Science Fact

Constructing a Habitable Planet

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The number of confirmed extrasolar planets has exceeded four thousand and keeps growing. When all data from the ongoing TESS mission are eventually analyzed, it may well exceed twenty thousand. A question inevitably arises: Is a habitable—even inhabited—world somewhere among them? Are they plural? Where should we look for one, and what conditions should a planet have to be—and stay—habitable? When I ask at conventions and other events, people typically list the following: *Liquid water. Solid surface. Suitable size and mass. Atmosphere. Stable star. Stable orbit in the habitable zone.* Are these, however, the only criteria of importance—or even the key criteria? Can we even say such a thing? Let's embark on a convoluted journey of models, feedback, and missions yet to come to find out more.

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Building a planet

To ascertain what makes a planet habitable, we can do a thought experiment. You're most likely familiar with *The Hitchhiker's Guide to The Galaxy*. There we can find Slartibartfast, a planetary architect responsible for the Earth. He even won an award for the fjords. Let's become architects as well and build a planet from scratch—to see if we can make it habitable.

Start out properly: with the host star. What kind should we choose? Stars come in many forms. The basic criterion is their spectral type, indicated with letters: M, K, G, F, O, B, A. M stars are dubbed red dwarfs: tiny, low-mass and low-luminosity stars that bide their time, burning hydrogen into helium in their cores ever so slowly. They can provide tens of billions years' worth of warmth, but tend to be very active—variable, flaring, eruptive. Not so good for life as we can imagine it, or even for keeping an atmosphere. Their habitable zone (HZ)—the region where the amount of light is just right to keep liquid water on a planet's surface, provided it has a surface and a suitable atmosphere—is so close that any planet in it would almost certainly end up tidally locked, forever facing the star with one side, the other drowned in perpetual darkness. Could such a world be friendly to life? Let us return to it later and explore the other options. K stars are sometimes called orange dwarfs, G type stars yellow dwarfs—our Sun is one. The more massive yellow-white F stars burn their fuel faster and run out of hydrogen in their cores in less than four billion years—less than the current lifetime of the Solar System. In contrast, the Sun will stay in this so-called main sequence for approximately ten billion years in total. F type stars also produce more high-energy radiation, basking their planets in intense UV that might be damaging even to potential alien life, easily breaking many complex molecules. As to even more massive stars, their main sequence lifetimes are so short that we can discount them as harbors of life for the moment—but we'll briefly visit them again toward the end of our journey . . . and theirs, too.

Is the spectral type everything? I've already hinted at stellar activity. Though it's associated with the type to some extent, there is variance. Basically, all main sequence stars are variable. Our Sun has an 11-year solar cycle, during which its activity and number of starspots change. But the difference is so little that most of the time, it scarcely matters for Earth's life. Though we have indirect records of severe solar storms from history, they are still negligible to what we could witness, for example, near our closest stellar neighbor, Proxima Centauri. Stellar rotation plays a role, too. Slower rotators produce milder stellar winds, making them less likely to strip a planet of its atmosphere. Though stars' rotation generally slows as they age, there is variance again, and where they start and how fast they slow down may differ. We should try to aim for a stable, less active, and slowly rotating star, then. We must also consider the question of stellar systems—most stars come in pairs, or even triple, more rarely quadruple and other systems. The Sun is a bit of an outlier in being a sole star. However, orbits will almost necessarily become more complicated and less stable in multiple systems. Let's seek out a single star for the moment.

The star's metallicity is of our concern as well. Astronomers generally call all elements heavier than the primordial hydrogen and helium "metals," and this variable indicates enrichment of the star in these heavier elements. In a young cosmos, they were scarcer than now—too few supernova explosions managed to create and scatter them around the Galaxy. Older stars, for this reason, tend to have lower metallicity, while younger ones have a higher value. Again, this rule has exceptions, and other factors such as the star's place in the Galaxy can affect it. Should we favor a low- or high-metallicity star? In general, the disc around a newborn star follows the star's composition, having been born of the same region of a protostellar cloud. With more abundant heavier elements, we can more likely create terrestrial planets—a crucial part of our task as architects. Rocky planets can also exist around extremely old stars, as worlds such as Kapteyn b indicate, but let's aim for a more high-metallicity host star. We're almost ready with the new sun—just to pick the spectral type to our liking. Should we choose the road of our system and pick a G type star? Or a more long-lived orange dwarf? In discussions at various events, people favored all kinds from M to F dwarfs. I'd personally like to see a more long-lived system, so a K-type star (quite numerous in the cosmos as well) it is: A higher-metallicity, slow-rotating, relatively stable orange dwarf of let's say 0.7 solar masses, making it almost 30% as luminous as the Sun, in a more or less peaceful galactic neighborhood.

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Keep all the plates spinning

We can finally come to the planet itself. "Liquid water" is nice, but is itself a consequence of other parameters we can pick first. What about the orbit? Close to circular would be nice for stable irradiation, but how far? The habitable zone (as conventionally calculated) around our orange star, which has a surface temperature around 4700 Kelvins, stretches from approximately 0.5 to 1 au (the Sun-Earth distance). This is far enough not to get a tidally locked world. In order for the planet to spend longer within the HZ, we may place it near the outer edge, let's say 0.9 au. There, the planet receives approximately half as much sunlight as the Earth. It might seem little, but it's more than Mars does, and Mars lies within our Sun's HZ.

Why isn't Mars still habitable, do you ask? It comes down to its size and mass. Being smaller than the Earth, it cools more rapidly, and that may have caused heat-fueled convection in its core to stop and its magnetic field—which it had had for some time, as evidenced by remnant magnetism in old Martian regions—to vanish, leaving its atmosphere vulnerable to the incessant attack of the solar wind. And being less massive, with surface gravity approximately one third of the Earth's, it couldn't hold onto the atmosphere with sufficient strength. We can observe evidence of long-lost water ocean and rivers on Mars, but as it had gradually lost most of its atmosphere, the temperature and pressure became too low to support liquid water. Had a more Earth-like planet been in Mars' place, it would have most likely remained habitable.

We probably don't want a smaller, low-mass planet, then. But what about a bigger one? The so-called super-Earths (and sub-Neptunes) seem to be the most numerous class of planets, though most of our discovery methods have an observation bias toward more massive, bigger, and also closer-in planets, so it may well be that exo-Marses or exo-Mercuries end up the most frequent exoplanets eventually. Most models suggest that up to a radius of 1.5 Earth's radii, a planet will likely have a solid surface, while a bigger one won't have a clear surface-atmosphere boundary, resembling an ice giant such as Neptune or Uranus. What if we go as big as we can, then?

A super-Earth would offer a much greater surface area, which seems like a good thing for habitability. Indeed, in a 2015 paper, astrophysicists René Heller and John Armstrong argued that a super-Earth set around a K type star may be "superhabitable": Its star would be long-lived, and thanks to the planet's greater-than-Earth's sources of internal heat, the world could remain habitable just as long. While very massive super-Earths' interior dynamics might not support plate tectonics, a planet of approximately two Earth masses and 1.25 Earth's radii may have a similar geophysical regime while having over 50% more surface area. Thanks to its higher gravity, it would acquire a denser atmosphere, and mountains wouldn't rise as high and would erode faster, making its surface much flatter. The authors imagine such a world as an aqua planet with widespread shallow oceans dotted with archipelagos. Such is an appealing image, isn't it?

However, there might be problems with this class of planets, as already hinted above. Even if we forgo the possibility of a low-density ocean world (which seems exciting at first sight, but with enough pressure at the bottom of the sea, it might have a layer of high-pressure ices between the liquid water and rock, potentially halting efficient geochemical cycles) and stick to a mostly rocky planet with a density roughly comparable to Earth, would its surface features resemble our world at all, and would it possess biogeochemical feedbacks needed to cycle elements between the interior and atmosphere of the planet, and eventually the biosphere?

On Earth, plate tectonics fulfill this role. In a 2007 study, planetary scientist Diana Valencia and colleagues made a case for plate tectonics being more likely on super-Earths thanks to easier plate motion and lower plate thickness—going as far as calling it "inevitable." But a single paper is rarely the last word in science. In contrast, planetary geologist Paul Byrne's geophysical model presented at the Lunar and Planetary Science Conference in 2019 has shown that with the greater pressure exerted by their gravity on the interior rock, the so-called brittle-ductile boundary (delineating the point where rocks stop behaving like brittle solids and start resembling a dense viscous fluid) can be extremely close to the surface of super-Earths, making the litosphere too thin to have plate tectonics. Especially if they possess a greater heat flux and a dense atmosphere (which can be expected with more likelihood than around less massive, smaller planets), super-Earths might not have any solid lithosphere at all, becoming instead "toffee planets."

In addition, many super-Earths may not be Earth-like at all. Several studies suggested that planets over two Earth masses will acquire too-dense atmospheres, so that planets above approximately 1.25 Earth radii might not be conventionally habitable. In our exercise, then, let's use this upper estimate and create a planet with two Earth masses and 1.25 Earth radii. The surface gravity would be roughly 1.3 times greater than on Earth—still well survivable, if physically demanding, even for a human. Just in case you want to eventually colonize your brand new world . . .

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It's all in the system

We've got our planet in its orbit. Does it mean we're done? Not by far. Now we need to start all the processes leading to the origin of life and enabling its long-term existence. First, we need volatiles: water and atmospheric gases. Some are bound in rocks that constitute the planet's interior and will gradually escape their rocky prison via geologic activity, especially volcanism. But the chances are, lots of volatiles were lost during the planet's formation. We need to deliver more—and for that, we need impacts. Water-rich asteroids and comets can serve our purpose. All planetary systems are off to a rough start, and collisions will inevitably occur. But are they going to suffice? What if we need some special event to haul more frozen balls inward from the outer reaches?

Other planets can help us out. After all, we can hardly expect our system to have a single planet. While it's not completely inconceivable, we can safely say it's extremely improbable. A protoplanetary disc around a relatively low-mass K-type star would be smaller than around more massive stars, but based on the observed exoplanetary systems so far, we can expect several planets and some small bodies to arise from it. The budding planets' gravitational interactions might be just so that our world receives its fair share of water and gases. But many vastly different scenarios can occur at this point, stemming from the chaotic properties of the disc. Some planets might migrate inward as they gather more gas, interact with the disc, and lose angular momentum, disrupting orbits of other bodies in their way. Some might get locked in resonances, such as we can see for example in Jupiter's moons Io, Europa, and Ganymede, chained in their regular gravitational dance. Other resonances, though, may be disruptive and shoot one of the bodies into an eccentric orbit, or even away from the system whatsoever, thus creating a new rogue planet. We need to be careful about our world. Ever since the start of exoplanetary science, astronomers kept discovering the so-called hot Jupiters—gas giants orbiting close to their stars.

Even if our world escapes orbital disruption, it may not be completely safe. Low-mass stars tend to have more compact systems, and in turn there is a greater likelihood of orbital resonances. While they may be stabilizing and so at first sight beneficial, with them comes another aspect: tides. When there is a gradient of gravitational force between two bodies, they periodically exert greater or lesser influence on each other, tugging at the planetary body and straining it. The most familiar tides are Earth's oceans (but also rock and atmosphere)—caused by the Moon. Another is Jupiter's moon Io, tugged at not just by the giant planet, but also the moons Europa and Ganymede, with which it is in orbital resonance. Io's interior is so strained by this tug that it heats substantially, making the moon extremely volcanically active. Io has over four hundred known volcanoes and no observed impact craters at all, meaning that it's surface is very young—just compare it with our own heavily cratered Moon, or the moon Callisto in Jupiter's system. Io has long since lost its volatiles, leaving only heavier elements behind.

We certainly don't want that to happen to our planet, so we better make sure the potential tidal forces are *just right*—a phrase we need to be conscious of at every moment of our venture. They could also influence the existence and strength of a planet's magnetic field, created by convection in the liquid core—which is also tugged at by tidal forces. Tidally driven flow in Earth's core distorts its "basic" internal magnetic field, but the effect is negligible for our planet. Elsewhere, it might become crucial, and with that, we've come to an important aspect of habitability: magnetic field. A planet without one is less protected from charged particles and more prone to losing its atmosphere to stellar wind, especially if the planet is low-mass and the wind strong. We've chosen a higher-mass, rocky planet and a calmer star, but a magnetic field would still protect any surface life. Would a super-Earth possess one? The more likely answer seems to be yes, but we've still got a lot to learn about fine-tuning the interior dynamics sustaining a liquid convective core and thus a magnetic field. Of all rocky worlds in the Solar System, only Mercury, Earth, and Jupiter's moon Ganymede have one, while Venus, Mars, and all other moons lack it. Amount of inner heating, chemical composition, size (which influences heat flux), tides, rotation rate, and other factors all play a role.

You've probably been wondering for a while already how closely interconnected the various aspects of habitability are. You're absolutely right. Basically all of them are connected by feedbacks; sometimes positive, sometimes negative, sometimes more complex than that. Before we look at our "final pre-life" version of our planet, already possessing oceans, atmosphere, and prebiotic molecules, we should briefly stop by two other aspects, though: chemical composition and rotation. I've mentioned both as potentially influencing a planet's internal magnetic field, but they do much more than that.

This turn of our journey takes us all the way back to stellar metallicity. Remember how the disc around a newborn star follows the star's composition? Now is the time to point out that stars—and so likely their planets—come in many different compositions. Hydrogen always vastly predominates, followed by helium and other light elements—but even minute changes in the rarer heavier elements can have great consequences. Consider the carbon to oxygen ratio, for instance. In our Sun, it's around 0.54, meaning that there are roughly two atoms of oxygen for one atom of carbon. In other systems, it can be more. While observations of stars with C/O > 1 have been disputed as statistical errors, we can be fairly certain that some high-metallicity stars with planets have C/O ~ 0.8, which would mean that their planets would probably be richer in carbon, which might shift their heat flux and whole geophysics away from what we know from our Earth. And if rocky planets do exist around stars with C/O > 1, we could even expect worlds with diamond surrounding their metallic cores, carbides making up the upper mantle, oil flowing in rivers carved in the graphite landmass, and carbon oxides, possibly methane, in the atmosphere.

The magnesium/silicon ratio (1.05 in case of the Sun) is another we should pay close attention to. On Earth, most of the mantle and lithosphere is composed of various silicates—compounds of silicon and oxygen, with other elements thrown in. For instance, olivine, the primary component of Earth's mantle, is a magnesium iron silicate. On planets with much lower Mg/Si ratios, garnets would likely dominate the mantle. Under the same pressure and temperature, they would be stiffer, potentially prohibiting plates from flowing on the astenosphere, the uppermost mantle layer. As we've seen, plate tectonics seem to be beneficial for keeping the planet's thermostat on and biogenic elements cycling. Do we, then, want a planet with an Earth-like chemical composition, or could something be even better? To ascertain that, we need more mathematical models and high-pressure experiments, as well as observations of rocky exoplanets that we're currently lacking.

The rotation rate and axis are equally important, having the power to completely change a planet's climate. On a relatively fast-rotating planet, such as the Earth, clouds most frequently form in bands following the pattern of atmospheric cells, caused by the Coriolis force—basically by rotation. In contrast, on a slow-rotating planet, cloud cover would be most prominent near the substellar spot—the place currently receiving most sunlight—effectively shielding the planet from a part of the irradiation and reflecting it back to space. Models also suggest that slowly rotating planets would be more cloudy in general, although all of this also depends e.g. on the ratio and distribution of water and landmass. It appears that at the same value of irradiation, the two planets could have vastly different climates.

We do have a very slowly rotating terrestrial planet in our system: Venus. Its climate, however, is the very definition of hell: over 460 °C on the surface under the pressure of ninety Earth atmospheres. Does it mean that our models are wrong? Not really. We're not sure when and how Venus acquired its current rotation rate. That is crucial for the question of its potential past habitability. Studies counting with slow rotation since the beginning show that it may have had liquid water oceans for over two billion years—nearly half of the existence of our Solar System, more than enough time for life to arise and proliferate. If Venus' current slow rotation is only secondary, liquid water's lifetime may have been much, much shorter.

It's not just the rotation rate, however; the axis matters too. It can vary wildly. Venus, for instance, rotates "on its poles." Since it also rotates (extremely slowly) in the opposite direction than the majority of Solar System planets, its axial tilt is 177°. For our purposes, it doesn't matter whether a tilt is zero or 180°. If all other parameters stay the same, it has the same effect on climate: no seasons. All points on the planet receive constant insolation throughout the year, the equator the most, the poles the least. Compare this to the Earth with a tilt of 23.5°. This is the fact that makes seasons come and go. Uranus has an axial tilt of 98°, "rolling on its side." On an approximation, so does Pluto with a tilt of 120°. This means rather extreme seasonal changes—but they are still regular. We can argue whether it's better for life to have no seasonal changes or some, but what might not go so well with climate and biosphere are axial tilt changes.

Mars is currently tilted by 25°, almost the same as Earth. But geologic features on its surface provide indirect evidence that it hasn't always been so. In fact, Mars could have undergone rather extreme tilt shifts in the past, impacting its climate. Imagine *The Game of Thrones*: Winter is coming. It comes irregularly and may last very long, and you're never certain whether you're sufficiently prepared . . . That, in a somewhat exaggerated nutshell, is what life with axial tilt shifts might look like.

Worried that something like that might happen to Earth? Don't be. Earth has a unique feature that stabilizes its axial tilt: a large moon. We can thank cosmic accident for its existence, as it was created by material from a large impact (some models also show multiple subsequent smaller impacts) in early Solar System history. The Moon's gravitational tug could have also have helped start plate tectonics, and oceanic tides provide periodically dry and wet areas where prebiotic molecules could mix and concentrate, possibly leading to the origin of life, though many other environments have been suggested as well. Other habitable planets might not be so lucky as to acquire their own massive moon, and it's up to future astronomers to find out whether it's crucial, somewhat beneficial, or largely irrelevant for habitability of an Earth-like world.

Let's recap what we've tried to fine-tune for our habitable planet: A suitable star (in terms of spectral type, activity, single/multiple system, metallicity), planetary orbit, size, mass, volatile delivery, system configuration, chemical composition, rotation rate, and axis . . . All of these parameters and more could make a planet on a nice circular orbit within the HZ into hell, or keep a world on a wildly eccentric orbit habitable. They could enable life on a tidally locked planet closely orbiting a red dwarf, and inhibit it on an otherwise Earth-like world circling a Sun-like star. Contrary to what the term "habitable zone" seems to suggest, planetary habitability is an insanely complex question.

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Why not go exotic?

Upon hearing all this, you might be feeling pessimistic about the chances of life elsewhere. After all, if so many fine-tuned criteria are needed to build a habitable planet, what are the chances we find one nearby? Do not despair, though. We've been trying to build an Earth-like planet that sports surface liquid water thanks to the stellar irradiance and greenhouse effect. That's what we know most intimately and also the logical target for telescopes that will be able to ascertain a lower-mass planet's atmospheric composition (such as the James Webb Space Telescope or Atmospheric Remote-sensing Infrared Exoplanet Large-survey), potentially revealing whether it hosts life. However, we needn't look far for places that defy the traditional HZ and still might support life. Our own Solar System has several moons with liquid water oceans locked under an icy shell, receiving too little sunlight to allow surface liquid water even if they could keep a dense atmosphere (which is not out of the question—Saturn's moon Titan has one). Europa and Enceladus seem like the most promising targets for searching for alien life, if likely very simple. It's not hard to imagine whole planets like them—indeed, for instance TRAPPIST-1 f, g, and h have densities and levels of irradiation that allow such an outlook.

We could even have *surface* liquid water very far from a star—we just need enough inner heating (so more massive planets and/or more radioactive elements are welcome) and more powerful greenhouse gases than the good old CO_2 and H_2O. Molecular hydrogen is one, and an atmosphere rich in H_2 is very much conceivable far from a star. Even rogue planets could remain habitable with sufficient inner heat sources and a dense H_2-rich atmosphere. We might even imagine a system with a central hydrogen-atmosphere world with a system of moons heated by tidal forces, allowing them to keep subsurface oceans like Europa: a multi-habitable-world system without any central star. Multi-habitability in a compact system of planets or moons seems like a nice thing (and great science-fictional setting): just imagine you could glimpse features on another inhabited world with a naked eye! What would astronomy and space exploration have looked like then?

Habitable planets might also be found around less than typical host stars (here we briefly come back to the high-mass stellar types, as promised): stellar remnants such as white dwarfs and even neutron stars. How could a habitable planet survive such a cataclysm that precedes their existence, you ask? It would not. Habitability in such systems would be secondary, arising only after impacts of volatile-rich bodies seeded the scorched planets with water and biogenic elements anew. Habitable worlds orbiting white dwarfs are very feasible; neutron stars are a much more speculative location, but they have also been investigated in scientific literature in this regard.

And why focus only on liquid water? Other solvents have been proposed as potentially suitable to exotic life forms. Simple hydrocarbons such as methane or ethane are one of the many options, and we have a world with methane-ethane lakes, rivers, and precipitation right in our own Solar System: Saturn's Titan. Underneath its hazy methane-rich greenhouse atmosphere is a world that looks remarkably like Earth, only with water replaced by hydrocarbons. It's not out of the question that Titan might support simple forms of exotic life, and we have yet to find out whether it actually does or not.

Several compounds of sulfur; ammonia; formamide; hydrazine; hydrogen fluoride; liquid nitrogen; even lots of supercritical fluids—the list of potential solvents proposed for exotic life is long, and so far it's only up to your imagination which you deem plausible. As our knowledge of other worlds will inevitably amass, so will hopefully our understanding on which of these compounds can really be found in sufficient amounts and could support life forms very exotic to us. The main problem with most of them is that they're rare. Water is a compound readily found all over the Universe, and we know it can support life, so it's logical to focus on it—but we should bear in mind that other options might be feasible as well.

There is no single recipe for building a habitable planet. We can have our imagination run wild—but ideally on the scientific foundations of what we've ascertained as of yet. With Transitivity Exoplanet Survey Satellite potentially expanding our exoplanet sample by an order of magnitude, the Characterising Exoplanet Survey Satellite probe looking for transits of planets discovered by the method of radial velocity and thus adding size to minimum mass (and providing us with a measure of density, constraining a given planet's composition), and planned telescopes such as JWST and ARIEL able to probe an exoplanet's atmosphere, we can expect to know much, much more already within this decade. Our budding planetary architects have a lot of exciting news to look for.

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