Characterization of inhomogeneous exoplanets using flux and polarization: a numerical model

Theodora Karalidi [1,3]; Daphne Stam [1]; Joop Hovenier [2]

1: SRON - Netherlands Institute for Space Research 2: Astronomical Institute “Anton Pannekoek”, University of Amsterdam

3: Astronomical Institute, University of Utrecht, all in the Netherlands

T.Karalidi@sron.nl

1. Introduction

Although for years to come, images of exoplanets will remain unresolved pixels on a detector, it is interesting to investigate how horizontal inhomogeneities on a planet influence the retrieval of atmospheric and surface properties, and whether such inhomogeneities could in principle be retrieved. A number of numerical models have been presented to calculate fluxes of inhomogeneous exoplanets (e.g. Ford et al.,2001; Oakley & Cash ,2009). Polarization signals for inhomogeneous planets have been presented by e.g. Zugger et al. (2010), but the polarization calculations of these models are too simple, and hence not accurate. More advanced models that fully include the calculation of polarization (e.g. Seager et al., 2000; Saar & Seager, 2003; Stam et al., 2006; Stam 2008) treat horizontally homogeneous planets and use weighted averages of signals of different homogeneous planets to simulate signals of horizontally inhomogeneous planets (Stam 2008). Here, we present our newly developed code that is based on the code of Stam et al. 2006, but that can calculate signals of truly horizontally inhomogeneous planets.

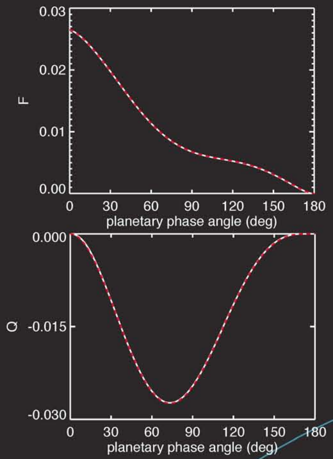

Figure 1: Reflected fluxes F and Q as functions of a for a horizontally homogeneous model planet with a black surface and a cloud-free, Rayleigh scattering atmosphere: results of the Stam et al. (2006) code (white) and ours (red).

2. Our numerical code

Our planets are split in pixels small enough to 1. assume a locally plane parallel surface and atmosphere, and 2. capture horizontal inhomogeneities. For each pixel, we can choose the surface albedo, and the composition of the overlying atmospheric layers. The number of atmospheric layers is arbitrary, and can be chosen to accurately describe vertical inhomogeneities. Each layer contains gas molecules, and, optionally, aerosol and/or cloud particles. Using an adding-doubling algorithm (de Haan et al., 1987; Stam et al., 1999), and given the planetary phase angle α, we calculate for each pixel the total and polarized reflected fluxes F , Q and U respectively. Integration of these fluxes over the planetary disk, yields the disk-integrated total flux F, polarized flux Q, U, and degree of polarization, sqrt(Q^2+U^2)/F . We have tested our code against that for horizontally homogeneous planets (Stam et al., 2006), which uses a similar adding-doubling algorithm, but treats the whole planet as a single scattering particle, and found agreement (for horizontally homogeneous planets) within the order of 10^{-5} (see Fig.1).

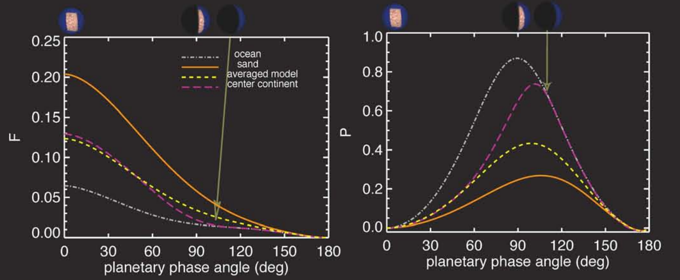

Figure 2: Reflected F and P as functions of α for a planet covered by ocean and with a sandy continent in the middle of the disk (purple, long-dashed). Also shown, for comparison, F and P of planets that are completely covered by ocean (gray, dot-dashed) or sand (oranje, solid), and of a planet that is a weighted average of these ocean and sand planets (with weights based on the planet with ocean and continent) (yellow, dashed). All planets have overlying cloud-free, Rayleigh scattering atmospheres.

3. Traces of inhomogeneities

In Fig.2 we show F and P as functions of α for a model planet covered by ocean that contains a centrally located sandy continent and that is overlaid by a cloud-free atmosphere. The comparison with the quasi-horizontally inhomogeneous planet, the signals of which are a weighted average of those of an ocean planet and a sand planet (as described by Stam 2008), shows that the truly horizontally inhomogeneous planet does have different flux and in particular different polarization signals as functions of the phase angle. Indeed the signals do contain information on the distribution of the inhomogeneities. The inversion of these signals, possibly at different wavelengths, will be subject for further study.

4. Limitations of our code

Multiple scattering calculations with polarization can be very time-consuming, and depending on the number of different pixels, the surface and atmosphere properties of those pixels, and the planetary phase angle, our code can easily require several hours for one wavelength. In comparison, for a horizontally homogeneous planet, the code by Stam et al. (2006) requires about as much computing time for the whole planet (and yielding results for all phase angles) as our code needs for a single pixel. It is therefore very important to investigate for which planets the extra information acquired with our code balances the added computational load. As a first investigation, we ran a number of simulations for model planets with or without the sandy continent and a range of cloud coverages to see at which cloud coverage one ceases to notice the continent (see Fig.3). The clouds have an optical thickness of 2. It appears that even for the most heavily covered planets, at this optical thickness, the contribution of the continent is large enough so that we cannot treat the planet as a horizontally homogeneous one.

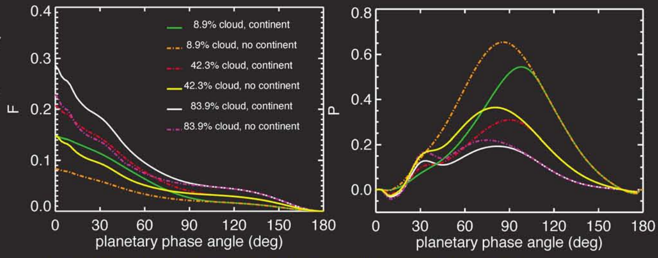

Figure 3: Reflected F and P as functions of α for planets covered by ocean and with or without a sandy continent in the middle for different amounts of clouds.

5. Conclusions & future work

We have created a numerical code to calculate flux and polarization signals of truly horizontally inhomogeneous exoplanets. Comparisons with signals of quasi horizontally inhomogeneous planets, obtained with the weighted averages method (Stam 2008), show that surface inhomogeneities *do* leave traces in reflected fluxes and polarization. Measuring the flux and polarization of reflected starlight could thus potentially provide a wealth of information about the curface coverage. More investigations are needed to find the limits of the information that could be acquired, taking into acount the diurnal rotation periods of planets and integration times (using instrument simulators). As an example, in Fig.4, we show F and P as functions of the planetary phase angle for a planet with one center continent and a cloudy atmosphere including diurnal rotation. Testing for which integration times, there is still information on horizontal inhomogeneities will be interesting for the design of future missions and observation strategies.

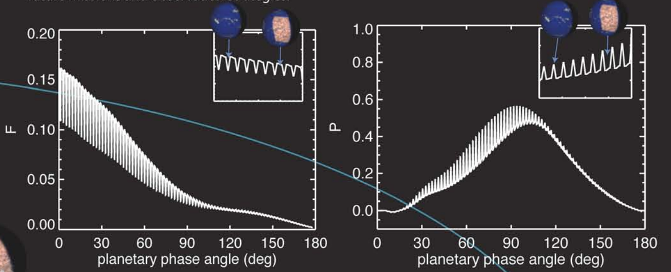

Figure 4: Reflected F and P as functions of α for a planet covered by ocean and with a sandy continent overlaid by a cloudy atmosphere. The planet rotates around its vertical axis, completing one rotation every 2 degrees of phase angle. The overplotted windows show a magnification of the curves for $60^0 < \alpha < 70^0$.

SRON
Netherlands Institute for Space Research / www.sron.nl