Atmospheric characterisation of gas giants using polarimetry

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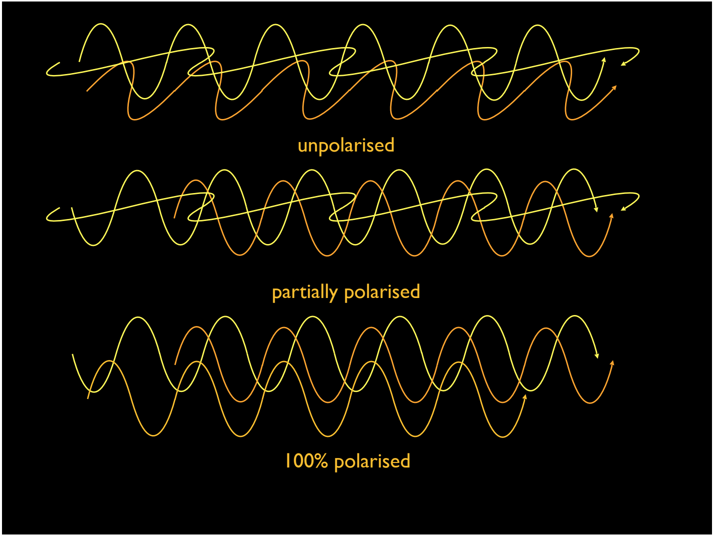
What is polarisation?



Polarisation in our everyday lives

Polarising sunglasses

3D cinema glasses

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https://www.fashioneyewear.co.uk/blog/wp-content/uploads/2012/07

Phase angle

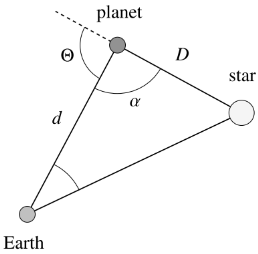


Image credits: Stam, D.M., Hovenier, J.W., &Waters, L. B. F. M. 2004, A&A

- α is the angle between the star, the planet, and the observer (known as the phase angle, or STO angle).

- The outer Solar System is only observable in a small phase angle range, for example, Jupiter is only accessible to Earth-based observations for phase angles of up to $\approx 12^\circ$.
- Exoplanets are generally observable at phase angles between $(90 - i)^\circ$ to $(90 + i)^\circ$, with i the orbital inclination angle. Phase angle 90° occurs at least twice every orbit (independent of i).

Light reflected by a planet

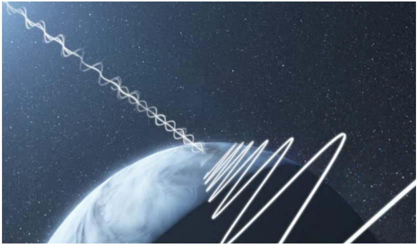


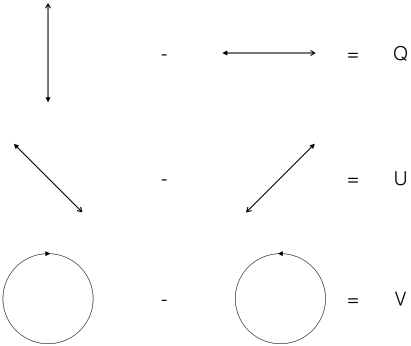
Image credit: ESOcast 60:
https://www.eso.org/public/announcements/ann13069/

- Incident unpolarised stellar light interacts with the planet's atmosphere and/or surface.
- The reflected light is polarised.
- The polarisation, as a function of both wavelength and phase angle, depends on the microstructure and vertical distribution of the atmospheric/surface constituents.

What do we measure?

The Stokes vector

$$\underline{S} = \begin{pmatrix} F \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} F'_{0^\circ} + F'_{90^\circ} \\ F'_{0^\circ} - F'_{90^\circ} \\ F'_{45^\circ} - F'_{-45^\circ} \\ F'_{RHC} - F'_{LHC} \end{pmatrix}$$



- F is the total flux from the source.
- Q and U represent linear polarisation.
- V represents the circular polarisation, which can be left or right-handed depending on which way the electric field vector is rotating around the propagation axis.

The scattering matrix

- Assuming unpolarised incident starlight, the Stokes vector of the reflected light is equal to that of the incident light, multiplied by the planetary scattering matrix.
- The scattering matrix depends on the local atmospheric/surface properties. For a symmetric exoplanet, the following holds true:

$$\begin{pmatrix} F \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \begin{pmatrix} F_0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

- For calculating reflected light from exoplanets, you have to integrate the locally reflected vectors across the illuminated and visible part of the planetary disk.
- Observationally, the above would have an additional term to include instrumental & telescope effects.

Why we need polarimetry

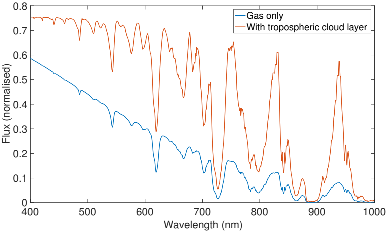
- Polarimetry can disentangle the polarised signal of an exoplanet from the (unpolarised) overwhelming glare of the parent star.
- Polarisation is a relative measure, so it is independent of the distance between the planet and the star, the radius of the planet, and the incident stellar flux.
- Signatures in polarisation spectra can reveal the presence of certain aerosol species - which cannot be seen in the flux spectra.
- Cold planets (such as those in the Solar System) are not very bright in the infrared, so cannot be detected through thermal emission.

Description of the model

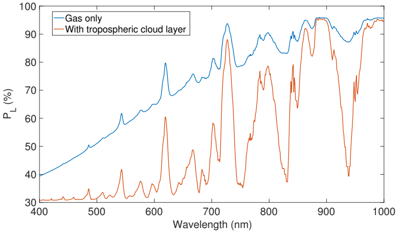
- Description of model can be found in Stam et al. 2004, A&A, 428, 663; Stam 2008, A&A, 482, 989.
- The model atmosphere is locally plane-parallel, and consists of a number of layers.
- Horizontally homogeneous, but vertically inhomogeneous.
- Each layer can contain any combination of gas, cloud and haze particles. ('cloud' is used to describe thick layers of large particles ($\geq 1\mu m$), whilst 'haze' is used in relation to optically thin layers of sub-micron sized particles).
- The radiative transfer code is an adding-doubling algorithm, fully incorporating multiple scattering and polarisation. For exoplanet models, the integrated signal from the illuminated part of the planetary disk is considered.
- All cloud particles considered are spherical, with their scattering properties calculated using Mie theory.

Spectral variation of flux and polarisation from an exo-Jupiter:

Models for a Jupiter-like planet at $\alpha = 90^\circ$. Blue lines show an atmosphere with gas only, red lines show one with a thick tropospheric ammonia cloud.



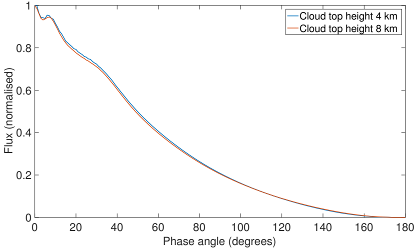
Flux



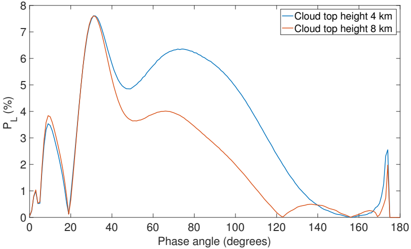
Polarisation

Phase angle variation for an exo-Earth:

Models for an Earth-like planet at 550 nm, with thick tropospheric water clouds. Blue line shows models with a cloud top of 4 km, red line shows models with a cloud top of 8 km.



Flux



Polarisation

The Solar System as a benchmark

- Many exoplanets are expected to have similar physical characteristics to bodies of the Solar System (?).
- Observations and model interpretations of Solar System planets and moons are thus crucial for our understanding of the structure of exoplanet atmospheres.
- There are still many open questions in Solar System planet composition.

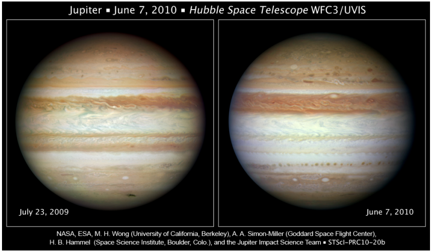


Image credit:
http://www.nasa.gov/images/content/462982main_p1020bw-m.jpg

Polarimetric characterisation of the clouds of Venus

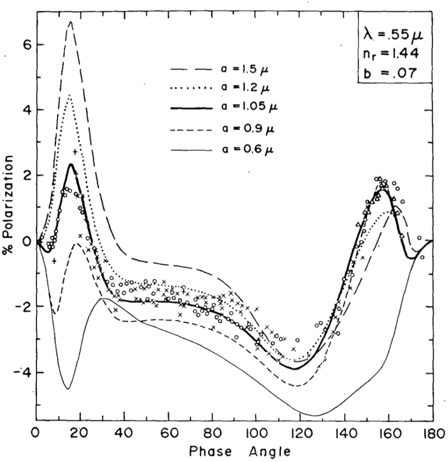
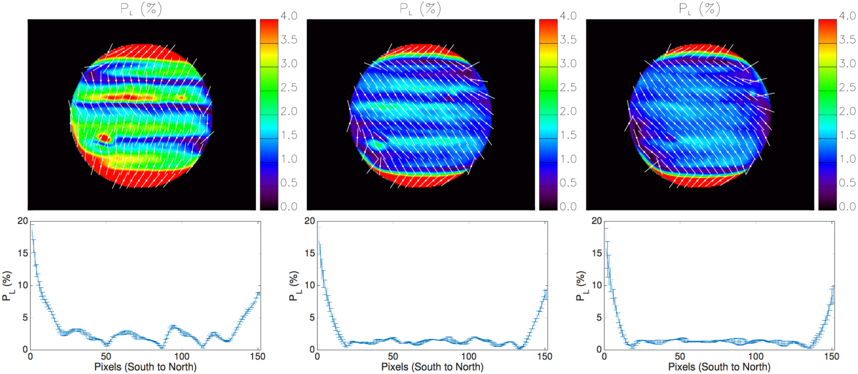


Image credit: Hansen, J. E., & Hovenier, J. W. 1974, J. Atmosph. Sci., 31, 1137

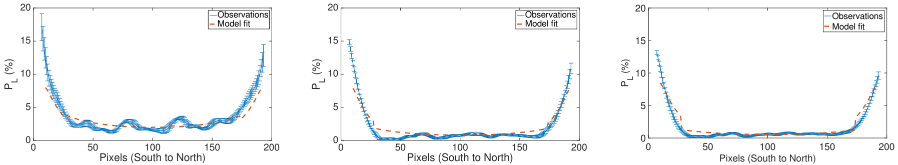
- Different curves show models with different effective radii. The points on the graph represent observations ranging from 1929 till 1971.
- The cloud particle type could not be derived from the intensity observations.
- Polarimetry was able to show that the cloud particles are spherical droplets, with an effective radius of 1.05 μm, and refractive index 1.44, consistent with sulphuric acid droplets. Later spacecraft observations confirmed this, thus showing that polarimetric observations are a very powerful tool for the remote sensing of planetary atmospheres.

Imaging polarimetry of Jupiter

Left to right: polarimetric maps of Jupiter, in the *B*, *V*, and *R* filters, constructed from data obtained with the 1 metre telescope at the Calern Observatory, France. Arrows indicate the direction of polarisation. Below each map a plot of the polarisation along the central meridian is shown.



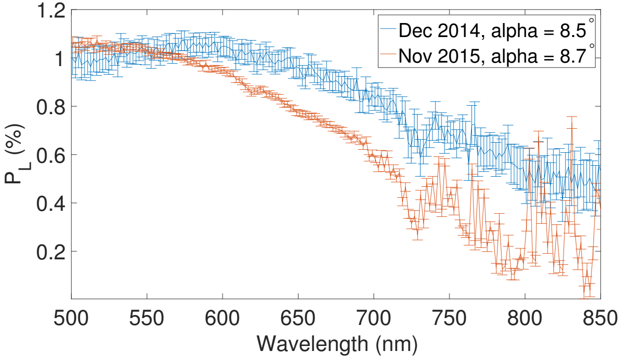
Model interpretation of these data



- Models fitted to the latitudinal profiles, consisting of a tropospheric ammonia cloud layer, and a diffuse stratospheric haze layer.
- Three parameter spaces to fit: planetary latitude, wavelength, and phase angle.
- Some model configurations fit 2/3 of these...but can't find one which is concurrent with all three parameters.
- Possible resolution to this could be to try different particles shapes - currently only using spherical particles (except for polar haze particles, which are fluffy aggregates).

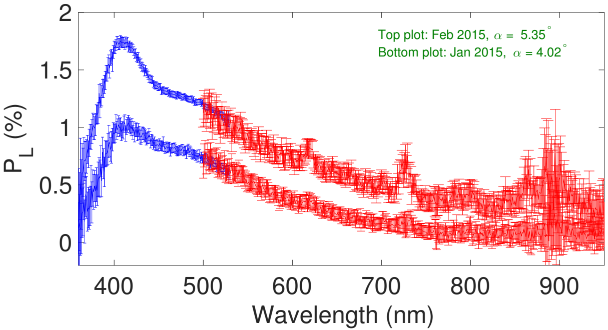
Spectropolarimetry of Jupiter

Two epochs: data for both taken with FoReRo2 in polarimetric mode, at the 2 metre telescope of NAO Rozhen, Bulgaria.



Spectropolarimetry of Saturn

Two epochs: data for both taken with ISIS in polarimetric mode, at the 4.2 metre WHT, La Palma.



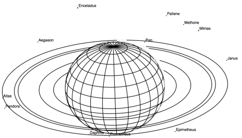


Image credit:
http://pds-rings.seti.org/

Integrated signal vs disk resolved

- Signal from the entire planet is a combination of the light scattering from all types of aerosol particles, and also rings, if present.
- Disk resolved signal can yield information about specific parts of the planet.
- For exoplanets, the entire signal will be contained within an area as small as one pixel on a CCD.
- Disk resolved observations of Solar System bodies (not just planets) can pave the way towards understanding future disk-integrated observations of all types of exoplanet.

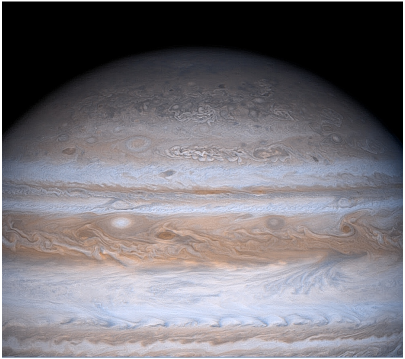


Image credit: Cassini Imaging Team, Cassini Project, NASA

Modelling: ways to improve

- Non-spherical particles cause quite different behaviour in the polarisation, so more models with these should be tested.
- Improved variation of refractive indices with wavelength - currently constrained with laboratory measurements.
- Absorption coefficients - changes in these influence model spectra.

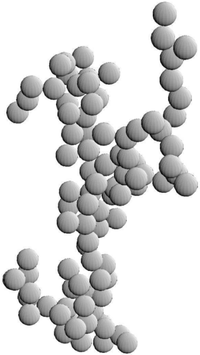


Image credit: Karalidi, T., Stam, D. M., & Guirado, D. 2013, A&A, 555, A127

Present state and future prospects

- HD189733b has been the subject of several polarimetric studies, with different groups reporting conflicting measurements.
- GPI and SPHERE both have polarimetric modes, and may be able to resolve polarised light from long-period exoplanets.
- Future instruments on the E-ELT will harness the larger collecting area (39 metres).

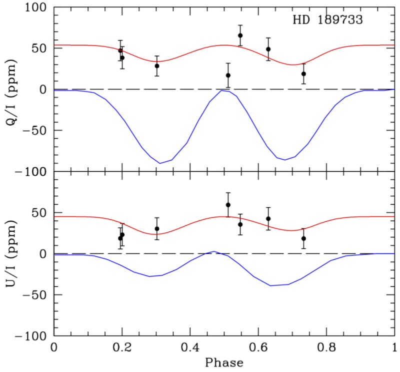


Image credit: Bott et al. 2016, arXiv:1603.05745v1 [astro-ph.EP].

Conclusion

- Polarimetry is a powerful tool for probing the atmospheric structure of exoplanets.
- It can disentangle the polarised reflected planetary radiation from the overwhelming (unpolarised) signal of the star.
- Variation with phase angle and wavelength can infer the type of cloud particle, and cloud altitude in the atmosphere.
- Further study of the atmospheres of the gaseous planets of the Solar System, and modelling of expected signals from exoplanets are the best ways with which to understand what to expect from future observations.

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Thank you