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Colors of an Earth-like exoplanet

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Abstract

A better understanding of the flux and polarization signals of the Earth and their temporal variability is essential for the future characterization of Earth-like exoplanets. While the temporal variability of total fluxes reflected by the Earth has been investigated before, limited attention has been given to the temporal variability of the polarization of this light. Here, we provide a preview of numerical simulations of the total flux and degree of (linear) polarization of incident unpolarized light that would be reflected by the Earth itself, as if it were an exoplanet, using land and cloud coverage data obtained from Earth-observing satellites.

1. Numerical algorithm and data

We describe the light that is reflected by the planet by a vector $\mathbf{F} = [F, Q, U, V]$, with F the total flux, Q and U the linearly polarized fluxes, and V the circularly polarized flux. The latter is very small and will subsequently be ignored. The degree of polarization is defined as

$$P = \sqrt{Q^2 + U^2}/F. \quad (1)$$

To compute F, Q, U, and P of our model planet, we first divide the latter into a grid of square pixels and specify for each pixel the properties of the atmosphere and surface. Locally, the atmosphere is plane-parallel, consisting of a stack of homogeneous layers filled with gas. Optionally, we add liquid water cloud particles to one of the layers. An overview of the different atmospheric parameters is provided in Table 1. The local surface is one of the following: rough (i.e. wavy) ocean, forest, grasslands, steppe, desert, shrub-lands, or ice/snow. The choice of atmospheric and surface parameters is based on MODIS Earth observation data.

Given a pixel's atmospheric and surface parameters, we compute the pixel's F, Q, U, and P using PyMieDAP, a Python–Fortran doubling–adding radiative transfer code [1][1]. By summing the locally computed total and polarized fluxes (all defined with respect to the same reference plane), we obtain the disk-integrated fluxes and the disk-integrated P. Our fluxes are normalized such that the incoming solar flux equals π W/m^2.

Parameter	Symbol	Value(s)
Surface (bounding) pressure [bar]	P_{surf}	1
Depolarization factor	δ	0.03
Mean molecular mass [g/mol]	m_g	29
Acceleration of gravity [m/si^2]	g	9.81
Cloud particle effective variance	v_{eff}	0.1
Cloud particle effective radius [μm]	r_{eff}	10;12.5;15;17.5
Cloud particle distribution	-	Two parameter gamma
Cloud particle refractive index	$n_c = n_r + i * n_i$	$1.33 + 10^{-8} i$
Cloud optical thickness [-]	τ	0(clear);5;10;20
Cloud top pressure [mb]	P_c	500;700;850
Cloud vertical extend [mb]	-	100

Table 1: Overview of the properties of the model atmosphere that are used in the planetary model.

2. Results

Figure 1 shows the resolved disks of our model planet at various phase angles α. For all wavelengths (from 350 to 865 nm), the horizontally inhomogeneous surface and cloud coverage of our model planet generate diurnal oscillations in the phase curves as the planet rotates around its axis. The F, Q, and P phase curves of the rotating model exoplanet are shown in Figure 2.

Spherical liquid water particles generate a pronounced rainbow feature near $\alpha = 40°$ in F, Q, and P [2, 3]. The rainbow is most pronounced in Q, especially at the longer wavelengths, where the gas optical thickness above the clouds is small, and more light thus reaches the clouds.

The phase curves of F, Q and P for the different wavelengths intersect, i.e. the color changes from blue, through white, to red, at α equal to about $119°$, $140°$ and $145°$, respectively, as recently presented by [4] for cloudy ocean planets. These color changes can be explained by the wavelength dependence of

[1]PyMieDAP is available online under the GPL license http://gitlab.com/loic.cg.rossi/pymiedap

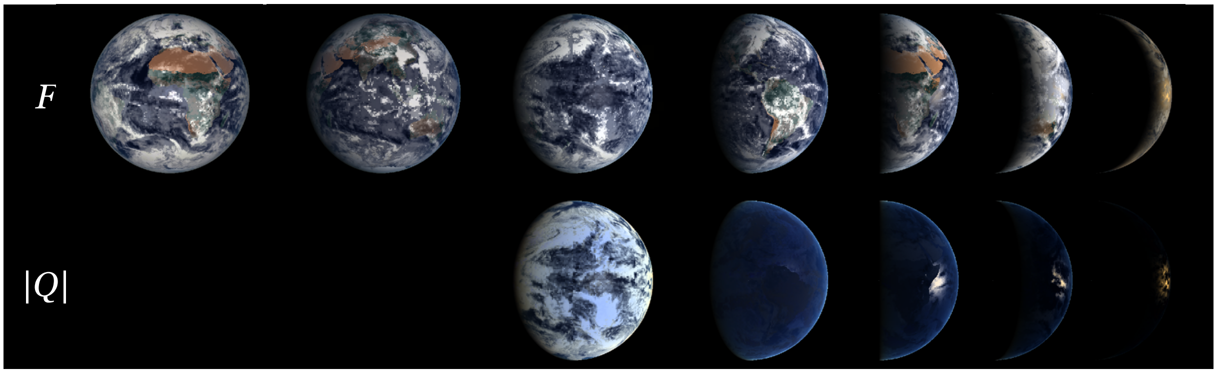

Figure 1: RGB(A) images of our model Earth for various sub-observer longitudes at phase angles α equal to (from left to right): 0°, 20°, 40°, 60°, 90°, 110°, and 135°. Shown are the total flux F and polarized flux $|Q|$.

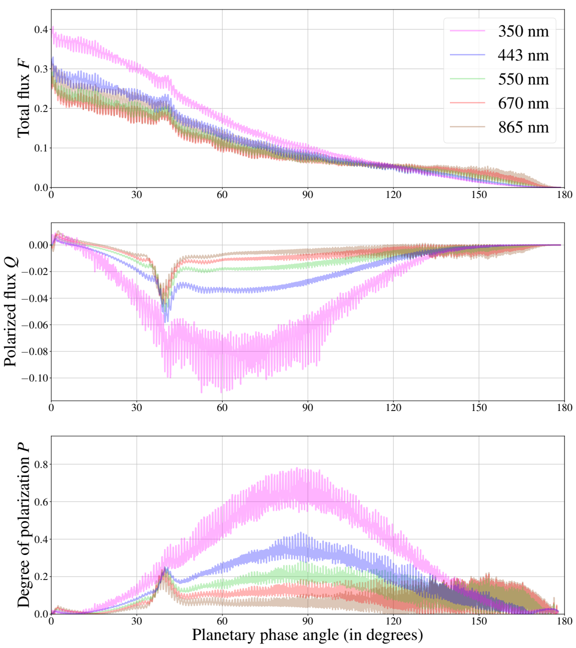

Figure 2: Total flux F, linearly polarized flux Q, and degree of (linear) polarization P, as functions of phase angle α at 350 nm (pink), 443 nm (blue), 550 nm (green), 670 nm (red), and 865 nm (brown).

Rayleigh scattering combined with the highly polarized reflection by the ocean surface [4].

The variability in Q and P decreases with increasing wavelength, because with increasing wavelength, the contribution of relatively highly polarizing Rayleigh scattering decreases, and hence the difference between the polarization signals of cloudy and non-cloudy pixels decreases.

3. Summary

We computed effects of Earth's temporal and spatial variability on the fluxes of reflected sunlight. These variations leave rapid oscillations on the phase curves of the total and polarized fluxes, and of the degree of polarization. Despite oscillations, the rainbow feature at a phase angle of 40° remains clearly visible in the curves, in particularly in that of Q. The Earth's phase curves all show a color change from blue, through white, to red. Such a color change in Q has been shown to identify ocean planets. Measuring polarized light in addition to total fluxes thus seems to offer better prospects to characterize habitability of exo-Earths.

4. Acknowledgements

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