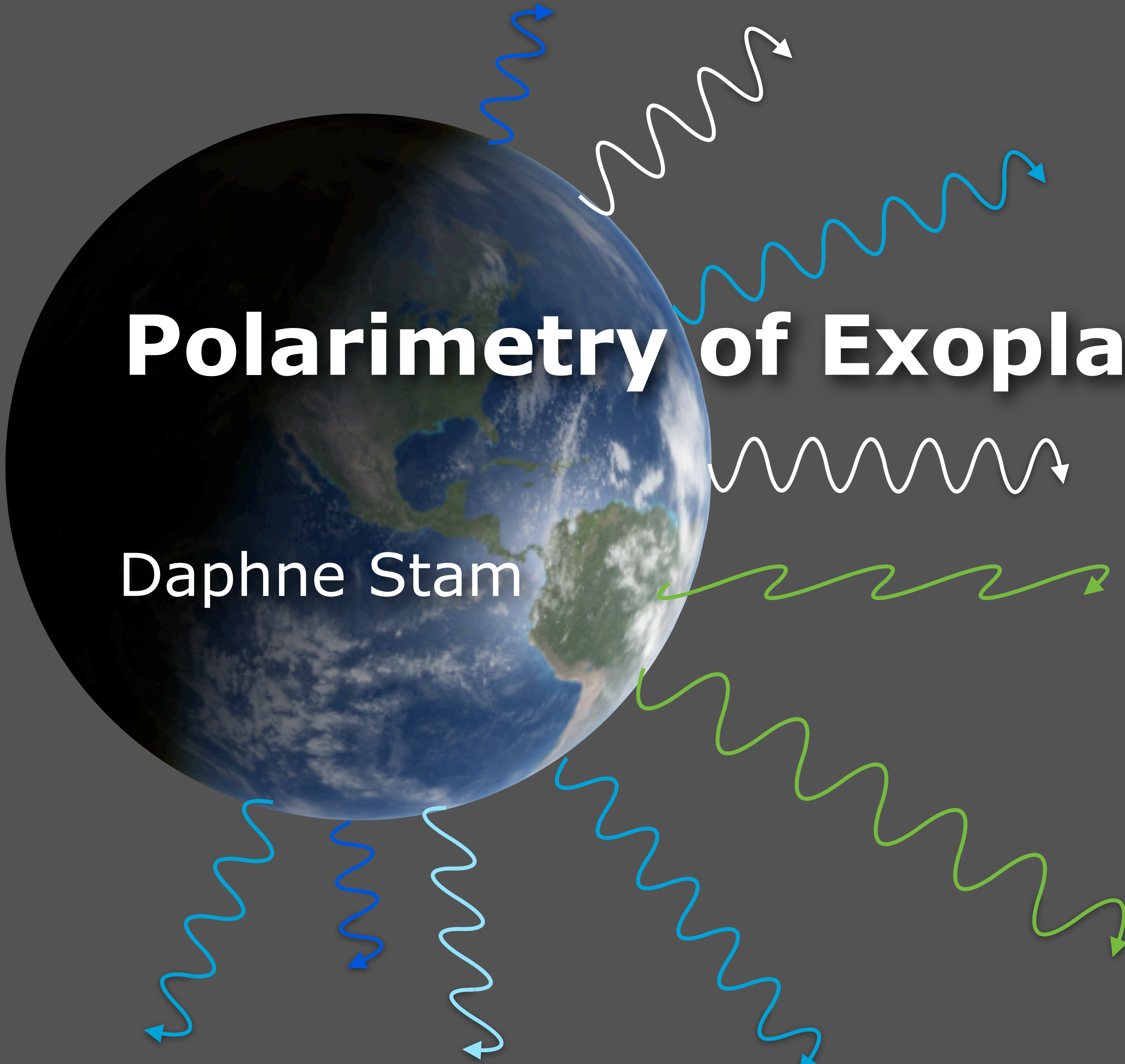
Polarimetry of Exoplanets



Daphne Stam

Theodora Karalidi (SRON, UU)
prof. Joop Hovenier (VU, UvA)
prof. Christoph Keller (UU)
prof. Rens Waters (UvA)

SRON
Netherlands Institute for Space Research

What is polarisation?

Light is fully described by a vector:

$$\mathbf{F}(\lambda)=[F(\lambda), Q(\lambda), U(\lambda), V(\lambda)]$$

unpolarised

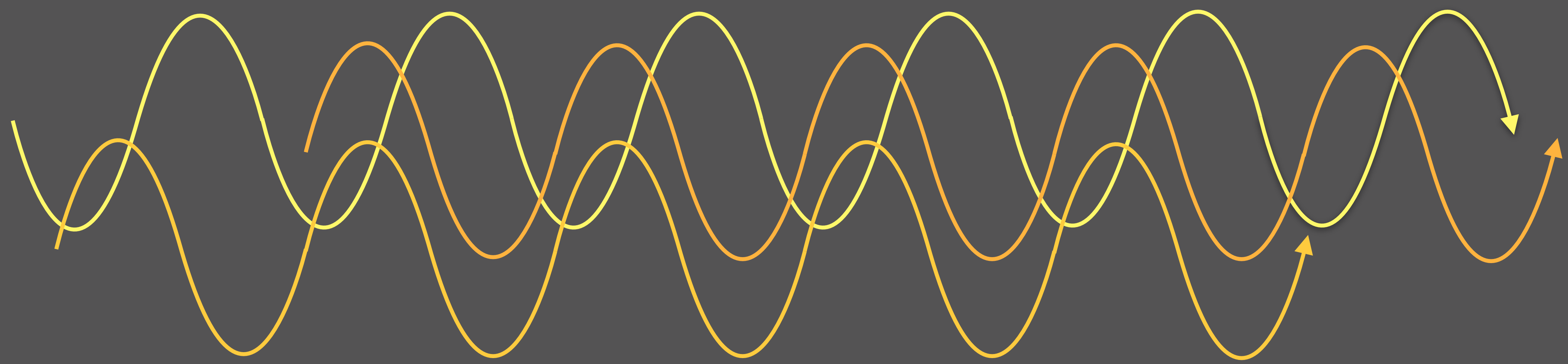
The degree of linear polarisation of the light is:

$$P(\lambda)= \frac{\sqrt{Q^2(\lambda) + U^2(\lambda)}}{F(\lambda)}$$

What is polarisation?

Light is fully described by a vector:

$$\mathbf{F}(\lambda)=[F(\lambda), Q(\lambda), U(\lambda), V(\lambda)]$$



100% polarised

The degree of linear polarisation of the light is:

$$P(\lambda)= \frac{\sqrt{Q^2(\lambda) + U^2(\lambda)}}{F(\lambda)}$$

SRON

What is polarisation?

Light is fully described by a vector:

$$\mathbf{F}(\lambda)=[F(\lambda), Q(\lambda), U(\lambda), V(\lambda)]$$

partially polarised

The degree of linear polarisation of the light is:

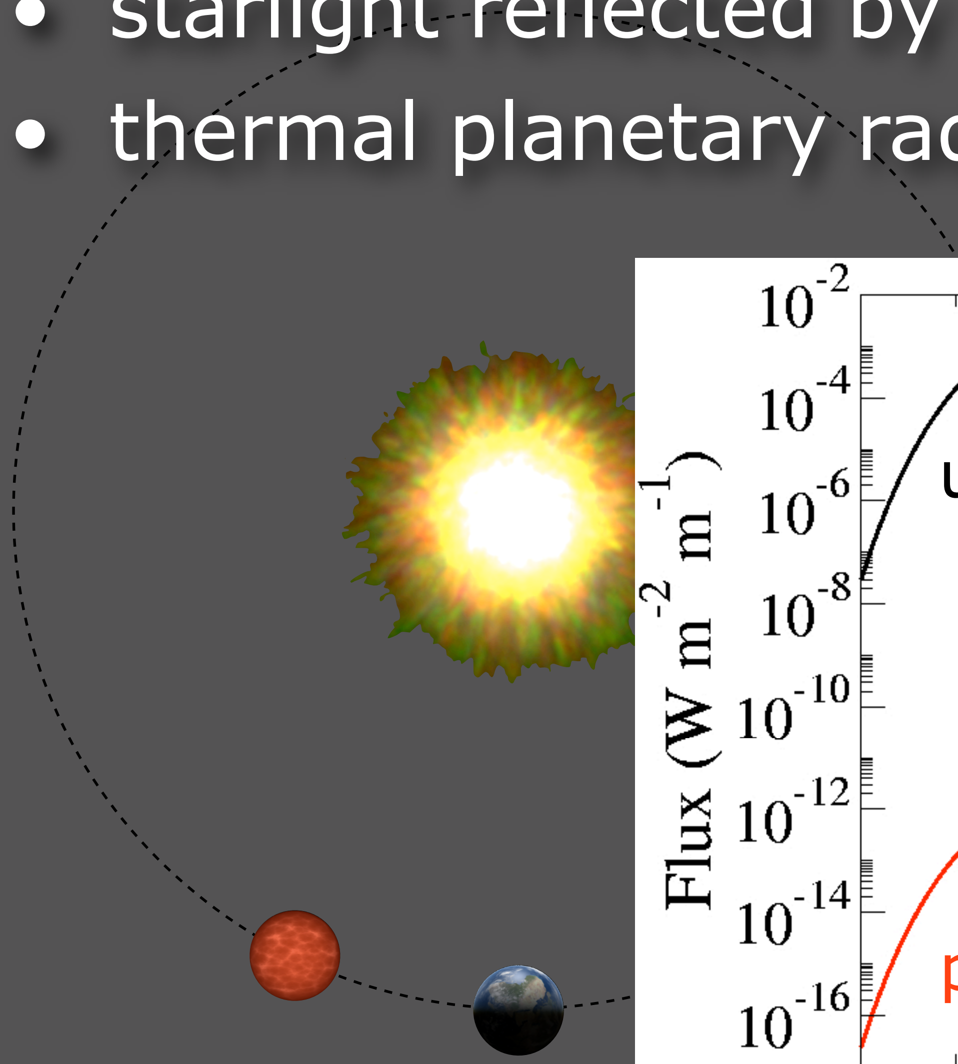
$$P(\lambda)= \frac{\sqrt{Q^2(\lambda) + U^2(\lambda)}}{F(\lambda)}$$

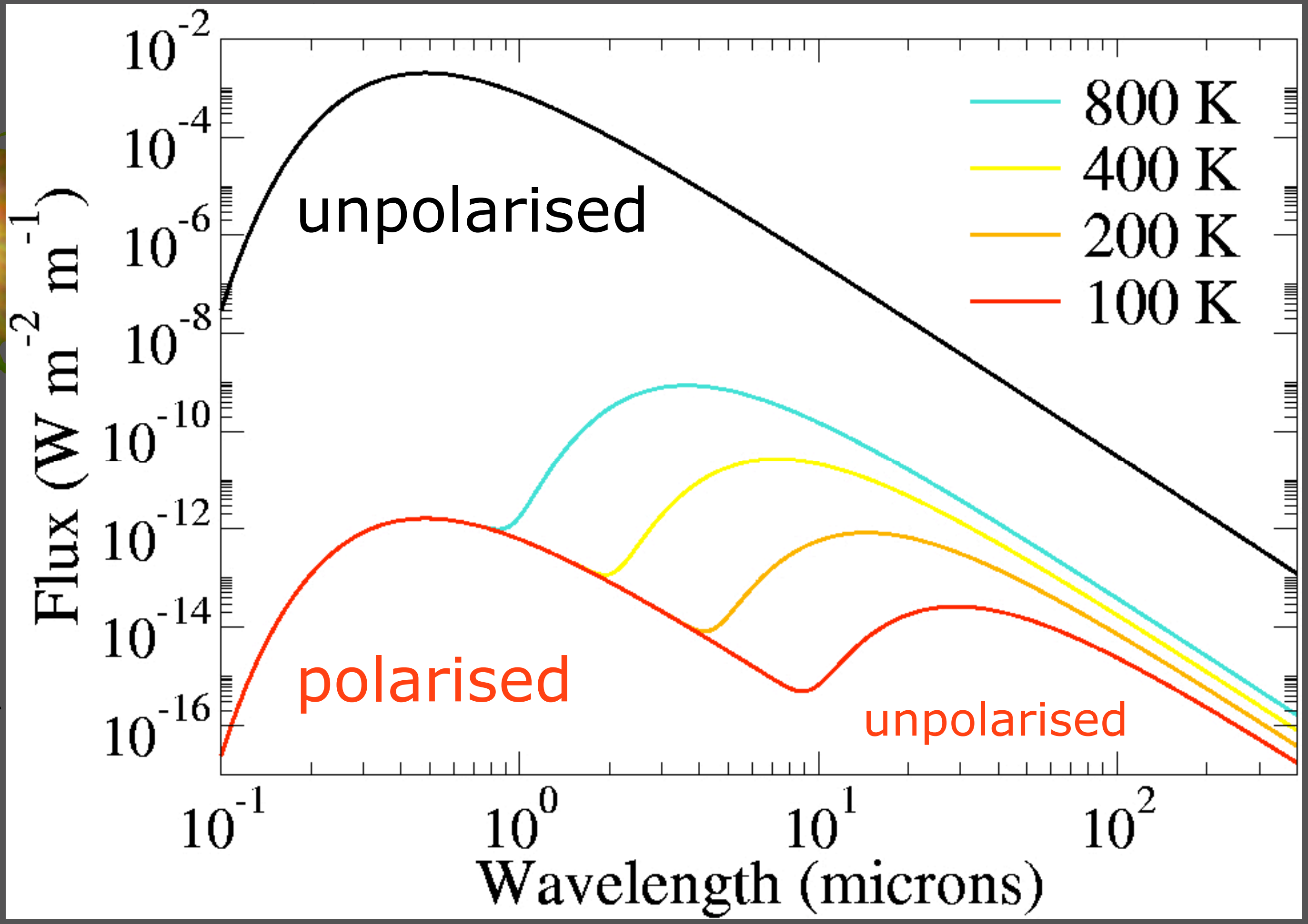
SRON

Sources of polarisation

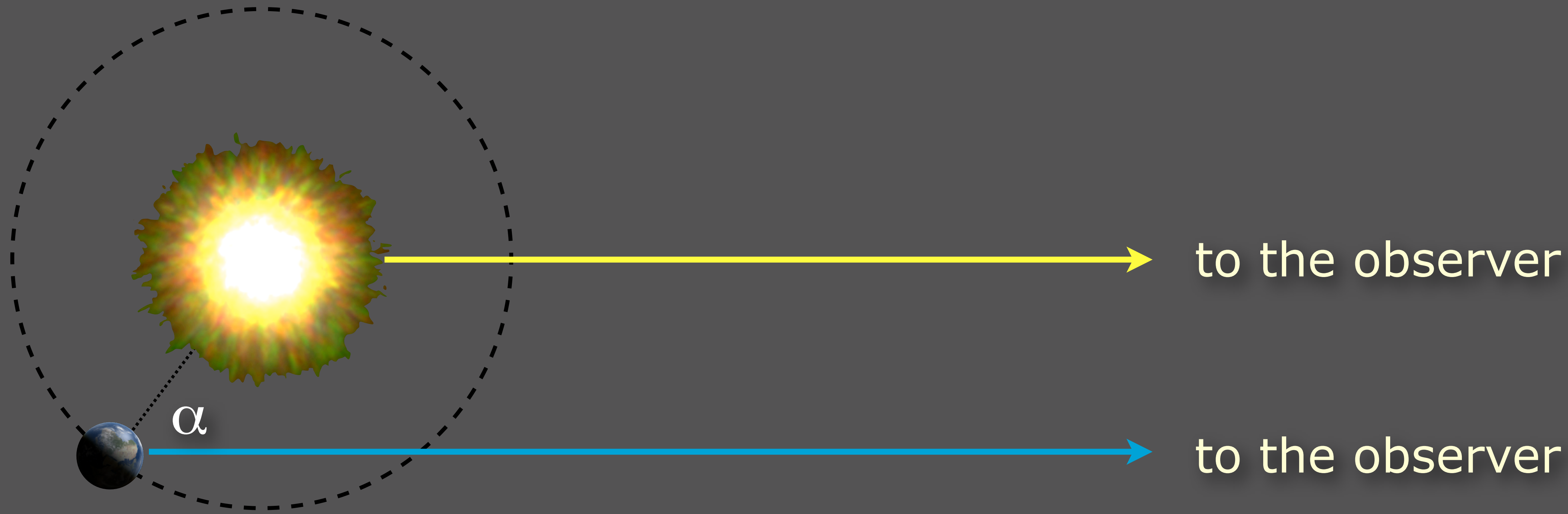
Integrated over the stellar or planetary disk:

- direct starlight is usually unpolarised
- starlight reflected by a planet will usually be polarised
- thermal planetary radiation will usually be unpolarised





Polarimetry for detection & confirmation



The degree of polarisation of reflected starlight depends on*:

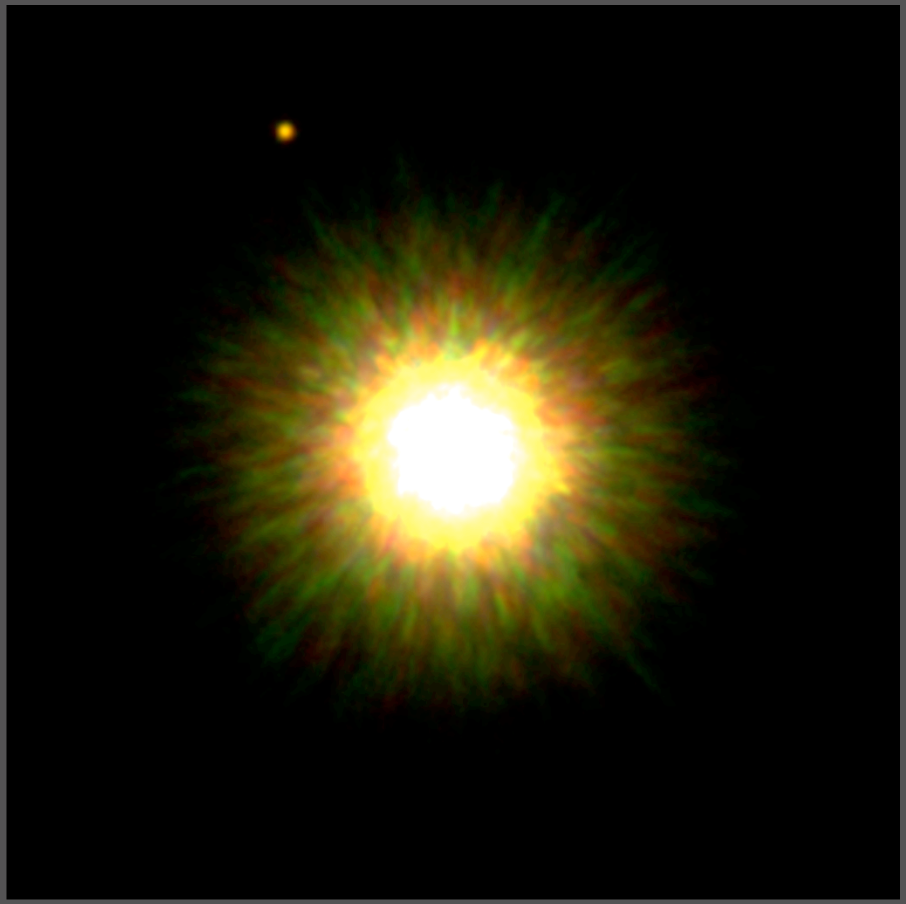
- The composition and structure of the planet's atmosphere
- The reflection properties of the planet's surface
- The wavelength λ of the light
- The planetary phase angle α

SRON

* P does not depend on: planet's size, distance to the star, distance to the observer!

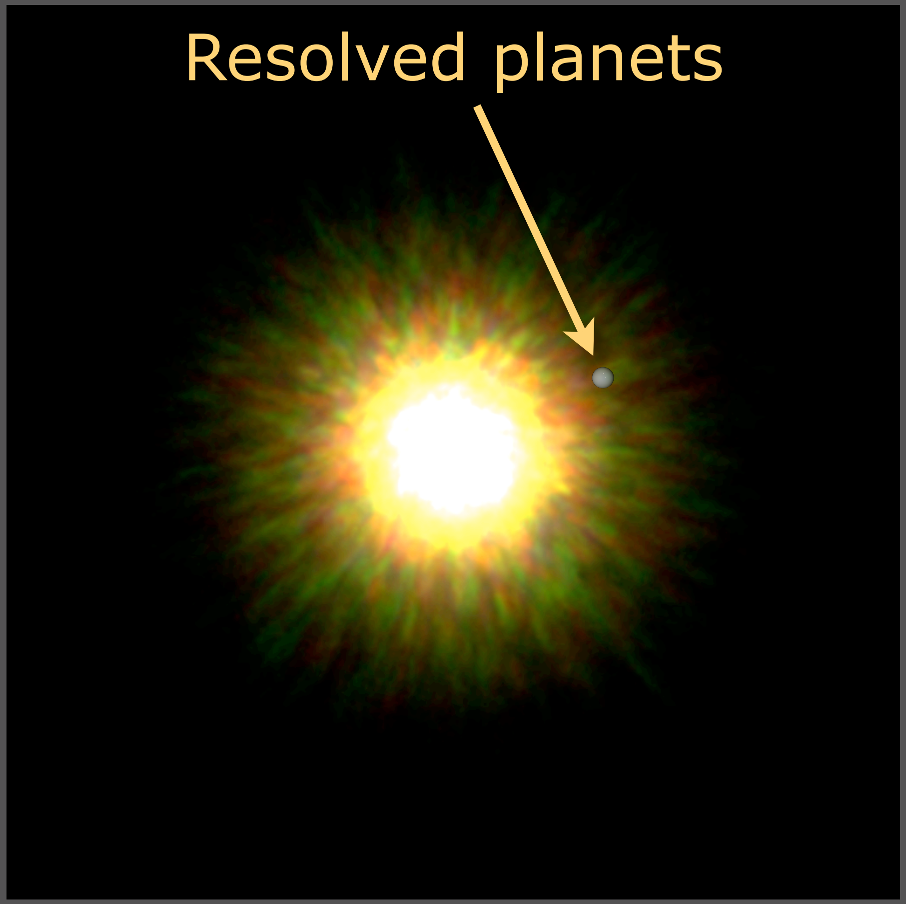
Polarimetry for detection & confirmation

The degree of polarisation that can be observed depends strongly on the amount of background starlight:



See: Seager et al. (2000)
Instrument example: PlanetPol (Jim Hough)

First detection (of HD 189733b) claimed by Berdyugina et al. [2008]

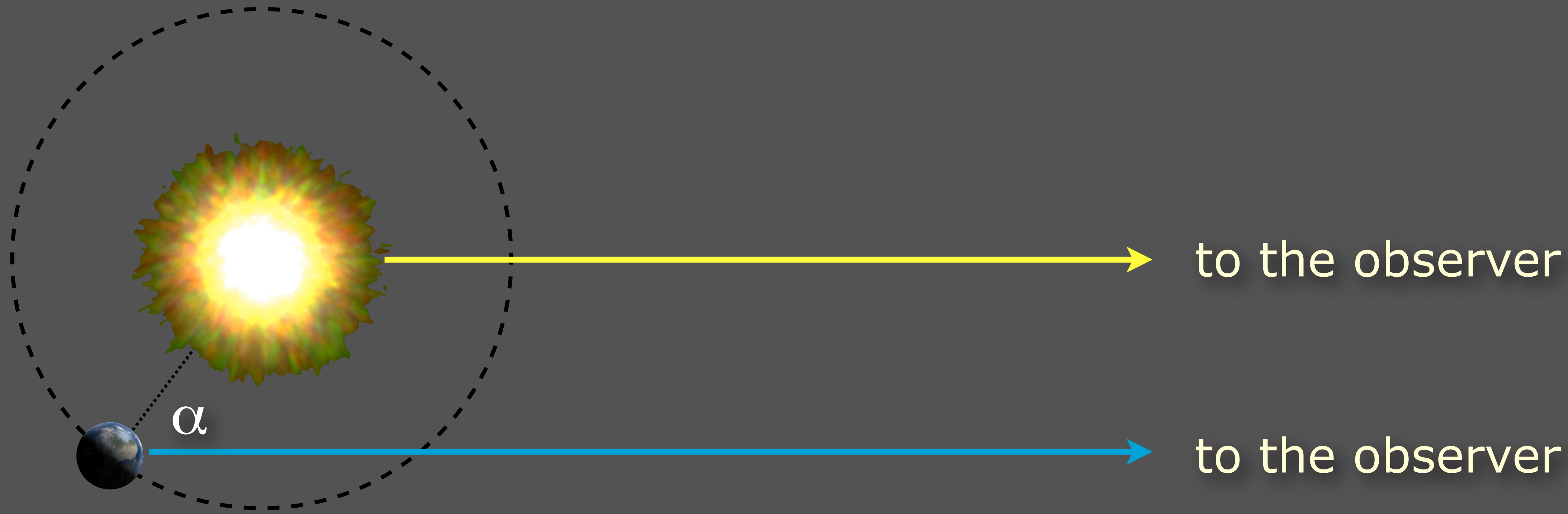


Instrument examples: ExPo (WHT), SPHERE (VLT), GPI (Gemini), EPICS (ELT), ...

SRON

Star image from Lafrenière, Jayawardhana, & van Kerkwijk [2008]

Polarimetry for exoplanet charactersation



The degree of polarisation of reflected starlight depends on*:

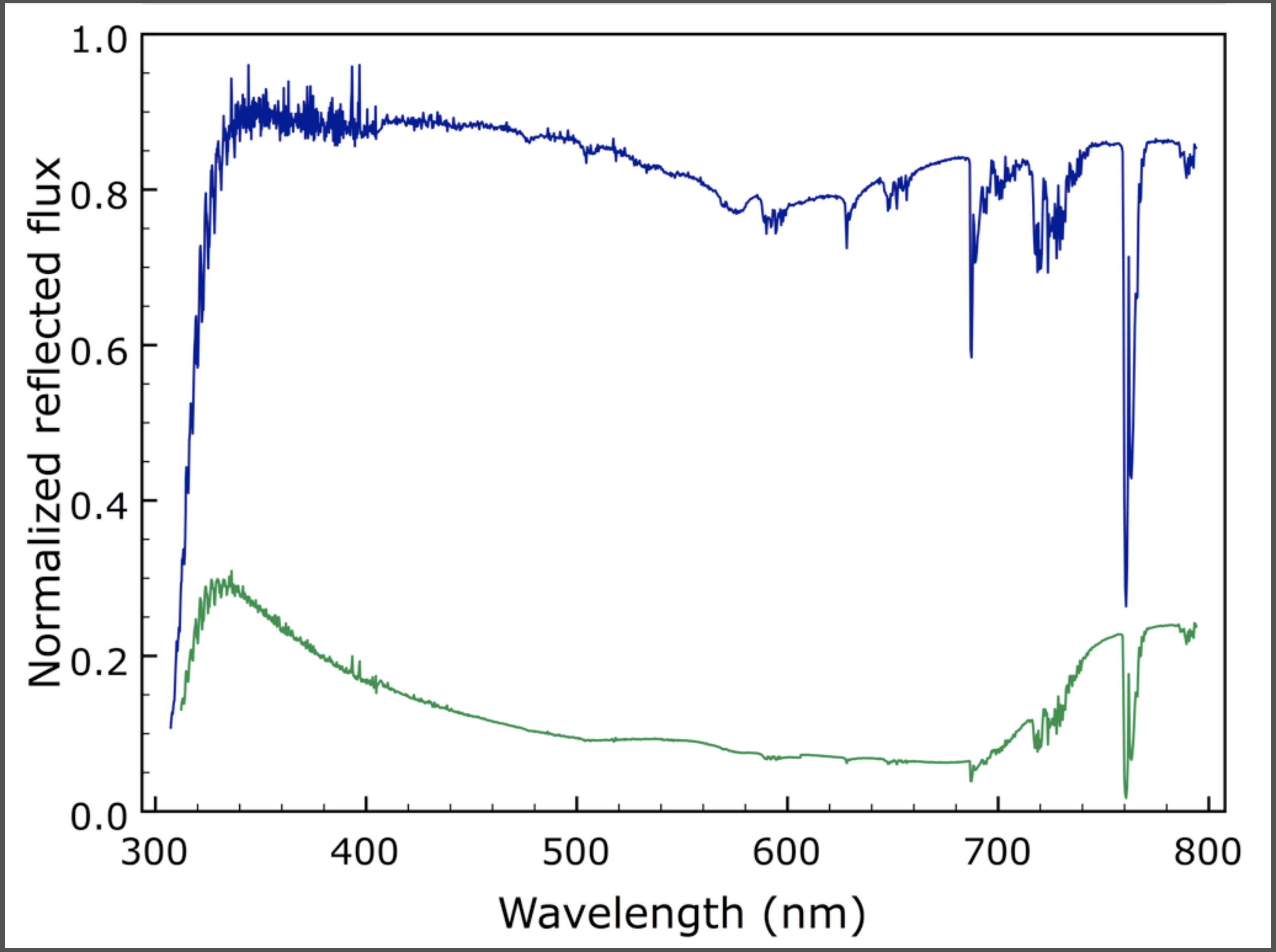
- The composition and structure of the planet's atmosphere
- The reflection properties of the planet's surface
- The wavelength λ of the light
- The planetary phase angle α

SRON

* P does not depend on: planet's size, distance to the star, distance to the observer!

Polarimetry for exoplanet characterisation

Example: spectrometry of a region on the Earth

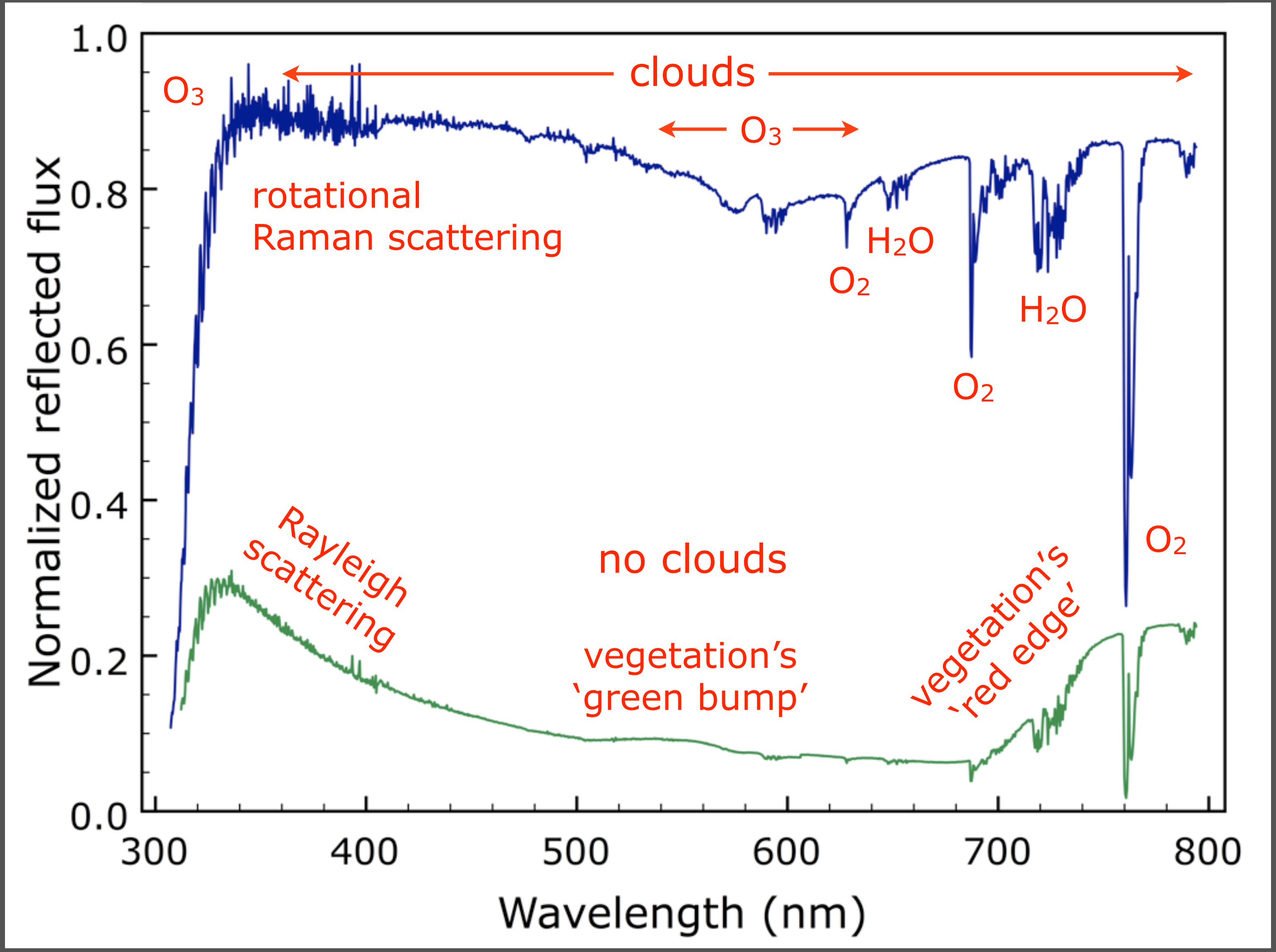


Spectrometry of a region on Earth measured by GOME on the ERS-2 satellite, for nadir viewing angles and solar zenith angles of 34°

SRON

Polarimetry for exoplanet characterisation

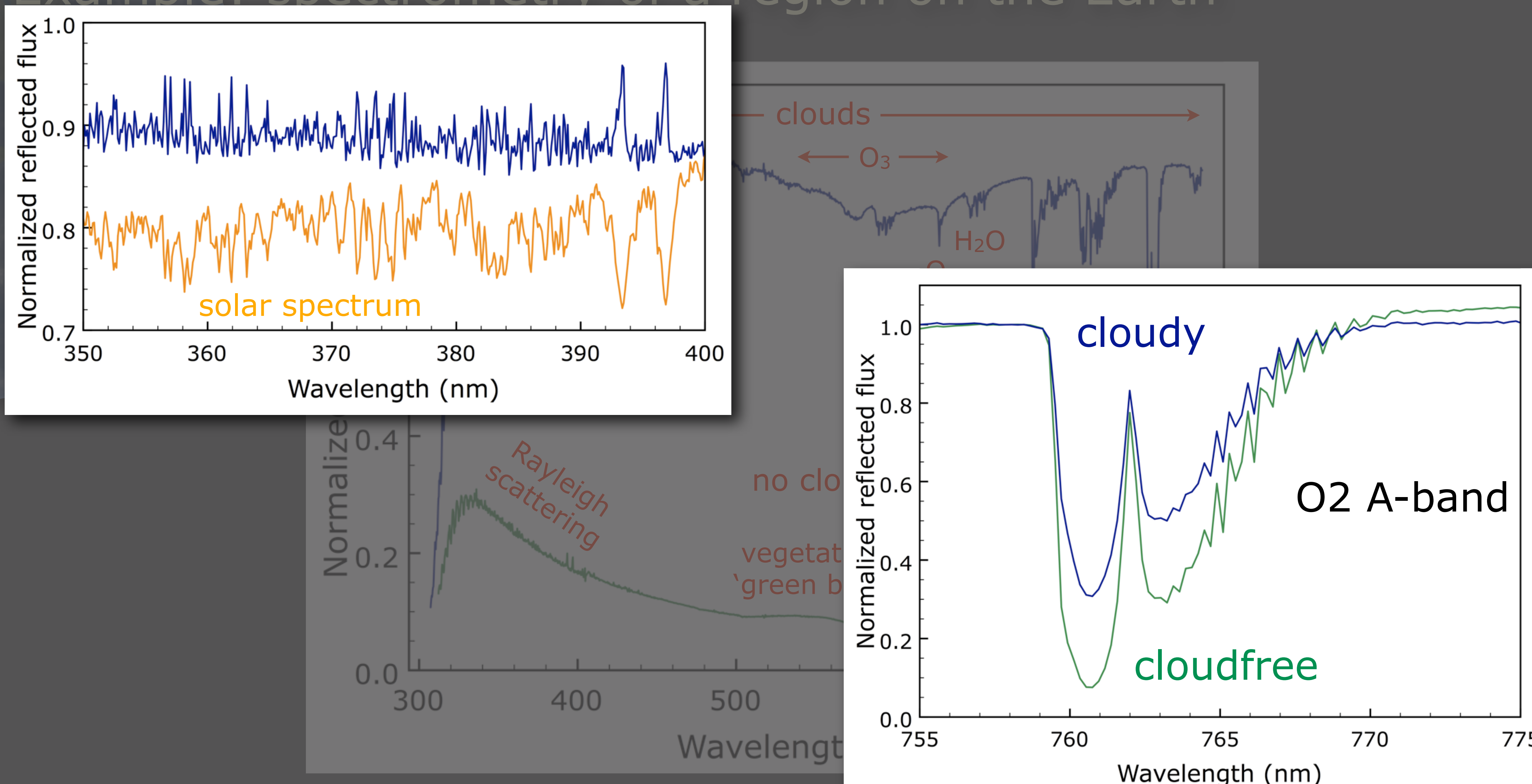
Example: spectrometry of a region on the Earth



Spectrometry of a region on Earth measured by GOME on the ERS-2 satellite, for nadir viewing angles and solar zenith angles of 34°

Polarimetry for exoplanet characterisation

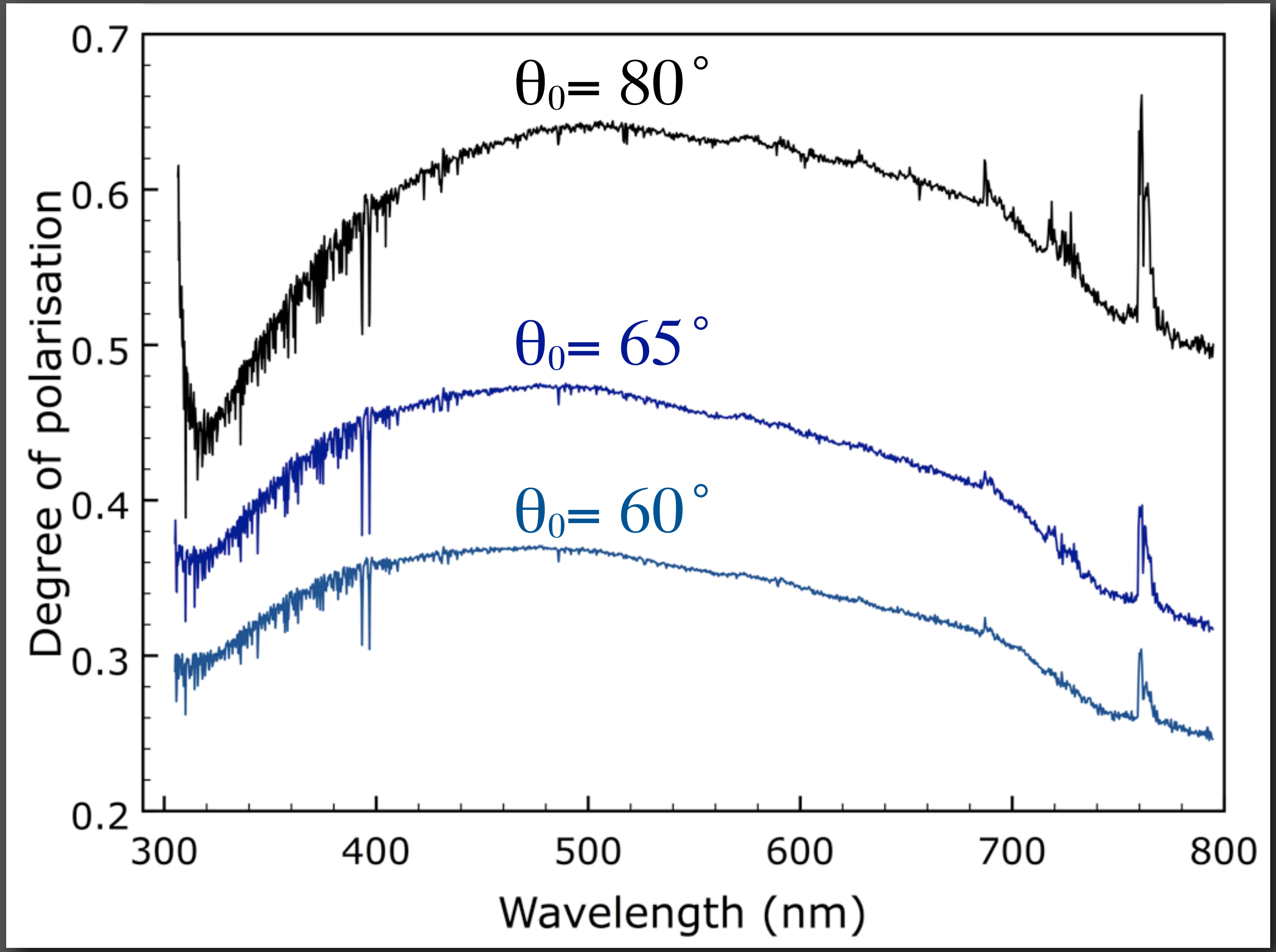
Example: spectrometry of a region on the Earth



Spectrometry of a region on Earth measured by GOME on the ERS-2 satellite, for nadir viewing angles and solar zenith angles of 34°

Polarimetry for exoplanet characterisation

Example: spectropolarimetry of the Earth's zenith sky

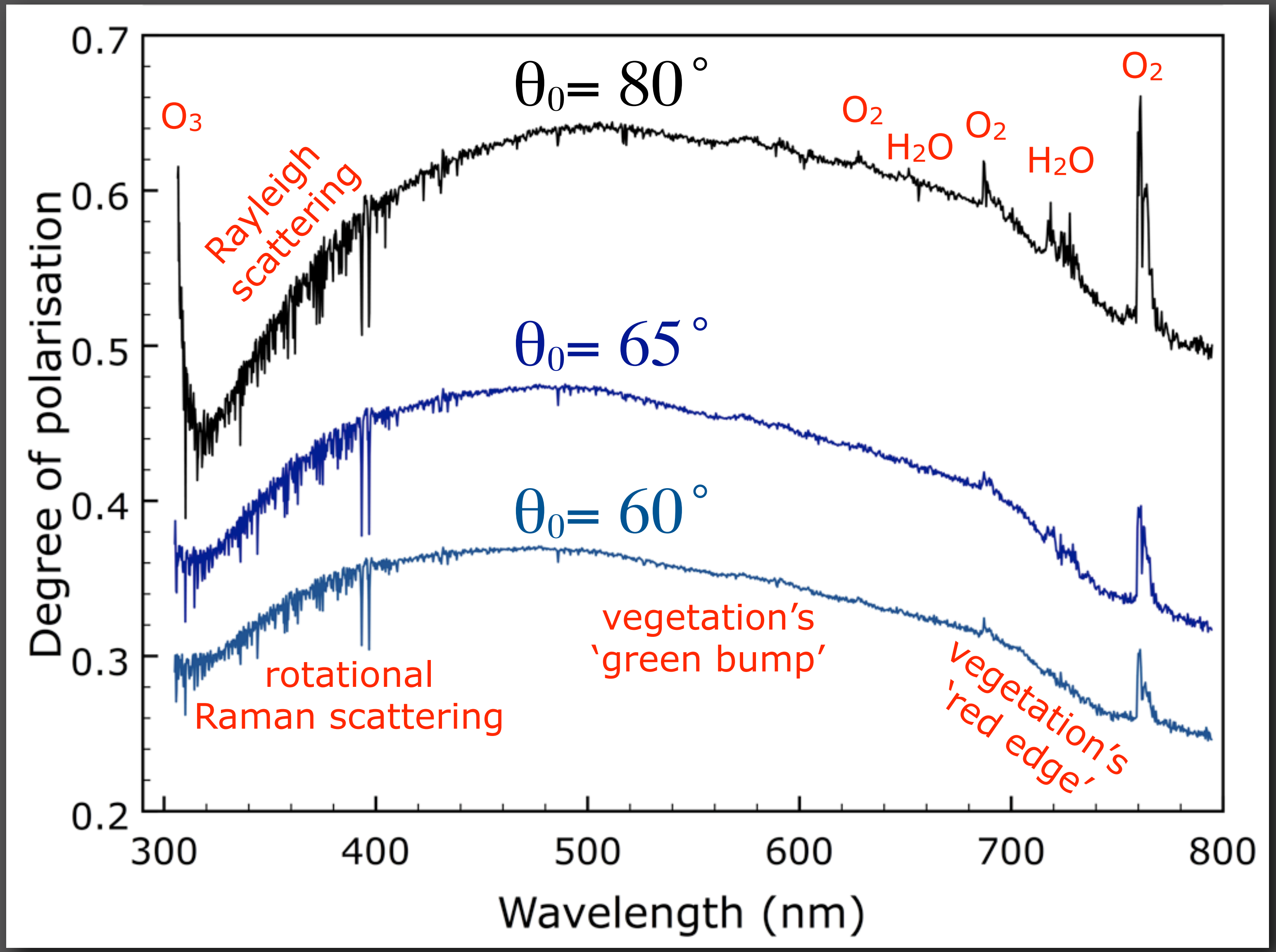


Ground-based polarimetry of the cloud-free zenith sky at three solar zenith angles θ_0 with the GOME BBM [from Aben et al., 1999]

SRON

Polarimetry for exoplanet characterisation

Example: spectropolarimetry of the Earth's zenith sky

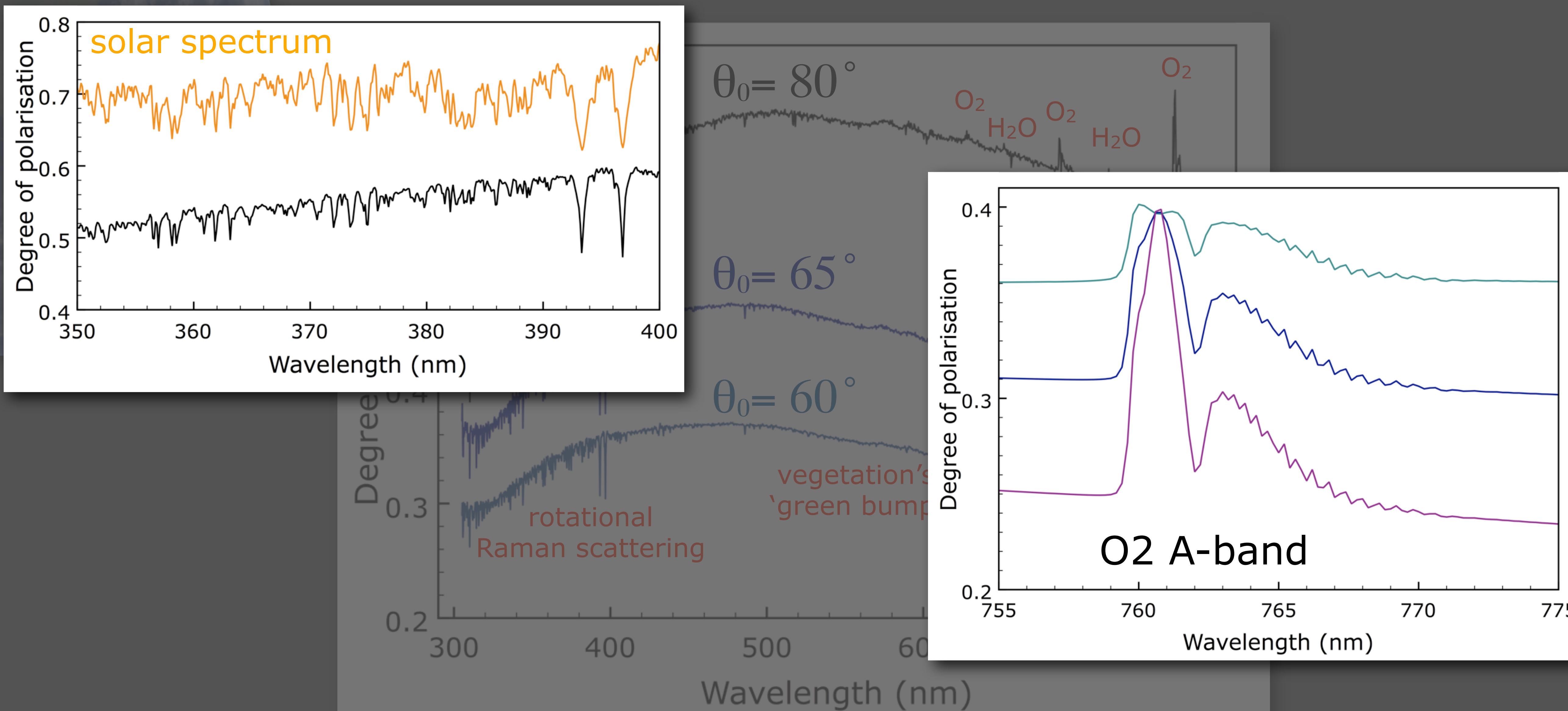


Ground-based polarimetry of the cloud-free zenith sky at three solar zenith angles θ_0 with the GOME BBM [from Aben et al., 1999]

SRON

Polarimetry for exoplanet characterisation

Example: spectropolarimetry of the Earth's zenith sky



Ground-based polarimetry of the cloud-free zenith sky at three solar zenith angles θ_0 with the GOME BBM [from Aben et al., 1999]

Polarimetry for exoplanet characterisation

Example: derivation of Venus cloud particle microphysics

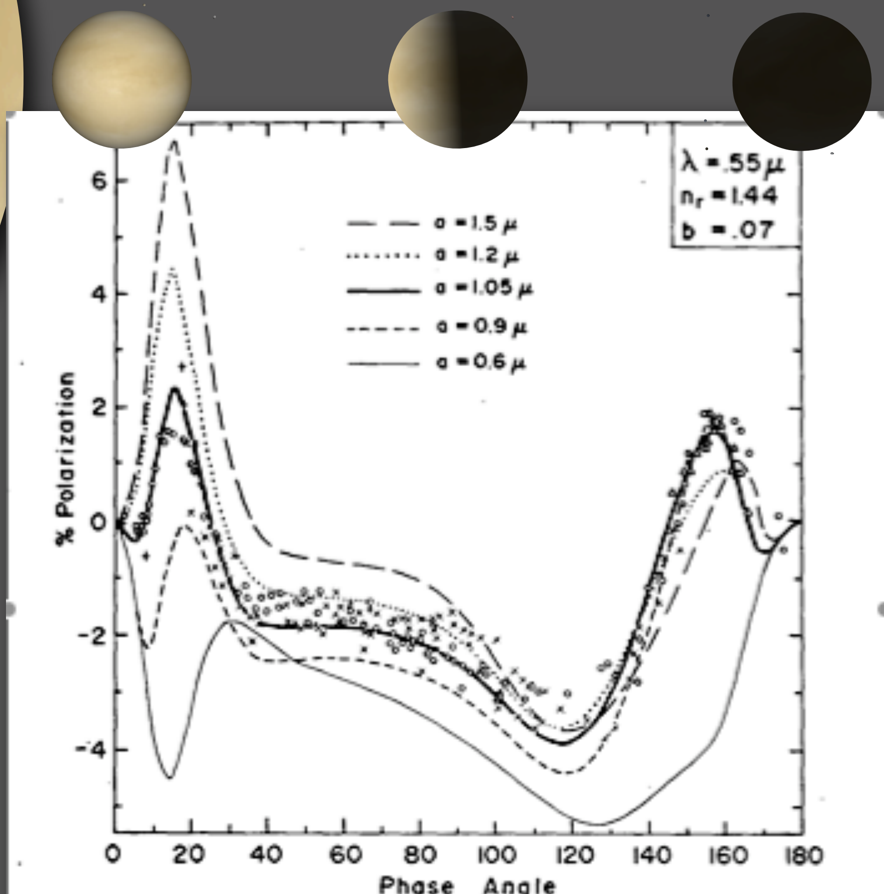


Fig. 4. Observations of the polarization of sunlight reflected by Venus in the visual wavelength region and theoretical computations for $\lambda = 0.55$ μm. The ○'s are wide-band visual observations by Lyot (1929) while the other observations are for an intermediate bandwidth filter centered at $\lambda = 0.55$ μm; the ×'s were obtained by Coffeen and Gehrels (1969), the +'s by Coffeen (cf. Dollfus and Coffeen, 1970), and the Δ's (which refer to the central part of the crescent) by Veverka (1971). The theoretical curves are all for a refractive index 1.44, the size distribution (8) with $b = 0.07$, and a Rayleigh contribution $f_R = 0.045$. The different curves show the influence of the effective radius on the polarization.

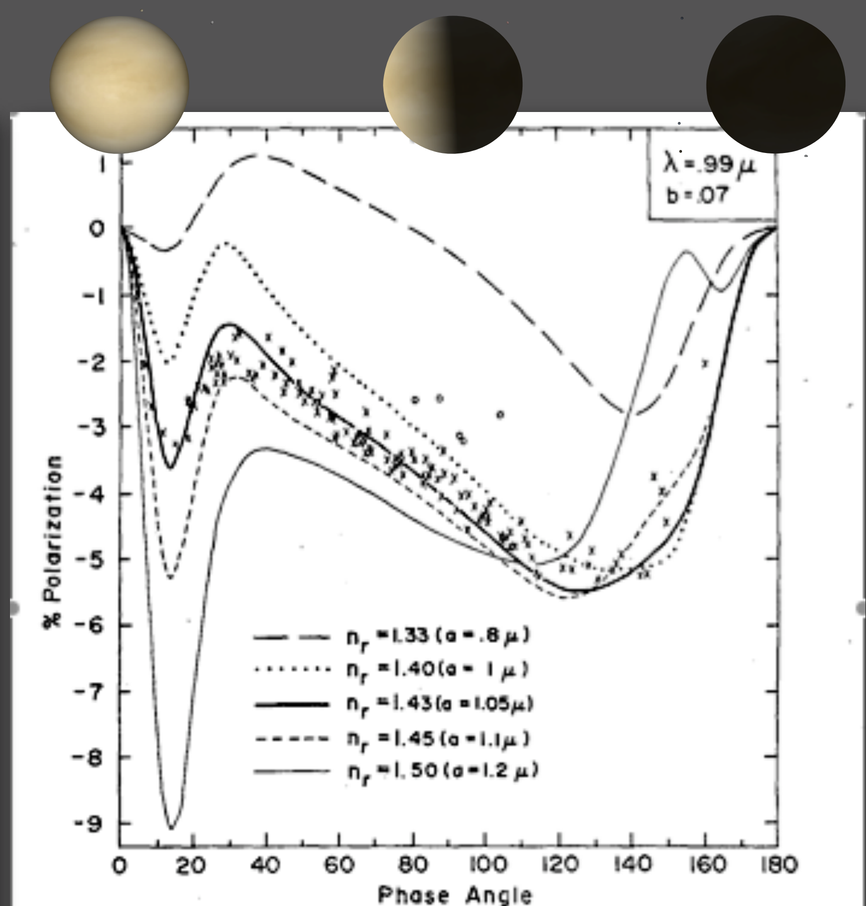


Fig. 7. Observations and theoretical computations of the polarization of sunlight reflected by Venus at $\lambda = 0.99$ μm. The observations were made with an intermediate bandwidth filter, the ×'s being obtained by Coffeen and Gehrels (1969) in 1959–67 and by Coffeen (cf. Dollfus and Coffeen, 1970) from 1967 to March 1969, and the ○'s being obtained by Coffeen (cf. Dollfus and Coffeen, 1970) in May–July, 1969. The theoretical curves are for spherical particles having the size distribution (8) with $b = 0.07$. The different theoretical curves are for various refractive indices, the effective particle radius being selected in each case to yield closest agreement with the observations for all wavelengths.

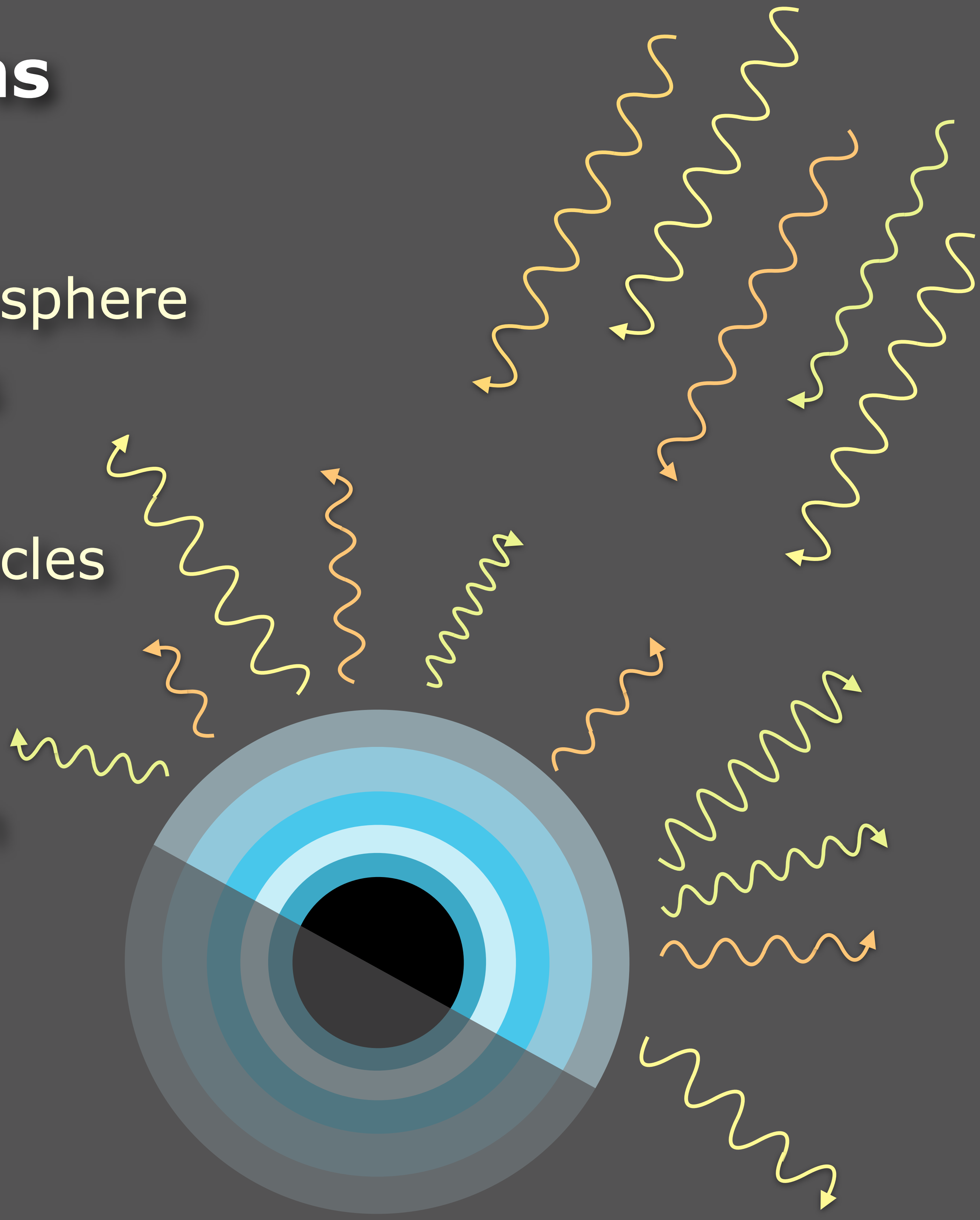
Hansen & Hovenier [1974] used ground-based polarimetry at different wavelengths across a range of phase angles to derive the size, composition, and altitude of Venus' cloud particles

SRON

Numerical simulations

Planet models:

- locally plane-parallel atmosphere
- horizontally homogeneous
- vertically inhomogeneous
- gases, aerosol, cloud particles

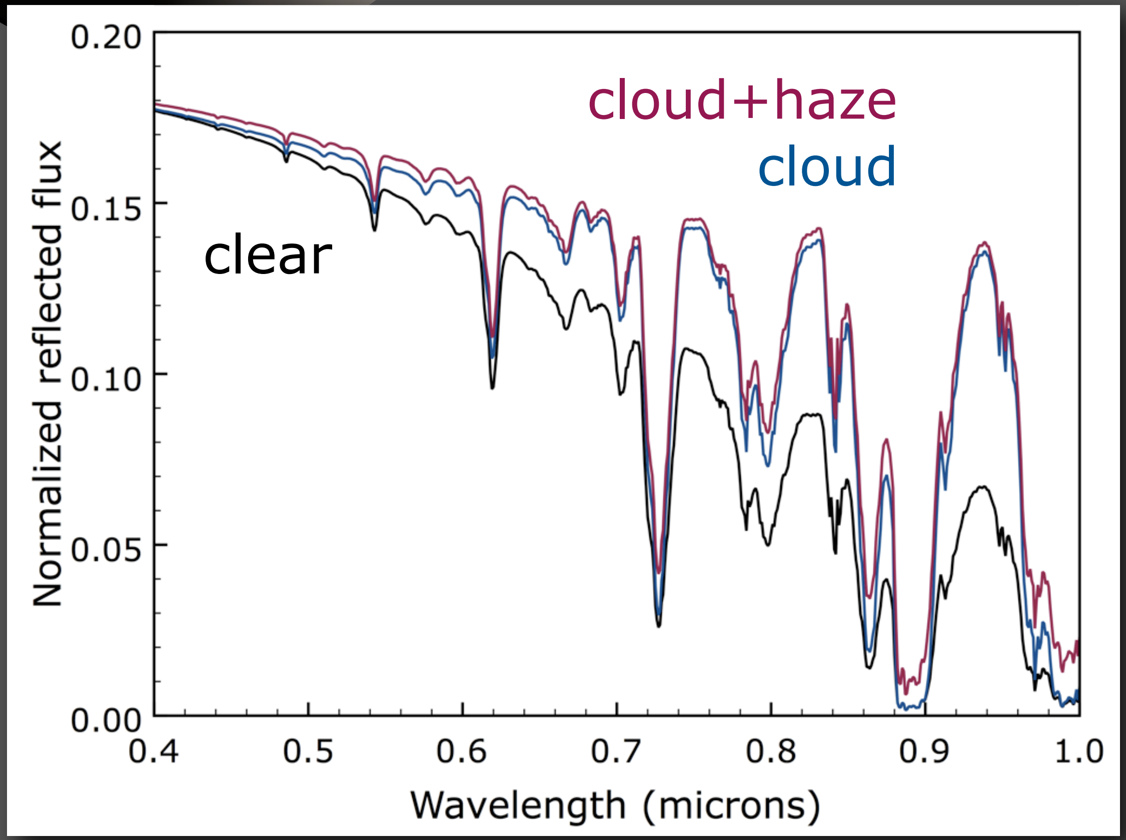


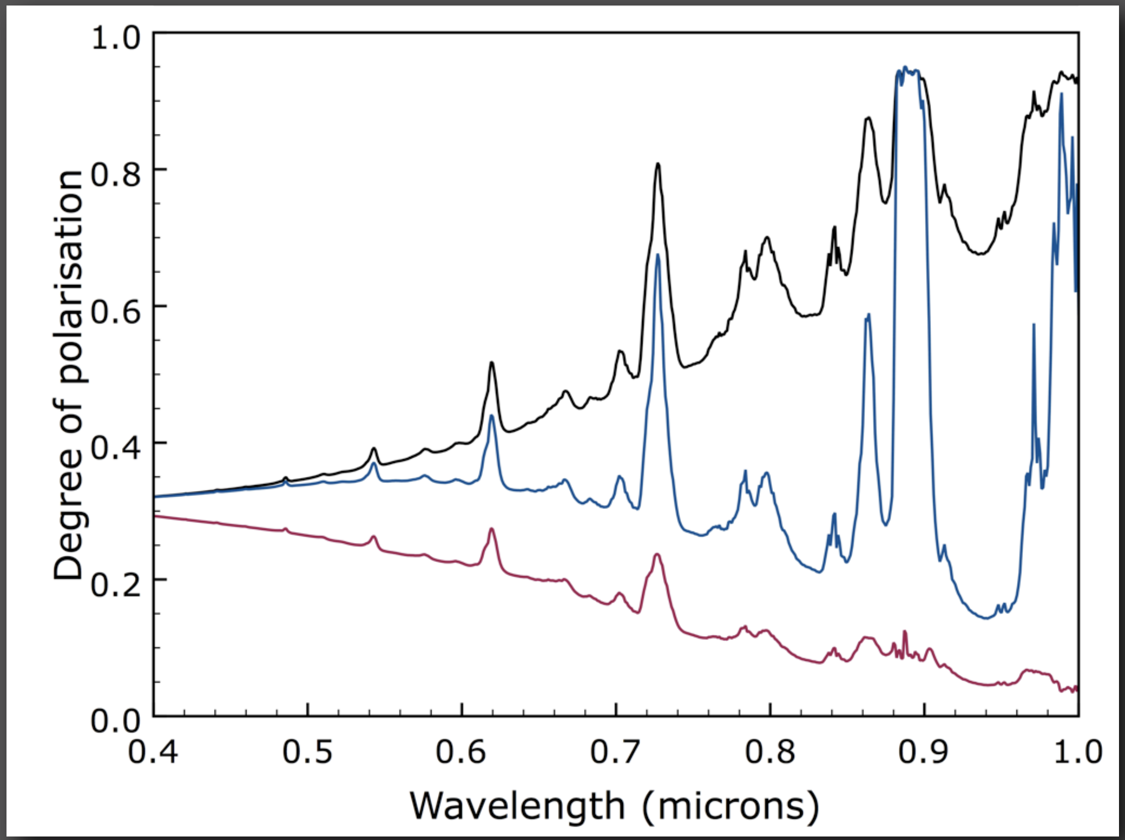
Radiative transfer code:

- adding-doubling algorithm
- fluxes and polarisation
- efficient disk-integration
- no Raman scattering

(for details, see e.g. Stam 2008)

Simulations of gaseous exoplanets





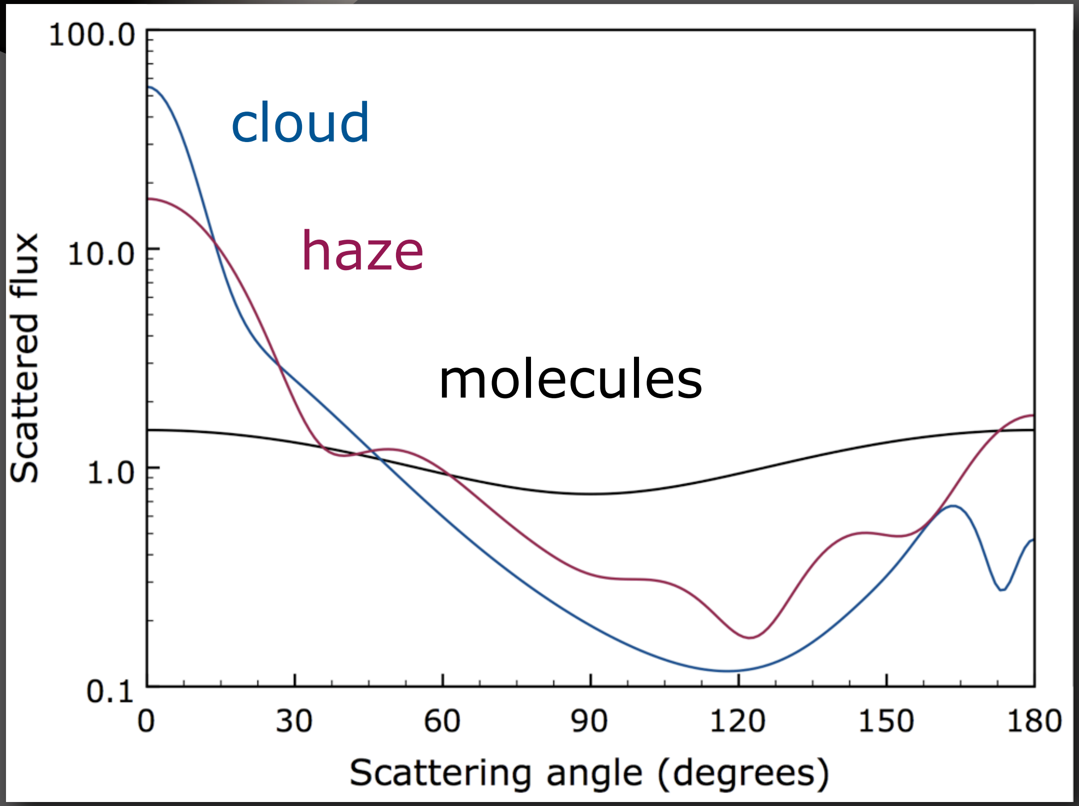
Jupiter-like horizontally homogeneous atmospheres.

Planetary phase angle $\alpha=90°$ (Stam et al., 2004)

SRON

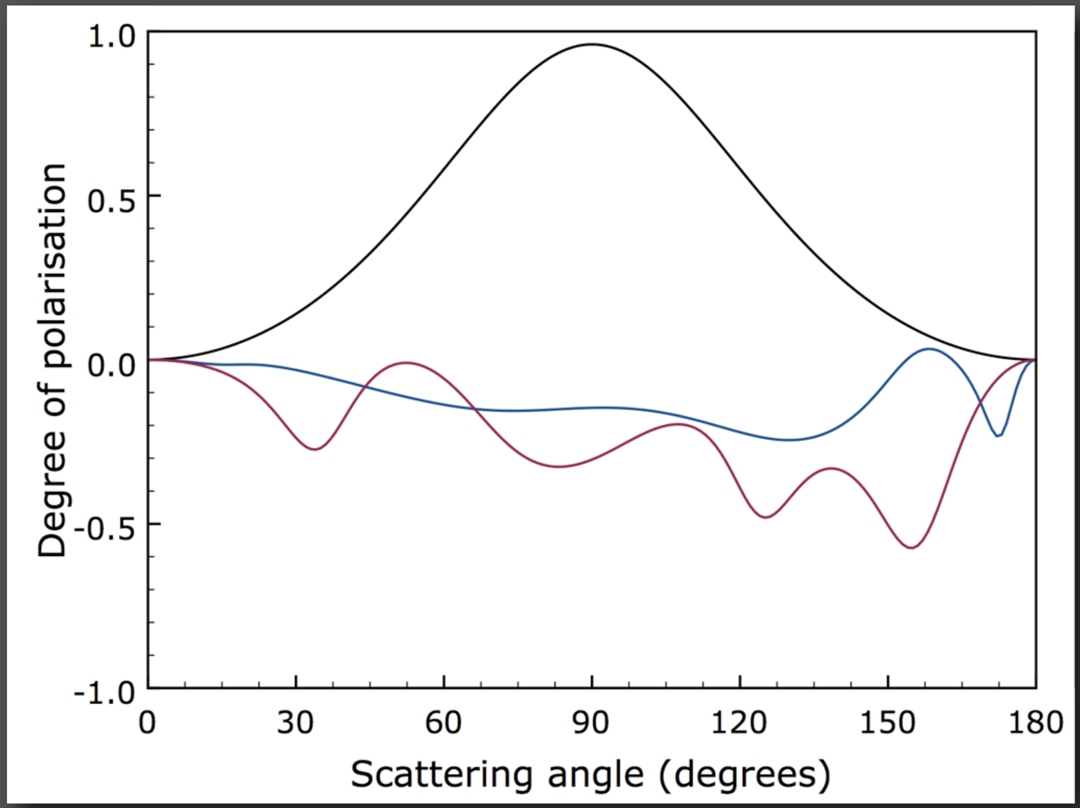
Simulations of gaseous exoplanets

Single scattering properties of the atmospheric particles

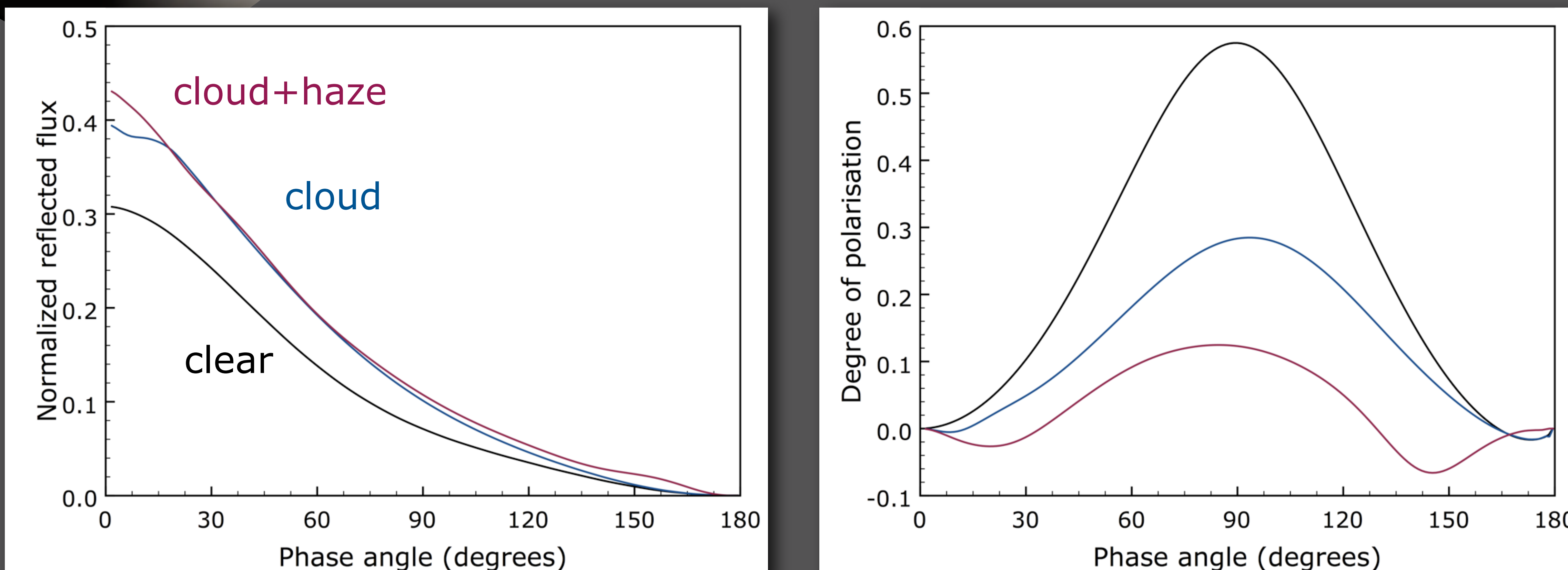


Flux

Polarisation



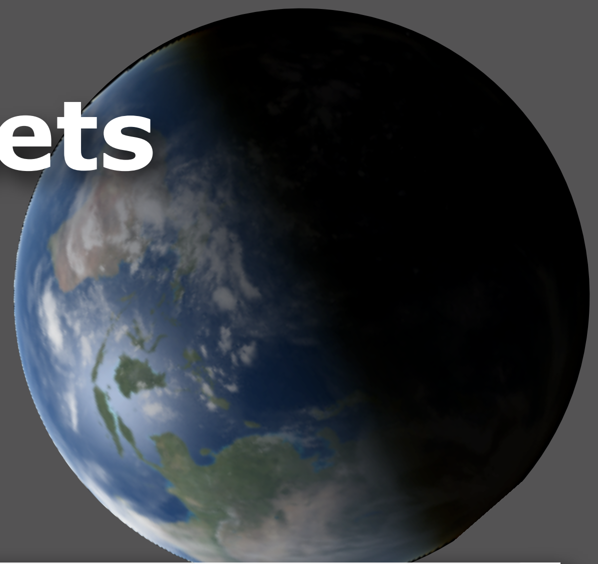
Simulations of gaseous exoplanets



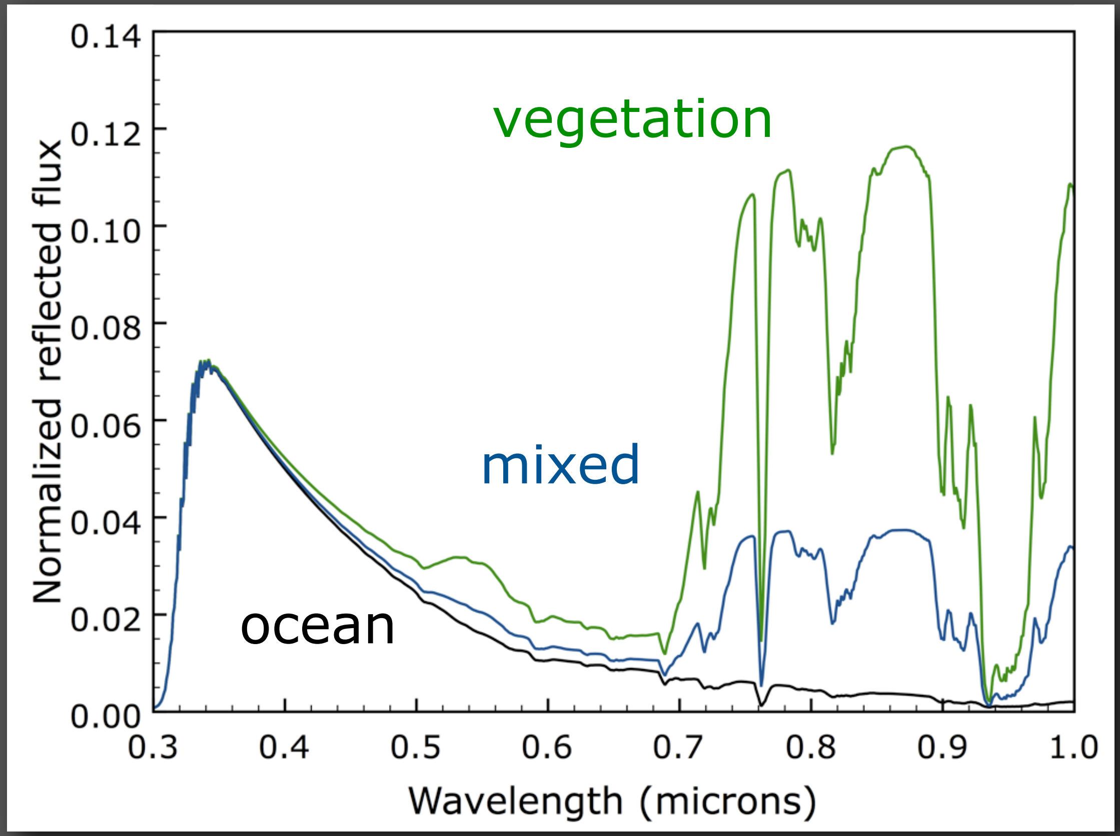
Jupiter-like horizontally homogeneous atmospheres
wavelength λ from 0.65 to 0.95 microns (Stam et al., 2004)

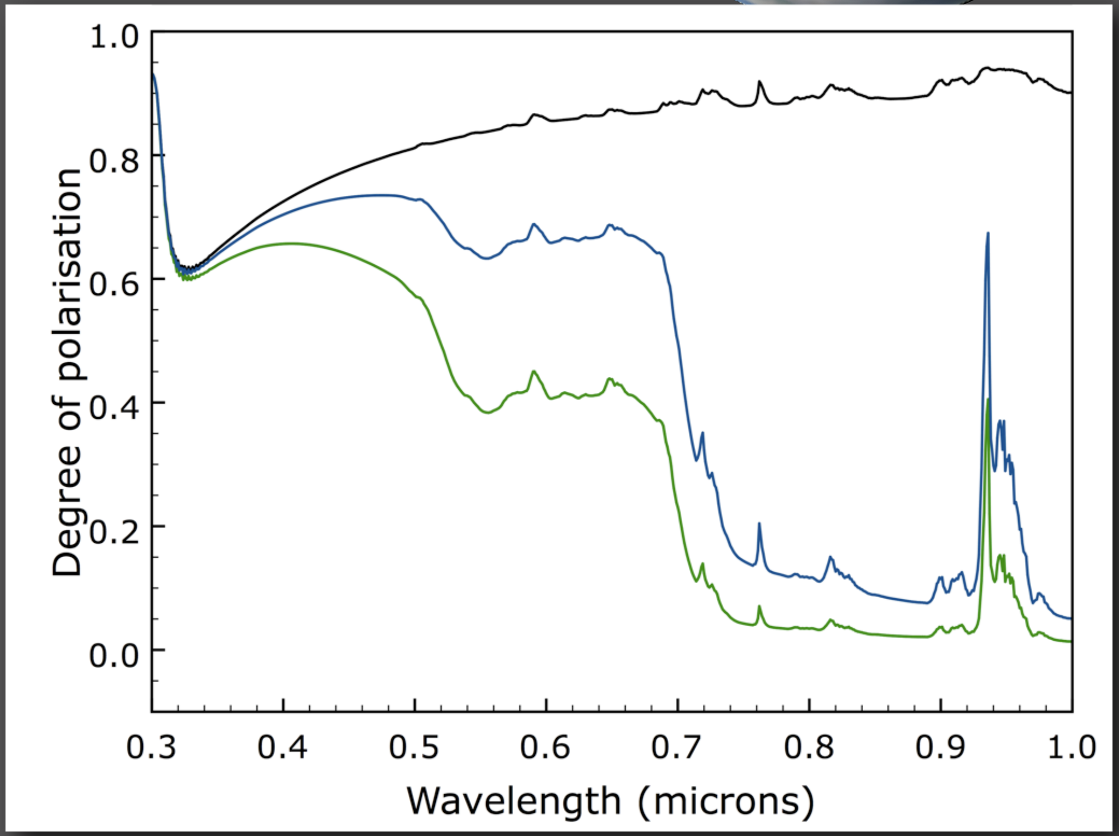
SRON

Simulations of Earth-like exoplanets



Planetary phase angle α=90°



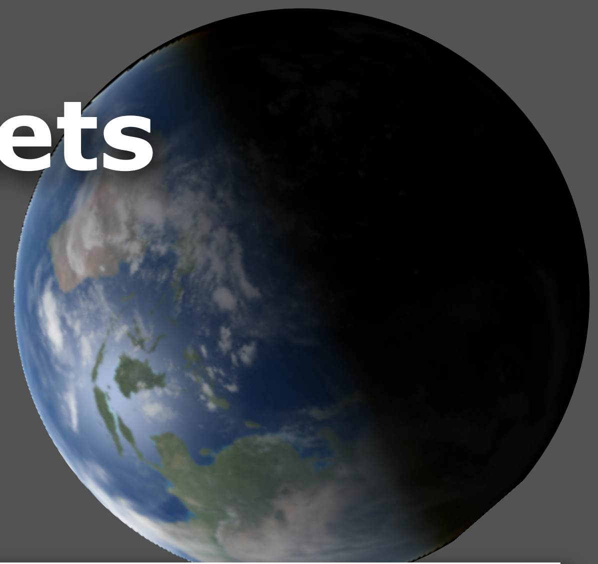


Cloud-free planets with surfaces covered by:
100% vegetation, 100% ocean, and 30% vegetation + 70% ocean.

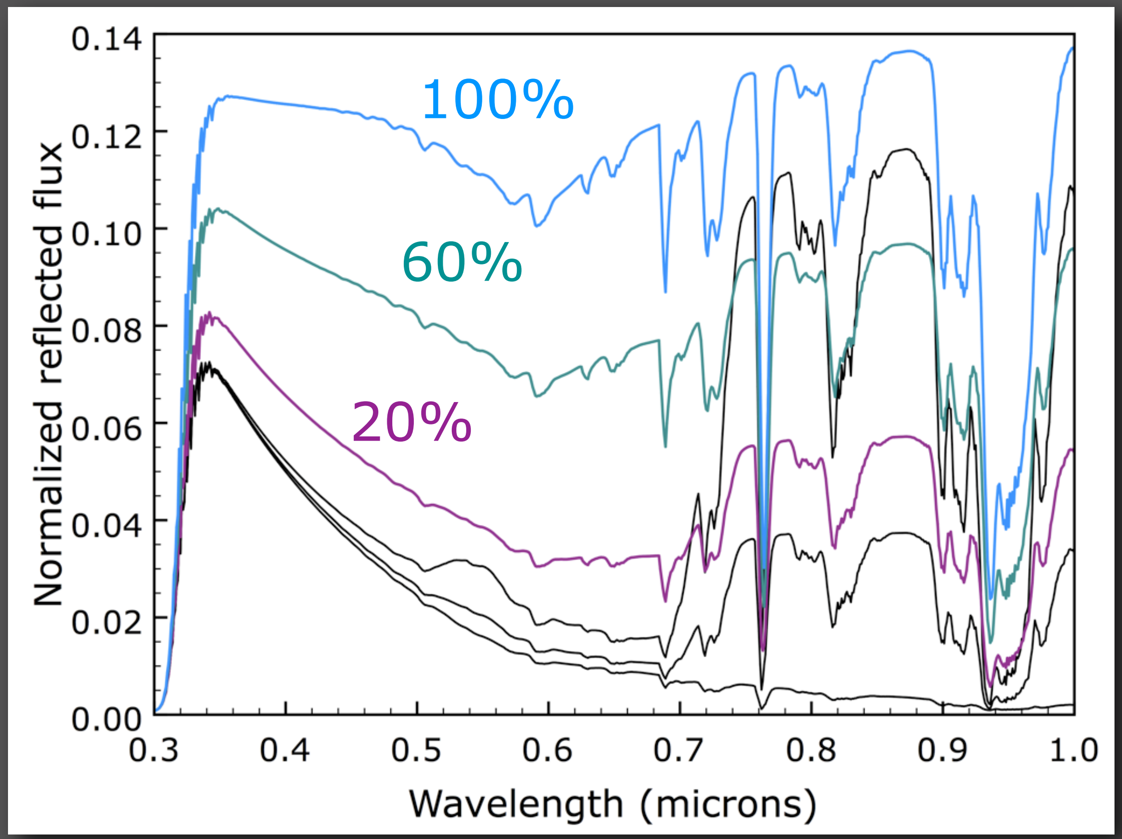
(see Stam et al., 2008)

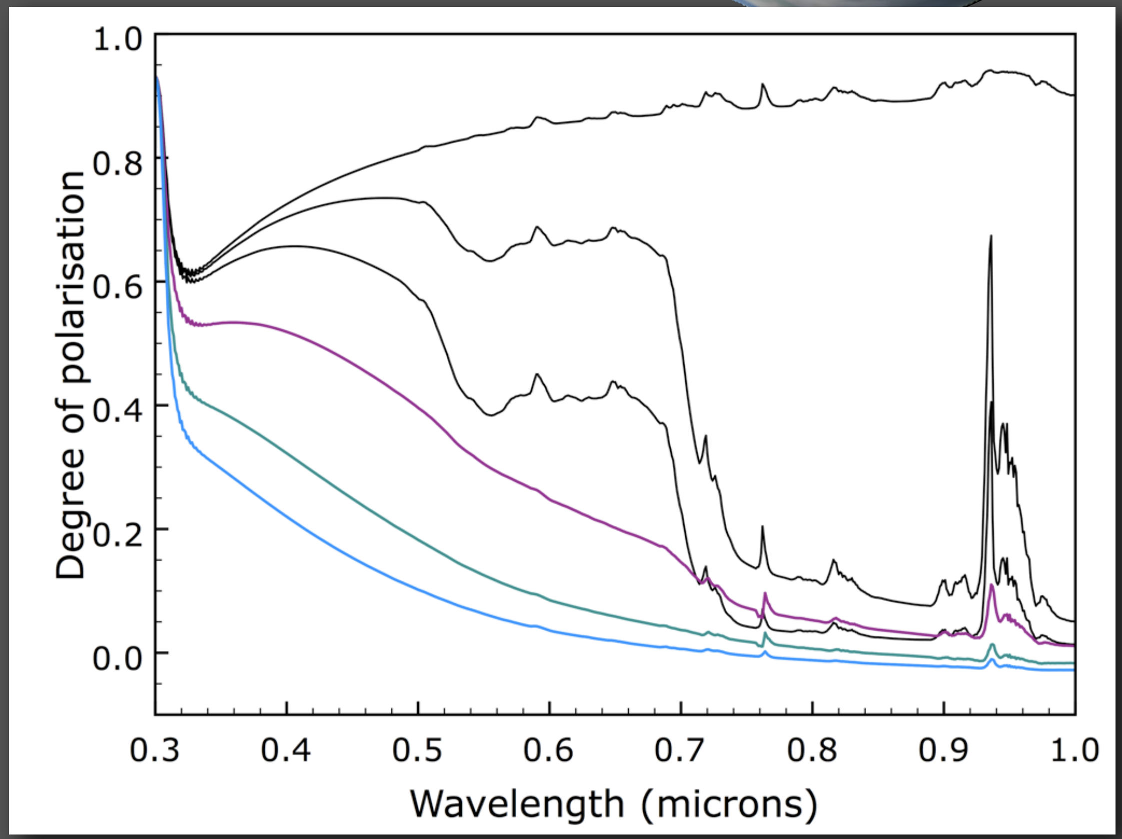
SRON

Simulations of Earth-like exoplanets



Planetary phase angle α=90°





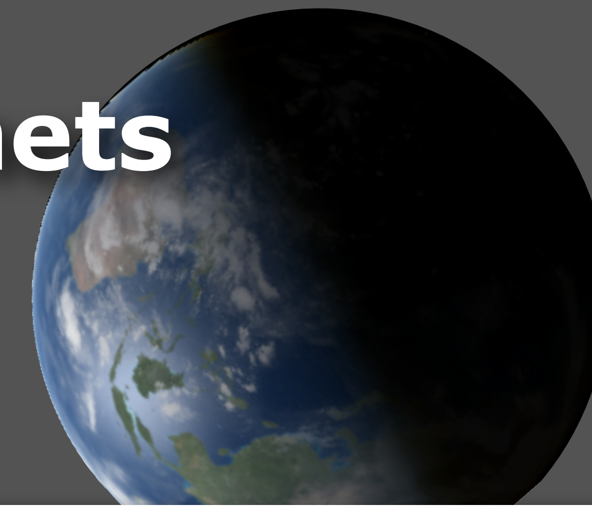
Cloud-free planets with surfaces covered by:

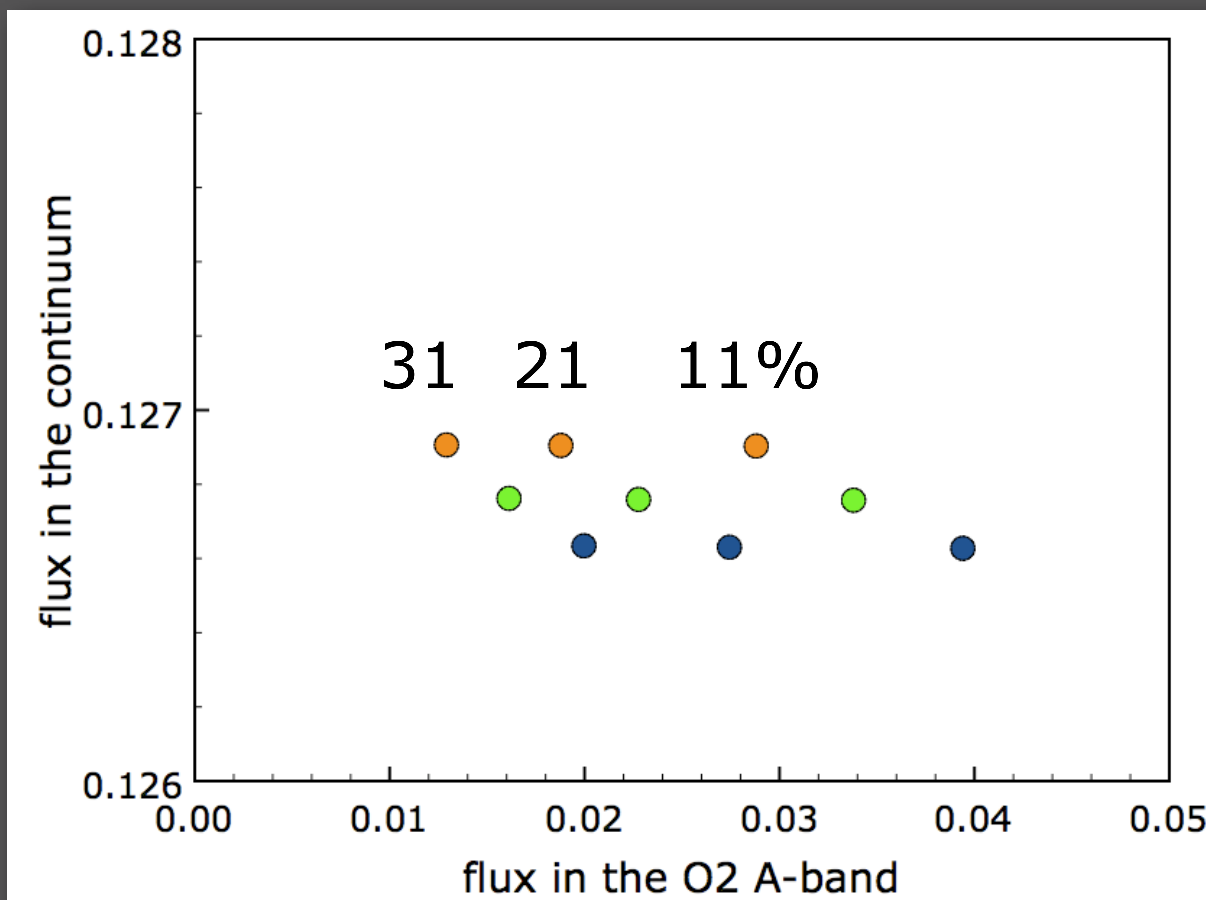
100% vegetation, 100% ocean, and 30% vegetation + 70% ocean.

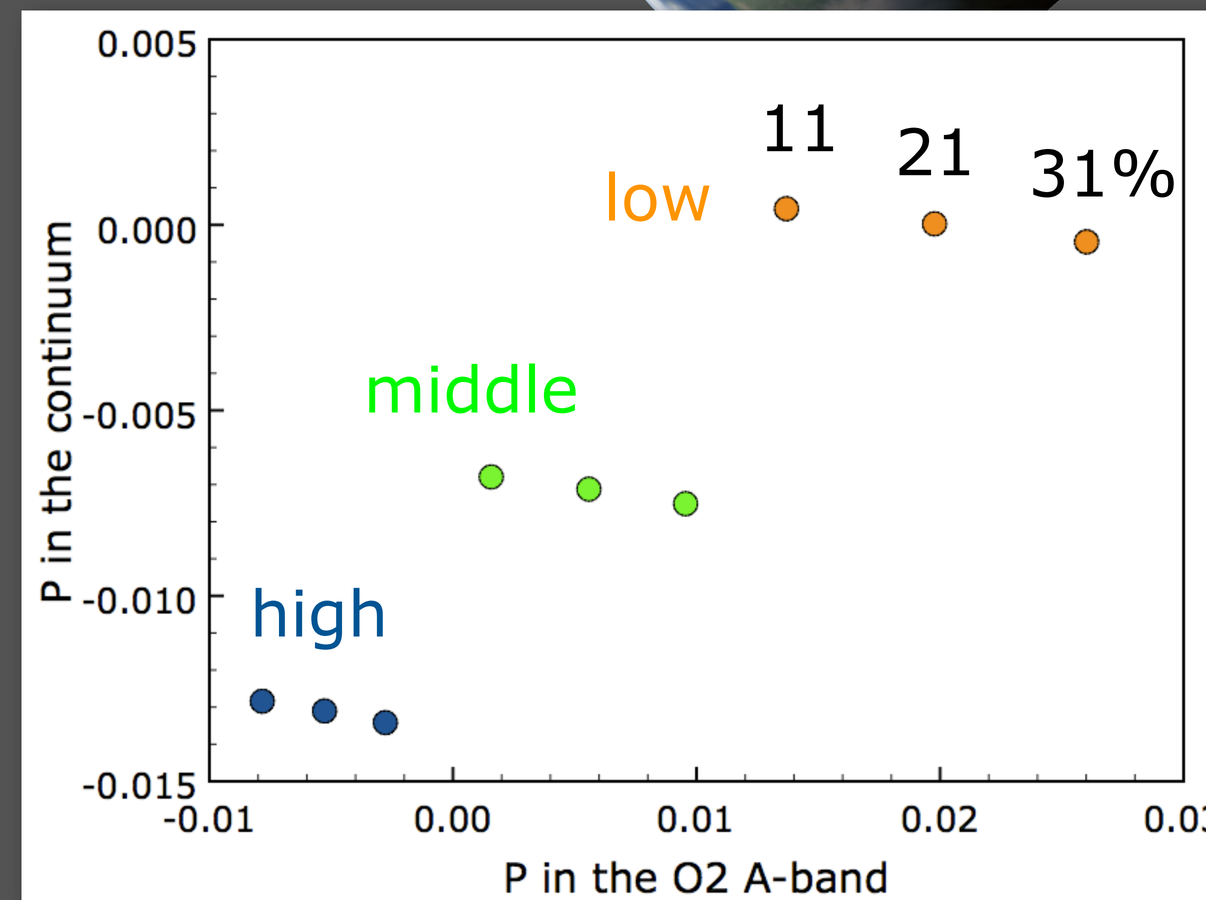
The mixed planet with cloud coverages of 20%, 60%, and 100%.

(see Stam et al., 2008)

Simulations of Earth-like exoplanets







The reflected flux and degree of polarisation in and outside of the O2 A-band (0.76 microns) for completely cloudy planets with high clouds (blue), middle clouds (green), or low clouds (orange) and for different O2 mixing ratios (Stam et al., 2008)

SRON

Warning: Polarisation sensitive instruments

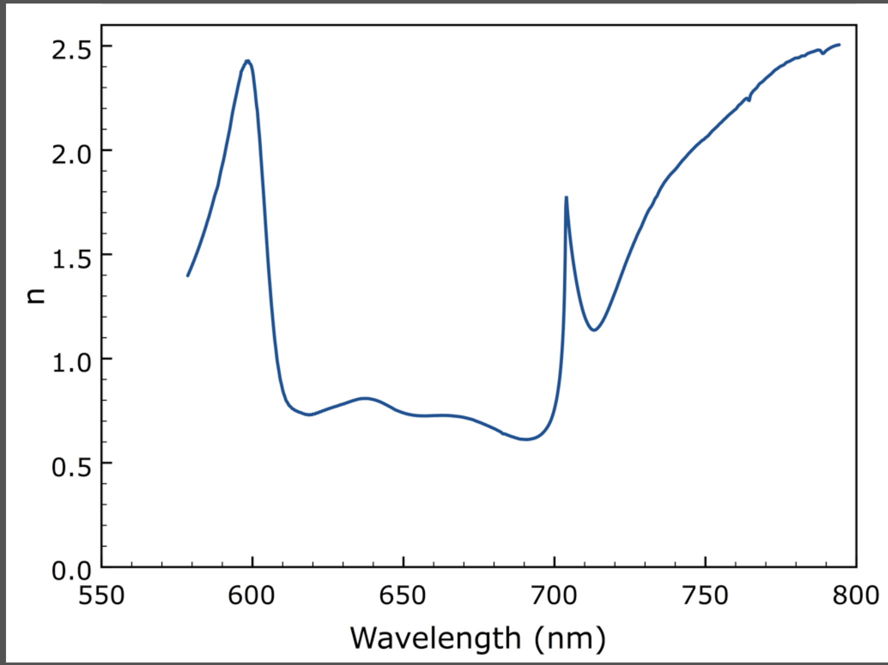
Many (most) spectrometers are polarisation sensitive; the measured F_m depends on F_{in} and e.g. Q_{in} of the incoming light:

$$F_m = 0.5\, a^l\, [(1 + \eta)\, F_{in} + (1 - \eta)\, Q_{in}]$$

a^l instrument's response to parallel polarised light

a^r response to perpendicularly polarised light

η the ratio a^r/a^l



GOME's polarisation sensitivity (mainly due to dispersion gratings and dichroic mirror) (see Stam et al., 2000)

SRON

Warning: Polarisation sensitive instruments

Many (most) spectrometers are polarisation sensitive; the measured F_m depends on F_{in} and e.g. Q_{in} of the incoming light:

$$F_m = 0.5\, a^l \left[(1 + \eta)\, F_{in} + (1 - \eta)\, Q_{in}\right]$$

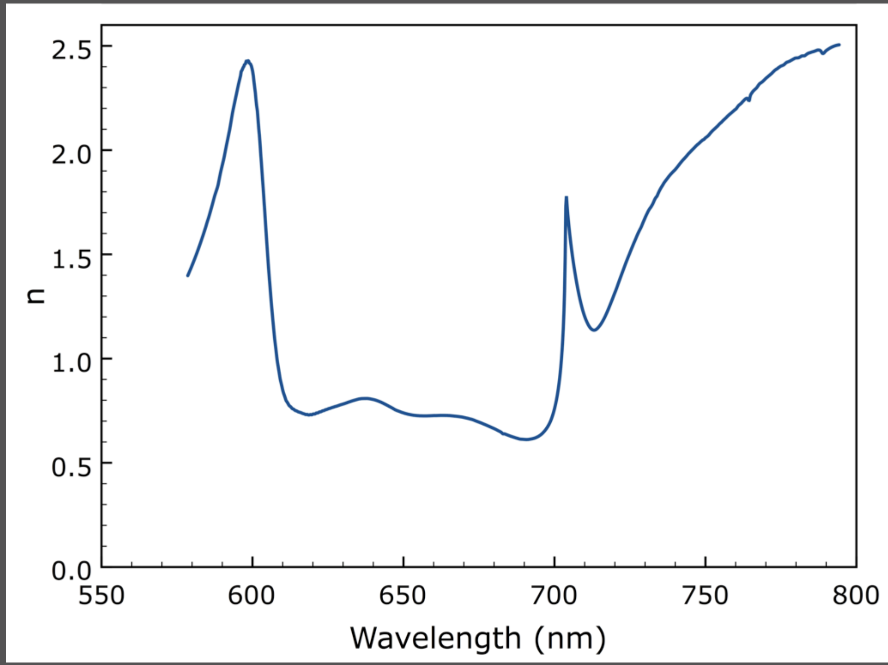
a^l instrument's response to parallel polarised light

a^r response to perpendicularly polarised light

η the ratio a^r/a^l

Assuming $Q_{in}=0$ (ignoring polarisation) leads to errors in the derived flux, F_{in}':

$$\varepsilon = \frac{F_{in}' - F_{in}}{F_{in}} = \frac{(1 - \eta)\, Q_{in}}{(1 + \eta)\, F_{in}} = \frac{(1 - \eta)}{(1 + \eta)}\, P_{in}$$



GOME's polarisation sensitivity (mainly due to dispersion gratings and dichroic mirror) (see Stam et al., 2000)

Summary

- Polarimetry is a powerful tool to detect, confirm, and characterise exoplanets
- Polarimetry provides extra, different information about a planet; it can help to solve degeneracy problems
- Polarisation should be in your mind even when you want to focus on ‘just’ a spectrometer

Future work

- ‘Make’ truly horizontally inhomogeneous planets
- Work on retrieval algorithms