

The Early Solar System

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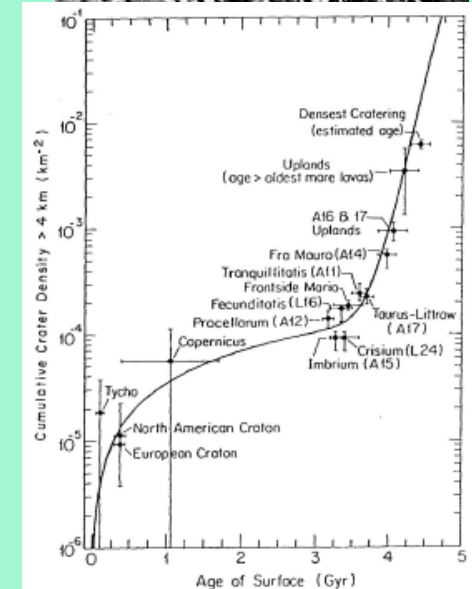
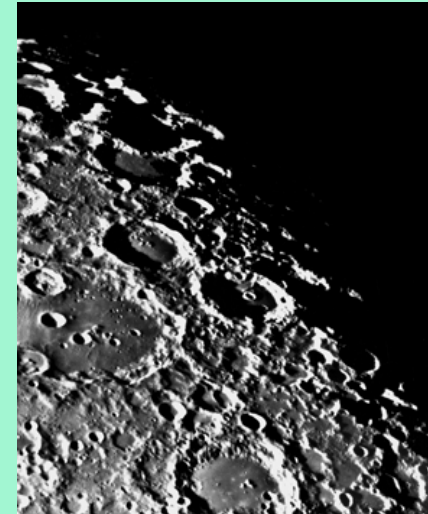
The Early Solar System??

means...

***before the Late Heavy Bombardment
(LHB)***

The Late Heavy Bombardment

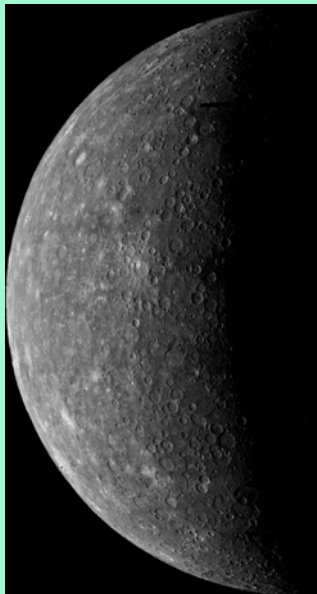
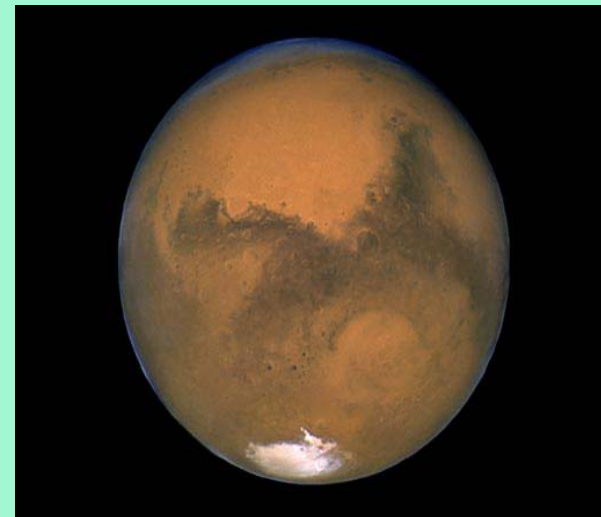
- The **cratering of the Lunar highlands** occurred ~3.9 Gyr ago
- The whole surface was **saturated with craters**
- Surface rocks were **shocked**, and **impact melts** from this time are common



Properties of the LHB

- Decay e-folding time: ~ 30-100 Myr
- ***Very likely episodic*** (lack of older impact melts, no traces of older impact basins, small amount of crustal siderophiles)
- ***Total impactor mass*** for the Moon from crater counts: ~ 10^{19} kg

Consequences...



(?...)



The “Nice Model”

- The Solar Nebula lived for ~ 5 Myr
- The *Giant Planets* accreted within a narrow zone (~ 5.5 -14 AU) during this time
- They formed on circular orbits with $P_S/P_J < 2$
- Outside the GP zone there was an outer *planetesimal disk* of $\sim 35 M_E$
- *Scattering of planetesimals during several hundred Myr \Rightarrow planetary migration \Rightarrow Sat and Jup cross the 2/1 resonance \Rightarrow **havoc!***

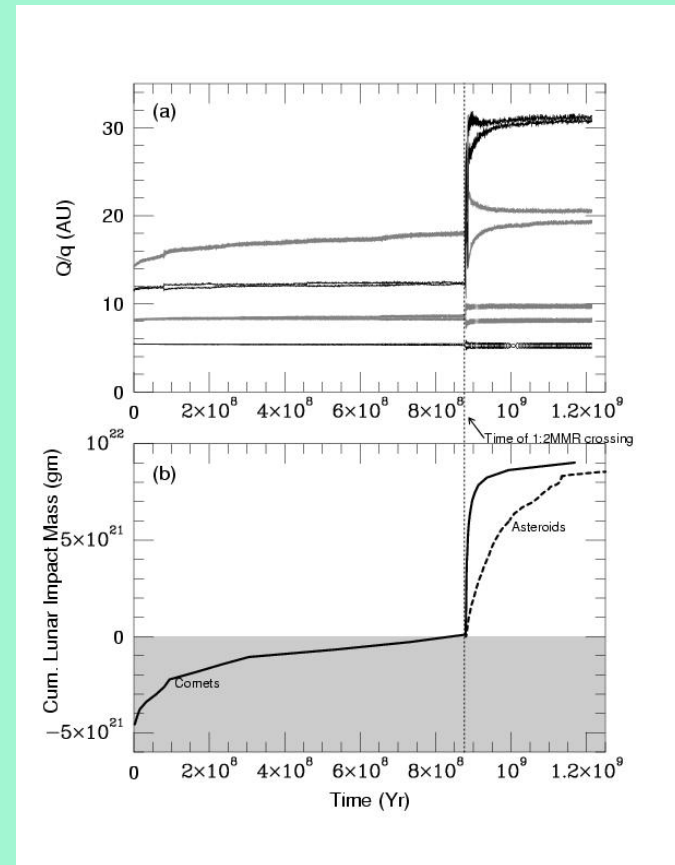
Nice Model Simulation

Tsiganis et al (2005)
Courtesy A. Morbidelli

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

Nature of the impactors

- The Nice Model predicted a ~ *50/50 mix of “asteroids”* (from the Main Belt) *and “comets”* (from the outer disk)
- However... when the model was checked on Earth & Mars, these planets got ejected from the Solar System
- So, the initial conditions have to be tweaked to save the inner planets!



Gomes et al. (2005)

The Greenland rocks

- U.G. Jørgensen et al. (2009) report iridium measurements on *~ 3.8 Gyr sedimentary rocks from Isua, Greenland*
- A *~ sevenfold enhancement of Ir content over usual crustal rocks* was found, indicating *worldwide impact debris deposit*
- But *lunar highland Apollo samples have no Ir enrichment...*
- Conclusion: ***The impactors were cometary*** (with higher velocities than asteroids)

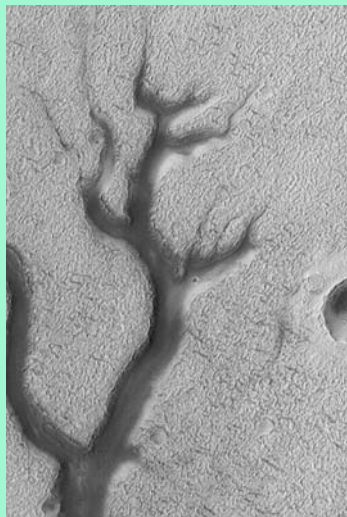
Back to the Nice Model

- Yes, indeed, *the Nice Model can be modified* so that essentially the same things happen, but the Earth is saved
- But then, *~ 90% of Earth/Moon impactors are cometary*, in agreement with Jørgensen et al. (less havoc in the Main Belt and inner Solar System)

LHB water delivery



- Scaling from Moon to Earth, *the amount of H_2O deposited on the Earth is much less than the ocean mass (1.5×10^{21} kg)*
 \Rightarrow ***early source for Earth's water***

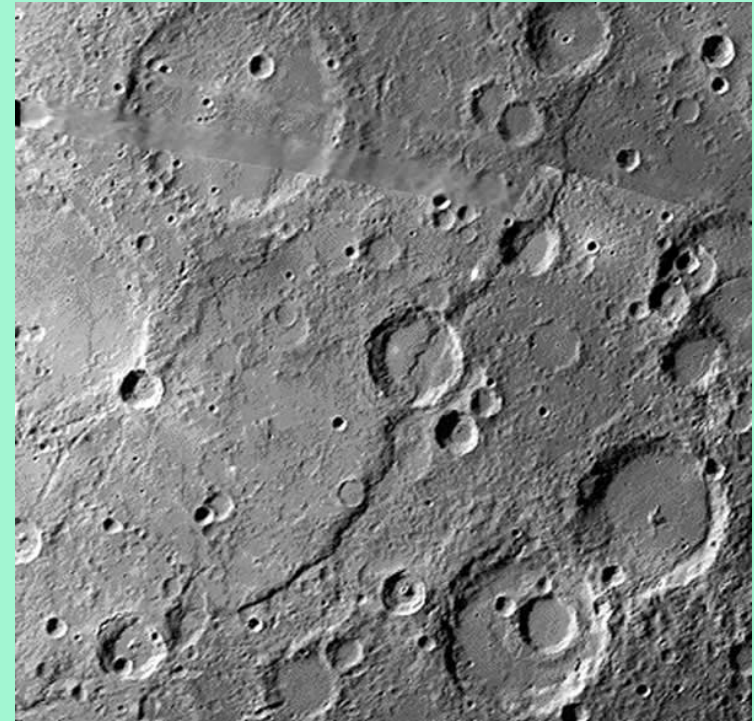


- Mars may have acquired *enough H_2O and CO_2 to form a temporary, shallow sea and stabilizing atmosphere (~ 1 bar surface pressure)*

What about Mercury?

Tentatively:

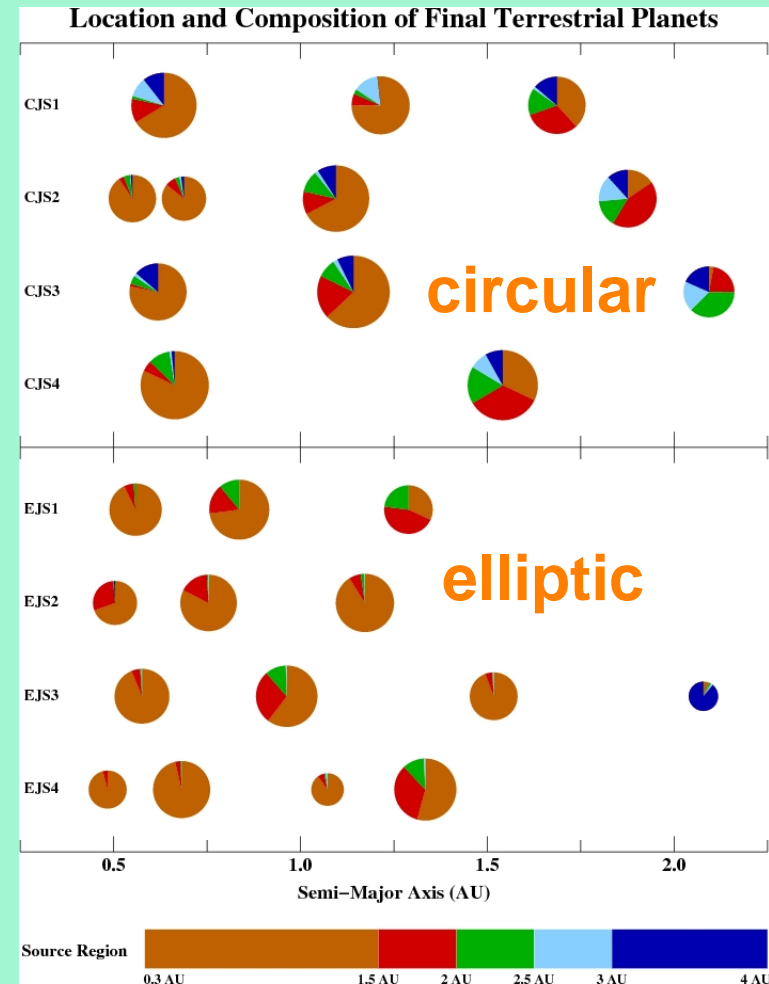
- Short-period comets rarely reach perihelion distances < 0.5 AU
- If the LHB was “cometary”, very few impacts would have occurred on Mercury
- *Do Mercury’s surface features date back to much older epochs?*



Mercury: Discovery Rupes

Terrestrial Planet accretion

- **Preferred scenario from dynamical simulations:**
 - (1) local embryos by oligarchic growth
 - (2) accretion into planets on ~100 Ma time scale with Jupiter and Saturn on quasi-circular orbits
- *This explains the formation chronology based on extinct radioisotopes, and predicts ~1-10% of TP masses as H₂O-rich Carbonaceous Chondrite material*



Morbidelli 2009

Early water – Grace or problem?

- **Earth:** certainly a grace, explains *early ocean and present H₂O/CO₂ content*
- **Venus:** likely a grace, explaining *current CO₂ and lost H₂O*
- **Mercury:** explain the present lack of volatiles by *stripping of the early mantle?*
- **Mars:** *early phyllosilicates, missing near-surface carbonates, H₂O/CO₂ at depth?*

Space Missions

- *Lunar*: more highland/farside samples, better siderophile abundances
- *Martian*: history of surface water and atmosphere, early crustal samples (mineralogy/lithology, carbonate deposits)

MARS EXPRESS, EXOMARS...

- *Hermean*: establish absolute dating, improve mineralogical characterization of surface rocks

MESSENGER, BEPICOLOMBO