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Summary

Protoplanetary disks and exoplanets in scattered light

The formation of planets occurs in protoplanetary disks around pre-main-sequence stars. These flattened disks of gas and dust are a natural by-product of star formation, and contain the building blocks for planetary systems. Most of the gas and dust reservoir is accreted or dispersed within approximately ten million years such that the formation of asteroids, comets, terrestrial planets, and gas giants should take place on a relatively short timescale. Intriguingly, planet formation appears to be a highly efficient process as more than 3600 exoplanets have been detected in our neighborhood of the Galaxy. Statistical analyses predict occurrence rates of several tens of percents for rocky planets orbiting low-mass stars, meaning that the Galaxy is expected to be crawling with planets. These findings are posing major questions regarding the formation and evolution of planetary systems, the cosmic context of the Solar System, and the habitability of exoplanets.

Research on planet formation has entered a new era with the advent of high spatial resolution observations. Substructures are commonly detected in many protoplanetary disks, including gaps, cavities, and spiral arms, which are possibly related to planet-disk interactions or other evolutionary processes. Resolving the birth environment of planets is a challenging endeavor because their angular size is typically less than an arcsecond in the nearest star-forming regions, that is, approximately 2000 times smaller than the angular diameter of moon. The relative brightness of the central star introduces another observational challenge at short wavelengths because the scattered light flux from the disk is typically several orders of magnitude fainter. Therefore, high-contrast differential imaging techniques are used to resolve the morphology of protoplanetary disks in scattered light, as well as detecting the thermal emission from self-luminous exoplanets. The SPHERE instrument is a dedicated imager for the direct detection of exoplanets and circumstellar environments, which was installed on the Very Large Telescope in Chile several years ago.

In this thesis, I study protoplanetary disks with high-contrast, high-resolution scattered

light observations, aiming to reveal substructures and brightness asymmetries in their surface layers. The scattered light images provide insight into the structure of protoplanetary disks, the distribution and properties of small dust grains, and the physical processes driving disk evolution. Shadow variability is demonstrated as a unique diagnostic for probing the innermost disk regions which are beyond the reach of high-contrast imagers. State-of-the-art radiative transfer simulations are used to place quantitative constraints on the disk structure and dust properties. Self-luminous exoplanets are potentially also detectable in polarized light which provides an opportunity to study atmospheric asymmetries. A new scattering code is used to predict the spatially-integrated polarization signal from self-luminous planets with non-uniform cloud distributions and circumplanetary disks.

In Chapter 2, we present a new three-dimensional scattering radiative transfer code for (exo)planetary atmospheres (ARTES) which includes a full treatment of multiple scattering and polarization. The code applies the Monte Carlo radiative transfer technique by stochastically following photon packages through an atmospheric grid, allowing for arbitrary density distributions and scattering properties. Simulations of reflected light and thermal radiation are possible for which spectra, phase curves, and images can be computed. After careful benchmark calculations, we make predictions on the spatially-integrated degree and direction of polarization from self-luminous exoplanets with horizontal cloud variations, circumplanetary disks, oblate atmospheres, and various cloud scattering properties. We find that the degree of polarization is maximum for a rotationally-flattened planet with high-altitude clouds with a thickening of the cloud deck around the equatorial regions. For a flattened planet, the degree of polarization can either increase or decrease with respect to a spherical planet which depends on the horizontal distribution and thickness of the clouds. The integrated direction of polarization is either parallel or perpendicular to the projected spin axis if clouds are zonally distributed. Finally, the presence of a hot or cold circumplanetary disk may also produce a polarization signal up to $\sim 1\%$ due to obscuration of the planet atmosphere by the circumplanetary disk, and scattering of photons in the circumplanetary disk.

In Chapter 3, we construct a numerical method to map scattered light images to the intrinsic surface geometry of protoplanetary disks. Understanding the physical distances and scattering angles associated with each pixel is in particular important for inclined disks which are affected by projection effects. By parameterizing the height of the scattering surface with a power law, stellar irradiation-corrected images can be calculated which correct for both the inclination and height of the disk. Additionally, the scattering phase functions of the dust can be extracted which requires, for polarized intensity images, an assumption about the degree of polarization. We apply the method on polarized scattered light images of the protoplanetary disk surrounding HD 100546. In contrast to earlier studies, we report that the near side of the disk is brighter in polarized intensity than the far side. The retrieved phase functions reveal, under the assumption that the degree of polarization is bell-shaped, part of a forward scattering peak which increases in

strength towards shorter wavelengths. This indicates that approximately micron-sized (or larger) dust grains dominate the scattering opacity in the disk surface, presumably with an aggregate structure.

In Chapter 4, we present SPHERE scattered light imagery of the transition disk around HD 135344B, obtained with polarimetric differential imaging in the R -, I -, Y -, and J bands. The spiral arms and cavity edge are confirmed with high spatial resolution and sensitivity, and multiple localized brightness minima are discovered. We suggest that the innermost, sub-au disk regions are casting shadows on the outer disk. A broad shadow is identified in northern direction in all images while one of the shadow lanes is only present in the J -band image, indicating a transient or variable phenomenon. We explore the possibility of a disk warp with a radiative transfer model which qualitatively matches some of shadow characteristics. Apart from the azimuthal shadowing variations, we identify a global brightness gradient which coincides with the asymmetry in the (sub)millimeter continuum emission, hinting at a possible link between the enhanced disk height and a temperature and/or density perturbation by the passing spiral arms. The wavelength-dependent scattering efficiency increases towards longer wavelengths which we attribute to dust grains that are similar to or larger than the observed wavelength such that forward scattering causes a red color. The spiral arms are best explained by one or multiple protoplanets in the exterior of the disk although no gap is detected beyond the spiral arms up to $1''.0$. Part of the non-azimuthal signal in the high signal-to-noise J -band image could be a result of multiple scattering in the disk.

In Chapter 5, we continue the investigation of the shadows of HD 135344B with multi-epoch scattered light observations, combined with visible and near-infrared photometry, and near-infrared interferometry. We present four additional SPHERE data sets in which we identify azimuthal brightness variations with temporal variations between all epochs. The shadows appear as narrow lanes, possibly cast by localized density enhancements, and broader features which possibly trace the larger scale dynamics of the inner disk. The near-infrared photometry shows variations up to 10%, partially overlapping with the SPHERE observations, and possibly correlated with the presence of the shadows. Analysis of archival VLT/PIONIER H -band visibilities shows that the inner disk is presumably aligned with the outer disk or misaligned by at most a few degrees. A minor disk warp could explain the broad, quasi-stationary shadowing in the north to northwest direction which we illustrate with a radiative transfer model. A grid of radiative transfer models is computed to quantify the correlation between the near-infrared excess of the inner disk and the illumination/shadowing of the outer disk. The variability of the scattered light contrast requires the presence of dust at relatively high altitudes in the inner disk atmosphere, up to a disk opening angle of $\sim 10^\circ$. Several mechanisms are discussed that might be responsible for the azimuthally asymmetric optical depth variations through the inner disk, including turbulent fluctuations and a dusty disk wind.

In Chapter 6, we study the protoplanetary disk around the Herbig Ae star HD 97048 with polarimetric- and angular differential imaging observations and reveal for the first

time substructures in the flaring surface layer of the disk. We detect four ring-like brightness enhancements and corresponding gaps, at distances between 39 au and 341 au from the central star. Ellipse fitting of the concentric features provides an estimate of the inclination, position angle, and height of the scattering surface with distance from the star. The disk height is well described by a single power law up to 270 au while the disk becomes likely optically thin further out. We measure the scattering phase function along one of the rings, which is consistent with numerical calculations of compact dust aggregates. Planets could be responsible for the radial gaps. The gap widths are used to estimate the planet masses which are expected to be less massive than Jupiter. Upper limits on the brightness and therefore the mass of embedded planets are derived from the angular differential imaging observations.

In Chapter 7, we report on SPHERE observations of another transition disk, HD 100453, which we detect in polarized scattered light in the *R*-, *I*-, and *J* bands. Additionally, angular differential imaging observations in the near-infrared reveal the total scattered light flux of the disk. We identify a cavity edge with an azimuthal brightness modulation, two localized shadows, and a symmetric pair of spiral arms. The M dwarf companion at 119 au is likely responsible for the spiral arms. However, we speculate that the spiral arms could be related to the shadows as the spiral arms appear to originate close to the location of the shadows. A faint feature is visible on the near side of the disk which could be tracing the bottom side if the disk is tidally truncated by the companion. We construct a radiative transfer model with a strongly misaligned inner disk which matches both the location and width of the shadows. The azimuthal brightness variation is well explained by the effect of the scattering angle but we also discuss the possibility that the scale height is modulated by the shadows, depending on the heating and cooling timescales.