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PRM: A database of planetary reflection matrices

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Abstract

We present the PRM database with reflection matrices of various types of planets. With the matrices, users can calculate the total, and the linearly and circularly polarized fluxes of incident unpolarized light that is reflected by a planet for arbitrary illumination and viewing geometries. To allow for flexibility in these geometries, the database does not contain the elements of reflection matrices, but the coefficients of their Fourier series expansion. We describe how to sum these coefficients for given illumination and viewing geometries to obtain the local reflection matrix. The coefficients in the database can also be used to calculate flux and polarization signals of exoplanets, by integrating, for a given planetary phase angle, locally reflected fluxes across the visible part of the planetary disk. Algorithms for evaluating the summation for locally reflected fluxes, as applicable to spatially resolved observations of planets, and the subsequent integration for the disk-integrated fluxes, as applicable to spatially unresolved exoplanets are also in the database.

1. Introduction

Most planetary observations are limited to the intensity or flux of e.g. sunlight that is reflected by a given location on a planet. The state of polarization of this light is, however, also a strong tool for the characterization of the composition and structure of the atmosphere and/or surface of a planet, because especially the angular distribution of the degree of polarization is very sensitive to the microphysical properties (size, shape, composition) of the scattering particles. And while multiple scattering of light in a planetary atmosphere tends to wash-out single scattering features in the reflected flux, it just adds mostly unpolarized light, which subdues angular features in the polarization, but does not change their characteristic shapes and/or locations. Because the degree of polarization P is a relative measure (the ratio of the polarized to the total flux), it can in principle be measured very accurately. A classic example of the use of polarimetry for the characterization of a planetary atmosphere is the derivation of the particle properties of the upper clouds of Venus using Earth-based polarimetry at a few wavelengths and a range of planetary phase angles [2].

The Venus observations of [2] are spatially unresolved and thus a good example of the value of polarimetry for exoplanet characterization. For such research, polarimetry has the added advantage that it allows distinguishing the weak, but polarized planetary signal from the strong, but mostly unpolarized stellar signal. Because of the advantages for exoplanet research, the new instruments SPHERE on the VLT and Gemini on the Gemini telescopes both have a polarimetric channel for the direct detection of starlight that is reflected by giant exoplanets. EPICS's polarimeter that is being planned for the E-ELT can target rocky exoplanets around nearby stars.

Compared to total flux calculations, radiative transfer calculations that fully include polarization are much more complex and computing time consuming. The files in the PRM database allow a user to rapidly evaluate total and/or polarized fluxes of unpolarized incident sun- or starlight that is locally reflected by a planet (i.e. for a given angle of incidence and reflection), or that is reflected by a spatially unresolved planet (i.e. integrated across the illuminated and visible part of the planetary disk for a given value of the planetary phase angle). These fluxes could be used for the analysis of data, and for the development of polarimeters for planetary or exoplanetary research.

2. The database files

A full description of light uses a (column) vector $\mathbf{I} = [I, Q, U, V]$, with I the total intensity, Q and U the linearly, and V the circularly polarized intensity (all in W m^{-2} sr^{-1}), and with the degree of linear polarization $P = \sqrt{Q^2 + U^2}/I$. If $U = 0$, $P = -Q/I$. Similar definitions hold for flux vector $\pi\mathbf{F} = \pi[F, Q, U, V]$ (in W m^{-2}). With unpolarized incident light, the light that is reflected locally by a planet is calculated using

$$\mathbf{I}(\mu, \mu_0, \phi) = \mu_0 \mathbf{R}_1(\mu, \mu_0, \phi) F_0, \quad (1)$$

with πF_0 the incident flux, $\mathbf{R}_1$ the first column of the local reflection matrix, μ the cosine of the local viewing zenith angle, μ_0 cosine of the local solar zenith angle, and ϕ the azimuthal angle. Vector $\mathbf{R}_1$ is calculated as a Fourier series expansion of $\mathbf{R}_1$ [1]:

$$\mathbf{R}_1(\mu, \mu_0, \phi) = C_m \sum_{m=0}^{M} \mathbf{B}^m(\phi) \mathbf{R}_1^m(\mu, \mu_0) \quad (2)$$

with $\mathbf{R}_1^m$ the mth coefficient, $\mathbf{B}^m(\psi) = \mathrm{diag}(\cos m\psi, \cos m\psi, \sin m\psi, \sin m\psi)$, and $C_m = 2$, except $C_0 = 1$. The PRM database contains the coefficients $\mathbf{R}_1^m$, for various μ and μ_0, and with interpolation, values at other μ and μ_0 are obtained.

The flux vector of an exoplanet at a distance d from the observer follows and at phase angle α from integrating Eq. 1 over the planetary disk [4]

$$\pi \mathbf{F}(\alpha) = \frac{1}{d^2} \int \mu \mu_0 \mathbf{R}_1'(\mu, \mu_0, \phi - \phi_0) F_0 dO, \quad (3)$$

with dO a surface element on the planet.

An atmosphere of a model planet is a stack of layers filled with Rayleigh scattering gas molecules and/or aerosol or cloud particles. An atmosphere can be bounded below by a homogeneous, reflecting surface. [3, 5] have details on how the scattering and/or absorption properties of the layers are calculated. To calculate the flux vector reflected by a horizontally inhomogeneous planet, one can choose different Fourier coefficients for different locations on the planet.

Figure 1 shows sample simulations from the database: the total flux and degree of polarization of light reflected by four different, horizontally homogeneous Venus-like exoplanets with a black surface and a CO_2 atmosphere of optical thickness 7.2. Three of the model atmospheres have an H_2SO_2 cloud [2] of optical thickness 10.0, with the top at different altitudes. The fluxes have been normalized such that at a phase angle of 0°, they equal the planet's geometric albedo.

3. Summary

The PRM database contains reflection matrices (as coefficients of their expansion in a Fourier series) of various types of planets. The datafiles can be used to obtain total and polarized fluxes of unpolarized incident light that is reflected by a planet, both locally (i.e. for the interpretation of observations of Solar System planets) and integrated over the planetary disk (i.e. for simulating observations of exoplanets).

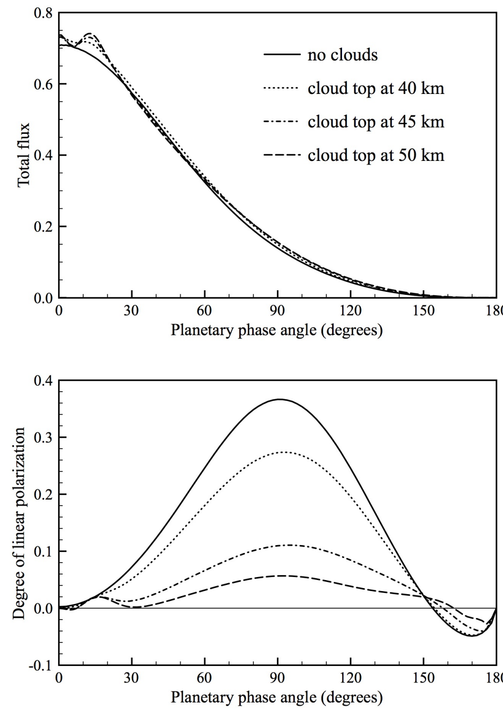

Figure 1: πF and P of light reflected by unresolved Venus-like exoplanets as functions of the phase angle.

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