Novel approaches for direct exoplanet imaging: Theory, simulations and experiments

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English summary

Since antiquity, humanity haas hypothesized about the plurality of worlds and the existance of extraterrestrial life. It is only in recent years that we have started to answer this question. The first exoplanet, a planet that orbits stars other than our own Sun, was discovered in 1992. Since then, we have found thousands of others, from large gas giants more massive than Jupiter that orbit their star every few days, to planets that look remarkably close to Earth.

Many different methods have been developed over the years to find these exoplanets. Most of these methods are indirect and infer the existance of the planet by looking at the light from their host star. For detecting the chemical composition of the atmospheres of exoplanets, we however need to detect the light from the planet itself. Direct exoplanet imaging can play a big role in this effort. By spatially separating the light from the star and the planet, it is able to provide high-quality spectra of the light passing through the planets atmosphere. This enables us to search for the spectral signatures of their constituent gases of their atmospheres.

Direct exoplanet imaging is however not as simple as pointing a telescope at a star and taking an image. First, exoplanets are located extremely close to their star. Their angular separations range from one arcsecond to several milli-arcseconds, corresponding to a few tens to a few tenths of the Rayleigh limit, the fundamental resolving limit due to the wave nature of light, for current-generation observatories at the relevant wavelengths. Secondly, exoplanets are extremely faint. At optical wavelengths we are looking for the light reflected off the planet surface. At these wavelengths, Earth-like exoplanets are expected to have contrasts ranging from 10^{-9} to 10^{-11} with respect to their host star. Even at near-infrared wavelengths, where we instead see the thermal radiation, especially for young exoplanets which are stil hot from their formation process, gas giants still have contrasts of only 10^{-5} to 10^{-6}.

These challenges of direct imaging can be overcome with advanced instrumentation. A typical high-contrast imaging instrument employs three vectors of attack, all of which have to work together to produce the highest quality images.

1. **A coronagraph.** Coronagraphs are intricately designed optical devices that filter out starlight in our images. At the same time, the coronagraph must transmit as much of the planet light as possible. Coronagraphs should be compared based on their optical complexity, their level of starlight suppression, their planet throughput and their minimum angular separation where they achieve sufficient throughput, their robustness against small wavefront aberrations and their ability to efficiently measure wavefront aberrations.

2. **An adaptive optics or wavefront control system.** Polishing errors in the mirrors and lenses, vibrations and deformations in the optical system and, on ground-based telescopes, the turbulence in the atmosphere, distort the incoming light and produce a cloud of speckles in our coronagraphic image. We employ an adaptive optics or wavefront control system to stabilize the wavefront, which lets the coronagraph filter out the starlight. Typically, an adapitve optics system measures the distortion of the incoming light a few hundred to a few thousand times per second and uses a deformable mirror to induce an opposite and equal distortion to cancel it out.

3. **Image post-processing algorithms.** After the adaptive optics system and coronagraph, we are still left with a cloud of speckles in our images. This is the result of imperfections in these two systems. Advanced image post-processing algorithms exploit any redundant information in our images to filter out the residual starlight. This finally leaves us with a calibrated image of the stellar environment.

This thesis aims to further our knowledge of coronagraphs and their integration into high-contrast imaging instruments.

Chapter 2: optimal design of apodizing phase plate coronagraphs
An apodizing phase plate (APP) coronagraph consists of a single phase-only pupil-plane apodizer mask. Contrary to most other coronagraphs, the APP coronagraph does not filter out starlight completely, but only inside a region of interest in the coronagraphic focal plane, also known as the “dark zone”. This chapter presents a new way of optimizing the phase pattern of the apodizer. This new algorithm is guaranteed to find the phase pattern with highest possible planet throughput for a given contrast, and dark zone and pupil geometry. This result provides us with the fundamental limits of this type of coronagraph.

Chapters 3 & 4: the Single-mode Complex Amplitude Refinement (SCAR) coronagraph The SCAR coronagraph combines a microlens-fed single-mode fiber array in the focal plane and an upstream pupil-plane phase-only apodizer mask. The mode filtering capabilities of the single-mode fibers significantly relaxes the phase pattern on the pupil mask. This makes the SCAR coronagraph reach much smaller angular separations compared to the APP coronagraph for similar values of the planet throughput. These two chapters cover the theory, simulations and a prototype laboratory demonstration that reached a raw contrast of 10^{-4} at an angular separation of just $1\lambda/D$.

Chapter 5: High-Contrast Imaging for Python (HCIPy) HCIPy is an open-source software package written in Python for simulating the interplay between wavefront control and coronagraphic systems. It aims to provide a modular object-oriented framework to enable rapid prototyping of the full high-contrast imaging system. HCIPy is currently used at multiple institutes around the world, both for research and for education.

Chapter 6: the asymmetric wind-driven halo The high-altitude jet stream layer in the atmosphere is notorious for producing a butterfly-shaped halo in high-contrast images. This halo is caused by the lag between the measurement and correction by the adaptive optics system. However, we also commonly observe an asymmetry in the halo, where one wing of the butterfly becomes brighter than the other. In this chapter, we identify the origin of this asymmetry as the interference between lagged phase speckles and scintillation speckles caused when light propagates from the high-altitude jet stream layer to the ground. This asymmetry can now be incorporated into the design of future high-contrast imaging instruments and potentially be removed with image post-processing techniques.

Chapters 7 & 8: the phase-apodized-pupil Lyot coronagraph The PAPLC combines a phase-only pupil-plane apodizer mask with a standard Lyot-style coronagraph architecture. In particular with a one-sided dark zone and a knife-edge focal-plane mask, this coronagraph provides inner working angles as close as $1.4\lambda/D$ at contrasts of 10^{-10} with a maximum post-coronagraph throughput of $> 75\%$. Furthermore, the light reflected off the focal-plane mask can be used for high-order wavefront sensing. Chapter 7 covers the design process and theoretical performance of this new coronagraph. Chapter 8 presents the first laboratory demonstration at the

Très Haute Dynamique 2 (THD2) testbed at the Observatoire de Paris. This demonstration reached a mean raw contrast of 1.9×10^{-8} from $2\lambda/D$ to $9\lambda/D$ in monochromatic light. Furthermore, we demonstrated wavefront sensing using the light reflected off the focal-plane mask at $\sim 3\times$ the fundamental wavefront sensing limit due to photon noise.

Future outlook While the first generation of high-contrast imaging instruments, VLT/SPHERE and Gemini/GPI, were our first attempt at combining extreme adaptive optics and coronagraphy, these are currently being upgraded with new coronagraphs and more advanced control systems. Additionally, new imagers such as Magellan/MagAO-X and Keck/KPIC are being built from the ground up to take full advantage of the developed new technologies. High-contrast imaging from space will see its first major test with the launch of the Roman Space Telescope. This will demonstrate high-order wavefront control with a coronagraph to raw contrast levels not achievable with ground-based imagers.

Over the next few years, we will start to see the first on-sky results of these new imagers. Application of the same technologies on future ground-based observatories, such as the ELT, GMT and TMT, will allow us to characterize rocky exoplanets around nearby lower-mass stars in the near and mid-infrared. Photometric monitoring of these planets can reveal their rotational periods and perhaps even their seasons and continents on their surface. Smaller-aperture space-based observatories will search for and characterize rocky planets around solar-type stars. Finally in a few decades, future large space-based observatories will have the angular resolution and sensitivity to characterize dozens of Earth-like exoplanets, enabling us to maybe answer whether there is life anywere else in the Universe.