GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet habitable?

Exoplanets

Lecture 19

Tuesday 4 June 2019

Lecture 1 Key points

- **A useful definition of a habitable world is one that maintains T < 400 K liquid water on its surface continuously for timescales that are relevant for biological macroevolution**
- **Earth has stayed habitable for >3 Gyr**
  - Continuously
  - Earth inhabited only by microbes pre-1 Gya
- A \`difficult step' is a step in biological evolution whose characteristic wait time (given a habitable planet) is >> 10 Gyr. There are at least three candidate difficult steps on the evolutionary path leading to people.
- Earth's continuous habitability implies that Earth's climate has stayed within the habitable range at least for the last 3.5 Ga
  - **However, Earth's pO2, pCO2, and ocean chemistry have changed over time.**

For last time Lecture 2 key points: From Earth history to the Circumstellar Habitable Zone concept

Reminder: Class website is http://geosci.uchicago.edu/~kite/geos32060_2019/

- **Small imbalances between the geologic release rate of pCO2 and the geologic consumption rate of pCO2 would have seriously threatened Earth's habitability.**
- **This strongly suggests a negative feedback has regulated pCO2 over geologic time.**
  - In the last ~10 years, the evidence for a negative feedback has gotten stronger - some people would go further and say a weathering feedback is required to explain the geologic data.
- **A candidate mechanism for the weathering feedback is carbonate-silicate weathering.**
- **The Habitable Zone is defined as the range of distances from a star within which a weathering feedback *might* operate.**

Lecture 3: Atmospheric science basics: Key points

- **Describe and qualitatively explain vertical temperature structure of rocky-planet atmospheres.**
- **Apply elementary models of radiation balance.**
- **Explain the greenhouse effect in terms of vertical temperature structure and opacity at visible and thermal wavelengths.**
- **(Explain the theoretical basis for expecting an atmosphere-surface temperature offset).**

Lecture 4 – volatile supply – key points

- Volatiles can be supplied directly as molecules, or contained within hydrated minerals, within clathrates, or adsorbed to ice particles
- Within protoplanetary disks, the habitable zone is in a region that theory suggests should be dry
- Volatiles can be delivered to the habitable zone by within-disk migration of impactors, scattering of impactors, or whole-planet migration
- Volatiles can be released on impact, or as the result of planetary differentiation.

Lecture 6 key concepts

- Bottlenecks for atmospheric escape
  - Energy supply, exobase, homopause, condensation in atmosphere, condensation at surface
- Energy sources for atmospheric escape
  - Thermal, individual-photons, solar wind, impacts
- Escape parameter, exobase, Jeans escape
- The role of the sonic point in hydrodynamic escape

Lecture 7 topics

- Energy-limit: XUV driven escape more-likely-than-not sculpts the exoplanet radius-period distribution ('photo-evaporation valley')
- Diffusion limit: what regulates H loss from Venus, Earth and Mars today
- Impact erosion – giant impacts and planetesimal impacts

Lecture 8 wrap-up
Runaway greenhouse – key points

- The (H_2O-)runaway greenhouse is a geologically rapid increase in planet surface temperature from <500K to >1000K caused by a positive feedback between the saturation vapor pressure of water vapor and the planet surface temperature
- Be able to explain the mechanism of the runaway greenhouse
- It is almost certain that release of CO_2 by humans cannot cause a runaway greenhouse
- The exact threshold for the runaway greenhouse depends on cloud cover, land fraction, and planet rotation rate

Outer limits of the habitable zone – **Lecture 9 outline**

- **CO_2-atmosphere collapse**
- "Maximum greenhouse" - CO2 condensation
- Ice-albedo feedback, snowball states
- Limit cycles

What controls the weathering rate?

- **Water supply (to flush away dissolved products)**
- CO_2 concentration (acidity; thermodynamics)
- Temperature (→ kinetics)
- Reactive surface area (uplift/tectonics/erosion)

Tests for the carbonate-silicate weathering feedback hypothesis:

- Seek *present-day* gradients weathering corresponding to present-day gradients in temperature between watersheds.
- Seek evidence for weathering increases during *geologically-sudden past warm events*.
- (Because of the Faint Young Sun) look for evidence of higher pCO2 in the distant geologic past.

Key points for Lecture 14

- Mechanisms by which biology / organic carbon sequestration might affect long-term climate regulation
- Understand/explain the Daisyworld model
- How ^{7}Li may be used to track weathering intensity vs. time: examples from the geologic record
- Discuss nutrient limitation on modern Earth; pre-photosynthetic Earth; and Earth when dominated by anoxygenic photosynthesis.

Climate stabilization on early Mars

MODERN MARS CLIMATE

CARBON FEEDBACKS?

SULFUR FEEDBACKS?

HYDROGEN?

INTERMITTENCY?

Ice-covered oceans

- evidence for global sub-ice oceans in the outer Solar System;
- the “ideal” sub-ice ocean for biology (and ways in which Europa, Ganymede and Enceladus deviate from that ideal).

Persistent global ice cover:

DATA

PHYSICAL BASIS FOR LONG-TERM OCEAN STABILITY

ENERGETIC CONSTRAINTS ON BIOSPHERES

FUTURE TESTS AND TECHNIQUES

Exoplanet habitability (Lecture 19)

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE NUMEROUS

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- MG/SI/FE
- WATER
- CARBON

THE M-STAR OPPORTUNITY

- PROBLEMS FOR HABITABILITY FOR PLANETS ORBITING M-STARS

FUTURE MISSIONS