Painting with starlight : optical techniques for the high-contrast imaging of exoplanets

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Chapter 7

English Summary

For centuries, philosophers, scientists, and science fiction writers alike have been fascinated by the idea of planetary systems existing around stars other than the sun. And, like Giovanni Schiaparelli claiming to see artificial canals on Mars in 1877 or early 19th Century fantasies about tropical paradises existing below the thick clouds of Venus, this interest is almost always combined with the desire to know: could there be life on these planets?

Since these early musings, our scientific understanding of these extra-solar planets (exoplanets) has grown extraordinarily rapidly. Starting with the discovery of the first exoplanet in 1992, we now know of almost 4,000 planetary-mass companions and are increasingly able to characterise their composition, atmospheres and likely surface conditions.

7.1 How do we find exoplanets?

7.1.1 Indirect detection methods

The majority of exoplanets detected to-date have been found using indirect methods, via the influence of the planet on the light of its host star. The most prolific of these are the transit method, where the planet blocks a small but detectable part of the star's light as it passes in front, and the radial velocity method, where the orbital motion of the host star about the common centre of mass of the star-planet system causes features in its spectrum to shift periodically in wavelength.

These indirect techniques have produced large numbers of detections primarily because it is possible to achieve high precision using relatively small telescopes and simple instrument designs, making them highly suited to carry out large-scale surveys. They are also more sensitive to massive close-orbiting planets, which is a more populated area of the exoplanet parameter space than those accessible by other detection methods, including direct imaging.

These indirect methods do however have the disadvantage that are only sensitive only if the planet's orbit aligns with our line of sight, and so they naturally miss a large fraction of the total exoplanet population where this is not the case. The detectability of planets via these methods is also intrinsically tied to their orbital periods, meaning that surveys must span years or even decades when looking for solar system-like planets in order to obtain detectable signals.

7.1.2 Direct imaging

If we instead wish to directly resolve the light of an Earth-like exoplanet from its host star, we require instruments which are capable of spatially resolving angles on the sky of a fraction of an arcsecond (1/3600th of a degree), and teasing out planet light which is approximately one billion times fainter than that of the star. This technical challenge is equivalent to trying to detect a firefly fluttering just a few centimetres from a lighthouse, from a distance of over 200 km. If this can be achieved however, direct imaging offers a powerful tool to study and characterise these planets in unprecedented detail.

Such precision is best achieved by using the largest available telescopes, and advanced coronagraphic optics which filter out unwanted starlight while preserving the signal of the planet. A variety of complementary techniques which are capable of differentiating planet light from starlight by their fundamental properties, such as polarimetry and spectroscopy, are now also widely used to help tease out the faint planet light from the sea of starlight in which it is embedded.

Instruments attached to ground-based telescopes also have the added challenge of looking through the turbulent, distorting effects of the Earth's atmosphere. Adaptive optics technologies, which adjust one or more deformable mirrors thousands of times per second, are now advanced enough to effectively compensate for this distortion. The general optical layout and performance of such an adaptive optics system is shown in Fig. 7.1. As we push towards detecting fainter and closer-orbiting planets however, distortions due to imperfections in the optics of the instrument itself now also becomes a significant consideration. In particular, so-called non-common path aberrations (NCPAs), which are produced in regions of the instrument which are not properly controlled by the adaptive optics system, are currently a major limiting factor of these planet-hunting instruments.

One solution to these NCPAs is a technique called focal-plane wavefront sensing, where information from the science imaging camera is used to determine the exact correction which must be made to perfect the image. A large fraction of this thesis is dedicated to developing effective ways to perform this technique.

7.2 How do we characterise exoplanets?

Simply detecting the existence of planetary mass companions around other stars already gives us an idea of how abundant exoplanets are in our galaxy. However, in order to develop our understanding of these complex bodies beyond the level of a single data point, we need to perform detailed characterisation studies using the many available observation techniques.

Transit and radial velocity observations respectively provide estimates of the radius and mass of these planets compared to their host star. By combining these two measurements we can estimate the planet's overall density, and hence infer whether they are rocky, icy or gaseous in composition.

However, high-resolution spectroscopic study provides by far the most powerful and versatile tool for determining additional properties of these planets. Not only can it be used to identify the spectral fingerprint of molecules present in the atmosphere, but analysis of the spectral features themselves can be used to determine properties such as the temperature and pressure in the upper layers of the atmosphere, and even the spin rate of the planet. For unresolved transiting planets, this can be achieved by analysing the small fraction of starlight that passes through the planet's atmosphere, picking up its spectral fingerprint. It is also possible to couple a spectrograph directly to high-contrast imaging systems, allowing non-transiting planets to be characterised in the same detail if they can be directly imaged.

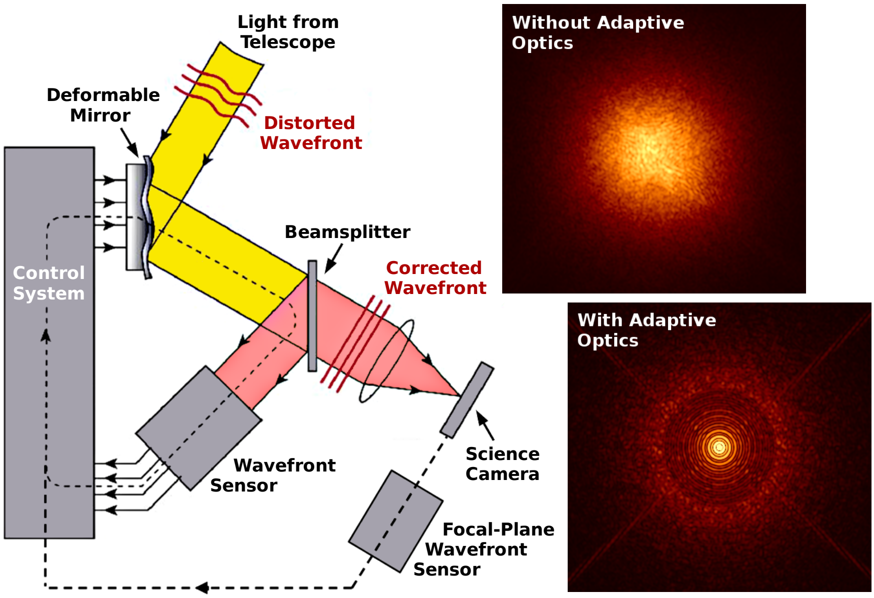

Figure 7.1: Schematic of an adaptive optics (AO) system: part of the light from the telescope is split off from the science beam into a wavefront sensor, which controls a deformable mirror in order to compensate for atmospheric distortions. The image panels show the simulated image of a star before (top) and after (bottom) AO correction. Non-common path aberrations occur in the red-shaded regions of the instrument, which are not correctly sensed by the adaptive optics system. These can be controlled by adding a focal-plane wavefront sensor, which uses images from the science camera to determine the right correction. Figure adapted from http://lyot.org.

7.3 Protoplanetary disks and planet formation

Protoplanetary disks form during the initial collapse of dust and gas that constitutes the first stage of star formation, and in turn are the birthplace of planets. Therefore, understanding the physical processes operating in these disks allows us to better determine how planets form and evolve into the objects we detect in mature star systems. By observing a large number of these young systems with different ages, we can also piece together a timeline for the formation of our own solar system.

Imaging these disks at near-infrared wavelengths tells us about their outermost layers: detecting gaps and spiral features in this surface gives us an indication of their age, and also potential regions of ongoing planet formation. However, due to the faintness of these disks compared to the light of their host star, imaging them is almost as technically challenging as finding planets themselves, especially as it must also be achieved over a large area without creating unphysical image artefacts.

Polarimetry has proved an extremely effective technique for overcoming this challenge, since starlight is naturally un-polarised but becomes partially polarised when scattered by dust particles. Measuring and subtracting all un-polarised light therefore leaves behind an undistorted image of the regions where starlight is being scattered. The current-generation high-contrast imaging instrument SPHERE at the VLT has been particularly successful in this field, and the task of further optimising the performance of this instrument is the subject of three chapters of this thesis.

7.4 This thesis

In this thesis I focus two main goals: developing new optical techniques to improve the final contrast ratios achievable by direct imaging, and addressing some of the outstanding limitations of current-generation instruments. This work is split into the following chapters:

Chapter 2: The main challenge of focal-plane wavefront sensing is in effectively utilising images from the science camera, since information about the aberrations which are distorting the light beam is fundamentally lost during the normal image formation process. In this chapter we present the theory, laboratory implementation and first on-sky validation of the coronagraphic Modal Wavefront Sensor (cMWS): an optic which uses holographic techniques to engineer the light falling on the science camera in such a way as to provide simultaneous coronagraphic imaging and straightforward low-order wavefront retrieval. After validating the concept in numerical simulations, we deployed a prototype cMWS design at the 4.2 m William Herschel Telescope (WHT) in La Palma. We show that this cMWS is capable of passively sensing low-order wavefront aberrations at high speeds (50 Hz frame-rate) and over a wide observing bandwidth (50 % in R-band), both of which are major challenges for most focal-plane sensing techniques. Since the work in this chapter was published, the cMWS has been further validated as part of the Leiden EXoplanet Instrument (LEXI), including successful on-sky closed-loop operation. In addition, a number of cMWS optics have been installed at telescopes around the world, including a recent successful flight on the HiCIBaS high-altitude balloon pathfinder mission.

Chapter 3: While non-common path aberrations are a commonly-cited limiting factor of direct imaging instruments, this is not always the most significant effect. In this chapter we develop and test a potential control solution for the so-called low-wind effect (LWE) seen in the SPHERE high-contrast imager: this is a wavefront control issue which is seen to significantly degrade the imaging performance of the instrument under otherwise optimal observing conditions. In this chapter we adapt the so-called “Fast & Furious” (F&F) focal-plane wavefront control algorithm to the specific case of the LWE, and simulate its closed-loop performance under realistic observing conditions emulating those of the SPHERE instrument. We find that the algorithm is extremely stable against all simulated observing conditions, offering an effective method of eliminating the LWE which is in principle immediately implementable as a software-only solution for SPHERE.

Chapter 4: Following on directly from Chapter 3, in this chapter we validate F&F on the MITHIC high-contrast testbench at the Laboratoire d’Astrophysique de Marseille, in order to evaluate its effectiveness in combating the LWE in a realistic laboratory environment. We find that the laboratory performance of F&F is highly consistent with simulations, and is capable of robustly eliminating artificially injected LWE aberrations within five closed-loop iterations, even when using low-signal-to-noise images as input. Although it remains necessary to validate the algorithm in parallel with a live adaptive optics system performing atmospheric correction, we conclude that F&F represents an excellent solution to the LWE in the SPHERE instrument, capable of robust real-time wavefront control under even the most challenging observing conditions without degrading the image feed for science observations.

Chapter 5: Optimal data reduction techniques are just as crucial as high-precision optics when it comes to making the most of the data produced by current high-contrast imaging facilities. This chapter presents a characterisation effort of the apodised Lyot coronagraph system of the IRDIS near-infrared subsystem of SPHERE, in order to develop a calibration algorithm capable of properly reducing coronagraphic, polarimetric image data. This is important since the innermost regions of circumstellar disk observations, which are crucial for the identification of central cavities in transitional protoplanetary disks, are often dominated by artefacts of the imaging system. Calibration observations were made of the minor planet Ceres in order to accurately determine the extinction profile of the coronagraph, and combined with extensive optical modelling in order to fully understand the observed signal. We conclude that coronagraphic, polarimetric observations of protoplanetary disks require full forward-modelling in order to properly account for non-linear diffraction and polarimetric effects: it is not sufficient to simply normalise for coronagraphic throughput losses. We validate the accuracy of our calibration routine on polarimetric observations of the well-studied TW Hydrae protoplanetary disk, successfully recovering the known central cavity feature after correcting for instrumental effects.

7.5 Overall conclusions

The work in Chapters 2 to 4 addresses the first goal of this thesis, by demonstrating multiple valid techniques for performing focal-plane wavefront sensing using science camera images. If implemented in cutting-edge instruments, techniques such as these will allow us to gain multiple orders of magnitude in final contrast performance by providing better image stabilisation. The use of holographic techniques to customise the information content provided by an image is also a powerful and highly flexible tool, which is already finding applications in other areas of high-contrast imaging. With the next generation of planet-hunting instruments for ELT-class telescopes currently due to see first-light in the late 2020s and early 2030s, Chapters 3 to 5 also highlight how combined expertise in both optics and data reduction will almost certainly be required to tackle unforeseen challenges faced by these instruments. It is therefore hoped that the work in this thesis will help to inform the design of these next-generation instruments, ultimately enabling them to directly image and characterise fainter, closer-orbiting and hence more Earth-like planets.