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Polarization Models for Rayleigh Scattering Planetary Atmospheres

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Abstract We present Monte Carlo simulations for the polarization of light reflected from planetary atmospheres. We investigate dependencies of intensity and polarization on three main parameters: single scattering albedo, optical depth of a scattering layer, and albedo of a Lambert surface underneath. The main scattering process considered is Rayleigh scattering, but isotropic scattering and enhanced forward scattering on haze particles are also investigated. We discuss disk integrated results for all phase angles and radial profiles of the limb polarization at opposition. These results are useful to interpret available limb polarization measurements of solar system planets and to predict the polarization of extrasolar planets as a preparation for VLT/SPHERE. Most favorable for a detection are planets with an optically thick Rayleigh-scattering layer. The limb polarization of Uranus and Neptune is especially sensitive to the vertically stratified methane mixing ratio. From limb polarization measurements constraints on the polarization at large phase angles can be set.

Keywords Polarimetry · Planets · Atmospheres

1 Introduction

Light reflected from planetary atmospheres is generally polarized due to scattering on different types of particles with characteristic polarization properties. Rayleigh scattering on gas molecules produces 100% polarization for a single right angle scattering. Haze particles in Titan's or Jupiter's atmosphere scatter light mainly in forward direction but show Rayleigh-like polarization (Tomasko et al. 2008 and Braak et al. 2002). Reflection from clouds typically produces only a small positive (perpendicular to scattering plane) or even negative (parallel) polarization. Multiple scatterings randomize the polarization direction of the single scatterings and lower the observable polarization.

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For Jupiter, Saturn and Titan polarimetric data at large phase angles are available at few wavelengths from spacecrafts (e.g. Smith et al. 1984; Tomasko et al. 1984; Tomasko et al. 1982). With earth-bound observations the giant planets are always near opposition. At such small phase angles the disk integrated polarization is low because single back-scattering is unpolarized and the multiple scattering polarization cancels for a symmetric planet. However a second order scattering effect produces a measurable limb polarization in radial direction. Uranus and Neptune display a limb polarization of $\sim 1-3\%$ along the entire limb which is enhanced in methane absorption bands and decreases in the visible towards longer wavlengths (Schmid et al. 2006; Joos et al. 2007). Jupiter and Saturn show a similar behavior only at the poles (Joos et al. 2005), where the polarization is also high at large phase angles.

Measurements of the polarized light from close-in extra-solar planets have been attempted but so far no convincing detection has been made (e.g. Lucas et al. 2009). Upper limits indicate that these objects are not covered with a well reflecting Rayleigh scattering layer.

The future VLT planet finder SPHERE will be equipped with a polarimetric mode (ZIMPOL) for the search and characterization of extra-solar planets around nearby stars that are resolved from their central star (Beuzit et al. 2008). To prepare for the SPHERE observations and to interpret the available limb polarization data we have calculated a model grid to explore the parameter space in a systematic way. Here we present selected model results for Rayleigh scattering atmospheres and discuss how they fit the available data.

2 Model Description

Our simulations were made with a Monte Carlo code which calculates the intensity and polarization of the reflected light, described by the Stokes vector $\mathbf{I} = (I, Q, U, V)$ and the fractional polarization Q/I and U/I, for all phase angles α (the angle Star-Planet-Earth). Our planet model consists of a spherically symmetric body of radius R illuminated by a parallel beam. Each surface element is approximated by a plane parallel atmosphere consisting of one or multiple homogeneous scattering layers above a Lambert surface.

The basic model atmospheres are described by three parameters: the single scattering albedo ω, the (vertical) optical depth for scattering τ_{sc} of the scattering layer, and the albedo A_S of the Lambert surface. The single scattering albedo ω describes the ratio of scattering to absorption plus scattering. The basic models only include Rayleigh scattering. Extensions also consider isotropic scattering or enhanced forward scattering by haze particles as well as multiple layers. We treat absorption like an addition of absorbing particles to a layer with a given scattering optical depth τ_{sc}. This approach is suited for discussing the reflected intensity and polarization inside and outside of absorption features like CH_4 or H_2O-bands. The total optical depth τ of the layer is given by $\tau = \tau_{sc}/\omega$.

For extra-solar planets it will not be possible to resolve the disk in the near future. We concentrate on disk-integrated results, where Q is defined positive (negative) for a polarization perpendicular (parallel) to the scattering plane (star-planet-observer). For the study of the limb polarization in resolved planets at opposition we use the radial Stokes parameter Q_r, which is positive for an orientation of the polarization parallel to the radius vector $\mathbf{r}$ (see e.g. Schmid et al. 2006). The Stokes U or U_r parameters have to be zero for a spherically symmetric planet.

3 Results

Figure 1 shows the intensity I, polarization fraction Q/I or Q_r/I and polarized intensity Q or Q_r as a function of phase angle and as function of radius at opposition for selected examples. The maximum $Q = 0.081$ is reached for a semi-infinite conservatively scattering atmosphere at $\alpha = 65°$ where $I(\alpha) = 0.35$ and $Q/I(\alpha) = 23\%$. The maximum of Q/I is generally near 90° but shifts towards large phase angles for models with thin scattering layers and large surface albedos. For the limb polarization the maximum is reached at $r \gtrsim 0.95$.

General dependencies on the main parameters for a Rayleigh scattering layer are:

- lowering the Rayleigh single scattering albedo ω (more absorption) results in a lower I, Q and Q_r and in a higher polarization Q/I at large phase angles. Contrary to this at opposition Q_r/I is reduced for smaller ω,
- lowering the optical depth τ_{sc} results in a strong reduction in Q or Q_r in the optically thin case ($\tau \lesssim 1$) and causes essentially no change in Q or Q_r for $\tau \gtrsim 1$,
- lowering A_S lowers I and enhances Q/I or Q_r/I, but Q or Q_r are unaffected.

The polarization Q mainly probes the atmosphere to an optical depth of ~ 2. Below this depth polarization is washed out due to multiple scatterings. For the intensity and fractional polarization, an absorbing surface under a scattering layer can be noticed even at $\tau \gtrsim 10$.

A main difference between the limb polarization Q_r/I and the disk-averaged polarization $Q/I(\alpha)$ is their opposite dependence on ω. This occurs because absorption reduces multiple scatterings more strongly than single scatterings, but the limb polarization at opposition is mainly due to photons undergoing two to about six scatterings rather than one. However, observations of the solar system gas giants show that within methane bands the limb polarization is enhanced (Joos et al. 2007). Models with more than one scattering layer

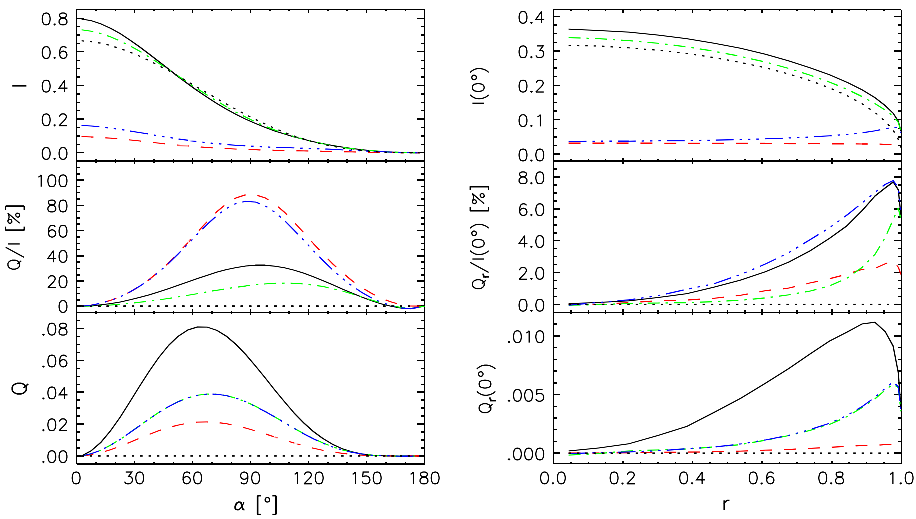

Fig. 1 *Left*: Intensity, polarization fraction and polarized intensity as a function of phase angle α for Rayleigh scattering atmospheres: Semi-infinite atmosphere with single scattering albedo $\omega = 1$ (*solid black*), 0.4 (*dashed red*), finite atmosphere ($\tau_{sc} = 0.3$) with $\omega = 1$ and surface albedo $A_S = 1$ (*dash-dot green*), 0 (*dash-dot-dot blue*). *Right*: Radial dependence at opposition for the same atmosphere models

achieve this if absorption mainly occurs in the lower layer. The maximum possible limb polarization with Rayleigh scattering is 9.5% near the limb or 5.25% disk integrated for a scattering layer with $\tau_{sc} = 0.8$, $\omega = 1$ above a completely dark surface. Enhanced forward scattering by haze particles can result in a much higher limb polarization (up to ≈20% at peak), but the intensity is much lower than for Rayleigh scattering as soon as some absorbers are present.

At large phase angles, the maximum polarization for a fixed intensity is given by the model with a conservative ($\omega = 1$) scattering layer over a dark ($A_S = 0$) surface. This limit is lower for brighter planets due to multiple scatterings. The radial (limb) polarized intensity $Q_r(0°)$ constrains the polarized intensity $Q(\alpha)$ at large phase angles, even if the detailed atmospheric structure is unknown (Fig. 2).

4 Conclusions

Simple Rayleigh scattering models are a good first approximation to the polarization of light reflected from planetary atmospheres. For extra-solar planets future measurements will mainly provide the polarimetric contrast: $C(\alpha) = R^2/D^2 \cdot Q(\alpha)$, where R is the radius of the planet, D the distance from its central star and α the phase angle. $Q(\alpha)$ is maximal for the semi-infinite, non-absorbing atmosphere, such as a deep cloudless H_2/He atmosphere. Absorption bands are less favorable despite the higher polarization, because the intensity is reduced more than the polarization is enhanced. High altitude clouds give a high albedo but low polarization. Forward scattering and polarizing haze particles as seen on Titan or Jupiter's poles result in a lower Q than a pure H_2/He atmosphere but could be favorable above absorbing layers.

For the interpretation of the limb polarization data the single layer models are not sufficient. Spectropolarimetric observations appear to be particularly sensitive to the vertical abundance stratification of absorbers (e.g. CH_4), which are not well constrained from albedo spectra alone (e.g. Sromovsky et al. 2007). A fit of more sophisticated models to limb polarization data of Uranus and Neptune will be attempted in a forthcoming paper.

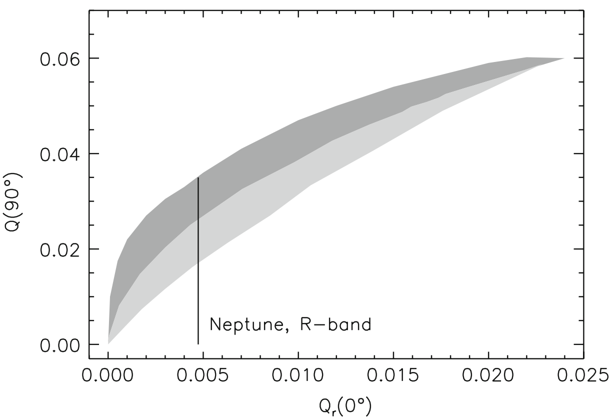

Fig. 2 Polarized intensity at quadrature vs radial polarized intensity at opposition. Dark shaded is the parameter space covered by Rayleigh scattering models, the total shaded area includes isotropic scattering. Indicated is a limb polarization measurement of Neptune (Schmid et al. 2006)

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