AstroTalk: Behind the news headlines; April 2024

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The search for extrasolar water is heating up, literally!

Using the *James Webb Space Telescope* (*JWST*), an international team of astronomers led by scientists from Leiden University (Netherlands) has made the first two-dimensional inventory of ice in a planet-forming disk of dust and gas surrounding a young star.

Ice is important for the formation of planets and comets. Thanks to ice, solid dust particles clump together into larger chunks, from which planets and comets form. Moreover, the impacts of ice-bearing comets probably contributed significantly to the amount of water on Earth, forming its oceans.

This ice also contains atoms of carbon, hydrogen, oxygen and nitrogen that are important in the formation of the molecular building blocks of life. However, ice in planet-forming disks had never been mapped in detail before. That's because Earth-based telescopes are hampered by our planet's atmosphere, since the abundant water vapour in Earth's atmosphere degrades the astronomical signals. In addition, other space telescopes were not large enough to detect and resolve such faint targets. The *JWST* solves these problems.

The researchers studied the starlight from the young star HH 48 NE as it passes through its planet-forming disk towards the space telescope. The star and disk are located about 600 light-years from Earth in the southern constellation Chameleon. The disk looks like a hamburger, with a dark central lane and two bright buns because we are looking at it from the side, edge-on.

On its way to the telescope, the starlight collides with many molecules in the disk. This creates absorption spectra with peaks specific to each molecule. The downside is that little light reaches the telescope, particularly from the densest part of the disk in the dark lane. But because the *JWST* is more sensitive than any other telescope, the low levels of light do not pose a significant problem.

The researchers observed distinct traces of water ice (H_2O), carbon dioxide ice (CO_2), and carbon monoxide ice (CO) in the absorption spectra. They also found evidence of ice of ammonia (NH_3), cyanate (OCN^-), carbonyl sulphide (OCS) and heavy carbon dioxide ($^{13}CO_2$).

The ratio of regular carbon dioxide to heavy carbon dioxide allowed one to calculate, for the first time, how much carbon dioxide is present in the disk. One of the interesting outcomes is that the CO ice the researchers detected may be mixed with the less volatile CO_2 and water ice, allowing it to stay frozen closer to the star than previously thought.

> "*The direct mapping of ice in a planet-forming disk provides important input for modelling studies that help to better understand the formation of our Earth, other planets in our solar system and around other stars. With those observations, we can*

now begin to make firmer statements about the physics and chemistry of star and planet formation," says the study's lead author, Ardjan Sturm.

"*In 2016, we created one of the first* JWST *research programmes,* Ice Age*. We wished to study how the icy building blocks of life evolve on the journey from their origins in cold interstellar clouds to the comet-forming regions of young planetary systems. Now the results are starting to arrive. It's a really exciting time*," says team leader and co-author Melissa McClure, also from Leiden University.

The *Ice Age* team will soon study more extensive spectra of the same planet-forming disk. In addition, they are now able to observe other planet-forming disks. If the finding about CO ice mixtures holds, this would modify the current understanding of planetary compositions, potentially leading to more carbon-rich planets closer in to their stars.

Ultimately, the researchers intend to learn more about the formation pathways and the resulting composition of planets, asteroids and comets.

More evidence of water as planet-forming lubricant

Meanwhile, other researchers have also found water vapour in the disk around a young star exactly where planets may be forming. Water is a key ingredient for life on Earth and is also thought to play a significant role in planet formation, yet until now, astronomers have never been able to map how water is distributed in a stable, cool disk—the type of disk that offers the most favourable conditions for planets to form around stars.

In another first, astronomers have now weighed the amount of water vapour around a typical planet-forming star. The new findings were made possible thanks to the Atacama Large Millimeter/submillimeter Array (ALMA)—a collection of telescopes in the Chilean Atacama Desert.

Dr. Anita Richards from the University of Manchester says,

"*Directly measuring the amount of water vapour where planets are forming takes us a step closer to understanding how easy it could be to make worlds with oceans—how much water is attached to the agglomerating rocks, or is it mostly added later to an almost-fully-formed planet? This sort of observation needs the driest possible conditions and could only be made in such detail using the ALMA array in Chile*."

The observations reveal at least three times as much water as in all of Earth's oceans in the inner disk of the young sun-like star HL Tauri, located some 450 light-years away from Earth, in the constellation Taurus.

Stefano Facchini, an astronomer at the University of Milan, Italy, who led the study, says,

"*I had never imagined that we could capture an image of oceans of water vapour in the same region where a planet is likely forming*."

Co-author Leonardo Testi, an astronomer at the University of Bologna, Italy, added,

> "*It is truly remarkable that we can not only detect but also capture detailed images and spatially resolve water vapour at a distance of 450 light-years from us*."

These ALMA observations, which show details as small as a human hair at a kilometre distance, allow astronomers to determine the distribution of water in different regions of the disk.

A significant amount of water was found in the region where a known gap in the HL Tauri disk exists—a place where a planet could potentially be forming. Radial gaps are carved out in gas- and dust-rich disks by orbiting, young, planet-like bodies as they gather up material and grow. This suggests that this water vapour could affect the chemical composition of planets forming in those regions.

ALMA, operated by the European Southern Observatory, together with its international partners, sits at about 5,000 metres elevation and is built in a high and dry environment specifically to minimise this degradation, providing exceptional observing conditions. To date, ALMA is the only facility able to map the distribution of water in a cool planet-forming disk.

The dust grains that make up a disk are the seeds of planet formation, colliding and clumping into ever larger rocky bodies orbiting a star. Astronomers believe that where it is cold enough for water to freeze onto dust particles, things stick together more efficiently—an ideal spot for planet formation.

Ocean worlds

With all this focus on extrasolar water and liquid ice, in recent years astronomers have been on the hunt for a new kind of exoplanet—one especially suited for habitability. They're called Hycean worlds, and they're characterised by vast liquid water oceans and thick hydrogen-rich atmospheres. The name was coined in 2021 by University of Cambridge astronomer Nikku Madhusudhan, whose team got a close-up look at one possible Hycean world, K2-18b, using the *JWST* in 2023.

In a research article from January 2024, Madhusudhan and his colleague Frances Rigby examined what the internal structure of Hycean planets might look like, and what that means for the possibility of finding life within.

Hycean worlds are unlike anything we have seen in our own solar system, expanding the very definition of a habitable planet. They tend to be much bigger than Earth-like planets, earning them the moniker 'mini-neptunes.' Their size makes them easier to detect than smaller rocky worlds, and their thick atmospheres give them a wider habitable zone.

Those same properties also make them ideal candidates for spectroscopic analysis, where measuring the chemical composition of the atmospheres might reveal biosignatures.

To tease out the potential characteristics of a habitable Hycean world, Rigby and Madhusudhan used a new modelling tool to map out possible planetary structures. They limited their models to only allow for habitable temperatures and pressures at the ocean's surface, where the water meets the air.

Even with those strict conditions in place, the results showed a wide variety of possible internal structures. The ocean depths of a habitable Hycean world could range from tens of kilometres deep to thousands of kilometres (for comparison, Earth's oceans average a depth of about 3.7 km).

One factor that potentially limits the habitability of these worlds is that they are likely to have a thick layer of ice between the ocean floor and the rocky core of the planet. On Earth, the weathering of the rocky seafloor produces nutrients that are essential to life—ice might inhibit that process. Nonetheless, there is still the possibility that these nutrients could be transported through the ice via convection, or delivered to the planet in other ways, for instance via comet and asteroid impacts or atmospheric condensation.

Their study also looked at several real Hycean world candidates, and among them, there are three that stand out as having good chances of habitability. Although these three candidates orbit red dwarf stars—known for their violent, hostile solar flares—these planets' stars are comparatively calm. They are TOI-270 d, TOI 1468 c, and TOI-732 c (TOI refers to planets observed by the *TESS* space telescope: *TESS* Object of Interest).

Each of these three planets is scheduled for observation with the *JWST* in its second year of observing. In other words, we're about to get a more detailed look at some exciting new exoplanets. Last year's observation of the exoplanet K2-18b was just the beginning of Hycean world research, and Rigby and Madhusudhan's recent research article will help astronomers constrain the possible internal structures of these worlds, and help determine the prospect of finding life on them.

What about K2-18b?

The exoplanet K2-18b has become somewhat of a poster child for Hycean world research. Recently, a multi-institutional team of astronomers, Earth scientists and planetary physicists has found evidence, based on data from the *JWST*, that some Hycean exoplanets may have molten surfaces rather than watery oceans. The team analysed *JWST* data of K2-18b.

Prior research had suggested that there are certain exoplanets that have attributes that classify them as archetypically Hycean. Such exoplanets are typically sized between Neptune and Earth and have an atmosphere that suggests the presence of surface water. Such planets are typically targeted by researchers looking for life beyond Earth.

For this new study, the team focused their efforts on K2-18b. It has received attention before as a possible host of extraterrestrial life, but this is the first time it was studied using data from the *JWST*.

The team looked at models of the planet constructed by previous teams, some of whom found evidence that the planet might be too hot to host an ocean—water would have evaporated. *JWST* data revealed evidence that agreed with such assessments; the researchers then conducted an analysis of the planet's atmosphere. They looked at it in two ways: as if the planet hosted an ocean, and as if the planet instead had a molten surface. They found that either scenario matched the *JWST* data. But because the planet is so hot, the latter scenario is more likely correct.

The research team suggests that efforts involved in looking for life on exoplanets should first test planetary temperatures to ensure that they are not too hot to host an ocean. They further state that *JWST* data could prove to be indispensable in the coming years for such studies.

The authors conclude,

> "*Developing clear disambiguating atmospheric tracers for the presence of liquid water versus magma oceans is key in our quest of finding potentially habitable worlds among the* exoplanet *population*."

The search for water in liquid, frozen or molten form is heating up, literally! We can look forward to many more exciting results now that the *JWST* has moved to routine operations.

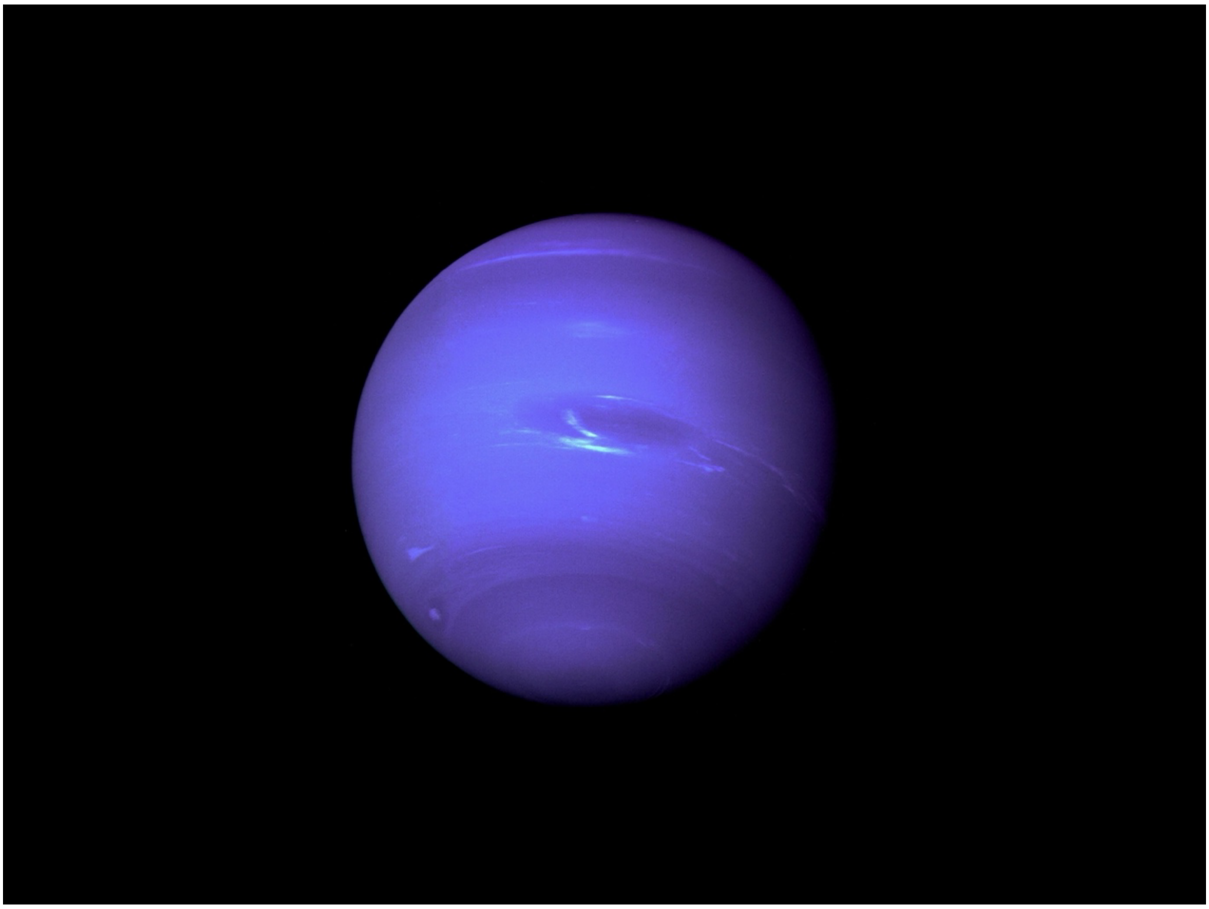

Figure 1. (Credit: Unsplash/CC0 Public Domain)

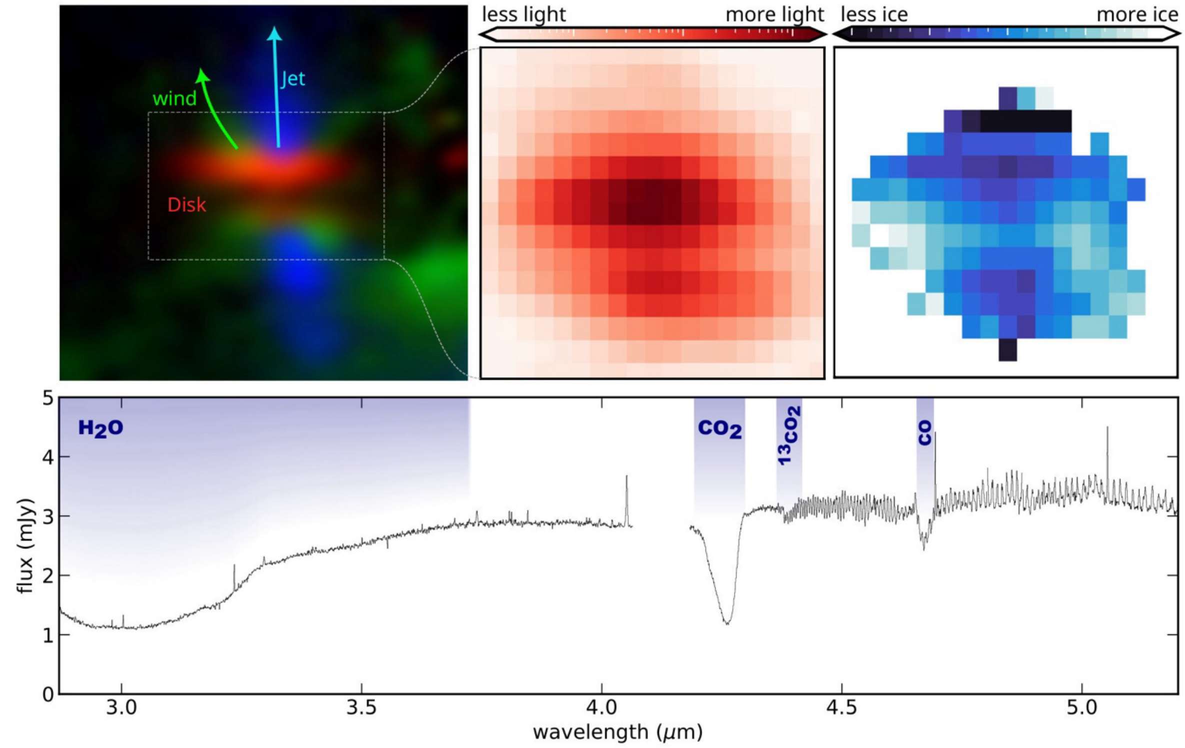

Figure 2. The study by Sturm and colleagues at a glance. (top left) Region observed. (top right) Details about the observed light and the water ice feature. (bottom) Spectrum showing peaks and troughs that result from different molecules. (Credit: Sturm et al.)

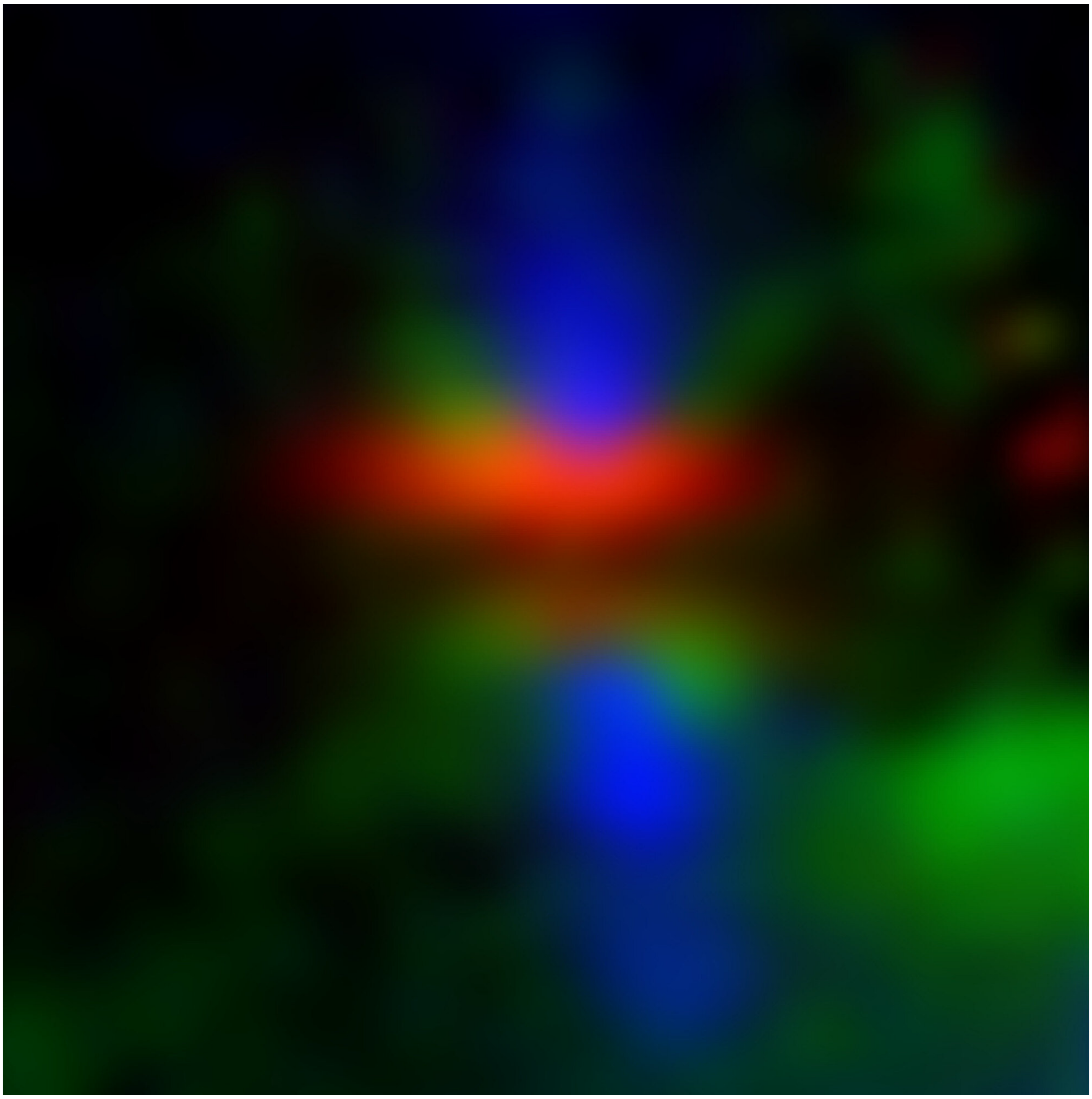

Figure 3. Composite image of the area around the protoplanetary disk HH 48 NE. The scattered light on the disk is red. The gas from a wind above the disk is green. The jet is blue. (Credit: HST, JWST, Sturm et al.)

Figure 4. Artist's impression of the possible Hycean world K2-18 b. (Credit: NASA, ESA, CSA, Joseph Olmsted–STScI)

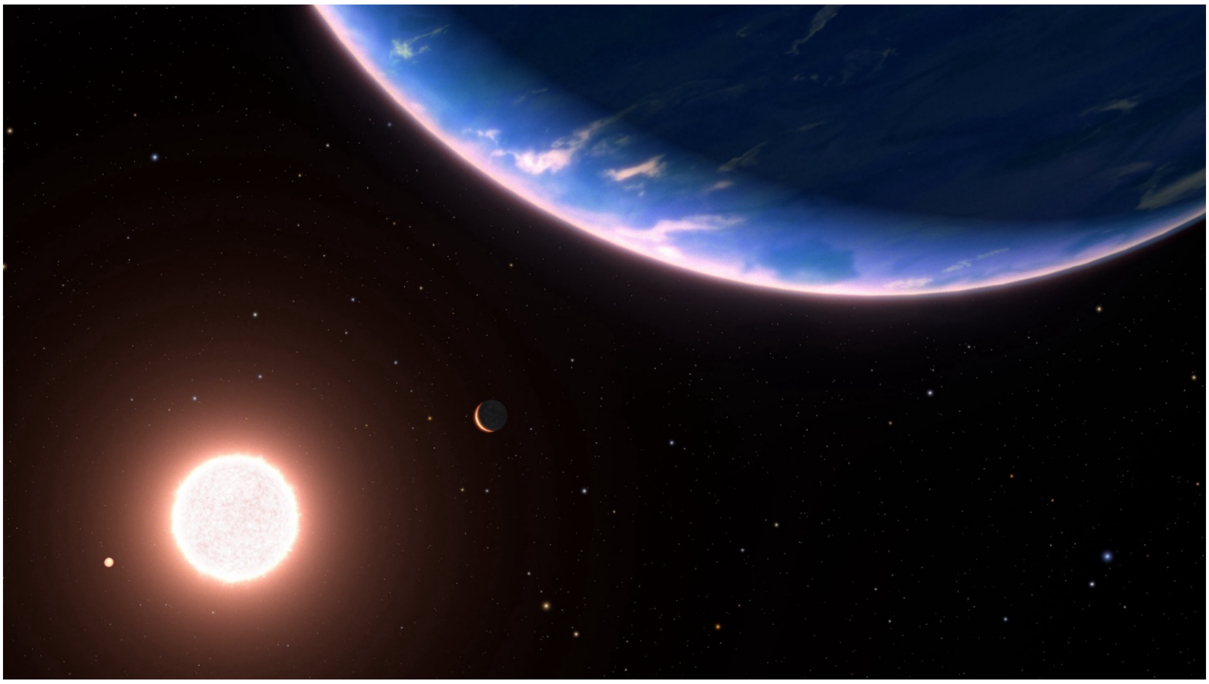

Figure 5. (Credit: NASA, ESA, Leah Hustak and Ralf Crawford–STScI)

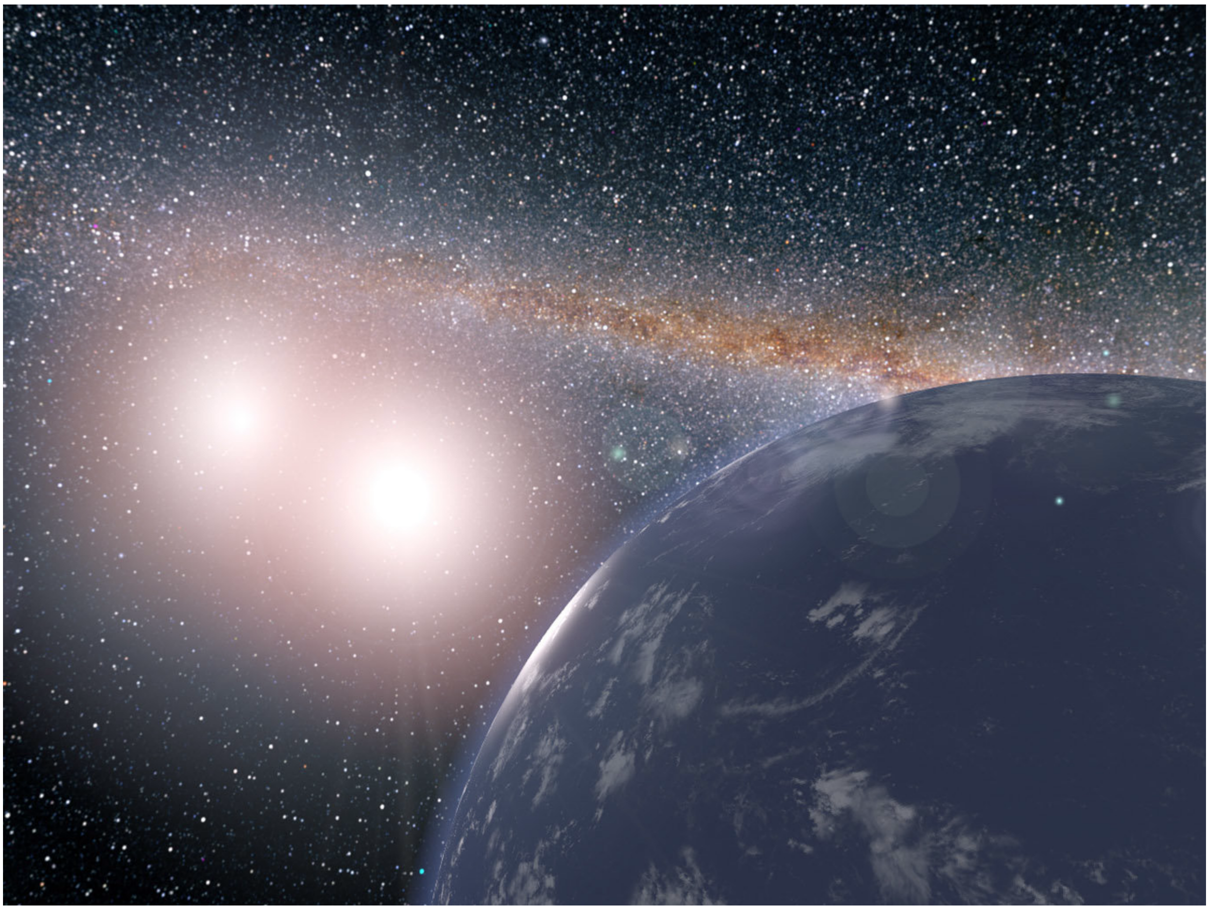

Figure 6. Artist's conception of a putative water world—an Earth-size exoplanet completely covered in water—based on the example of the binary star system Kepler-35A and B. (Credit: NASA/JPL-Caltech)