ZIMPOL-3: a powerful solar polarimeter

San Diego, SPIE, 1. July 2010

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Summary

• Scientific relevance of high precision polarimetry
• General overview on polarimeters
• ZIMPOL
  – overview
  – ZIMPOL cameras: demodulation
    • the previous versions and the evolution
    • ZIMPOL 3
  – modulators
  – setup at IRSOL
  – first observations with the new ZIMPOL3 cameras
• Concluding remarks
Polarimetry

- Polarimetry allows to get information about the magnetic fields

Zeeman effect:

Polarization signals up to several tens of %

Zeeman effect allows to extract the tridimensional information of strong oriented magnetic fields.
Scattering polarization and the Hanle effect

- The improvement in the polarimetric accuracy (at $10^{-4}$ level or better) opened a new window in the observation of scattering polarization (mainly) near the limb.

- Scattering polarization profiles in spectral lines are sensitive also to weak and mixed-polarity magnetic fields through the Hanle Effect (which mainly manifests itself as depolarization and ev. a rotation of plane of polarization).

- Powerful tool to get information about weak and (unresolved) mixed polarity magnetic fields (to which Zeeman effect is blind).
Second solar spectrum

Gandorfer (2000)
Task of polarimeter

- change polarization state of incoming light in a controlled way

\[ \mathbf{S}_{\text{in}} \rightarrow \mathbf{M} \rightarrow \mathbf{S}_{\text{out}} \rightarrow \text{CCD} \]

\[ \mathbf{S}_{\text{out}} = \mathbf{M}(t) \cdot \mathbf{S}_{\text{in}} \]

- detectors measure only intensities
- combine intensity measurements to obtain polarization state of incoming light

Stokes Parameters

- \( \mathbf{S}_{\text{in}} \): incoming Stokes vec.
- \( \mathbf{S}_{\text{out}} \): outgoing Stokes vec.
- \( \mathbf{M} \): Müller Matrix

\[ \mathbf{S}_{i} = \left( \begin{array}{c} I_{i} \\ Q_{i} \\ U_{i} \\ V_{i} \end{array} \right) \]

\[ \begin{array}{c|c} \mathbf{Q} & = \begin{array}{c} \uparrow \downarrow \rightarrow \leftarrow \end{array} \\ \mathbf{V} & = \begin{array}{c} \circ \circ \leftarrow \rightarrow \text{+} \text{+} \text{+} \right. \end{array} \end{array} \]
for each measurement we get an intensity $S_j$ which depends on the first row of the Müller Matrix $M_j$:

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

To obtain a full Stokes measurement one needs at least 4 independent measurements with different $M_j$:

$$
\begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix} =
\begin{pmatrix}
m_{1,11} & m_{1,12} & m_{1,13} & m_{1,14} \\
m_{2,11} & m_{2,12} & m_{2,13} & m_{2,14} \\
m_{3,11} & m_{3,12} & m_{3,13} & m_{3,14} \\
m_{4,11} & m_{4,12} & m_{4,13} & m_{4,14}
\end{pmatrix}
\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}
$$

$X$ : Modulation Matrix (made with first rows of $M_j$)
• If component of modulation Matrix $X$ are linearly independent one can invert it and obtain the Stokes vector of the incoming beam from the Intensity measurements

• **Demodulation Matrix $Y$**

  $$ Y = X^{-1} $$

  $$
  \begin{pmatrix}
  I \\
  Q \\
  U \\
  V
  \end{pmatrix}
  =
  Y
  \begin{pmatrix}
  S_1 \\
  S_2 \\
  S_3 \\
  S_4
  \end{pmatrix}
  $$

• **Note:** to determine only one polarization component one needs just 2 intensity measurements
Simple one beam technique

- Problem if intensity is not constant: if modulation $< \sim 100$Hz, measurements are disturbed by seeing
Two beams technique

- The modulation is “spatial”
- Advantage: high photon collection efficiency
- Problems: gain table noise (flat field), differential aberrations
- Other disadvantage: requires larger sensors
Two beams exchange technique

- combination of spatial and temporal modulation
- data reduction allows to reduce many artifacts
ZIMPOL system

- Zurich IMaging POLarimeter
- One beam and fast modulation (1kHz or 42 kHz)
- Allows measurements free from seeing spurious effects
- Fractional polarization measurements (after a good calibration) are mostly free from gain-table noise effects
- Precision limited basically by photon statistics
- It is possible to obtain measurements with relative precision down to $10^{-5}$
Typical ZIMPOL Setup
ZIMPOL principle

Syncronisation

Modulator
(Variable retarder)

Polarizer

Maked CCD sensor
(Demodulation)

Gisler (2005)
Demodulation: ZIMPOL1

(Animated image)

- every 2 rows, 1 row is masked (buffer)
ZIMPOL 1

• operated mainly in the period 1994-1998
• with 1 camera it is possible to measure only 1 polarization component
• simultaneous full Stokes measurements need 3 cameras (complicated)
• smaller detectors
Demodulation: ZIMPOL2

- 3 out of 4 raws are masked
- full Stokes measurement with one camera

(Animated image)
ZIMPOL2

- first version since 1998
- since 2001 UV cameras
- since 2006 sensors with cylindrical microlenses
  - ca. 4 X more light
- currently working in a very stable configuration
- for the future the maintenance will be difficult, many components are no more available on the market
- sensitive area: 770x560 pixels
ZIMPOL3

New generation camera system which is being implemented for observations at IRSOL, Locarno, Switzerland
ZIMPOL3

Improvements with respect to ZIMPOL2:

• more flexible and compact system
• adaptable to different cips
  – new larger cips for UV with microlenses
• more efficient and faster
• exposure and readout simultaneously
• based on newer technology (replace components available on the market)
• more functions (readout modes, binning, subframe readout, different demodulation schemes, electronic compensation of telescope pol. offset)
• night astronomy application possible: longer integration time, better cooling
ZIMPOL3 microlenses

Diagram showing the structure of ZIMPOL3 microlenses with labels for substrate, stripmask, airspace, CCD-chip, and bonding with ML-array.
ZIMPOL 2-3 Modulators

- Photoelastic Modulator (PEM)
  - Quartz plate oscillates at resonance frequency 42kHz
  - Introduce variable retardance (due to stress)
  - Advantages: optical quality, good transparency, also in the UV

![Graph showing intensity vs modulation phase](image)
• with single PEM
  - With one PEM is possible to measure only 3 Stokes parameters simultaneously
  - IQV and IUV measurements obtained alternatively through mechanical rotation of the analyser optics by 45°

• dual PEM system
  - Would allow to measure simultaneously IQUV
  - Synchronisation of the two PEM’s difficult
  - Project planned to be pursued at SUPSI, Lugano
Intensity modulation with dual PEM
Ferroelectric Liquid Cristal Modulator

- Rotation of fast axis of retardation
- 1 kHz (driven frequency)
- Possible to synchronise Dual modulator system → allows to measure simultaneously all 4 Stokes parameters
- Possible simultaneous usage at different wavelengths (e.g. 2 cameras @ Themis)
- Measurements from 450nm to 1000nm
  - goal to go in future down to 400nm
ZIMPOL3 Setup at IRSOL
ZIMPOL3 Setup at IRSOL

- calibration and modulator package after the exit window of the telescope

- telescope instrumental polarization is small and easy to correct since it is a function of declination and stays constant during one day of observations

- cross-talks measurements from time to time with a polarizing sheet in front of the telescope to determine declination dependence
The ZIMPOL3 setup at IRSOL

45 cm aperture
Gregory - Coudé
telecope (f = 25 m)

Calibration optics
linear polarizer +
quarter wave plate

Linear polarization
compensation plate

Modulator
Linear Polarizer

Half wave plate

Derotator

Adaptive optics

Im Littrow prism
pre-disperser or
preselection filter

Czerny Turner
Spectrograph

Focal reducer

ZIMPOL3
camera

water cooling

encoders
Primary Image
sensor

Primary Image
Guiding (PIG)

PIG
GUI

Step motor
controller

Secondary full disc
H₂ telescope
camera server

GUI

AO control

Slit jaw
camera

Spectrograph
controller

Slit jaw
camera control

FP
controller

Command Script
Interpreter (CSI)

GUI

scripts display
interactive
commands

online analysis
tools and display
clients (pre-processing)

command line
client

Ethernet connections

Planned connections
GUI and online analysis tools
First ZIMPOL3 observations

Scattering polarization observation at ~12 arcsec inside N-limb

(integration time 250 sec.)
First ZIMPOL3 observations
Overhead time ZIMPOL-3 vs -2

Present situation!

<table>
<thead>
<tr>
<th>Integration time per frame (seconds)</th>
<th>ZIMPOL-2 CCD55-20 804 × 576 pixel (12 bits)</th>
<th>ZIMPOL-3 CCD55-20 804 × 576 pixel (16 bits)</th>
<th>ZIMPOL-3 CCD55-30 1280 × 576 pixel (16 bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>66%</td>
<td>46%</td>
<td>57%</td>
</tr>
<tr>
<td>1</td>
<td>50%</td>
<td>28%</td>
<td>40%</td>
</tr>
</tbody>
</table>

Coming soon:

- Improvement of the pipelining of the readout
- Parallel integration and readout of the CCD
Concluding remarks

• With ZIMPOL-3 we could obtain first promising observations

• **ZIMPOL-3** has advantages with respect to the old ZIMPOL-2 in terms of overall efficiency, flexibility and compactness.

• We haven’t yet exploited all potentialities of the new ZIMPOL-3 camera and we are still doing improvement and optimization works. In particular we plan to be able to further increase the system speed.

• Once we will have gained sufficient experience with the new system, in order to demonstrate its reliability in comparison with the old ZIMPOL-2 system, we plan to completely replace ZIMPOL-2 with ZIMPOL-3 system in the all-days observations.

• It is planned to observe also at larger telescopes like Gregor and Thémis.

• We think that the ZIMPOL technology could be very interesting also for the new large telescope projects (ATST-EST)

• For the future projects, exploration of new technologies (like e.g. CMOS).