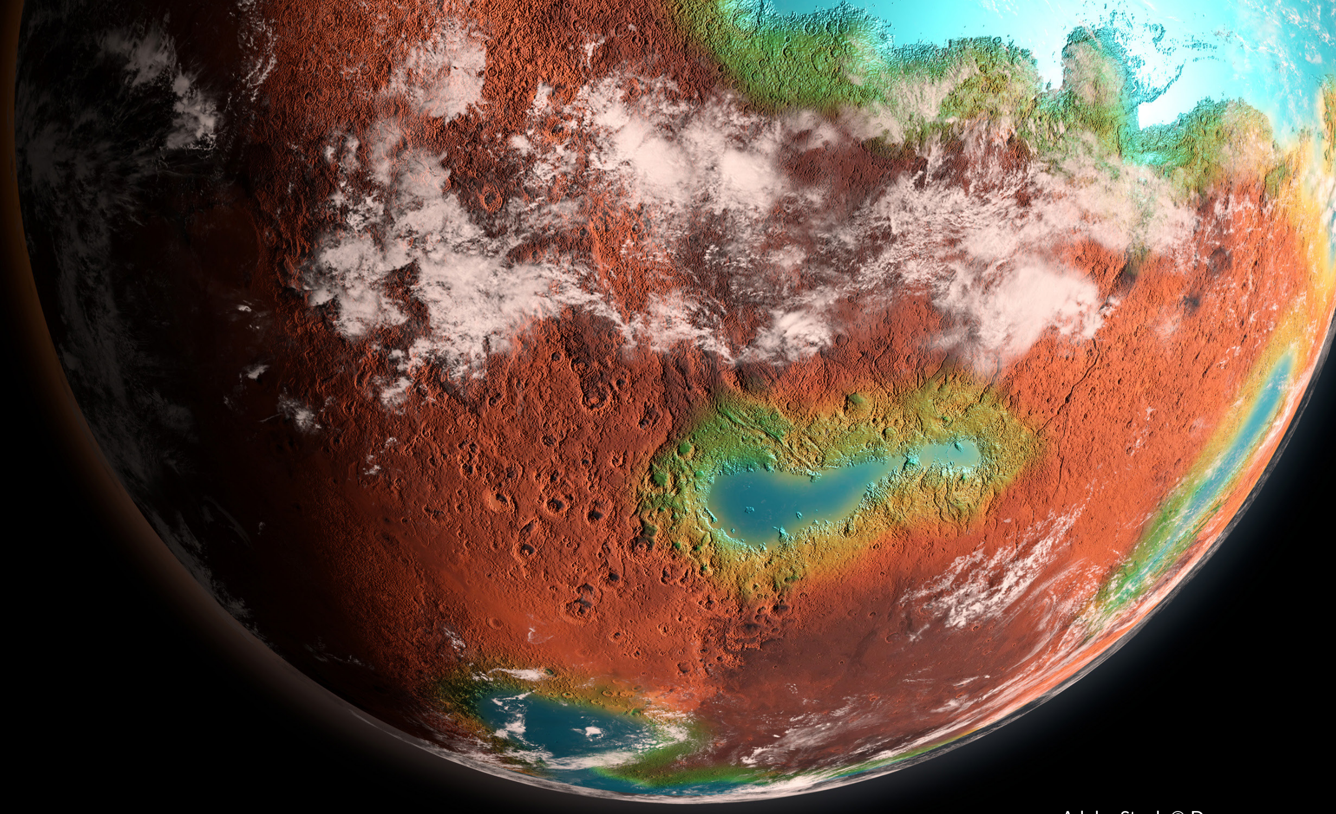
Paving the way for improving exoplanet imaging with ground-based telescopes



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The French author Bernard le Bovier de Fontenelle famously wrote in his popular science book *Entretiens sur la pluralité des mondes*[1] published in 1686: "The fixed stars are so many Suns, every one of which gives light to a world." It was an era when such bold statements and heliocentric beliefs were unacceptable by the church. However, the author cleverly presented his book as a casual conversation between a philosopher and a marquise. Unlike Galileo, who was kept under house arrest until his death in 1642 for having similar ideas, Bernard somehow escaped the usual punishment.

Our generation is fortunate to witness such philosophies taking shape into remarkable discoveries. Today we know of such worlds which are unlike the eight famous planets of our solar system. A planet that orbits a star other than our sun is called an exoplanet. The current family portrait of exoplanets in our Milky Way galaxy includes at least 4,000 members ranging from hot Jupiters, super-Jupiters, gas giants to rocky-giants, super-Earths and mini-Neptunes. The question isn't if we will ever find an Earth-analogue but rather how soon!

In the near future, the upcoming James Webb Space Telescope (JWST) could provide us with opportunities to study the first exoplanets where conditions could be favourable for life to flourish. Though we rely on future space telescopes to find Earth-like planets around Sun-like stars, we can use facilities on the ground to detect other types of exoplanets and address fundamental questions such as: What kind of exoplanets are the most common in the neighbourhood of our solar system? What kind of conditions are required for the circumstellar material around stars to transform into planets? What can we learn from the atmospheric composition of exoplanets?

Direct imaging of exoplanets

Several methods can be used to find an exoplanet, and this article is focused on a technique known as direct imaging[2] or high-contrast imaging (HCI). Using this method, a snapshot of exoplanets and their surroundings is captured directly on the cameras or detectors. This technique reveals an immediate portrait of planetary systems including circumstellar disks, planets in the process of formation, exomoons and exoplanetary ring systems etc. It can estimate temperatures, gravities and chemical composition of exoplanets.

HCI technique sounds straightforward, but it is extremely challenging to carry out. We need telescopes that can provide high-angular resolution and instruments that can achieve high-contrast between a star-planet system. Big telescopes can see finer details by better separating the images of the star and its planets. Hence, the bigger the telescope, the better the resolution to detect exoplanets lying at less than five astronomical units from their stars (the same distance as Jupiter-Sun). Ground-based telescopes with a diameter of 30 metres or more are required to detect rocky exoplanets and Jupiter-sized gas giants at such small angular separations[3].

Moreover, a planet is at least a million times fainter than its star. Finding planetary signatures in raw images of a star-planet system is equivalent to searching for a grain of rice in a paddy field. The overwhelming brightness of the star obscures the faint signal of the planet. A telescope must have an instrument capable of suppressing the starlight and creating regions of high-contrast in raw images. It is like switching off a street lamp to reveal fireflies fluttering around the light.

There is yet another issue when it comes to imaging exoplanets with the ground-based telescopes. The Earth's atmosphere makes the starlight swirl around as famously represented in Vincent van Gogh's Starry Night painting. A telescope diffracts the light of a star (a point source) and creates a pattern with diffraction rings. This shape is known as the point spread function (PSF) of the star. Each telescope has a theoretical PSF, i.e. a prior knowledge of how the shape of a star should look like on the detectors. So when the energy packets of starlight traverse the atmosphere, they deviate from their normal path and smear up before reaching the telescope. The telescope then focuses this distorted starlight on to the detector and creates a blob of light instead of forming the expected sharp image of the star defined by the theory of diffraction.

State-of-the-art

To address the problems previously mentioned, HCI of exoplanets from the ground relies on two techniques, adaptive optics (AO) which is an art of shaping the light, and coronagraphy which is a means of blocking it. Figure 1 summarises how HCI is performed from the ground.

An AO system has two main components, a wavefront sensor (WFS), and a deformable mirror (DM). A WFS quantifies the effect of Earth's atmospheric turbulence on the astronomical images by measuring how much light or wavefront is distorted and in what direction. A DM is literally a thin sheet of mirror that can be moulded to give a desired shape to the light packets. At a telescope, when an AO system receives light from a star-planet system then the AO's WFS measures the atmospheric aberrations, computes the wavefront correction using control algorithms and applies this correction by changing the shape of the DM in real-time. Thus, an AO system is a must-have technology that improves the performance of an optical system and provides the PSFs of a star-planet system closer to their expected shapes. Once the image is formed on the detector, the AO-corrected PSF of the star is then blocked by a coronagraph.

A French astronomer Bernard Lyot invented the first coronagraph in 1930 to study the corona of the sun and to observe solar prominences. Instead of relying on the natural phenomenon such as solar eclipses to mask the sunlight, he used a fixed opaque optical element to block the light of the sun inside his instrument. This process immediately revealed the surroundings of the sun. His innovation led to the more recent development of stellar coronagraphs which are widely used to unveil stellar companions by blocking the light of a star inside the HCI instrument. Once the starlight is blocked, a region of high-contrast is created in the images where a faint planetary signal is then searched.

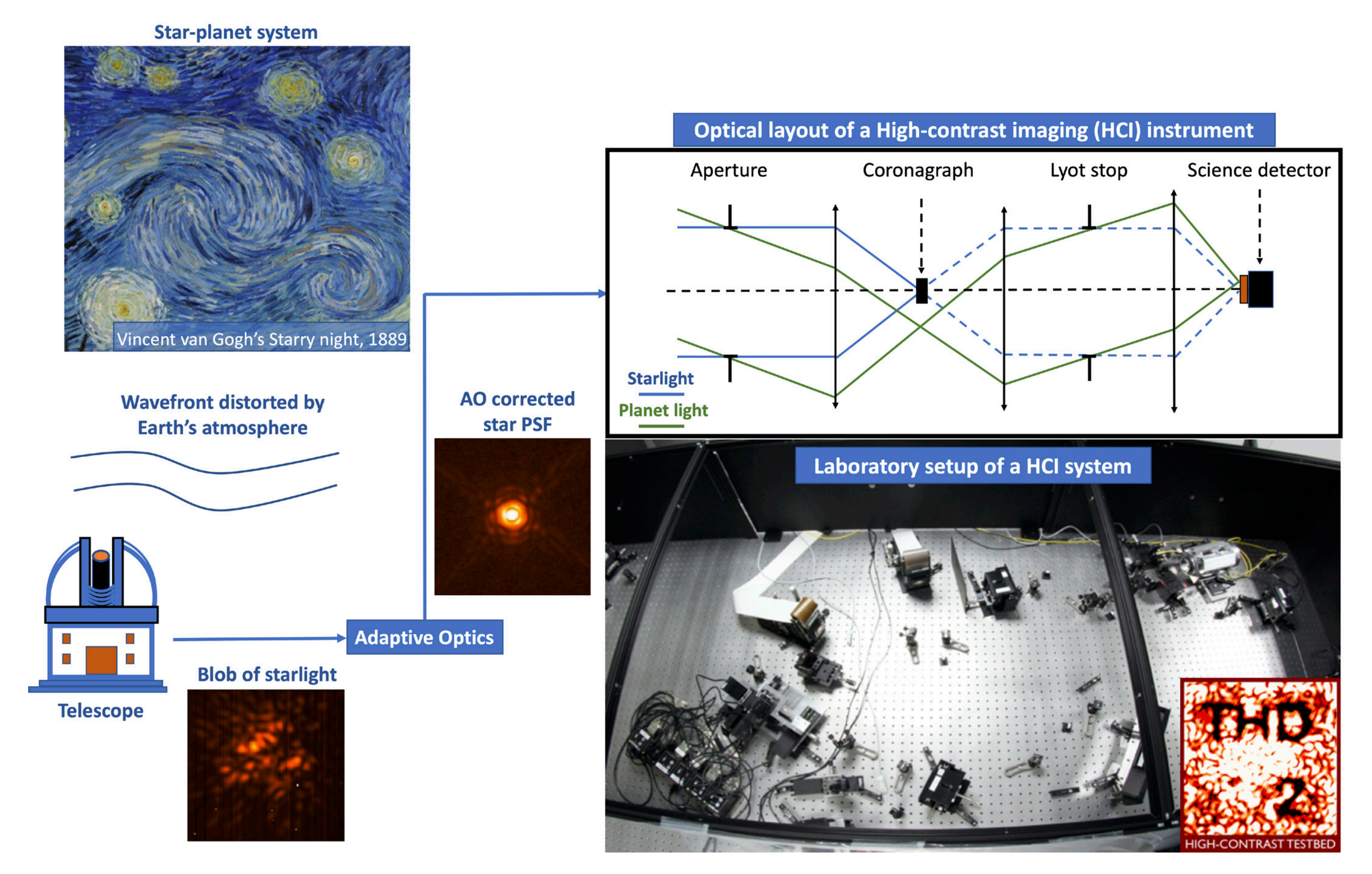

Figure 1: Concept of direct imaging of exoplanets.

Gemini Planet Imager[4] and Spectro-Polarimetric High-contrast Exoplanet Research[5] (SPHERE) are the two popular planet imaging instruments, and both are installed at the world-class telescopes (eight metres). These instruments can create dark regions in the star-planet raw images where the starlight is attenuated by a factor of 10^5. This means that any planet which is 10^5 times (gas-giants) fainter than its star would be imaged easily.

These powerful instruments, however, can image only those exoplanets which are far away from their stars and able to produce their own light through thermal activities. This is because the AO correction is not perfect, and there are residual aberrations present in the images, which makes it impossible to disentangle star-planet signals.

Causes of residual aberrations

1. Telescope and optical-mechanical vibrations that move the starlight around the coronagraph. This results in starlight leaking through the mask and reaching the detector, thus making it impossible to find planetary signals. During my PhD, I developed a Lyot-stop Low-Order WFS (LLOWFS[6]) to address this issue and improved the HCI capabilities of one such system installed at Subaru Telescope (eight metres) in Hawaii.
2. Thermal distortions, temperature variations and alignment errors can produce slowly evolving patterns called speckles. Speckles are well known to mimic planetary signals. Several smart post-processing algorithms exist to eliminate the contribution of speckles from the images. Though real-time speckle control algorithms have been successfully tested at telescopes, no such algorithm is used regularly to actively suppress speckles given the challenging requirement of fast operation.

These are some of the main challenges that prevent ground-based HCI instruments from imaging all known exoplanets and/or detecting new systems. Out of roughly 4,000 known exoplanets, only 49 of them have been imaged as of today. Thus, an improvement in the current HCI technology is of paramount importance to prepare the ground for imaging rocky exoplanets[3] (required raw contrast between 10^7–10^8) using the future extremely large telescopes (ELTs).

Très Haute Dynamique banc (THD2)

The THD2 bench is an HCI testbed at Observatoire de Paris, which provides a powerful platform to develop, implement and test novel techniques to obtain the highest contrast in the images. The bench has been used to test different types of coronagraphs by several European and international institutions and has also been considered for testing and comparing several speckle suppression algorithms for future space telescopes.

In the laboratory, the starlight is simulated using optical and near-infrared sources (with wavelengths between 500nm and 900nm) and fed as an input inside THD2. It is assumed that the starlight is already corrected by an upstream AO system. The PSF of a simulated star is then blocked by a coronagraph at the focal plane. The LLOWFS makes sure that the starlight is well-centred on the coronagraph. The system has two DMs for providing wavefront correction. The THD2 bench is known to have developed and thoroughly tested a novel wavefront sensing technique called self-coherent camera (SCC) to suppress speckle intensities. It has been demonstrated that SCC can obtain a contrast of roughly 10^8 in star-planet images under space-related environment. One of my projects on THD2 was focused on simulating, testing and characterising SCC under ground-based conditions. The atmospheric turbulence that the SPHERE instrument encounters was simulated on THD2 for testing the performance of the SCC. Our recently published article[7] showed that a raw contrast of 10^6 could be achieved in images, thus demonstrating an improvement in raw contrast by a factor of roughly ten as compared with the current capabilities. To conclude, such a technique if implemented on current and future HCI instruments could improve the sensitivity to detecting exoplanets at small angular separations as per one of the required goals of ELTs.

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SUMMARY

The project seeks to develop and demonstrate wavefront sensing and control techniques that will enhance the planet detection sensitivity at small angles and will aid the existing high-contrast imaging (HCI) instruments in directly imaging young Jovian-like exoplanets at small angles around nearby stars. We characterised a technique on a unique R&D HCI facility in Europe and present the encouraging results.

PROJECT LEAD PROFILES

Garima Singh has obtained her Bachelors in Information Technology (2008) from India and Masters and PhD (2015) in Astronomy and Astrophysics (Instrumentation) from Université de Paris-Sud XI and Observatoire de Paris respectively. She conducted three years of her PhD research at Subaru Telescope in Hawaii. Prior to receiving the Marie Skłodowska-Curie postdoctoral fellowship, she worked at the Jet Propulsion Laboratory as a NASA Postdoctoral Fellow in California.

Pierre Baudoz holds the position of an Astronomer at Observatoire de Paris since 2005 and is the Principal Investigator of THD2, an advanced HCI testbed in Europe. He has been involved in the building of the coronagraph on JWST and SPHERE and is responsible for the HCI module of MICADO on the ELT.

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FUNDING

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 798909.