Comparative planetary interiors and the effects on habitability

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in collaboration with

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Outline

• How does the planetary interior influence the habitability?
  • General concept
  • Difference between plate tectonic and stagnant lid planets

• Would an Earth-like planet be habitable without plate tectonics?
  • Coupling the interior with atmosphere models
Habitability and Habitable zone

Potential of an environment to support life (presence of liquid water at the surface)

- Distance to the star
- Presence and composition of atmosphere
Planetary Interior Dynamics

- Volcanic and tectonic history
- Magnetic field
- Atmosphere evolution
What influences the thermal, magnetic and atmosphere evolution?

• Tectonic mode
  (plate tectonics – stagnant lid convection)

• Mass, Size, Interior structure and composition
One-Plate-Planet

Atmosphere

Biosphere

Hydrosphere

Crust

Volcanism

Mantle

Degassing

Erosion by solar wind; Impacts

Space

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Plate Tectonic Planet

Atmosphere

Biosphere

Hydrosphere

Crust

Volcanism

Mantle

Degassing

Erosion by solar wind; Impacts

Space

Eroision by solar wind; Impacts
Subduction, regassing, and enhanced cooling

Shelining by solar wind; Impacts

Erosion by solar wind; Impacts

Convective Cooling

Dynamo Action
Plate tectonics and habitability

Plate tectonics recycles near-surface rocks and volatiles with the planet’s interior through subduction. This helps

• to create **geologic diversity**, e.g., granitic cratons that will form continents and continental shelves and mid oceanic ridges with their black smokers
• to replenish depleted surface rock as the base for the **nutrition chain**
• to stabilize the **atmosphere temperature** and create clement conditions through the carbonate-silicate cycle
• to cool the deep interior and to generate a **magnetic field** in the core
• The strong dependence of rock viscosity on temperature naturally leads to the formation of a stagnant lid
• The ultimate reasons why plate tectonics occurs only on Earth are unknown, let alone on extrasolar bodies, whether of larger or similar size
The big debate: Plate tectonics on exoplatents

• Increase in mass results in stronger lithospheric stresses $\Rightarrow$ PT more likely
  ‣ Valencia et al. (2007)
  ‣ Valencia and O’Connell (2009)
  ‣ Van Heck and Tackley (2011)
  ‣ Foley et al. (2012)

• Increase in mass results in stronger increase of yield stress $\Rightarrow$ Pt less likely
  ‣ O’Neill and Lenardic (2007)
  ‣ O’Neill et al. (2007)
  ‣ Stein et al. (2004)

• Increase in internal heating rate $\Rightarrow$ Pt equally or less likely
  ‣ Van Heck and Tackley (2011)
  ‣ Stein et al. (2013)
  ‣ Foley et al. (2012)
  ‣ Stamenkovic and Breuer (2014)
The big debate: Plate tectonics on exoplanets

- History dependent (e.g. initial conditions)
  - Lenardic and Crowley (2012)
  - Weller and Lenardic (2012)
  - Noack and Breuer (2013)
  - Stamenkovic et al. (2014)
  - Weller et al. (2015)
  - Wong and Solomatov (2016)
  - O’Neill et al. (2016)
The strong dependence of rock viscosity on temperature naturally leads to the formation of a stagnant lid.

The ultimate reasons why plate tectonics occurs only on Earth are unknown, let alone on extrasolar bodies, whether of larger or similar size.

Would an Earth-like planet without plate tectonics be habitable, i.e. have liquid water at the surface?
Interior + atmosphere modelling

- **Interior evolution** of an Earth-like, stagnant lid planet
- **Outgassing** of $\text{H}_2\text{O}$ (via fractional melting) and $\text{CO}_2$ (via redox melting)
- **Atmospheric temperature** and boundaries of the habitable zone determined exclusively from $\text{H}_2\text{O}$ and $\text{CO}_2$ outgassed from the interior

Tosi et al., 2016
Atmospheric model


• Model features:
  ‣ cloud-free
  ‣ steady-state temperature and pressure calculation
  ‣ H₂O profile derived from temperature and relative humidity profiles
  ‣ energy transport via moist convection and radiative transfer
  ‣ linear increase of Sun’s luminosity with time (Gough, 1981)
  ‣ no primordial H-He atmosphere, no atmosphere from magma ocean, only H₂O and CO₂ degassing from the interior
Outgassing of H$_2$O and CO$_2$ into the atmosphere ultimately depends on their solubilities in surface (basaltic) melts.

H$_2$O solubility is more than a factor 100 larger than CO$_2$ solubility \( \Rightarrow \) as the atmospheric pressure grows, H$_2$O tends to be retained in the melt, while CO$_2$ outgassed.
Thermal and crustal evolution

- Initial heating phase between 500 and 1500 Myr followed by secular cooling
- Rapid crust production followed by delamination with the crust quickly becoming as thick as the stagnant lid

Tosi et al., A&A (2017)
Crustal Recycling by Delamination
Outgassing evolution of H$_2$O and CO$_2$

- Outgassing of H$_2$O limited by its high solubility in basalt
- ~20 bar H$_2$O outgassed from the interior for H$_2$O concentrations up to 1000 ppm
- Low solubility of CO$_2$ allows all CO$_2$ in the melt to be outgassed throughout the evolution
- ~2 bar CO$_2$ outgassed from the interior for fO$_2$ at IW, ~20 bar for fO$_2$ at IW+1, ...

Tosi et al., A&A (2017)
Atmospheric evolution at 1 AU

Reference model: $T_m^0 = 1700 \text{ K}$, $X_{H_2O}^0 = 500 \text{ ppm}$, $\Delta J/W = 0$

- Surface temperature rises due to linear brightening of the Sun and increase in greenhouse gases from the interior
- Water vapour in the atmosphere increases with surface temperature
- A liquid water reservoir of $\sim 2\%$ of an Earth ocean can build up

Tosi et al., 2017
Habitable zone evolution

Reference model: $T_m^0 = 1700$ K, $X_{H_2O}^0 = 500$ ppm, $\Delta/I = 0$

- Inner HZ controlled mainly by increasing solar luminosity
- Outer HZ controlled by outgassed CO$_2$ and increasing solar luminosity
- A stagnant lid Earth could be habitable today at Mars’ orbit, but not at Venus’ orbit
Present-day habitable zone
Habitable zone varies with time and depends on

- Initial volatile content (oxygen fugacity)
- Tectonic style
- Mass and size of the planet
- Interior structure
- Atmosphere loss processes
  - Solar activity
  - Weathering rates
**Conclusion**

- The Earth has a fine-tuned balance between volatiles in the interior, the atmosphere and hydrosphere.
- But a stagnant lid Earth can be also habitable although surface conditions are less stable.
- We need to consider also weathering and atmosphere loss processes as well as different planetary masses and sizes.