High-contrast imaging polarimetry of exoplanets and circumstellar disks

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English summary

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Understanding the formation and evolution of planetary systems is one of the most fundamental challenges in astronomy. The formation of planets is closely related to the formation of stars. Stars form inside massive clouds of molecular gas and dust that are located in the interstellar medium. Parts of such a molecular cloud fragment and collapse under their own gravity, resulting in the formation of dense cores that further collapse to form stars. Because the collapsing core has a net angular momentum, a rotating disk of dust and gas forms around the forming star. This circumstellar disk is often called a protoplanetary disk because planets as well as brown dwarfs are believed to form in this disk. Together these planets and brown dwarfs are called substellar companions, that is, objects that are less massive than stars and that orbit around a star. Substellar companions may form through the coagulation of the dust in the circumstellar disk into kilometer-sized planetesimals and the subsequent accretion of planetesimals and gas, the local collapse of part of the disk, or the direct collapse of a separate core in the molecular cloud. In all these scenarios the companions are expected to have their own disks from which in turn moons may form. As time progresses, the circumstellar disk disperses through various mechanisms, leaving a planetary system similar to our own Solar System.

To study the formation and evolution of planetary systems, we can directly image exoplanets (planets around stars other than the Sun), brown dwarf companions, and circumstellar disks by spatially separating the near-infrared or visible light from these objects from the light from the central star. However, this is a very challenging task because substellar companions and circumstellar disks are generally located very close to their star and are orders of magnitude fainter than the star. To overcome this challenge, dedicated high-contrast imaging instruments are built. These instruments are installed on the largest ground-based telescopes and have complex optical systems designed to suppress the light from the star and create images with a spatial resolution close to the theoretical limit of the telescope.

Several of the high-contrast imaging instruments have polarimetric modes. With polarimetry, we measure the polarization state of the light, that is, the direction of the oscillation (in case of linear polarization) or rotation (in case of circular polarization) of the electric fields of the light. Polarimetry is particularly powerful to reach the large contrasts required to directly image circumstellar disks and substellar companions. The direct light from the central star is generally unpolarized: The light is a mixture of equal amounts of all possible polarization states. As this starlight scatters off dust grains in the circumstellar disk or off the companion's atmosphere, it becomes linearly polarized. Therefore, when taking an image in linearly polarized light, the direct starlight is strongly suppressed, while the polarized light from the circumstellar disk or companion is revealed. Polarimetry can also be used for characterization because polarimetric images contain information on the physical properties of the scattering particles. Measurements of polarization can, for instance, be used to constrain the composition, size, and shape of the dust grains in circumstellar disks and to determine the properties of the atmospheres or surfaces of companions. However, performing polarimetry on a high-contrast imaging instrument is not straightforward because many different instrumental effects can limit the attainable sensitivity and accuracy of the measurements.

This thesis

The goals of this thesis are to improve the sensitivity, accuracy, and capabilities of high-contrast imaging polarimeters for the detection and characterization of substellar companions and circumstellar disks. In addition, this thesis presents the first direct detections of linear polarization from substellar companions. The focus of this thesis is mostly on ground-based high-contrast imaging polarimetry, in particular with the instrument SPHERE-IRDIS at the Very Large Telescope.

In Chapter 2 we characterize the instrumental polarization effects of the near-infrared polarimetric mode of SPHERE-IRDIS using measurements with SPHERE's internal light source and observations of unpolarized stars. We find that the telescope and SPHERE's first mirror produce significant polarization. In addition, we find that the image derotator (a rotating assembly of three mirrors that is used to rotate the image) causes severe loss of signal at some orientations and wavelengths as it converts incident linearly polarized light into circularly polarized light that cannot be measured. We develop a data-reduction method that corrects these effects and apply it to observations of a circumstellar disk. We have incorporated the correction method in a highly automated end-to-end data-reduction pipeline called `IRDAP`, which we made publicly available[1]. IRDAP enables us to accurately measure the polarized intensity and angle of polarization of circumstellar disks and substellar companions. As such, IRDAP is the go-to pipeline for IRDIS polarimetric data and laid the foundation for many scientific publications.

In Chapter 3 we perform a preliminary characterization of the instrumental polarization effects of the near-infrared spectropolarimetric mode of SCExAO-CHARIS at the Subaru Telescope. From measurements with the internal light source we find that the image derotator can cause significant loss of signal at some wavelengths. We calculate the polarization produced by the telescope using theoretical models. We plan to measure the telescope polarization with observations of an unpolarized star and add a correction method similar to that of IRDAP to the existing CHARIS data-reduction pipeline. Once finished, these calibrations will enable unique quantitative polarimetric studies of circumstellar disks and substellar companions at a spectral resolution beyond that possible with SPHERE-IRDIS' broadband filters.

In Chapter 4 we introduce an observing scheme that combines high-contrast imaging polarimetry with the angular-differential-imaging data-reduction technique to reach the sensitivity required to characterize substellar companions that are located at small angular separations from their stars. We have implemented this scheme for SPHERE-IRDIS and developed the corresponding observing strategies and data-reduction approaches. Using this technique, we observed the planets of HR 8799 and the substellar companion PZ Tel B. We do not detect near-infrared polarization from these companions and estimate upper limits on their degree of polarization. The achieved sensitivity and accuracy

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[1] `https://irdap.readthedocs.io`

of the measurements show that our technique enables the characterization of faint substellar companions located close to their stars.

In Chapter 5 we use SPHERE-IRDIS to measure the near-infrared linear polarization of 20 known, directly imaged exoplanets and brown dwarf companions. We report the first direct detection of polarization originating from substellar companions, with a polarization of several tenths of a percent for DH Tau B and GSC 6214-210 B. Because these companions have previously measured hydrogen emission lines and red colors, the polarization most likely originates from disks around these companions. Through radiative transfer modeling, we constrain the position angles of the disks and find that the disks must have high inclinations. The presence of the disks around DH Tau B and GSC 6214-210 B as well as the misalignment of the disk of DH Tau B with the disk around its host star suggest in-situ formation of the companions. For the 18 other companions, we do not detect significant polarization and place upper limits on their degree of polarization. These non-detections may indicate the absence of disks around the companions, a slow rotation rate of young companions, the upper atmospheres containing primarily submicron-sized dust grains, and/or limited inhomogeneity of the atmospheric clouds. Our work shows that the polarization of substellar companions can indeed by detected and that polarimetry can be used to characterize these objects.

In Chapter 6 we develop the observing scheme, data-reduction methods, and analysis tools to measure near-infrared circular polarization with SPHERE-IRDIS. Because the instrument is not designed to measure circular polarization, we use the image derotator to convert incident circular polarization into measurable linear polarization. We tested the technique with observations of the red hypergiant VY CMa and its surrounding nebula. To accurately measure the circular polarization, we use the spatial variation of the linear polarization around VY CMa to distinguish between real, astrophysical circular polarization and instrument-induced signal. We find that the light from VY CMa is circularly polarized, in agreement with the literature, but do not conclusively detect circular polarization in the nebula surrounding VY CMa. Our observing scheme enables the first measurements of circular polarization at high spatial resolution. The method is promising for the characterization of the dust and magnetic fields in circumstellar disks, and could even shed light on the emergence of homochirality in biomolecules.

In Chapter 7 we investigate polarization aberrations produced by reflection off flat metallic mirrors at the fundamental level. Polarization aberrations are polarization-dependent variations of the electromagnetic field across a beam of light. These aberrations create polarization structure in the images that limits the sensitivity of the most sensitive high-contrast imagers. We numerically compute the polarization aberrations and interpret the results in terms of the Goos-Hänchen and Imbert-Federov shifts of the beam of light as described in the physics literature. We find that the beam shifts are fully reproduced by our numerical calculations and study the origin, size, and direction of the shifts. The beam shifts in an optical system can be mitigated by keeping the focal ratios large and angles of incidence small as well as by designing mirror coatings to have a retardance close to 180° rather than maximum reflectivity. Our insights can be applied to improve the performance of current and future ground- and space-based high-contrast imagers that aim to reach the extreme contrasts required to directly image exoplanets in reflected, and thus polarized, visible light.