Cloud Killer : Mapping the Surface of Cloudy Exoplanets

Lucas Teinturier[1,2,3], Youssef Bestavros[2], Nicholas Vieira[1,2], Elisa Jacquet[2], Juliette Geoffrion[2], Nicolas B. Cowan[1,2,4]

[1] McGill Space Institute, 3550 Rue University, Montreal, QC, H3A 2A7, Canada

[2] Department of Physics, McGill University, 3600 Rue University, Montreal, QC, H3A 2A7, Canada

[3] Ecole Centrale de Lyon, 36 Avenue Guy de Collongue, 69134 Écully, France

[4] Department of Earth & Planetary Sciences, McGill University, 3450 Rue University, Montreal, QC, H3A 0E8, Canada

Abstract
Reflected light photometry of terrestrial exoplanets could reveal the presence of oceans and continents, hence placing direct constraints and the current and long-term habitability of these worlds. Inferring the albedo map of a planet from its observed light curve is known to be degenerate because different maps may yield indistinguishable light curves. This degeneracy is aggravated by the effects of changing clouds. It has previously been suggested that disk-integrated photometry spanning multiple days could be combined to obtain a cloud-free surface map of an exoplanet. We demonstrate this technique as part of a Bayesian retrieval by simultaneously fitting for the fixed surface map of a planet and the time-variable overlying clouds. We test the limits of this approach on synthetic data before applying it to real disk-integrated observations of Earth from the Earth Polychromatic Imaging Camera aboard the DSCOVR mission. We find that ten days of continuous observations are sufficient to reconstruct a faithful low-resolution surface albedo map of the planet, without needing to make assumptions about cloud physics.

Introduction

The hability to map exoplanets surface would be very useful as it allows us to have insights on the possible habitability of the exoplanets. These maps would allow us to locate features such as oceans, continents, forests,etc. Exocartography entails mapping the surface of an exoplanet based on its time-varying brightness. It is an under-constrained problem made worst by the effect of changing clouds. Observing the planet over long enough timescales allows to tackle this degeneracy, as the clouds move and disperse and the actual surface map can emerge. We developped a model using Bayesian inference and Markov Chain Monte-Carlo to directly retrieve the surface albedo and the cloud covering fraction of a planet. Our model also retrieves the albedo of the clouds, and the rotational angular speed of the planet under study.

Model

Our model uses light curves spanning on few days to constrain the surface and cloud covering fraction maps. We longitudinally slice the planet and retrieve the mean features of each slice.
We generated synthetic data to test our approach, assuming random clouds from one day to another. Therefore, the cloud cover changes drastically from one day to another in our synthetic data.

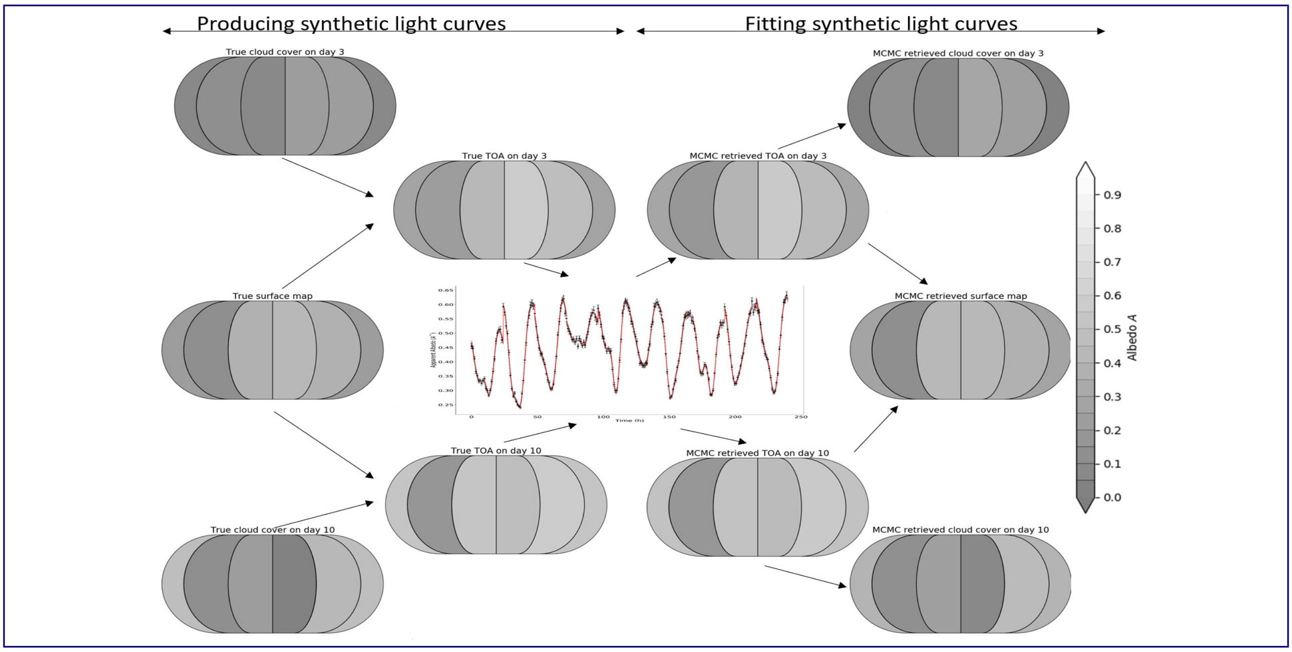
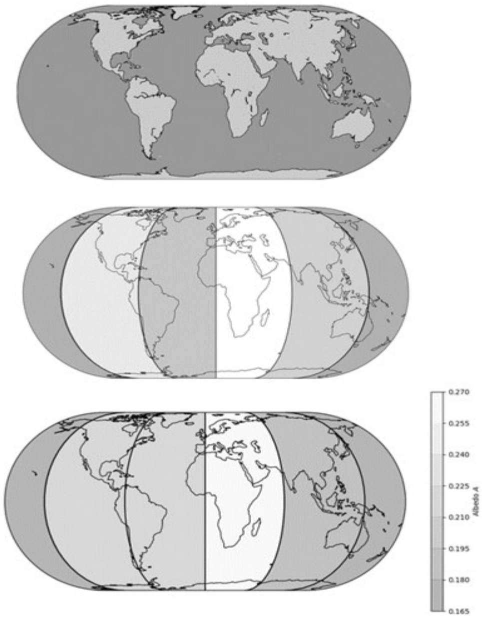


Figure 1: Schematic description of the different steps of our numerical experiment, from producing the synthetic light curves to the MCMC retrieval of the surface and time-varying cloud maps. We only show day 3 and 10 in this illustration but the surface map is fitted all ten days of data. We use 5 longitudinal slices here.

Using MCMC simulation, we construct a top-of-atmosphere albedo map which is use for comparison with the light curve. This allows us to directly solve for the time-varying clouds and the surface map. We also fit for the rotational angular speed of the planet and the albedo of the clouds. We assumed that clouds have a unique albedo on all the planet, so we fit for only one value of the cloud albedo. For all fitted parameters, we retrieve its estimated uncertainty by computing the 16^{th} and 84^{th} percentiles of the marginalized posterior distribution for the parameter.

Results

We tested our approach on synthetic data and on the EPIC data set. The synthetic data enabled us to find the optimal number of slices to use, and the required number of planetary rotations to put accurate constraints on the retrieved maps. We chose to use 5 longitudinal slices and 10 planetary rotations, as these values yielded the best accuracy, precision and Z-score distribution. We performed 50 retrievals on synthetic data, which allowed us to have an accuracy, precision and bias of respectively 0.003, 0.025, -0.003 for the surface maps. Computing the standard deviation of the Z-score on the time-varying cloud maps, the top_of_atmosphere albedo maps and the surface albedo maps showed that we underestimate our retrieved uncertainties. However, we constrain the retrieved surface maps to within 10% of errors.



Top: True Earth map with continents and land. Middle: The gray scale map we intend to recover from single band observations. Bottom: Five-slice surface albedo maps retrieved fitting the EPIC data light curve and modeling the time-varying clouds.

Using these values, we perform a retrieval on the EPIC data set using 10 days of data starting on August 11th 2017. We use single band observations from the EPIC instrument at 779.5 nm, as cloud coverage is the least impactful at this wavelength. The DSCOVR spacecraft is positionned at the 1st Lagrange point, and therefore sees Earth at full phase. We retrieve a good approximation of Earth's surface features: The far left and right side of the projection is a low albedo features corresponding to the Pacific Ocean, west of Greenwich Meridian are higer albedo slices corresponding to the Atlantic Ocean, North and South America and a part of the Pacific Ocean. East of Greenwich, the highest albedo slice corresponds to Europe and Africa, especially the Sahara desert, close to the equator and therefore well illuminated to an observer at L_1. Therefore, our approach is accurate enough to distinguish features on a planet such as oceans,lands, deserts, with a low resolution.

Discussion

Our approach allows us to identify features of Earth such as oceans, lands and deserts, but we used a few assumptions to symplify the problem. First, we approximate the nonlinear radiative problem of scattered light from a surface overlaid by and atmosphere and clouds by a linear relation between the surface albedo, the cloud albedo and the cloud covering fraction.
To match the EPIC viewing geometry, our experiments are run in full phase. But exoplanets cannot be observed at full phase, and direct imaging is most sentitive to planets near quadrature.
As we did not use any model for the physics of clouds while generating synthetic data and we chose to randomly form and dissipate them, the cloud pattern is utterly different from one day to another, which seems to be the a pessimistic assumption as the cloud covering fraction might then by harder to constrain. However, we did not take into account clouds that change on a long timescale and which could be harder to remove.
Finally, we retrieve surface maps from synthetic light curve to within 10% of errors.

Conclusion & Future Work

We developped a model capable to infer surface features from observed light curves of a planet. We tested our model on synthetic data and EPIC data, using Earth as a proxy exoplanet, and were able to construct low resolution maps that reveal the presence of oceans, deserts and lands. Future work will focus on changing the geometry of view to match those of future space telescopte such as JWST or Ariel.

References

All references used in this study are available here