High-resolution integral-field spectroscopy of exoplanets

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8 English Summary

The field of exoplanets has seen rapid development in the past three decades since the discovery of the first few exoplanets. In 1992 the first planet around a star other than our own had been found, and just three years later in 1995 the first exoplanet orbiting a solar-like star was discovered. We now have found several thousands of planets, that are so diverse that it seems like that almost every system is unique. There are strange planets like Kepler 51 b and d that have densities similar to cotton candy or the extremely hot KELT-9b that has gaseous iron and titanium in its atmosphere. Not only is there a large diversity in the planets themselves but there is also a large diversity in the composition of planetary systems. On one side there is Trappist-1 with seven Earth-mass planets with short orbital periods around a red dwarf star, and on the other extreme there is HR8799 with four giant gas planets on very wide orbits. This challenges our theories of planet formation as it should be able to explain the diversity. One of the key questions is how the planet interact with their birth environment, as this plays an important role in their composition and final orbital configuration.

Direct imaging plays an important role here. By spatially resolving the disk and embedded planets we can witness their interaction. Another added benefit is the enhanced intrinsic contrast between the star and planet for young luminous planets. For old systems such as our own solar system the best signal we could use to detect Earth or Jupiter from a distance is through reflected light. The intensity ratio between the Sun and the reflected light of Earth and Jupiter are 10^{-10} and 10^{-9} respectively. This is a huge contrast to overcome. But during the first stages of planet formation the planets are still very hot. This increases the intrinsic contrast in the near-infrared to $10^{-5} - 10^{-6}$ making the detection of such exoplanets orders of magnitude easier.

But direct imaging of exoplanets is still a challenging task even for the hot young gas planets because the contrast needs to be reached at very close angular separations. While current generation telescope like the Very Large Telescope (VLT) of ESO, with an 8.2 meter diameter, would be able to resolve the closest by planets we have not been able to do this. For ground based telescope there are two challenges to overcome. The first being turbulence in the atmosphere and the second is the intrinsic contrast between the planet and its host star. This turbulence will create wavefront aberrations that degrade the resolving power of the telescope. In median weather conditions at good observing sites such as Paranal, La Palmca or Mauna Kea the effective resolution due to the atmosphere is about 1 arcsecond, almost 40 times larger than the diffraction limit! Nowadays all the large telescopes use adaptive optics, where a deformable mirror is controlled at several hundreds of Hz to several kHz to counteract the atmosphere. For direct imaging the AO systems are pushed to their extremes and are therefore called eXtreme AO (xAO) systems.

With the current generation of xAO systems we can reach diffraction-limited performance in the near-infrared. But this is not enough to find faint planets as the planet is still much fainter than the Airy rings of the diffraction pattern. With the high quality correction of xAO systems such as SPHERE and GPI we can use coronagraphs to remove the diffraction effects of the star. A coronagraph is a specialized optical device that is designed as an extreme angular filter; the on-axis starlight needs to be suppressed as much as possible while leaving the off-axis planet light unaltered. But any wavefront error in the system will limit the performance of the coronagraph and will scatter starlight back into the region that we want to make and keep dark. The residual wavefront errors come from two sources, the first being residual wavefront errors from the atmosphere that are not correctable or not completely removed. The second are due to a difference in the optical path between the coronagraphic optics and the wavefront sensor optics. Because these parts of the instrument have different optics they will see a slightly different wavefront error causing differential wavefront errors between the two paths. These wavefront errors are called the Non-Common Path Aberrations (NCPA). Both the NCPAs and the residual turbulence causes speckles that can look like planets. Image processing algorithms are used to further remove these speckles and enhance the contrast.

With medium to high-resolution spectroscopy we can make use of the difference between the planet spectrum and the star spectrum to remove the starlight. Spectral filters tuned to the host star can be used to remove the starlight while leaving the exoplanet's spectrum largely undisturbed. A distinct advantage of this technique is that it is not limited by speckle noise, which hampers other post-processing techniques. High-resolution spectroscopy and medium-resolution integral-field spectroscopy in the near-infrared has been used to characterize several exoplanet atmospheres. None of the current direct imaging instruments have the capability of higher-resolution spectroscopy and adding this would allow us to probe closer to the star and search for lower mass planets. In this thesis we have explored several aspects of high-resolution integral-field spectroscopy for direct imaging.

Chapter 2+3: The Leiden EXoplanet Instrument
We have build several iterations of the Leiden EXoplanet instrument (LEXI), which is visitor instrument for the William Herschel Telescope at La Palma. The purpose of LEXI was to test different ways of coupling an AO-corrected beam to an integral-field spectrograph. To date LEXI has been use on-sky during three different observing campaigns. The first iteration of LEXI consisted of an AO-assisted long-slit spectrograph. The on-sky results showed that AO improves both throughput and spatial resolution of diffraction-limited slit spectrographs. Between the different campaigns LEXI was continuously upgraded to improve its performance. The second observing campaign was focused on improving the imaging performance and the spectrograph bandwidth. The adaptive optics upgrade from a Shack-Hartmann wavefront sensor to the new generalized Optical Differentiation Wavefront sensor together with the strategy to stop down the aperture made it possible to create diffraction-limited images with LEXI and paved the way towards on-sky tests of extreme AO techniques. This resulted in a successful demonstration of non-common path correction with the coronagraphic Modal Wavefront Sensor, that was able to increase the on-sky contrast by a factor of 1.5-2.

Additional due to the high performance of the AO system we were able to couple starlight into a single-mode fiber. A single-mode fiber can be considered as a diffraction-limited fiber. With the single-mode fiber, LEXI feeds a compact cross-dispersed echelle spectrograph designed to have a resolving power close to 100000. From the on-sky observations of Aldebaran we could measure the resolving power of the spectrograph to be 92000, which is very close to the design resolution. This result encouraged us to continue and develop a single-mode fiber-fed integral-field spectrograph, which was used during the third observing campaign.

Chapter 4+5: The Single-mode Complex Amplitude Refiner (SCAR) coronagraph
In these chapters the concept and first lab results of the Single-mode Complex Amplitude Refiner (SCAR) coronagraph are demonstrated. The SCAR coronagraph exploits the design freedom offered by the use of single-mode fibers as a mode filter. The fibers are fed by micro-lenses for increased field coverage making it possible to use single-mode fibers to search for exoplanets. We combined this with a pupil-plane phase plate, yielding the SCAR coronagraph that has several advantages including low inner-working angle and high throughput over a sizeable bandwidth. Our lab results confirm the working principle and demonstrated a coronagraph that reaches a

contrast 10000 at 1 λ/D.

Chapter 6: A duo of accreting proto-planets around the young star PDS 70
In this chapter I presented the results that were obtained with the adaptive-optics assisted, medium-resolution, integral-field spectrograph MUSE at the Very Large Telescope of ESO. With MUSE we were able to detect two proto-planets, that are still actively accreting, around the young star PDS 70. Our observations show that IFUs are highly efficient instruments to observe accretion emission spectra from planets in formation. We suspect that more accreting planets could be found and characterized in transition disks with this technique. Another exciting opportunity, which is now possible due to the high observing efficiency, is the detailed investigation of accretion on short and long time scales. This will shed light on the variability of planetary accretion and will lead to a better understanding of the formation of planets, allowing us to infer the formation history of the solar system.

Chapter 7: Highly multiplexed Bragg gratings
For a given detector there is a trade off between the spectral range, spectral resolution and field of view of an integral-field spectrograph. In this chapter we propose a novel method based on multiplexed Volume Bragg Gratings (VBGs) to analyse the spectrum optically, that eliminates the need to measure the complete spectral bandwidth. We have shown that such VBGs with many multiplexed gratings can be used for the quantitative detection of gas species with a significantly smaller detector than a comparable hyperspectral imager. This allows for a larger field-of-view given the same amount of detector real estate. We proposed to implement the VBGs with acousto-optical gratings that can be dynamically tuned at high speed and work from the near UV to the infrared. The dynamical aspect of the acousto-optical materials will allow us to use the same optics to detect different species. This simplifies the whole instrument as we can digitally choose what we would like to observe and thereby making the instrument highly flexible.

Outlook
Our observations with MUSE show that higher-resolution spectroscopy is very well suited for direct imaging of exoplanets. In the next few years several xAO systems will be upgraded with high-resolution spectroscopy. SPHERE will be coupled with CRIRES+, the KECK telescope will also get a fiber link between KPIC and NIRSPEC and SCEXAO on the SUBARU telescope will be coupled to RHEA. The techniques that were developed in

this thesis can be used to implement the actual coupling between the xAO systems and their spectrographs.

This work at medium resolution lays down the foundation for visible-light high-resolution integral-field units and high-contrast imaging for the detection of reflected light from cold and old exoplanets, like Earth, and biosignatures such as the O_2 band with the Extremely Large Telescopes (ELT). High-resolution spectroscopy for exoplanets is a photon-starved observing technique. The detection limits are therefore set by the amount of light that we can collect from the star and the planet. Proxima Centauri b could be characterized with the current telescopes but almost a hundred nights spread over three years are necessary to guarantee a detection. The effective observing time can be drastically lowered by using one of the ELTs. ELTs come with two advantages, the first being the larger collecting area, and the second is the increased spatial resolution. With an ELT the detection of Proxima Centauri b can obtained in a single night instead of the hundred nights of VLT time. With the addition of high-resolution integral-field units to extreme adaptive optics systems at ELTs, we will start to study older, potentially habitable planets, and thus address humanity's ultimate question: Are we alone?