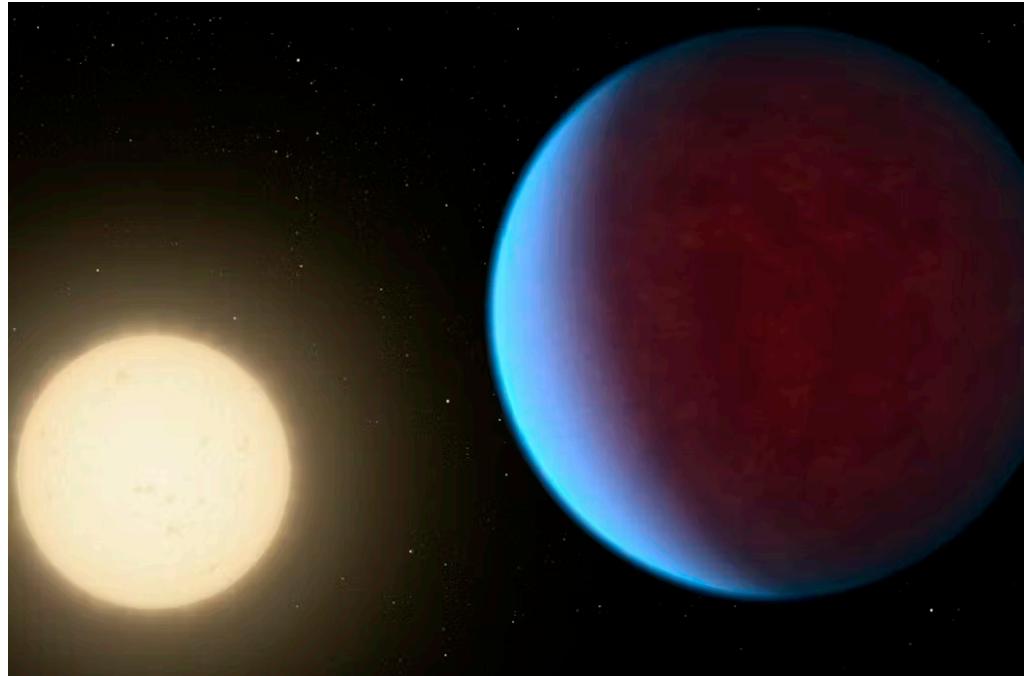


Beyond the habitable zone: Exoplanet atmospheres are the next clue to finding life on planets orbiting distant stars

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Published: November 19, 2025 8:25am EDT



Some exoplanets, like the one shown in this illustration, may have atmospheres that could make them potentially suitable for life.

NASA/JPL-Caltech via AP

When astronomers search for planets that could host liquid water on their surface, they start by looking at a star's habitable zone. Water is a key ingredient for life, and on a planet too close to its star, water on its surface may "boil"; too far, and it could freeze. This zone marks the region in between.

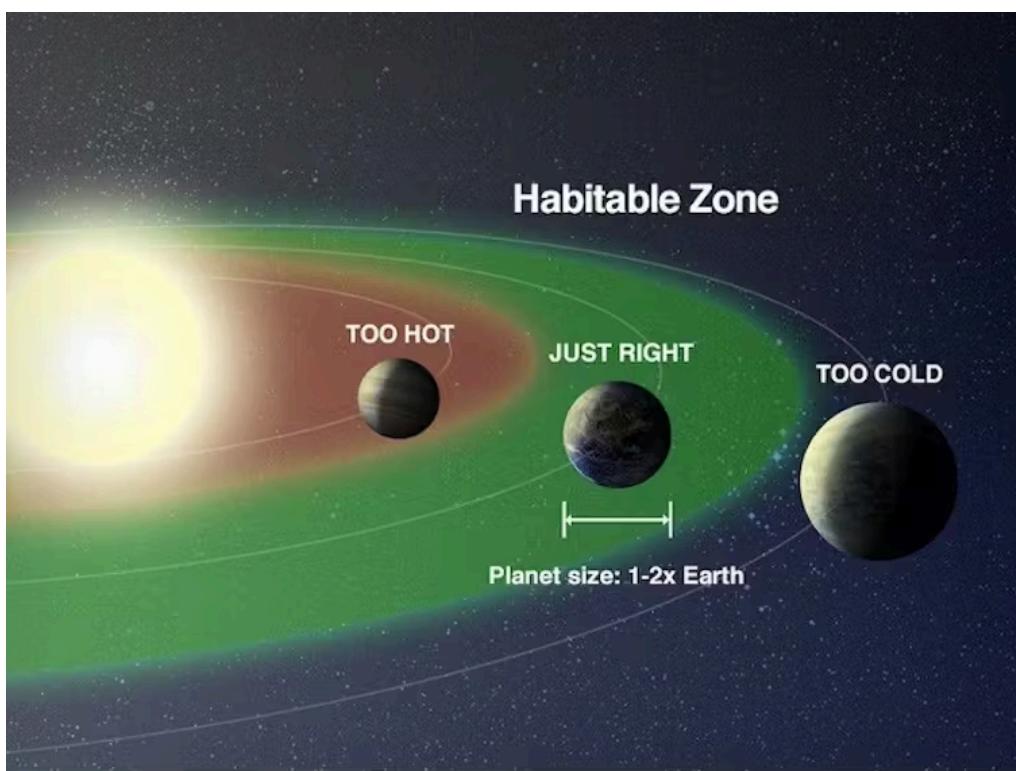
But being in this sweet spot doesn't automatically mean a planet is hospitable to life. Other factors, like whether a planet is geologically active or has processes that regulate gases in its atmosphere, play a role.

The habitable zone provides a useful guide to search for signs of life on exoplanets – planets outside our solar system orbiting other stars. But what's in these planets' atmospheres holds the next clue about whether liquid water — and possibly life — exists beyond Earth.

On Earth, the greenhouse effect, caused by gases like carbon dioxide and water vapor, keeps the planet warm enough for liquid water and life as we know it. Without an atmosphere, Earth's surface temperature would average around zero degrees Fahrenheit (minus 18 degrees Celsius), far below the freezing point of water.

The boundaries of the habitable zone are defined by how much of a “greenhouse effect” is necessary to maintain the surface temperatures that allow for liquid water to persist. It's a balance between sunlight and atmospheric warming.

Many planetary scientists, including me, are seeking to understand if the processes responsible for regulating Earth's climate are operating on other habitable zone worlds. We use what we know about Earth's geology and climate to predict how these processes might appear elsewhere, which is where my geoscience expertise comes in.



Picturing the habitable zone of a solar system analog, with Venus- and Mars-like planets outside of the ‘just right’ temperature zone.

NASA

Why the habitable zone?

The habitable zone is a simple and powerful idea, and for good reason. It provides a starting point, directing astronomers to where they might expect to find planets with liquid water, without needing to know every detail about the planet's atmosphere or history.

Its definition is partially informed by what scientists know about Earth's rocky neighbors. Mars, which lies just outside the outer edge of the habitable zone, shows clear evidence of ancient rivers and lakes where liquid water once flowed.

Similarly, Venus is currently too close to the Sun to be within the habitable zone. Yet, some geochemical evidence and modeling studies suggest Venus may have had water in its past, though how much and for how long remains uncertain.

These examples show that while the habitable zone is not a perfect predictor of habitability, it provides a useful starting point.

Planetary processes can inform habitability

What the habitable zone doesn't do is determine whether a planet can sustain habitable conditions over long periods of time. On Earth, a stable climate allowed life to emerge and persist. Liquid water could remain on the surface, giving slow chemical reactions enough time to build the molecules of life and let early ecosystems develop resilience to change, which reinforced habitability.

Life emerged on Earth, but continued to reshape the environments it evolved in, making them more conducive to life.

This stability likely unfolded over hundreds of millions of years, as the planet's surface, oceans and atmosphere worked together as part of a slow but powerful system to regulate Earth's temperature.

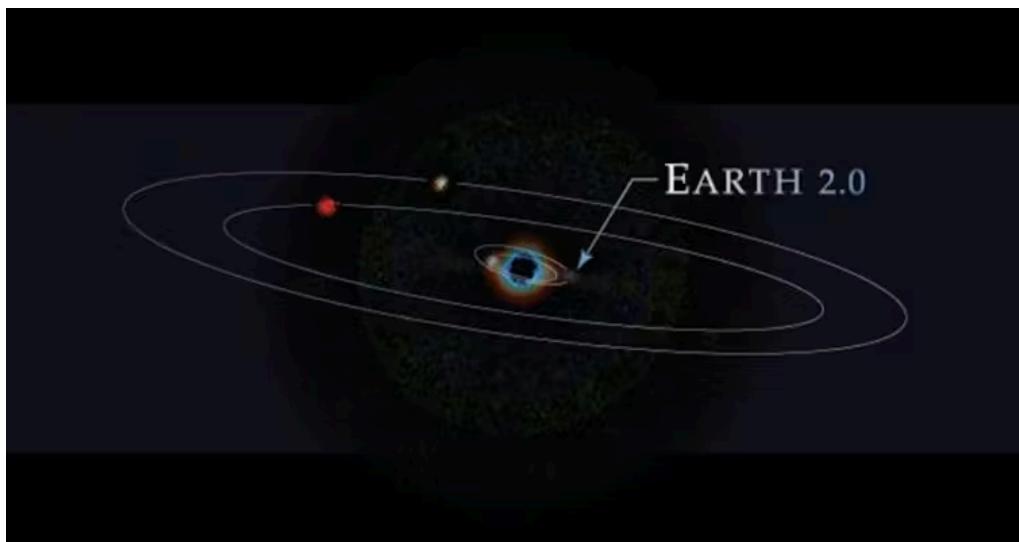
A key part of this system is how Earth recycles inorganic carbon between the atmosphere, surface and oceans over the course of millions of years. Inorganic carbon refers to carbon bound in atmospheric gases, dissolved in seawater or locked in minerals, rather than biological material. This part of the carbon cycle acts like a natural thermostat. When volcanoes release carbon dioxide into the atmosphere, the carbon dioxide molecules trap heat and warm the planet. As temperatures rise, rain and weathering draw carbon out of the air and store it in rocks and oceans.

If the planet cools, this process slows down, allowing carbon dioxide, a warming greenhouse gas, to build up in the atmosphere again. This part of the carbon cycle has helped Earth recover from past ice ages and avoid runaway warming.

Even as the Sun has gradually brightened, this cycle has contributed to keeping temperatures on Earth within a range where liquid water and life can persist for long spans of time.

Now, scientists are asking whether similar geological processes might operate on other planets, and if so, how they might detect them. For example, if researchers could observe enough rocky planets in their stars' habitable zones, they could look for a pattern connecting the amount of sunlight a planet receives and how much carbon dioxide is in its atmosphere. Finding such a pattern may hint that the same kind of carbon-cycling process could be operating elsewhere.

The mix of gases in a planet's atmosphere is shaped by what's happening on or below its surface. One study shows that measuring atmospheric carbon dioxide in a number of rocky planets could reveal whether their surfaces are broken into a number of moving plates, like Earth's, or if their crusts are more rigid. On Earth, these shifting plates drive volcanism and rock weathering, which are key to carbon cycling.



Simulation of what space telescopes, like the Habitable Worlds Observatory, will capture when looking at distant solar systems.

STScI, NASA GSFC

Keeping an eye on distant atmospheres

The next step will be toward gaining a population-level perspective of planets in their stars' habitable zones. By analyzing atmospheric data from many rocky planets, researchers can look for trends that reveal the influence of underlying planetary processes, such as the carbon cycle.

Scientists could then compare these patterns with a planet's position in the habitable zone. Doing so would allow them to test whether the zone accurately predicts where habitable conditions are possible, or whether some planets maintain conditions suitable for liquid water beyond the zone's edges.

This kind of approach is especially important given the diversity of exoplanets. Many exoplanets fall into categories that don't exist in our solar system — such as super Earths and mini Neptunes. Others orbit stars smaller and cooler than the Sun.

The datasets needed to explore and understand this diversity are just on the horizon. NASA's upcoming Habitable Worlds Observatory will be the first space telescope designed specifically to search for signs of habitability and life on planets orbiting other stars. It will directly image Earth-sized planets around Sun-like stars to study their atmospheres in detail.

Instruments on the observatory will analyze starlight passing through these atmospheres to detect gases like carbon dioxide, methane, water vapor and oxygen. As starlight filters through a planet's atmosphere, different molecules absorb specific wavelengths of light, leaving behind a chemical fingerprint that reveals which gases are present. These compounds offer insight into the processes shaping these worlds.

The Habitable Worlds Observatory is under active scientific and engineering development, with a potential launch targeted for the 2040s. Combined with today's telescopes, which are increasingly capable of observing atmospheres of Earth-sized worlds, scientists may soon be able to determine whether the same planetary processes that regulate Earth's climate are common throughout the galaxy, or uniquely our own.

Morgan Underwood receives funding from NASA-funded CLEVER Planets (Cycles of Life-Essential Volatile Elements in Rocky Planets) research project.

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