10

The Nature and Evolution of Habitability

The Nature and Evolution of Habitability

(in our solar system)

LEARNING GOALS

10.1 THE CONCEPT OF A HABITABLE ZONE
- How does a planet's location affect its prospects for life?
- Could life exist outside the habitable zone?

10.2 VENUS: AN EXAMPLE IN POTENTIAL HABITABILITY
- Why is Venus so hot?
- Could Venus have once been habitable, and could life still exist there?

10.3 SURFACE HABITABILITY FACTORS AND THE HABITABLE ZONE
- What factors influence surface habitability?
- Where are the boundaries of the Sun's habitable zone today?

10.4 THE FUTURE OF LIFE ON EARTH
- How will the Sun's habitable zone change in the future?
- How long can life survive on Earth?

THE PROCESS OF SCIENCE IN ACTION

10.5 GLOBAL WARMING
- What is the evidence for global warming?
- What are the potential consequences of global warming?

Focus will be on Surface Habitability

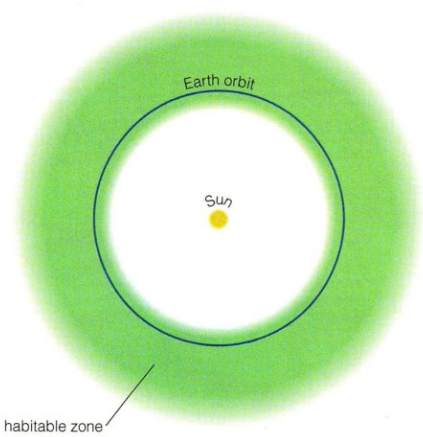
The Habitable Zone

Defined as the spherical shell (region) around a star **where the conditions on planets are such that liquid water is stable on the surface of a planet.**

The more luminous a star is, the farther out is the habitable zone is in its planetary system.

As we have seen, habitability also depends upon planetary mass. Very small planets may not be able to sustain liquid water on their surface even if they are in the habitable zone for an Earth-like planet.

Thus, we keep in mind that the definition of the habitable zone implies "for Earth-like planets".



As we have seen, some moons around planets have subsurface liquid water oceans and that these environments can meet the conditions for habitability.

However, we will limit our discussion to surface water.

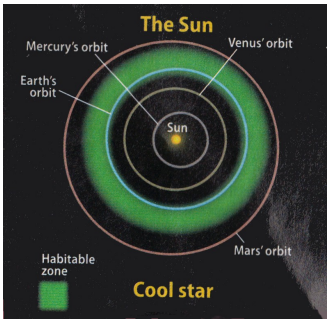
The Habitable Zone

Some Additional thoughts

- The concept of a habitable zone is based on the range of distances at which worlds similar to Earth could exist. In other words, a habitable zone is a zone in which it is possible for a world to have abundant liquid water on its surface.
- Simply being in a star's habitable zone is not sufficient to make a world habitable. The Moon presents an obvious case in point: As a companion to our planet, it is located at essentially the same distance from the Sun as Earth, but it is not habitable.
- Habitable zones evolve with time. In particular, because stars like the Sun tend to brighten as they age, we expect a star's habitable zone to move outward over time.

In summary, at any particular time, a star's habitable zone is the range of distances around it at which a planet could potentially have surface conditions that would allow for abundant liquid water.

- Venus is inside the sun's HZ.
- Mars is outside the sun's HZ.
- Earth is close to the inner edge of the sun's HZ.



In this diagram, the elliptical nature of the planetary orbits is shown accurately; note that Earth has a nearly circular orbit. In more extreme cases, a planet may spend only part of its orbit in the habitable zone.

The Role of the Greenhouse Effect

Without the greenhouse effect, Venus, Earth, and Mars would be locked in permanent ice-frost or be permanent snow-ball planets.

Table 9.1 Comparisons of Actual Temperatures and "No Greenhouse" Temperatures for Venus, Earth, and Mars

Planet	Actual Average Surface Temperature	"No Greenhouse" Average Surface Temperature*	Greenhouse Warming (actual temperature minus "no greenhouse" temperature)
Venus	470°C	–43°	513°C
Earth	15°C	–17°C	32°C
Mars	–50°C	–55°C	5°C

* The "no greenhouse" temperature is calculated by assuming no change in the atmosphere other than lack of greenhouse warming. The "no greenhouse" temperature for Venus is colder than that for Earth, even though Venus is closer to the Sun, because Venus is completely wrapped in bright clouds that reflect much more sunlight than is reflected by the Earth. Because the light at Venus's surface is thus very dim, the surface would be chilly if there were no greenhouse effect.

KEY QUESTION: why does the greenhouse effect operate at such dramatically different levels on Venus, Earth, and Mars?

The Role of the Planet's Properties

Table 9.2 Distance from the Sun and Radius for Venus, Earth, and Mars

Planet	Actual Values		Values Relative to Earth	
	Average Distance from Sun	Radius (at equator)	Distance from Sun (AU*)	Radius (Earth = 1)
Venus	108.2 million km	6,051 km	0.72	0.95
Earth	149.6 million km	6,378 km	1	1
Mars	227.9 million km	3,397 km	1.52	0.53

*1 AU is the Earth's average distance from the Sun, 149.6 million kilometers.

Venus is Earth-like in mass and size, but 30% closer to the sun than Earth. This would suggest that distance from the Sun is an important factor of climatic evolution ans thus habitability (assuming early conditions on Venus were similar to Earth's).

Mars is 50% the size of Earth and 50% farther from the sun than Earth. In this case, both mass and distance from sun differ from Earth's, but planetary mass is clearly an important property for determining climatic evolution.

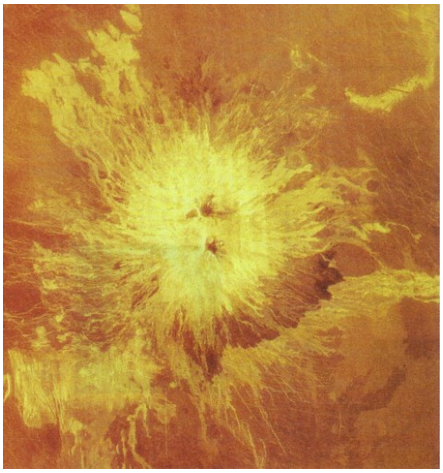
Venus…

Venus roughly has the same amount of carbon dioxide as Earth, but it is almost all locked in its atmosphere, whereas Earth has a carbon dioxide cycle that keeps most of it locked in carbonate rocks in the bottom of the oceans.

The presence of the oceans in critical…

Why no oceans on Venus?

Mass is similar to Earth's, so distance from sun must be critical.



Water on Venus… what happened to it?

Today… Venus is too hot for water to be chemically locked into surface rock. Earth has about 10,000 time more water than Venus, where water is vapor in the atmosphere; the lithosphere and mantle of Venus are very "dry".

Two possibilities:

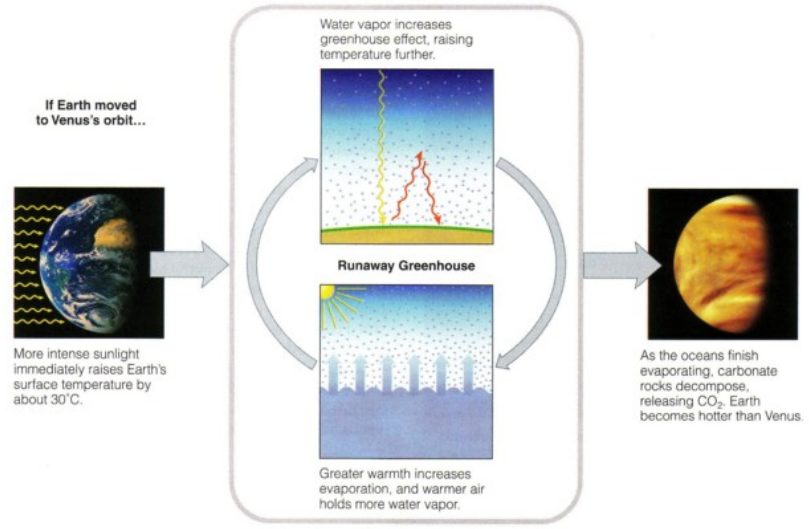
1. Venus never had the water to form oceans
2. Venus once had similar water content, but lost it to space

No. 2 more likely

Evidence for large quantities of water on Venus in the past from deuterium abundance on Venus, which is higher than on Earth (135x more) and higher than the naturally occurring cosmic abundance.

Suggests Venus could have has an ocean. Lower limit is a global ocean several meters deep. Where did it go…???

Venus… and the Runaway Greenhouse Effect



Surface Habitability Factors

1. Distance from Sun

   This cannot be a factor independent of other two, but there is likely a minimum and maximum distance that dictates whether surface water can remain stable. This is shown through Venus because it has similar size to Earth.

2. Planetary Size

   Carbon dioxide cycle is very dependent upon process of plate tectonics. There is probably a minimum/maximum planets size the governs if plate tectonics remains stable. Mars too small (internally cooled). But why no tectonics on Venus? Crust too dry. But that was result of water loss process (distance from sun).

3. Atmospheric Loss Process

   Again, this is interdependent with distance to sun and size of plane. Recall that Mars lost atmosphere due to lack of magnetic field, which resulted from internal cooling (small size). Without tectonics, Mars does not replenish its atmosphere.

The Habitable Zone

Inner Limits:

0.84 AU – simple greenhouse effect
0.95 AU – moist greenhouse effect

Moist Greenhouse effect is gradual escape of water vapor in upper atmosphere by evaporating oceans, followed by carbon dioxide release from the now exposed carbonate rocks

Outer Limits:

1.4 AU – if carbon dioxide rain
1.7 AU – greenhouse effect ineffective

At some critical distance, a planet with a suitable mass will still not be warmed by the greenhouse effect to the point of surface water in liquid form… if the carbon dioxide condensed out and formed a rain, the outer limit is even smaller

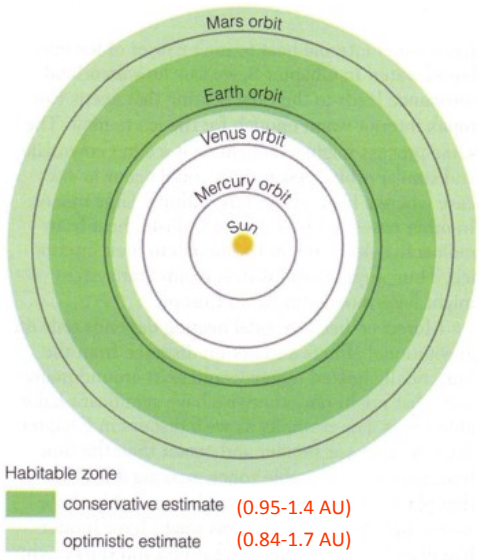


FIGURE 9.4 Boundaries of the Sun's habitable zone today. The narrower set of boundaries represents a model based on the more conservative assumptions, while the wider set represents the most optimistic scenarios.

The Fate of the Sun/Earth

The sun will become more luminous and a lot larger before it dies.

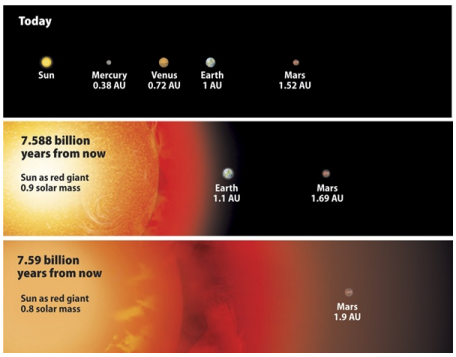
This will dramatically effect Earth, because the habitable zone will migrate outward in the solar system

There is a point of no return for the sun and solar system when the Sun is 12 billion years old. That is in about 7.5 billion years from now.

At this time, the sun will expand to the Earth's orbit and be 1000 times more intense in total light energy emitted.

Then it will go unstable, go through a "hiccup" period, and become a nebula with a white dwarf in its center.
Very massive stars don't do this, they just blow their brains out (supernova).

The sun will NOT become a supernova, and will never explode. It dies quietly and with "dignity".

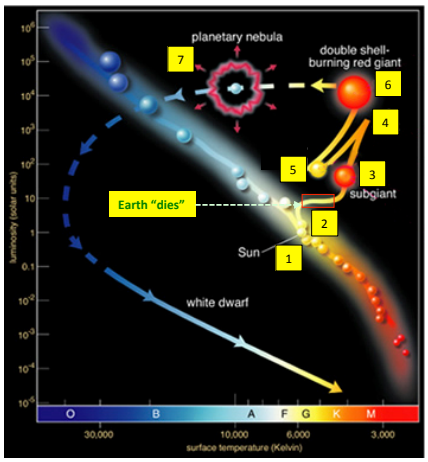


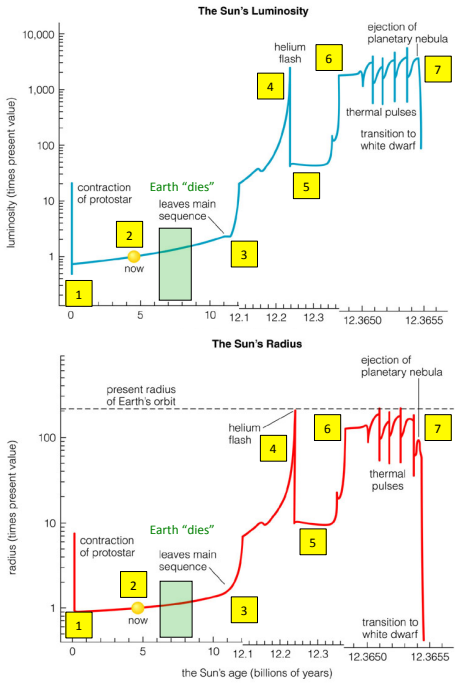
A diagram of the Sun's luminosity and size as it ages; NOTE: the orbits of the planets are to scale with the size of the sun, but the sizes of the planets are greatly exaggerated.

Earth will not continue to be habitable for the rest of the Sun's "life".

In 1.0-3.5 billion years Earth will suffer a runaway greenhouse effect.

	stage	Age (bill yr)	L/L_0	R/R_{Eorb}
1	born	0	0.7	0.0045
2	now	4.6	1.0	0.005
3	subgiant	11.5	1.1	0.01
4	He flash	12.26	5000	1.0
5	He burn	12.26	100	0.05
6	supergiant	12.33	10000	2.0
7	nebula	12.36	10000	0.0001





The Continuously Habitable Zone

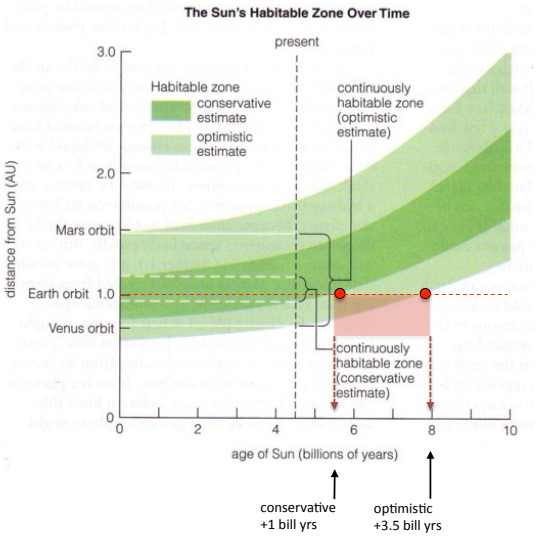
The habitable zone changes as the Sun ages, because stars get more luminous as they age.

The **continuously habitable zone** is defined as the lower and upper limits of the habitable zone from when the Sun formed to the present time.

Even in optimistic estimates, the Earth will not lie within the HZ in about 3.5 billion years.

In conservative estimates, the Earth will not lie within the HZ in about 1 billion years.

The habitable zone moves outward with time and eventually will lie beyond the orbit of Earth.



Planetary Nebulae

The fate of our solar system in about 8 billion years