Polarimetry Techniques

K. Sankarasubramanian ISRO Satellite Centre Bangalore India sankark@isac.gov.in







Outline

- □ Introduction
 - Why Polarimetry?
 - Requirements
- Polarization Basics
 - Stokes Parameters & Mueller Matrices
 - Optical Components
- Simple Polarization Measurements
 - Use of Polarizer and Quarter-Waveplate
 - Modulation and Demodulation
- Solar Polarimeters
 - ASP-type and ZIMPOL-type
 - Balanced Vs Unbalanced Modulation
- Future Directions
 - C³PO
 - Achromatic and Tunable Polarimeters

Remote Measurement

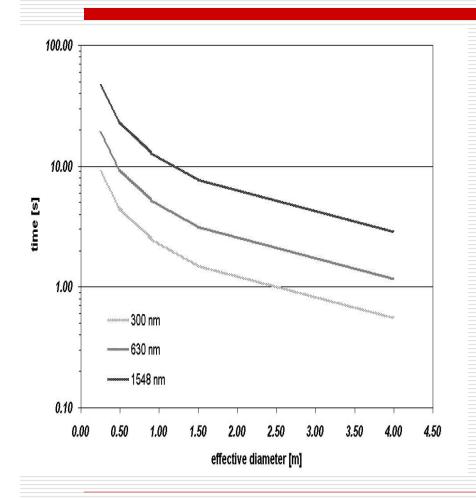
For astronomical Sources: Source of Information is Photons.

- Energy content of the photons at UV, Visible, IR etc.. **Photometry.**
- Relative absorption of photons at a spectral line because of atoms and molecules present in the atmosphere – Spectroscopy.
- State of polarization of the light Polarimetry.

Why Polarimetry?

- □ Polarimetry: Study of polarization nature of the source (Any Source of Interest..!)
- ☐ Few Examples of Applications:
 - (i) Astronomy
 - (ii) Imaging of Earth (Synthetic Aperture Radar Polarimetry in Geoscience)
 - (iii) Non-destructive Optical testings
 - (iv) Used in Food, Chemical, and Pharmaceutical industries
 - (v) Medical (or bio-medical) applications (Eyes, Tissues, Birefraction which allows detection of small size cancers)
 - (vi) Material characterisation
 - (vii) VLSI designs (Silicon wafer designs and thicknesses) (viii) Much more.....

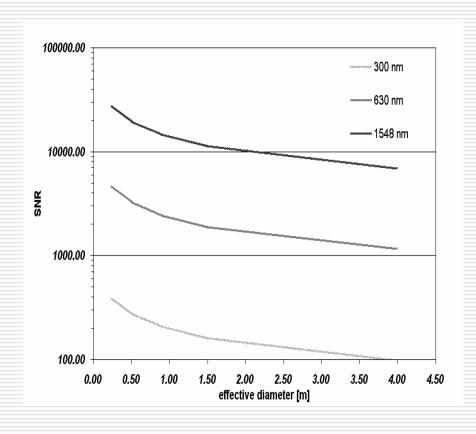
Do we have enough Photons?



C. U. Keller, 2002, SPIE, 4843

- ☐ Hydrostatic Condition
- □ Pressure Scale Height= Photon Mean freepath ~ 70km
- □ Required Aperture ~ 1.5m
- □ Sound Speed ~ 7km/sec
- Exp. Time ~ 5sec@6000A

SNR - Requirements

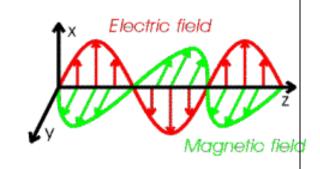


C. U. Keller, 2002, SPIE, 4843

- Unobscured Aperture
- □ 10% Overall Efficiency
- Maximum horizontal motion of the features ~5km/sec
- Nyquist Sampling
- □ Spectral Resolution ~ 150,000
- Effective integration time from the previous figure

Polarization: Basics

Light is a transverse wave, an electromagnetic wave



$$\vec{E}_{x}(z,t) = E_{0x} \cos(kz - \omega t) \vec{x}$$

$$\vec{E}_{y}(z,t) = E_{0y} \cos(kz - \omega t + \varepsilon) \vec{y}$$

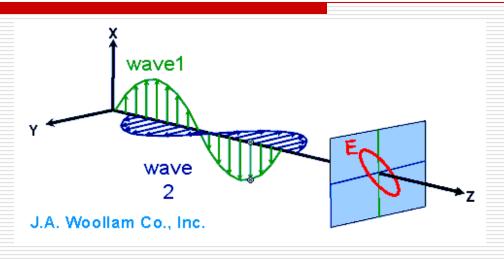
Generalised State

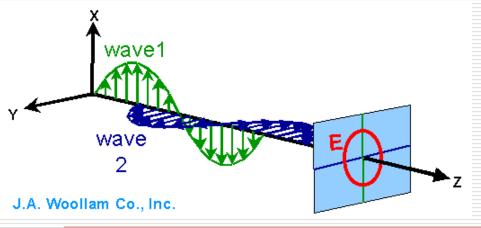
$$\left(\frac{E_x}{E_{0x}}\right)^2 + \left(\frac{E_y}{E_{0y}}\right)^2 - 2\frac{E_x}{E_{0x}}\frac{E_y}{E_{0y}}\cos \varepsilon = \sin^2 \varepsilon$$

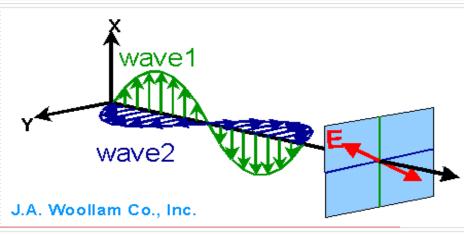
An ellipse can be represented by 4 quantities:

size of minor axis size of major axis orientation (angle) sense (CW, CCW)

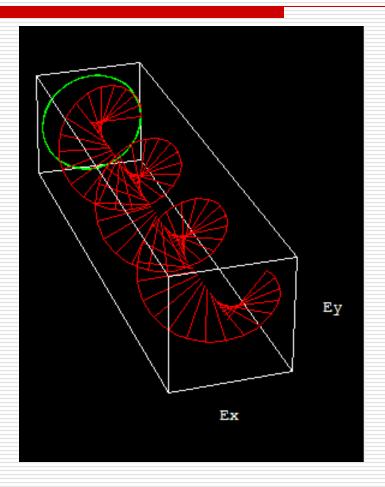
Representations



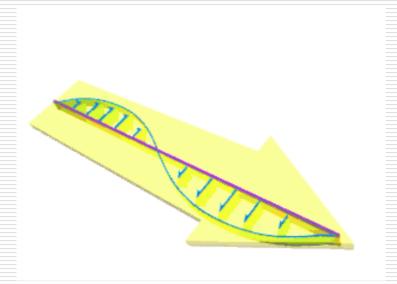




Circular polarization



Unpolarized light (natural light)



Stokes parameters

The polarization ellipse is only valid at a given instant of time (function of time):

$$\left(\frac{E_{x}(t)}{E_{0x}(t)}\right)^{2} + \left(\frac{E_{y}(t)}{E_{0y}(t)}\right)^{2} - 2\frac{E_{x}(t)}{E_{0x}(t)}\frac{E_{y}(t)}{E_{0y}(t)}\cos \varepsilon = \sin^{2} \varepsilon$$

To get the Stokes parameters, do a time average (integral over time)

Stokes parameters

$$(E_{0x}^2 + E_{0y}^2)^2 - (E_{0x}^2 - E_{0y}^2)^2 - (2E_{0x}E_{0y}\cos\epsilon)^2 = (2E_{0x}E_{0y}\sin\epsilon)^2$$

The 4 Stokes parameters are:

$$S_0 = I = E_{0x}^2 + E_{0y}^2$$

 $S_1 = Q = E_{0x}^2 - E_{0y}^2$
 $S_2 = U = 2E_{0x}E_{0y}\cos \varepsilon$
 $S_3 = V = 2E_{0x}E_{0y}\sin \varepsilon$

Pictorial Rep. of Polarization

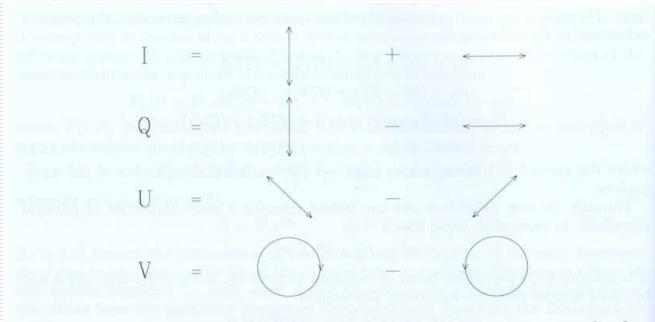
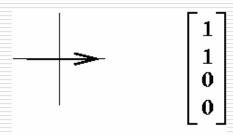


Figure 1. Pictorial representation of the Stokes parameters. The observer is supposed to face the radiation source.

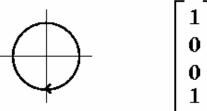
Schurcliff, Polarized Light

Example

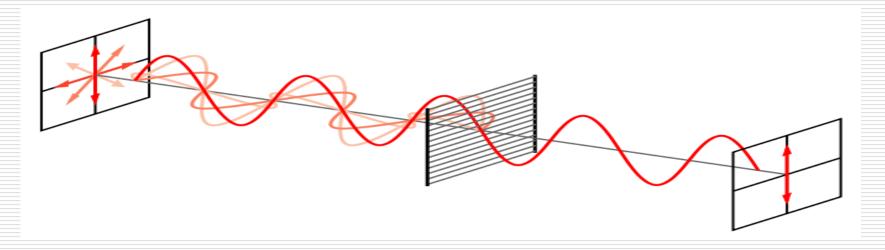
- □ I represents the total Intensity (pol.+unpol.).
- Q & U represents the linear polarization.
- V represents the circular polarization.
- Stokes parameters completely specify the polarization state.





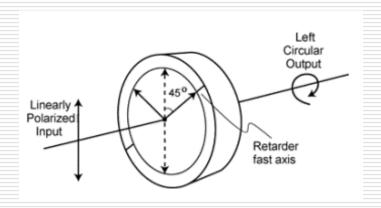


Optics: Polarizer



Allows only the light vibrating along the axis of the polarizers (e.g. wire grid polarizers, Dichroic crystal polarizers, Dichroic sheet polarizers, crystal polarizers, and thin film polarizers)

Optics: Retarder



- Retards one polarization compared to the orthogonal polarization
- Quarter wave 90deg retardance
- □ Half wave 180deg retardance
- Materials used: Quartz, Mica, Calcite, and Polymers

Representation of Polarized Light

Jones Calculus: For coherent source

(Schurcliff, Polarized light, 1962)

Mueller Calculus: For incoherent source

(Gerrard and Burch, Matrix methods in optics, 1975)

Poincare Sphere: Pictorial representation

(Ramachandran and Ramaseshan, Geometrical representation of polarization, 1962)

Mueller matrices

If light is represented by Stokes vectors, optical components are then described with Mueller matrices:

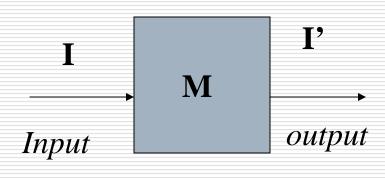
[output light] = [Muller matrix] [input light]

$$\begin{pmatrix} \mathbf{I'} \\ \mathbf{Q'} \\ \mathbf{U'} \\ \mathbf{V'} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} \mathbf{I} \\ \mathbf{Q} \\ \mathbf{U} \\ \mathbf{V} \end{pmatrix}$$

Mueller Calculus

- \square I = [I, Q, U, γ]
- \square I' = [I',Q',U',V'₁]
- M 4X4 matrix
- □ For 'N' optical elements:

$$M' = M_N M_{N-1} \dots M_2 M_1$$



$$I' = M.I$$

Mueller Matrix

QWP at 45°

$$k \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \mp 1 \\ 0 & 0 & 1 & 0 \\ 0 & \pm 1 & 0 & 0 \end{pmatrix}$$

Linear Polarizer at an angle

$$\frac{1}{2} \begin{pmatrix}
1 & \cos 2\chi & \sin 2\chi & 0 \\
\cos 2\chi & \cos^2 2\chi & \sin 2\chi \cos 2\chi & 0 \\
\sin 2\chi & \sin 2\chi \cos 2\chi & \sin^2 2\chi & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}$$

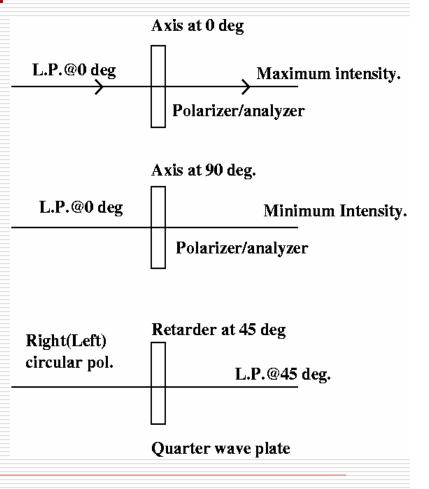
Mueller matrix of retarders

• Retarder of retardance τ and position angle ψ :

with:
$$G = \frac{1}{2}(1 + \cos \tau)$$
 and $H = \frac{1}{2}(1 - \cos \tau)$

A simple polarimeter

- Use Polarizer to detect linear polarization
- Rotate the polarizer to four different positions (0, 45, 90, and 135) Modulation
- □ Difference in intensity between 0 and 90 gives Q Demodulation
- □ Difference in intensity between 45 and 135 gives U Demodulation
- Introduce retarder at 45 degree to convert the circular to linear -Demodulation
- Use the polarizer at 0 and 90 degrees to detect the linear polarization (converted from the circular polarization
- Note: Polarization measurements are differential intensity measurement

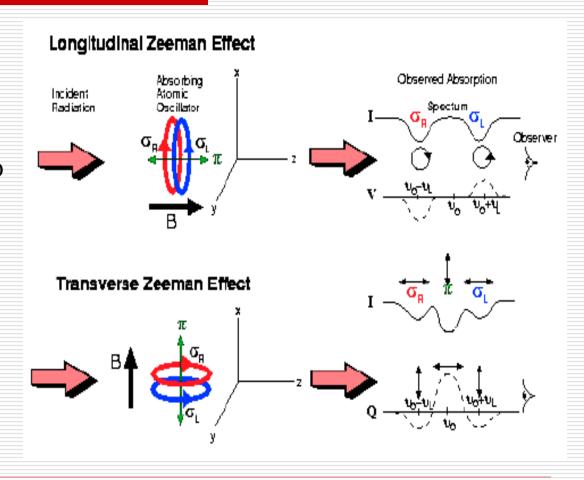


Relation between Magnetic field and polarization.

Zeeman Effect:
 Splitting of spectral lines in the presence of magnetic field.

Splitting is proportional to the field strength and square of the wavelength.

Field strength should be greater than few hundred Gauss for complete splitting



Relationship between magnetic field and polarization

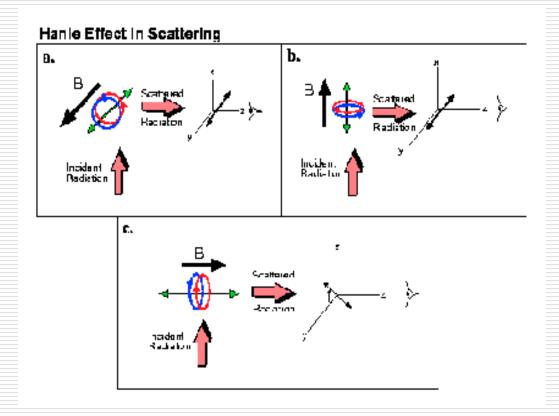
☐ Hanle effect:

Due to coherence scattering in the presence of magnetic field.

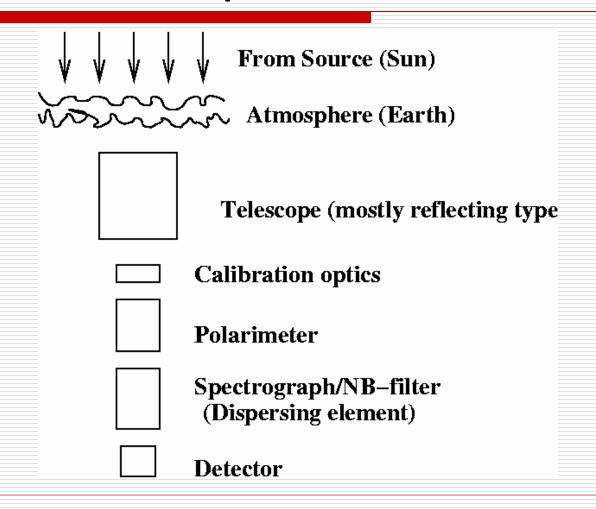
Plasma density should be low.

Anisotropic incident beam.

Larmor frequency be comparable to the spontaneous emission rate.



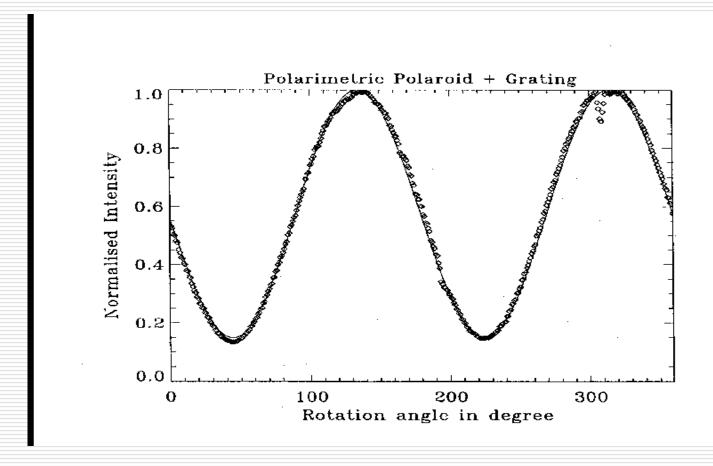
Basic Technique



Modifications of Polarization

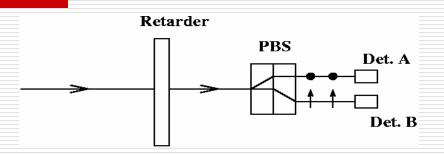
- Source: Range of height for the spectral line formation.
- ☐ Atmosphere: Changes in the atmospheric condition within the measurement time.
- ☐ Telescope: Preferred symmetric optics.
 Reflecting telescope changes polarization.
- Polarimeter: Optical elements in the polarimeter.
- □ Spectrograph: Efficiency changes with the input polarization.
- Detector: Pixel to pixel gain variation.

Efficiency of the grating for different polarization input.



ASP-Type Polarimeter

- Rotating Modulator
- Modulate the polarization on to the intensity.
- Detect the modulated intensity.
- Find the intensity difference between two orthogonal measurement.
- Demodulate the difference intensity to get the Stokes parameters.



 $Retardance = \delta$

 $RotationFreq. = \Omega$

$$\rho = \Omega.t$$

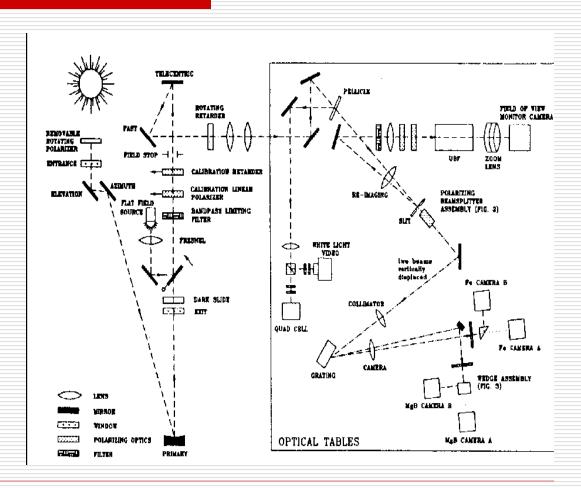
$$DQ = \frac{1}{2}[(1 + \cos\delta) + (1 - \cos\delta)\cos 4\rho]$$

$$DU = \frac{1}{2}(1 - \cos\delta)\sin 4\rho$$

$$DV = -\sin(2\rho)\sin\delta$$

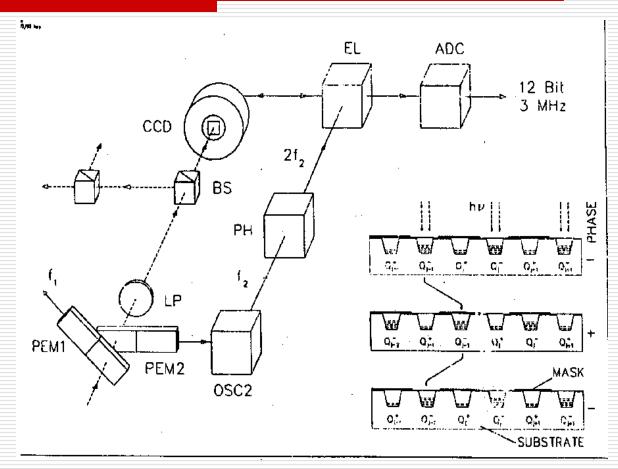
Instruments: ASP

- □ Advanced Stokes
 Polarimeter Two
 beam system to
 reduce the seeing
 contribution (spatial
 modulation).
- Retarder kept before the focus and in the collimated beam.
- Uses a polarizing beam splitter.

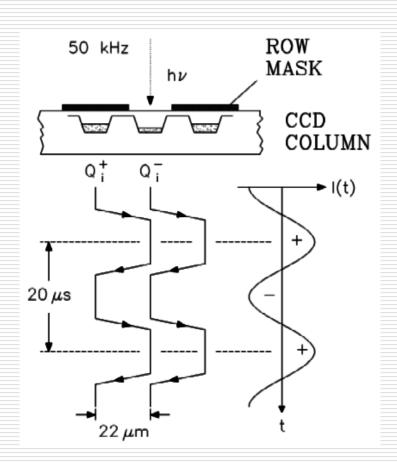


Instrument: ZIMPOL - I

- Fast temporal modulation using the PEM's.
- ☐ Good polarization accuracy.
- Specially made detectors in order to do fast measurements.



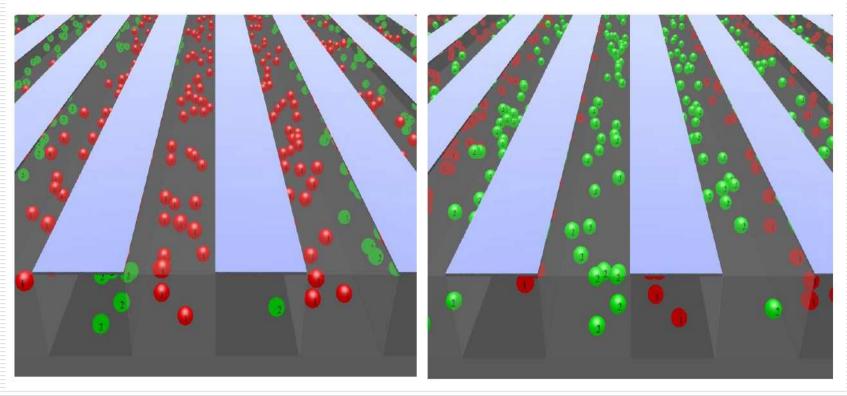
ZIMPOL - I



- Alternate detectors masked
- Possibility of long integration
- □ Sensitivity ~ few times 10⁻⁶
- Low Efficiency since alternate pixels are masked

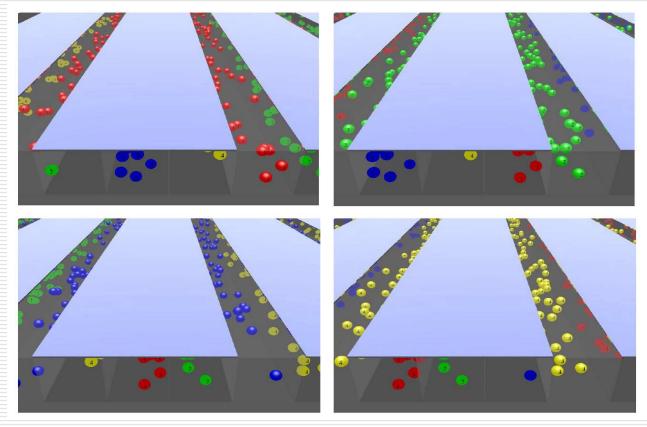
Courtesy: C. U. Keller

ZIMPOL - I



Courtesy: C. U. Keller

ZIMPOL - II



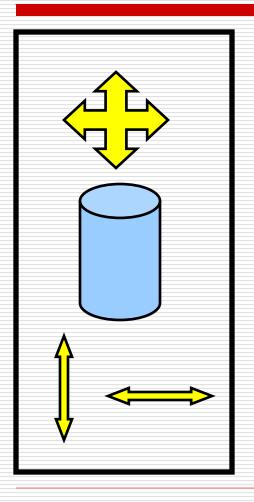
Courtesy: C. U. Keller

Comparison

Modulation Scheme	Advantages	Disadvantages
Temporal modulation (ZIMPOL)	□Negligible flat-field effect. □High polarization accuracy.	□Influence of seeing if modulation is slow. □Regular array detector limits modulation frequency. □Expensive with fast modulation.
Spatial (ASP)	□Off-the-shelf array detector can be used. □High photon collecting efficiency.	□Requires up to 4-times large array detector. □Influence of flat-field □Influence of differential aberration.

Dual-beam polarimeters

Switching beams - Semel's Technique

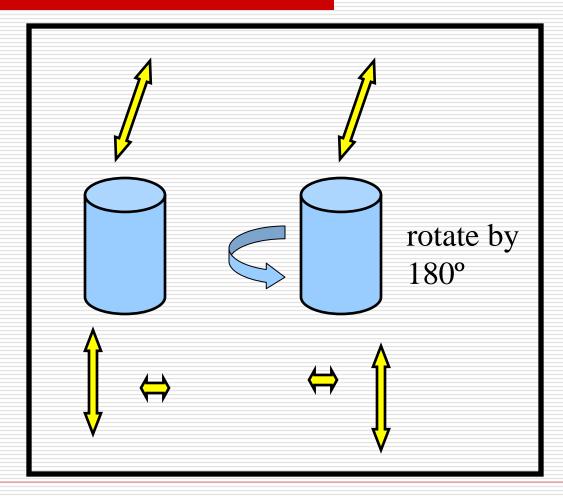


- Unpolarized light: two beams have identical intensities whatever the prism's position if the 2 pixels have the same gain
- To compensate different gains, switch the 2 beams and average the 2 measurements

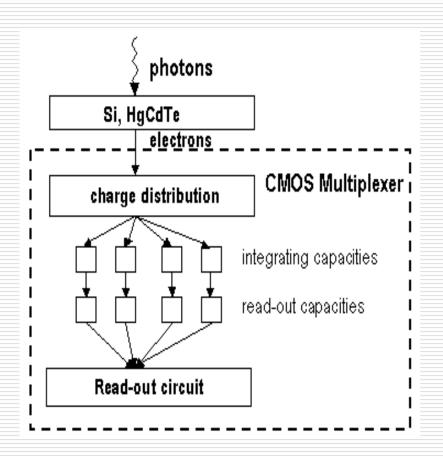
Courtesy: Manset, CFHT

Dual-beam polarimeters

Switching beams by rotating the prism



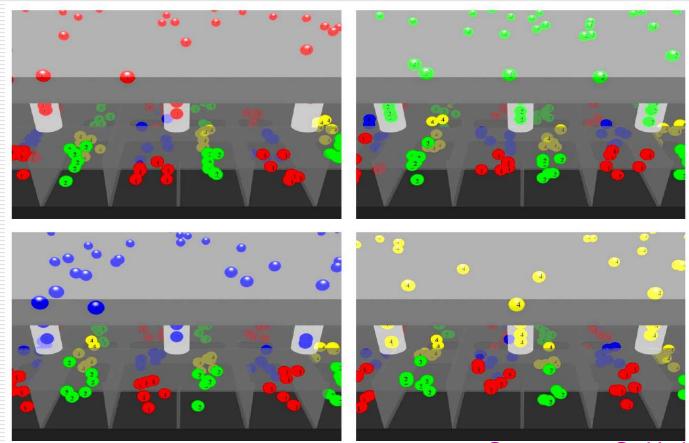
Future Directions: C³PO



	ZIMPOL II	C ³ Po
Geometric fill factor	<25%	100%
Peak quantum efficiency	<35%	>85%
Wavelengt h coverage	200 - 1100 nm	200 - 10,000 nm
Full-well depth	250,000	>500,000

Courtesy: C. U. Keller

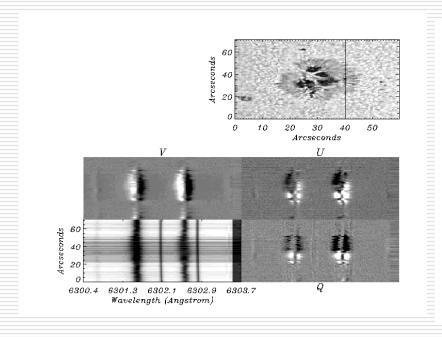
C^3PO

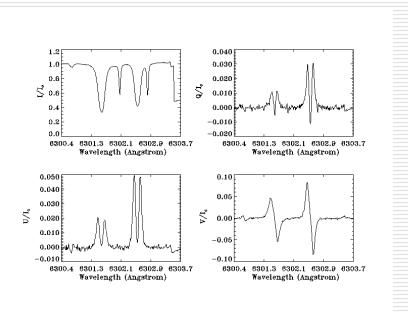


Requirement for C³PO

Item	Specification	Comments
Format	1024 by 1024 pixels	2048 by 2048 would be great
Pixel pitch	18 micrometers square	Larger pixels would hold more charges
Number of image states	4	2 is the absolute minimum
Full well depth per image state	>500,000 e	More would be better, but would require larger pixels
Geometric fill factor	100%	No incident photons blocked
Frame rate	>= 10 frames per second	goal of 25 frames/s
Dynamic range	>10000	Full well / readout noise
Readout noise	<300 e rms per pixel	goal of <150 e
Quantum efficiency	>85% @ 630 nm >85% @ 854 nm >5% @1083 nm	at operating temperature
Dark current	<5000 e per sec per pixel @ -15C	
Dark current stability	Better than 300 e/s/pixel rms over 12 hours	Courtesy: C. U. Keller
Flatness	<100 micrometer peak-peak	
Image lag	<0.2%	Signal remaining from previous frame

Observed Stokes profiles

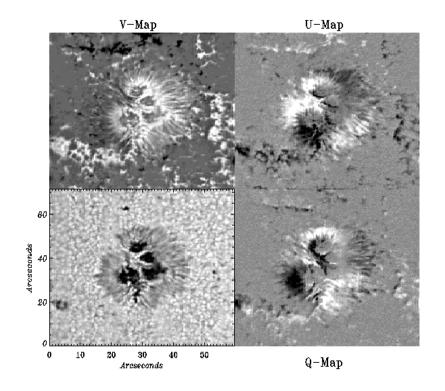




- Observed in the penumbral region of a sunspot.
- Stokes profiles are corrected for the instrumental polarization.

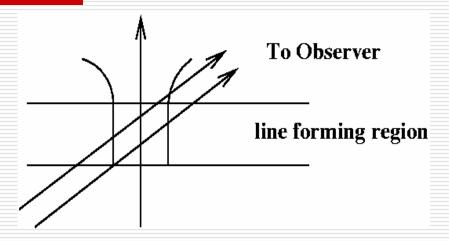
Stokes parameter map of a sunspot.

- □ Taken with the ASP and the AO.
- Maps are produced using few wavelength positions in the wing of the spectral line 6302.5.
- ☐ The whole spectrograph is moved to scan the region.
- Seeing was excellent.



Calculation of vector field.

- Need to know the physical processes which are happening in the line forming region.
- Radiative transfer processes.
- Good imagination with supportive physics.



$$\mu \frac{dI_{\lambda}}{d\tau_{\lambda}} = S_{\lambda} - I_{\lambda}$$

ASP inversion code.

- □ Input Calibrated I, Q, U, V; and a model file.
- Output Fitted parameters with associated errors.
- 10 fitted parameters Vector field (3), Doppler broadening, line depth, fill fraction, velocity, damping factor, source fn. (2), scattered light.
- Assumption: The atmosphere is a Milne-Eddington (ME) atmosphere. The parameters are constant with depth.

Forward Vs. Inverse

Forward Reverse □Compares the values of the □Infer the unknown model observed Stokes parameters parameters using the observed with that of a calculated one by Stokes profiles. solving the RTE using assumed □In doing so use a minimization model parameters. technique. □Time consuming once the □Large computation time number of model parameters are ☐Simple to use and can be used for large and also with large number large number of profiles and for of observed profiles. large number of model parameters.

Polarimetry at Other wavelengths

- Gamma Ray Polarimetry Not so important for solar but for GRBs
- X Ray Polarimetry Detected in solar flares
- VUV Polarimetry Not yet tried
- Visible Instrumentation well understood and fine tuning is going on
- EUV and UV polarimetry Still in the infant stage
- □ IR and Far-IR Detector development is the major hurdle but progress has been made
- Microwave Have produced some interesting results
- Radio wave Well established and under development for solar observations