Spectropolarimetry of Earth-like exoplanets

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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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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):
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):

- Rotational Raman scattering
- Vegetation’s ‘red edge’
- O3
- O2
- H2O
- Rayleigh scattering
- Vegetation’s ‘green bump’
- Clouds
- O2 A-band
- Cloudfree

Normalized reflected flux vs. Wavelength (nm)
Spectropolarimetry of the Earth

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

Aben et al. [1999]

[Graph showing polarization degree vs. wavelength for different scattering types and angles: θ₀ = 80°, θ₀ = 65°, θ₀ = 60°. Notations include rotational, Raman scattering, Rayleigh scattering, and the vegetation’s ‘red edge’ at specific wavelengths.]
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Spectropolarimetry in absorption lines

Figure 2.13: The wavelength dependence of the molecular absorption optical thickness $\Sigma b_{\text{abs}}^m$ 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 $A_0 = 0.0$ and the solar zenith angle $\theta_0 = 60^\circ$. (a) $\Sigma b_{\text{abs}}^m$. (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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reflection

transmission
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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Hansen & Hovenier (1974)
Phase angle ranges

inner planet

outer planet

you
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 inhomogenous (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)

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

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 ($b=10 @ 550 \text{ nm}$).

**Total flux $F$**

**Degree of polarization $P$**
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** $P$

primary rainbow

Rayleigh scattering
Information content of polarimetry

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

![Diagram showing unpolarized and polarized light]
Information content of polarimetry

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

**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 $r_{\text{eff}} = 2.0 \ \mu m$, $n_r = 1.3$ and $n_i = 0.00001$. 
Dependence on particle composition

- Total flux $F$
- Degree of polarization $P$

- 75% water
- 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.

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