AstroTalk: Behind the news headlines of July–September 2019

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Atmospheres of planets orbiting distant stars

Two astronomers from McGill University in Canada have assembled a "fingerprint" for Earth, which could be used to identify a planet beyond our solar system capable of supporting life.

Physics student Evelyn Macdonald and her supervisor, Prof. Nicolas Cowan, used over a decade of observations of Earth's atmosphere taken by the *SCISAT* satellite to construct a "transit spectrum" of Earth, a fingerprint for Earth's atmosphere in infrared light, which shows the presence of key molecules. This includes the simultaneous presence of ozone and methane, which scientists expect to see only when there is an organic source of these compounds on the planet. Such a detection is called a "biosignature."

> "*A handful of researchers have tried to simulate Earth's transit spectrum, but this is the first empirical infrared transit spectrum of Earth," says Cowan. "This is what alien astronomers would see if they observed a transit of Earth [across the face of the Sun]*."

The findings could help scientists determine what kind of signal to look for in their quest to find Earth-like exoplanets (planets orbiting a star other than our Sun). *SCISAT* was developed to help scientists understand the depletion of Earth's ozone layer by studying particles in the atmosphere as sunlight passes through it.

In general, astronomers can tell which molecules are found in a planet's atmosphere by looking at how starlight changes as it shines through the atmosphere. Instruments must wait for a planet to pass—or transit—across the star to make this observation. With sensitive telescopes, astronomers could potentially identify molecules such as carbon dioxide, oxygen, or water vapour that might indicate if a planet is habitable.

Since the first discoveries of exoplanets in the 1990s, astronomers have confirmed the existence of some 4,000 exoplanets. The holy grail in this relatively new field of astronomy is to find planets that could potentially host life—an "Earth 2.0."

A very promising system that might hold such planets, called TRAPPIST-1, will be a target for the upcoming *James Webb Space Telescope*, set to launch in 2021. Macdonald and Cowan built a simulated signal of what an Earth-like planet's atmosphere would look like through this future telescope.

The TRAPPIST-1 system, located 40 light-years away, contains seven planets, three or four of which are located in the "habitable zone," where liquid water could exist. The astronomers say this system might be a promising place to search for a signal similar to their Earth fingerprint since the planets are orbiting an M-dwarf star, a type of star that is smaller and colder than our Sun.

> "*TRAPPIST-1 is a nearby red dwarf star, which makes its planets excellent targets for transit spectroscopy. This is because the star is much smaller than the Sun, so its planets are relatively easy to observe*," explains Macdonald. "*Also, these planets orbit close to the star, so they transit every few days. Of course, even if one of the planets harbours life, we don't expect its atmosphere to be identical to Earth's since the star is so different from the Sun*."

Macdonald and Cowan affirm that the *Webb* telescope will be sensitive enough to detect carbon dioxide and water vapour. It may even be able to detect the biosignature of methane and ozone if enough time is spent observing the target planet.

Meanwhile, two current NASA space telescopes recently teamed up to identify, for the first time, the detailed chemical fingerprint of a planet between the sizes of Earth and Neptune. No planets like this can be found in our own solar system, but they are common around other stars.

The planet, Gliese 3470 b (also known as GJ 3470 b), may be a cross between Earth and Neptune, with a large rocky core buried under a deep crushing hydrogen and helium atmosphere. Many similar worlds have been discovered by NASA's *Kepler* space observatory, whose mission ended in 2018. In fact, 80% of the planets in our Milky Way galaxy may fall in this mass range.

However, astronomers have never been able to understand the chemical nature of such a planet until now. By inventorying the contents of GJ 3470 b's atmosphere, astronomers can uncover clues about the planet's nature and origin.

> "*This is a big discovery from the planet formation perspective. The planet orbits very close to the star and is far less massive than Jupiter—318 times Earth's mass—but has managed to accrete the primordial hydrogen/helium atmosphere that is largely 'unpolluted' by heavier elements*," said Björn Benneke of the University of Montreal (Canada). "*We don't have anything like this in the solar system, and that's what makes it striking*."

Astronomers enlisted the capabilities NASA's *Hubble* and *Spitzer* space telescopes to do a first-of-a-kind study of GJ 3470 b's atmosphere. This was accomplished by measuring the absorption of starlight as the planet passed in front of its star and the loss of reflected light from the planet as it passed behind the star (eclipse). In total, the space telescopes observed 12 transits and 20 eclipses. The science of analysing chemical fingerprints based on light is called "spectroscopy."

“*For the first time we have a spectroscopic signature of such a world*,” said Benneke. But he is at a loss for classification: Should it be called a “super-Earth” or a “sub-Neptune?”

Fortuitously, the atmosphere of GJ 3470 b turned out to be mostly clear, with only thin haze, enabling the scientists to probe deep into the atmosphere.

> “*We expected an atmosphere strongly enriched in heavier elements like oxygen and carbon which are forming abundant water vapour and methane gas, similar to what we see on Neptune*,” said Benneke. “*Instead, we found an atmosphere that is so poor in heavy elements that its composition resembles the hydrogen/helium-rich composition of the Sun.*”

Other exoplanets, called “hot Jupiters,” are thought to form far from their stars, and over time migrate much closer. But this planet seems to have formed just where it is today, says Benneke.

The most plausible explanation is that GJ 3470 b was born precariously close to its red dwarf star, which is about half the mass of our Sun. Benneke hypothesizes that essentially it started out as a dry rock, and rapidly accreted hydrogen from a primordial disk of gas when its star was very young. Such a disk is called a “protoplanetary disk.”

> “*We're seeing an object that was able to accrete hydrogen from the protoplanetary disk, but didn't runaway to become a hot Jupiter*,” said Benneke. “*This is an intriguing regime*.”

One explanation is that the disk dissipated before the planet could bulk up further. “*The planet got stuck being a sub-Neptune*,” said Benneke.

Another recent discovery added more excitement to this rapidly developing field. The exoplanet K2-18b, at eight times the mass of Earth, is now the only planet orbiting a star outside the Solar System known to have both water and temperatures that could support life. This discovery is the first successful atmospheric detection for an exoplanet orbiting in its star's habitable zone.

Angelos Tsiaras (University College London, UK; UCL), said:

> “*Finding water in a potentially habitable world other than Earth is incredibly exciting. K2-18b is not 'Earth 2.0' since it is significantly heavier and has a different atmospheric composition. However, it brings us closer to answering the fundamental question: Is the Earth unique?*”

The team used archival data from 2016 and 2017 captured by the *Hubble Space Telescope* and analysed the starlight filtered through K2-18b's atmosphere. The results revealed the molecular signature of water vapour, also indicating the presence of hydrogen and helium in the planet's atmosphere.

The authors believe that other molecules including nitrogen and methane may be present but, with current observations, they remain undetectable. The planet orbits the cool dwarf star K2-18, about 110 light-years from Earth. Given the high level of activity of its red dwarf star, K2-18b may be more hostile than Earth and is likely exposed to more radiation.

K2-18b was discovered in 2015 and is one of hundreds of super-Earths found by Kepler. NASA's Transiting Exoplanet Survey Satellite (*TESS*) mission is expected to detect hundreds more super-Earths in the coming years.

Ingo Waldmann (also from UCL), said:

> "*With so many new super-Earths expected to be found over the next couple of decades, it is likely that this is the first discovery of many potentially habitable planets. This is not only because super-Earths like K2-18b are the most common planets in our Galaxy, but also because red dwarfs—stars smaller than our Sun—are the most common stars*."

The next generation of space telescopes, including the *James Webb Space Telescope* and the European Space Agency's *ARIEL* mission, will be able to characterise atmospheres in more detail because they will carry more advanced instruments. *ARIEL* is expected to launch in 2028 and will observe 1,000 planets in detail to get a truly representative picture of what they are like.

Professor Giovanna Tinetti (UCL), Principal Investigator for *ARIEL*, said:

> "*Our discovery makes K2-18 b one of the most interesting targets for future study. Over 4,000 exoplanets have been detected but we don't know much about their composition and nature. By observing a large sample of planets, we hope to reveal secrets about their chemistry, formation and evolution*."

And finally, a super-scorched planet orbiting a nearby dim star has recently helped reveal the presence of two previously unseen planets—one of which could host liquid water and thus be friendly to life, astronomers say.

The blistering planet GJ 357 b, picked out by *TESS*, is located about 31 light-years away. It's only 22% larger than Earth and circles its star every 3.9 days—tracing an orbit that's 11 times closer to its star than Mercury's is to our Sun. This means that even though its M-dwarf star is roughly 40% cooler than our Sun, the planet is in all likelihood searingly hot even without the insulating effects of an atmosphere.

That uninhabitable world was the only one around this star spotted by *TESS*, which scans the skies looking for dips in a star's light that might indicate that a planet is transiting in front of it.

Astronomers used information from ground-based telescopes to confirm GJ 357 b's existence. In the process, they found clues that an additional pair of planets was also orbiting the same star.

These two planets, GJ 357 c and d, were found using the radial velocity method: by looking at the slight wobble in the star's motions caused by its planets' tiny gravitational tugs. GJ 357 c weighs in at about 3.4 times Earth's mass and orbits the star every 9.1 days at a distance more than double that of GJ 357 b.

It's the third planet, GJ 357 d, that actually holds some potential as a habitable world. It weighs at least 6.1 Earth masses and circles the star at a much greater distance, completing an orbit in 55.7 days. Even though this is just one-fifth the distance of the Earth to our Sun, GJ 357 d's dim star leaves the surface very cold. Without an atmosphere, a thermometer on the surface would hover around 53 degrees Celcius below zero—meaning no liquid water on the surface.

However, if GJ 357 d does turn out to have an atmosphere, this could be a game changer. A dense atmosphere with the right composition could trap some warmth and allow water to remain liquid on the planet's surface. That's similar to what scientists think happened on Mars, which today is frigid and dry but may once have had a thick atmosphere that allowed liquid water to exist.

The trick would be to try to catch a glimpse of GJ 357 d, if it can be seen transiting its star from our vantage point.

> "*If we can detect a transit of GJ 357d, it would become the closest transiting, potentially habitable planet in the solar neighbourhood*," the study authors wrote. "*Even if GJ 357d does not transit, the brightness of its star makes this planet in the habitable zone of a close-by M star a prime target for observations with extremely large telescopes as well as future space missions*."

Recent advances in our understanding of the atmospheres of planets orbiting distant stars have yielded amazing new insights. And this is, in all likelihood, only the beginning!

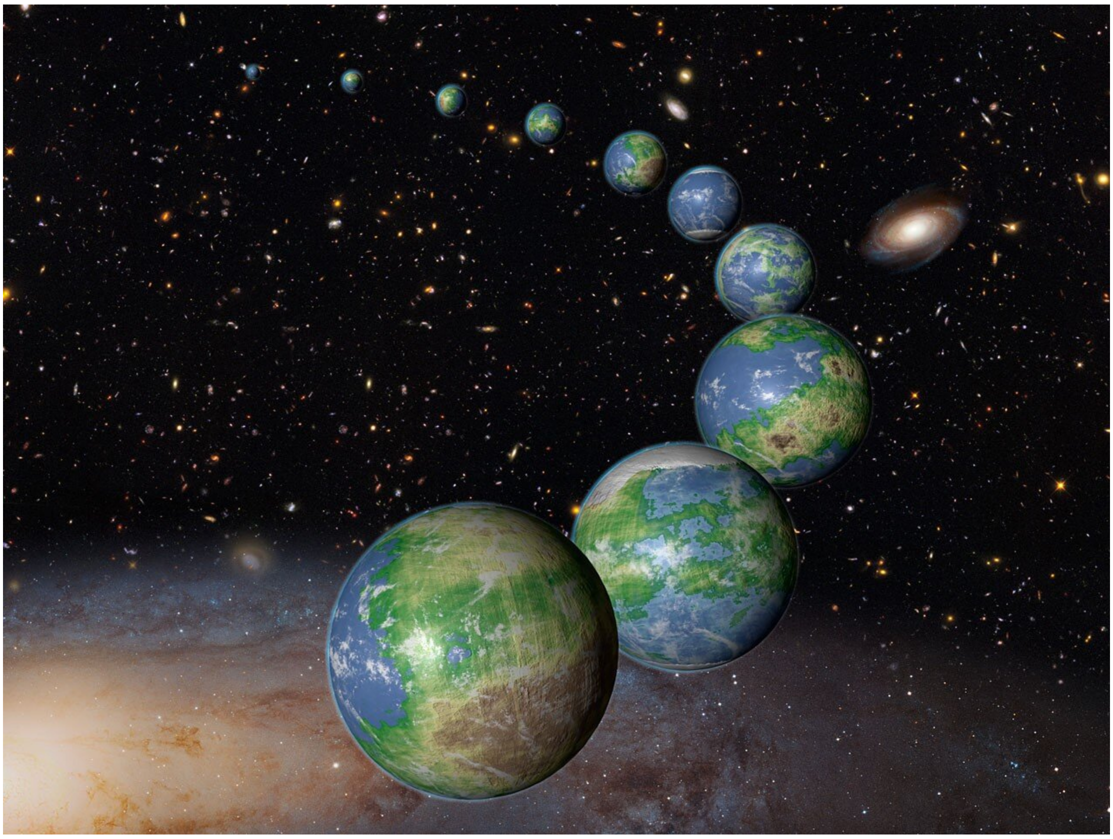

Figure 1: An artist's conception of Earth-like planets. *Credit: NASA/ESA/G. Bacon (STScI)*

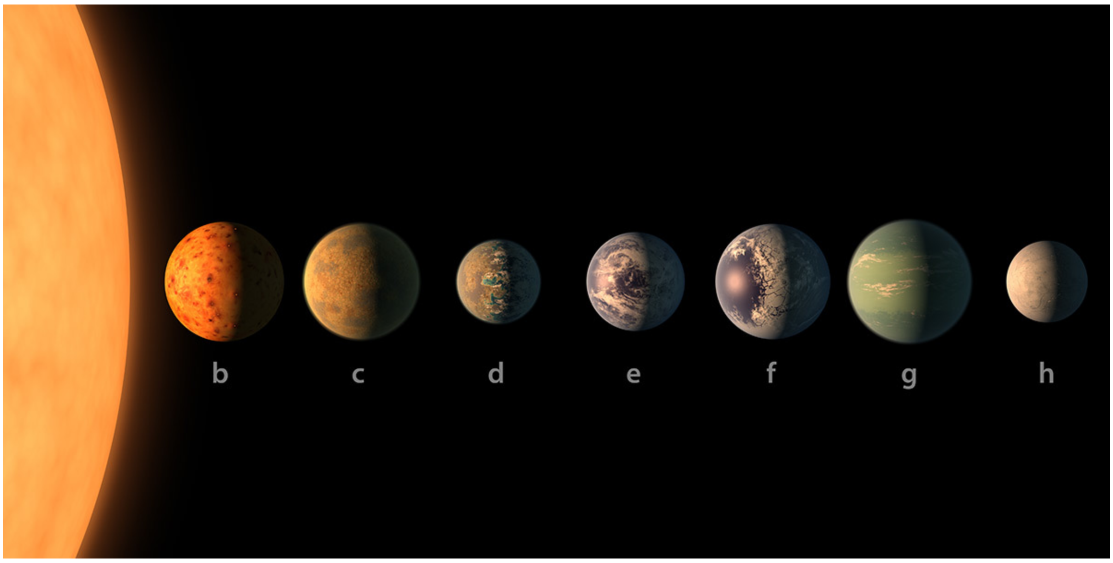

Figure 2: The ultra-cool dwarf star TRAPPIST-1 and its seven planets. *Credit: NASA*

Figure 3: This artist's impression shows the view from the surface of one of the planets in the TRAPPIST-1 system. At least seven planets orbit this ultracool dwarf star 40 light-years from Earth and they are all roughly the same size as the Earth. Several of the planets are at the right distances from their star for liquid water to exist on the surfaces. *Credit: ESO/N. Bartmann/ spaceengine.org*

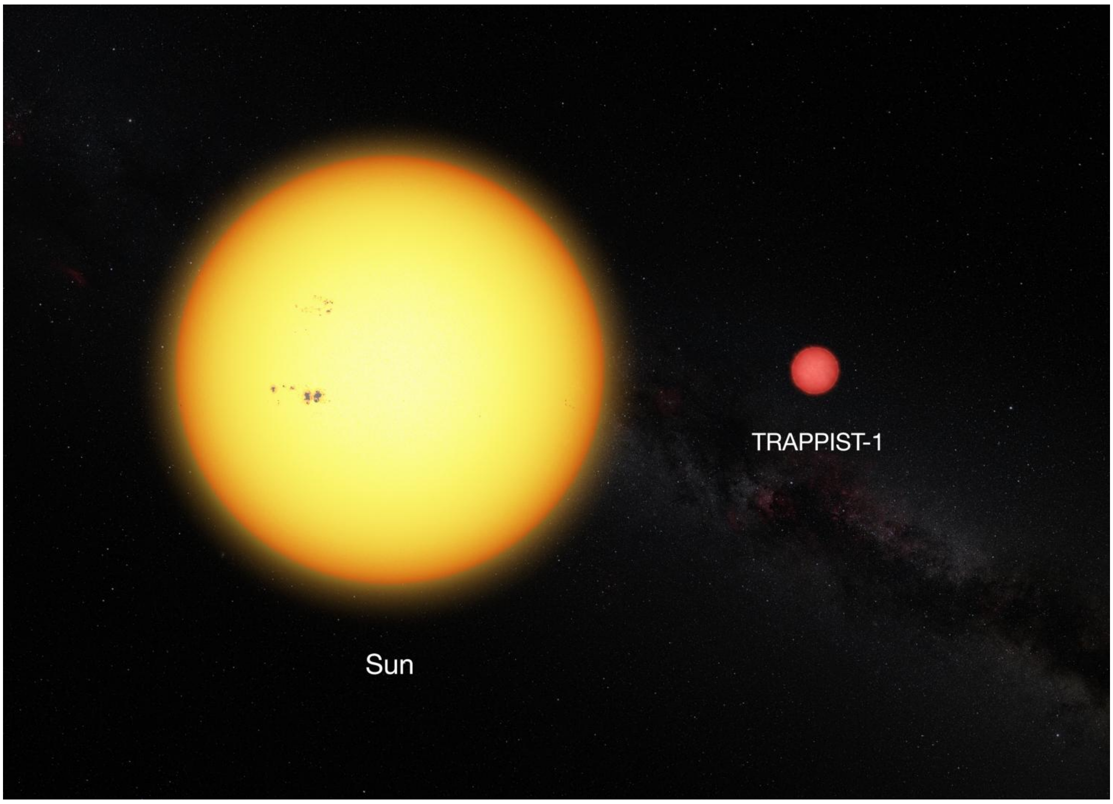

Figure 4: This picture shows the Sun and the ultracool dwarf star TRAPPIST-1 to scale. The faint star has only 11% of the diameter of the Sun and is much redder in colour. As the planets found around TRAPPIST-1 orbit much closer to their star than Mercury is to the Sun, they are exposed to similar levels of radiation as Venus, Earth, and Mars in the Solar System. *Credit: ESO*

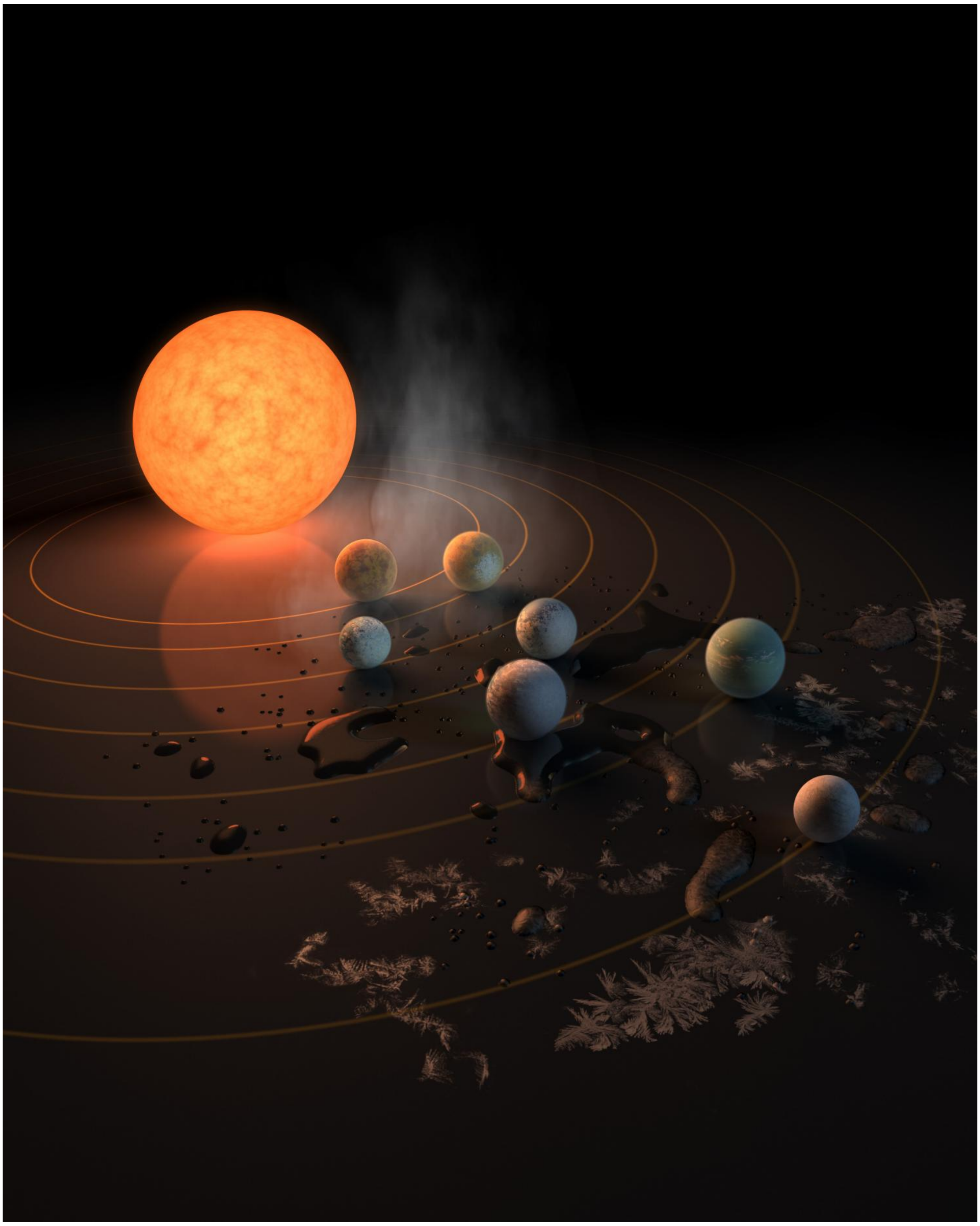

Figure 5: The TRAPPIST-1 system, depicted here in an artist's conception, contains seven roughly Earth-sized planets orbiting a red dwarf, which is a faint, low-mass star. This star spins rapidly and generates energetic flares of ultraviolet radiation and a strong wind of particles. The behaviour of this red dwarf makes it much less likely than generally thought that the three planets orbiting well within the habitable zone could support life. *Credit: NASA/JPL-Caltech/R. Hurt*

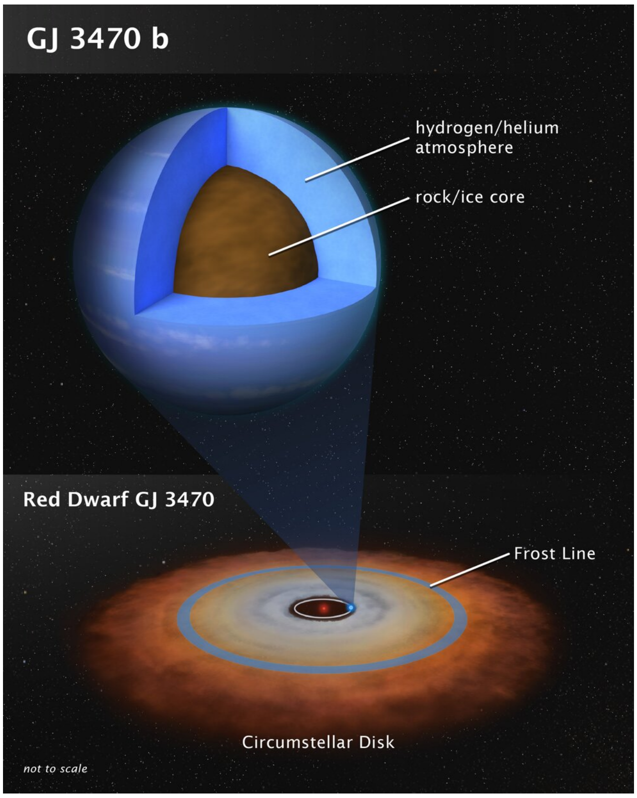

Figure 6: This artist's illustration shows the theoretical internal structure of the exoplanet GJ 3470 b. The bottom illustration shows the disk as the system may have looked long ago. *Credit: NASA, ESA, and L. Hustak (STScI)*

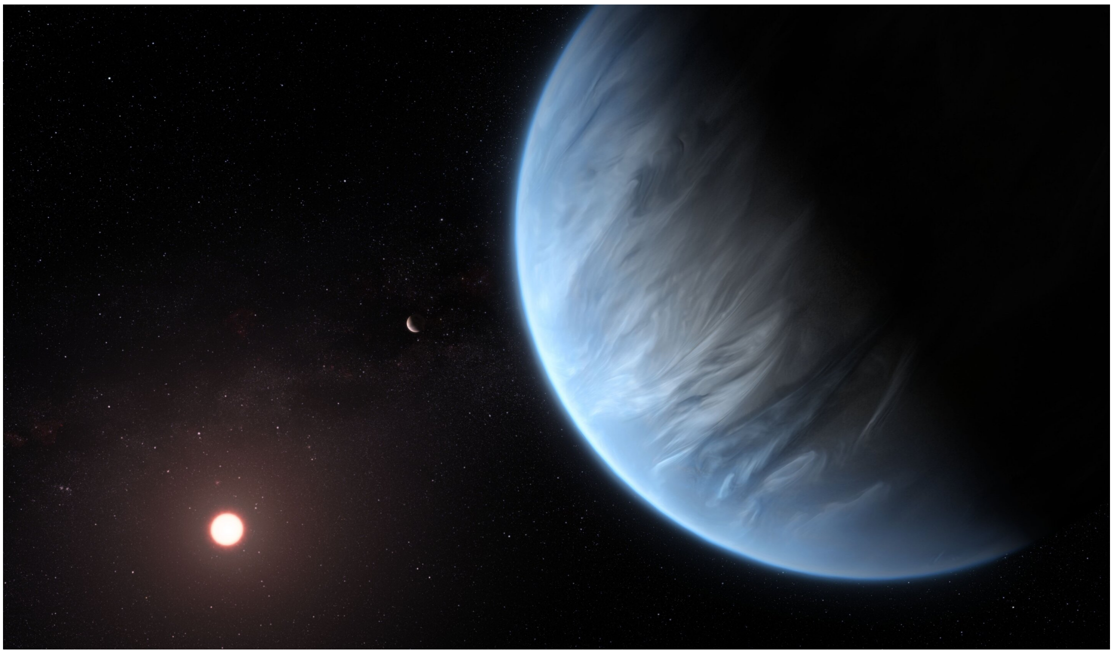

Figure 7: This artist's impression shows the planet K2-18b, its host star and an accompanying planet in this system. K2-18b is now the only super-Earth exoplanet known to host both water and temperatures that could support life. *Credit: Credit: ESA/Hubble, M. Kornmesser*

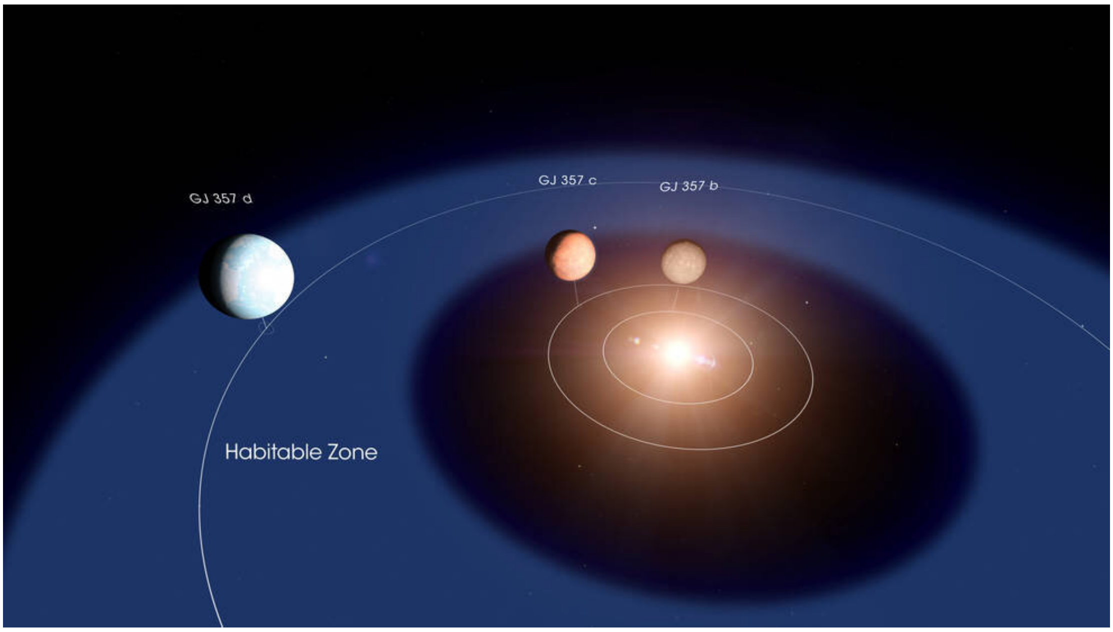

Figure 8: This diagram shows the layout of the GJ 357 system. Planet d orbits within the star's habitable zone, the orbital region where liquid water can exist on a rocky planet's surface.
Credits: NASA's Goddard Space Flight Center/Chris Smith