## What Makes a Planet Habitable?

The recent boom in exoplanet discoveries, especially of terrestrial planets which are becoming increasingly accessible to observations, makes the question "Are there habitable exoplanets?" more interesting than ever before. This reading list reviews some of the basic concepts and questions related to habitability. It is by no means comprehensive and instead meant to raise many more questions than it tries to answer.

1) Review

- Kasting, J. F. & Catling, D. Evolution of a Habitable Planet. *Annual Review of Astronomy and Astrophysics* **41**, 429–463 (2003).
- Zahnle, K. *et al.* Emergence of a habitable planet. *Space Science Reviews* **129**, 35–78 (2007).

These papers give an overview of some of the big issues that affect a planet's habitability. Kasting & Catling introduce the Faint Young Sun problem, the carbonate-silicate weathering feedback that stabilizes Earth's long-term climate evolution, atmospheric escape and outline the long-term chemical evolution of Earth's atmosphere. Read Zahnle for a complementary perspective discussion that discusses the evolution of the early solid Earth.

2) Habitable Zone & Climate Stability

- Kasting, J. F., Whitmire, D. P. & Reynolds, R. T. Habitable Zones around Main Sequence Stars. *Icarus* **101**, 108–128 (1993).
- Walker, J. C. G., Hays, P. B. & Kasting, J. F. A negative feedback mechanism for the long-term stabilization of the Earth's surface temperature. *J. Geophys. Res.* **86**, 9776–9782 (1981).

Kasting et al. is a classical paper on the concept of a star's habitable zone. Too close to the star, a planet undergoes either a "runaway greenhouse" or a "moist greenhouse" (loss of all surface water through photodissociation of $H_2O$ and subsequent hydrogen escape). Too far from the star, the planet falls into an irreversible snowball state once $CO_2$ condenses out of the atmosphere.
Walker et al. is the original paper that describes the silicate weathering feedback which is responsible for Earth's long-term climate stability.

3) Delivery of water

- Morbidelli, A. *et al.* Source regions and timescales for the delivery of water to the Earth. *Meteoritics & Planetary Science* **35**, 1309–1320 (2000).
- Raymond, S. N., Scalo, J. & Meadows, V. S. A Decreased Probability of Habitable Planet Formation around Low - Mass Stars. *The Astrophysical Journal* **669**, 606–614 (2007).

Where did Earth get its water from? These papers discuss possible mechanisms and also show the importance of orbital dynamics in thinking about a planet's habitability.

4) Formation of an atmosphere

- Owen, T. C. & Bar-Nun, A. Contributions of Icy Planetesimals to the Earth's Early Atmosphere. *Origins of Life and Evolution of Biospheres* **31**, 435–458 (2001).

What affects the evolution of a planet's atmosphere? This paper also discusses isotopic evidence from the Solar system.

5) Faint Young Sun problem

- Sagan, C. & Mullen, G. Earth and Mars: Evolution of Atmospheres and Surface Temperatures. *Science* **177**, 52 –56 (1972).

How does stellar evolution affect planetary habitability? Main-sequence stars evolve and become more luminous over their lifetime. Although the early Earth received less energy than now, it was clearly not frozen over. Sagen & Mullen introduced this "Faint Young Sun" problem and made a first attempt at resolving it (note that their favored explanation, which relies on ammonia, was later shown not to work).

6) The inner edge: Runaway Greenhouse

- Kasting, J. F. Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus* **74**, 472–494 (1988).
- Nakajima, S., Hayashi, Y.-Y. & Abe, Y. A Study on the 'Runaway Greenhouse Effect' with a One-Dimensional Radiative–Convective Equilibrium Model. *Journal of the Atmospheric Sciences* **49**, 2256–2266 (1992).

Kasting describes the runaway and moist greenhouse states and how they apply to Venus' evolution. Nakajima et al. is worth reading for a more mathematically detailed description.

8) The outer edge: Snowballs

- North, G.R. Analytical Solution to a Simple Climate Model with Diffusive Heat Transport. *Journal of the Atmospheric Sciences* **32**, 1301-1307 (1975).
- Pierrehumbert, R. T. & Erlick, C. On the Scattering Greenhouse Effect of CO2 Ice Clouds. *Journal of the Atmospheric Sciences* **55**, 1897–1903 (1998).

Towards the outer edge of the habitable zone, a planet irreversibly falls into a snowball state of global glaciation (note that Earth went through multiple snowballs in its past). North has a clear description of the feedback that enables these states and also shows that there is hysteresis between ice-free and snowball states.
Pierrehumbert & Erlick show that the outer habitable zone is not limited by $CO_2$ condensation.

7) Further Habitability Issues

Dynamical Evolution of solar systems

- Laughlin, G. & Adams, F. C. The Frozen Earth: Binary Scattering Events and the Fate of the Solar System. *Icarus* **145**, 614–627 (2000).

Potential role of the moon

- Lissauer, J. J., Barnes, J. W. & Chambers, J. E. Obliquity variations of a moonless Earth. *Icarus* **217**, 77–87 (2012).

Redefining & expanding the traditional habitable zone

- Stevenson, D. J. Life-sustaining planets in interstellar space? *Nature* **400**, 32 (1999).
- Abbot, D. S. & Switzer, E. R. The Steppenwolf: A proposal for a habitable planet in interstellar space. *The Astrophysical Journal* **735**, L27 (2011).
- Pierrehumbert, R. & Gaidos, E. Hydrogen Greenhouse Planets Beyond the Habitable Zone. *The Astrophysical Journal* **734**, 1–8 (2011).

The papers in the last section explore mechanisms for producing a planet with a liquid ocean which do not fit into the 'traditional' habitable zone picture.