Tracing life through light: towards detecting life on exoplanets with spectroscopy and spectropolarimetry

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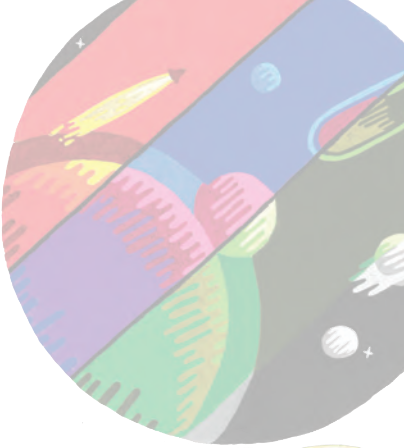

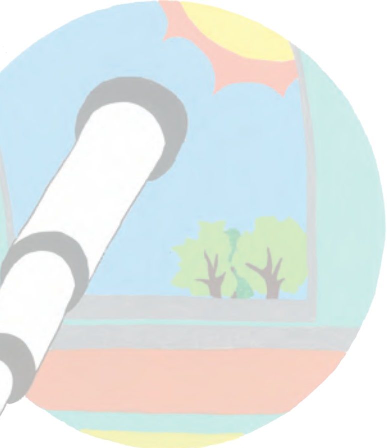

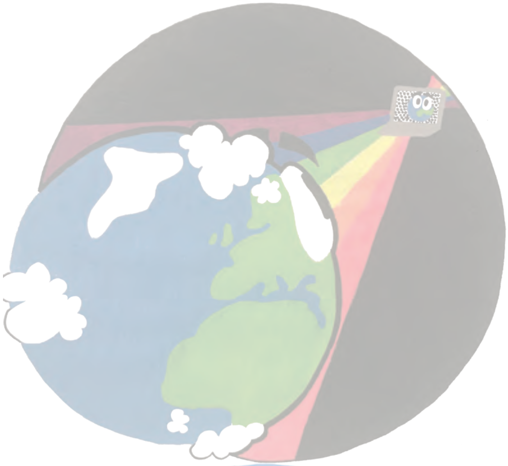

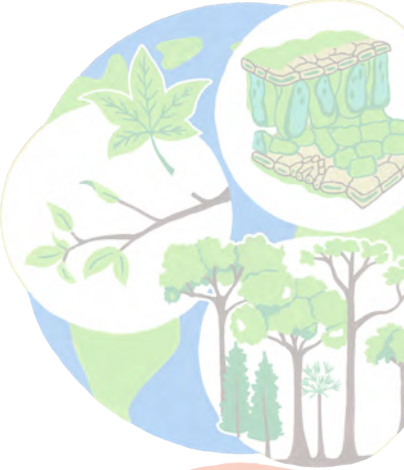


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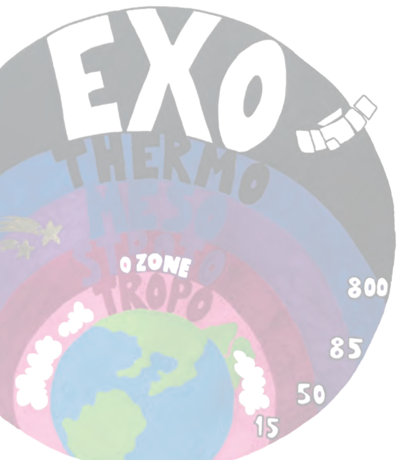
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English summary

How did we come into existence? Are we alone in this Universe? For centuries, these questions navigate and drive the limitless curiosity of humanity. Today, November 2026, the discovery of more than six thousand exoplanets offers a glimpse into the incredible diversity of worlds beyond our Solar System. In our desire to truly understand these distant worlds, discovery is merely the first step. We need to know their fundamental properties in order to assess their potential to host life, starting with the planet's size and mass. By calculating their densities we can classify the exoplanets as either rocky (e.g. Earth-like), or gaseous planets (e.g. Neptune-like, Jupiter-like, or even a colossal super-Jupiter). In addition, if we know the mass of the and the distance to their host star, we can find out whether a planet orbits within the so-called habitable zone. In this zone, temperatures allow liquid water to exist: one of the crucial ingredients of life as we know.

Observing distant worlds: direct imaging & spectroscopy

How can we study the invisible worlds that orbit distant stars? Firstly, what do I mean by invisible worlds? Stars, whether our Sun or far-off suns in the Milky way, emit light across the electromagnetic spectrum: infrared radiation that we can feel as warmth, visible light that we can see, and ultraviolet light that can even cause sunburn. Planets, on the other hand, are very different. They do not produce their own visible light. Instead, they shine only by reflecting the light of their host star and by emitting a faint amount of infrared radiation as they warm up under that starlight. In our own night sky, we can spot planets like Mars, Venus or Jupiter. With the naked eye, they appear as bright points of light, not so different from nearby stars. During the day, however, these planets completely disappear from our view. Not because they stop reflecting sunlight, but because the Sun is overwhelmingly bright and drowns out their faint reflected light.

The same principle applies to exoplanets, but on a far more extreme scale. These planets orbit stars that are not just brighter than the planets themselves, but also much farther away. From our vantage point, an exoplanet sits right next to its dazzling host star, and the contrast between them becomes enormous: the light from the star can be ten thousand to tens of billions of times brighter than the light reflected by the planet. This illustrates the difficulty of imaging exoplanets. To image an exoplanet, astronomers need to apply a technique called **high-contrast imaging**. High-contrast imaging allows telescopes to suppress the light from the host star, which would otherwise overwhelm the dim reflected light of the planets. This method is better known as **direct imaging**.

The possibility of directly imaging planets is inherently limited to the contrast of the planetary system. Fortunately, there are methods to examine distant words, like using **spectroscopy** which measures the wavelength (or 'colour') and the intensity of light. All exoplanets move in an orbit around their host star. When a planet passes directly between its star and a telescope, part of the starlight filters through its atmosphere. By analysing this light, we can reveal the planet's chemical composition. Spectroscopy allows us to detect the unique ‘fingerprints’ of atoms and molecules, and to determine the atmospheric composition, temperature, and the presence of clouds or hazes. Especially **high-resolution spectroscopy** is a powerful tool - sensitive enough to detect even trace gases and to measure atmospheric motions such as winds or planetary rotation.

In Chapter 2, we use high-resolution spectroscopy to study the atmospheres of three **brown dwarfs**. These are celestial objects that bridge the gap between planets and stars: they are more massive than giant planets, yet too light to sustain hydrogen fusion and therefore do not shine with stable starlight of their own. The observations are part of the *SupJup Survey*, which uses the CRIRES+ instrument on the Very Large Telescope in Chile to collect detailed spectra of a sample of brown dwarfs and super-Jupiters. The three spectra reveal an enhanced carbon-to-oxygen ratio and a higher metallicity compared to our Sun, suggesting that part of the oxygen may have been locked into solid materials during formation. We also measured the ratio between two isotopes of carbon, ^{12}C and ^{13}C, which provides clues about the chemical evolution of the region where the object was born. Our results show slightly less ^{13}C than typically found in the diffuse interstellar gas and dust within our Galaxy. Ongoing work within the SupJup Survey will analyse the remaining spectra to build a more complete picture of how planets and related substellar objects form and evolve.

The search for life as we know it: homochirality

While the study of distant exoplanets reveals the astonishing diversity of worlds in our Universe, one simple truth remains: the only planet we know that harbours life is our own Earth. If we aim to search for similar forms of life beyond the Solar System, we must first understand how to recognise unmistakable signs of life as seen from our own planet. One of the most compelling of these signs is a phenomenon known as **homochirality**. On Earth, the essential building blocks of life, such as chlorophyll, amino acids, proteins, DNA, and sugars, all exhibit a single molecular ’handedness’. This consistent preference for one mirror-image form over another does not occur naturally without biological influence, making it a unique and unambiguous fingerprint of life.

To prepare for future space missions that will search for extraterrestrial life, it is crucial to test whether we can detect this signature remotely, under realistic conditions outside the laboratory. One of the most powerful techniques for this purpose is **spectropolarimetry**. Unlike standard spectroscopy where we measure the intensity of specific wavelengths of incoming light, spectropolarimetry reveals how the light waves are oriented: a property known as **polarisation**. Light can become linearly polarised when it scattered by atmospheric particles or reflected from planetary surfaces such as oceans or deserts, an effect that is already well understood. A more elusive form, however, is **circular polarisation**, where the light waves twist into a spiral shape. Intriguingly, this type of polarisation can be produced when light interacts with biological molecules due to their homochiral nature. This makes circular polarisation a highly promising, and perhaps the most unambiguous, remote indicator of life.

Although existing models of how planetary surfaces and atmospheres reflect light already take various scattering effects into account, they often neglect circular polarisation contributions from vegetation and other biological materials. This omission is largely due to the extreme difficulty of measuring circularly polarised light: the signals are typically only a few tens to hundredths of a percent of the reflected light. In addition to that, there is no such thing as a perfect static circular analyser that can measure such weak circular polarisation reliably across the visible-light spectrum.

Having established that circular polarisation can serve as a unique indicator of biological activity, in Chapter 3 we aim to refine those models by incorporating the effects of circular polarisation produced by the **homochiral** nature of biological materials. In this study, we use a **hot-air balloon** as an observing platform, a choice that offers several advantages: it provides a remarkably stable flight, is considerably less costly than using a helicopter or aeroplane, and allows for real-time instrument adjustments during observations. We measure circular polarisation signals from diverse landscapes. such as forests, fields, and bodies of water, to better understand how living surfaces can be identified remotely. Furthermore, we evaluate the performance of a polarisation camera, assessing their potential for future airborne missions dedicated to the search for life.

Designing a snapshot Full-Stokes spectropolarimeter

While spectropolarimetry shows great promise for detecting life from a distance, one major challenge remains: we need extremely sensitive instruments to reliably measure these delicate signals. Building on our balloon-based observations, the next step is to design an instrument capable of measuring polarisation signals, including both circular and the promising linear component, from a vantage point where the Earth can be observed as if it were an exoplanet. Such a perspective can be achieved from space, for example from the International Space Station or even the Moon, allowing us to capture the full-disk polarisation signal of our planet. Instruments intended for these platforms must therefore be capable of detecting all components of polarisation in a single snapshot and without relying on moving or active (optical) parts. Developing such a full-Stokes spectropolarimeter is no easy task, and the final two chapters of this thesis focus on the opportunities and challenges involved in designing and realising such an instrument.

In Chapter 4, we introduce **LSDPol** (the Life Signature Detection Polarimeter), a prototype instrument designed to detect signs of homochirality using visible-light polarimetry. Building on the motivation to measure polarisation from a space-based perspective, the main goal of LSDPol is to detect extremely small polarisation signals - in particular the tiny fractions of circularly polarised light generated by biological matter. Crucially, the instrument must be able to distinguish these minute circular components from the far larger linearly polarised signals, which can reach tens of percent of the reflected light. One of the main challenges in the prototype is the appearance of unwanted, false-positive polarisation signals, primarily caused by the way light diffracts and spreads after passing through the polarisation modulator.

To understand where these signals come from, we run detailed computer simulations, followed by laboratory experiments. The results show that light bending (known as Fresnel diffraction) creates unexpected patterns in the measurements: small wavy features appear in parts of the data where none should exist, and shifts are observed even when measuring unpolarised light. We also find that the distance between the modulator and the subsequent optical components plays a significant role. Achieving the most accurate results therefore requires cautious calibration. To further improve LSDPol's performance and prepare for future space-based deployment, we recommend developing a comprehensive mathematical model that accounts for wavelength-dependent light behaviour.

Finally, in Chapter 5, the use of **spatial polarisation modulators** is investigated. These advanced optical elements, based on liquid-crystal technology, enable the measurement of all polarisation components of incoming light in a single snapshot. A major challenge with these modulators is the appearance of unwanted self-images. This occurs because the modulator and a linear polariser together function as a kind of virtual grating, giving rise to the Talbot effect. The pattern of this virtual grating repeats at specific distances, known as Talbot distances. Between these Talbot distances, the patterns change: the original pattern can appear doubled or shifted relative to the original grating pattern. These subtle intensity modulations can interfere with the measurement of the true polarisation state. Therefore, it is essential to carefully understand and correct for these effects to ensure reliable spectropolarimetric measurements.

Thanks to these technological advances, we are moving closer to building instruments capable of detecting clear and unmistakable signs of life on planets orbiting distant stars.