Red Dwarf Habitab

Life on worlds around the smallest, most common stars would have to cope with environments vastly different from our own.

It's hard to imagine life existing in an environment fundamentally different from Earth, a planet rich in vegetation and oceans orbiting a bright, yellow star. Indeed, for decades astronomers focused on Sun-like stars when hunting for habitable worlds, a decision that made logical sense for a number of reasons. Such stars have lifetimes of roughly 10 billion years, providing ample time for life to emerge if it follows the pattern it did on Earth. And Sun-like stars don't pose the hazardous threats that other stars might when it comes to flares and magnetic activity, instead living relatively quiet lives. Above all of the reasons to pursue life around stars like the Sun, though, is one single fact that cannot be overvalued: The only known example of a habitable planet orbits one of these stars.

Over the last two decades, however, astronomers' interest has shifted from Sun-like or "*G*-dwarf" stars to an entirely different class of stars: *M*-dwarf or "red dwarf" stars. The latter are much smaller and less massive than Sun-like stars, making planets around them easier to find. They're also far more common. As such, astronomers are discovering large numbers of planetary systems around these stars. As additional space- and ground-based telescopes come online in the coming decades, they will find many more such systems.

Some of these planets — including those orbiting the red dwarfs Proxima Centauri, Trappist-1, and LHS 1140 — have garnered widespread attention, largely because they're relatively nearby. The fact that their stars hang out in our stellar backyard means that we might soon be able to measure the planets' atmospheric compositions and search for biologically generated fingerprints, called *biosignatures*. The first habitable exoplanet discovered beyond our solar system might end up orbiting a star very different from our own.

Would life on such a world even exist? Astronomers have traditionally defined a star's *habitable zone* as the range of dis-

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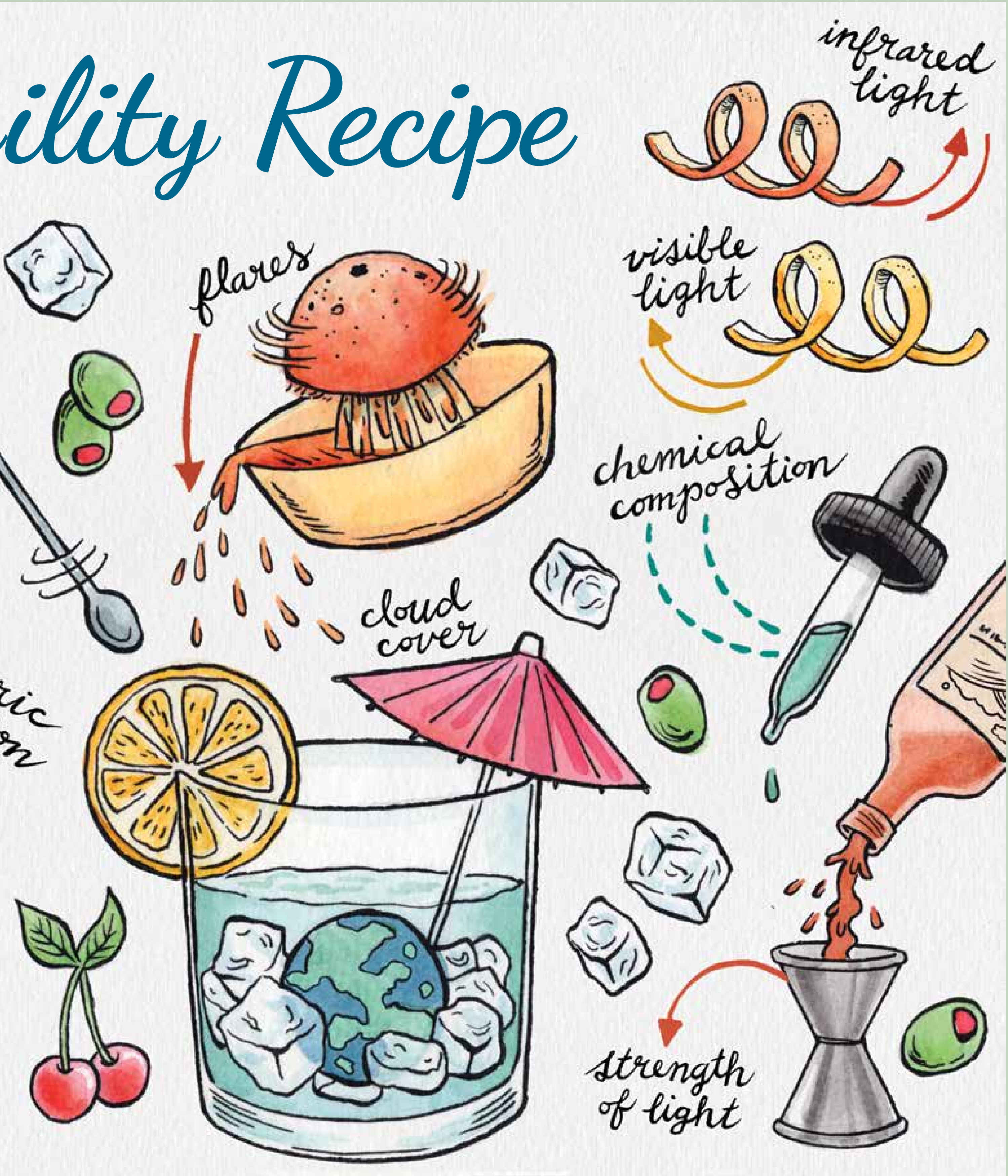
▶ **HOW TO BREW A HABITABLE PLANET** Although astronomers have traditionally defined a star's habitability based on the zone where temperatures permit liquid water, true habitability involves a cocktail of factors — and some might surprise you.

ility Recipe



tances from a star where conditions on an Earth-like planet would permit liquid water to flow on its surface. But true habitability involves a glorious cocktail of factors, from the host star's luminosity and magnetic activity to the planet's rotation rate and the composition of its atmosphere and surface. When it comes to red dwarfs, the prospects are not all sunshine and rainbows, but life — perhaps an unfamiliar form of it — could still thrive.

Habitability Gamble

There are many reasons why red dwarf stars might be the best places to look for habitable planets. First among them is sheer numerical superiority. These puny stars comprise about 70% of all stars in the Milky Way. This means that when astronomers swivel their telescopes toward a random patch of the sky, most of the planets they'll find will orbit red dwarfs.

Furthermore, the two most widely used techniques for detecting exoplanets — the transit and radial velocity methods — work better with small stars. An Earth-size planet orbiting a small star will eclipse a higher percentage of the star's visible surface (and thus its starlight) than the same planet orbiting a large star. Similarly, an Earth-size planet orbiting a less massive star will cause that star to wobble more than if it orbited a heftier star. Thus, astronomers discover more planets around small stars using these methods.

Because these stars are much cooler than most other stars, their habitable zones are significantly closer to them, much like a person must stand closer to a small campfire than to a large one to feel the same amount of heat.

▼ **NEVER-ENDING STORMS** Red dwarf stars are tumultuous. On a typical day, they display gigantic arcing prominences and a wealth of dark sunspots, but they also erupt with intense flares that, over time, could strip a nearby planet's atmosphere. One look at this artist's conception and it's easy to see why astronomers initially thought that any planets around stars like this one would be sterile.

NASA / ESA / STSCI / G. BACON

Furthermore, the gas clouds that collapse to make red dwarf systems appear to form small planets more easily than they do big ones. NASA's Kepler spacecraft found that although red dwarfs host far fewer gas giant planets than Sun-like stars do, they have 3.5 times more small planets in the Earth-size regime. In fact, 1 in 4 red dwarf star systems is estimated to have an Earth-size planet in the habitable zone.

For all these reasons, detecting habitable planets is not only easier but also more likely around red dwarfs than around other types of stars.

Unfortunately, because these stars are much cooler than most other stars, their habitable zones are significantly closer to them, much like a person must stand closer to a small campfire than to a large one to feel the same amount of heat. This close distance presents a number of complications to the habitability of orbiting planets.

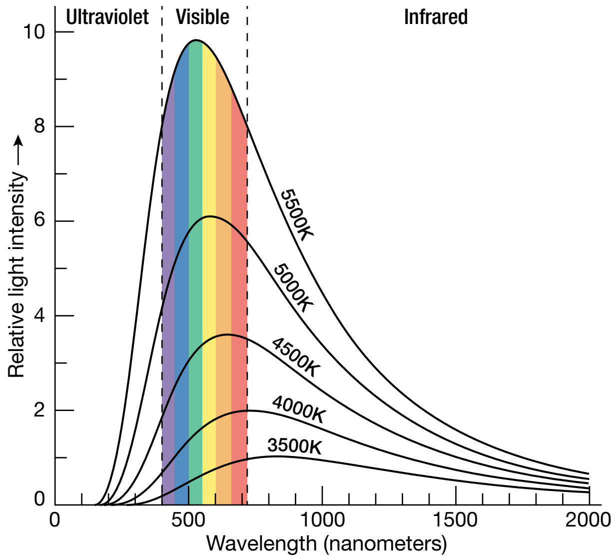
For starters, such proximity creates strong tidal forces, which can slow down the planet's rotation rate and affect its atmospheric circulation. This effect, known as *tidal locking*, can play out in a number of ways. It can slow down the planet only a little, or it can slow down the planet a lot, to a point called *synchronous rotation*, in which the same side of the planet always faces the star — meaning it's always daytime on that side of the planet and nighttime on the other. Who would want to live on a planet where it's always day or night? Could life even survive on such a world?

Indeed, the prevailing concern has long been that the nightside of a synchronously rotating planet could become so cold that the entire atmosphere would freeze out, condensing onto the surface to create an icy, airless world. Not the greatest prospect for a fun nightlife.

But all is not lost. Recent research using sophisticated global climate models has shown that a thick atmosphere could transport enough heat to the nightside of a synchronously rotating planet to prevent atmospheric freeze-out. Additionally, synchronous rotation might even create an advantage for habitability: If a tidally locked planet has an ocean, then the stronger convection in its atmosphere — a consequence of longer daytime illumination — could generate a thick blanket of clouds on its dayside. Those clouds would reflect the star's light back to space, lowering surface temperatures. This process might allow these planets to orbit their stars at much closer distances than they otherwise would, essentially buffering them against so-called *runaway greenhouse* states.

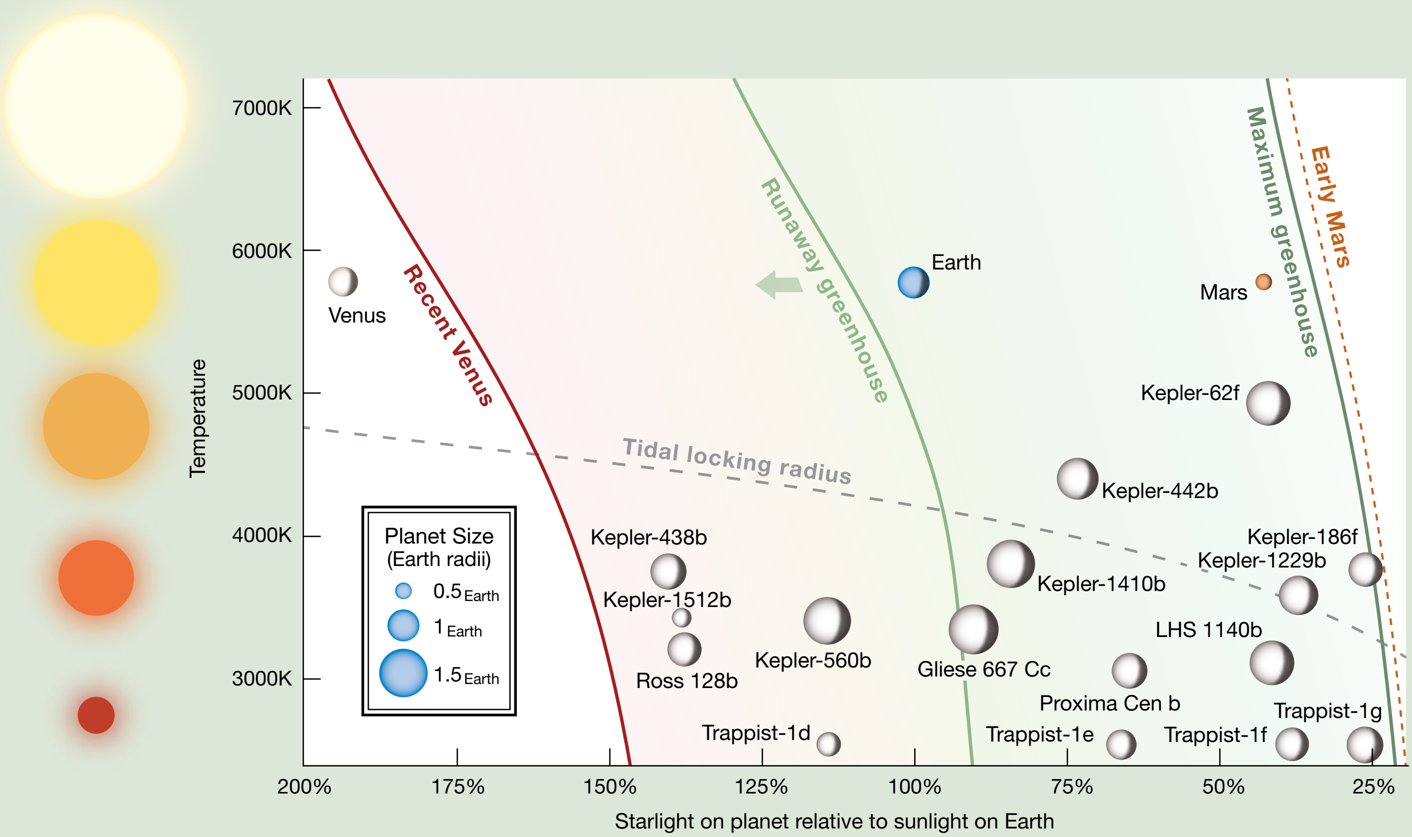
Besides the tidal interactions between a planet and its parent star, there may also be interactions between planets, as worlds around *M*-dwarfs often form closely packed together. In such cases, the gravitational pull of a planet's neighbors will change its rotation rate and might even transform the shape of the planet's orbit, making it more (or less) elongated. Since the orbit's shape, or *eccentricity*, determines how much starlight reaches the planet throughout its year, each interaction will change the total amount of light the planet receives. If the planet's spin axis is also tilted, then the interaction will also change how that starlight is distributed across different parts of the globe. There could be bizarre planets where climate conditions change significantly throughout the year.

Eccentric orbits aren't all bad, though. As a planet in an eccentric orbit swings through its closest approach to its



▲ **PEAK WAVELENGTHS** Cooler stars emit most of their radiation at longer wavelengths. While the Sun emits mostly visible and ultraviolet light, red dwarfs emit more infrared — a difference that could affect nascent life on an orbiting planet. (Color intervals are approximate.)

▼ **SHIFTING ZONES** Shown here are confirmed, potentially rocky exoplanets that fall in their stars' habitable zones, as compiled by Chester Harman (NASA Goddard Institute for Space Studies). The tidal locking radius was calculated by Jun Yang (Peking University) and colleagues.



WAVELENGTHS: WIKIPEDIA; ZONES: GREGG DINDERMAN / *S&T*, SOURCE: JUN YANG ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2014 AND CHESTER HARMAN, JR.

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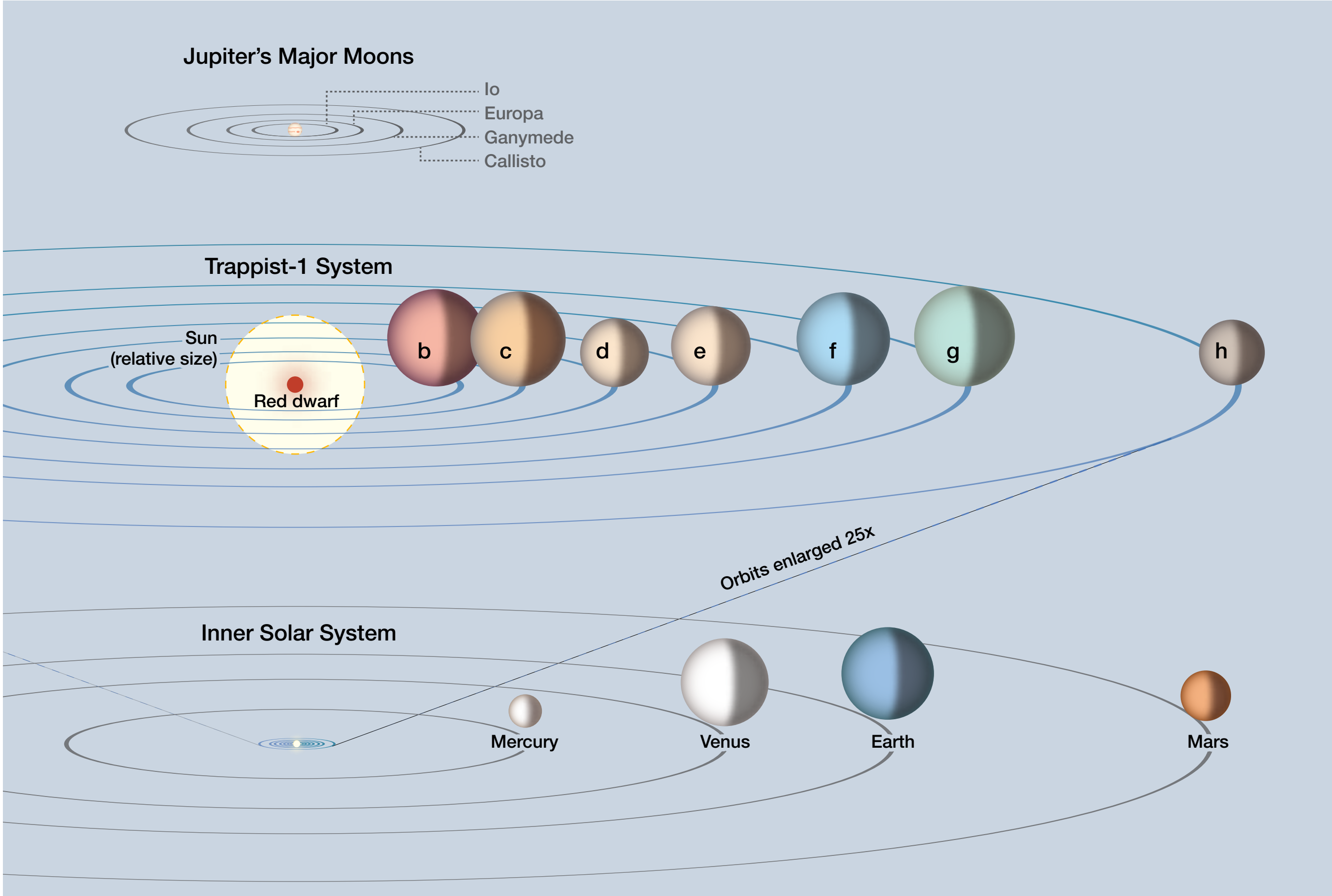

▲ **SEVEN WILD ABODES** The Trappist-1 system, which contains the largest number of known planets in the habitable zone around a single red dwarf, might be habitable — despite harsh conditions. A recent study suggests that at least one of the seven worlds might still possess liquid water.

GREGG DINDERMAN / S&T, SOURCE: NASA / JPL-CALTECH

star, the induced tidal stretching and squeezing can heat the planet's interior and drive plate tectonics, which scientists think enhances habitability by recycling carbon and other materials (*S&T:* July 2013, p. 18).

Forever Young and Tempestuous

Another complication that awaits planets around red dwarfs relates to the inordinately long lives of the parent stars. Because of their low masses, red dwarfs burn through their nuclear fuel *very* slowly. They are the tortoises of the stellar family. As a result, they have lifetimes that are significantly longer than those of Sun-like stars. We're talking trillions of years for the lowest-mass red dwarfs — compared with 10 billion years for our Sun. Because those lifetimes are longer than the current age of the universe (13.8 billion years), no red dwarf star has ever died.

Now, this could be a good thing or a very bad thing from a habitability standpoint. On the one hand, red dwarf stars' long lifetimes provide ample time for life to emerge, develop, and evolve way past any kind of life on Earth, including humans. And that's an exciting prospect. Perhaps life on a red dwarf planet will have evolved to be so technologically advanced that we won't have to worry about figuring out how to find it. It will find us.

On the other hand, the lengthy lifetimes of red dwarf stars also mean that they take a long time to settle down. Stars are much more active when they are young, spewing out flares and significant amounts of extreme ultraviolet (EUV) light towards an orbiting planet. For red dwarfs, this tumultuous period can last as long as a billion years. That's one *long* phase of the terrible twos. Over the course of that time, strong EUV emission could pelt the surface of the planet, evaporating its oceans and sending water vapor high into the atmosphere, where radiation can break it up into its separate components of hydrogen and oxygen. The lighter hydrogen escapes more easily to space, while the heavier oxygen would remain behind, creating an O_2-rich world. Any future observational measurements of such a world from space might erroneously assume that the detection of oxygen indicates the world is teeming with life, when the

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reality is that the planet has long been desiccated.

However, if a planet begins with enough water that it can retain some over its star's tumultuous time, a planet could remain habitable. This scenario might be the case for the Trappist-1 system. Trappist-1 hosts the largest number of known planets in the habitable zone orbiting a single red dwarf star. A recent study has shown that, even if the system's seven detected worlds are subject to high amounts of EUV emission and flares from their host star, at least one of the seven planets may still possess enough liquid water to preserve habitable surface conditions. And the Trappist-1 worlds aren't alone: Data on the thousands of planets detected by the Kepler space telescope suggest that the universe might be rich in water worlds.

Unfortunately, those red dwarf planets that manage to preserve their oceans might still become uninhabitable due to the side effects of orbiting a cool, small star. Strong stellar winds — another consequence of the red dwarf environment — might render the Trappist-1 planets uninhabitable by stripping away their atmospheres. Additionally, intense ultraviolet light, typical of red dwarf flare events, may remove most of a planet's atmospheric ozone, a crucial element in shielding Earth's surface from harmful ultraviolet rays. Yet, the amount of atmospheric depletion can vary greatly depending on each star's behavior, and surface conditions might mitigate its dangers. If the world has large oceans, for example, life could still develop underwater even in the absence of a thick ozone layer.

Even a planet's magnetic field could suffer because the planet is too close to the star. This field is powered by the churning motion of liquid metal deep within the planet and sustained by both the planet's rotation and the flow of heat from the core to the outer layers. A magnetic field has long been considered a characteristic of a habitable planet, because it can protect the atmosphere from the harmful effects of stellar flare activity, charged particles, and cosmic rays. But unfortunately, planets orbiting red dwarfs might host fairly weak fields. Some scientists suggest that, because the planets are tidally locked and tidally heated, their interiors might not sustain the churning motion needed to power a global field. The topic remains an active area of research.

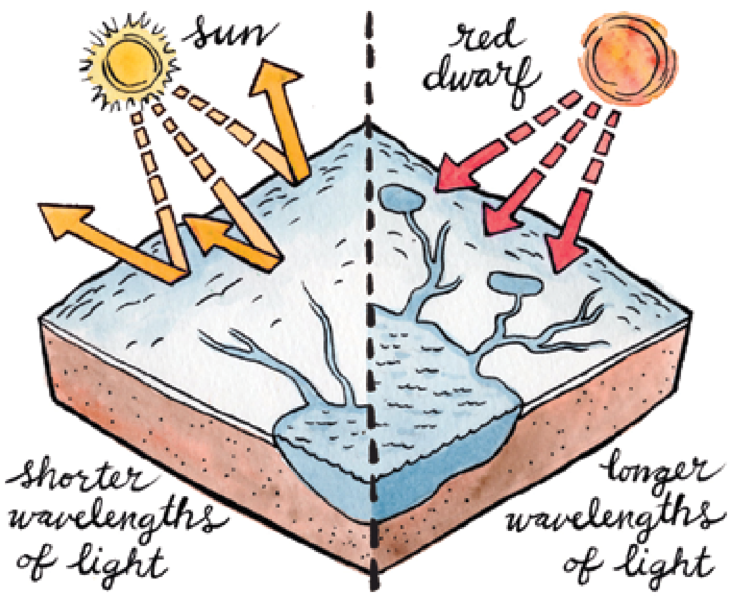
Life-giving Glow?

Another key difference between red dwarfs and other stars is that the type of light they produce — and that planets receive — is quite different. Whereas visible and ultraviolet light make up a large fraction of what Earth receives from the Sun, red dwarfs emit primarily at longer wavelengths (particularly in the infrared waveband). This difference is key to their planets' habitability, as recent research shows that infrared radiation interacts differently with planetary atmospheres and surfaces than does visible or ultraviolet light.

Stars are much more active when they are young, spewing out flares and significant amounts of extreme ultraviolet light. For red dwarfs, this tumultuous period can last as long as a billion years.

Molecules prevalent in planetary atmospheres, such as water, carbon dioxide, and methane, strongly absorb infrared radiation. And the more that an atmosphere absorbs, the warmer it (and its planet) will be. Thus, despite red dwarfs' cool, dim nature, their planets might more easily maintain balmy surface temperatures than worlds around hotter, brighter stars. In addition, red dwarf planets wouldn't need as much CO_2 or other greenhouse gases in their atmospheres in order to stay warm.

Additionally, it isn't just atmospheric molecules that can absorb this longer-wavelength emission. Water ice and snow also strongly absorb infrared wavelengths. The interaction between the red dwarf spectrum and icy or snowy surfaces may have an important effect on planetary climate — one very different than the one we experience here. On Earth, water ice reflects the shorter wavelengths of sunlight, sending them back to space and cooling the globe, which leads to the formation of more ice (which reflects more sunlight, further lowering temperatures, etc.). At its best, this process regulates our planet's climate; at its worst, it leads to ice ages.



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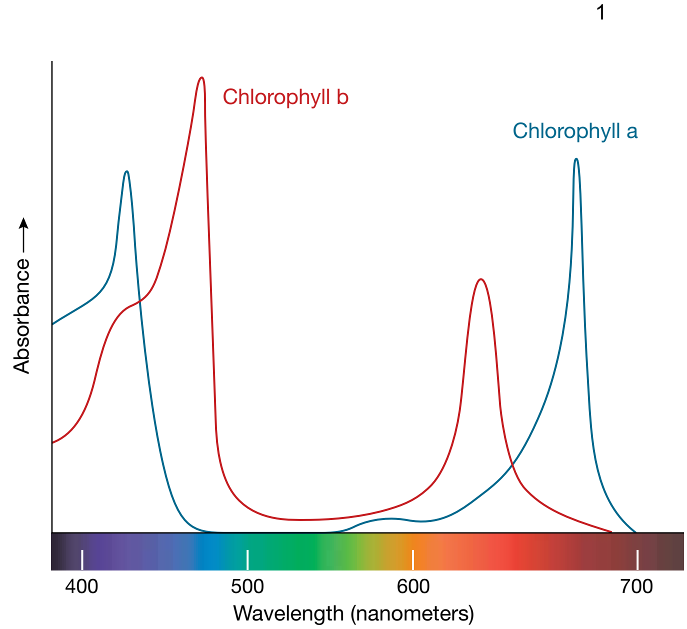
▶ **FIRE AND ICE** On Earth, water ice reflects the relatively shorter wavelengths of sunlight, sending them back to space and cooling the globe. Then more ice forms, which reflects more sunlight, further lowering temperatures in a feedback loop. But on a planet orbiting a red dwarf, water ice absorbs the star's longer wavelengths, creating a warming effect instead.

But on a planet orbiting a red dwarf, ice and snow will instead absorb much of the incoming light from its star. This warming effect, combined with the warming from the atmosphere, means that water-dominated planets might be more resistant to freezing over than similar planets orbiting brighter stars. If planets around a red dwarf do freeze, they might thaw out more easily over time as their host stars — like all other stars — naturally brighten. The fact that these planets are fairly resistant to climate extremes and exit those extremes easily on the rare occasion they do happen, means that they're more climatically stable and will therefore provide a greater chance for life.

Scientists are just beginning to consider the climatic impacts of different types of surface environments on red dwarf planets. The news isn't all balmy. New research finds that if temperatures within a red dwarf planet's oceans plummet below -23°C, salt could crystallize in bare sea ice, forming what is known as a *hydrohalite crust*. At infrared wavelengths, hydrohalite is brighter than snow, which means that it doesn't absorb starlight but reflects it — so much so that its presence could cool the surface more than researchers had thought possible. We still have much to learn about how different surfaces — from distinct kinds of soil and vegetation to ocean and ice — might interact with the light from red dwarfs.



▲ **ABSORBING LIGHT** On Earth, plants primarily use the pigments chlorophyll a and b, which absorb sunlight strongly in the visible range of the spectrum. Plants on red dwarf planets might be able to absorb light at these wavelengths as well, but they would have to rely on stellar flares, which emit light across the entire electromagnetic spectrum. The growth of vegetation would then depend not on seasons but on the red dwarf's cycles of flare activity.

Life's Spark

It is far too soon for us to comprehensively answer the question of what kind of life might be possible on a red dwarf planet. But we can ask a more specific question: Is photosynthesis possible?

On Earth, plants use the pigment chlorophyll, which absorbs stellar light strongly in the visible range of the spectrum (400–700 nanometers), to transform sunlight and carbon dioxide into food. In the process, they produce oxygen, vital to respiration and in the production of the protective ozone layer around Earth. Given the small amount of visible light that red dwarfs emit, photosynthesis as we know it might not be possible on planets around such stars. However, life on these planets would presumably evolve to harvest the wavelengths most available. Vegetation on planets around red dwarfs might absorb radiation across a wider range of the spectrum or specifically use infrared wavelengths.

The star's flares might also provide what its calmer glow does not. Stellar flares emit radiation across the entire electromagnetic spectrum, including visible light. So it might be the case that the strong flare activity, usually thought of as damaging to life, could supply vegetation with enough visible light to conduct the kind of photosynthesis that plants do on Earth. In this scenario, the cycle governing the loss and growth of vegetation could become inextricably tied to the cycles of flare activity for a red dwarf, an unusual symbiotic prospect.

This relationship could be even more profound at ultraviolet wavelengths — and that's crucial. Researchers think that ultraviolet radiation is a necessary ingredient in the chemical processes leading up to the formation of basic life. If that's true, then the paucity of ultraviolet light coming from *M*-dwarfs would pose an obstacle to the development of life. But flares might solve the problem: The blasts of ultraviolet photons that bombard the planet with every stellar outburst might compensate for this intrinsic deficit — providing enough light to help life emerge.

We are only at the beginning of understanding what worlds around these stars might be like. But over the next decade, we'll see space- and ground-based projects with instruments sensitive enough to observe an abundance of small terrestrial planets. NASA's Transiting Exoplanet Survey Satellite (TESS; *S&T:* Mar. 2018, p. 22) spacecraft, for example, spends 27 days staring at each patch of sky, a length of time comparable to the orbital period of planets in the habitable zones around red dwarfs. These cool, dim stars are thus the favored targets for the TESS mission. In fact, 75% of the planets TESS is expected to detect should orbit red dwarfs. The most promising planets will be close enough that follow-up studies might identify biosignatures in their atmospheres, telling astronomers that life is likely present.

If there exists a habitable planet orbiting a red dwarf, we now have a real chance of finding it.

■ **IGOR PALUBSKI** is a graduate student at the University of California, Irvine. **AOMAWA SHIELDS** is the Clare Boothe Luce Assistant Professor of Physics and Astronomy at the University of California, Irvine, and Director of the Shields Center for Exoplanet Climate and Interdisciplinary Education.

