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Publication date
2017

Document Version
Final published version

Citation (APA)
Rossi, L., Stam, D., & Turbet, M. (2017). *Retrieving the cloud coverage on Earth-like exoplanets using polarimetry*. Abstract from European Planetary Science Congress 2017, Riga, Latvia.

EPSC Abstracts
Vol. 11, EPSC2017-523, 2017
European Planetary Science Congress 2017

Retrieving the cloud coverage on Earth-like exoplanets using polarimetry

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Abstract

Clouds in the atmospheres of exoplanets have a significant impact on the habitability of these bodies. Clouds can also introduce ambiguities in the retrieval of atmospheric properties, such as gas mixing ratios. We present here numerical models of different types of liquid water cloud covers on Earth-like exoplanets and the degree of linear polarization of starlight that they reflect. Our results show that the type of cloud cover and the amount of coverage on an exoplanet can be retrieved by using polarimetry at different wavelengths.

1. Introduction

Clouds have a large impact on the radiative balance of a planet and therefore on its climate and habitability. But they will also influence the retrieval of a planet's surface and atmosphere properties. They can, for example, create a bias in the retrieved surface temperature [2], and affect the depth of absorption bands in the IR [6] and in reflected sunlight [2]. Clouds will in particular create ambiguities when retrieving mixing ratios of biomarker gases like O_2 from the depth of e.g. the O_2 A-band [1]. Transit spectroscopy of exoplanets is also affected by clouds, as the spectral behavior of clouds on an exoplanet's limb can mimic a gaseous atmosphere with a high molecular mass [3]. In direct detections, clouds can hide potential biosignatures on the surface of an exoplanet, such as the red edge of (terrestrial) vegetation [4] or signatures of liquid surface water. Knowledge of the cloud coverage of an exoplanet is thus crucial in order to to gain insight into its habitability.

2 Atmosphere and cloud models

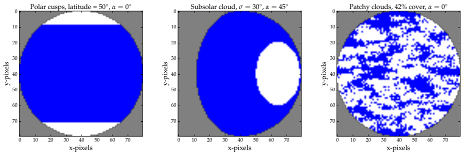

Figure 1: Illustration of the three cloud coverage types: polar cusps, sub-solar clouds and patchy clouds.

To model the atmospheres of Earth-like exoplanets, we use an Earth-like surface pressure and temperature profile, and horizontally homogeneous liquid water clouds ($r_{\rm eff} = 8$ µm, $\nu_{\rm eff} = 0.10$). The cloud resides at a pressure level $p_{\rm cloud}$ from 800 to 600 mb.

We use three types of coverage: (1) sub-solar clouds, extending an angle $\sigma_{\rm c}$ away from the subsolar point; (2) polar caps, with clouds covering everything above threshold latitude $L_{\rm t}$; (3) patchy clouds. For each type of coverage, $F_{\rm c}$ indicates the fraction of the planetary surface that is covered by clouds.

We compute the starlight reflected by our planets by dividing the planet as seen by the observer, thus at a given phase angle α, in a grid of square pixels. The cloud optical thickness in cloudy pixels is 6.0, a typical value at visible wavelengths, while it is zero in the cloud-free pixels. We use the adding-doubling method to then compute the locally reflected Stokes vectors for the center of each pixel. These local Stokes vectors are rotated to a common reference frame before being summed to obtain the disk-integrated values of I, Q, U, and V.

3. Results

The degree of linear polarization $P = \sqrt{Q^2 + U^2}/I$, of planets with the three types of cloud coverages for similar values of $F_{\rm c}$ is shown in Fig. 2 at 300 nm and at 500 nm.

First, we'll discuss the 500 nm case. As can be seen, a sub-solar cloud should be quite obvious to detect since it disappears from sight as the planet rotates and the polarization becomes determined by the

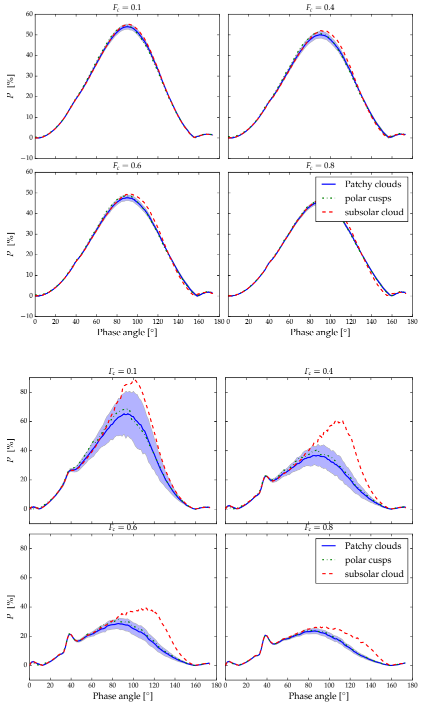

Figure 2: Degree of polarization P as a function of phase angle for different F_c and different cloud coverage types at $\lambda = 300$ nm (top) and 500 nm (bottom). Shaded areas indicate the 2-σ variability in the signal of the patchy cloudy planet due to 300 randomly chosen patterns.

Rayleigh scattering of the cloud-free pixels. The phase angle where this transition occurs depends on σ_c. The polar caps and patchy clouds have a similar average polarization pattern, but a large variability in the signal would indicate patchy clouds as it would result from different distributions of cloud patches across the planet.

For all three coverage types, the rainbow ($\alpha \approx 40°$) is visible (especially for large F_c) and with a similar strength regardless of the coverage type; as it depends on the refractive index and cloud particle size and shape, it could be used to retrieve cloud microphysical properties, independent of the cloud pattern. We've identified some ambiguities for in particular the patchy cloud coverage, because P is also determined by the cloud top altitude, with lower clouds usually yielding higher values of P. Variability in P could thus also be caused by variations in cloud top altitudes. Observations at different wavelengths could be used to solve this ambiguity, as Rayleigh scattering above the clouds is sensitive to the wavelength, as can also be seen in Fig. 2. Observations in gaseous absorption bands could also provide additional information [1].

4. Observational strategy

When observed in the blue, the different cloud coverage types appear nearly identical: at 300 nm, Rayleigh scattering above the clouds dominates the signal and makes the clouds nearly invisible. In the blue, one could assume a purely gaseous atmosphere to retrieve the planet's orbital parameters from polarimetry. Estimates of the cloud cover and composition could be made from the interpretation of observations at longer wavelengths, and used to refine the retrieval of the orbital parameters in an iterative process.

We intend to further investigate this by applying this retrieval method to simulations of possible polarization signals of Proxima b, using models for the possible climate and clouds on this recently discovered exoplanet [5].

Acknowledgements

We acknowledge the support of the Dutch Scientific Organization (NWO) through the PEPSci network of planetary and exoplanetary science.

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