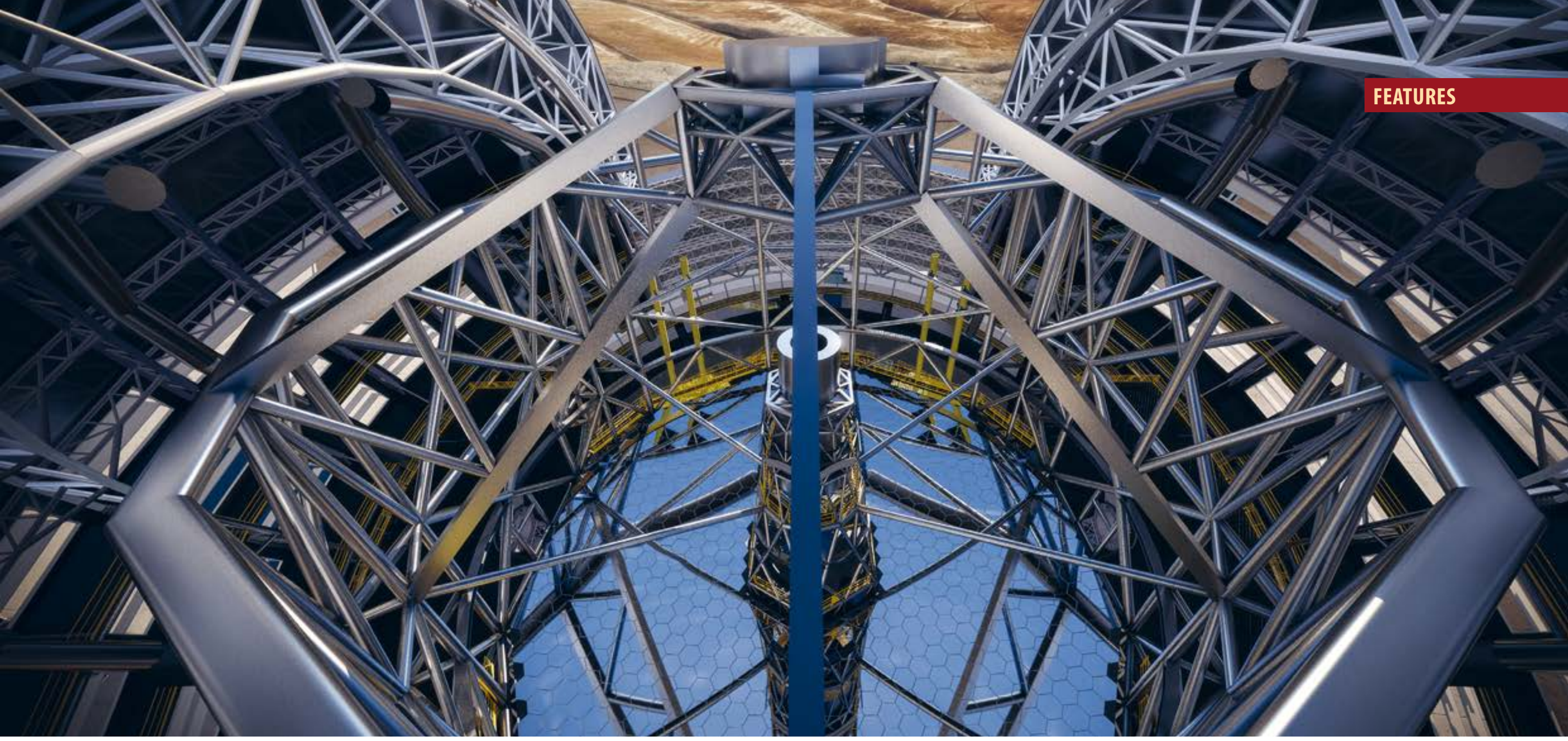

PLANETS ORBITING OTHER STARS

THE SEARCH FOR EXTRATERRESTRIAL LIFE

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Since the Nobel-prize-winning discovery of a planet orbiting a sun-like star, the field of extrasolar planets is undergoing a true revolution. Thousands of planets have been found, of which some may be like Earth. Could there be biological activity on any of these, and how do we find out?

Since the age of Copernicus and Galilei we know that Earth does not form the center of the Universe. We since have found out that it orbits the Sun as one of multiple planets. The Sun is a normal star in the outskirts of the Milky Way, and the Milky Way is one of the billions of galaxies in the observable universe. It may be argued that our home planet is nothing special, and that the universe is teeming with life. In reality, however, the Earth may be quite unique. Circumstances may need to be just right for life to form and evolve, in particular for highly evolved species which may require a stable planetary climate for billions of years. We simply do not know. The search for extraterrestrial life is an important philosophical endeavour, which will shed light on the place of humanity in the cosmos. *Are we alone?*

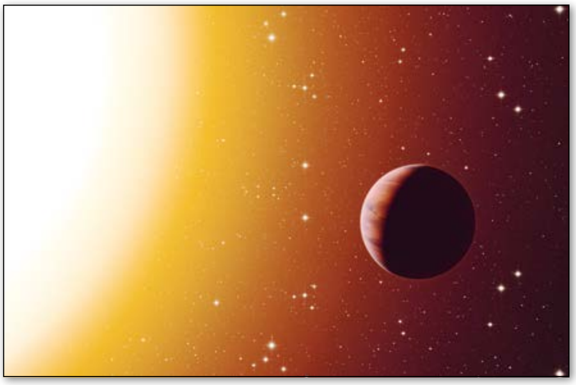
A particularly complicating aspect of the search for life is that we do not know much about what to expect. Life on Earth is the only reference available. Although many scenarios have been proposed, we do not know how life on Earth initially formed. Also, we cannot yet form living organisms from scratch in the lab. Still, any extraterrestrial organism should obey the laws of chemistry and physics – at least in a scientific context – and any biological function requires complex chemistry. Carbon-based molecules are generally seen as the only way to provide the intricate building blocks for this [1].

Follow the water

We also know that water has been playing a crucial role in the origin and development of life on Earth. Astronomers jump at this aspect. We can identify places in the universe where liquid water could exist, on the surfaces of rocky planets at the right distances from their host stars [2]. These may be places were life can form and evolve. This does not mean that life does not exist in other locations, even in our own solar system, such as deep underground on Mars, or in the sub-surface oceans of some moons of Jupiter and Saturn.

In the case of exoplanets, however, we need to be able to recognize biological activity from interstellar distances, meaning that it must significantly alter the chemical structure of its planet's atmosphere and/or surface – which can potentially be observed from many light years

▲ Artistic rendering of the European Extremely Large Telescope currently under construction to be operational in the mid 2020s. (Credit: ESO, L. Calcada, ACe consortium)



▸ **FIG. 1:** Artist's impression of a hot Jupiter (© ESO, L. calcada).

away. This is what astronomers will focus on in the next decade(s). Do rocky exoplanets have atmospheres? What are the main constituencies of these atmospheres? Are the planets wet or dry? Do we understand the atmospheric and geological processes involved? Can we identify gases that may be produced by biological activity, such as molecular oxygen on Earth? Ultimately, we will need a deep understanding of a planet's origin and evolution to make a conclusive case for extraterrestrial biological activity, requiring intensive collaborations between many scientific disciplines, including chemistry, geology, climatology and biology.

Planets everywhere

So, where are we now, and where do we go from here? Since the Nobel-Prize discovery [3], planets have been found everywhere. The two most successful methods are the radial velocity and transit techniques. The first measures the reflex motion of a star around a system's center of mass. This can reveal a planet's orbit, and a lower limit to its mass (depending on the orientation of the orbit). For the second method, the orientation of the planet's orbit needs to be nearly edge-on. The planet then regularly occults a part of the star, resulting in a small dip in the amount of starlight that we see. This reveals the size and orbit of the planet, and in combination with the radial velocity method, also its mass and mean density – providing first clues about its composition.

▾ **FIG. 2:** Artist's impression of the surface of exoplanet Proxima Centauri b. (© ESO/ M. Kornmesser)

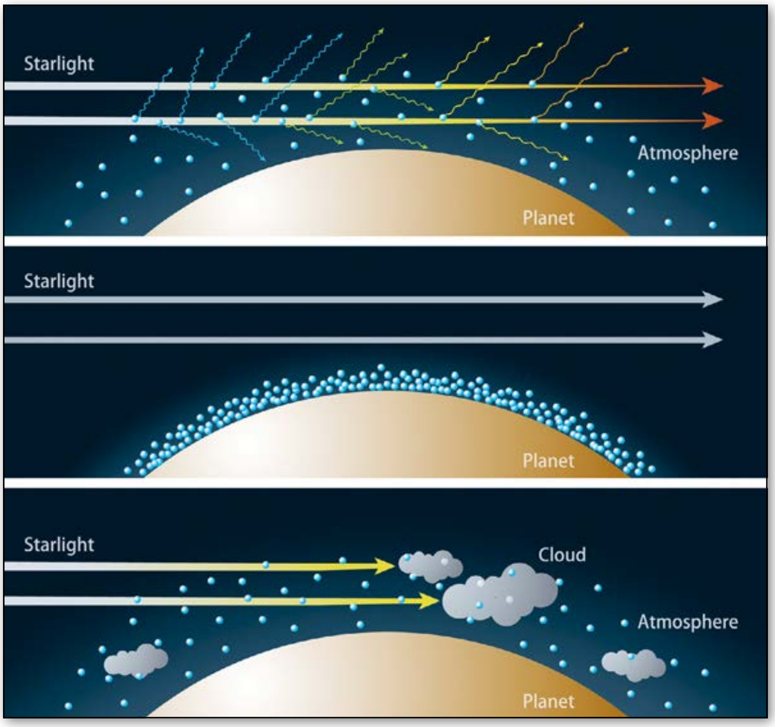
After 25 years of discoveries, we know that planets are very common. About one in ten stars harbour a gas giant like Jupiter, about one in three have Neptune-size planets, and most stars harbour Earth-mass objects. The latter is particularly pronounced around low-mass stars. Our nearest neighbour, Proxima Centauri at about 4 light years, has a small planet [4] in an 11-day orbit. Since the star is more than a thousand times less luminous than our Sun, the planet receives as much stellar energy as if it were a planet in an orbit between that of the Earth and Mars. Very exciting is also the nearby TRAPPIST-1 system [5], which harbors seven sister planets, all about the size of the Earth, and of which at least three could have a climate allowing liquid water on their surfaces. Therefore, even very nearby, we already know of several planetary systems where life possibly could form and evolve. Do note, however, that it is not clear whether the, in some aspects, harsh circumstances around red dwarf stars allow the onset biological activity [6].

Atmospheres

Studying the atmospheres of exoplanets is a whole different ball-game. Almost all planets found to date have been discovered without identifying a single photon from the planets themselves. For atmospheric studies this can no longer be the case – planet light needs to be separated from that of the star, with the latter being many orders of magnitude brighter.

There are basically two families of methods to accomplish this. The first has so far been the most successful and involves transiting systems, making use of temporal variations in how we see the planet. When a planet transits a star, in addition to occulting part of the stellar surface, starlight also filters through the planet atmosphere, leaving an imprint of atomic and molecular absorption and scattering. In addition, half an orbit later, the planet is occulted by the star, meaning that for a few hours the planet's light (either intrinsic thermal emission or starlight reflected off the planet's atmosphere) is missing and can be accounted for. Also during the rest of the orbit, varying parts of the dayside and nightside of the planet are visible, resulting in variations that reveal its heat distribution which can constrain global climate circulation models.

Making direct images of exoplanets, by angularly separating the planet from the star in the sky, is still very difficult. Ground-based telescopes require adaptive optics to mitigate the disturbing influence of our atmosphere, to approach their theoretical angular resolution. This is needed in combination with coronagraphy to block the star light such that a faint orbiting planet can be seen. Telescopes in space have the advantage not to need the former, but are costly, and are therefore smaller and have significantly less resolution, limiting their performance [7].



▲ **FIG. 3:** Schematic relation between the composition and structure of an exoplanet atmosphere and the observed transmission spectrum. Starlight travels through the planet atmosphere and is being scattered by molecules at certain wavelengths (top), is largely unaltered because of the small scale height of the atmosphere (middle), or absorbed by clouds (bottom). (Credit: NAOJ)

Most atmospheric characterization has been limited to warm gas giant planets, which have the largest atmospheric scale heights and therefore strongest transit signals, and emit most thermal emission. For direct imaging this needs to be accompanied by a large enough orbital distance to assure angular separation from their host stars, which means that only young gas giants, which are still hot from their formation, can be probed. So far, several different molecules, such as carbon monoxide and water have been identified with both families of methods, in addition to several atoms and ions, and evidence for Rayleigh scattering and the presence of clouds and hazes. Also, vertical and longitudinal temperature structures have been measured, including thermal inversions and atmospheric escape processes.

In the exoplanet group at Leiden University we focus on the use of ground-based telescopes for atmospheric characterization. In particular, performing transit and direct imaging observations at very high spectral resolving powers ($\lambda/\Delta\lambda \sim 100{,}000$) is very effective, revealing the tens to hundreds or thousands of individual rotational-vibrational lines of molecules. This has several advantages. Molecules are uniquely identified, even if their spectral bands overlap. Furthermore, the ground-based calibration is significantly more straightforward in this way, and the spectral features from the planet, our own atmosphere, and the star can be disentangled because of their different Doppler shifts – even if each exhibit features from the same molecule. This has been shown to be very powerful and probes exoplanet atmospheres in unique ways, also being sensitive to exoplanet atmospheric winds and spin rotation [8, 9]. Ultimately, this can also be used to target molecular oxygen, a biomarker gas, in nearby rocky exoplanets – the possible exoplanet-based oxygen and that in our own atmospheres will be separated in velocity and can be distinguished from each other.

En route to finding life

Atmospheric observations are currently still limited to gas giants, including a recent detection of water vapour in the atmosphere of a temperate mini-Neptune [10, 11]. But this will soon change. Astronomers around the world are eagerly awaiting the launch of the James Webb Space Telescope in 2021 – the successor of Hubble. It will target TRAPPIST-1 planets to see whether they have atmospheres, and if so, get a handle on their constituencies. This will be a major step forward, providing a first assessment of the climates of rocky planets around small red dwarf stars.

Personally, I am even more excited about the next-generation of ground-based telescopes, in particular the 39 meter European Extremely Large Telescope, which is being built in the Atacama Desert of northern Chile (first light in 2026). One of its first light instruments is METIS [12], a mid-infrared spectrograph with high spectral resolving power perfectly designed for atmospheric observations. METIS, and the second-generation optical spectrograph HIRES, can reveal possible water vapour, carbon dioxide, methane, and ultimately oxygen in the atmosphere of our nearest neighbour Proxima Centauri b. A very exciting prospect. If common, and nature is kind to us, we may find the first clues of extraterrestrial life within this decade. ■

About the Author

Ignas Snellen is a professor in astronomy at Leiden University in the Netherlands. He is an expert in the atmospheric characterization of extrasolar planets.

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