Techniques in solar polarimetry / magnetography

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MPS

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- description of polarized light
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What is polarimetry?

- polarimetry is the art of quantitatively determine the degree of polarization of light.
- spectropolarimetry is the even higher art of measuring the degree of polarisation as a function of wavelength

Why polarimetry

- polarization yields information that cannot be obtained via classical photometry, spectroscopy
- polarization information is „add-on“ to pure intensity measurements, not in competition
- not looking for polarization is wasting information! Photons are expensive, make use of them!

polarised light

- is a signature of the *transverse wave* character of light
- is a signature of broken symmetry in a system (something has a prefered direction/orientation; in other words: without a reason, light won´t be polarised!

Sources of (astrophysical) polarization

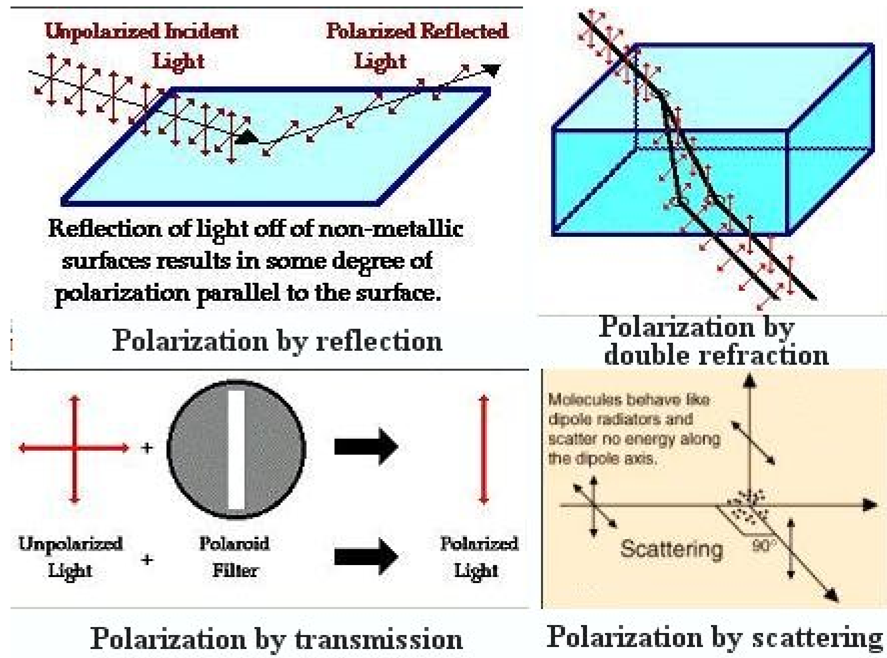
- light can be polarized
  – only by processes, in which light interacts with matter

  and

  – if – as seen from the observer – the rotational symmetry of the interaction process is broken.

effects that create polarization

- reflection
- total reflection
- refraction
- scattering
- dichroism
- (synchrotron radiation)
- Zeeman effect (magnetic fields!)



Polarization by reflection

Polarization by double refraction

Polarization by transmission

Polarization by scattering

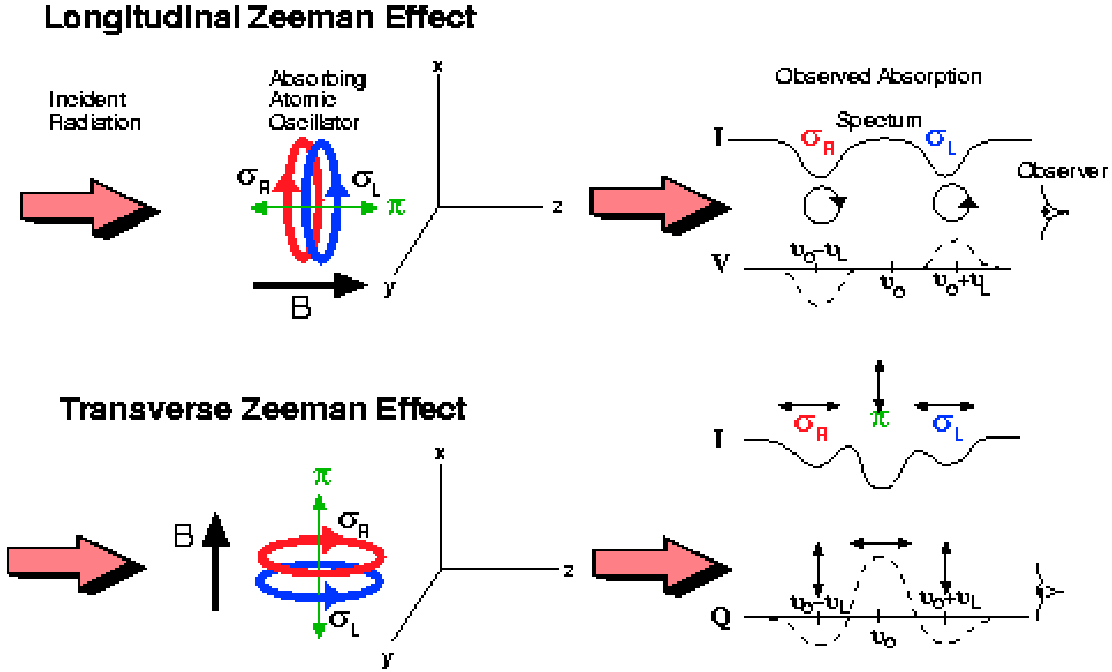
polarised light in optical solar physics

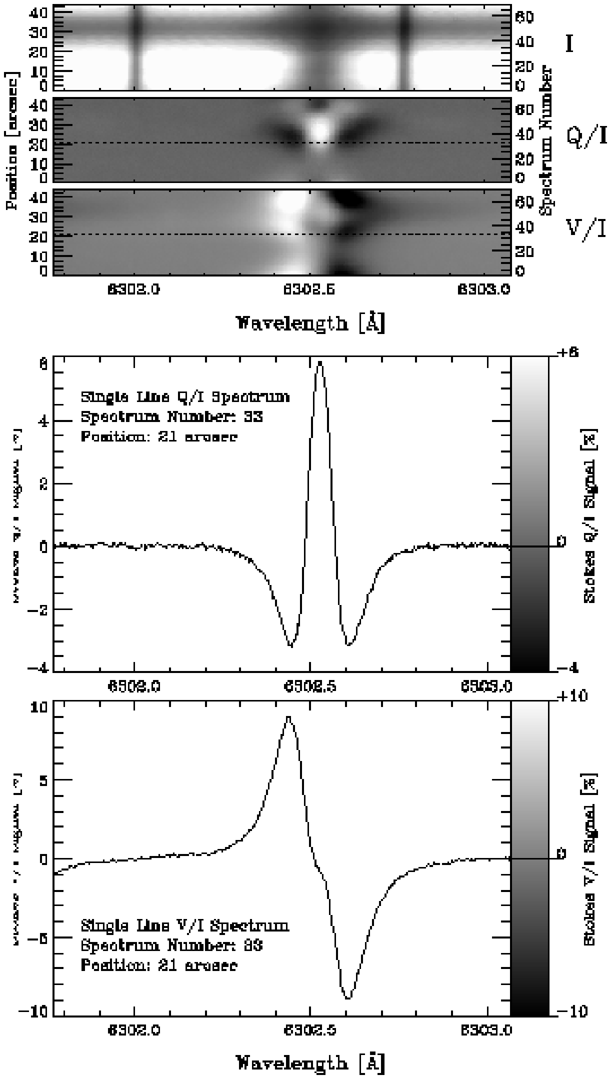
- In solar research polarimetry is to 99% related to the investigation of ***Zeeman effect*** induced polarisation → quantitative investigation of solar magnetic fields.

Zeeman effect

- describes the shift of atomic energy levels in the presence of a magnetic field. This shift removes the degeneracy of the m-state levels and leads to a ***splitting*** of the related ***spectral lines***. The ***components*** of the line are now ***polarised***, depending on the geometry of the situation (magnetic field direction AND observing direction).

Zeeman effect



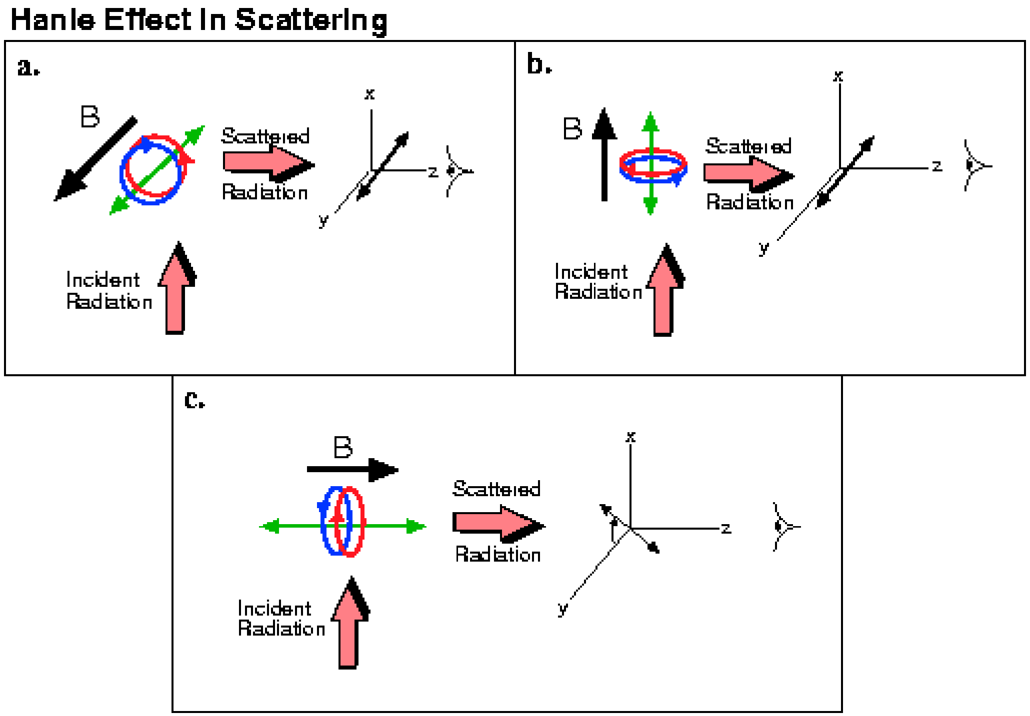


effects that alter polarization

- reflection
- refraction
- birefringence
- Faraday effect (magnetic fields)
- Hanle effect (magnetic fields)

Hanle effect

- Hanle effect: Modification of scattering polarisation (of spectral lines) in the presence of a magnetic field



characteristics of solar Zeeman polarisation

- magnetically induced splitting typically comparable to Doppler width of spectral lines → needs **very high spectral resolution** to be resolved!!
- leads to **tiny polarisation degrees** (since only small part of the resolution element is filled with magnetic field)

optical magnetometer

Magnetometer =

Wavelength selector

+

Polarimeter

spectrograph

„spectropolarimeter“

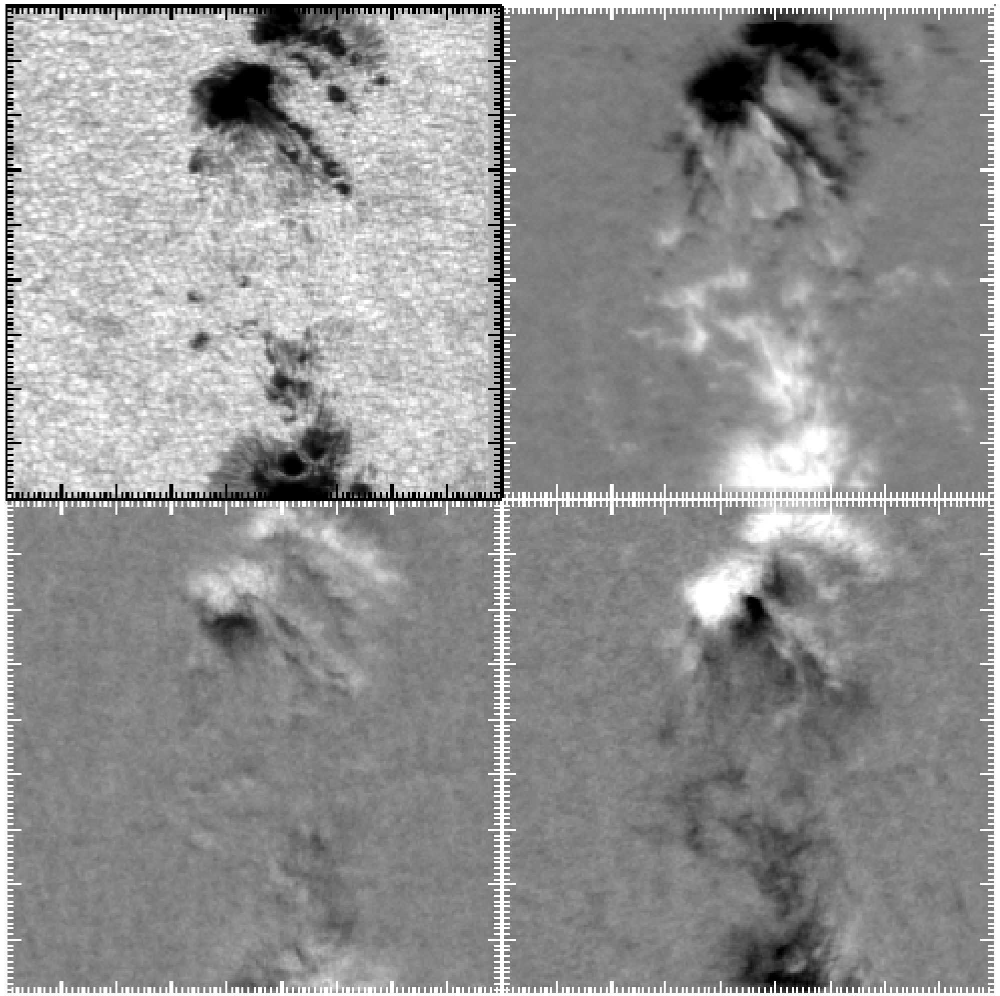
monochromatic filter

„(filter) magnetograph“

Example: picture of an active region in intensity and polarisation

Intensity image (what you would see with your eye or a CCD)

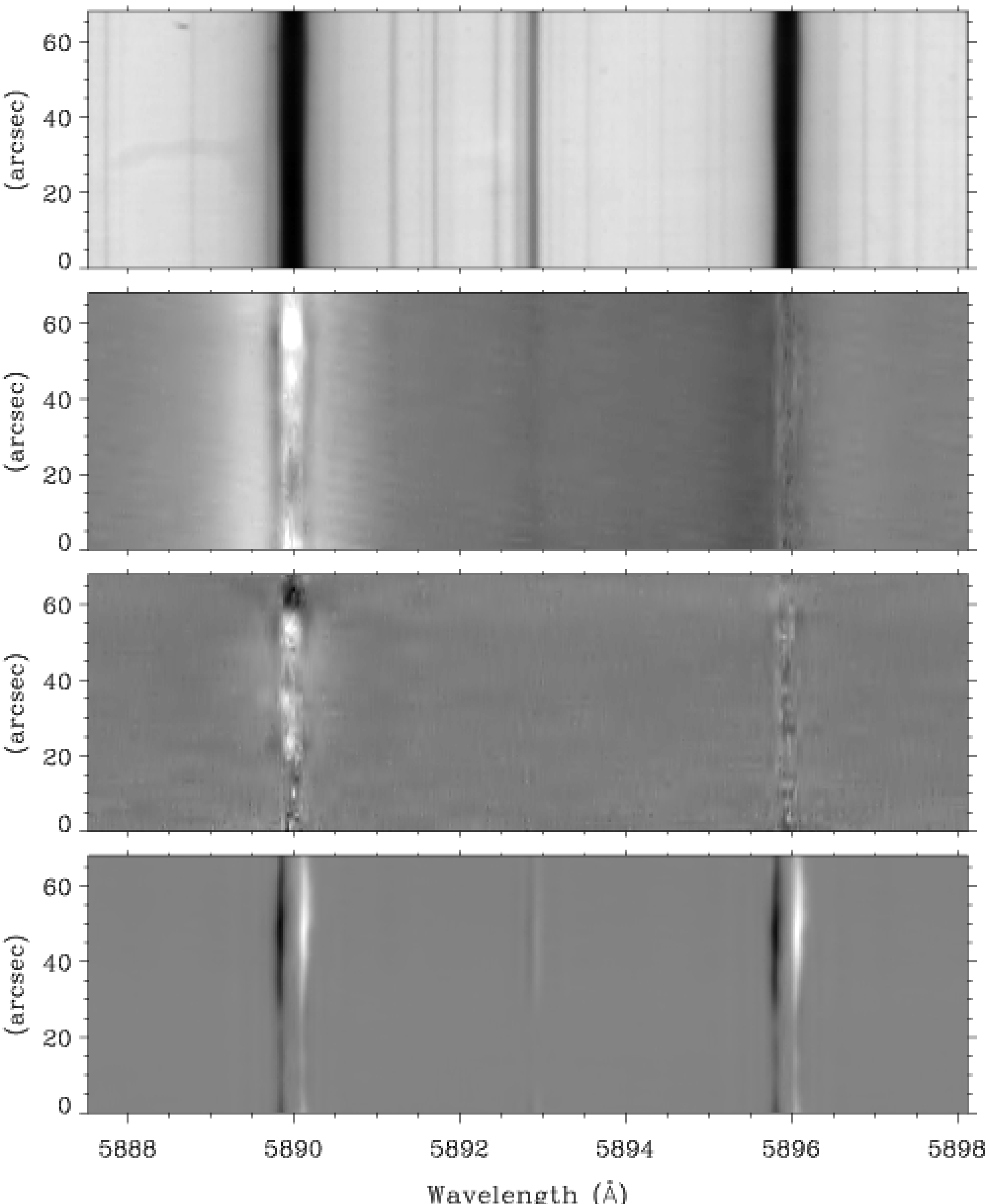
same scene, now the degree of linear polarisation is shown



same scene, now the degree of the other linear polarisation is shown

same scene, now the degree of circular polarisation is shown

Example: detail of solar spectrum in intensity and polarisation



Intensity image (what you would see with your eye or a CCD)

same spectrum, now the degree of linear polarisation is shown

same spectrum, now the degree of the other linear polarisation is shown

same spectrum, now the degree of circular polarisation is shown

Nota bene!

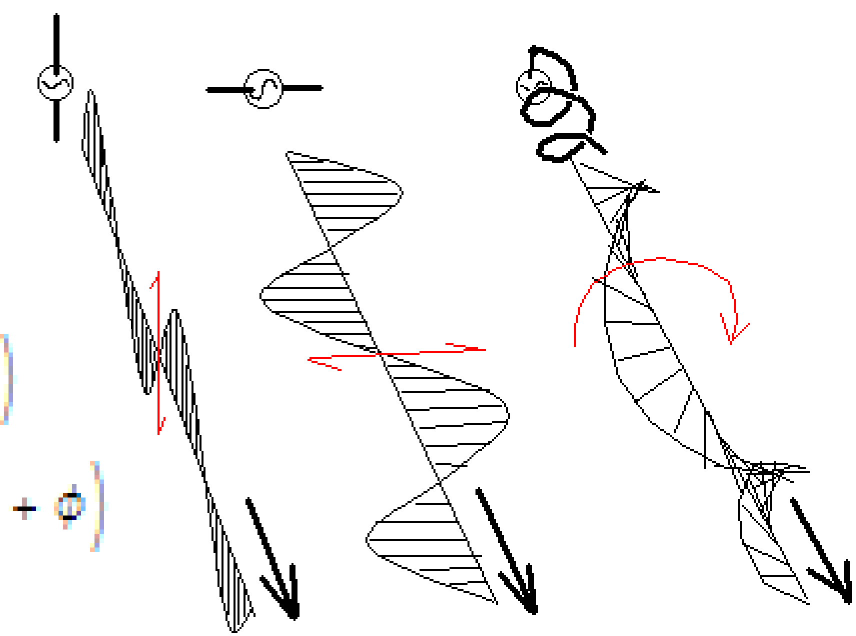
- in this lecture we will deal with the quantitative measurement of the polarization only, not of the magnetic field!!
  - no convertion from polarization maps→ magnetic field maps („inversion techniques“)
  - no interpretation of measured polarisation

Description of polarized light

- light represented as electromagnetic tranverse wave
- polarization is a characterisation of the *vibration plane of the electric field vector*

$$\vec{E}_1\left(\vec{r},\ t\right) = \vec{E}_x \cos\left(\omega t - \vec{k}_1 \cdot \vec{r}\right)$$

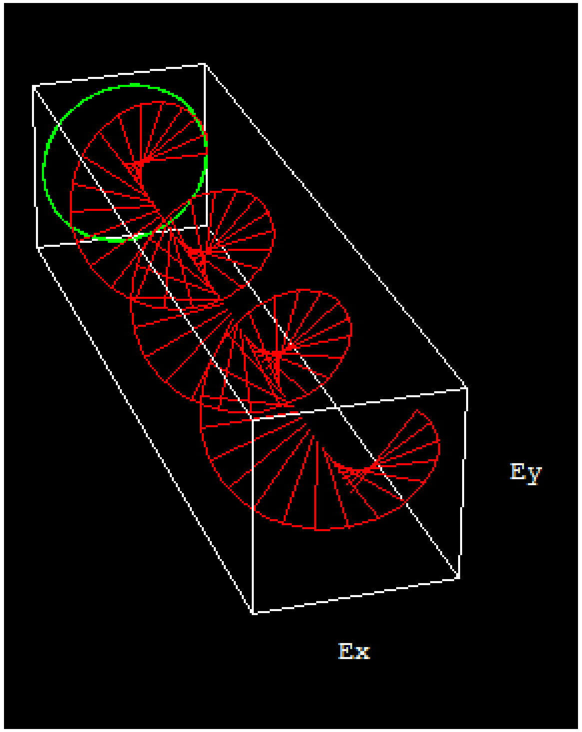
$$\vec{E}_2\left(\vec{r},\ t\right) = \vec{E}_y \cos\left(\omega t - \vec{k}_2 \cdot \vec{r} + \phi\right)$$



Jones formalism

- 2component vector containing complex E_x, E_y fields
- very convenient for description of elementary interaction processes
- only useful for idealised light: monochromatic!

$$\boldsymbol{E} = \begin{pmatrix} E_x \\ E_y \end{pmatrix} .$$



Stokes formalism

- Jones representation not adequate for „real“ light: partially polarized light with non zero frequency bandwidth
- better for daily life: representation in terms of intensity, not amplitude
  - time average over many periods (visible light: 10^{14} Hz!!!)
  - allows description of white light, partially polarized, incoherent, undirected......

→ Stokes representation (1852)

Stokes vector

- in the Stokes formulation light is represented by a four component vector $\underline{\boldsymbol{I}}$:
- I represents the ordinary scalar intensity, Q,U,V are *differences* of intensities measured by placing 6 ideal filters between source and intensity detector

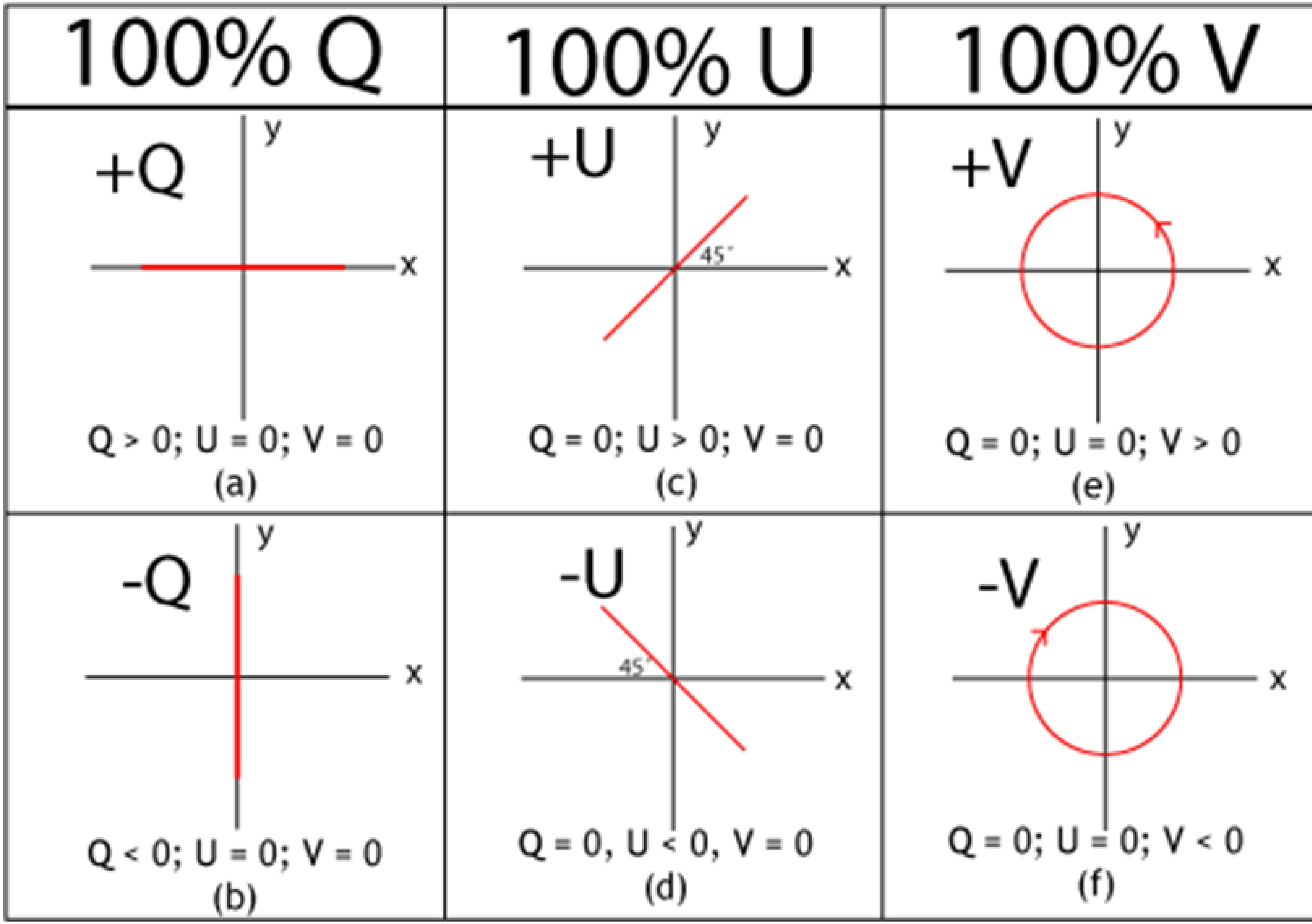
$$\boldsymbol{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

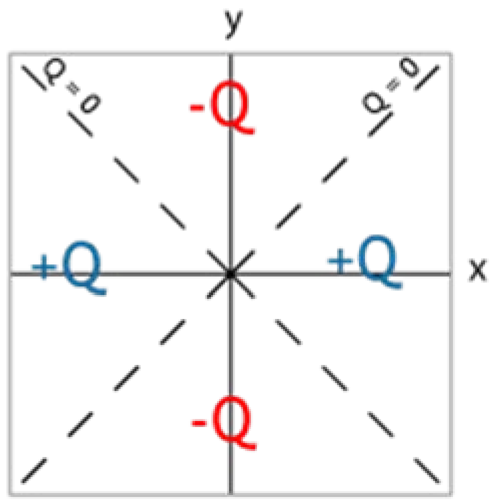
practical meaning of the Stokes components

- I, Q, U, V are measurable quantities
- each parameter represents the difference between TWO dedicated measurements:

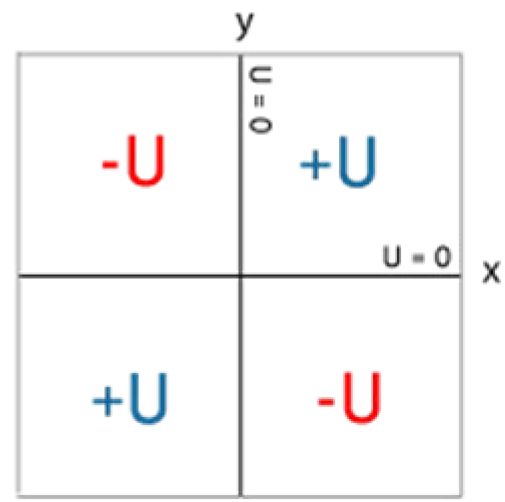
$$
\begin{aligned}
I &\stackrel{\text{def}}{=} |E_x|^2 + |E_y|^2, \\
&= |E_a|^2 + |E_b|^2, \\
&= |E_l|^2 + |E_r|^2, \\
Q &\stackrel{\text{def}}{=} |E_x|^2 - |E_y|^2, \\
U &\stackrel{\text{def}}{=} |E_a|^2 - |E_b|^2, \\
V &\stackrel{\text{def}}{=} |E_l|^2 - |E_r|^2,
\end{aligned}
$$

the six idealised filters for the Stokes description





Sign of Q
(a)



Sign of U
(b)

Sign of V
(c)

advantages of the Stokes representation

- perfectly represents measurement procedure
- not restricted to monochromatic light
- can describe unpolarized light
- (classical radiative transfer equation can be formally expanded to vector equation by replacing scalar I with vector $\boldsymbol{I}$)
- **optical components** altering polarisation can be very conveniently described by **matrices** („Mueller matrices“) acting on the Stokes vector

some facts about Mueller matrices

- an optical component acts on a Stokes vector

$$\boldsymbol{I}' = \mathsf{M}\boldsymbol{I} .$$

- M is a 4x4 matrix

$$\mathsf{M} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} .$$

- a complex optical train can be represented by the matrix product of its individual component matrices

$$\mathsf{M}' = \mathsf{M}_N \mathsf{M}_{N-1} \cdots \mathsf{M}_2 \mathsf{M}_1 .$$

some important Mueller matrices

$$\mathbf{P} = \frac{1}{2}\begin{bmatrix} p_x^2+p_y^2 & p_x^2-p_y^2 & 0 & 0 \\ p_x^2-p_y^2 & p_x^2+p_y^2 & 0 & 0 \\ 0 & 0 & 2p_xp_y & 0 \\ 0 & 0 & 0 & 2p_xp_y \end{bmatrix}.$$

partial linear polarizer (0°)

$$\mathbf{P} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

a total linear polarizer transmits only Stokes Q and makes U and V to zero!

$$\mathbf{V}(\phi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\phi & -\sin\phi \\ 0 & 0 & \sin\phi & \cos\phi \end{bmatrix}.$$

retardation plate (phase retarder, retardance Φ, birefringent element) mixes U and V!

always:

$$\mathbf{M}_{rot} = \mathbf{R}(-\alpha)\mathbf{M}\mathbf{R}(\alpha),$$

basic rules for Mueller matrices

- Mueller matrices can be multiplied

$$\vec{S}_o = \mathrm{M}_3\mathrm{M}_2\mathrm{M}_1\vec{S}_i \ .$$

- attention: don´t exchange components along the path!!!!!

$$\mathrm{M}_3\mathrm{M}_2\mathrm{M}_1\vec{S}_i \neq \mathrm{M}_1\mathrm{M}_2\mathrm{M}_3\vec{S}_i \ .$$

- optical component **M** rotated by angle α :

$$\mathbf{M}_{rot} = \mathbf{R}(-\alpha)\mathbf{M}\mathbf{R}(\alpha),$$

- with rotation matrix

$$\mathbf{R}(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Polarimetric basics

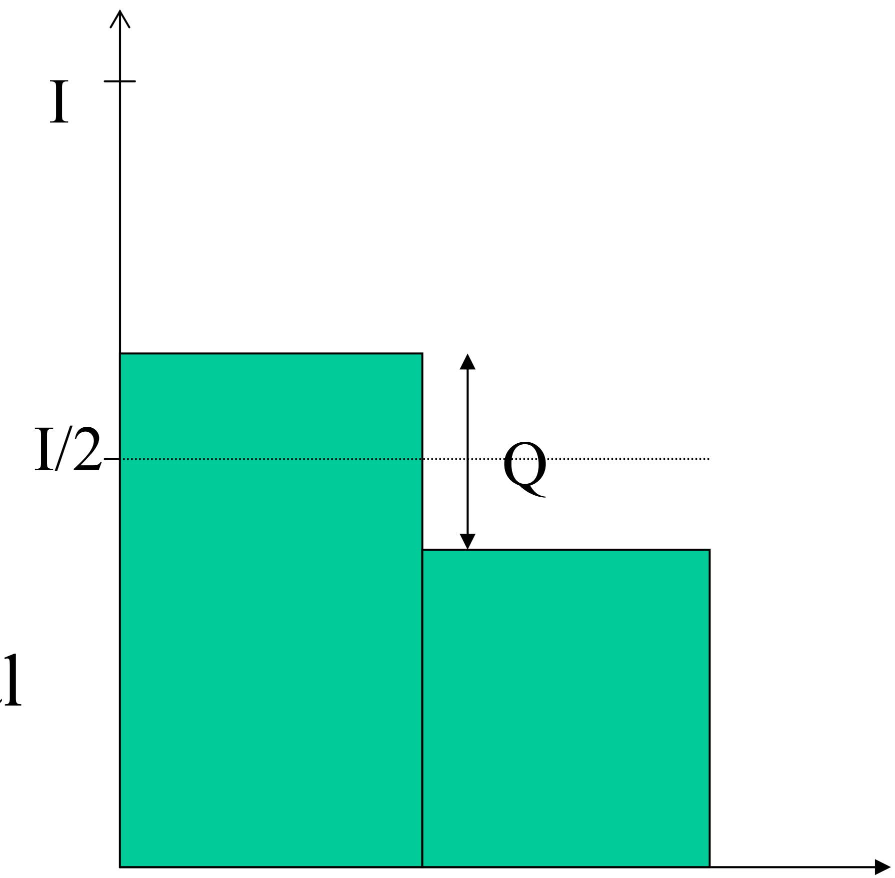
- **polarimetry = differential photometry**
- **polarisation images are linear combinations of photometric or spectral intensity images, which have been taken in different polarisation states**

Q,U,V, and I: The polarisation degree

- Q,U,V mostly << I
- *polarization degree* Q/I (U/I,V/I) small (typically $10^{-4}<Q/I<10^{-2}$)
- **detect small intensity difference on top of large intensity**

Example: detection of Stokes Q: two measurements: linear polarizer 0^o, 90^o

- $I_1=0.5(I+Q)$
- $I_2=0.5(I-Q)$
- $Q/I=(I_1-I_2)/(I_1+I_2)$ „normalized Stokes parameter“ : very accurate, since *efficiency* of detector divides out : differential measurement



Two basic techniques

- sequential detection with one detector (single beam polarimetry): Use of a modulator/polarizer combination to convert the polarisation information into a time-dependent intensity

→ *"temporal modulation"*

- simultaneous detection with two different detectors (dual beam polarimetry): Use a polarising beam splitter to spatially separate both orthogonal polarisation states at the same time

  → *"spatial modulation"*

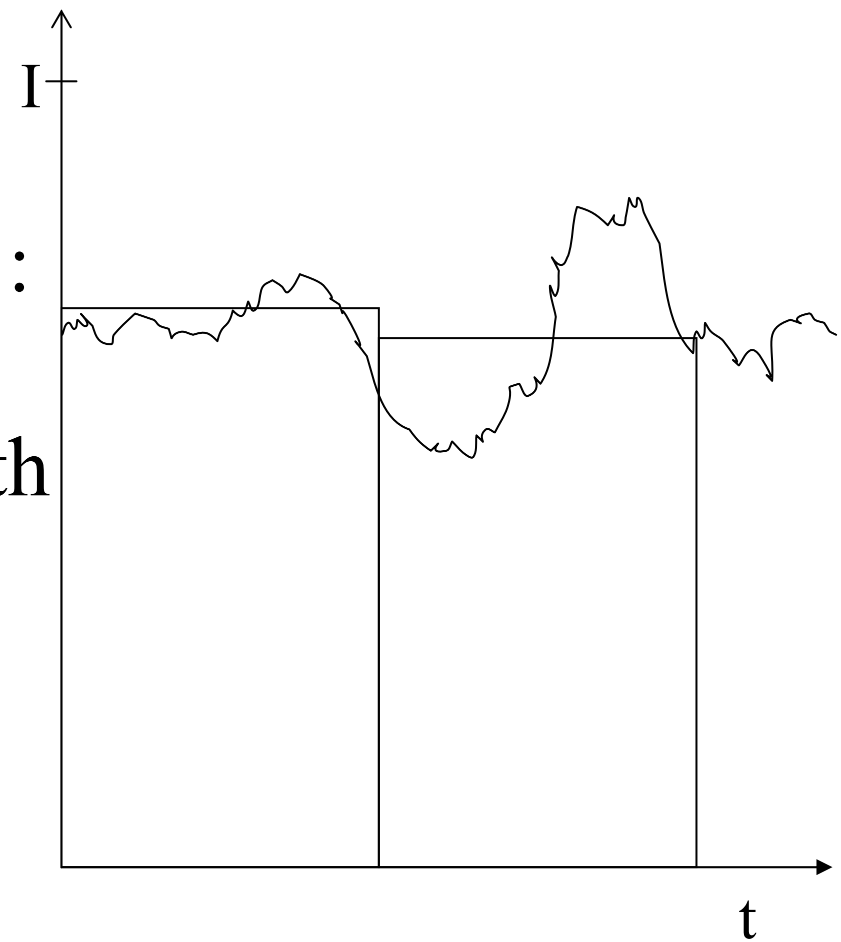
We repeat

- Since the eye or a CCD are not itself sensitive to polarisation, we **convert the polarisation information into an intensity-difference**, which we meausure. Sounds easy, let´s do it.

Systematic error sources

1. seeing:

   intensity changes during measurement : intensity difference has nothing to do with polarization



Systematic error sources

1. seeing
2. gain-table or flat field :

   detector sensitivity varies from 1 exposure to the other → signal difference has nothing to do with polarisation

Systematic error sources

1. seeing
2. gain-table or flat field
3. photon noise: statistical character of photons $\sigma \sim \sqrt{N}$, N number of photons

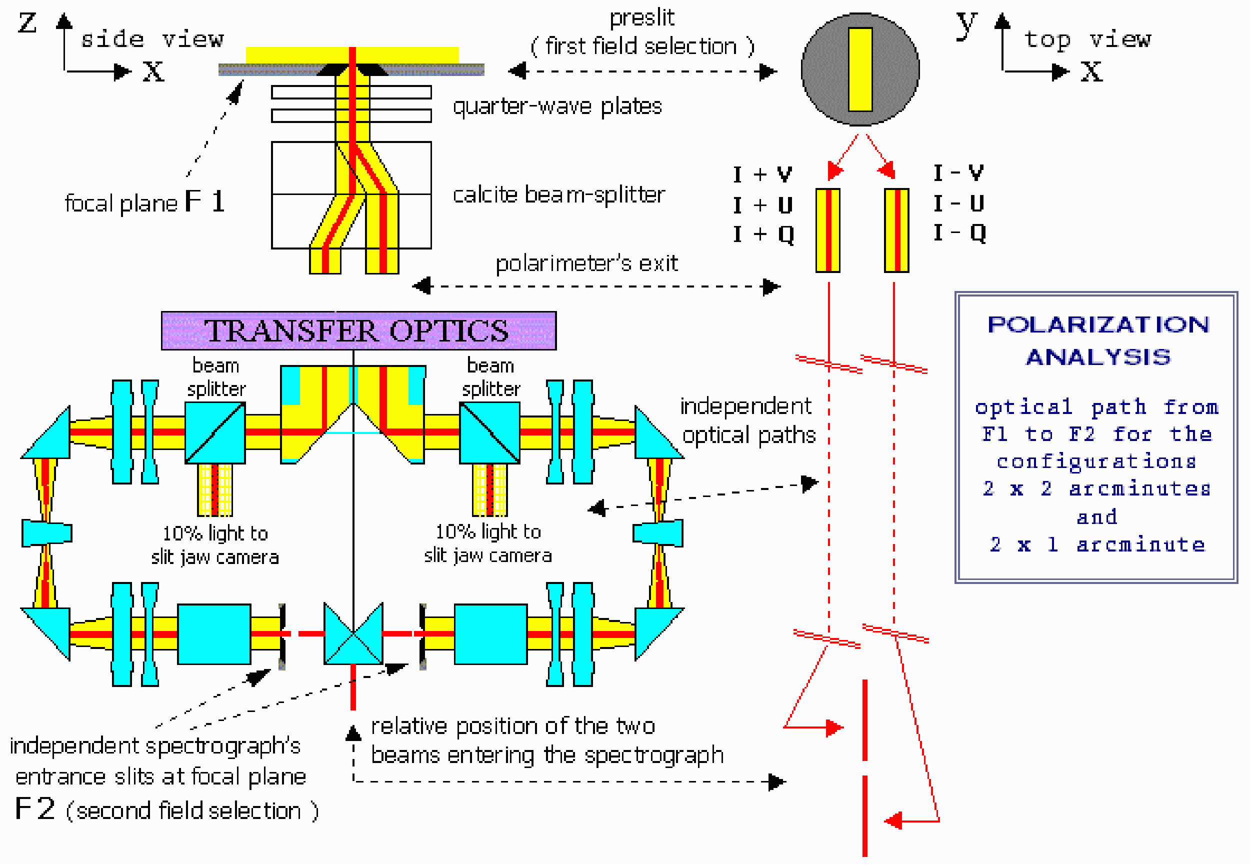
→ noise increases with number of photons, but Signal-to-noise decreases!

How to do sensitive polarimetry?

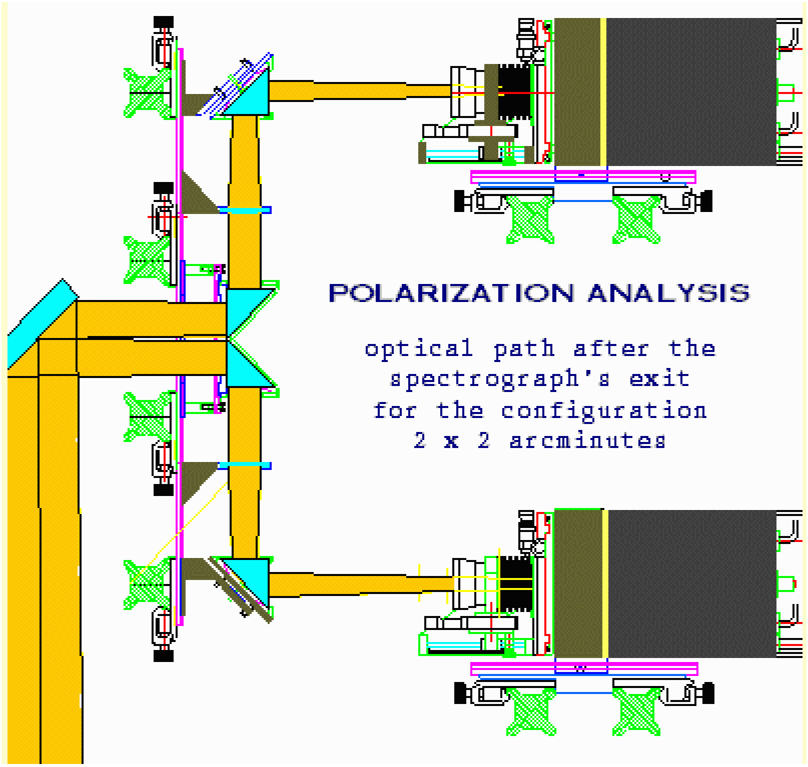
- seeing noise
- gain table noise
- photon noise

- fast polarization modulation
- use identical detector elements for differential images
- increase statistics by frame averaging

Dual beam polarimetry at THEMIS



Dual beam polarimetry at THEMIS



Dual beam polarimetry

- dual beam polarimetry is free of seeing induced errors (strictly simultaneously!)

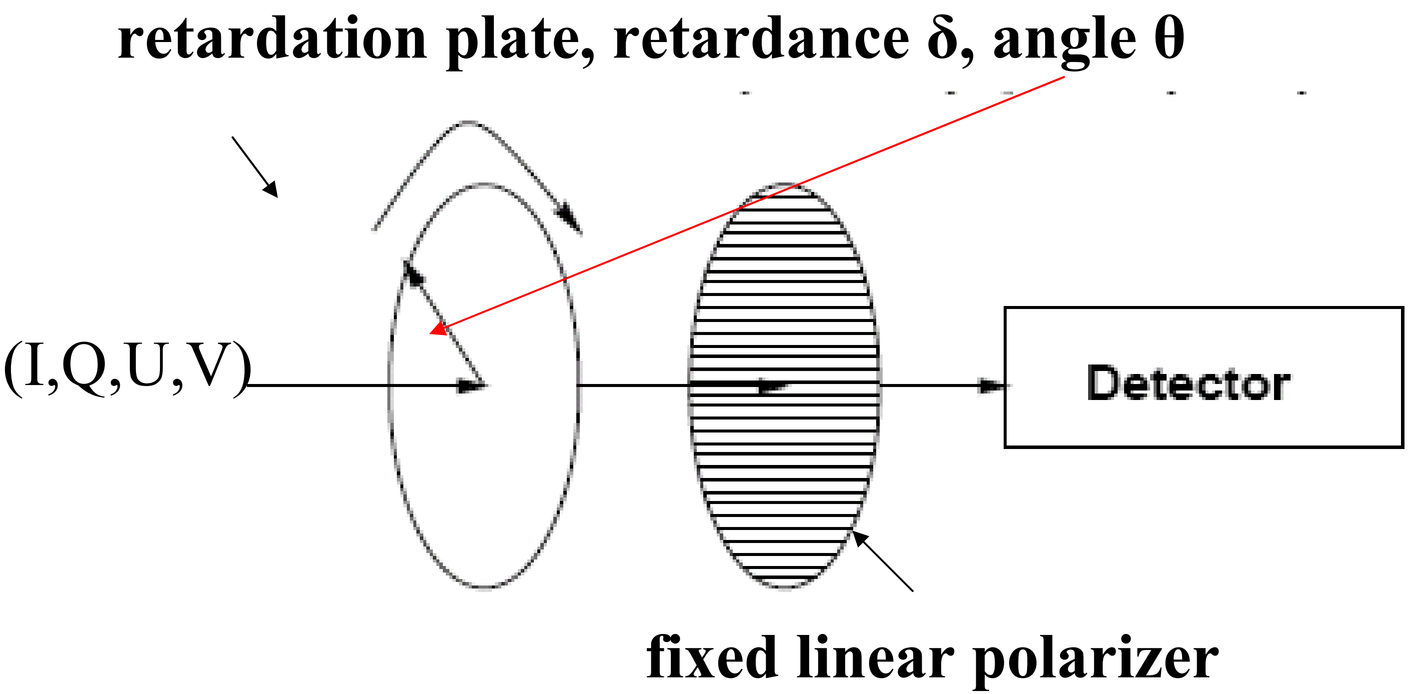
BUT

- suffers from different flat-field and misalignment of the two beams
- differential optical aberrations in both beams lead to spurious signatures in difference image
- **very limited accuracy without further trick**

Beam exchange

- put a half-wave retardation plate in front of the polarising beam-splitter
- half wave plate changes all signs in the polarization path, but the errors keep their sign!
- two images with two settings of wave plate (per Stokes parameter)
- four images yield fractional polarisation mostly free from systematic errors (polarisation induced image differences add up, while spurious signatures are subtracted)

a simple single beam polarimeter



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

Intensity depends on retardance δ, angle θ, and Q,U,V

polarization modulation

- Q,U,V not directly measurable
- convert polarization information into intensity
- intensity depends on Q,U,V, retardance δ, angle θ
- information about Q,U,V is encoded in $I_S(\delta,\theta)$ with S=Q,U,V
- → „*modulation functions*“

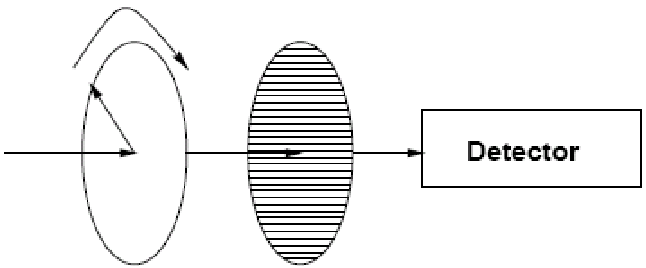
modulation schemes

- for „modulation“ you can change the retardance δ, the angle θ, or both of one, two, or even more retardation plates
- the polariser remains untouched

The rotating wave plate

A very simple but robust polarimeter consists of 1 wave plate (of retardance δ) followed by a linear polarizer.

(Hinode SP !!! Works, thanks to high pointing stability!! of S/C)



The measured intensity becomes:

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

Now, let´s rotate the wave plate:

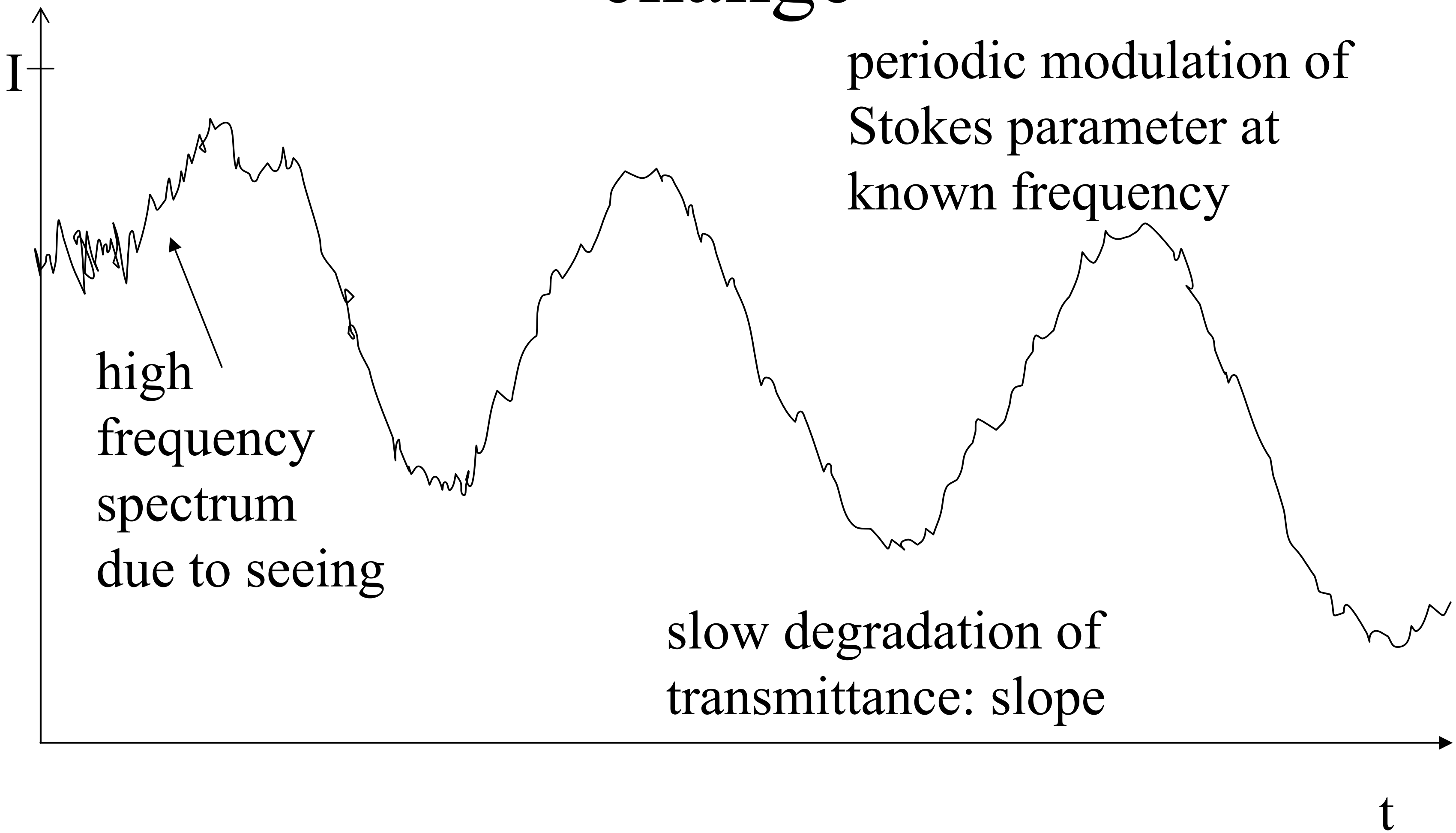
with θ=ωt → $\mathbf{I_S(t)}$ with S=Q,U,V

Q,U,V modulated at different frequencies and phases! → **phase sensitive detection possible!**

phase sensitive detection

1. encode polarisation into modulation functions with known frequencies (harmonics of the modulation frequency) and phases
2. from all potential signal fluctuations detect only those found at exactly these frequencies, integrate the rest to zero! ***LOCK-IN*** **principle**
3. choose modulation frequency such that it brings the signal out of the disturbance regime!

example: modulation with (fast) seeing and (slow) transmission change

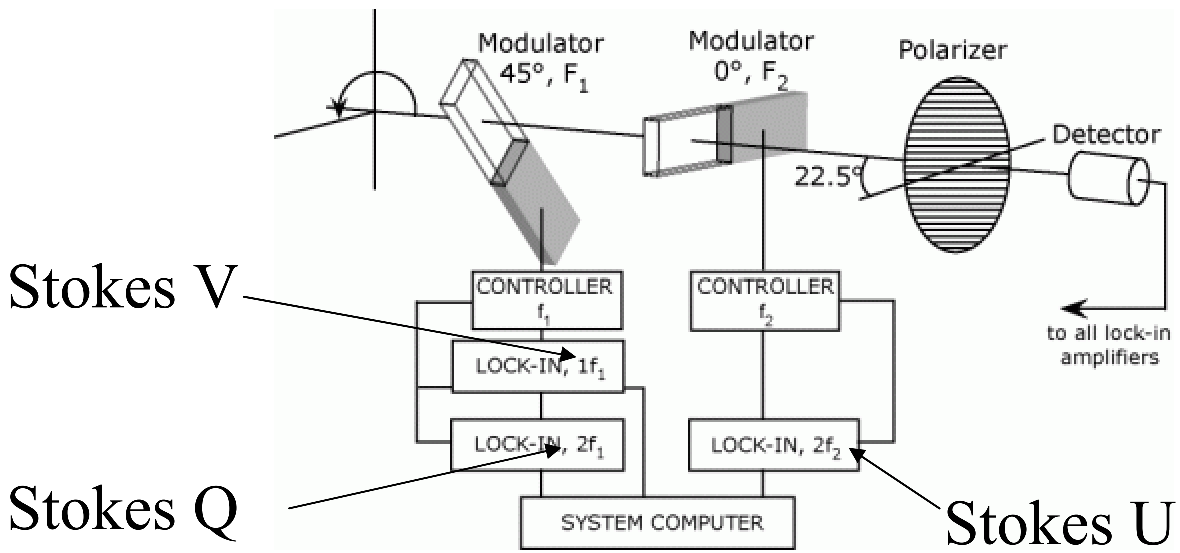


Modulators

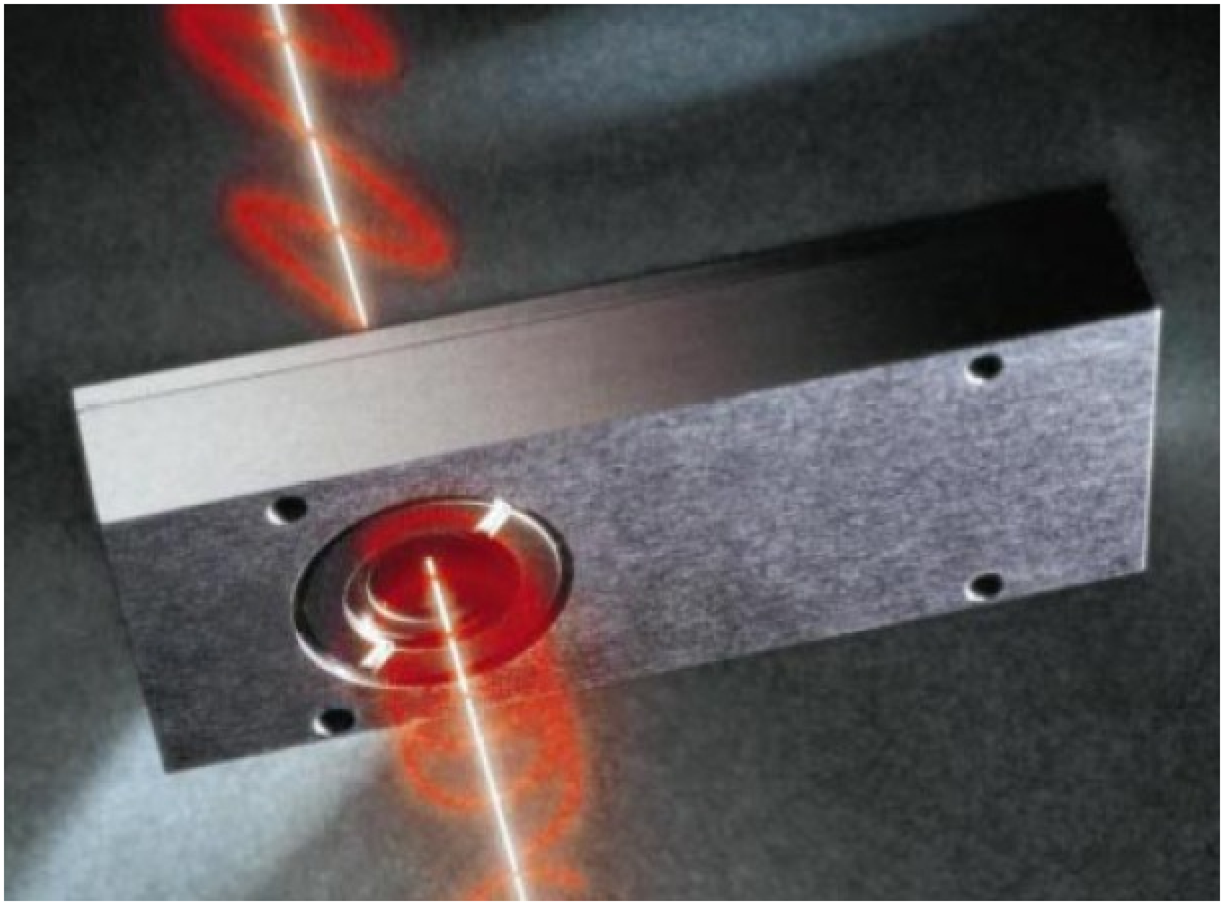
- to modulate polarisation you need a waveplate, characterised by its retardance δ and angle θ
- in principle you can alter both, δ and θ to get a modulation

Example: Two modulators, angles $\theta_{1,2}$ fixed, retardances $\delta_{1,2}$ modulated!

- two *photoelastic modulators* at two frequencies:



Photoelastic modulator



a slab of fused quartz (isotropic) vibrates at mechanical resonance frequency; mechanical stress induces anisotropy and birefringence→ sinusoidal variation of retardance with time. Typ. frequency: 50kHz

other modulators

- Liquid crystal retarders
  - nematic liquid crystals
    - electrically tuneable wave plates (retardance δ tuned)
    - fixed fast optical axis (angle θ fixed!)
    - slow (150ms rise time)
  - Ferroelectric liquid crystals (FLCs)
    - fixed retardance (δ NOT tuneable)
    - switchable fast optical axis (between two distinct values $\theta_{1,2}$)
    - fast (150 μs rise and fall time)

solar polarimeters

- with rotating (continuous or stepped) wave plate:
  - Advanced Stokes Polarimeter (Lites et al. 1990)
  - Hinode (Solar B) spectropolarimeter (Lites 2001)
  - POLIS (Schmidt et al. 2001)
  - IRSOL polarimeter (Bianda et al. 1998)
  - THEMIS (Paletou et al. 2001)
  - Yunnan S^3T telescope (Qu et al. 2001)

Solar polarimeters

- with Nematic liquid crystals
  - Potsdam polarimeter (Hofmann 2000; Horn and Hofmann, 1999)
  - Haleakala Imaging Vector Magnetograph (Mickey et al. 1996)
  - Big Bear Digital Video Magnetograph (Spirock et al. 2001)
  - IMaX onboard Sunrise
  - Solar orbiter: Polarimetric and Helioseismic Imager PHI

Solar polarimeters

- with Ferroelectric Liquid crystals
  - Zurich Imaging Polarimeter II (Gandorfer 1998)
  - SOLIS VSM (Keller et al. 1998)
  - La Palma Stokes Polarimeter (Martinez-Pillet et al. 1999)
  - Tenerife Infrared Polarimeter (TIP) (Collados et al. 1999)
  - Near Infrared Magnetograph (Rabin et al.)

How to demodulate the modulated signals?

- easiest way: read detector in synchronism with modulation
- drawbacks: detectors too slow, photon flux low, dominated by read noise

- better: use specialized detector architecture that allows for *on-chip demodulation*

Zurich ***IM***aging ***POL***arimeter
ZIMPOL I and **II**

- fast temporal modulation/demodulation system
- polarisation modulation in the kHz range
- special CCD sensor used as part of a synchronous demodulator

Povel, H.P., 1995, Optical Engineering 34, 1870

Gandorfer and Povel, 1997, A&A 328, 381

ZIMPOL II: Components

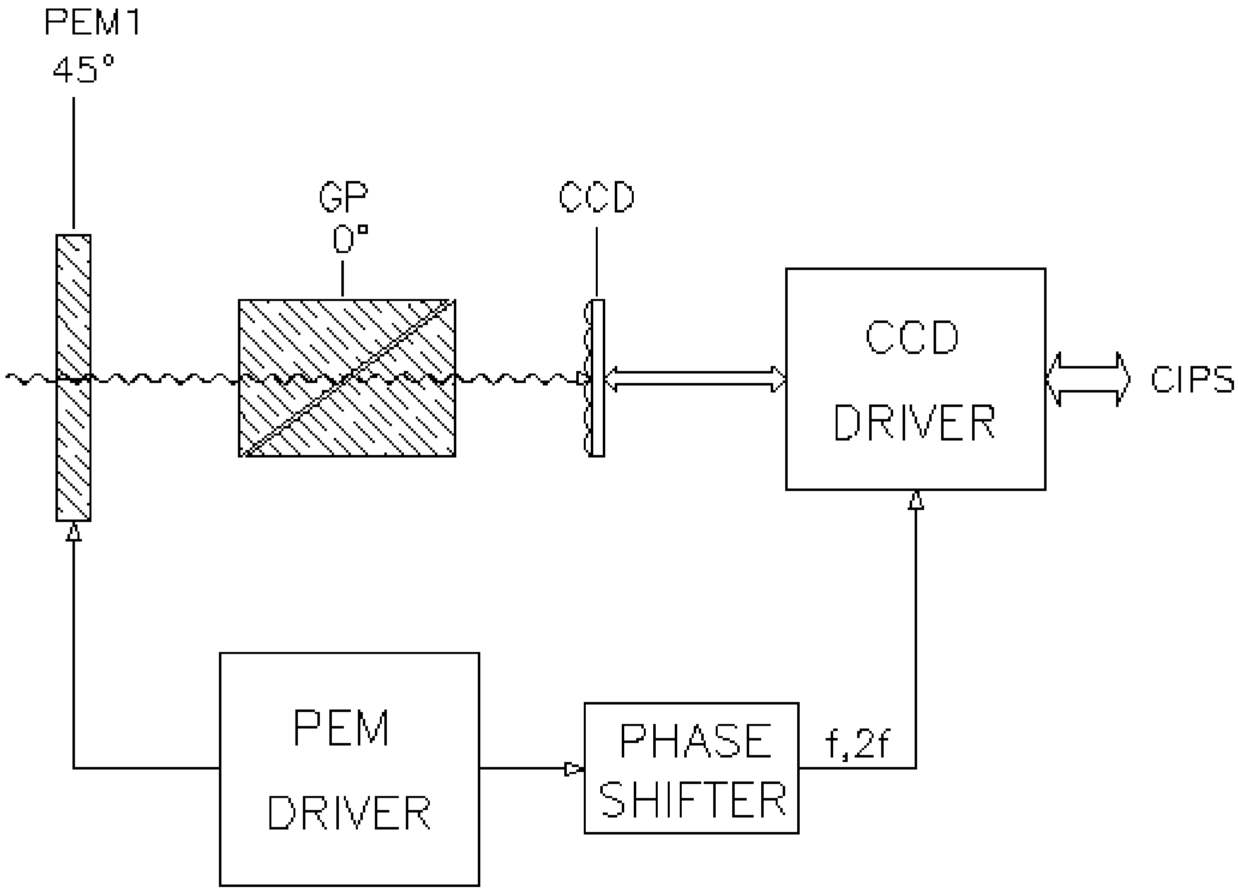
modulator unit:

- piezoelastic modulator or ferroelectric retarders allow polarisation modulation up to 84 kHz
- Glan linear polarizer as analyser

demodulation CCD:

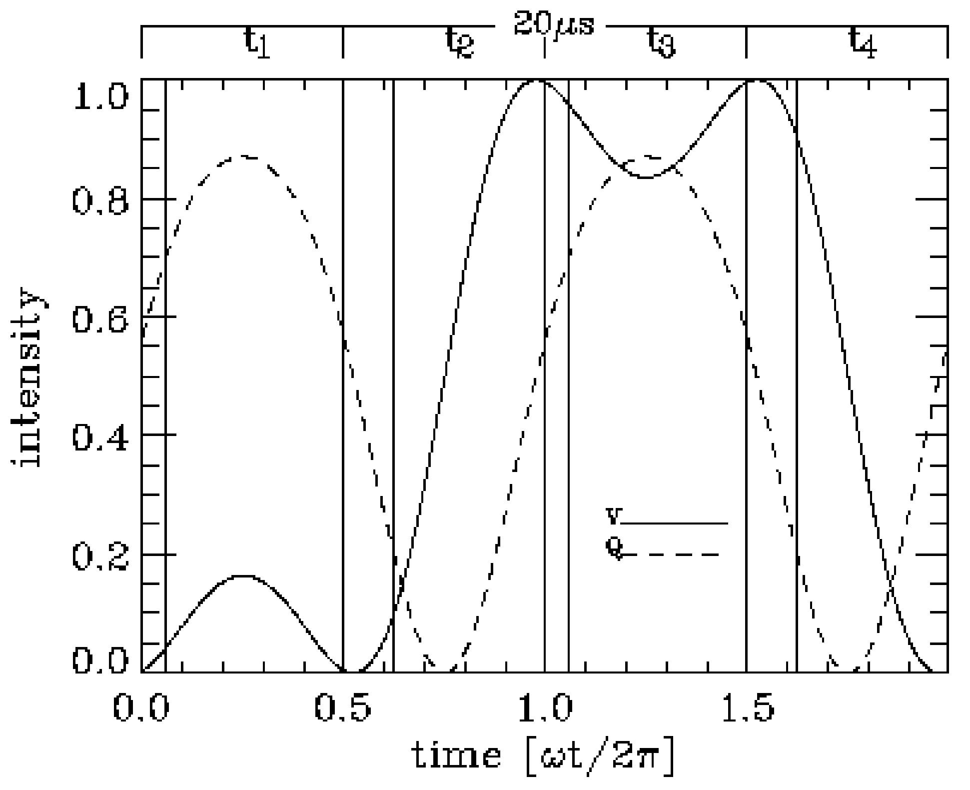
- 3 out of 4 pixel rows covered with opaque mask
- 4 interlaced charge images can be handled simultaneously in the same CCD
- rapid charge shifting in synchronism with modulation

ZIMPOL II: Principle



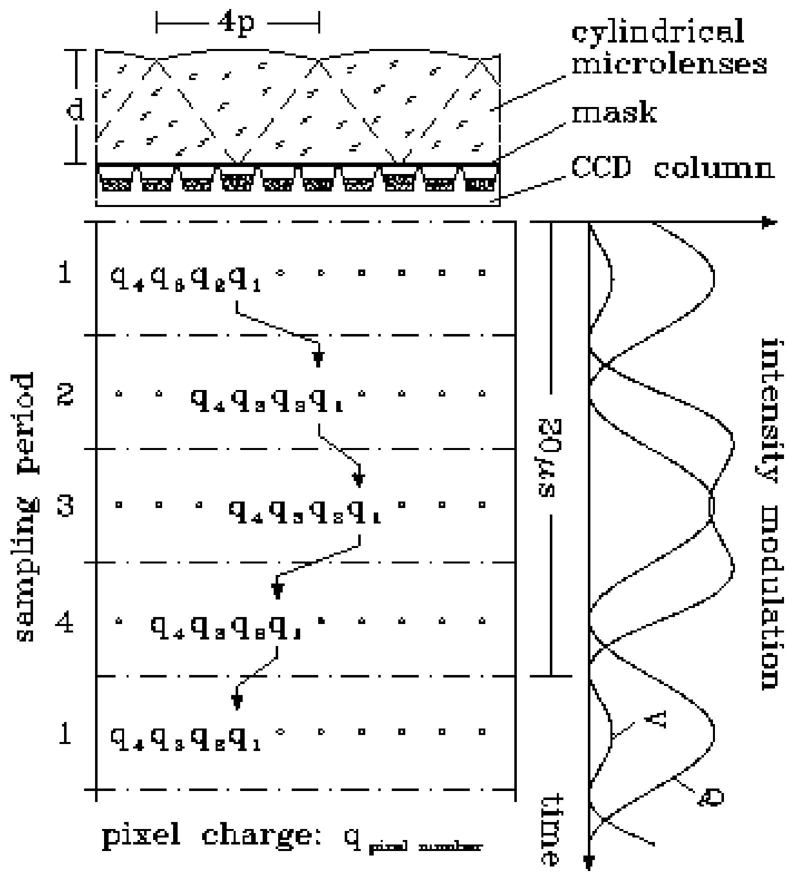
Gandorfer & Povel, 1997, A&A 328, 381

ZIMPOL II: Modulation functions and demodulation timing windows



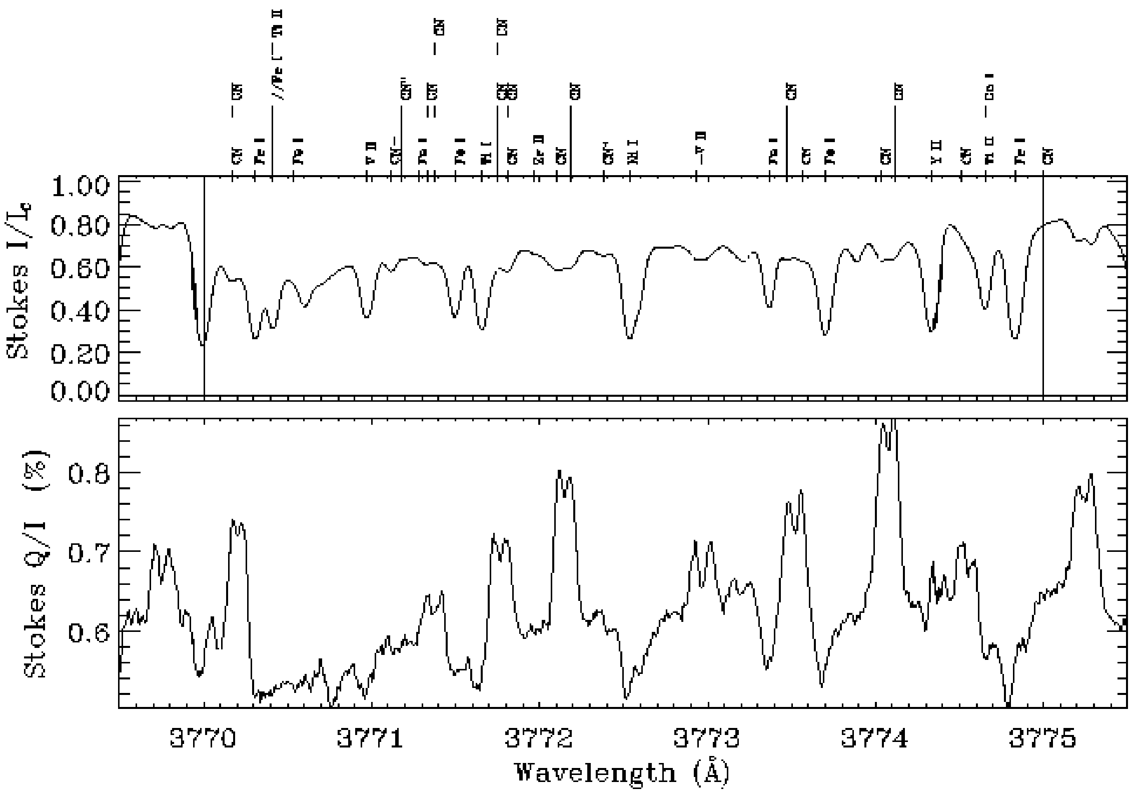
Gandorfer & Povel, 1997, A&A 328, 381

ZIMPOL II: Demodulation Principle by rapid charge shifting



Gandorfer & Povel, 1997, A&A 328, 381

ZIMPOL is the most sensitive polarimetric system in astronomy



Extending the wavelength range

some problems:

- CCD can work up to wavelengths of 1100nm (band gap of silicon)
- below 450nm special detector architecture is needed (thinned CCDs, backside illumination, etc.)
- liquid crystals do not withstand UV
- ...

Near infrared

- why?
  - large Zeeman splitting !
- how?
  - CMOS sensors (Nicmos, Hawaii)
- examples:
  - Tenerife Infrared Polarimeter (TIP I and II)
    - Nicmos 3 detector
    - FLC based spatio-temporal modulation

    (Collados et al. 1999)

The near UV

- why?
  - chromospheric diagnostics via scattering polarimetry and Hanle diagnostics
- how?
  - POLIS (standard blue sensitive back-thinned CCDs; special rotating wave plate) (Beck et al., 2005 Astronomy and Astrophysics, 437, 1159)
  - ZIMPOL II (highly specialised CCD architecture *(open electrode structure*); fused quartz photoelastic modulator) (Gandorfer et al., 2004, Astronomy and Astrophysics, 422, 703)

Instrumental polarisation

- optical elements before polarisation analysis change polarisation states
  - avoid oblique reflections!
  - take care about thick windows /lenses with temperature gradients (stress induced birefringence) !
- if not possible: make telescope model based on polarized ray tracing / geometry of telescope
- calibrate, calibrate, calibrate.......