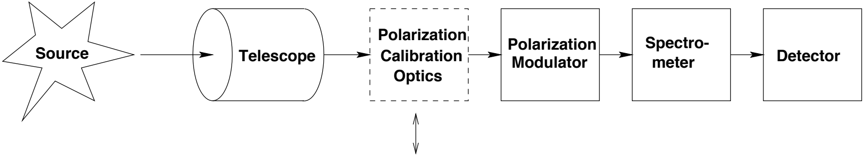
Polarimeters

1. Polarimetry Approaches
2. Some Polarimeters
3. Exoplanet Polarimetry with the E-ELT

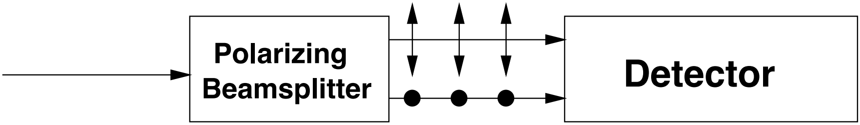
Temporal and Spatial Modulation

General Polarimeters



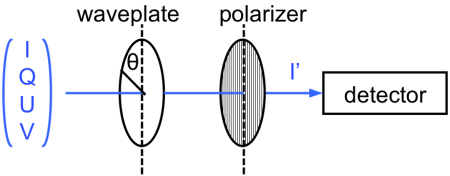
- polarimeters: optical elements (e.g. retarders, polarizers) that change polarization state of incoming light in controlled way
- detectors always measure only intensities
- intensity measurements combined to retrieve polarization state of incoming light
- polarimeters vary by polarization modulation scheme
- polarimeter should also include polarization calibration optics

Spatial Polarization Modulation



- polarizing beam-splitter polarimeter
- simple linear polarimeter: polarizing beam-splitter producing 2 beams corresponding to 2 orthogonal linear polarization states
- full linear polarization information from rotating assembly
- *spatial modulation*: simultaneous measurements of two (or more) Stokes parameters

Temporal Polarization Modulation



- rotating waveplate polarimeter
- rotating retarder, fixed linear polarizer
- measured intensity as function of retardance δ, position angle θ

$$I' = \frac{1}{2}\left(I + \frac{Q}{2}\left((1+\cos\delta) + (1-\cos\delta)\cos 4\theta\right) + \frac{U}{2}(1-\cos\delta)\sin 4\theta - V\sin\delta\sin 2\theta\right)$$

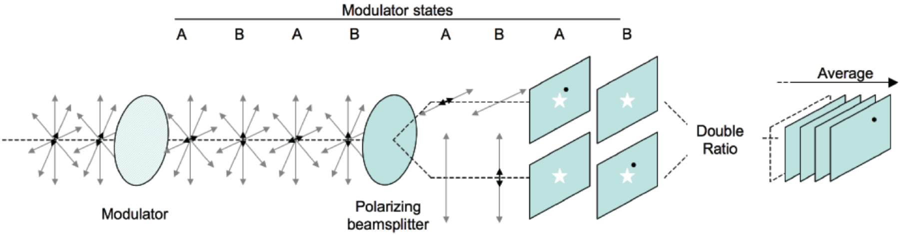
- only terms in θ lead to modulated signal
- equal modulation amplitudes in Q, U, and V for δ=127°
- *temporal modulation*: sequential measurements of $I\pm$ one or more Stokes parameters

Comparison of Temporal and Spatial Modulation Schemes

Modulation	Advantages	Disadvantages
temporal	negligible effects of flat field and optical aberrations	influence of seeing if modulation is slow
	potentially high polarimetric sensitivity	limited read-out rate of array detectors
spatial	off-the-shelf array detectors	requires up to four times larger sensor
	high photon collection efficiency	influence of flat field
	allows post-facto reconstruction	influence of differential aberrations

schemes rather complementary $\Rightarrow$ modern, sensitive polarimeters use both to combine advantages and minimize disadvantages

Double-Ratio Technique Implementation



- combination of spatial and temporal modulation
- rotating waveplate, polarizing beamsplitter
- waveplate switches between orthogonal polarization states
- both beams are recorded simultaneously

Double-Ratio Technique Data Analysis

- two intensity measurements in two beams each

$$S_A^l = g_l \alpha_A (I_A + Q_A), \quad S_A^r = g_r \alpha_A (I_A - Q_A)$$
$$S_B^l = g_l \alpha_B (I_B - Q_B), \quad S_B^r = g_r \alpha_B (I_B + Q_B)$$

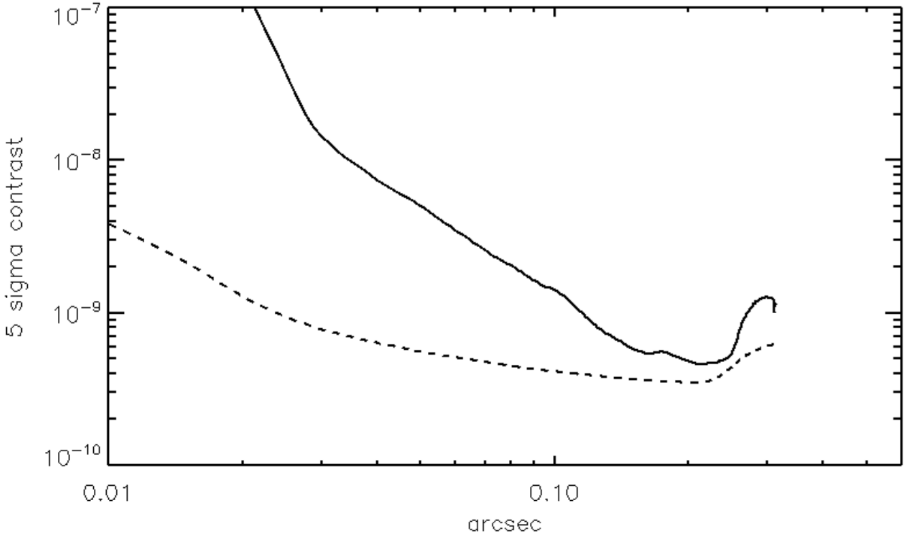
  - subscript A, B: modulator state
  - subscripts l, r: left, right beams
  - S: measured signal
  - g: gain in particular beam
  - α: transmission of atmosphere, instrument

- combine 4 measurements

$$\frac{1}{4}\left(\frac{S_A^l}{S_B^l}\frac{S_B^r}{S_A^r} - 1\right) = \frac{1}{2}\frac{I_B Q_A + I_A Q_B}{I_A I_B - I_B Q_A - I_A Q_B + Q_A Q_B} \approx \frac{1}{2}\left(\frac{Q_A}{I_A} + \frac{Q_B}{I_B}\right)$$

- average Q/I signal of two exposures
- no spurious polarization signals

Dual Beam Gain with EPICS at the E-ELT

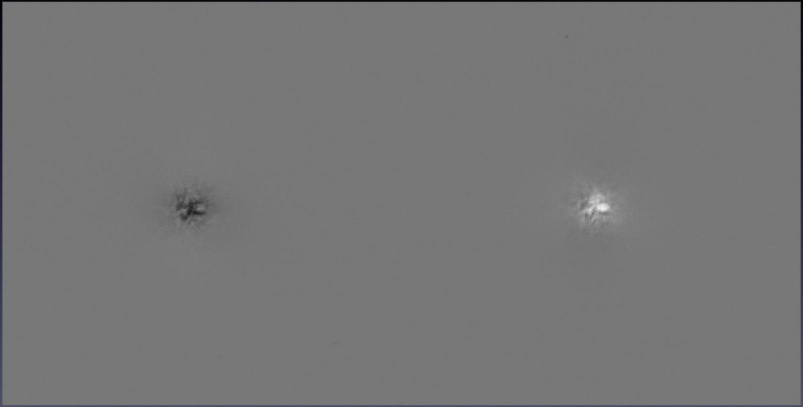


left beam right beam

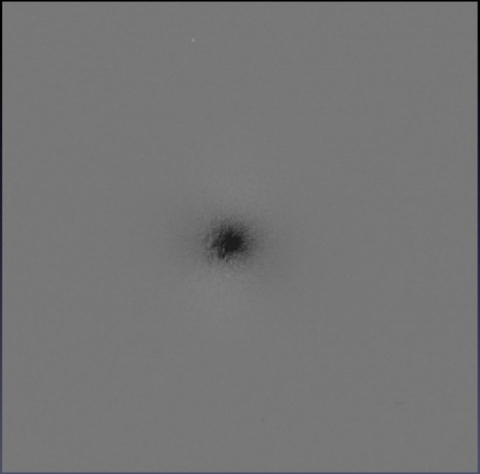
FLC state A

FLC state B

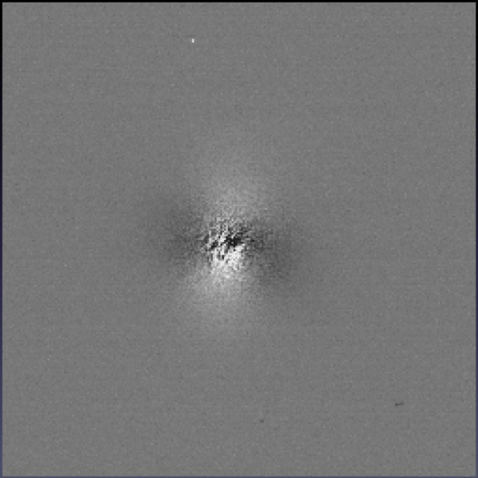
FLC states (A-B)



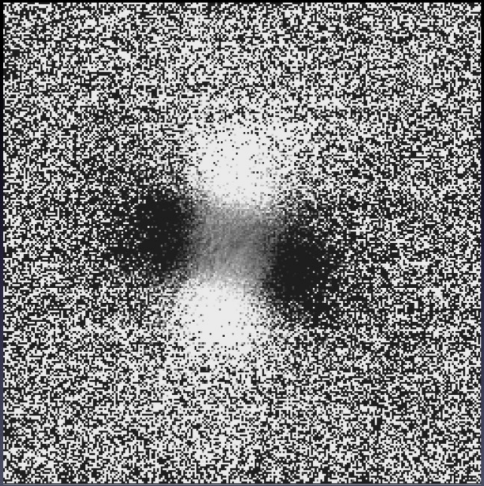
$(A\text{-}B)_{left} - (A\text{-}B)_{right}$



+ 0.7% * intensity



Division by Intensity



HARPS Polarimeter

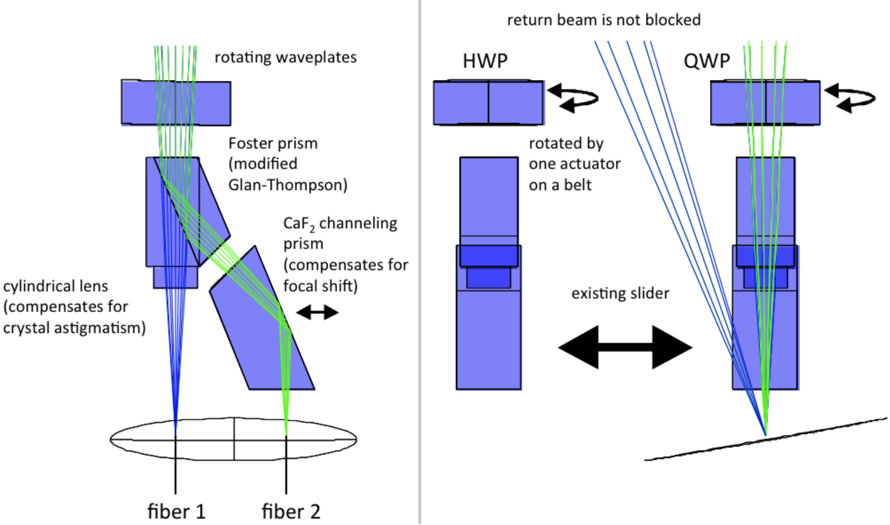
Introduction

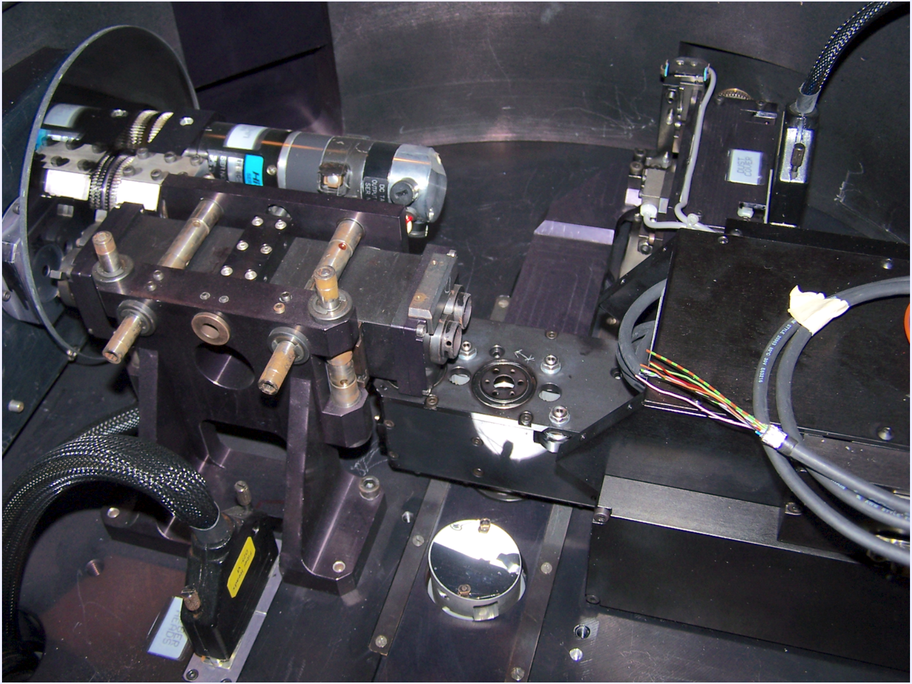
- HARPS: Radial Velocity exoplanet finder
- measure magnetic fields of planet-hosting stars
- best high-resolution spectropolarimeter in southern hemisphere

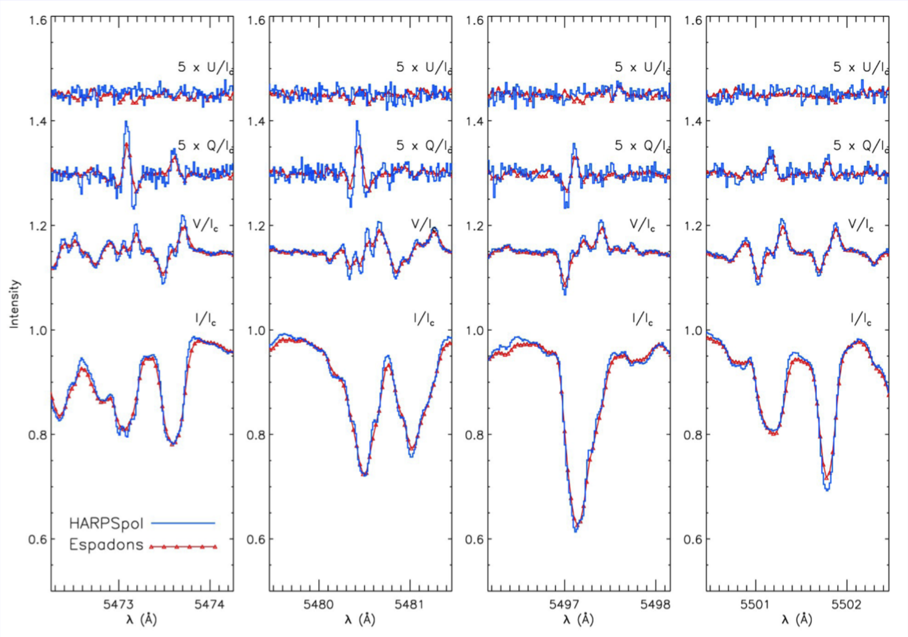
Requirements

- Use slider and volume of Iodine cell
- Do not compromise performance and operations of HARPS
- Full Stokes
- Polarimetric sensitivity 10^{-4} for one night on a bright star
- 380-690 nm
- Minimal instrumental polarization
- Minimal (polarized) fringes

optical design







5 x U/I$_c$
5 x Q/I$_c$
V/I$_c$
I/I$_c$
Intensity
HARPSpol
Espadons
λ (Å)

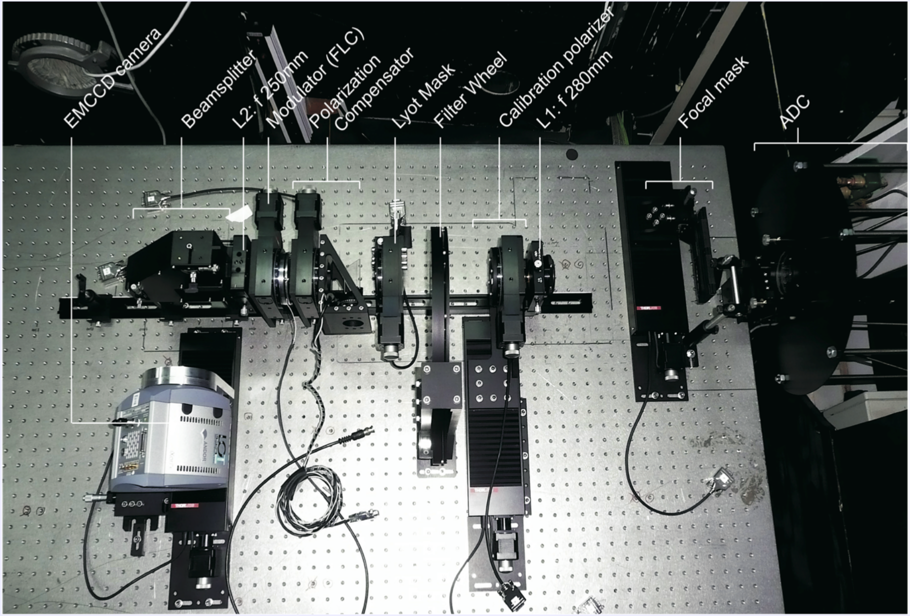
Liquid Crystal Polarimeters

Introduction

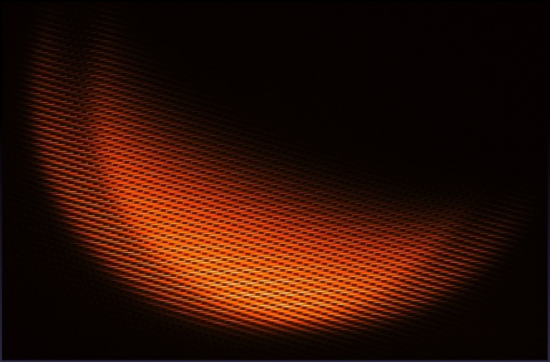
- no moving parts
- nematic liquid crystals
  - change retardance with applied electric field
  - relatively slow (<50 Hz)
  - electrically tunable for different wavelengths
- ferro-electric liquid crystals
  - flip fast axis orientation with applied electric field (2 states only)
  - fast (<10 kHz)
  - fixed retardation and optimum wavelength
- often combinations of variable liquid crystal retarders and fixed retarders

Extreme Polarimeter (ExPo)

- imaging polarimetry testbed at 4.2-m William Herschel Telescope
- 500-900nm dual-beam, FLC
- EM-CCD, <35 frames/s, <1e⁻ RON
- sCMOS, 50 frames/s, ~1e⁻ RON
- 97-actuator Adaptive Optics


EMCCD camera
Beamsplitter
L2: f 250mm
Modulator (FLC)
Polarization
Compensator
Lyot Mask
Filter Wheel
Calibration polarizer
L1: f 280mm
Focal mask
ADC

The Future: pIFU

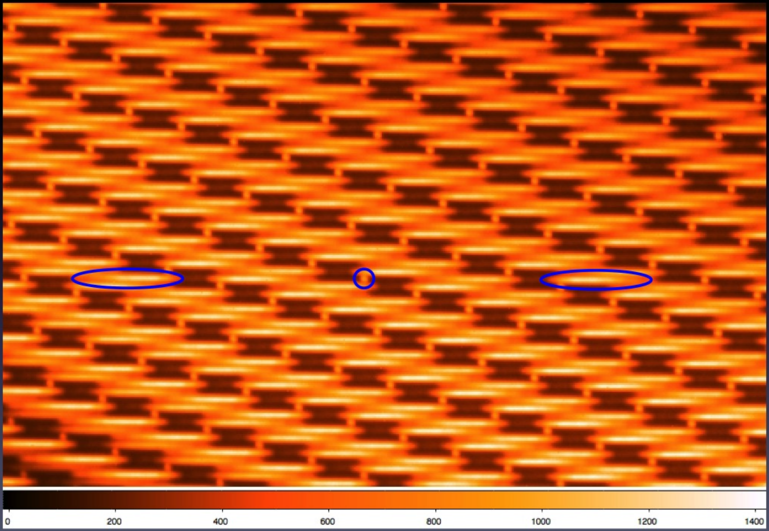


Venus
(Rodenhuis 2013)

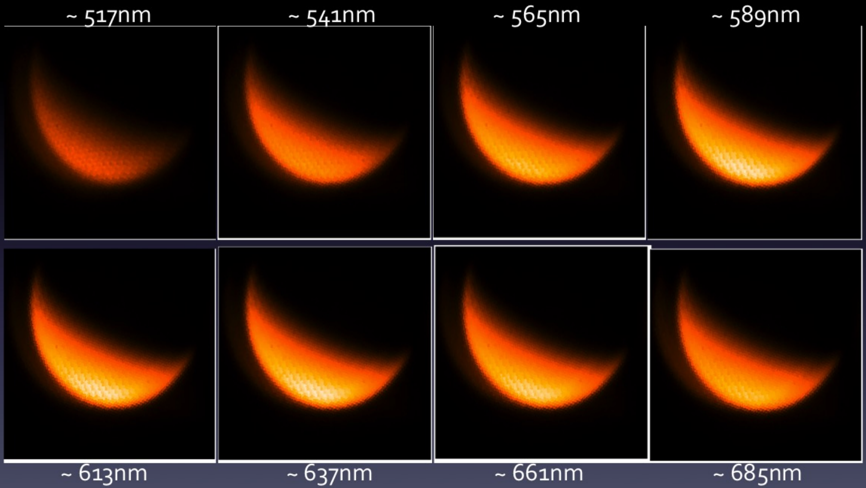
- 450-900 nm, R~25
- polarization grating: pol. beamsplitter and transmission grating
- polychromatic modulation at up to 50Hz
- solves all wavelength-dependent effects

Interleaved, Polarized Spectra

(0th & +/-1 order indicated)



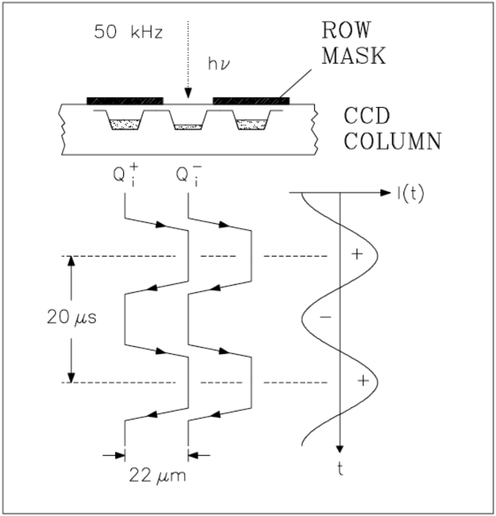
Extracted Intensity Images of Venus



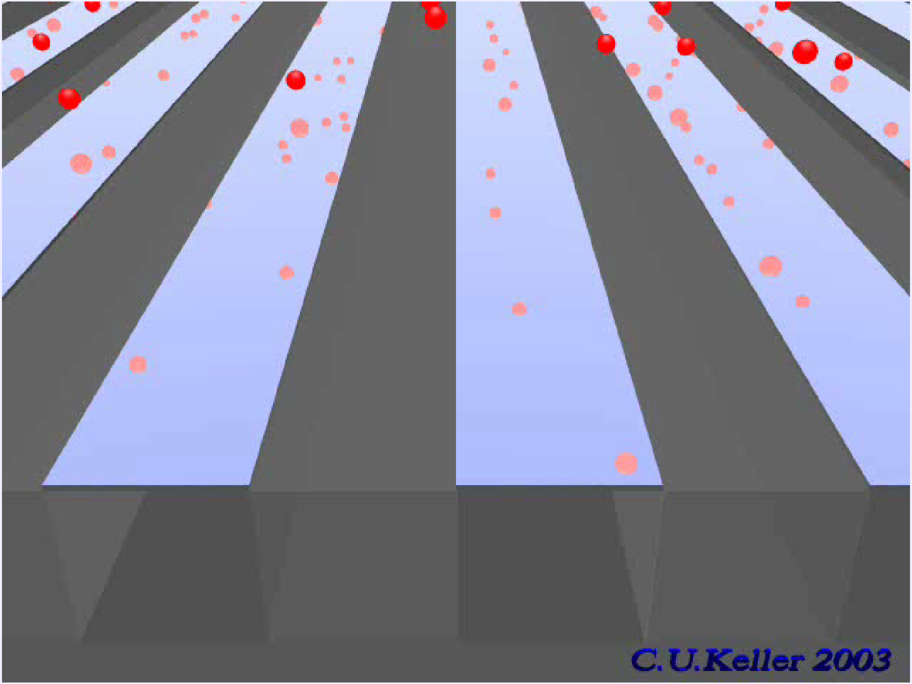
8 out of 18 wavelength bins, 500 – 800 nm

Zurich Imaging Polarimeter (ZIMPOL)

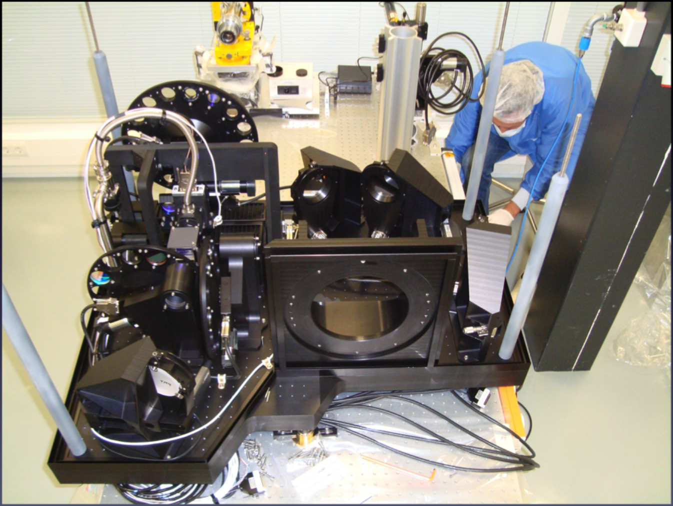
CCD Operating Principle



- developed at ETH Zurich by H.P.Povel and coworkers about 25 years ago
- center piece of SPHERE/ZIMPOL at VLT
- fractional polarization free of flat-field effects
- no seeing effects due to high modulation frequency

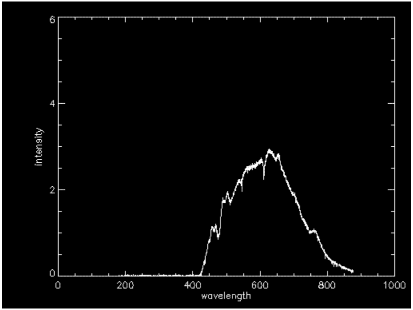

C.U.Keller 2003

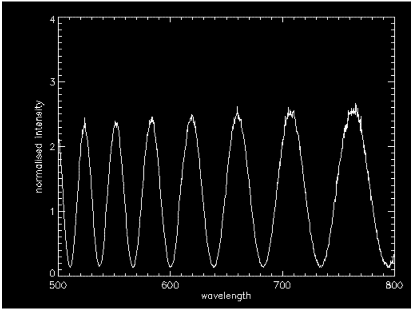
SPHERE/ZIMPOL for VLT



Spectral Modulation

Introduction

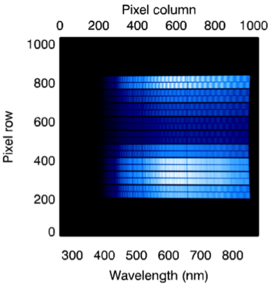


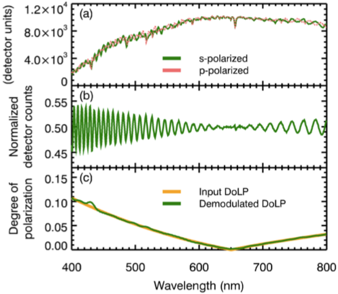


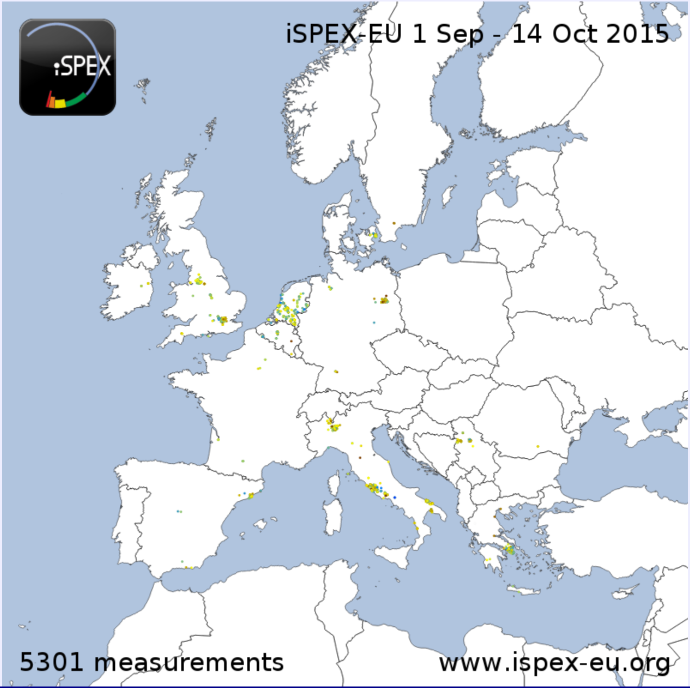
- modulation amplitude = degree of linear polarization ($\sqrt{Q^2 + U^2}/I$)
- modulation phase = orientation of linear polarization (arctan Q/U)
- completely passive, single-exposure measurement
- no differential effects

SPEX: Spectropolarimeter for Planetary EXploration

- measure size distribution and composition of dust in planetary atmospheres
- broad range of applications
  - groundSPEX: ground-based aerosol measurements
  - airSPEX on NASA ER-2
  - SPEX on PACE satellite
  - designs for Mars, Jupiter, Titan, Earth-as-exoplanet from moon
  - iSPEX

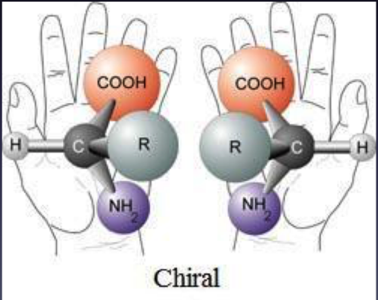


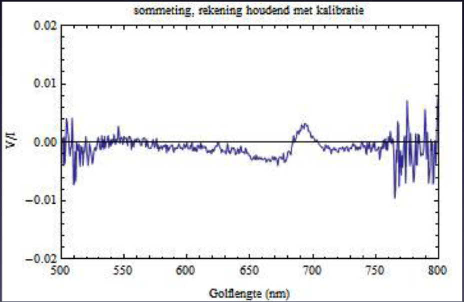



iSPEX
iSPEX-EU 1 Sep - 14 Oct 2015
5301 measurements
www.ispex-eu.org

Finding Life: Circular Polarization

- Amino acids, natural sugar twisted in same direction (homochirality)
- Twist makes circularly polarized light



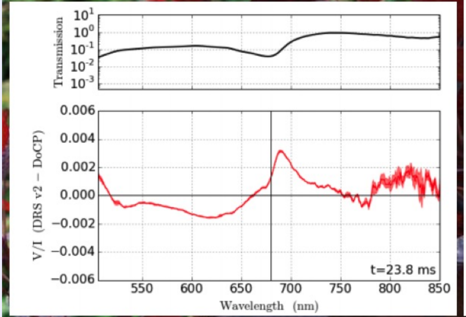


chemwiki.ucdavis.edu/Organic_Chemistry/Case_Studies/What_is_Organic%3F

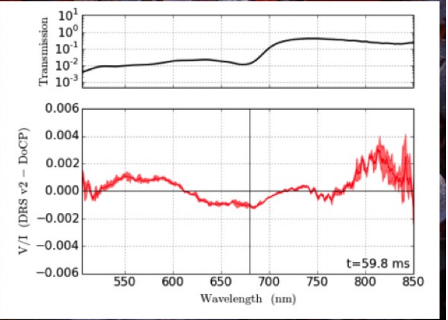
Lumens (2011)

red cotinus leaf (transmission)

freshly picked



after a week



Visser & Snik (2014)

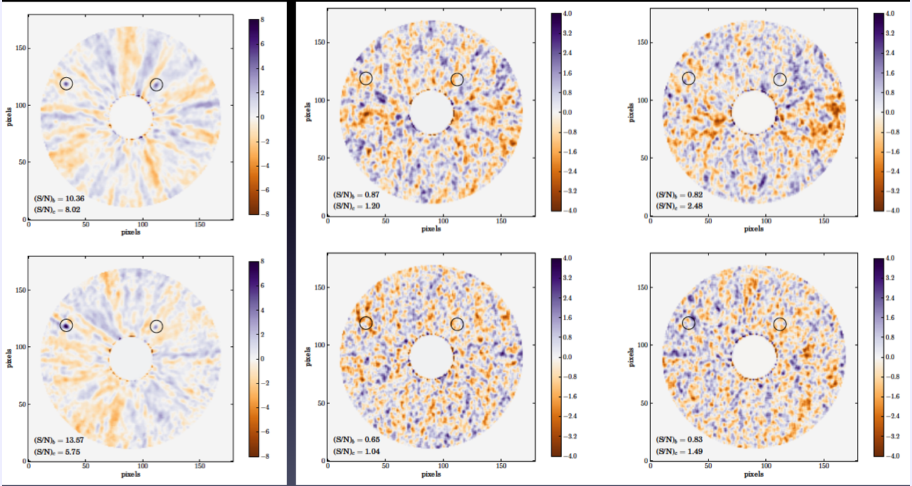
Exoplanet Polarimetry with the E-ELT

EPICS / PCS

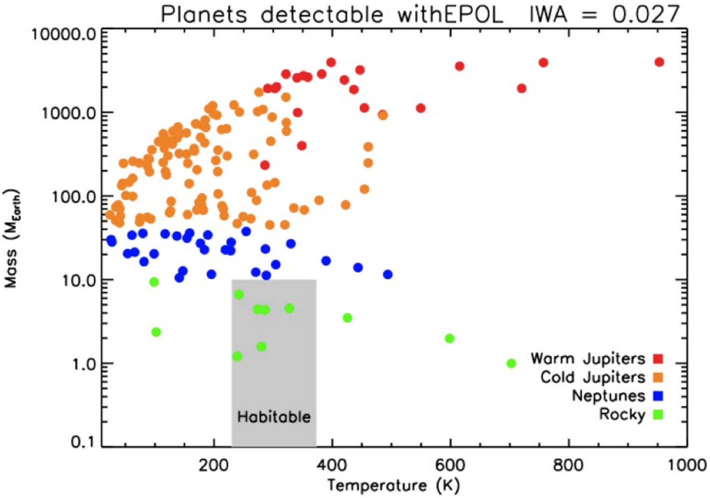
- Exo-Planets Imaging Camera and Spectrograph
- Addresses principal E-ELT science goal: detect and characterize exoplanets to answer question: are we alone?
- selected for construction subject to technical readiness
- SPHERE-like instrument for E-ELT
- will contain visible-light imaging polarimeter and/or imaging spectro-polarimeter

NACO/VLT HR8799 b,c

I Q U

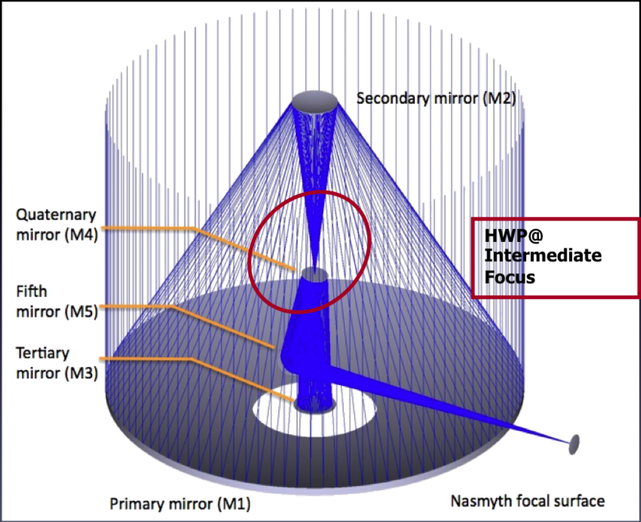


de Juan Ovelar, Snik et al., to be submitted

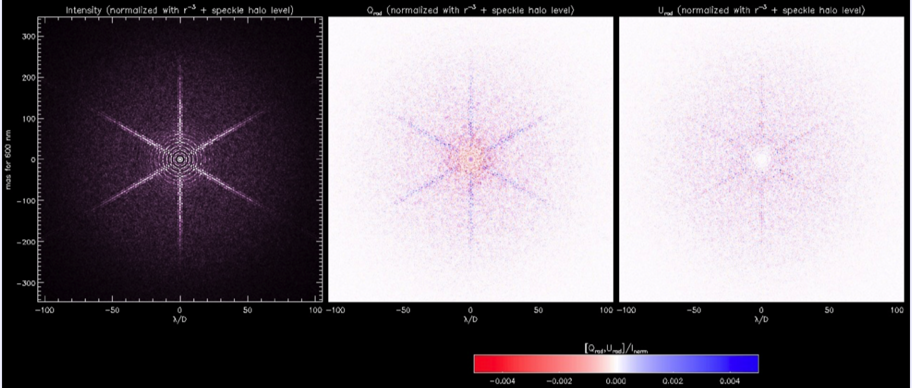


Simulations by: Mariangela Bonavita

E-ELT Telescope Polarization

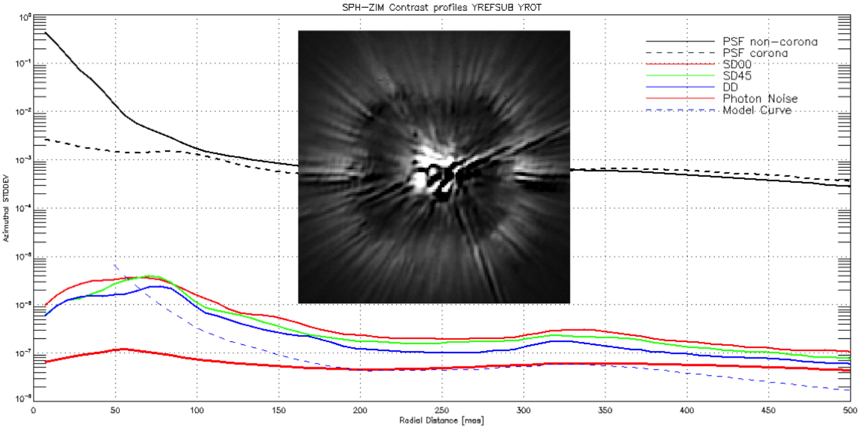


Polarized Diffraction Pattern



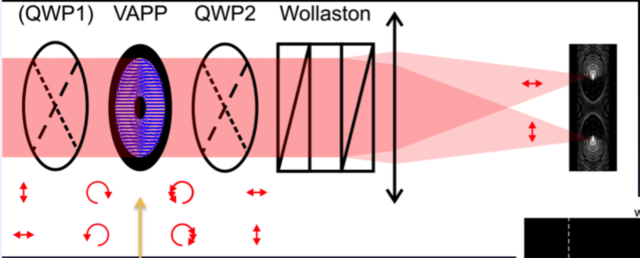
Snik, in preparaton

High-Contrast Polarimetry Issue



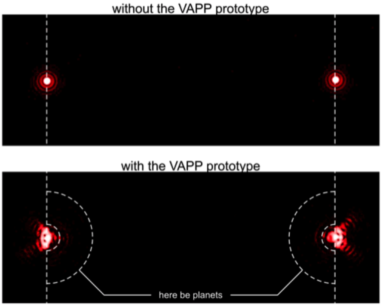
SPHERE-ZIMPOL, courtesy Ronald Roelfsema

Vector Apodizing Phase Plate

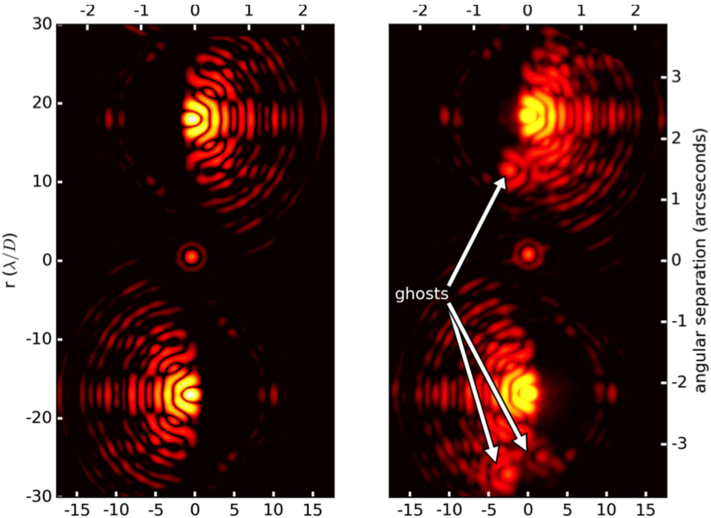


solid-state half-wave liquid crystal device with orientation pattern

Snik et al. (2012)



gvAPP at 6.5-m Magellan

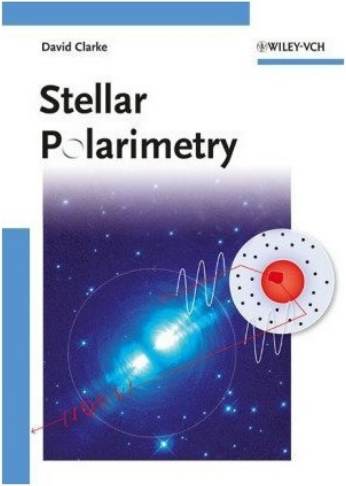


Otten, Snik, Kenworthy, Keller et al. (2015)

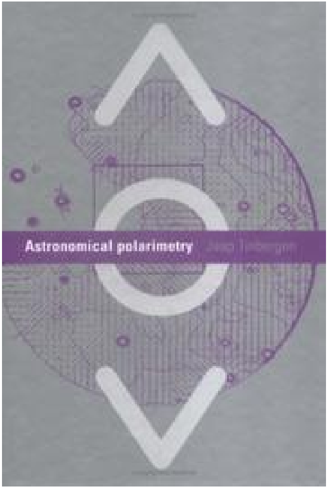
Rainbow Station Amsterdam Centraal

Recommended Books

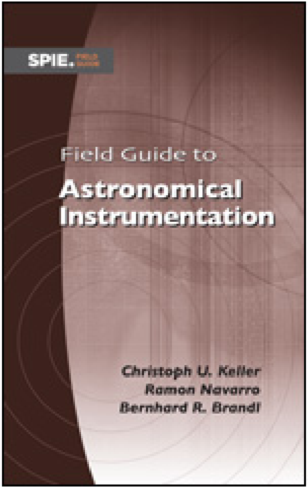
Stellar Polarimetry
David Clarke



Astronomical Polarimetry
Jaap Tinbergen



Field Guide to Astronomical Instrumentation
Keller, Navarro, Brandl



- summarizes all aspects of astronomical instrumentation
- 1 page per topic
- available at SPIE, Amazon
- on sale right now: USD 36