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Blue, white and red ocean planets

Simulations of orbital variations in flux and polarization colors

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Abstract

An exoplanet's habitability will depend strongly on the presence of liquid water. Future flux and/or polarization measurements of starlight that is reflected by exoplanets could be used to identify exo-oceans. With numerical simulations of reflected starlight, we investigate which broadband spectral features in flux and polarization phase functions uniquely identify exo-oceans. In particular, the degree of polarization of light that is reflected by an exoplanet containing an ocean surface that is partly covered by clouds will show a color change at phase angles above about 100°, with the color change phase angle increasing with the cloud coverage fraction.

1. Introduction

The spectral and temporal variations of starlight that is reflected by an exoplanet along its orbit, hold information about the composition and structure of the planetary atmosphere and/or the surface (if present). This is particularly true for the state of polarization of the reflected light [1].

Simulations of orbital variations of the total, the (linearly) polarized flux, and the degree of polarization of light reflected by potentially habitable exoplanets are crucial for the design and optimization of future instruments and telescopes for the direct detection of exoplanetary radiation, since the results of such simulations can be used to identify potential observables, to devise observational strategies (such as integration times and temporal coverage), and to develop data analysis algorithms.

Here, we focus on numerical simulations of the total and polarized fluxes, and the degree of polarization of starlight that is reflected by Earth-like exoplanets covered by liquid water oceans. The ocean surfaces are rough due to wind-ruffled waves with white caps. Fresnel reflection of light on an exo-ocean yields two main observable phenomena: a glint on the ocean, whose size increases with the surface roughness (i.e., with wind speed), and a maximum degree of polarization at the Brewster angle. Indeed, as the strengths of both phenomena depend on the local reflection angles, they both depend strongly on the phase angle.

2. Method

We describe light with the Stokes (column) vector [1]

$$\mathbf{F} = [F, Q, U, V], \tag{1}$$

with F the total flux, Q and U the linearly polarized fluxes, and V the circularly polarized flux. We neglect V, as it is very small. The degree of polarization of the reflected light is then defined as

$$P = \sqrt{Q^2 + U^2}/F. \tag{2}$$

With an adding-doubling algorithm [3] combined with a disk-integration algorithm [2], we compute the Stokes vector of unpolarized incident starlight that is reflected by cloud-free and (partly) cloudy, terrestrial-type exoplanets, for wavelengths from 350 to 865 nm. Our model planets are covered by oceans with waves composed of Fresnel reflecting wave facets [4]. We fully include scattering of (unpolarized and polarized) light within the water below the ocean surface and the reflection by wind-generated foam [5].

The clouds are embedded within the gaseous atmosphere (there is Rayleigh scattering gas below, within and above the clouds), and they are patchy, with a coverage fraction f_c. The cloud droplets consist of liquid water and scatter according to Mie-theory [6].

3. Results

Figure 1 shows the computed P phase functions of our ocean planets for different fractions f_c (in 300 different patterns for each f_c), a wind speed of 7 m/s, and various wavelengths. It can be seen that the primary rainbow feature near a phase angle α of 40° is very insensitive to f_c and the location of the cloud patches at

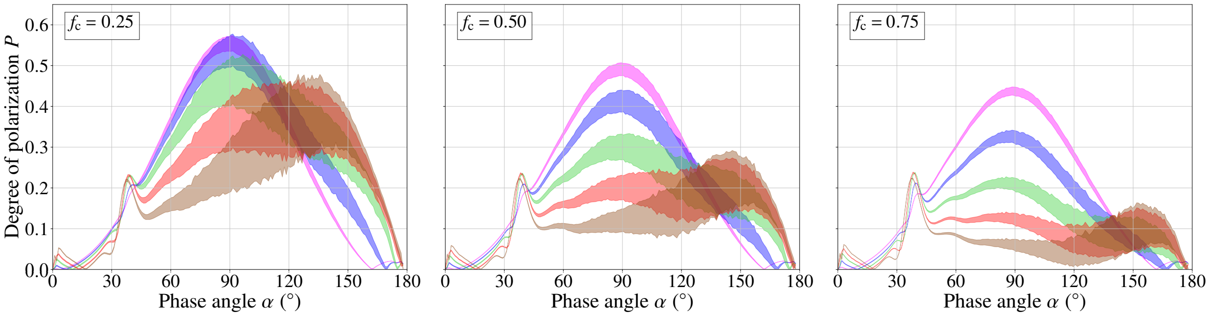

Figure 1: Polarization phase curve P of light reflected by ocean planets covered by patchy clouds with coverage fractions f_c of 0.25, 0.50, and 0.75, and for 5 wavelengths: 350 nm (pink), 443 nm (blue), 550 nm (green), 670 nm (red), and 865 nm (brown). The wind speed is 7 m/s. The colored areas represent the 1-σ standard deviation of P as computed for 300 different cloud patches configurations (for each value of f_c).

all colors. Furthermore, we can see that P of an ocean planet changes color from blue at small values of α to red at the largest values of α. The phase angle where the color change takes place, and where the planet is thus white in P, depends on the cloud coverage fraction f_c. Indeed, it only occurs for $0.03 \leq f_c \leq 0.98$ (not shown), with the color crossing α ranging from, respectively, $\sim 88°$ to $\sim 161°$.

The color change can be attributed to the wavelength dependence of Rayleigh scattering: with increasing α, the average atmospheric Rayleigh scattering optical path-length encountered by the light that reflected towards the distant observer increases. While short-wavelength light is scattered in the higher atmospheric layers, long-wavelength light reaches the surface to be reflected by the ocean, back toward space and the observer. Because this ocean reflection leaves the (long-wavelength) light highly polarized, the high polarization signal of the glint is strongly color dependent.

Indeed, this color change in P identifies the presence of an exo-ocean. Simulations show that a color change in F can also occur for a cloudy planet with a black instead of an ocean surface, while F of a cloud-free ($f_c = 0.0$) ocean planet will *not* change color for surface pressures larger than about 8 bars.

4. Conclusion

The color change of P of starlight that is reflected by an exoplanet, from blue, through white, to red with increasing α above 88°, appears to identify a (partly) cloudy exo-ocean. The phase angle where the color change takes place increases with the cloud coverage fraction f_c. Yet, at this color changing phase angle, the angular distance between a star and its planet is much larger than at the phase angle where the signal of the glint appears in the reflected light. The color change in polarization thus offers better prospects for detecting an exo-ocean than the glint itself.

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