The “Second Solar Spectrum” in the near UV

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Sonnenseminar Katlenburg-Lindau, July 5, 2005
Polarisation in astrophysics

• Polarisation as signature of spatial symmetry breaking
• Sources of polarisation:
  – Magnetic fields (Zeeman effect)
  – Scattering
Scattering polarisation at the solar limb

- Limb darkening:
  - Temperature stratification in photosphere
  - Anisotropic illumination
  - Scattering defines plane
  - POLARISATION
Scattering polarisation

• Weak!
• Highly wavelength dependent:
  – Atomic physics: Polarisability of the line
  – Solar physics: $\lambda$-dependence of illumination anisotropy
  – Polarised radiative transfer effects
    „spectrum of scattered radiation“
    „The Second Solar Spectrum“
History

- Individual recordings of strong signals for several decades (Brückner 1963; Wiehr 1974, 1975; Stenflo 1975, 1980)
- First systematic survey by Stenflo et al., 1980, 1983
A high resolution atlas of the second solar spectrum

- Atlas to guide future observations
- Data collection to guide and constrain future theoretical efforts
- Reference catalogue for direct comparison between lines over the whole optical spectrum
Why another atlas?

• 99% of the second solar spectrum were unknown. Why?
  – Most signals extremely weak ( < 0.1% )
  – Needs long integration times even with large telescopes
  – 1983 survey (Stenflo et al.) buries most signals in noise ( 0.3%)
  – Needs well adapted instrumentation
Instrumental aspects

• Basic requirements:
  – Highly sensitive polarimeter: must be free from systematic errors down to ≈ 0.003%
  – Very high spectral resolution 250,000
  – Moderate spatial resolution (1-2 arcsec in one direction), averaging along spatial direction
  – Large telescope to collect photons
  – Fast camera to minimize read-out dead time
Polarimeter

• (UV sensitive version of) ZIMPOL II detector in combination with 1 piezoelastic modulator for simultaneous recording of Stokes I, Q/I, and V/I
• ultra-fast polarization modulation to avoid seeing induced errors
• No gain table in fractional polarisation images
Telescopes

- IRSOL 45 cm Gregory-Coude (Vol I and II) 1999-2001
- 1.5m McMath-Pierce (Kitt Peak) (Vol III) 2002/2003
# Spectrograph

**IRSOL:**
- 10.0m Czerny Turner design
- 18cm times 36cm ruled grating with 300 grooves / mm
- 1m Littrow prism monochromator as preselector

**McMath-Pierce:**
- 13.7m Czerny Turner design
- 25cm times 48cm ruled grating with 600 grooves / mm
- metal/dielectric interference filters as order sorters
Observations

- solar pole (magnetically quiet region)
- Constant limb distance $\mu = 0.1$ (5” inside limb)
- Typically 4 Å per exposure with 6 mÅ pixel using telecentric focal reducer in the spectral plane
- Typically 25 min integration time with 4s per frame
- Typically $5 \times 10^{-5}$ rms noise in Q/I
- Covers 3165 Å to 3915 Å
Some statistics..

• CCD full well: ~500,000 e
  – Photometric (polarimetric) noise ~0.3 %
  – Averaging over 100 (full!) exposures: 0.03%
  – 0.003% needs min. of 10,000 frames
  – 0.001% requires at least 100,000 frames
• Even with 10 fps this takes hours!!!
• 0.001% level only possible in observations with course spatial resolution (evolution time…)

• Limit is not set by telescope, but by read-out rate!

• Excessive binning destroys spatial information → 1-dim spectropolarimetry
Second Solar Spectrum??

Gandorfer, A. "The second solar spectrum". vdf Zürich
Second Solar Spectrum!!

Gandorfer, A.: „The second solar spectrum“, vdf Zurich
Second Solar Spectrum as a diagnostic tool

• classical spectroscopy
  – isotope ratios, abundances
• thermodynamics, diagnostics of the quiet atmosphere
• atomic and molecular physics
• MAGNETIC FIELD DIAGNOSTICS
hyperfine structure of odd isotopes of the Ba atom

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

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Hanle diagnostics

- Hanle effect: Modification of scattering polarisation in the presence of a magnetic field
Hanle effect

• depolarisation
  – independent of field orientation
• rotation of the polarisation plane
  – depends on field orientation
• for unresolved mixed polarity fields there will always be a depolarisation effect!
  → TURBULENT FIELDS
When does the Hanle effect work?

- Needs scattering polarisation
- best in slightly upper layers of the solar atmosphere
- works best in near UV
- Works if Zeeman splitting is comparable to natural line width: 0.1 ... 100 G
  → WEAK FIELDS
- needs very high polarimetric sensitivity
From scattering polarimetry to Hanle diagnostics

1.: Observing the „second solar spectrum“
2.: Understanding the „second solar spectrum“
3.: Using the „second solar spectrum“ as a tool for magnetic field diagnostics
Atlas of the Second Solar Spectrum

- systematic exploration of the „second solar spectrum“
- covers 316 nm – 700 nm
- most comprehensive reference data-set available
Where are we?

- Second solar spectrum observed between 316 nm and 700 nm
- Many theoretical results by various groups
- Hanle diagnostics with low spatial resolution
- Promising future
Instrumental aspects

• Basic requirements:
  – Highly sensitive polarimeter: must be free from systematic errors down to 0.001%
  – Very high spectral resolution of 250,000
  – Moderate spatial resolution (1-2 arcsec in one direction), averaging along spatial direction
  – Large telescope to collect photons
  – Fast camera to minimize read-out dead time
Polarimetric basics

- Polarimetry = differential photometry
- Polarisation images are linear combinations of photometric or spectral images taken in different polarization states
Systematic error sources

1. Seeing noise
2. Gain-table or flat field noise
3. Photon noise
How to do sensitive polarimetry?

- Seeing noise
- Gain table noise
- Photon noise
- Fast polarization modulation
- Use identical detector elements for differential images
- Increase statistic by frame averaging
Problems in Hanle work

• intrinsic weakness of scattering signals
  ➔ very limited spatial resolution in most lines

Solution: Observations of Hanle effect with moderate spatial resolution in strongest polarising lines; these lines are all to be found in the UV
Zurich IMaging POLarimeter ZIMPOL II

- Fast 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
Polarimeter

- ZIMPOL II detector in combination with 1 piezoelectric modulator for simultaneous recording of Stokes I, Q/I, and V/I (Gandorfer and Povel 1997)
- Ultra-fast polarization modulation to avoid seeing induced errors
- No gain table in fractional polarization images
ZIMPOL II: Components

- Piezoelectric modulator or ferroelectric retarders allow polarisation modulation up to 84 kHz
- Glan linear polariser as analyser
- 3 out of 4 pixel rows covered with opaque mask
- 4 interleaved charge images can be handled simultaneously in the same CCD
- Rapid charge shifting in synchronism with modulation
ZIMPOL II: Principle

[Diagram of ZIMPOL II principle with labels for PEM1, GP, CCD, CCD DRIVER, PEM DRIVER, PHASE SHIFTER, and CIPS.]
ZIMPOL II: Principle

![Graph showing the principle of ZIMPOL II](image)
ZIMPOL II: Principle

Zeeman polarimetry

• Ideal remote sensing of strong isolated field components
• Works if Zeeman splitting is comparable to Doppler width: order of 1 kG
  → Works best in photosphere
• Sensitive to cancellation effects: needs high spatial and spectral resolution
  → NO WEAK / NO TURBULENT FIELDS
• sensitivity scales with $\lambda$ → works best in near IR