Constraints on the Geodynamical Evolution of Venus from Argon Degassing and the Cratering Record

Joseph G. O’Rourke\textsuperscript{1} and Jun Korenaga\textsuperscript{2}

\textsuperscript{1}California Institute of Technology, Pasadena, CA
\textsuperscript{2}Yale University, New Haven, CT
Two Related Questions

1. Has the surface of Venus suffered one or more episodes of rapid, global resurfacing?
   – Impact craters: O’Rourke et al., GRL, 2014

2. Were mantle dynamics dramatically different than stagnant-lid convection in the past?
   – Thermal evolution: O’Rourke & Korenaga, in revision
Types of Impact Craters

• Only \(~10^3\) craters seen today
  – Distribution governed by atmospheric screening, impactor populations, resurfacing events
  – Latitudes and longitudes are consistent with randomness

• Only \(~10\%\) are obviously embayed by external flows
  – Schaber et al. (JGR, 1992) suggested catastrophic resurfacing at \(~0.5\) Ga, followed by limited volcanism
Equilibrium Resurfacing Model

- Localized resurfacing events can produce random crater distributions
- Strom et al. (JGR, 1994) rejected this model for producing too many embayed craters
- Bjonnes et al. (Icarus, 2012) recognized that this model can be easily tuned
Mystery of Dark-Floored Craters

- ~80% have radar-dark floors in Magellan imagery
- Post-impact volcanic modification?
  - Incomplete halos and ejecta (Herrick & Rumpf, JGR, 2011)

\[ d_{bf} = 484 \text{ m} \left( \frac{D}{1 \text{ km}} \right)^{0.165} \]

\[ d_{df} = 424 \text{ m} \left( \frac{D}{1 \text{ km}} \right)^{0.108} \]

- Shallow rim-floor depths and low rim heights

D ~ 30 km
Modeling Cratering and Resurfacing

• Both Poisson processes occur everywhere on the surface with equal probability with time constants $\sim 1$ event/Gyr (exponential distribution)

• Test models using Monte Carlo simulations

• Localized resurfacing by thin, low viscosity flows

• Statistical analysis of results using $n$th-nearest neighbor statistics ($n = 1, 3, 6$)
Results: Impact Craters

A. Crater Topography

\[
\log_{10}(D \text{ [km]})
\]

- d_{bf} = 484 m (D / 1 km)
- d_{df} = 424 m (D / 1 km)

B. Size Distributions

- Obviously embayed, dark-floored (80)
- Obviously embayed, bright-floored (6)
- Not embayed, dark-floored (668)
- Not embayed, bright-floored (179)
Results: Impact Craters

Dark-floored
- Random? YES
- Model? YES!

Bright-floored
- Random? YES
- Model? YES!

Embayed
- Random? NO!
- Model? NO!!!
Simulating Thermal Evolution

1D parameterized model previously applied to Mars and “super-Venus” planets (e.g., O’Rourke & Korenaga, 2012)

Incorporates volatile transport ($H_2O$, $K$, $^{40}Ar$) and mantle plumes

Diagram:
- Core (Liquid?)
- Mantle (Convecting)
- Thermal lithosphere
- Includes volatile transport ($H_2O$, $K$, $^{40}Ar$) and mantle plumes
- Crust
- Depleted mantle lithosphere
- Mantle lithosphere
Argon Degassing from Venus

- $3.3 \pm 1.1$ ppb of Venus is atmospheric $^{40}\text{Ar}$
- Four landers measured abundances of K, U, and Th
- Fundamental assumptions:
  - All $^{40}\text{Ar}$ in processed mantle degasses instantly
  - All $^{40}\text{Ar}$ produced by decay of crustal $^{40}\text{K}$ degasses in 1 Myr
  - No atmospheric loss of $^{40}\text{Ar}$
Results: Thermal Evolution

- $T_{cm}$
- $T_u$
- $T_c$

- Heat Flow (mW m$^{-2}$)
- $F_{cm}$
- $F_m$
- $F_s$

- Thickness (km)
- $h_{ML}$
- $h_{DML}$
- $h_c$

- $\log_{10} [M_{atm, \, ^{40}Ar}]$ (kg)

- $[U]_{PM} = 17$ ppb
- $K/U = 7,220$

- $\sim 45\%$ of volatiles retained in interior

- Fraction Resurfaced
- >0.1 km
- >1 km

- 50% Extrusive
Results: Thermal Evolution

- Less crustal production than Armann & Tackley (JGR, 2012)
  - No “end-member assumption” that all magma immediately erupts
  - Consider lower values of $[U]_{PM}$
  - Relax assumptions of perfect degassing to permit recycling?
- Core is cooling, producing plumes but no dynamo
  - No contradiction because cooling is by conduction, not convection
  - Lots of ways to kill a dynamo…
Conclusions

• Two types of non-catastrophic volcanism produce the observed cratering record
  – Thin, morphologically similar flows can explain the number and distribution of dark-floored craters

• Thermal evolution simulations featuring evolution in the stagnant-lid regime satisfy many constraints
  – Atmospheric abundance of radiogenic $^{40}$Ar
  – Crustal and lithospheric thicknesses
  – No global magnetic field at present
  – Plumes upwelling from the CMB?
  – Crustal abundance of potassium