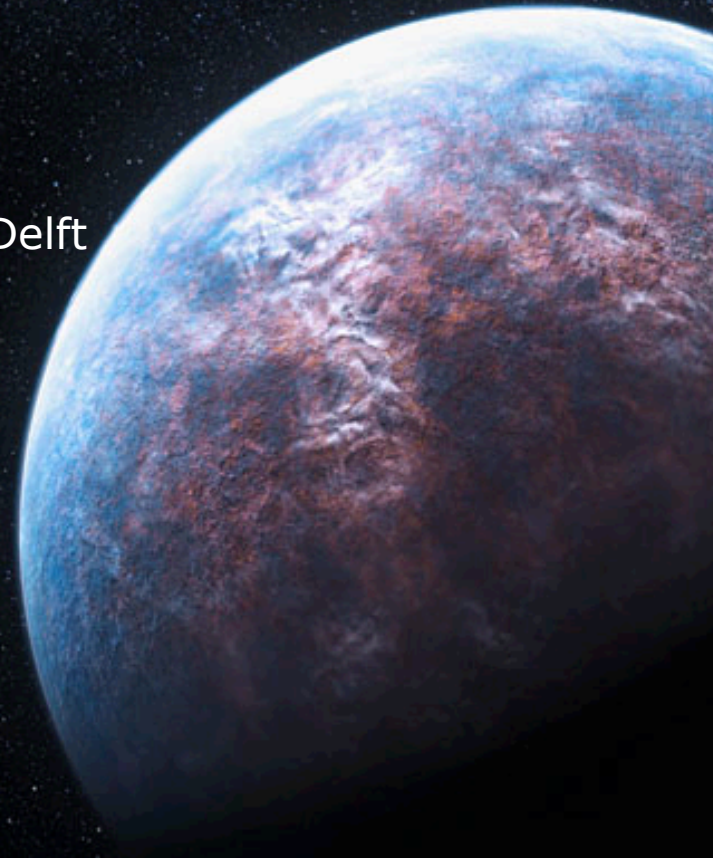


Spectropolarimetry of Earth-like exoplanets

Daphne Stam¹ & Theodora Karalidi²

1. Aerospace Engineering, Technical University Delft

2. Steward Observatory, Arizona University



Currently known exoplanets

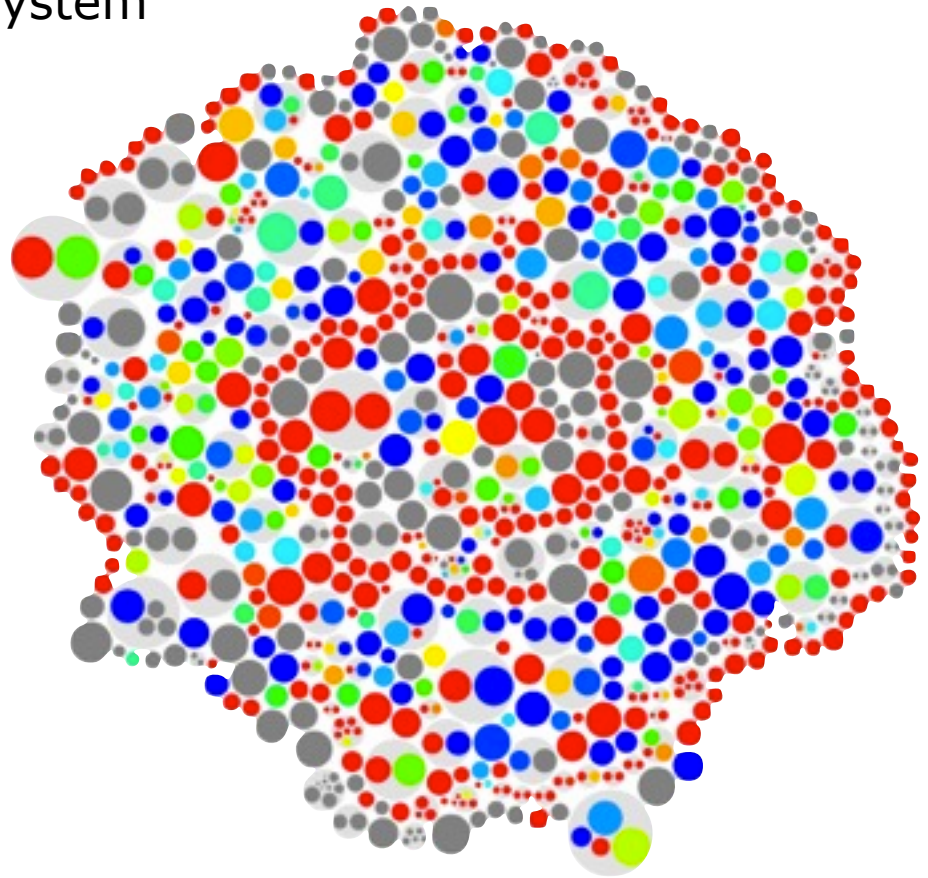
A bubble chart showing the relative sizes of the known exoplanets, those in the same planetary system grouped together.

Green: maybe ok for life

Blue: too cold for life

Red: too hot for life

Gray: no info



Plot from the Open Exoplanet Catalogue

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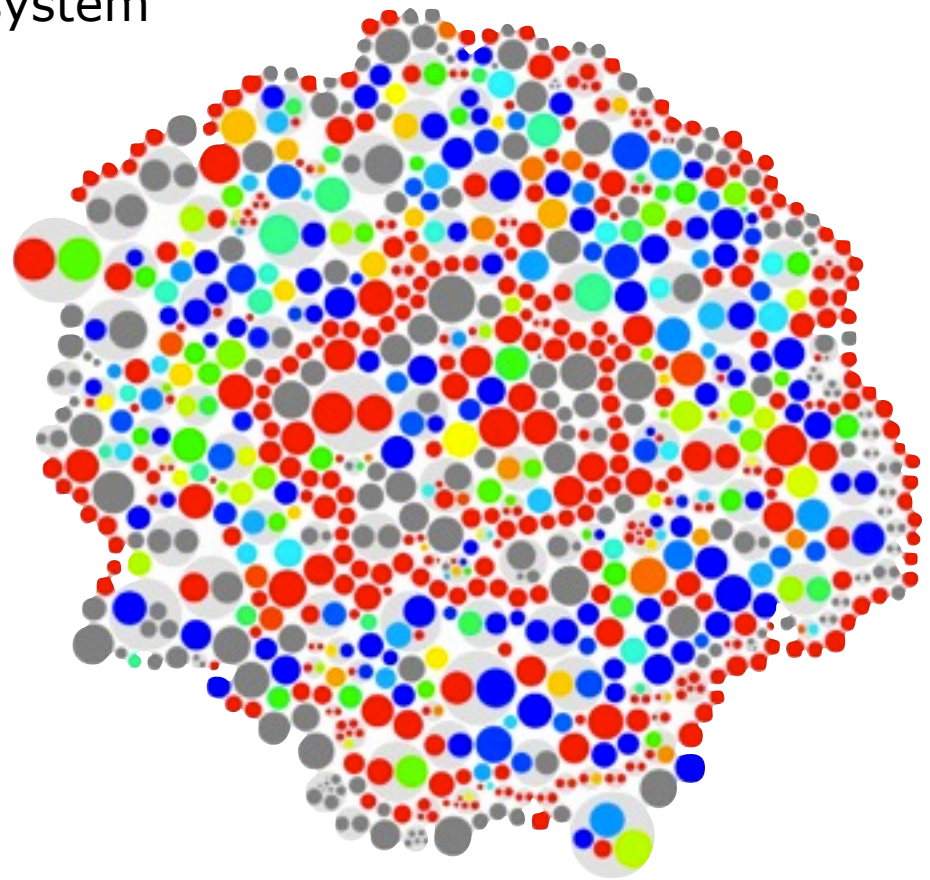
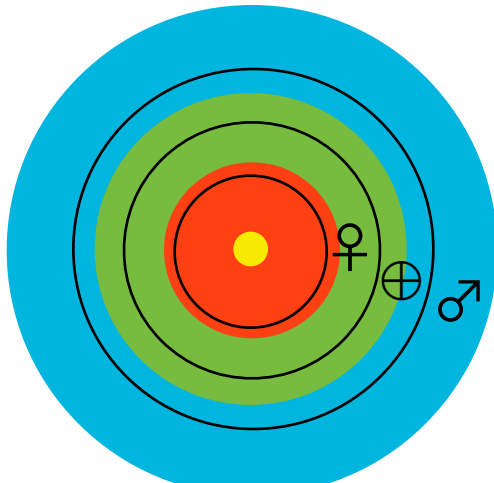
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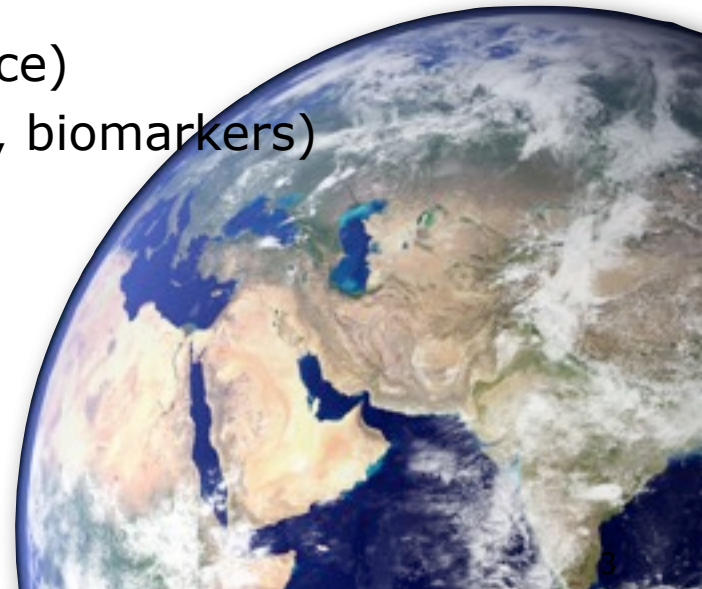
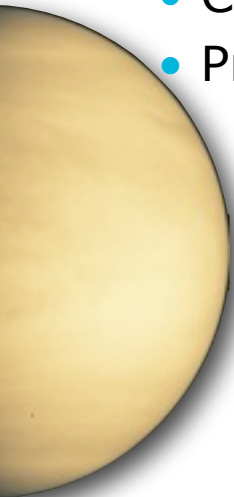
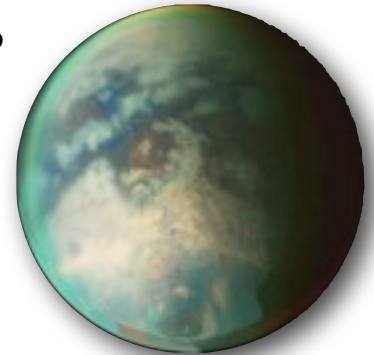


Plot from the Open Exoplanet Catalogue

Characterizing terrestrial exoplanets

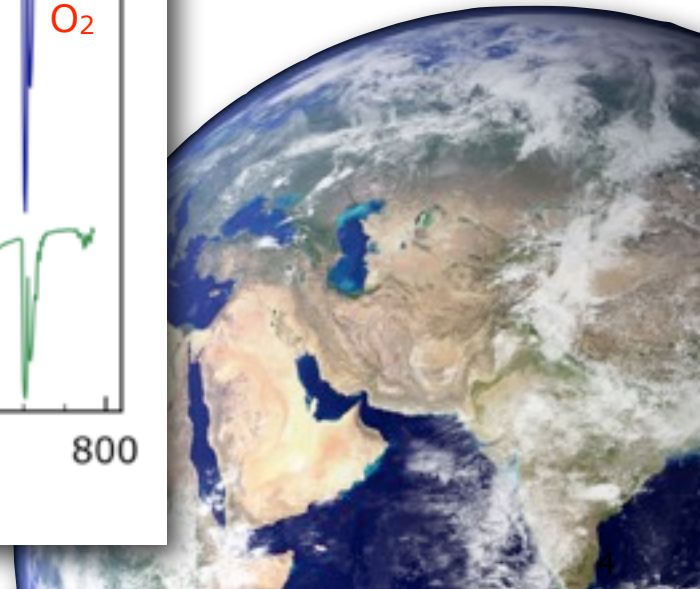
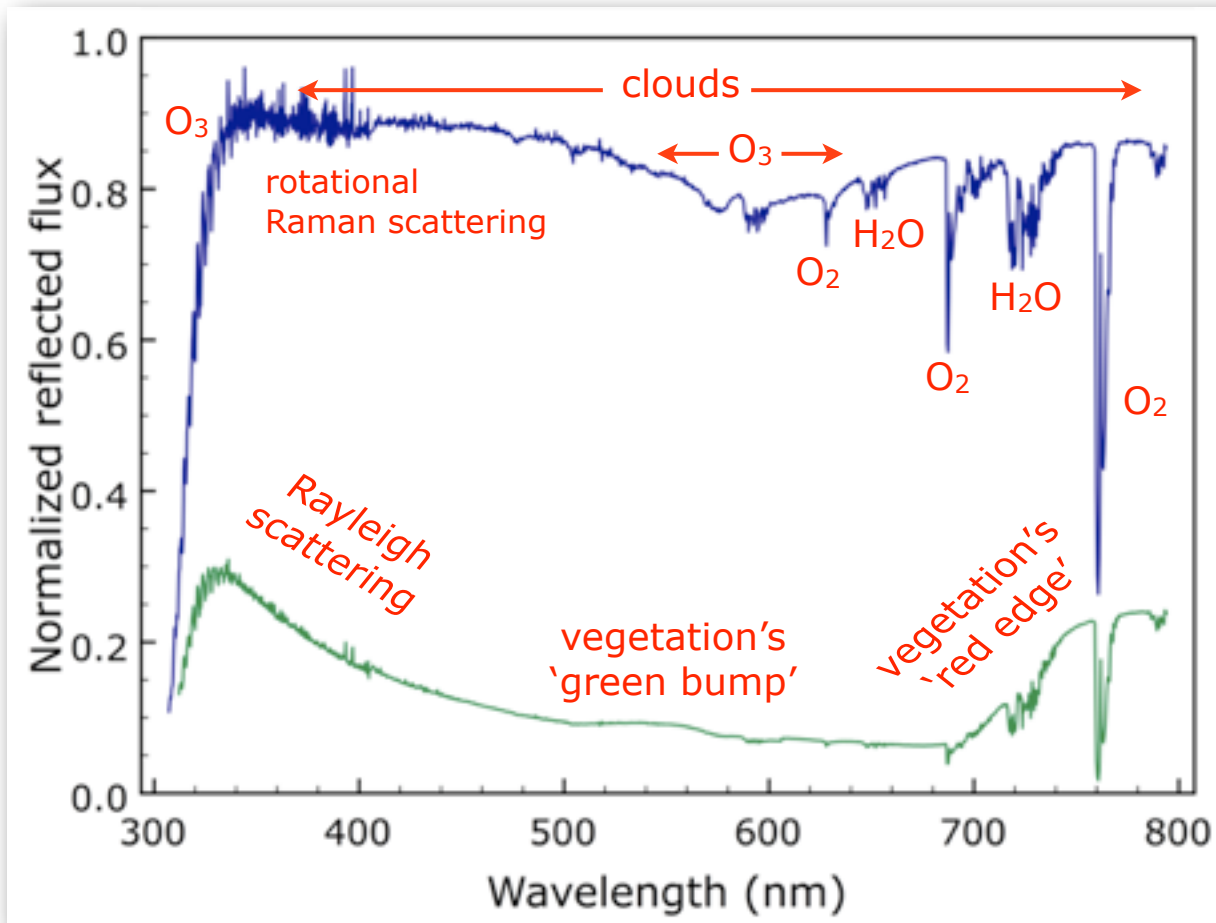
What would we like to know about small, rocky planets?

- Size (composition, plate tectonics)
- Rotation period
- Obliquity angle (seasons)
- Thickness atmosphere (surface pressure)
- Composition atmosphere (CO₂, N₂, O₂, trace gases ...)
- Composition and distribution of clouds (altitude, coverage)
- Surface coverage (continents, oceans)
- Composition of the surface (sand, water, ice)
- Presence of life as we know it (vegetation, biomarkers)



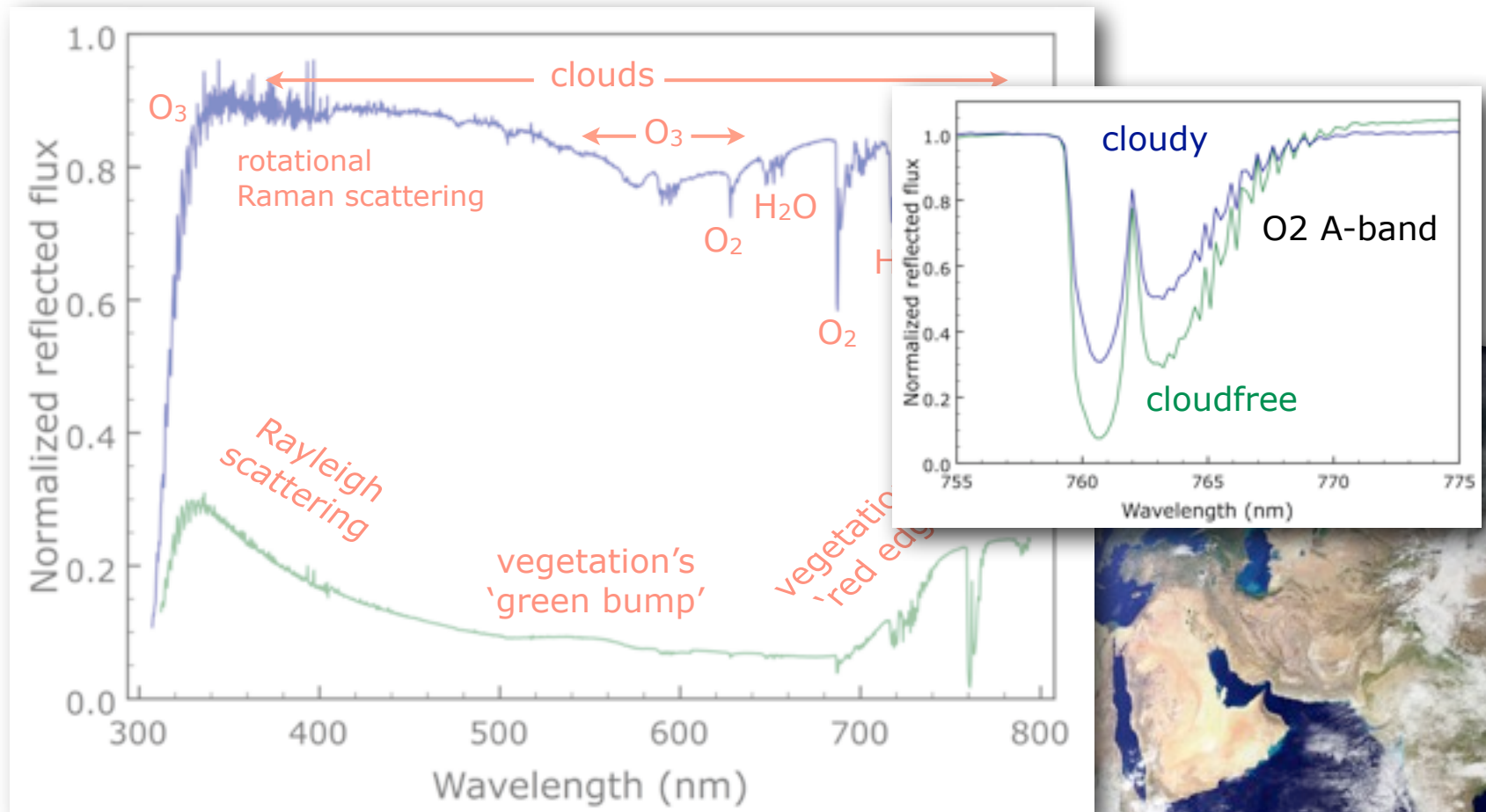
Starlight reflected by an Earth-like planet

The solar flux reflected by a cloudfree and a cloudy region on Earth measured by GOME (nadir viewing, 34° solar zenith angle):



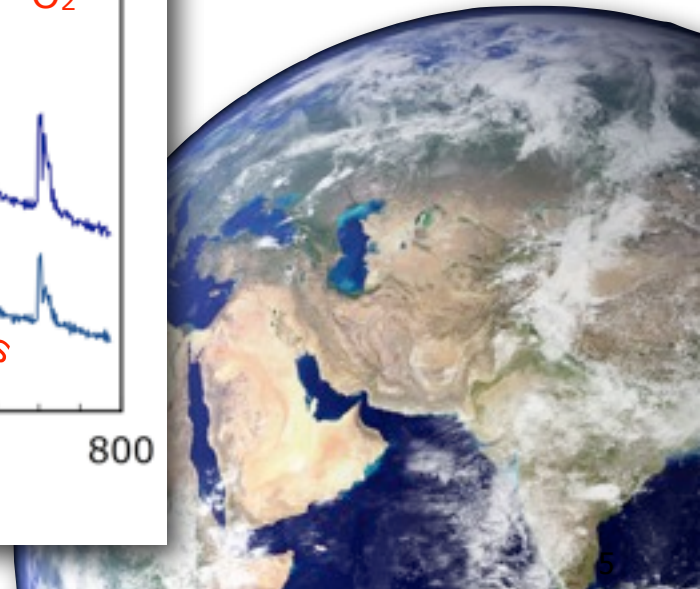
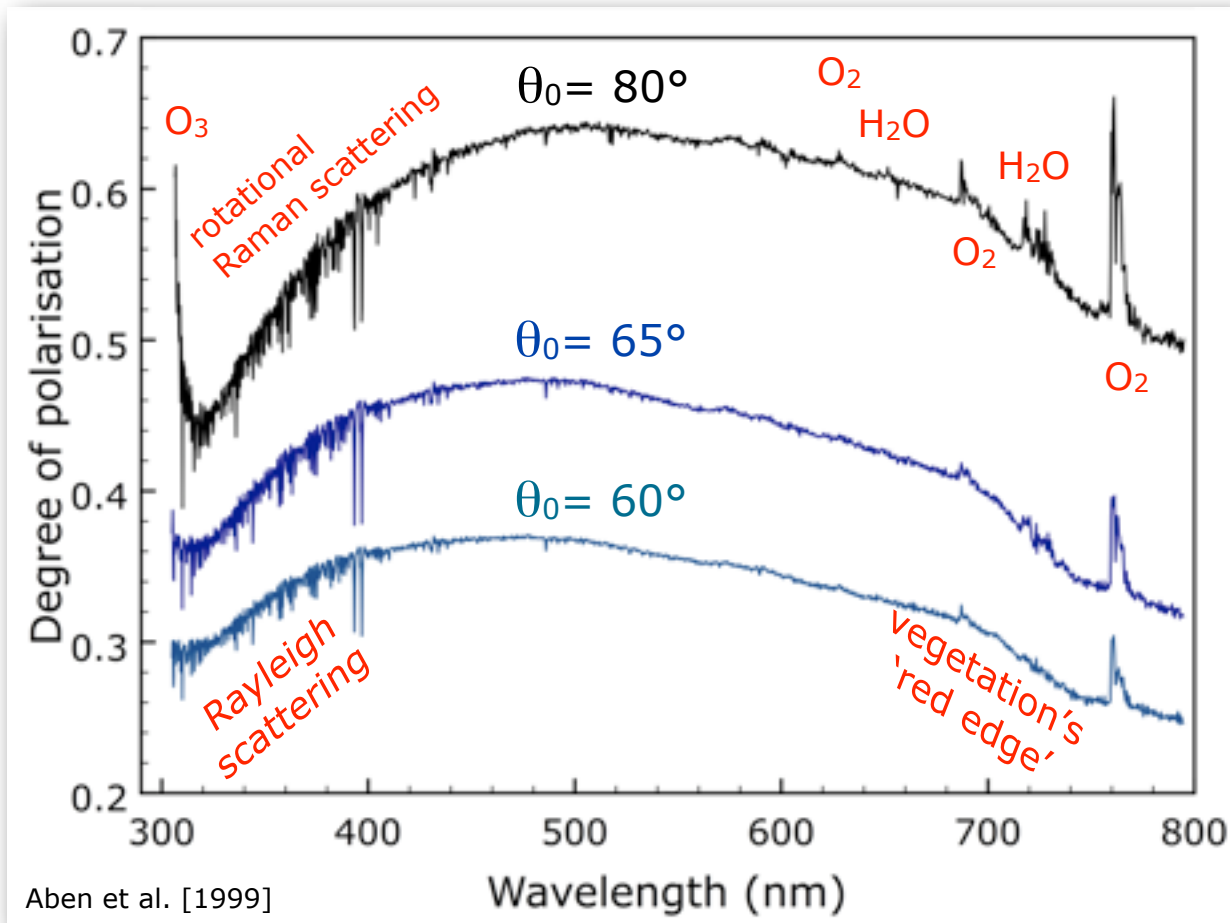
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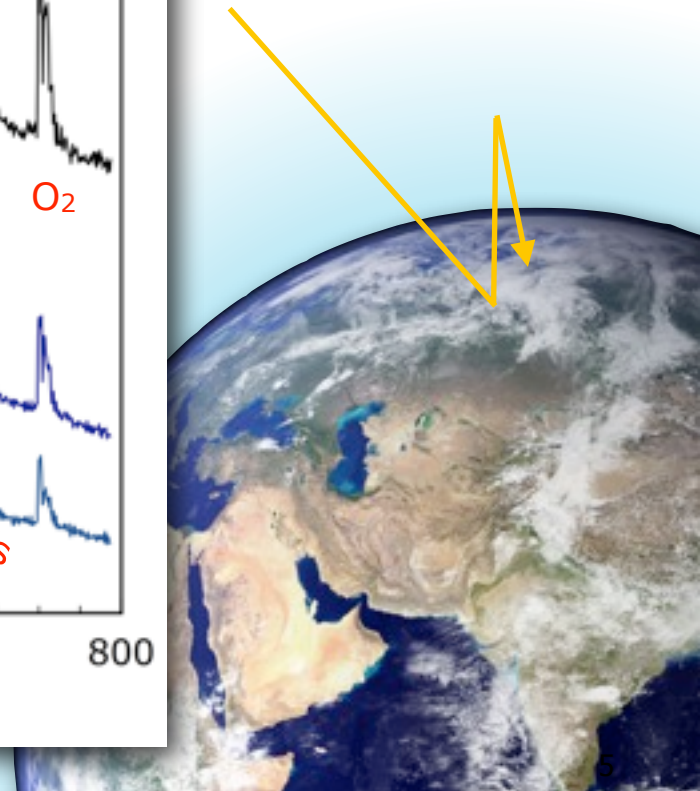
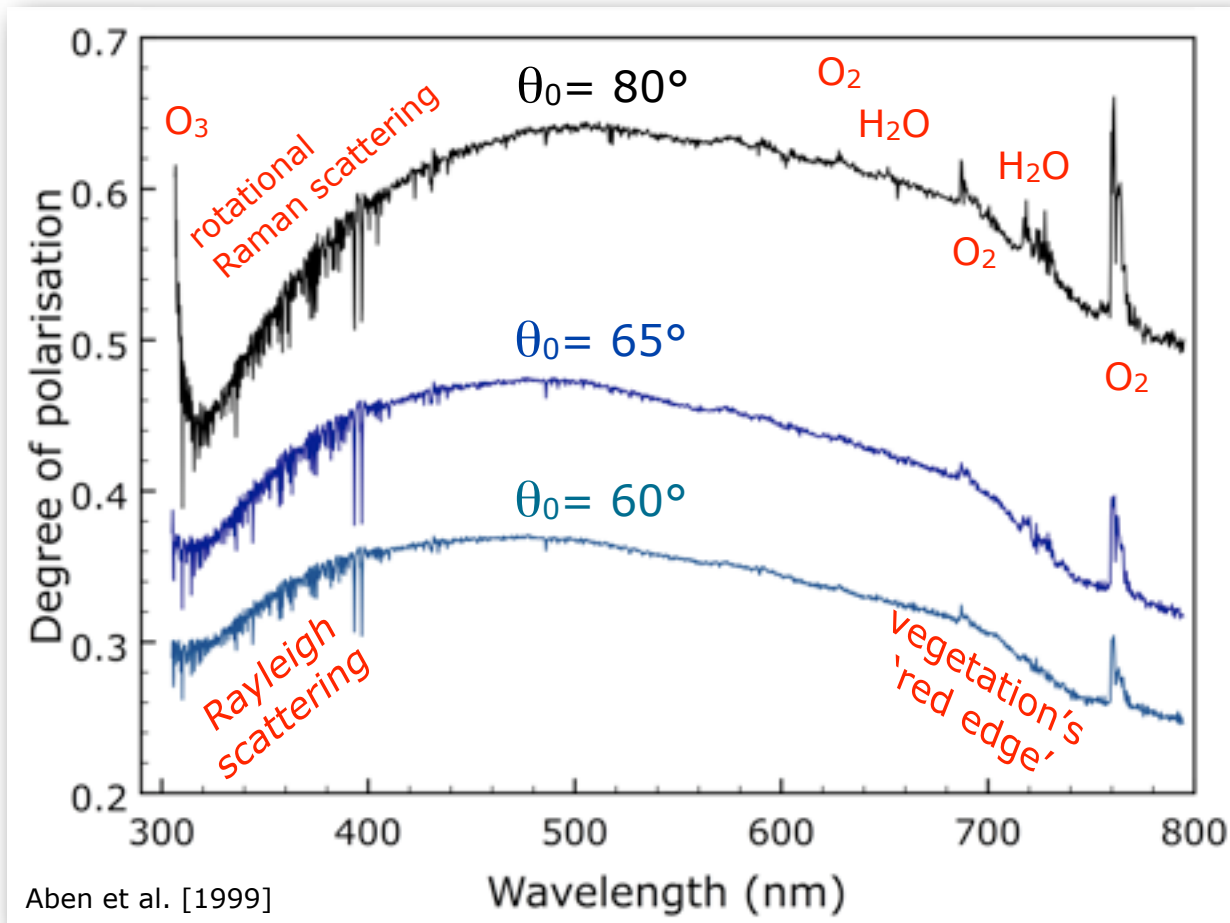
Spectropolarimetry of the Earth

The degree of linear polarization of a cloud-free zenith sky measured using GOME's breadboard-model outfitted with polarizers:



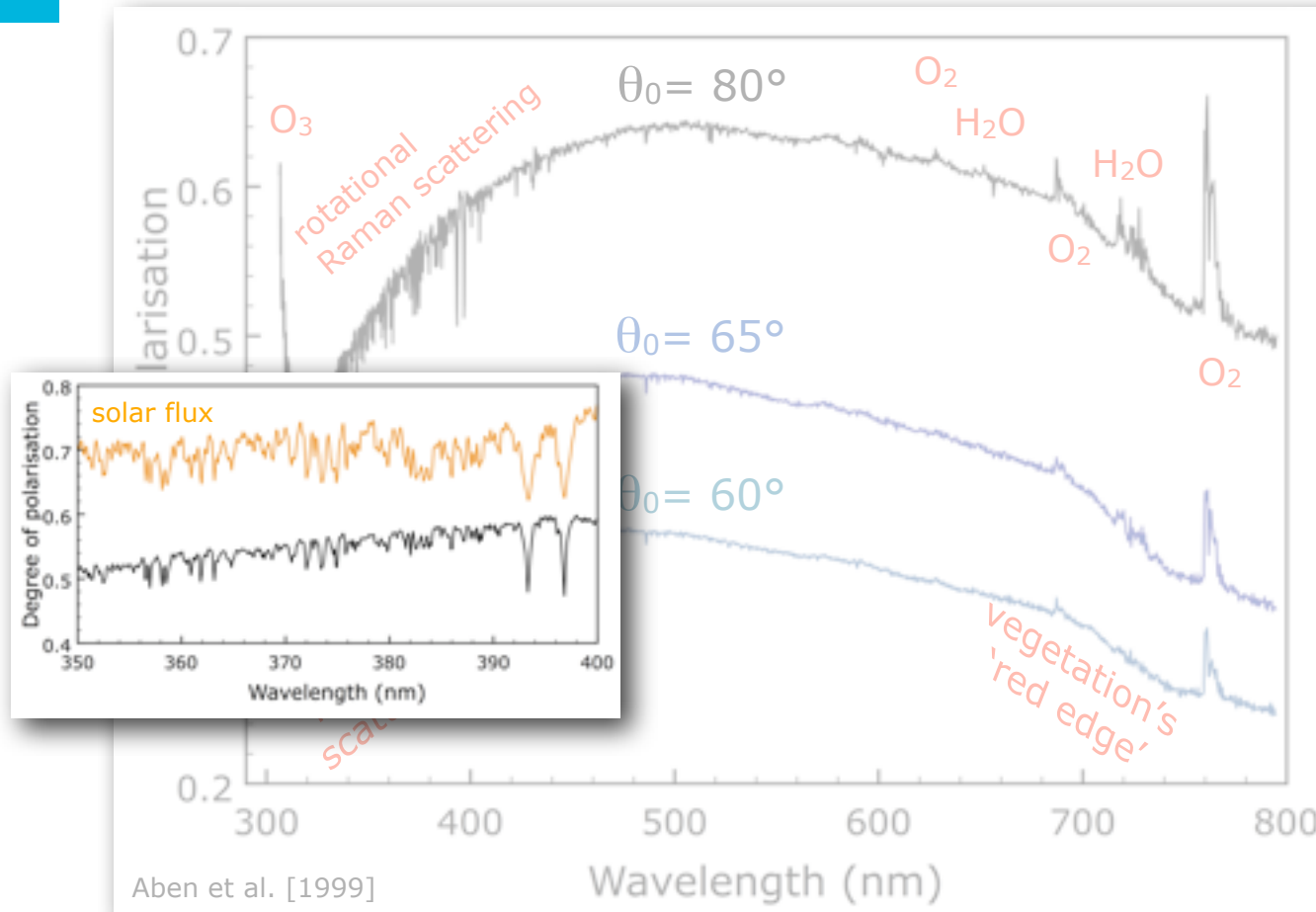
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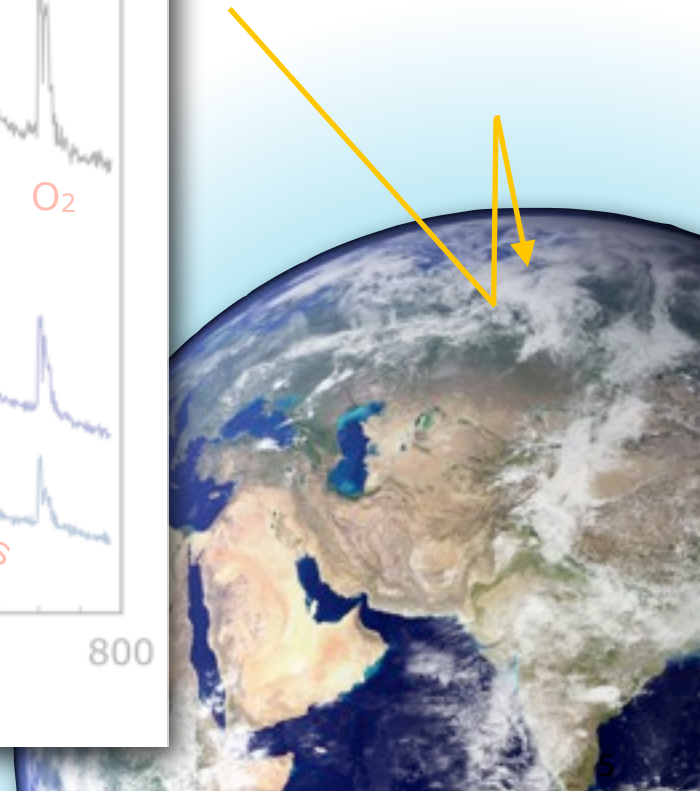


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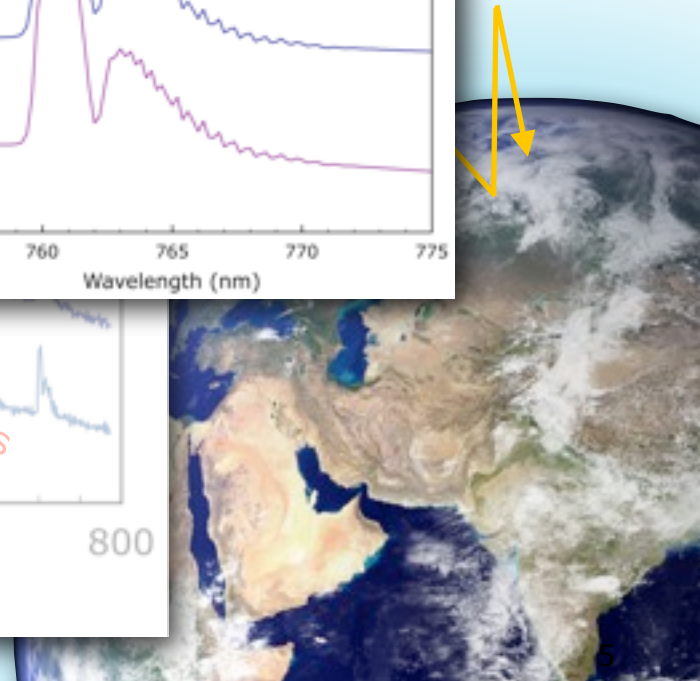
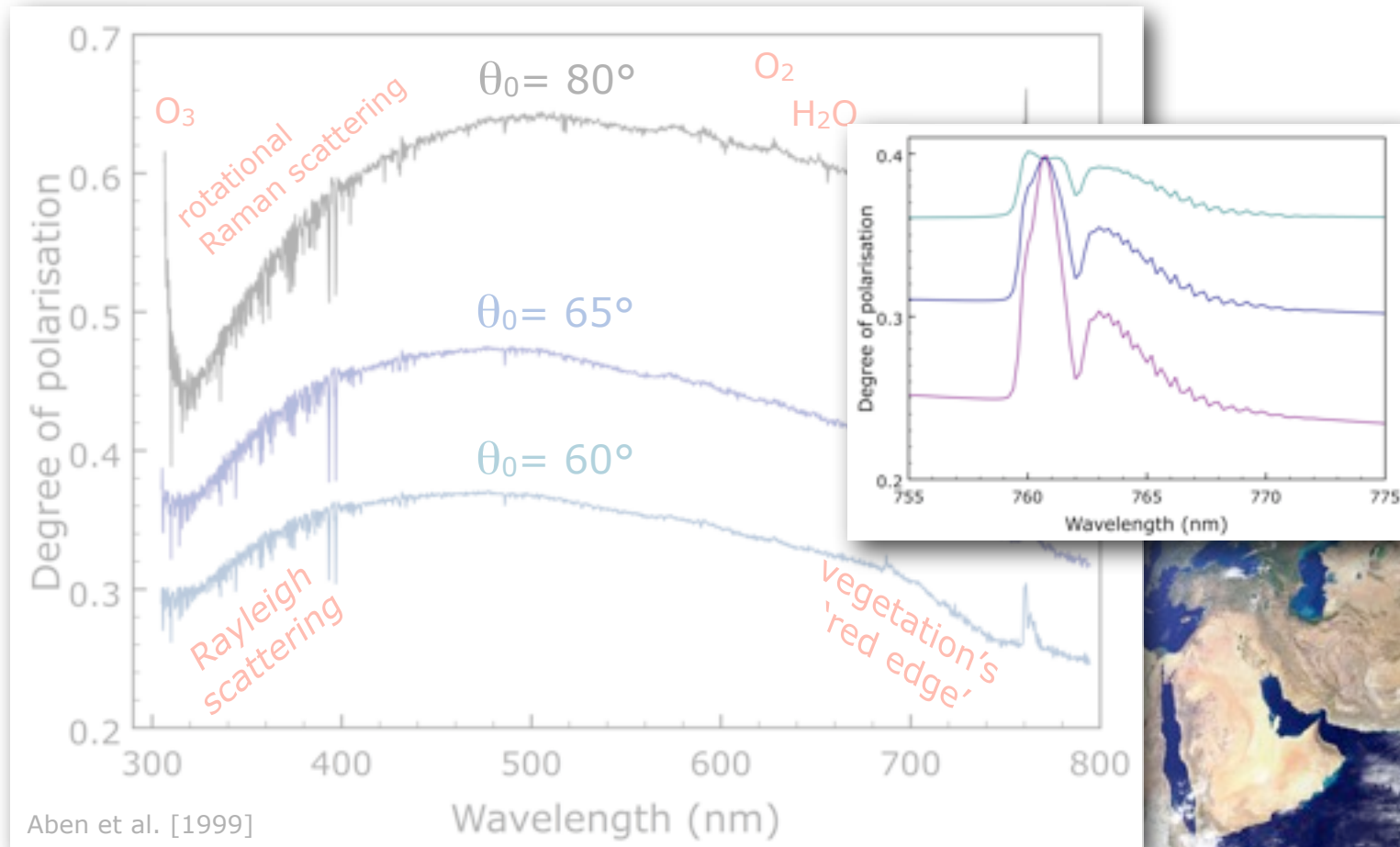


Aben et al. [1999]



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Spectropolarimetry in absorption lines

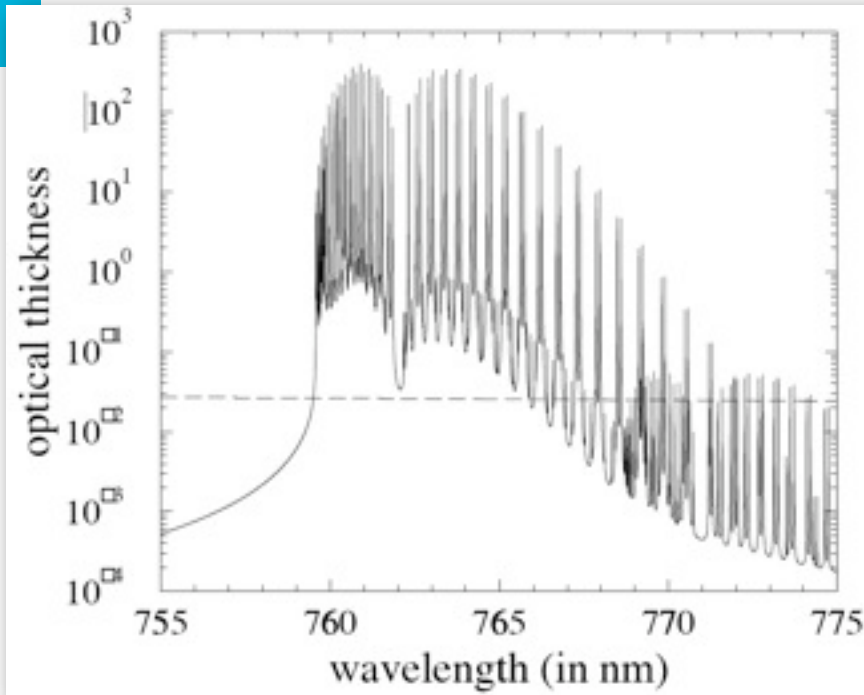
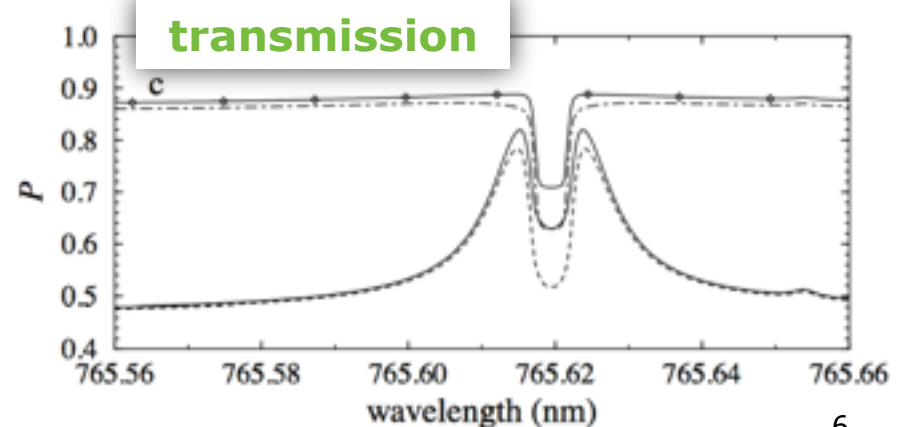
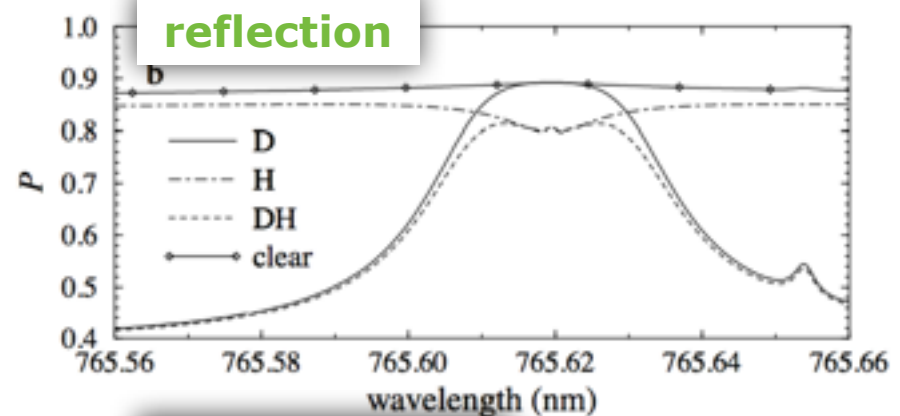
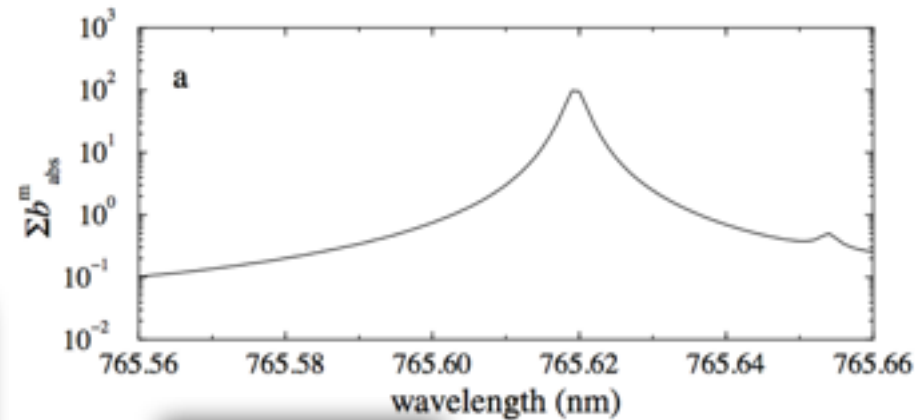


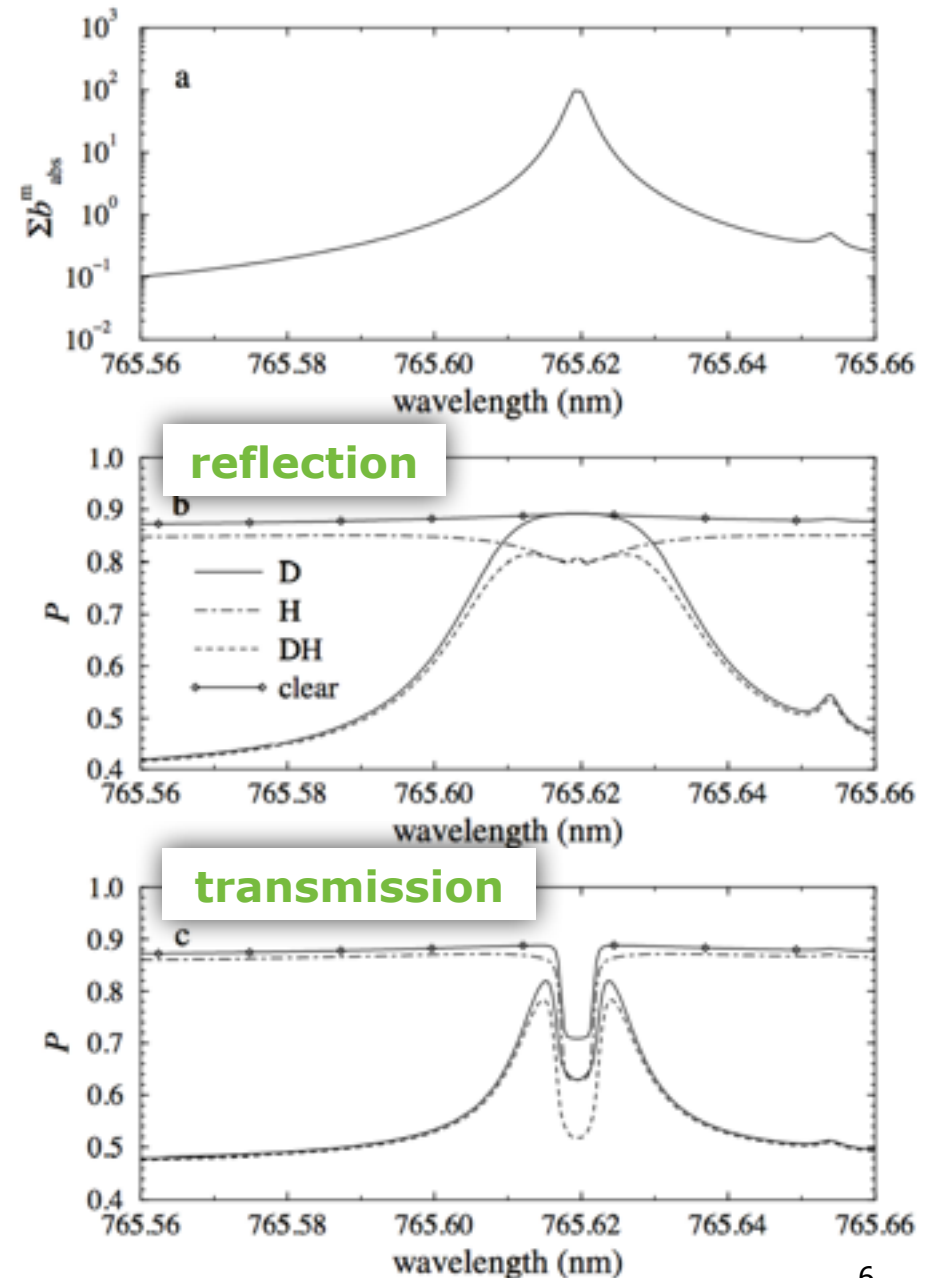
Figure 2.13: The wavelength dependence of the molecular absorption optical thickness Σb_{abs}^m and of the degree of linear polarization P of light emerging from the D-atmosphere (solid line), the H-atmosphere (dot-dashed line), the DH-atmosphere (dashed line), and the clear atmosphere (solid line with diamonds). The surface albedo $A_s = 0.0$ and the solar zenith angle $\theta_0 = 60^\circ$. (a) Σb_{abs}^m . (b) P of reflected light, with $\theta = 140^\circ$ and $\phi - \phi_0 = 0^\circ$. (c) P of diffusely transmitted light, with $\theta = 40^\circ$ and $\phi - \phi_0 = 180^\circ$.



Spectropolarimetry in absorption lines

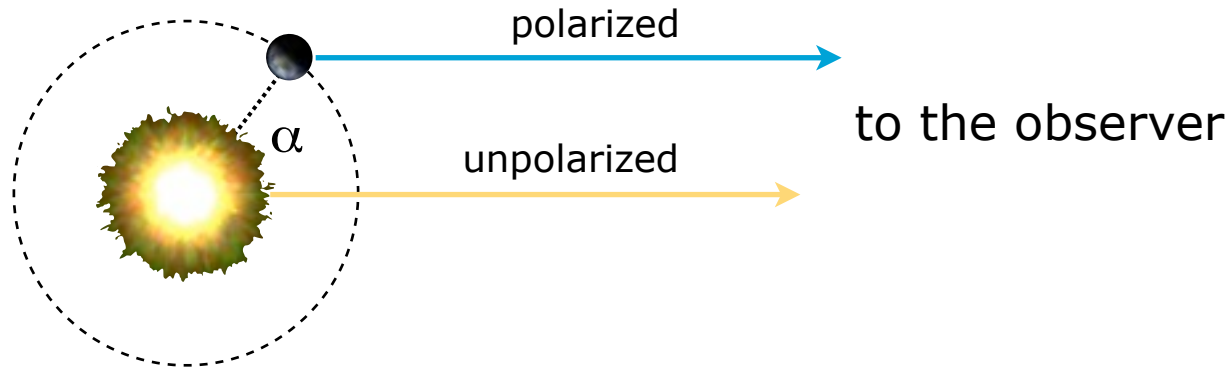
The degree of linear polarization of light emerging from the cloudless atmosphere in the O₂ A band -
Stam, de Haan, Hovenier, Stammes, JGR 104, 1999

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Polarimetry for exoplanet research

Polarimetry appears to be a strong tool for exoplanet research

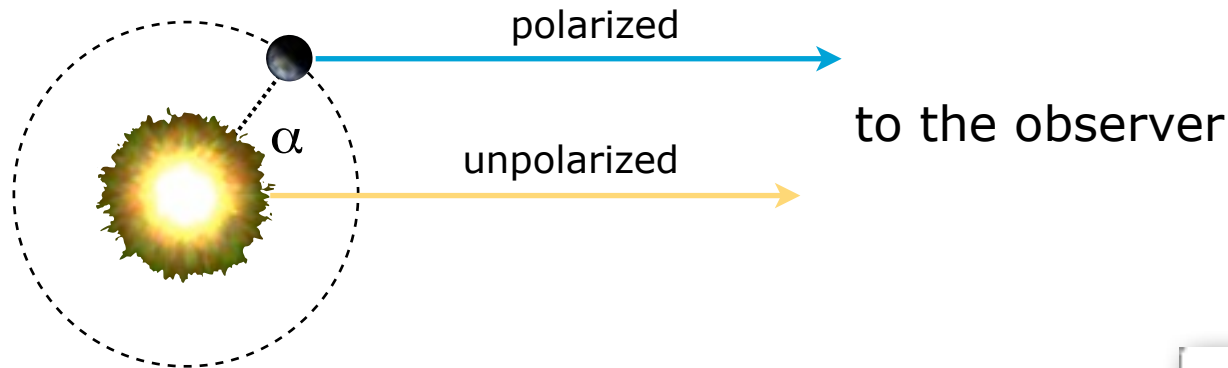


Advantages of polarimetry:

- It enhances the planet/star contrast
- It directly confirms the nature of the object
- It can be used to characterize a planet
- It is independent of sizes & distances

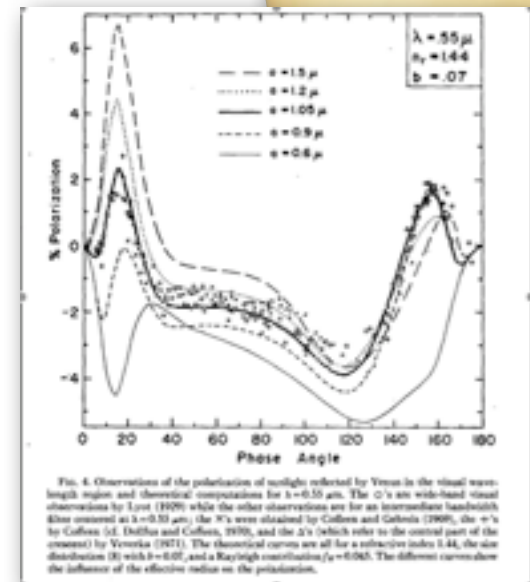
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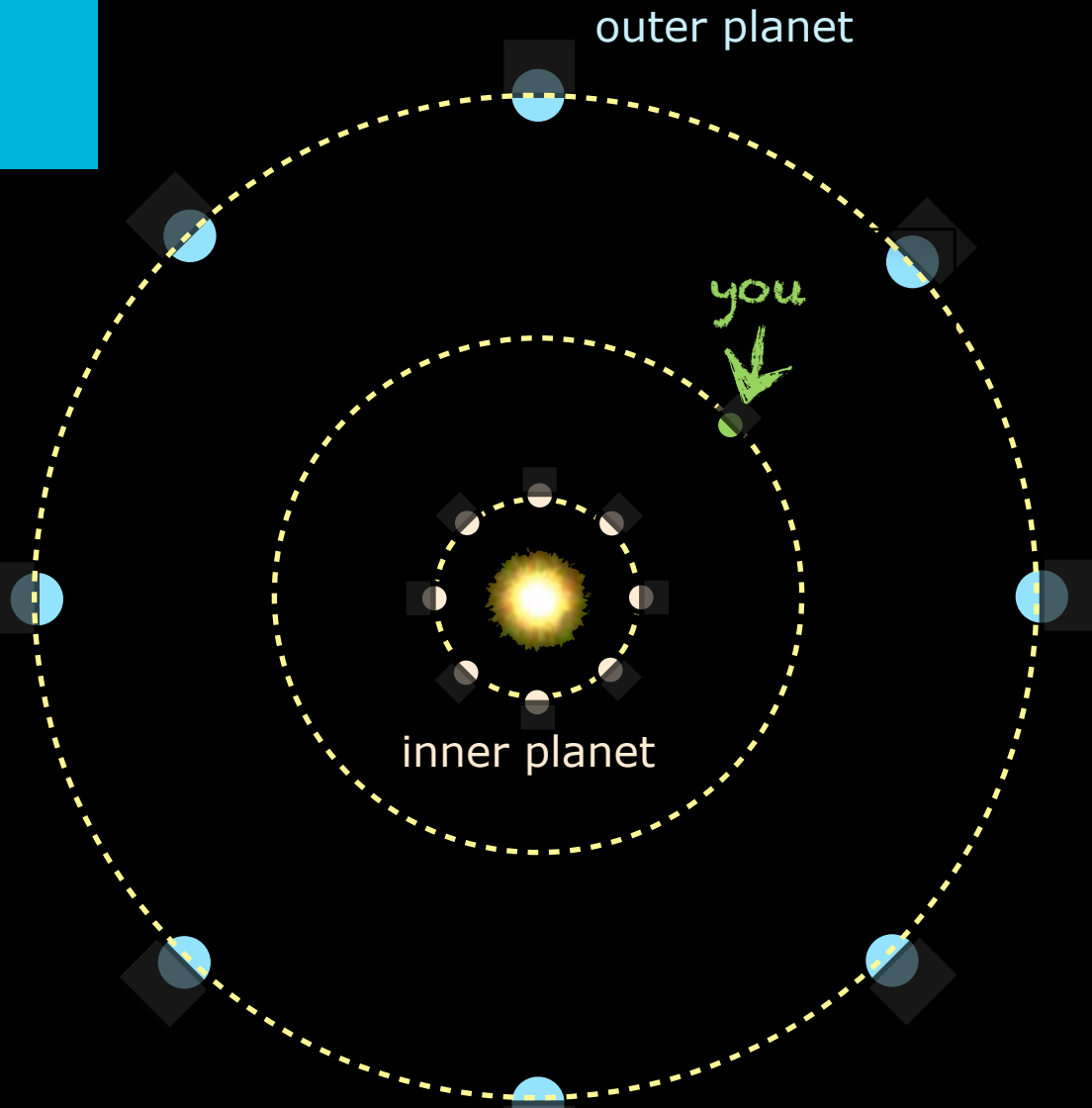
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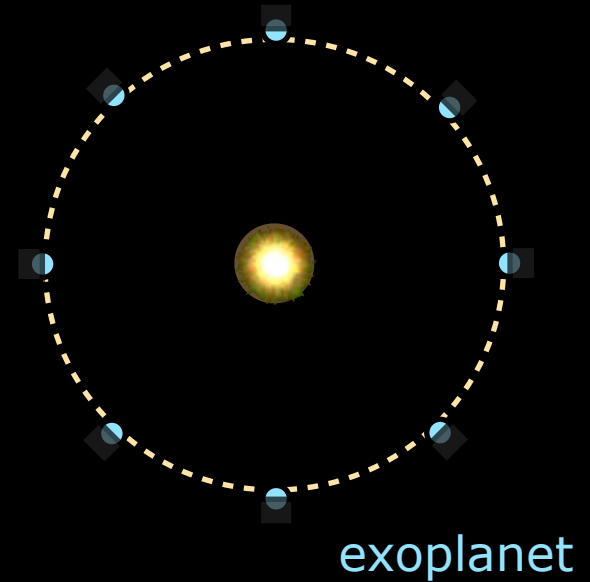
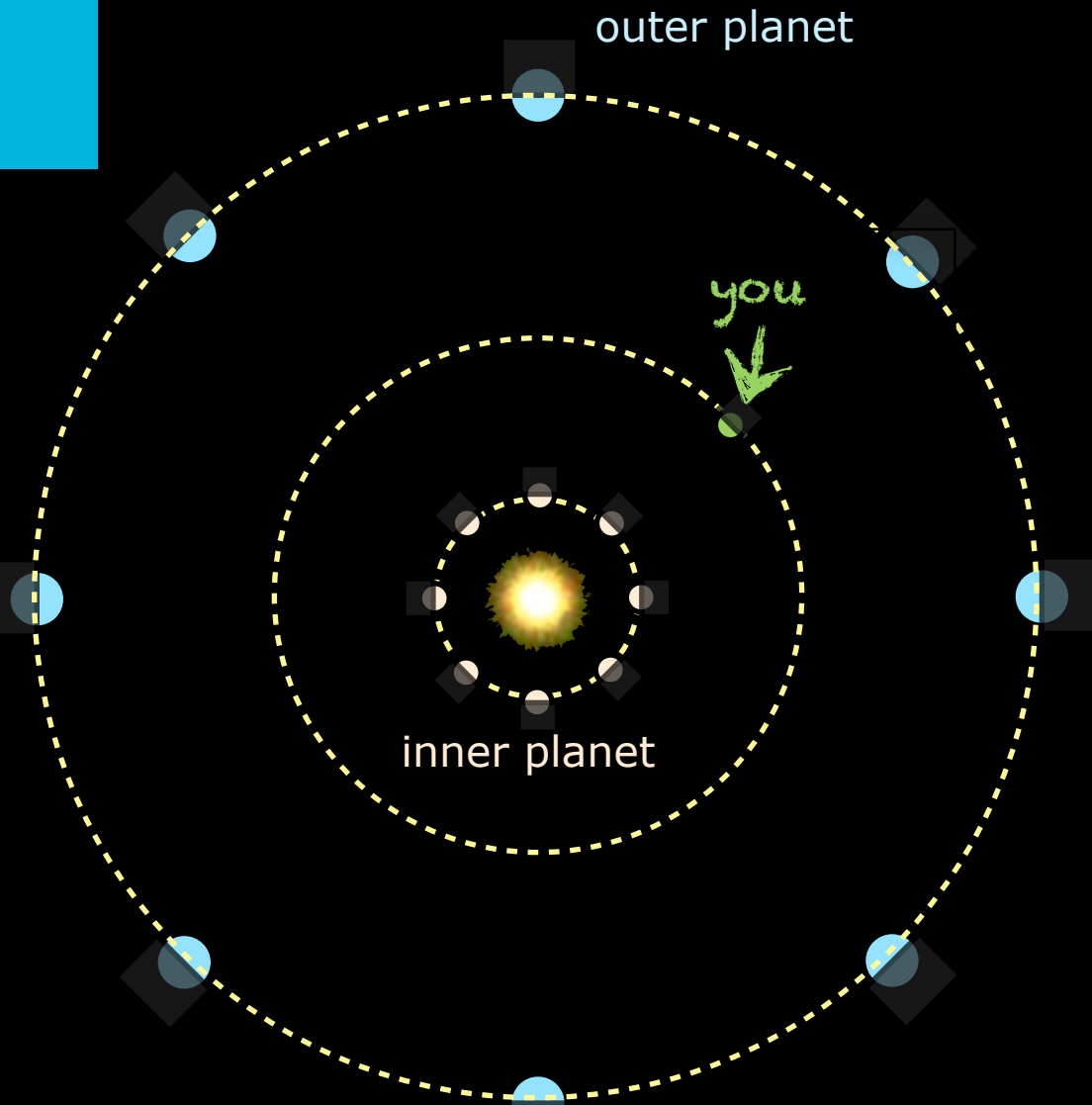


Hansen & Hovenier (1974)

Phase angle ranges



Phase angle ranges



The phase angle range at which an exoplanet can be observed depends on the inclination angle i of its orbit:

$$90^\circ - i \leq \alpha \leq 90^\circ + i$$

$i=0^\circ$ for a face-on orbit
 $i=90^\circ$ for an edge-on orbit

Numerical simulations

We calculate polarized reflected sun/starlight as follows:

Planet models:

- locally plane-parallel atmosphere
- vertically inhomogeneous (layers)
- horizontally homogeneous (fast) or inhomogeneous (slower)
- gases, aerosol, cloud particles (also non-spherical)
- surface (can be polarizing)

Radiative transfer code:

- adding-doubling algorithm
- fluxes, linear & circular polarization
- single & multiple scattering
- line-by-line or e.g. ck-distribution
- efficient disk-integration algorithm

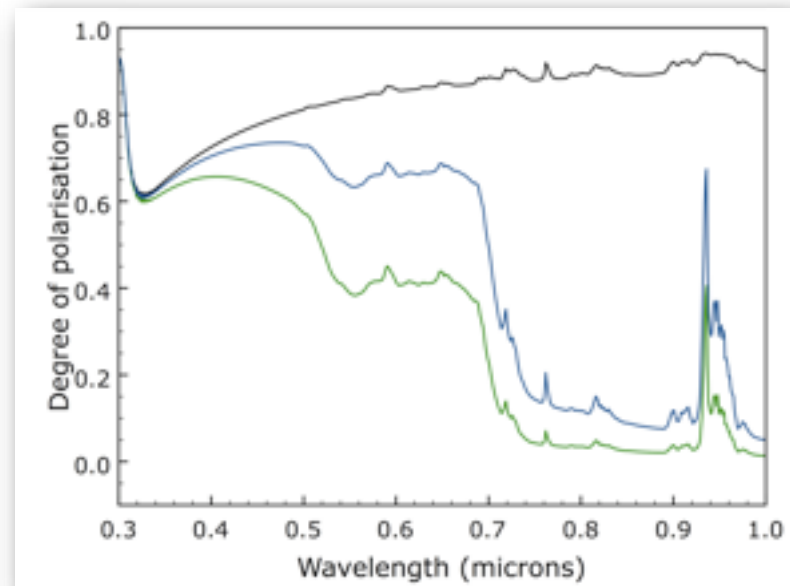
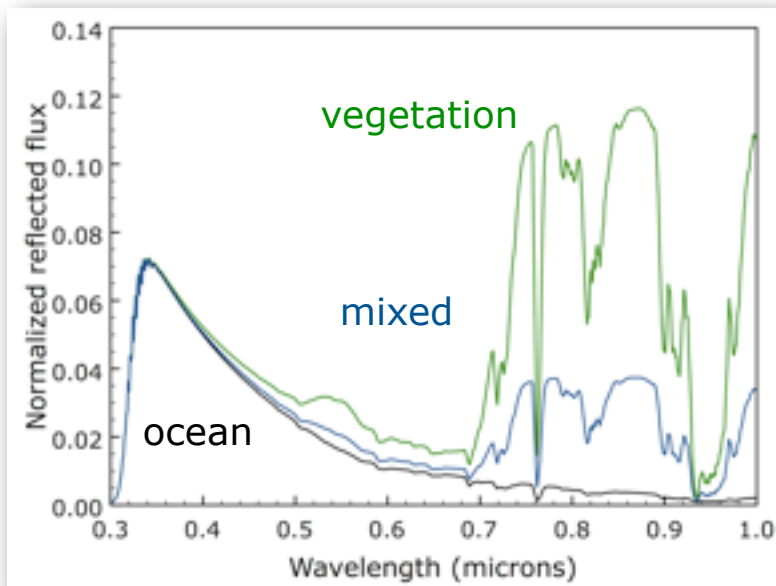


Disk-integrated polarimetry I

Calculated disk-integrated fluxes & linear polarization of homogeneous Earth-like planets at $\alpha=90^\circ$ (Stam 2008)

Total flux F

Degree of polarization P



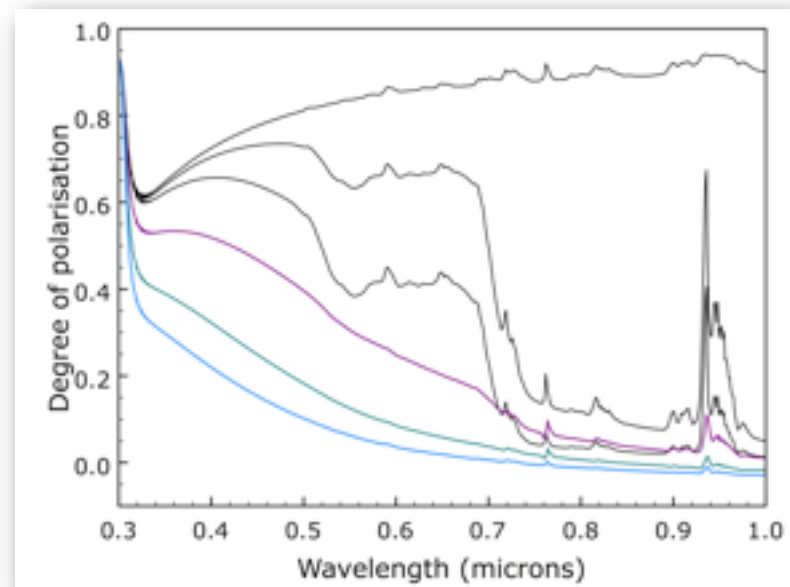
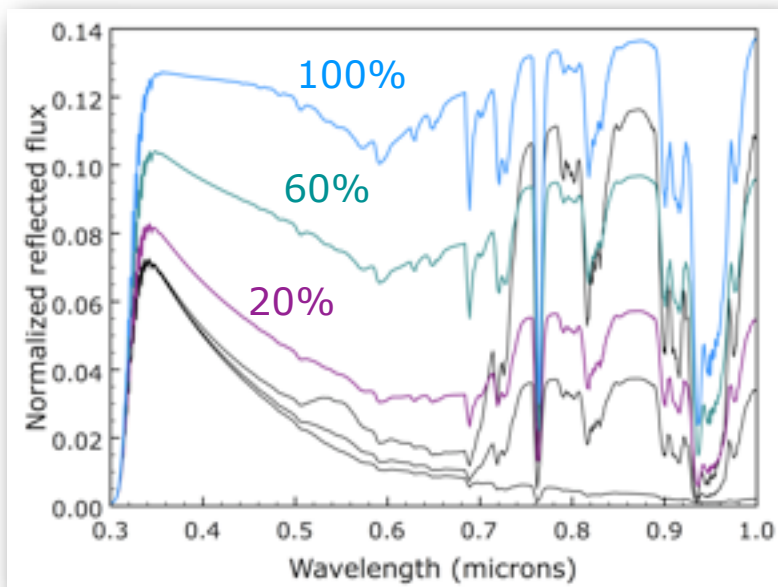
Cloud-free planets with surfaces covered by:
100% vegetation, 100% flat ocean, and 30% vegetation + 70% flat ocean.

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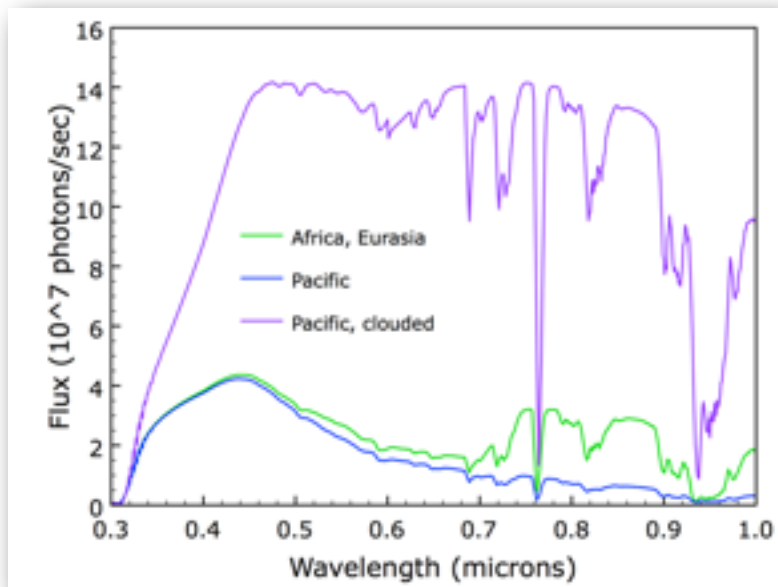


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The mixed planet with cloud coverages of 20%, 60%, and 100%.

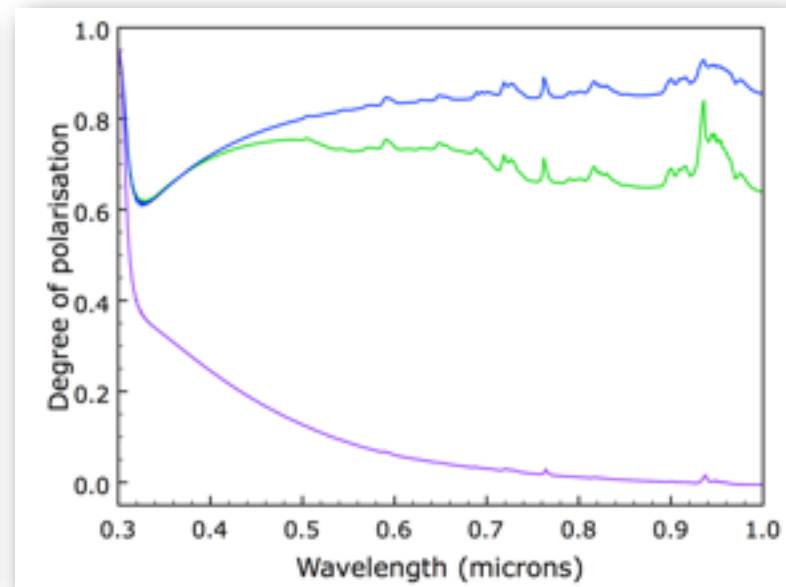
Disk-integrated polarimetry II

Calculated disk-integrated fluxes & linear polarization of inhomogeneous Earth-like planets at $\alpha=90^\circ$ (Karalidi et al., 2012)

Total flux F



Degree of polarization P

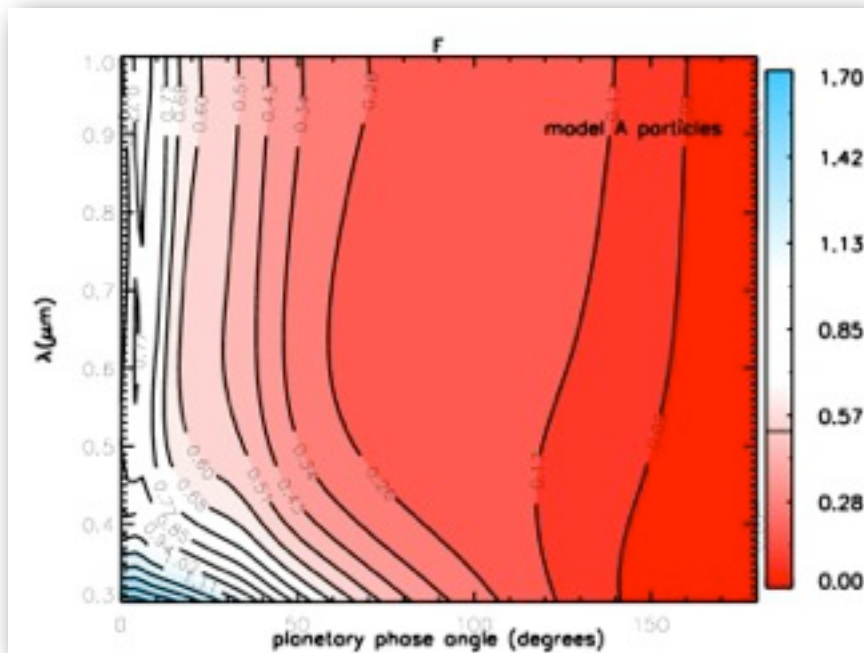


The reflected fluxes are folded with the solar flux.
The Saharan sand is polarizing (Amsterdam-Granada database).

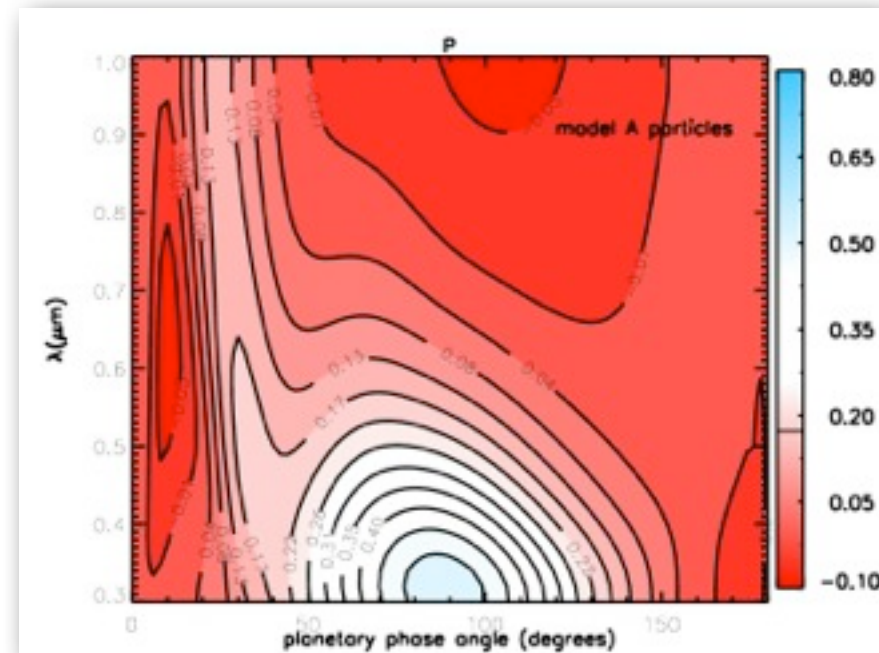
Disk-integrated phase angle dependence

Flux and polarization as functions of the planet's phase angle and the wavelength for a completely cloudy planet ($b=10$ @ 550 nm).

Total flux F



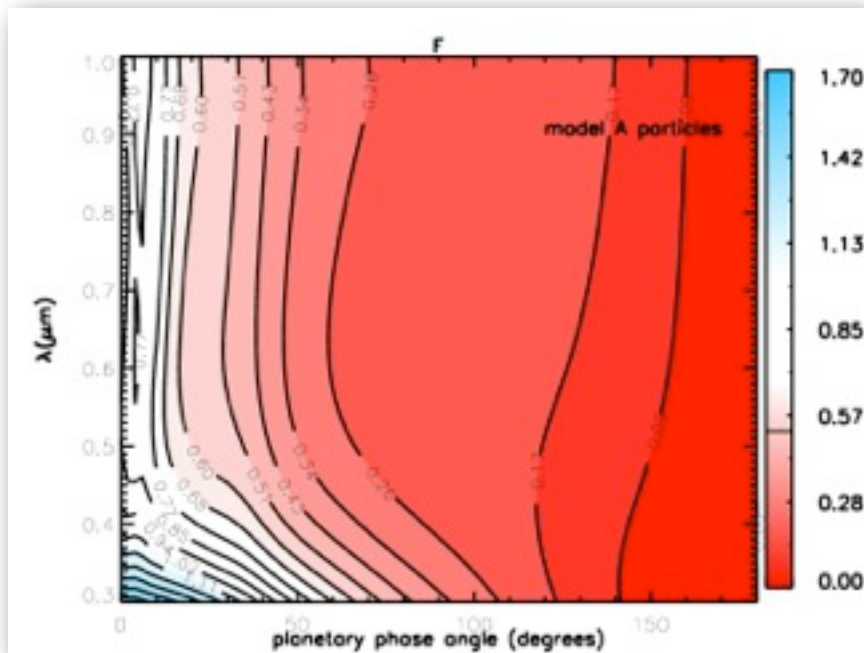
Degree of polarization P



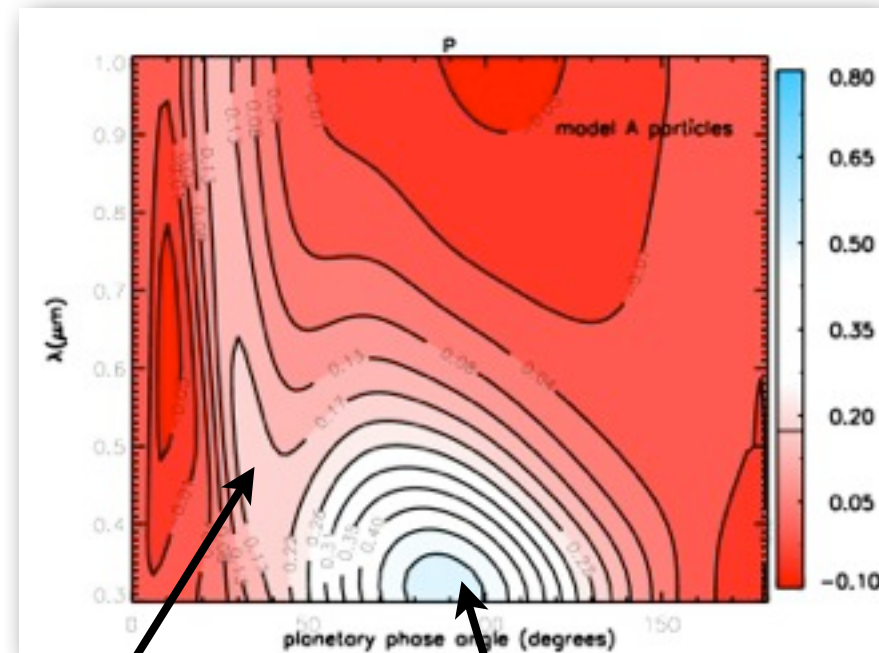
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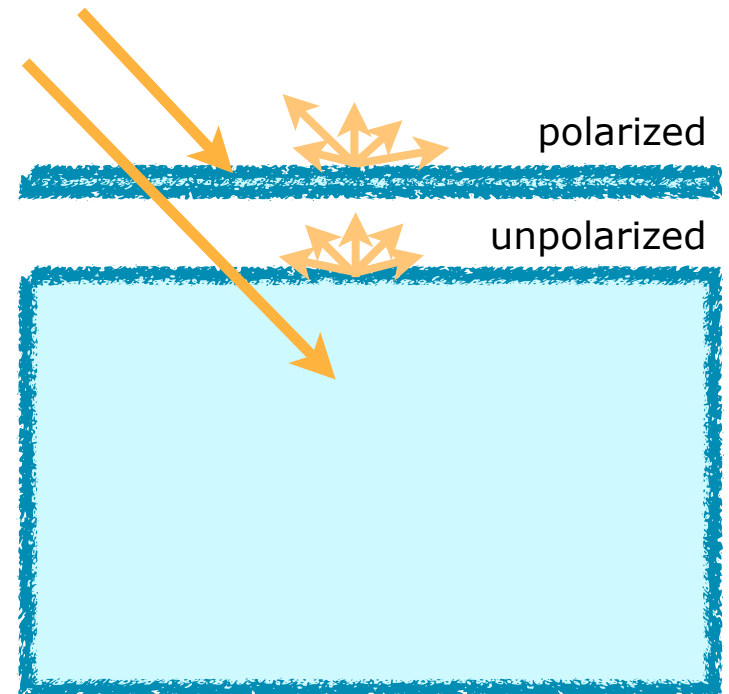


primary rainbow

Rayleigh scattering

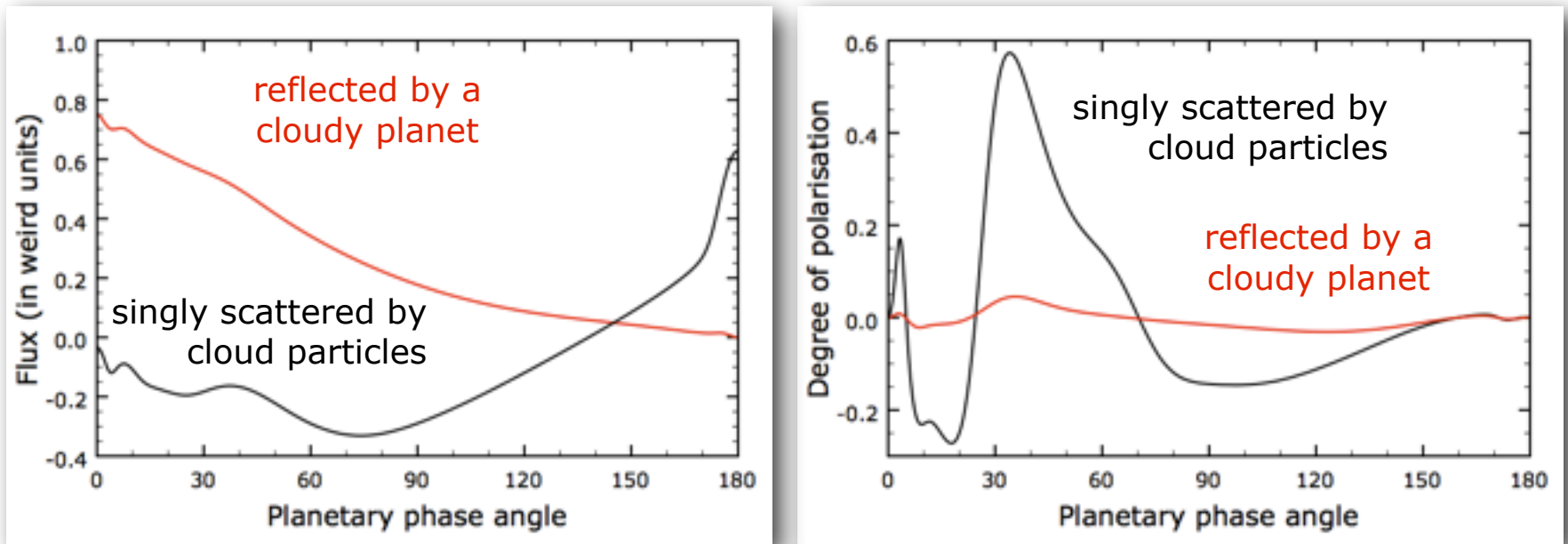
Information content of polarimetry

Single scattering angular features of the single scattering polarization phase function are preserved upon multiple scattering:



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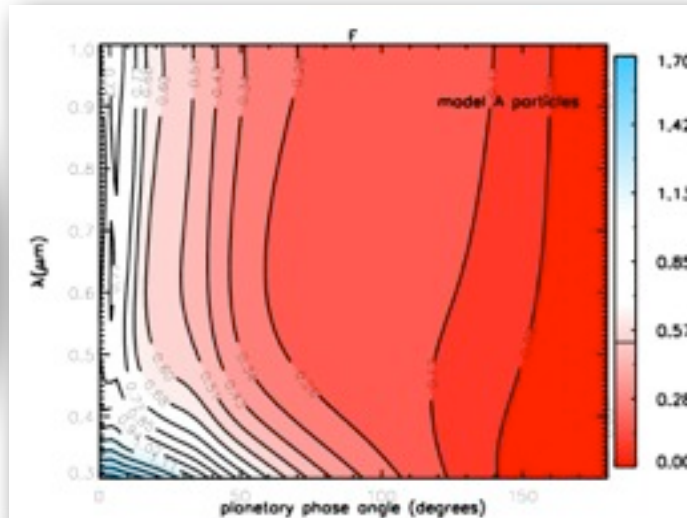


Comparison: light singly scattered by liquid water cloud droplets and light reflected by a fully cloudy planet with a cloud optical thickness of 100. Spherical liquid water cloud droplets, with $r_{\text{eff}}=2.0 \mu\text{m}$, $n_r=1.3$ and $n_i=0.00001$.

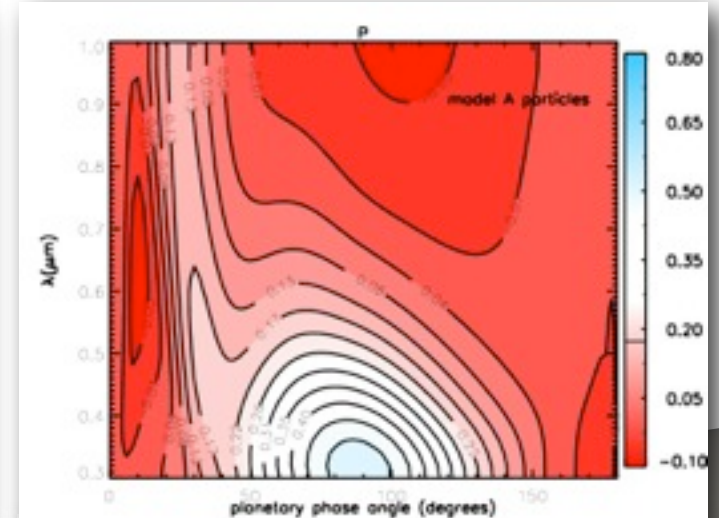
Dependence on particle composition

water

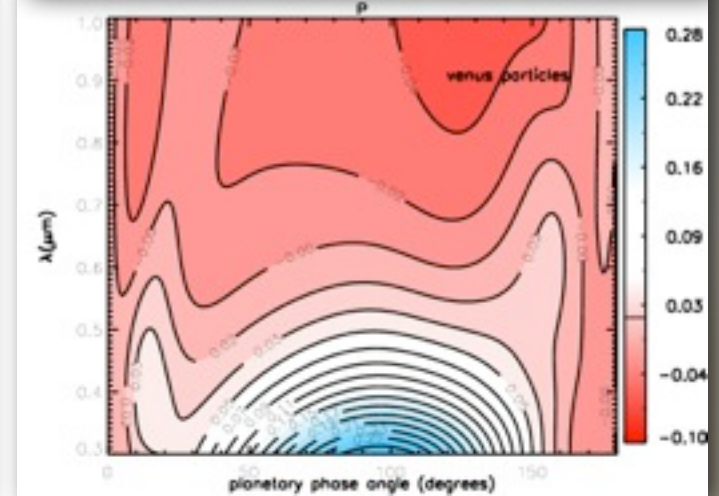
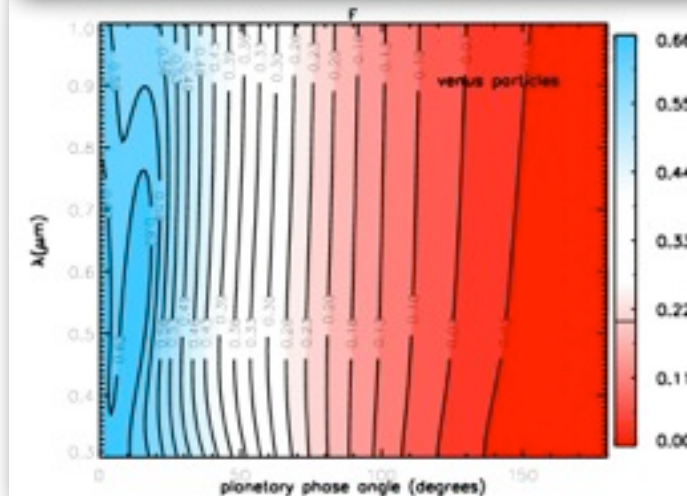
Total flux F



Degree of polarization P



75%
sulfuric
acid



A realistic, partly cloudy planet

Using Earth remote-sensing data, a model planet with observed cloud parameters was made (Karalidi, Stam & Hovenier, 2012):



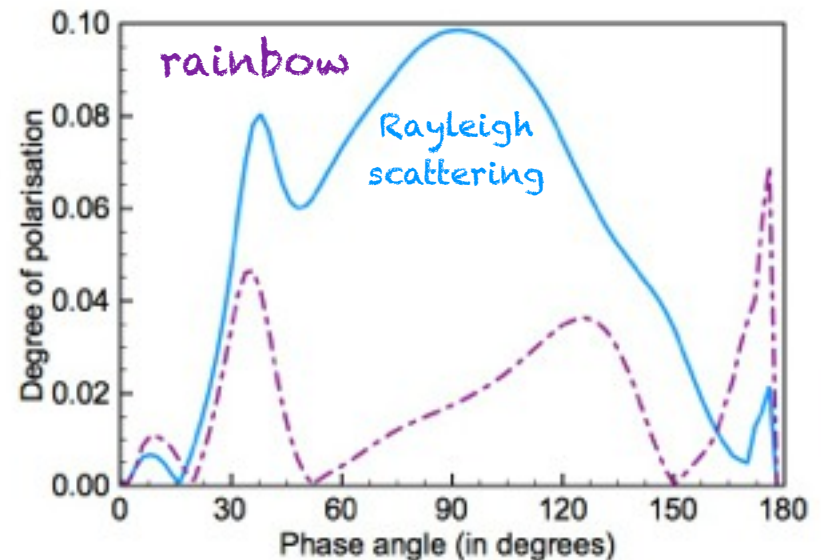
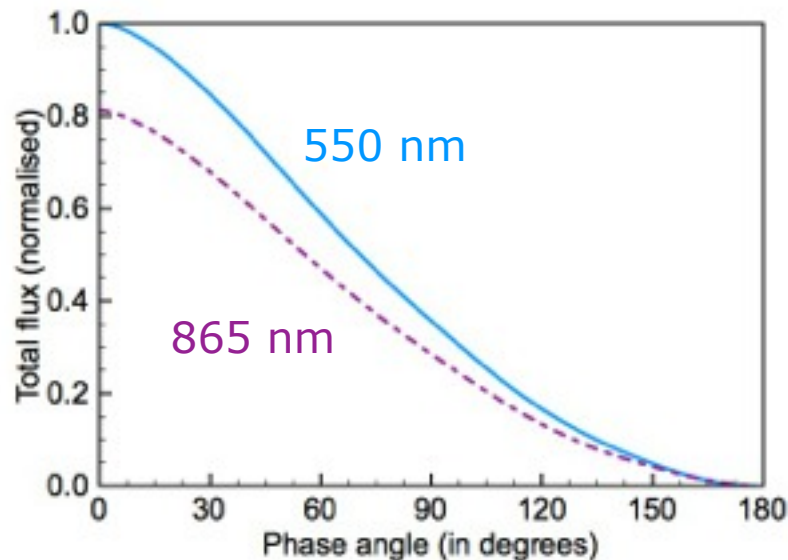
Earth's clouds on 25 April 2011 from MODIS data (NASA). The planet is covered by ~63% liquid water clouds (grey), and ~36% ice clouds (white). About 28% of the planet is covered by 2 cloud layers.

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Future instruments/telescopes

- LOUPE on the moon
- EPICS on the E-ELT
- A next L-class mission of ESA (L2 or L3)?

Theme: 'Exploring Habitable Worlds beyond our Solar System'



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Taking into account polarimetry on instruments/telescopes for exoplanet characterization is not only important for reaching the goal (characterization) of exoplanets, but also for accurately measuring fluxes!



PhD-position available

Modelling polarization of Earth-like exoplanets, in particular including realistic (polarizing) surface reflection and circular polarization effects (biomarkers).

Comparison with Earthshine observations and preparation for LOUPE, the Lunar Observatory for Unresolved Polarimetry of Earth.

More information: d.m.stam@tudelft.nl