Characterization of Planetary Systems in Scattered Light with Differential Techniques

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Abstract

This thesis is devoted to the study of scattered optical and near-infrared light received from planetary system objects, in particular solar and extrasolar giant planets and debris disks.

The light is originally emitted by the parent star and subsequently redistributed by the smaller bodies in a manner characteristic for their scattering particles. The measured scattered light therefore provides information on the size and composition of the individual particles, as well as on geometry and arrangement of an ensemble of particles. In this thesis, these are in particular gas and haze particles in planetary atmospheres, and dust particles in circumstellar debris rings.

A challenge in measuring scattered light from exoplanetary systems is the brightness of the central star, whose halo outshines the much fainter, smaller objects at optical and near-IR wavelengths by many orders of magnitude. The stellar light must be removed to reveal the planets or dust, and a powerful method to achieve this is to use differential techniques. Differential polarimetry makes use of the fact that the emitted starlight is generally unpolarized, while scattering processes usually induce some amount of polarization. Subtraction of orthogonal polarization states therefore effectively removes unpolarized stellar light while preserving scattered polarized light. A second such technique is angular differential imaging, where the observed field rotates around the star during the observations. The pupil plane, and therefore the stellar point spread function with its structure distortions introduced by the atmosphere and optics, remains fixed. Subtraction of optimally chosen rotated frames removes the stellar point spread function while preserving the fainter objects’ signals.

PART ONE investigates in detail the diagnostic potential of polarimetry for the characterization of giant planet atmospheres. Models are calculated for the polarization depending on atmospheric parameters and constituents for extrasolar and solar system gas giants with a Monte Carlo multiple scattering code.

First, a parameter study is performed with a large grid of simple models to determine the influence of scattering layer thickness, absorption and planet phase on intensity and polarization. Rayleigh scattering, isotropic scattering, and Henyey-Greenstein phase functions are considered. The disk-integrated polarization for phase angles typical for extrasolar planet observations, as well as the limb polarization effect observable for solar system objects near opposition, are discussed. The polarization as a function of wavelength is compared for a planet at quadrature and opposition, and predictions are made for broadband polarimetric observations.
Abstract

In a second step, a detailed model of the atmosphere of Uranus is constructed to interpret spectropolarimetric observations of the limb polarization of Uranus for the wavelength range 530 to 930 nm. For the first time, polarization properties of atmospheric constituents of Uranus are derived. The limb polarization is dominated by Rayleigh scattering on molecules. It is influenced by the polarization of a vertically extended tropospheric haze with wavelength dependent polarization properties, as well as a thin, highly polarizing stratospheric haze layer. From the limb polarization model, the polarization phase curve of Uranus and the spectropolarimetric signal at large phase angles is calculated in order to predict the polarization and detectability of an Uranus-like extrasolar planet.

Finally, a model of Jupiter’s polar haze is made for spatially resolved spectropolarimetry, focusing on the polarimetric signal at 600 nm in a slit spanning from the North to the South pole. The strong radial polarization at the poles, with a seeing corrected maximum of more than 10%, is well explained by strongly polarizing and forward scattering fractal aggregate haze particles.

Part two describes observations of scattered light from the debris disk around the star HD 61005. Ground-based high-contrast imaging data in $H$-band are reduced with optimized angular differential imaging. The observations are of higher resolution than previous observations by the Hubble Space Telescope, and the disk is newly revealed to be a narrow, highly inclined ring. The ring center is found to be offset from the star by approximately 3 AU, which could be a result of a planetary companion that perturbs the remnant planetesimal belt. An upper mass limit for companions that excludes any object above the deuterium-burning limit for angular separations down to 0.35") is found. From a previously imaged swept-back outer feature, the likely result of interaction with the interstellar medium, we see two distinct streamers originating at the ansae of the ring. The ring shows a strong brightness asymmetry along both the major and minor axis. The brightness difference between the ring ansae can only partly be explained by the ring center offset, possibly suggesting density fluctuations in the ring.

This thesis shows that scattered light observations with differential techniques are promising methods to detect and characterize planet atmospheres and debris disks as demonstrated on specific examples. These observations are very complementary to thermal light observations, and the sophisticated differential techniques make them feasible from large ground-based telescopes. In the outlook sections, ongoing observing programs are described that were initiated as a result of this thesis, in particular polarimetric observations of a hot Jupiter and follow-up observations of the HD 61005 debris disk for a characterization of the grain size distribution and a deeper planet search. Future prospects are discussed with a main emphasis on the upcoming 2nd generation instrument SPHERE for the Very Large Telescope.
Zusammenfassung


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Schliesslich wird ein Modell für die polaren Aerosole von Jupiter erstellt für räumlich aufgelöste Spektropolarimetrie, mit Fokus auf die Wellenlänge 600 nm in einem Spalt vom Nord- zum Südpol. Die hohe radiale Polarisation an den Polen, nach Seeingkorrektur höher als 10%, wird gut durch hochpolarisierende, vorwärtsstreuende, fractal zusammengesetzte Aerosolteilchen erklärt.
