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Polarimetry of planetary atmospheres: From the solar system gas giants to extrasolar planets

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Introduction - Polarized light from planets

Light reflected from a planetary atmosphere is generally polarized because of scattering processes, providing information on particle properties and distribution:

- Rayleigh scattering on molecules polarizes 100% at 90° scattering angle for single scatterings, while forward and backscattering is unpolarized. Because $\sigma_r \propto \tau^{-4}$, Rayleigh scattering is strong mainly at shorter wavelengths.
- Haze or cloud particles of size similar or bigger than λ polarize negatively
- Aggregate haze particles polarize similarly as Rayleigh scattering, but have a much more forward scattering phase function and different λ dependence.

The polarization depends on the phase angle, the angle observer-star-planet (Fig. 1):

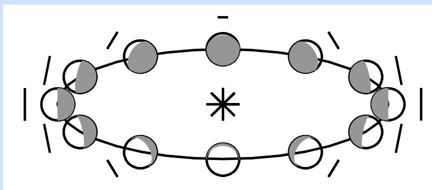

Figure 1: Polarization of a planet with Rayleigh scattering for an arbitrary inclination, depending on the phase angle. The shaded area is the illuminated part of the planet seen by the observer. The lines indicate the orientation and strength of the polarization.

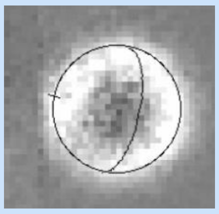

Figure 2: Polarimetric image of Uranus. White indicates a polarization in radial direction (~2% at limb) [1].

The solar system gas giants can only be observed at small phase angles from Earth. The polarization of the directly backscattered light is very small for symmetry reasons. However, near the limb the symmetry is broken, and multiply scattered photons produce a limb polarization of a few percent in radial direction (Fig. 2) seen with disk resolved observations.

Results from the solar system gas giants

Uranus mainly shows polarization due to Rayleigh scattering and haze particles. We have modeled the limb polarization spectrum of Uranus taken along a slit along the equator by [2] between 550 and 930 nm. This is the first spectropolarimetric model fit to observations for any planet and the first derivation of polarimetric properties of Uranus. We base our model on the atmospheric structure and scattering properties derived by [3] from detailed intensity measurements and derive polarimetric parameters. Our best model is shown in Fig. 3

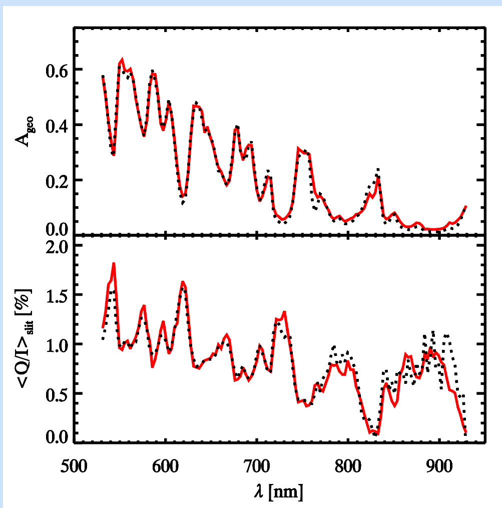

Figure 3: Geometric albedo spectrum (top) and limb polarization spectrum (bottom) of Uranus. The dotted line is the observation, the red line our best model.

Main model results for Uranus are:

- Rayleigh scattering on H_2 and He is mainly responsible for the limb polarization, but a negatively polarizing tropospheric haze is required to match the level and slope of the continuum polarization.
- The polarization enhancement within methane bands results from a methane depletion in the stratosphere. Additionally, a thin, positively polarizing stratospheric haze layer (small or aggregate particles) is required to match the polarization in the deep methane bands beyond 750 nm.
- The polarization is sensitive to the distribution of the tropospheric haze. An extended haze layer continuously mixed with the gas is favored over haze or cloud layers at fixed pressure levels.

Jupiter's polarimetric properties are distinctly different from Uranus: Limb polarization observations [4] show that the equatorial region is weakly negatively polarized, while the poles show a strong positive limb polarization of up to 10% (Fig. 4), not explainable by Rayleigh scattering. Our models indicate that an optically thick haze layer of aggregate particles (strong forward scattering, high polarization), provides a good match for the poles.

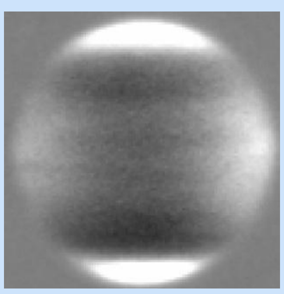

Figure 4: Linear polarization image of Jupiter. White indicates a polarization in N-S direction (≈ 10% at poles).

Prospects for extrasolar planets

The future VLT planet finder instrument SPHERE [5] will be equipped with the polarimetric mode ZIMPOL for the search and characterization of extra-solar planets around nearby star. ZIMPOL will target the nearest bright stars, searching for giant planets with separations between 0.1 and 1 AU in the wavelength range 550-900 nm. With differential polarimetry the unpolarized stellar halo is subtracted, directly revealing the polarized signal of the planet.

We made diagnostic diagrams from a grid of models to study the influence of the optical depth of the Rayleigh scattering layer above a cloud layer and the presence of absorbers [6]. As an example we produced spectra for planets with varying methane content and cloud altitude and convolved these with the SPHERE/ZIMPOL broad-band filters to derive a polarization flux-color diagram (Fig. 5).

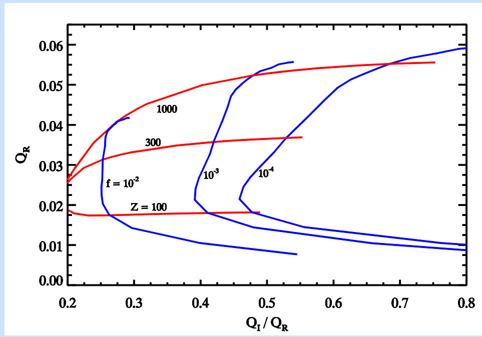

Figure 5: Polarization flux color diagram: linear polarization flux Q measured in the R band versus ratio of polarization flux measured in the I and R band. Lines indicate some values for the methane mixing ratio f (blue) and column density Z (red, in km-am) of the gas layer above clouds.

The detailed polarimetric model for Uranus allows a prediction for an extrasolar Uranus-analog at large phase angles (Fig. 6) The fractional polarization reaches p ≈ 30% at 90° phase angle.

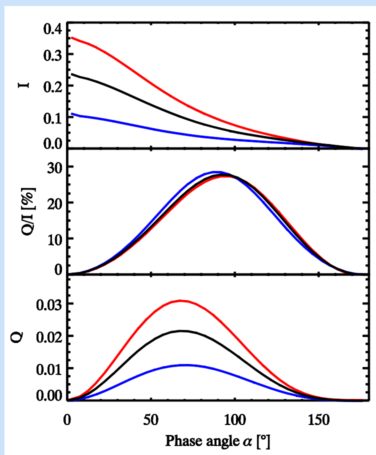

Figure 6: Intensity, polarization fraction and polarization flux predicted for Uranus as a function of phase angle for three filters: R (red), I (black) and RI (blue).

SPHERE/ZIMPOL will target warmer planets at smaller separations, but for the planned instrument EPICS for the E-ELT [7] ice giants around nearby M-dwarfs are within reach (Fig. 7).

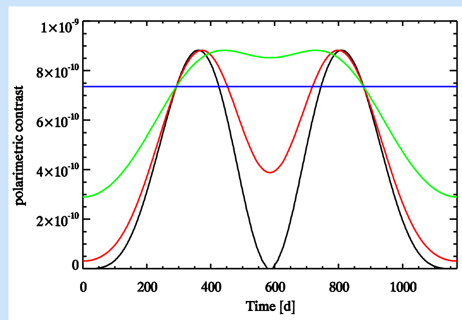

Figure 7: Polarimetric contrast of an Uranus analog around Barnard's star along its orbit for different inclinations (black: edge-on, red: 60°, green: 30°, blue: face-on)

Conclusion and outlook

The solar system gas giants show diverse and strong polarization features produced mainly by Rayleigh scattering or scattering on haze particles. The limb polarization provides a useful tool to characterize particle properties and vertical structure of the high scattering layers of the giant planets despite the small phase angle.

Polarimetry is an upcoming new method for exoplanet detection and characterization. Atmospheres with sufficient Rayleigh scattering or photochemical haze layers would produce a significant, measurable polarization signal. However, models for the temperature range of the SPHERE target planets are missing, and particular attention should be paid to the influence of photochemical haze.

References

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