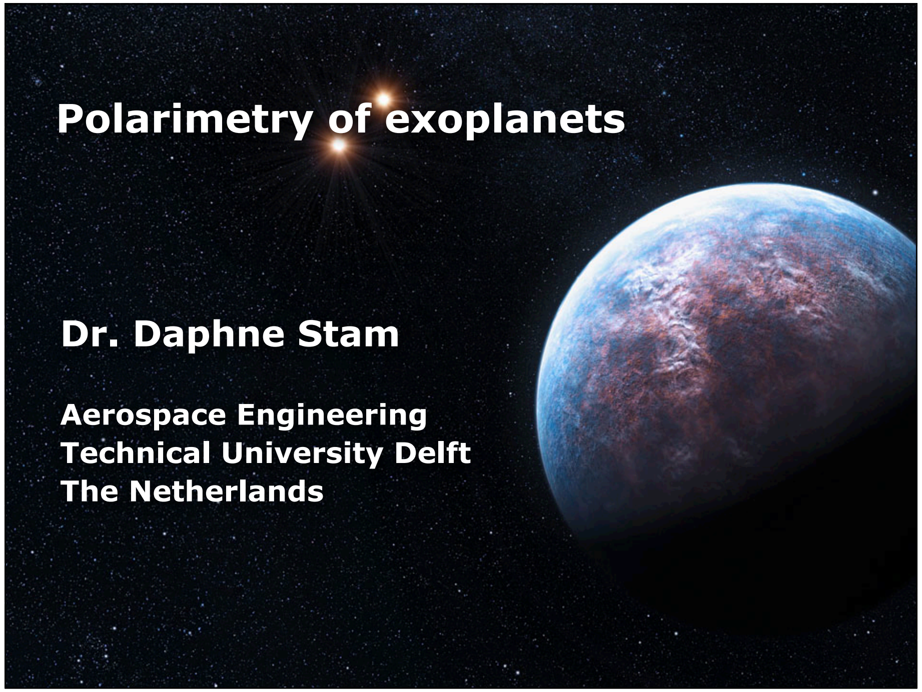


This lecture is about Polarimetry of Exoplanets.

Exoplanets or ‘extrasolar planets’ are planets that orbit other stars than the Sun.

Here is a beautiful artist’s impression of an exoplanet in orbit around 2 red dwarf stars.

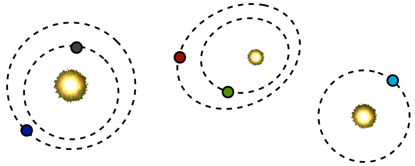
For centuries, people have looked up in the sky and wondered whether there were other worlds like the Earth.

The other planets in the Solar System are ...

A historical note on exoplanets

Christiaan Huygens (Cosmotheoros, 1698):

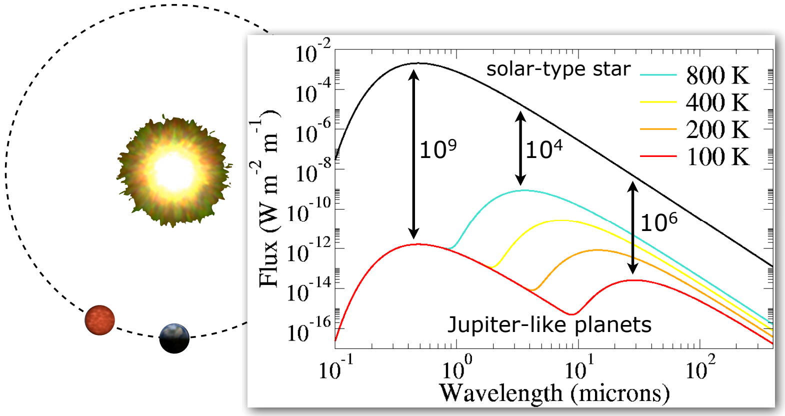
'What prevents us from believing that, just like our own Sun, each of those stars or Suns, is surrounded by planets, each in turn surrounded by their own moons?'



'We are far from observing planets around the stars because they are very faint, and because their orbits are indistinguishable from the observed spot of starlight.'

Why are exoplanets so difficult to detect? 1

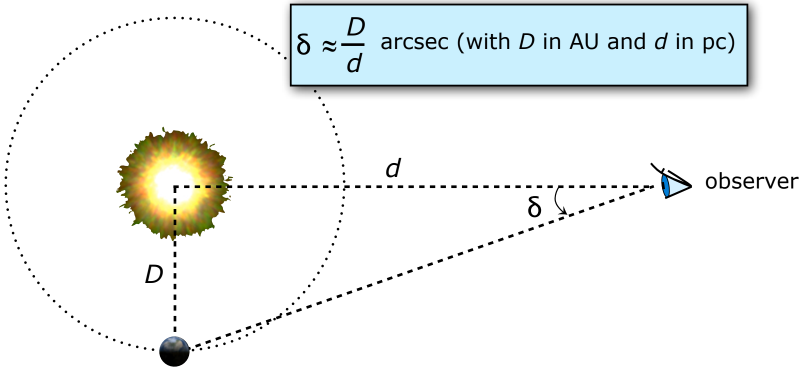
A planet is extremely faint compared to its parent star



Why are exoplanets so difficult to detect? 2

A planet is located very close to its parent star as seen from afar

$\delta \approx \dfrac{D}{d}$ arcsec (with D in AU and d in pc)



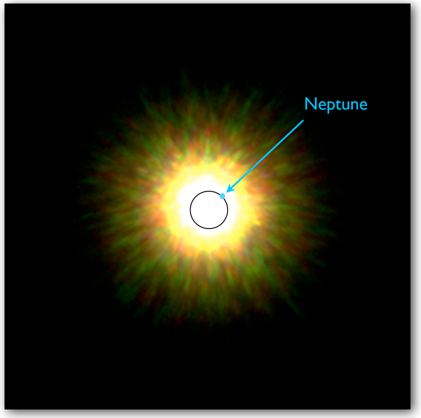
By definition: 1 AU at 1 pc is seen under an angle of 1 arcsec
1 pc = 1 parsec (parallax second)= 3.262 light years

Moon is half a degree on the sky: 30 arcminutes = 30*60=1800 arcseconds.

Best seeiing: 0.5”

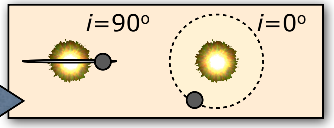
Why are exoplanets so difficult to detect? 2

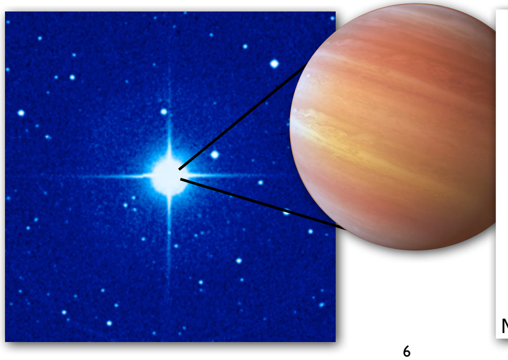
A sharp picture of a solar-type star using an 8-m, ground-based telescope with adaptive optics (Gemini North):

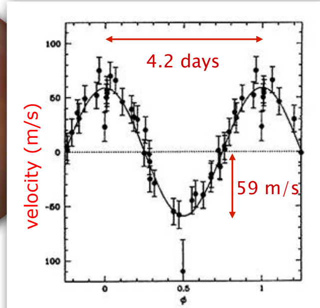


1995: First exoplanet around solar-type star!

- Parent star: 51 Peg (G5 star)
- Distance to Solar System: 15.36 pc
- Planet properties: D= 0.05 AU
  P= 4.2 days
  $M_p \sin i$= 0.5 M_{Jup}





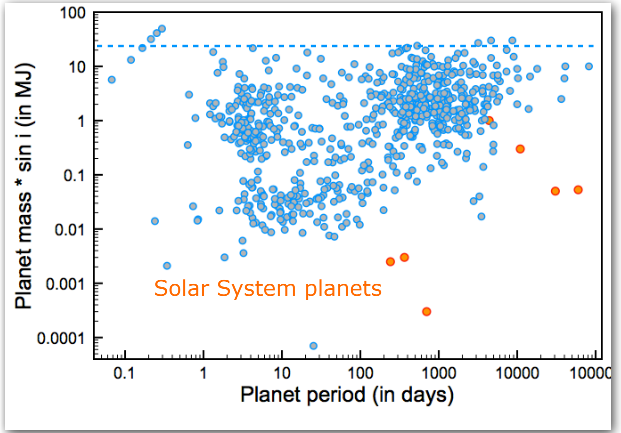


Mayor & Queloz [1995]

almost

All exoplanets found to date

The 889 exoplanets found with different detection methods:



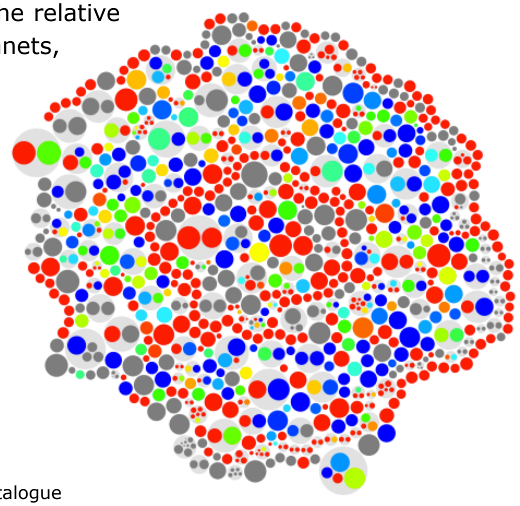
Data from exoplanet.eu

All found through indirect methods ... so we know little about their properties ...

A nice plot of the currently known exoplanets

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

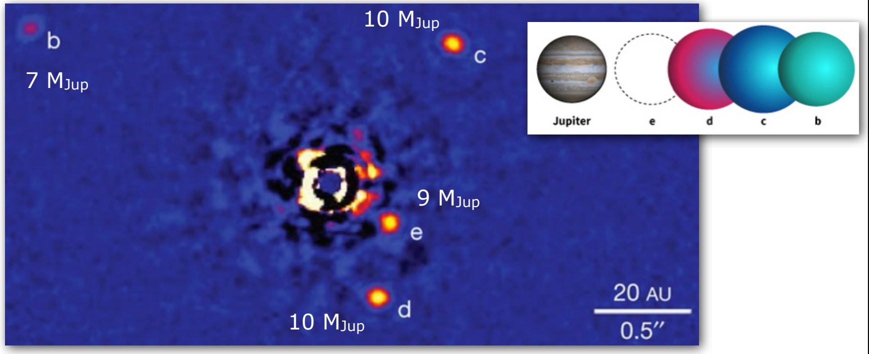
Green: maybe ok for life
Blue: too cold for life
Red: too hot for life
Gray: no info



Plot from the Open Exoplanet Catalogue

Next step: direct detections

With a direct detection, you measure either the thermal radiation of a planet or the starlight that is reflected by the planet:

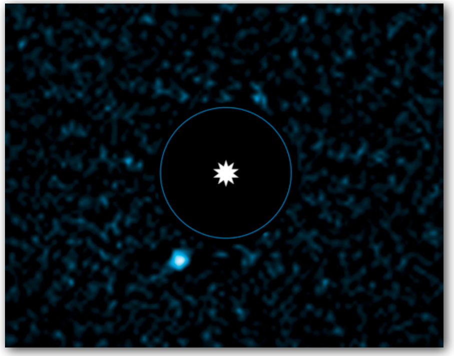


4 hot planets around HR 8799 [Marois et al., 2008, 2010], observed with the Keck and Gemini telescopes

These are hot planets!
And they are really far out!
Not suitable for life!

Next step: direct detections

A very recent (June 3, 2013) direct detection! This exoplanet would be the lightest imaged so far:

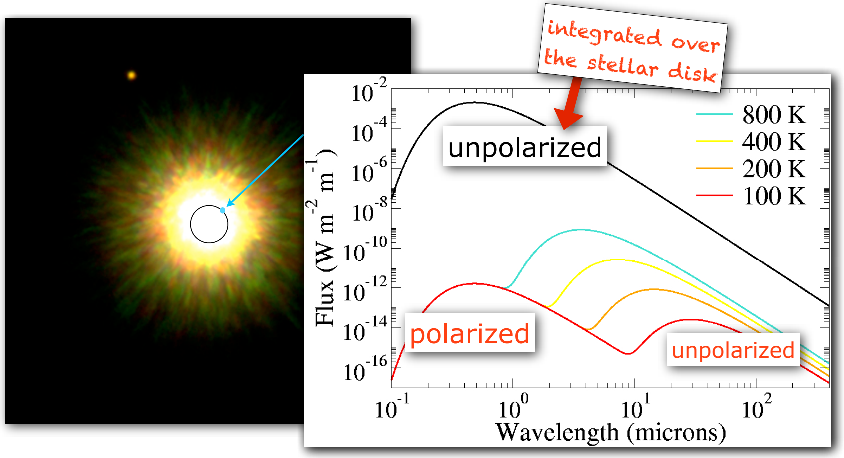


Observed in the IR with NACO/VLT [Rameau et al., 2013]. This planet has a mass of about 4-5 Jupiters, and orbits its star at about 56 AU.

These are hot planets!
And they are really far out!
Not suitable for life!

Directly detecting the Solar System:

A sharp picture of a solar-type star using an 8-m, ground-based telescope with adaptive optics (Gemini North):



Why is reflected starlight polarized?

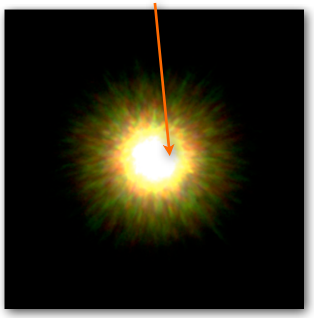
Starlight that is reflected by (exo)planets is usually polarized because it has been:

- scattered by gaseous molecules
- scattered by aerosol and/or cloud particles
- reflected by the surface (if there is any)

Polarimetric accuracy

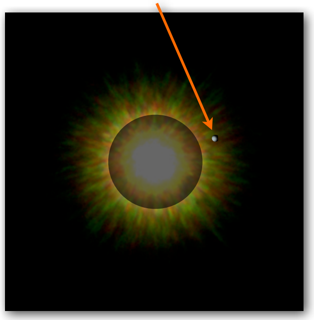
The accuracy that is needed to detect the polarized signal of an exoplanet depends strongly on the background signal of starlight and, e.g. exo-zodiacal light:

Close-in planets



Instrument example:
PlanetPol (Jim Hough)

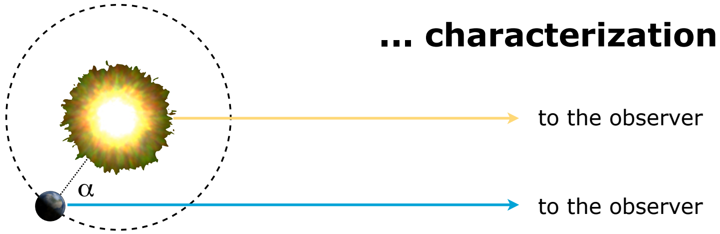
Resolved planets



Instrument examples:
SPHERE/VLT, GPI/Gemini, EPICS/ELT

In the following, I will concentrate on the polarized flux of a planet, spatially resolved from its star!

Polarimetry for exoplanet detection
... confirmation
... characterization



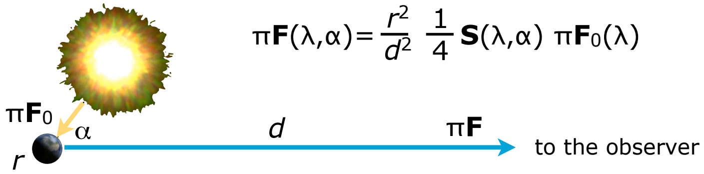
The degree of polarization *P* of reflected starlight depends on*:

- 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

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

Flux and polarization of reflected starlight

The Stokes vector $\pi\mathbf{F}$ of the reflected starlight is given by:



$$\pi\mathbf{F}(\lambda,\alpha) = \frac{r^2}{d^2}\,\frac{1}{4}\,\mathbf{S}(\lambda,\alpha)\;\pi\mathbf{F}_0(\lambda)$$

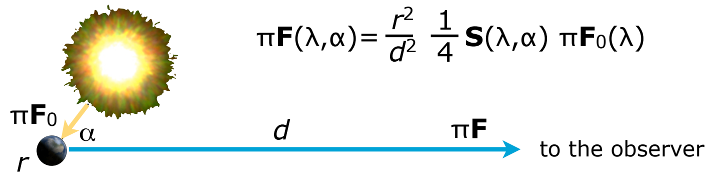
With:

- $\pi\mathbf{F}$ the flux vector arriving at the observer at a distance d
- $\pi\mathbf{F}_0$ the flux vector of starlight arriving at the planet with radius r
- $\mathbf{S}$ the planetary scattering matrix

We assume that the incident starlight is unidirectional!
The equation is thus not applicable for extremely close-in exoplanets!

Flux and polarization of reflected starlight

The Stokes vector $\pi\mathbf{F}$ of the reflected starlight is given by:



$$\pi\mathbf{F}(\lambda,\alpha) = \frac{r^2}{d^2}\,\frac{1}{4}\,\mathbf{S}(\lambda,\alpha)\;\pi\mathbf{F}_0(\lambda)$$

Written out:

$\frac{1}{4}S11$ = geometric albedo planet

$$\pi\begin{bmatrix} F(\lambda,\alpha) \\ Q(\lambda,\alpha) \\ U(\lambda,\alpha) \\ V(\lambda,\alpha) \end{bmatrix} = \frac{r^2}{d^2}\,\frac{1}{4}\begin{bmatrix} S_{11}(\lambda,\alpha) & S_{12}(\lambda,\alpha) & S_{13}(\lambda,\alpha) & S_{14}(\lambda,\alpha) \\ S_{21}(\lambda,\alpha) & S_{22}(\lambda,\alpha) & S_{23}(\lambda,\alpha) & S_{24}(\lambda,\alpha) \\ S_{31}(\lambda,\alpha) & S_{32}(\lambda,\alpha) & S_{33}(\lambda,\alpha) & S_{34}(\lambda,\alpha) \\ S_{41}(\lambda,\alpha) & S_{42}(\lambda,\alpha) & S_{43}(\lambda,\alpha) & S_{44}(\lambda,\alpha) \end{bmatrix}\pi\begin{bmatrix} F_0(\lambda) \\ Q_0(\lambda) \\ U_0(\lambda) \\ V_0(\lambda) \end{bmatrix}$$

Flux and polarization of reflected starlight

In the following, we assume unpolarized incident starlight:
$\pi \mathbf{F}_0(\lambda) = \pi F_0(\lambda)\,[1, 0, 0, 0]$

Written out:

$$\pi \begin{bmatrix} F(\lambda,\alpha) \\ Q(\lambda,\alpha) \\ U(\lambda,\alpha) \\ V(\lambda,\alpha) \end{bmatrix} = \frac{r^2}{d^2}\frac{1}{4} \begin{bmatrix} S_{11}(\lambda,\alpha) \\ S_{21}(\lambda,\alpha) \\ S_{31}(\lambda,\alpha) \\ S_{41}(\lambda,\alpha) \end{bmatrix} \pi\, F_0(\lambda)$$

$$P(\lambda,\alpha) = \frac{\sqrt{(S_{21}{}^2(\lambda,\alpha) + S_{31}{}^2(\lambda,\alpha) + S_{41}{}^2(\lambda,\alpha))}}{S_{11}(\lambda,\alpha)}$$

The planetary scattering plane

The planetary scattering plane (through star, planet, and observer) is the reference plane for the polarized fluxes:

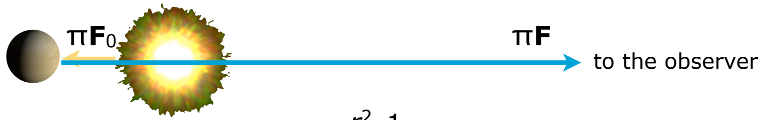
If the planet is mirror-symmetric with respect to the reference plane:

- the reflected starlight is linearly polarized, not circularly V=0!
- the direction of polarization is perpendicular or parallel to the plane!

U=0!

Mirror-symmetric planets

If the planet is mirror-symmetric with respect to the reference plane, *U* and *V* equal zero!



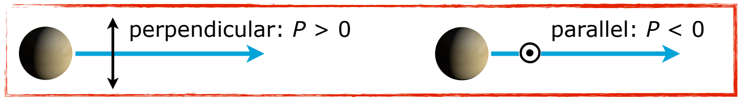
Thus:

$$\pi F(\lambda,\alpha) = \frac{r^2}{d^2}\frac{1}{4}\, S_{11}(\lambda,\alpha)\, \pi F_0(\lambda)$$

$$\pi Q(\lambda,\alpha) = \frac{r^2}{d^2}\frac{1}{4}\, S_{21}(\lambda,\alpha)\, \pi F_0(\lambda)$$

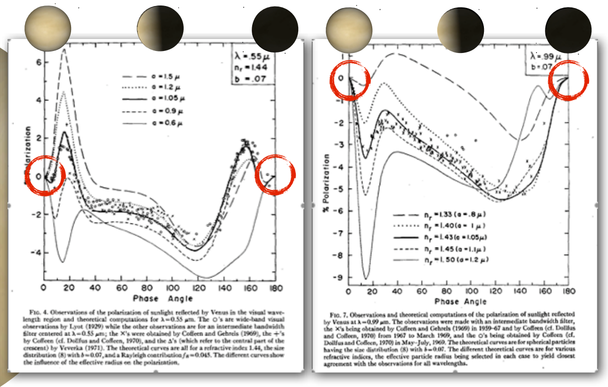
And:

$$P(\lambda,\alpha) = \frac{\sqrt{S_{21}^2(\lambda,\alpha)}}{S_{11}(\lambda,\alpha)} = - \frac{S_{21}(\lambda,\alpha)}{S_{11}(\lambda,\alpha)}$$



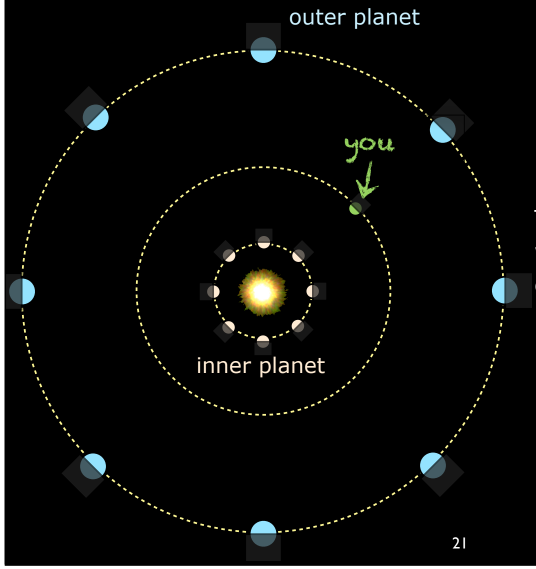
Solar System example: polarimetry of Venus

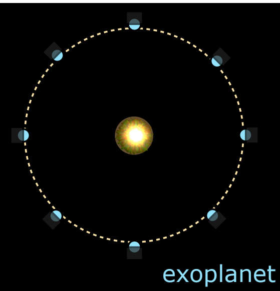
The degree of linear polarization *P* of sunlight reflected by Venus as function of phase angle α, for two different wavelengths λ:



Hansen & Hovenier [1974] used ground-based polarimetry to derive the size, composition, and altitude of Venus' cloud particles

Phase angle ranges





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

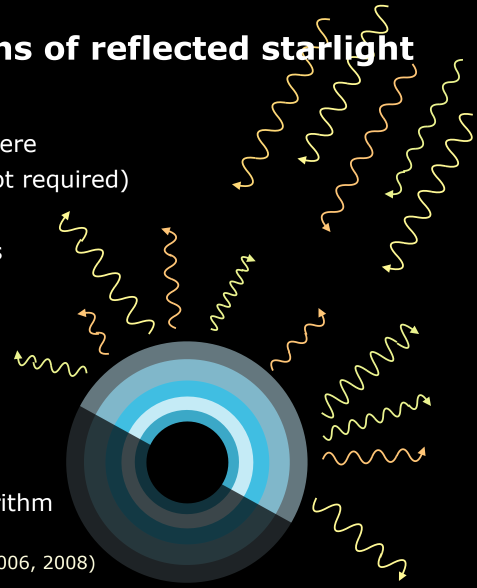
$$90^\circ - i \leq \alpha \leq 90^\circ + i$$

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

Numerical simulations of reflected starlight

Planet models:
- locally plane-parallel atmosphere
- horizontally homogeneous (not required)
- vertically inhomogeneous
- gases, aerosol, cloud particles

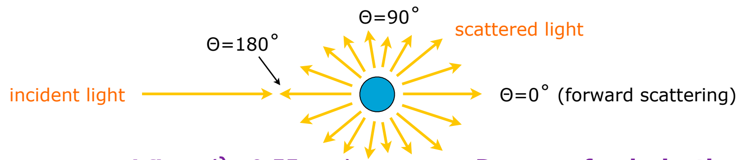
Radiative transfer code:
- adding-doubling algorithm
- fluxes and polarization
- single and multiple scattering
- efficient disk-integration algorithm



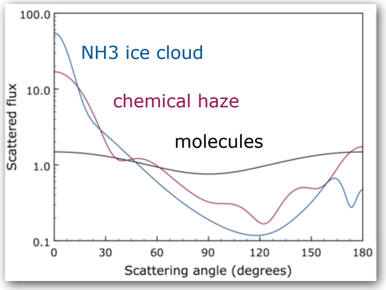
(for details, see e.g. Stam et al. 2004, 2006, 2008)

Single scattering fluxes and polarization

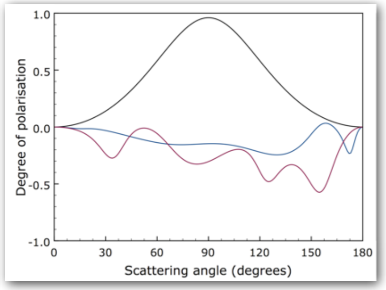
The flux and polarization of an exoplanet depend strongly on the single scattering flux and polarization of atmospheric particles:



Total flux (λ=0.55 μm)



Degree of polarization *P*

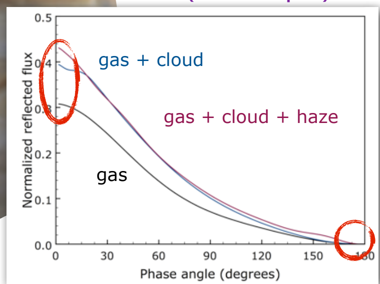


Fluxes and polarization as functions of α

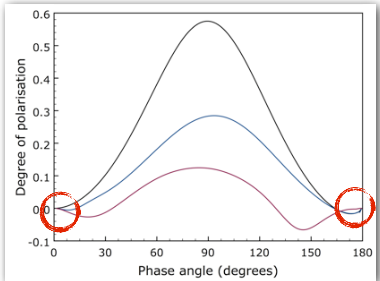
The flux and polarization of starlight reflected by 3 Jupiter-like model exoplanets as functions of the phase angle α (Stam et al., 2004):

Atmosphere 1: only gas molecules
Atmosphere 2: gas + tropospheric ice cloud
Atmosphere 3: gas + cloud + stratospheric haze

Total flux (λ=0.55 μm)



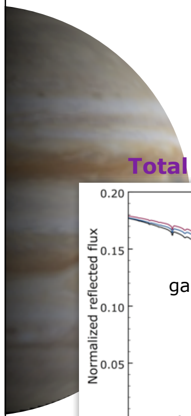
Degree of polarization *P*



Red circles: difficult to observe!

Fluxes and polarization as functions of λ

The flux and polarization of starlight reflected by 3 Jupiter-like model exoplanets as functions of the wavelength λ (Stam et al., 2004):

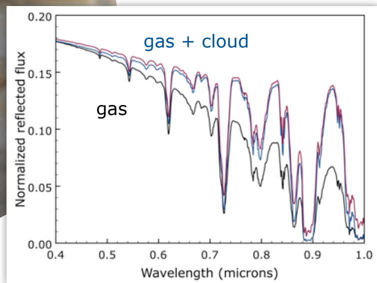


Atmosphere 1: only gas molecules (0.18% CH_4)

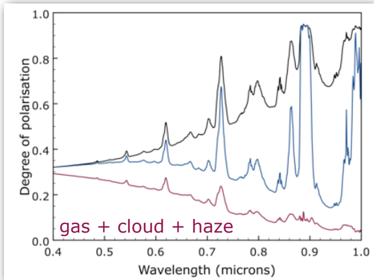
Atmosphere 2: gas + tropospheric ice cloud

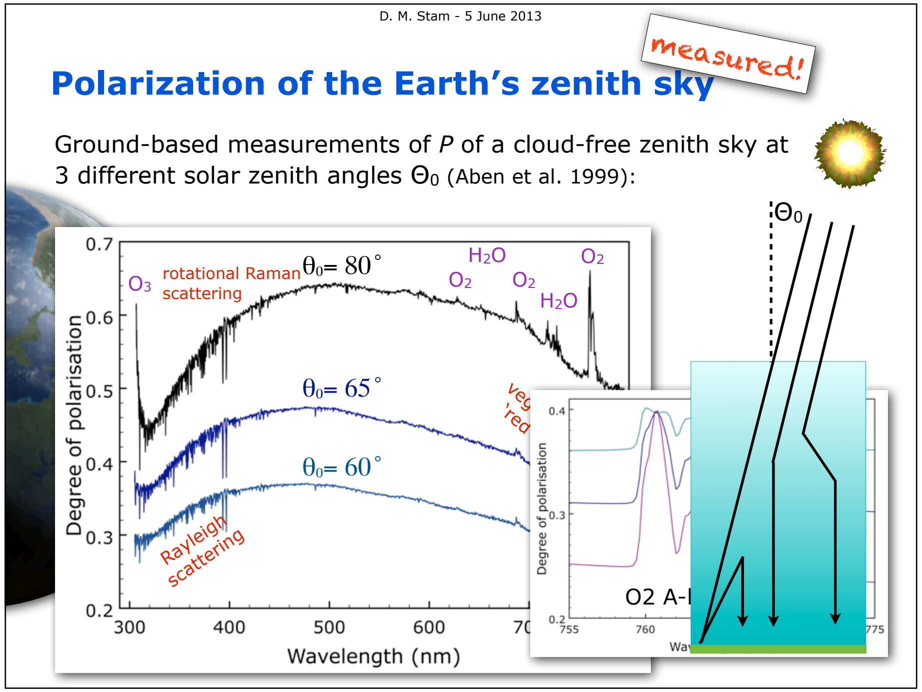
Atmosphere 3: gas + cloud + stratospheric haze

Total flux (α=90°)



Degree of polarization *P*

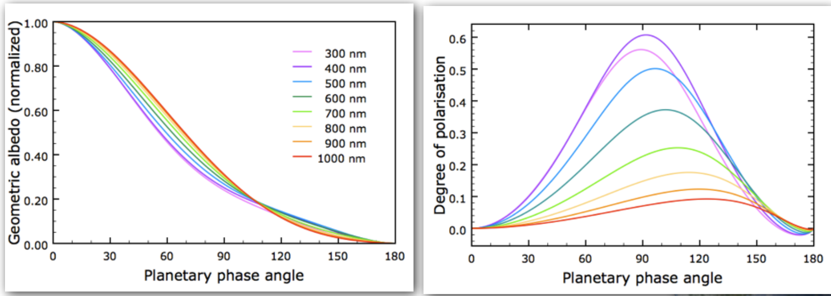




Dit is hoge spectrale resolutie: moeilijk te meten voor exoplaneten omdat je daarvoor veel fotonen nodig hebt!

Fluxes and polarization of exo-Earths

The flux and polarization of starlight reflected by an Earth-like model exoplanet with a purely gaseous atmosphere as functions of α:



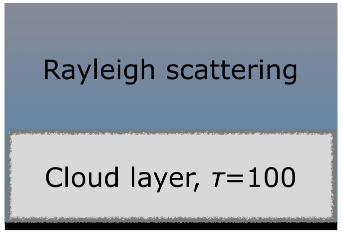
The atmosphere's optical thickness varies approximately from:

1 (@ 300 nm) to 0.1 (@ 500 nm) to 0.01 (@ 1000 nm).

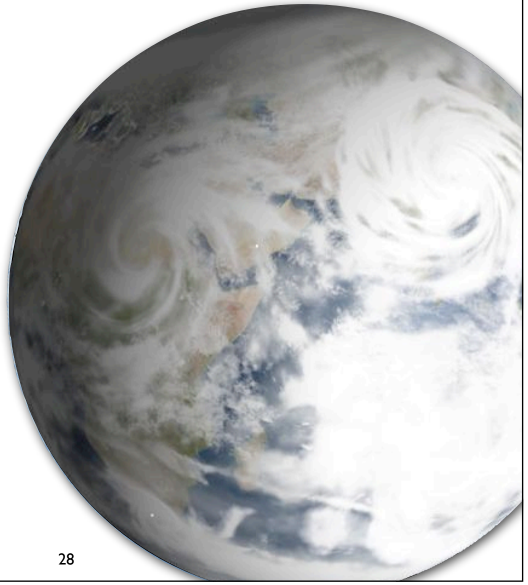
The surface reflects unpolarized light and has an albedo of 0.1.

Fluxes and polarization of cloudy exo-Earths

The model atmosphere:

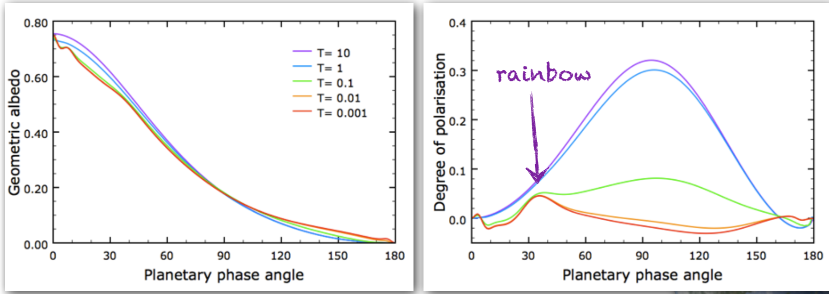


Almost black surface

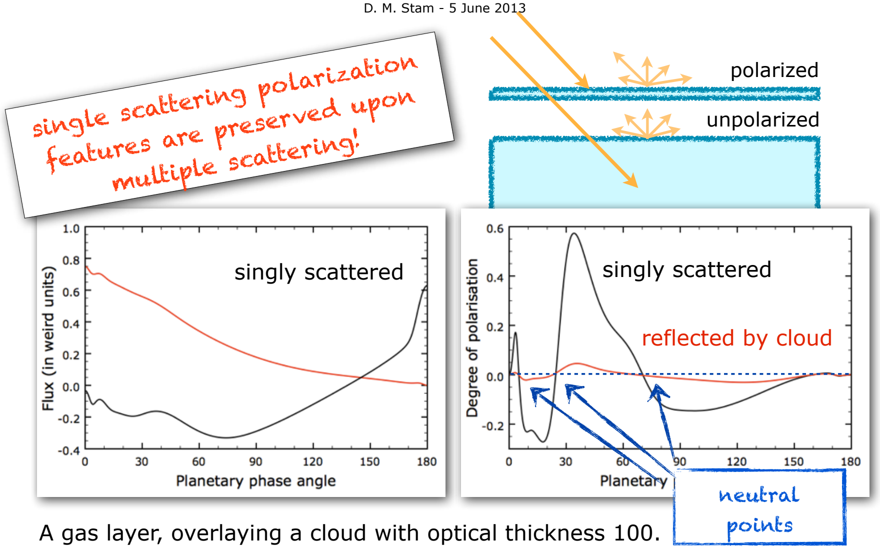


Fluxes and polarization of exo-Earths

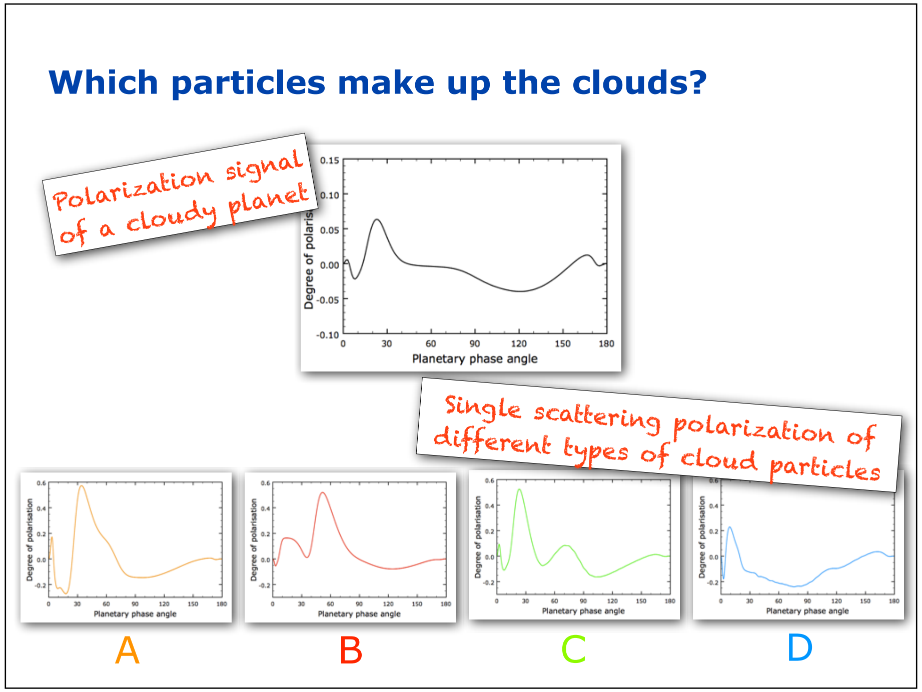
The flux and polarization of starlight reflected by an Earth-like model exoplanet with a **cloud below a gas layer** as functions of α:



A gas layer, overlaying a cloud with optical thickness 100.
Spherical cloud droplets, with r_{eff}=2.0 μm, n_r=1.3 and n_i=0.00001.
The cloud top altitude/optical thickness τ of the gas layer is varied.



A gas layer, overlaying a cloud with optical thickness 100.
Spherical cloud droplets, with r_{eff}=2.0 μm, n_r=1.3 and n_i=0.00001.
The optical thickness τ of the gas layer is 0.001.

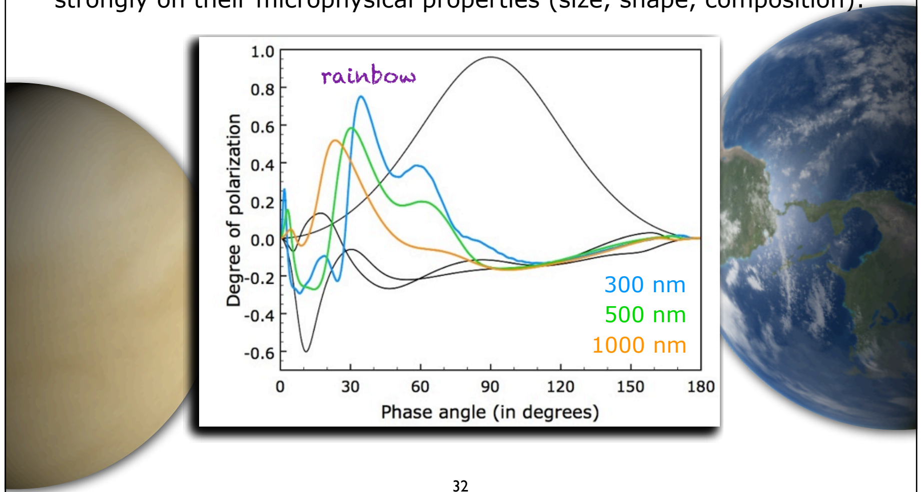


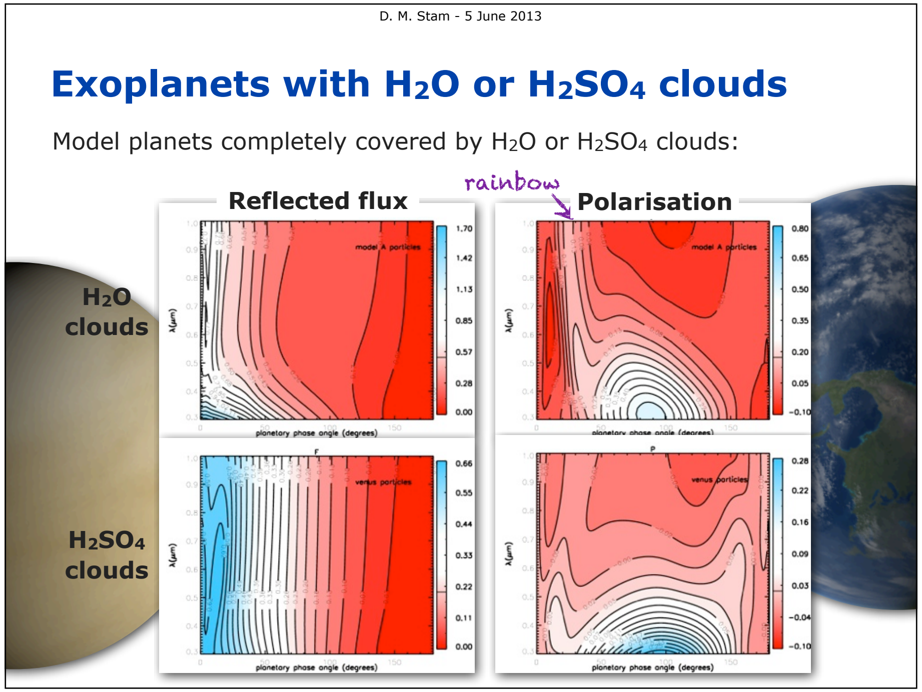
A: 1.2
B: 1.3
C: 1.4
E: 1.6

All 2 micron sized!

Single scattering by cloud particles

The single scattering polarization phase function of particles depends strongly on their microphysical properties (size, shape, composition):

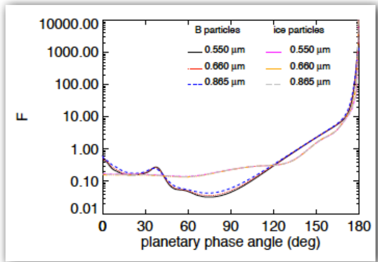


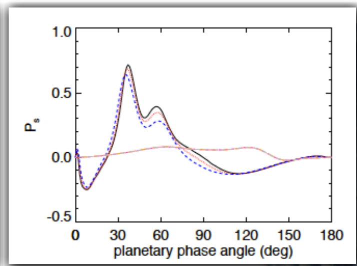


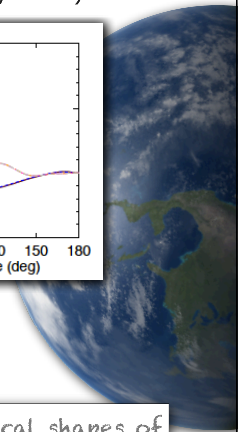
The rainbow would indicate liquid water on a planet, at least in the clouds.
These model planets are completely covered by the clouds.
For an Earth, that is not very realistic!

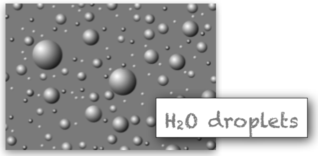
Signals of a realistic Earth-like exoplanet

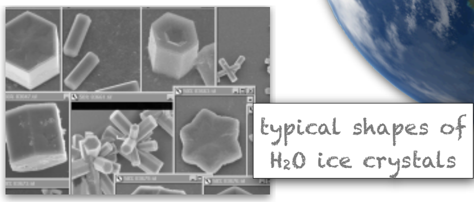
The Earth is not completely covered by clouds and has liquid water clouds as well as water ice clouds (from Karalidi et al., 2013):





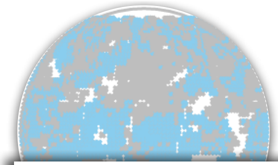




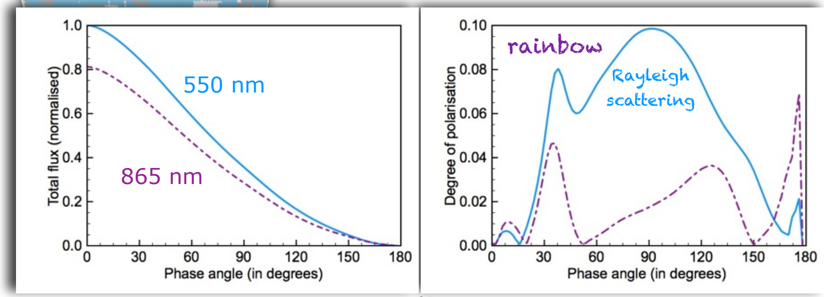


Signals of a realistic Earth-like exoplanet

Using cloud parameter data from an Earth remote-sensing satellite, an Earth-like model planet with a realistic cloud coverage was made:



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.

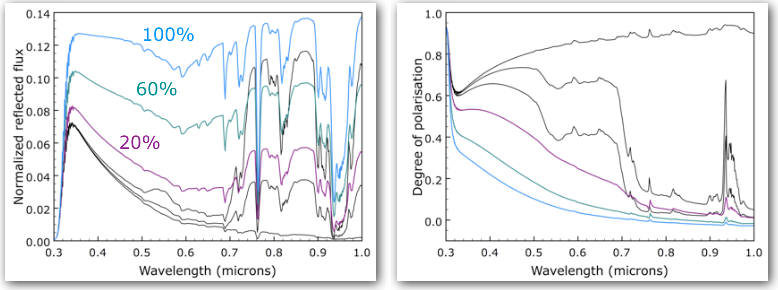


Ice clouds can disturb the detection of

Spectral signatures of exo-Earths

The flux and polarization of starlight reflected by Earth-like model exoplanets as functions of the wavelength λ (Stam, 2008):

Total flux ($\alpha=90^\circ$) **Degree of polarization *P***



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%.

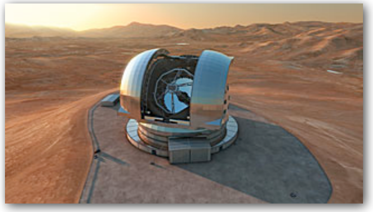
Ice clouds can disturb the detection of

Polarimeters for exoplanet research

Polarimetry for the direct detection and characterization of exoplanets is a growing field:

SPHERE/VLT (2013)

GPI/Gemini South (2013)



EPICS/E-ELT (202?)

A space telescope (20??)

A spectropolarimetry for exoplanet research

LOUPE: The Lunar Observatory for Unresolved Polarimetry of Earth

From the moon, we can monitor the whole Earth:

- during its daily rotation
- at phase angles from 0° to 180°
- throughout the seasons
- outside the Earth’s atmosphere

This cannot be done from:

- Low Earth Orbit satellites
- geostationary satellites
- Earth-shine observations
- non-dedicated missions (e.g. Galileo, Venus Express, ...)

A first detection of exoplanet polarization?

The Astrophysical Journal, 673: L000–L000, 2008 January 20
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FIRST DETECTION OF POLARIZED SCATTERED LIGHT FROM AN EXOPLANETARY ATMOSPHERE

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Received 2007 October 22; accepted 2007 November 28; published 2007 December 20

ABSTRACT

We report the first direct detection of an exoplanet in the visible polarized light. The transiting planet HD 189733b is one of the very hot Jupiters with shortest periods and, thus, smallest orbits, which makes them ideal candidates for polarimetric detections. We obtained polarimetric measurements of HD 189733 in the *B* band well distributed over the orbital period and detected two polarization maxima near planetary elongations with a peak amplitude of $\sim 2 \times 10^{-4}$. Assuming Rayleigh scattering, we estimated the effective size of the scattering atmosphere (Lambert sphere) to be $1.5 \pm 0.2\ R_J$, which is 30% larger than the radius of the opaque body previously inferred from transits. If the scattering matter fills the planetary Roche lobe, the lower limit of the geometrical albedo can be estimated as 0.14. The phase dependence of polarization indicates that the planetary orbit is oriented almost in a north-south direction with a longitude of ascending node $\Omega = (16° \text{ or } 196°) \pm 8°$. We obtain independent estimates of the orbit inclination $i = 98° \pm 8°$ and eccentricity $e = 0.0$ (with an uncertainty of 0.05), which are in excellent agreement with values determined previously from transits and radial velocities. Our findings clearly demonstrate the power of polarimetry and open a new dimension in exploring exoplanetary atmospheres even for systems without transits.

Subject headings: planetary systems — stars: individual (HD 189733)techniques: polarimetric

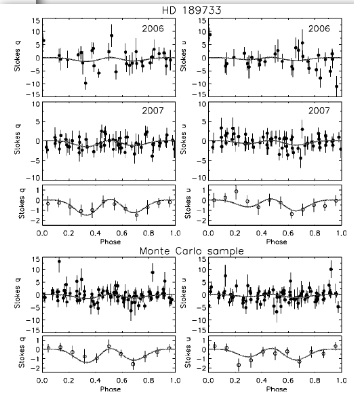

Fig. 1.—Polarimetric data (Stokes q and u with $\pm 1\ \sigma$ error bars on the scale of 10^{-4}) for HD 189733 and a Monte Carlo simulated sample. The original data are shown with filled circles: for HD 189733 in the year 2006 (*top*) and for 2007 (*middle*), and for the Monte Carlo simulated data combined for both years (*bottom*). The data rebinned for equal phase intervals are shown with open circles in separate panels. For HD 189733, the constant shifts in Stokes parameters Δq and Δu were subtracted from the data according to Table 1.

Still a bit controversial:

- These measurements have not yet been confirmed by other polarimeters.
- To fit the data, this exoplanet should have a very high degree of polarization.
- The model calculations include no multiple scattering of light.

Summary

- Polarimetry appears to be a strong tool for the detection and confirmation of exoplanets
- Polarimetry can help to characterize exoplanetary atmospheres and surfaces because it is very sensitive to their composition and structure, while the reflected flux is far less sensitive

Common sense:

- We will get so few photons from exoplanets, we have to retrieve all the information they carry with them
- When observing polarized light, such as starlight reflected by exoplanets, the telescope and instrument design *have* to take polarimetry into account even if the science case only calls for total flux measurements!