On the Origin of the Rocky Planets, Fugue in Venus Megacollision

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And art thou, then, a world like ours,
Flung from the orb that whirled our own
A molten pebble from its zone?
How must the burning sands absorb
The fire-waves of the blazing orb,
Thy chain so short, thy path so near
Thy flame-defying creatures hear
The maelstroms of the photosphere!

- Oliver Wendell Homes, Sr
Paper 1: Narrow Annulus Formation

- Basic premise:
  - Majority of terrestrial planet-forming mass was concentrated in an annulus from 0.7-1.0 AU
  - Computational simulations of accretion from this annulus can produce solar system-like results
  - Effects constraints on disk condensation, initial accretion, comsochemical signatures, and *collisional environment*
Background

• Prior planetary formation models tend to produce systems that are dynamically “too hot” – meaning too much eccentricity and inclination

• Prior solutions:
  – Include a small-bodies to damp out orbits
    • But how do the small bodies survive long enough?
  – Giants sweeping orbital resonances
Hypothesis

• Rather than invoking a way to later reduce angular momentum, simply have less to begin with

• Concentrate all planet-forming mass in ring between present Earth and Venus orbits

• Assume totally oligarchic accretion, removing small-body effects
Initial Conditions

• Total of $2\, M_\oplus$ of mass spread over 0.7 and 1.0 AU, in 400 equal mass bodies
  – Surface density of 333 kg/m$^2$

• Currently $1.98\, M_\oplus$ of mass between 0.4 and 1.5 AU, density of 80 kg/m$^2$

• Each object $0.005\, M_\oplus \approx$ Europa Mass
Orbital Simulation

- Orbits circular, low inclination, and spread randomly across annulus
- Four-day timestep for 1 billion years
- Jupiter at perturbing at 5.2 AU

- Mercury6 open-source orbital integrator (Chambers et al. 1999)
Example Results

[Diagram showing a comparison between simulated and actual solar system data. The x-axis represents 'a (AU)', with values ranging from 0.5 to 2 AU. Different simulations (Sim23, Sim1, Sim5, Sim4, Sim15, Sim14) are plotted, each with error bars indicating variability.]
Discussion: Collisions

• Tend to form multiple large planets in 0.7-1.0 AU zone, which then collide in giant impacts

• Higher probability of planet-disrupting impactors hitting Earth and Venus

• On Earth => Moon-forming impact
• On Venus => ???
Discussion: Mars Formation

- Mars-analog forms in most cases
  - Low-mass, scattered out from main annulus

1. Mars accretes in Earth-region
2. Is then scattered out and remains coupled to the proto-Earth
3. Until the intermediary embryos are removed, finally isolating Mars
Discussion: Mercury Formation

- Much harder to form Mercury-analog
- Generally requires both scattering and large collisions
- Could explain Mercury’s huge density / apparently large core (Urey 1951)

- Not really helped by additional matter interior of main annulus
Discussion: Timescale

- Compact annulus allows for fast planetary accretion to near-final mass
Broader Implications

• If a narrow annulus is a natural effect, then would be a function of disk structure

• The disk structure is a function of stellar mass

• Thus, the locations of the largest terrestrial planets may be some function of stellar type
Paper 2: Venus MEGA-COLLISION!

- Venus has several striking differences from the Earth, both physically and chemically.
- A giant impact can influence both simultaneously.
- A nearly head-on collision appears to have enough energy to dry Venus.
  - And is more likely than previous anticipated.
Venus Background

- Earth-like mass
- Slow, retrograde rotation rate
- Atmosphere very dry
- Interior inferred to also be very dry

- Why and How?
Water and Venus

- Solar losses can explain atmosphere, not interior
- Gravity strongly matches topography, limited lithospheric relaxation in craters
- Implies stronger rheology than Earth

- Only possible in Venusian temperatures if interior has an order of magnitude less water than Earth
Why so dry?

• Three previously proposed possibilities:

1. Venus formed from dry embryos from interior to its present orbit
2. Earth just as dry, water delivered later
3. Venus just never recycled, because no subduction
Mega-Collision

• Basis of Moon-forming impact theory was the dryness of returned Moon rocks

• A planet-disrupting impact could have a similar effect on Venus

• Would require two similar-mass proto-Venuses, impacting head-on
  – Totally disrupts, but combines as a single body
Impact Conditions

- Requires >10 Gpa across most of mantle(s) to totally dehydrate

- Scaling off Canup et al.’s Moon-forming impact simulations, two similar-sized impactors

- Also, low impact angle (<30°) more probable than Earth-Moon glancing impact
Atmospheric Effects

• After impact, the CO$_2$ should survive longer than H$_2$O due to lower UV photolysis and solar wind loss

• Also, the impact would devolatilize any carbonates, further increasing the CO$_2$ in the atmosphere
Compositional Effects

- Impact would initially produce large amounts of rock and iron vapor, insulated by CO$_2$ layer
- Most available water vapor oxidizes iron
- Mantle forms as a magma ocean, exclusive of water and CO$_2$
- Remaining water in atmosphere is gradually stripped away
(a) Mantle - solid
(b) Mantle - liquid
(c) Mantle - vapour
(d) Core - liquid
(e) Core - vapour
(f) Atmosphere
(g) Shocked outflow
(h) Hydrogen driven hydrodynamic escape
Spin Effects

• Final angular momentum is controlled by last few impacts (Agnor et al, 1999)

• Low angular momentum, retrograde spin consistent with near head-on collision (Canup and Ward, 2001)
  – Also consistent with no satellite formation
Venus Summary

• Single, very large impact could explain Venus’s
  – Apparently dry atmosphere
  – Thick CO$_2$ atmosphere
  – Slow retrograde rotation

• However, needs proper simulations for verification