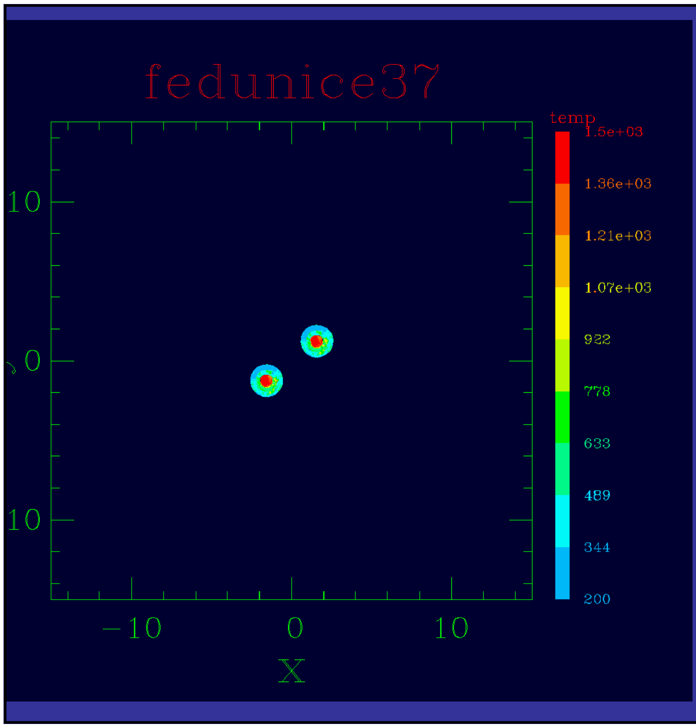
An impact formation of Pluto-Charon?

	Earth-Moon	Pluto-Charon
M_{SAT} / M_{Plan}	0.012	0.12 ± 0.008*
L_{TOT}/L_*	0.35	>1

**from Olkin et al. 2003*

$$L_* \equiv K M_T R_T^2 \sqrt{G M_T / R_T^3}$$

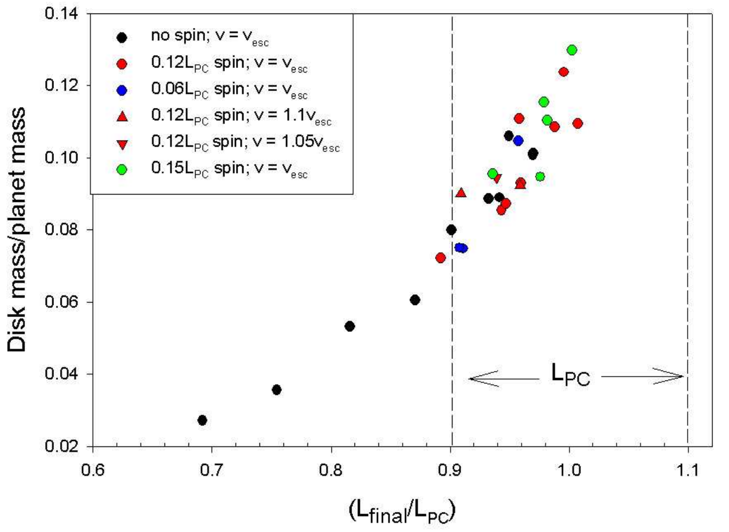
critical angular momentum for rotational stability for a spherical body of mass M_T



- 40% ice/60% rock objects
- $v = v_{esc}$
- $L_{imp} \sim 1.17 L_{PC}$
- $N = 20{,}000$

- $M_{disk}/M_p \sim 0.13$
- $L_{final}/L_{PC} \sim 1$

(with $L_{PC} = 6.3 \times 10^{37}$ g-cm^2/sec)



Preliminary results:

Most favorable collisions involve similar sized objects, low impact velocities ($v_\infty < 0.5$ km/sec). Suggest $\rho_C < \rho_P$

Implications:

1. Impact generation of satellites should be common in late stage accretion
    - Large collisions between similarly sized objects
    - Random impact orientation → many oblique impacts: 50% of collisions have $b > 0.7$
2. Terrestrial planets, giant planet cores may have all had impact-generated satellites
3. Eventual fate determined by later events:

Later impacts, tidal evolution, or runaway gas accretion

Galilean satellites

Io:

•$3.5\ g/cm^3$

•Silicate

Europa:

- $3.0\ g/cm^3$
- Hydrated silicate

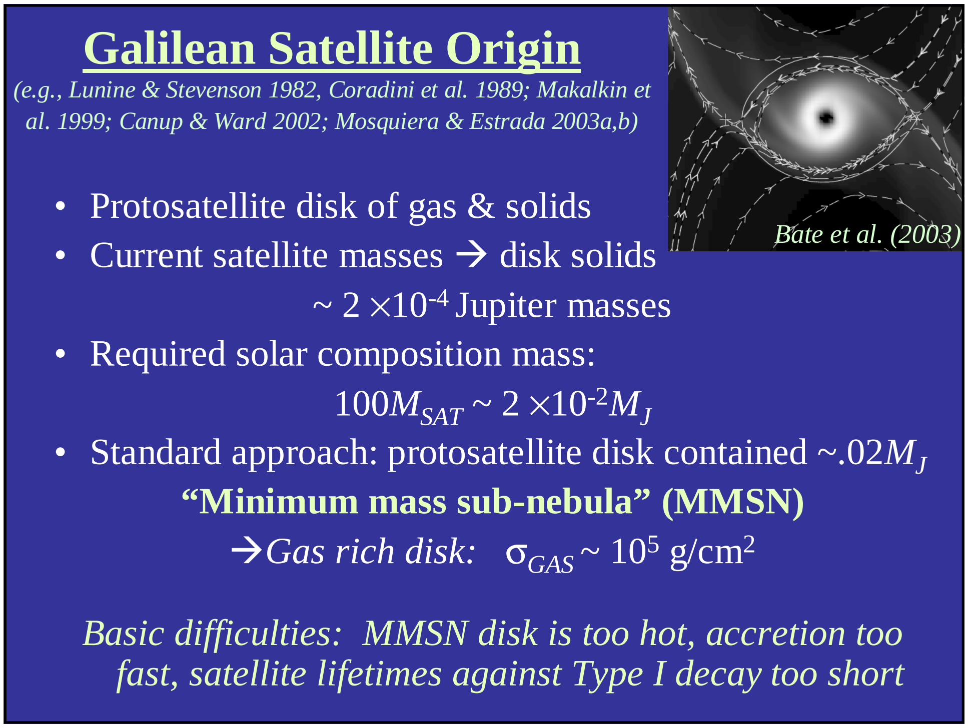
Ganymede:

- $1.9\ g/cm^3$
- 50% rock, 50% ice

Callisto:

- $1.8\ g/cm^3$
- 50% rock, 50% ice
- **Partially differentiated**

(e.g., Anderson et al. 2001)



Galilean Satellite Origin

(e.g., Lunine & Stevenson 1982, Coradini et al. 1989; Makalkin et al. 1999; Canup & Ward 2002; Mosquiera & Estrada 2003a,b)

Bate et al. (2003)

- Protosatellite disk of gas & solids
- Current satellite masses → disk solids

$$\sim 2 \times 10^{-4} \text{ Jupiter masses}$$

- Required solar composition mass:

$$100M_{SAT} \sim 2 \times 10^{-2} M_J$$

- Standard approach: protosatellite disk contained ~$.02M_J$

"Minimum mass sub-nebula" (MMSN)

→*Gas rich disk:* $\sigma_{GAS} \sim 10^5$ g/cm^2

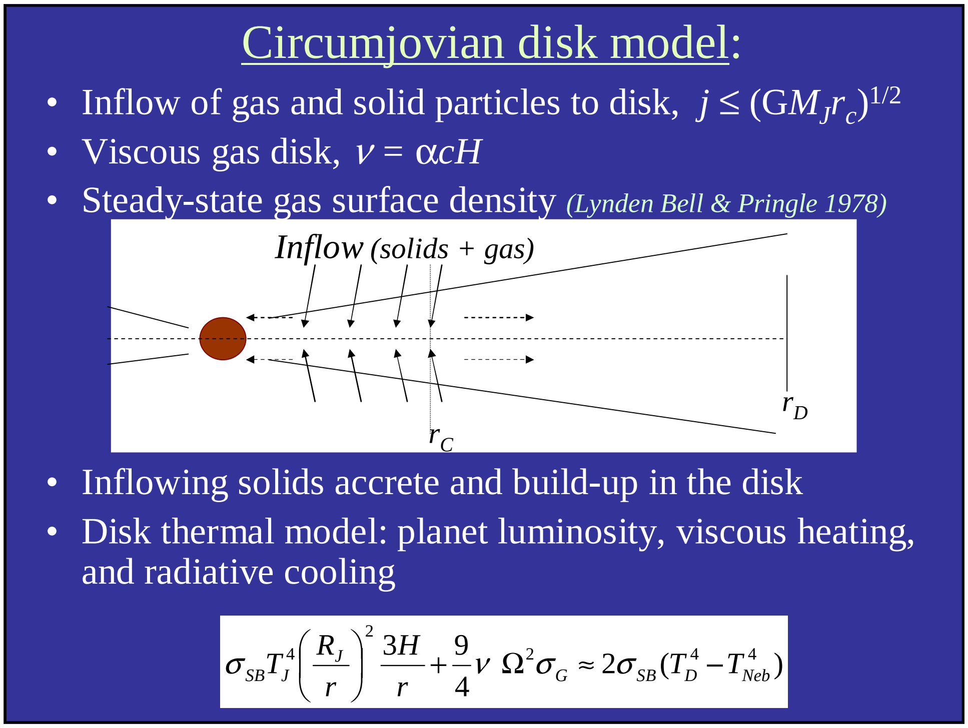
Basic difficulties: MMSN disk is too hot, accretion too fast, satellite lifetimes against Type I decay too short

Alternative model: Slow-inflow accretion disk

(Canup & Ward 2002)

- Gas & solids delivered during final stages of Jovian accretion
- ~$10^{-2}M_J$ is minimum mass that was processed through satellite disk, but not necessarily in disk all at one time
- Gas maintains quasi steady-state; solids accrete and build-up in disk with time
- Result: prolonged satellite formation over >10^5 years in a cool, "gas-starved" disk

Consistent with incompletely differentiated Callisto, icy outer satellites, satellite survival against Type I decay



Circumjovian disk model:

- Inflow of gas and solid particles to disk, $j \leq (GM_J r_c)^{1/2}$
- Viscous gas disk, $\nu = \alpha c H$
- Steady-state gas surface density *(Lynden Bell & Pringle 1978)*

- Inflowing solids accrete and build-up in the disk
- Disk thermal model: planet luminosity, viscous heating, and radiative cooling

$$\sigma_{SB} T_J^4 \left(\frac{R_J}{r}\right)^2 \frac{3H}{r} + \frac{9}{4}\nu\ \Omega^2 \sigma_G \approx 2\sigma_{SB}(T_D^4 - T_{Neb}^4)$$

Constraint on inflow rate, *F*:

- Effective disk temperature depends on F_0 (g/sec), but is independent of disk viscosity, ν

$$T_D^4 \approx \frac{9\Omega^2}{8\sigma_{SB}} \nu \sigma_{GAS} \quad , \quad \sigma_{GAS}(r) \propto \frac{F_0}{\nu} \quad \longrightarrow \quad T_D^4 \propto F_0$$

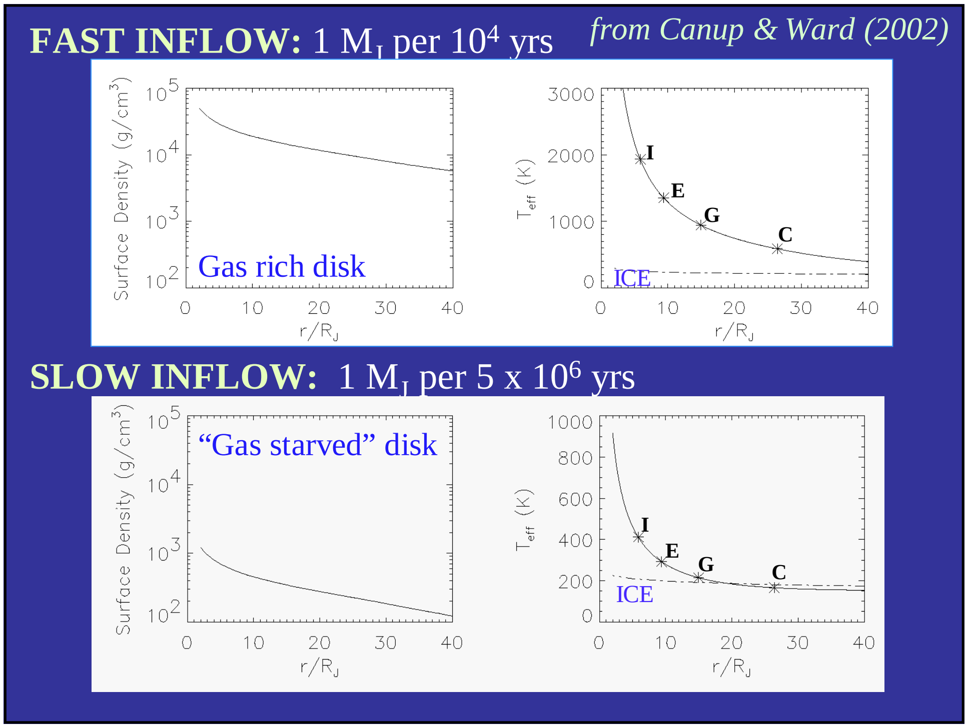
- Temperature constraint: Icy Ganymede/Callisto

$T_D \leq 200$ K → *F* < (1 Jupiter mass)/5 x 10^6 years

or **_F_ < few x 10^{-5} $M_\oplus$ per year**

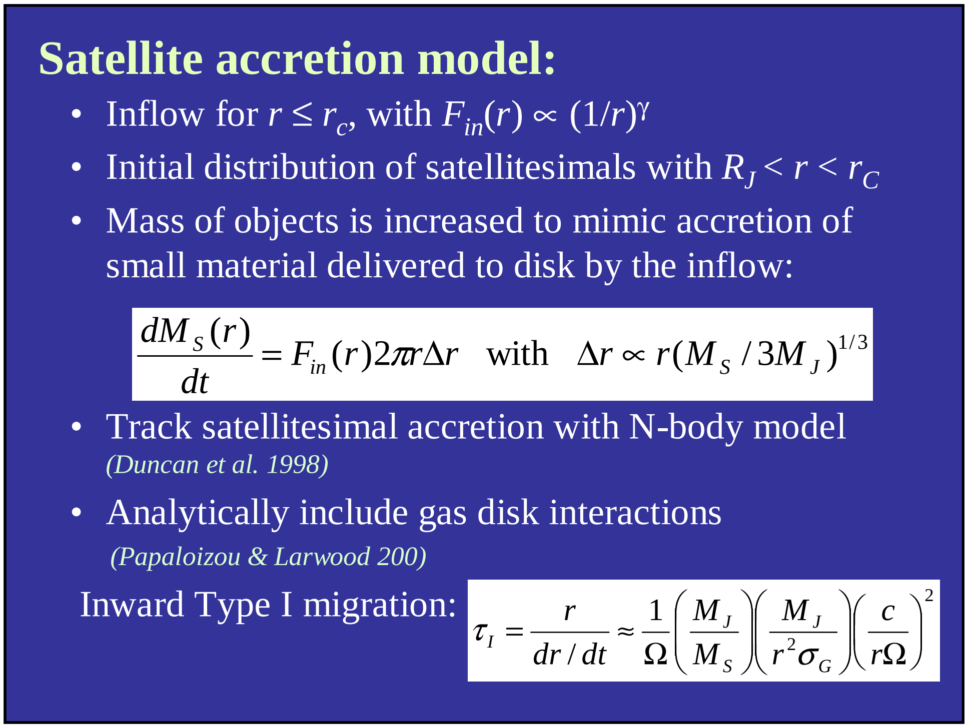
→ Galilean satellites formed as gas accretion onto Jupiter was slowing down

→ Low disk gas surface densities



FAST INFLOW: 1 M_J per 10^4 yrs *from Canup & Ward (2002)*

SLOW INFLOW: 1 M_J per 5 x 10^6 yrs



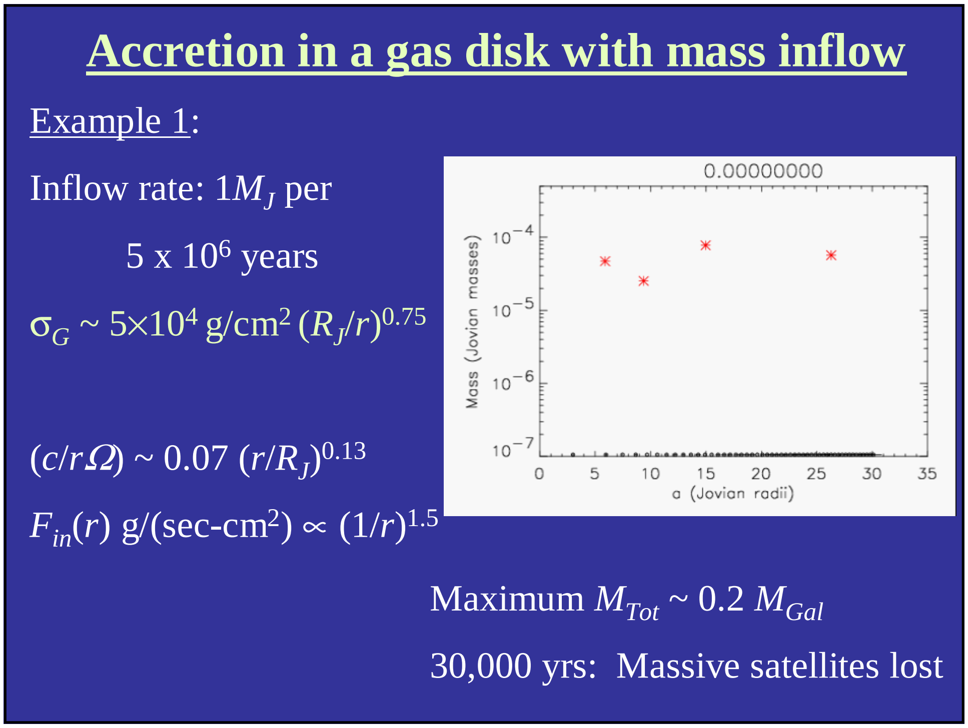
Satellite accretion model:

- Inflow for $r \le r_c$, with $F_{in}(r) \propto (1/r)^{\gamma}$
- Initial distribution of satellitesimals with $R_J < r < r_C$
- Mass of objects is increased to mimic accretion of small material delivered to disk by the inflow:

$$\frac{dM_S(r)}{dt} = F_{in}(r) 2\pi r \Delta r \quad \text{with} \quad \Delta r \propto r(M_S/3M_J)^{1/3}$$

- Track satellitesimal accretion with N-body model *(Duncan et al. 1998)*
- Analytically include gas disk interactions *(Papaloizou & Larwood 200)*

Inward Type I migration: $\tau_I = \frac{r}{dr/dt} \approx \frac{1}{\Omega}\left(\frac{M_J}{M_S}\right)\left(\frac{M_J}{r^2\sigma_G}\right)\left(\frac{c}{r\Omega}\right)^2$



Accretion in a gas disk with mass inflow

Example 1:

Inflow rate: $1M_J$ per

5×10^6 years

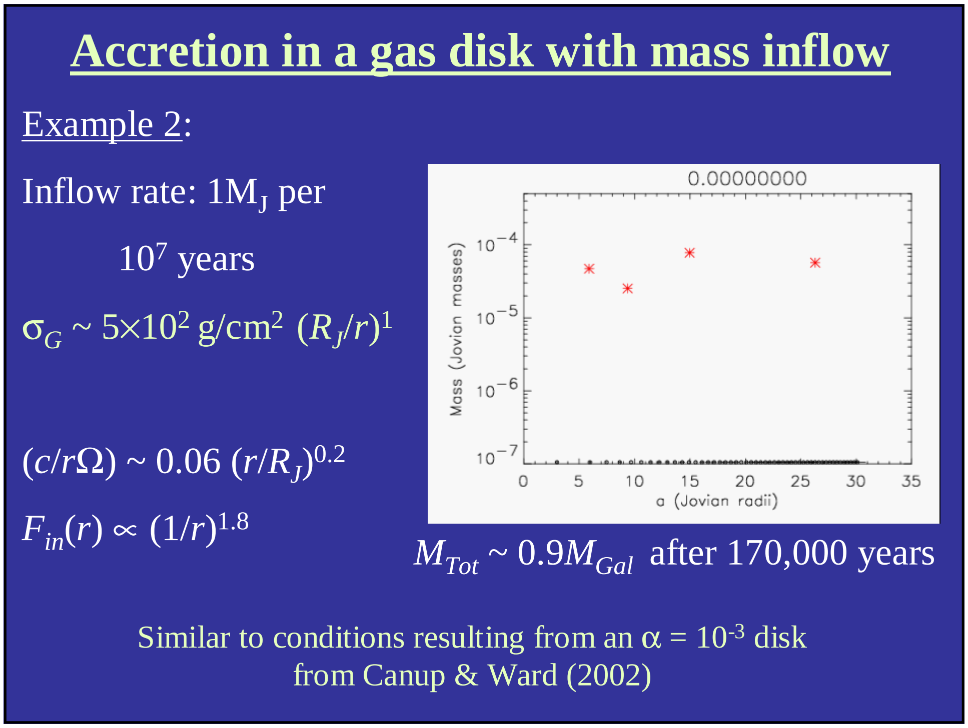
$\sigma_G \sim 5{\times}10^4$ g/cm^2 $(R_J/r)^{0.75}$

$(c/r\Omega) \sim 0.07\ (r/R_J)^{0.13}$

$F_{in}(r)$ g/(sec-cm^2) $\propto (1/r)^{1.5}$

Maximum $M_{Tot} \sim 0.2\ M_{Gal}$

30,000 yrs: Massive satellites lost



Accretion in a gas disk with mass inflow

Example 2:

Inflow rate: $1M_J$ per

10^7 years

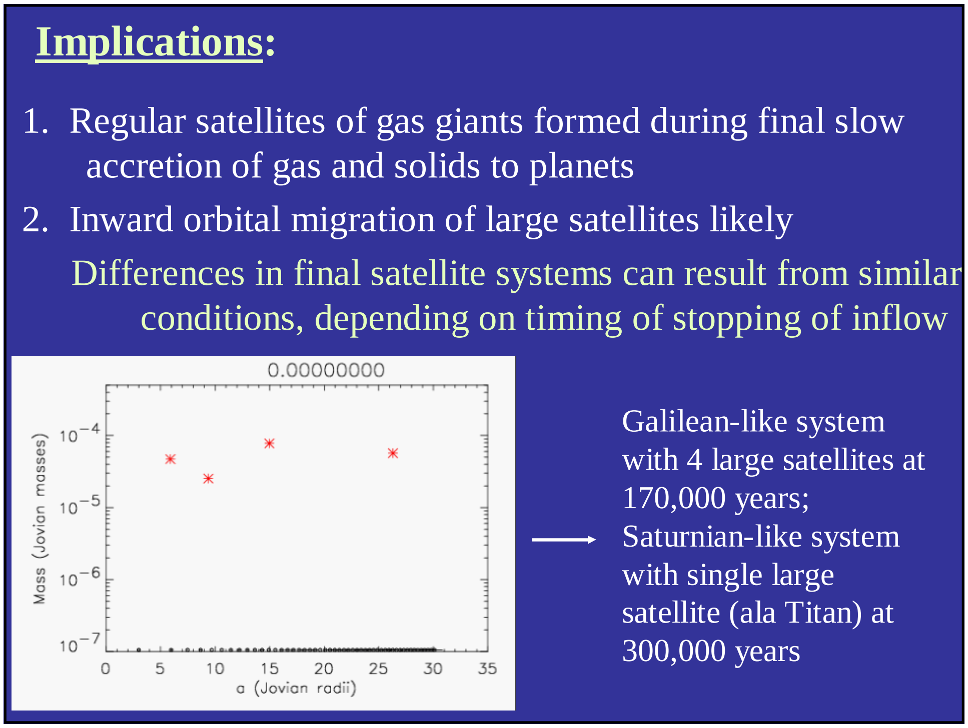
$\sigma_G \sim 5{\times}10^2$ g/cm^2 $(R_J/r)^1$

$(c/r\Omega) \sim 0.06\ (r/R_J)^{0.2}$

$F_{in}(r) \propto (1/r)^{1.8}$

$M_{Tot} \sim 0.9M_{Gal}$ after 170,000 years

Similar to conditions resulting from an $\alpha = 10^{-3}$ disk
from Canup & Ward (2002)

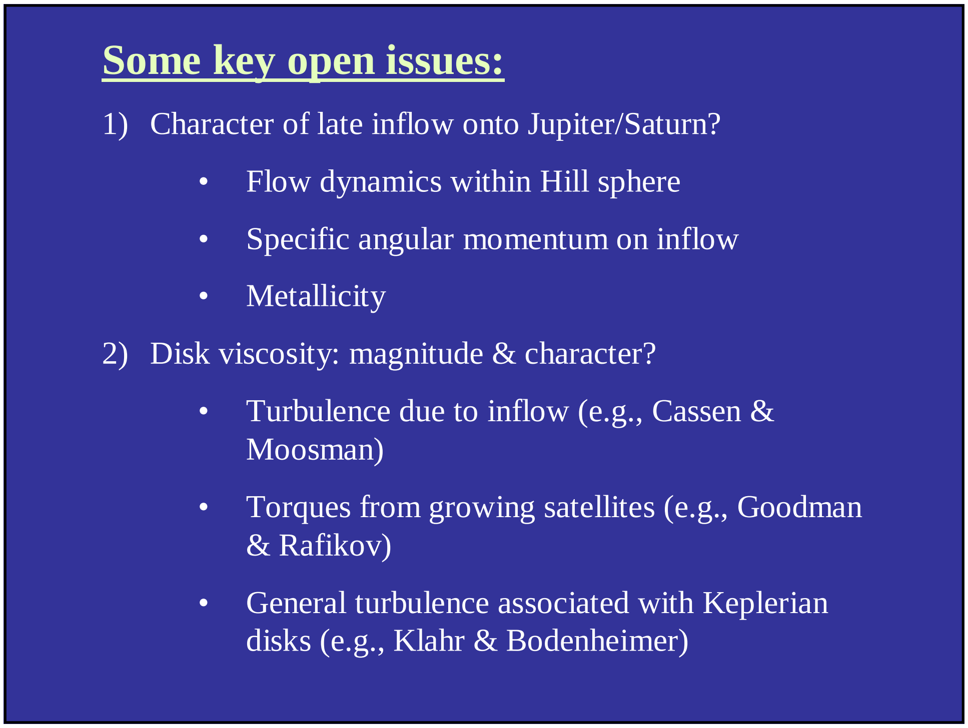


Implications:

1. Regular satellites of gas giants formed during final slow accretion of gas and solids to planets
2. Inward orbital migration of large satellites likely

Differences in final satellite systems can result from similar conditions, depending on timing of stopping of inflow

→ Galilean-like system with 4 large satellites at 170,000 years; Saturnian-like system with single large satellite (ala Titan) at 300,000 years



Some key open issues:

1) Character of late inflow onto Jupiter/Saturn?
   - Flow dynamics within Hill sphere
   - Specific angular momentum on inflow
   - Metallicity
2) Disk viscosity: magnitude & character?
   - Turbulence due to inflow (e.g., Cassen & Moosman)
   - Torques from growing satellites (e.g., Goodman & Rafikov)
   - General turbulence associated with Keplerian disks (e.g., Klahr & Bodenheimer)