

Storytelling with Uniview #14 The Habitable Zone

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In Storytelling with Uniview #06, we looked at the conditions that make Earth suitable for life, followed by the evolution of the atmospheres of Venus, Earth, and Mars in column #09. Building on those topics, let us look into more detail at the concept of the habitable zone.

Since life as we know it requires liquid water to exist, we can define the habitable zone around the Sun for which an orbiting terrestrial (or rocky) planets has a surface temperature that allows *liquid water to exist on its surface*. This is an important qualifier, and is in contrast to studies of other bodies in the Solar System that reveal the potential for habitats *beneath* the surface. These include the oceans underneath Europa's icy crust; potential hotspots below the surface of Mars where pockets of liquid water may exist; and the strange environment of Titan with its methanological cycle—similar to the hydrological cycle on the Earth but with methane and ethane as the chief elements. These locations were not traditionally viewed as being hospitable to life, but they have excited astrobiologists into wondering about the possibilities of life away from the surfaces of rocky planets.

However even when restricting ourselves to the simple requirement of a region not too hot and not too cold for liquid water to exist, one might suppose that the HZ around the Sun is narrow, with Venus too close in and Mars too far out. However this cannot be the whole story: for instance, the Moon orbits the Sun at the same distance as the Earth, but obviously cannot sustain life as we know it. (A world has to be large enough, with enough gravity, to hold onto its atmosphere and water.) Also from stellar models, the Sun is thought to have been much less luminous in the past, and has brightened continuously over the history of the Solar System (and will continue to brighten into the future). Thus the HZ early on would have been far interior to that of the Earth's orbit, while we have good evidence that life has existed on the Earth for roughly 3.8 billion years. The early Sun was 30% less luminous as it is today, so some process like the CO₂ cycle discussed in column #09 must have regulated Earth's climate. A Sun that pumps out more heat and energy with time would imply that the HZ spreads further out with time. However we also have good evidence that Mars was once warmer in the past, with a thick atmosphere that allowed liquid water to flow, but has gotten *cooler* in the last several billion years. To understand the history of the HZ and why Venus, Earth, and Mars are the way they are today, we must use comparative planetology and study the histories of the three large terrestrial planets over time.

Greenhouse gases

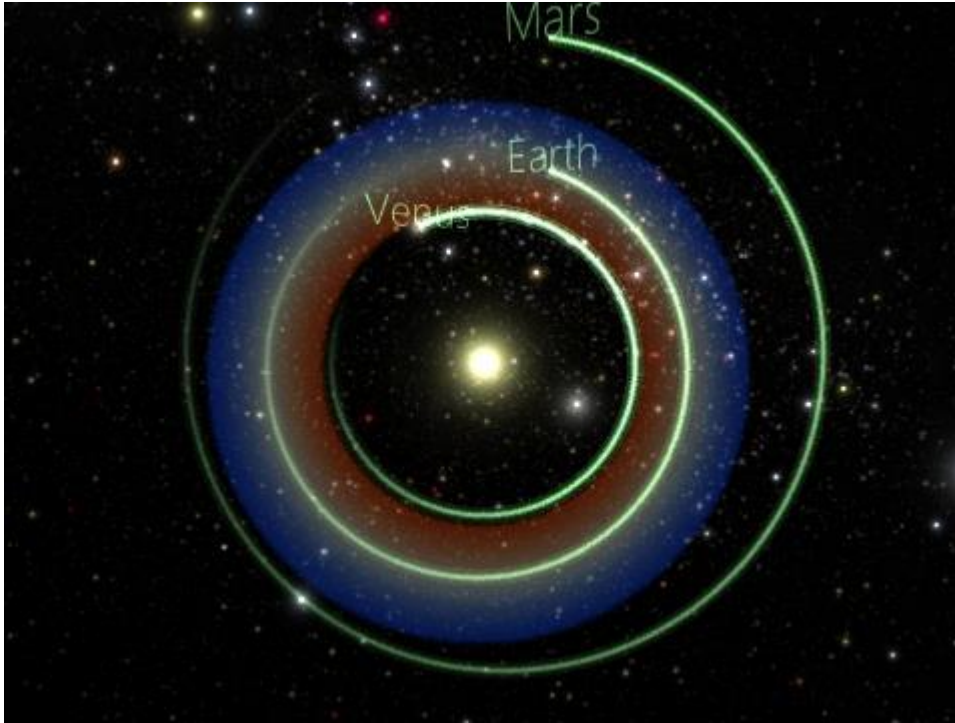
The most important factor that sustains the surface temperatures of the three large terrestrial planets is the greenhouse effect, chiefly from carbon dioxide (CO₂), but also water vapor and methane. The surface temperatures of the planets *without* heat-trapping greenhouse gases but keeping the same albedo (reflectivity of clouds) would all be below freezing! Here is a comparison of each planet's actual surface temperature and its no-greenhouse-effect surface temperature:

	Distance from Sun	Actual Temperature	Temperature without Greenhouse Gases
Venus	0.72 AU	470 C	-43 C
Earth	1.00 AU	15 C	-17 C
Mars	1.52 AU	-50 C	-55 C

Without its greenhouse effect, Venus is actually *colder* than the Earth, because its bright clouds actually reflect most of the Sun's light back into space.

Habitable Zone in Uniview

When you turn on **Solar System**→**Habitable Zone** in Uniview, a circular band centered on the Sun appears, with a red inner edge at 0.75 AU, and a blue outer edge at 1.30 AU, with a whitish middle band where the Earth orbits.



To determine the size of the HZ, we need to calculate the locations of the inner and outer edges based on careful atmospheric evolution models for a terrestrial planet. The inner edge would be defined by the distance at which an Earth-like planet would suffer a *runaway greenhouse effect* like Venus. This happens by the following sequence of events: as the surface temperatures increases due to heat trapping gases in the atmosphere, more water switches from a liquid state in the oceans to a gaseous water vapor state in the atmosphere. But water vapor is also a very strong heat-trapping greenhouse gas, so adding more of it increases the greenhouse effect even more, which again ups the surface temperature, which causes more water vapor to evaporate, leading to even more warming, and so on. This process is known as a positive feedback loop, since the effect is self-amplifying. Worse, if water vapor circulates high into the stratosphere, the molecules get broken up by UV radiation from the Sun, after which it is easy for the individual atoms to escape into space. Thus not only has Venus boiled away the oceans it might have once had, but its water is no longer in its atmosphere either, resulting in a planet that is much drier than Earth.

Increased water vapor also means increased cloud formation. Since clouds are bright, having more clouds will also mean more solar radiation is reflected back out into space, leading to a cooling effect. However a recent computer model for Earth by Leconte et al. (2013) showed that instead of reflective clouds forming at low altitudes, high cirrus clouds form instead which trap heat, feeding the warming effect. This means that the inner edge of the HZ is only at 0.95 AU. In Uniview, this inner edge is defined by the transition between red and white in the **Habitable Zone** module.

At the other end of the HZ, the opposite effect occurs, where conditions are too cold for CO₂ to stay

as a gas in the atmosphere. If you push a planet into a more distant orbit, the middle atmospheric layer will at some point become too cold, and CO₂ will begin to condense out of the atmosphere. This reduces the greenhouse warming, which causes more CO₂ to rain out, and so forth. This is yet another positive feedback loop, which over time leads to the planet freezing like Mars. One estimate of where this will occur is at 1.4 AU, which is a bit further out than the blue edge of the Uniview HZ. A hypothetical planet much larger than Earth would hold onto a thicker, denser atmosphere, and the outer habitable edge could be at 1.7 AU instead.

The Future Habitability of Earth

Since the Sun will continue to brighten as it ages, it is estimated that the inner edge of the HZ marches outward at 1 meter/year. As the solar luminosity inches up, at some point in the future, the surface temperature of Earth will increase past the threshold where a runaway greenhouse effect is possible. This will occur even if the damping effect of the CO₂ cycle that regulates Earth's climate is still in play. One estimate by Rushby et al. (2013) shows that there is between 1.75 to 3.25 billion years left of habitability on Earth. Since Earth is 4.54 billion years old, we are 70% of the way through Earth's history when life can exist comfortably on its surface. However even after Earth's surface becomes untenable for life, we are still well away from the Sun turning into a red giant large enough to swallow the inner planets. That is not predicted to happen until 7 billion years from the present, or at least 3 billion years after Earth becomes uninhabitable.

Knowing all this, I would be careful disseminating the future history of Earth to our youngest visitors. Young children do not have a good conception of time, and do not understand what a billion years really means. They may not be amazed by this story, as you hope they will.

References

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