Instrumentation for high-resolution spectropolarimetry in the visible and far-ultraviolet.

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- Linear spectropolarimetry of spectral lines
- Southern African Large Telescope (SALT) spectropolarimeter
- Far Ultraviolet SpectroPolarimeter (FUSP)

High-Resolution Spectropolarimetry

- Linear spectropolarimetry of resolved spectral lines a poorly exploited technique
  - not enough photons to do other than bright lines in bright objects
  - little experience in applying techniques
- Past applications: eg dust or electron scattered emission lines. In theory, doppler profiles give access to 3rd dimension (polarimetric tomography)
  - Scattered Hα in M82 (Visvanathan), η Car (Schulte-Ladbeck)
  - Need efficient imaging spectropolarimeter
Circumstellar Magnetic Field Diagnostics

• New techniques: magnetic diagnostics (solar physics heritage)
  • Zeeman (circular):
    – Visible: stellar photospheres, > 100 G
  • Hanle (linear: fluorescent scattering):
    – Dynamic winds (unresolved source), 0.1 – 1000 G
    – Developed in Sun only
  • Realignment:
    – Outer circumstellar envelopes (resolved reflection nebulae), < 1 µG?
    – Undeveloped

Instruments and techniques

• Spectral resolution: R ~ 2000 – 10,000 to resolve lines, avoid unpolarized continuum contamination and noise
• Etendue. For resolved nebulae, need high spectral resolution of diffuse sources
• Signal/ Noise. Need bigger telescopes, higher efficiency (SALT)
• Wavelength range. Most scattering lines in UV (FUSP)
Southern African Large Telescope Prime Focus Imaging Spectrograph

- Based on Hobby-Eberly Telescope (HET)
  - F/1.2 spherical primary: 11m aperture, hexagonal array
  - “Tilted Arecibo”: primary at fixed elevation; pick an azimuth, focal plane tracks. Track duration 0.75 – 2.5 hr.
  - Emphasis: spectroscopy and high S/N work
- 4-mirror Spherical Aberration Corrector (SAC), 8 arcmin field of view
- Prime Focus Imaging Spectrograph (PFIS) permanently mounted - spectropolarimeter
Instrumental Polarization

- **Concerns**
  - Steep reflections in SAC
  - Variable pupil during track

- **Coatings**
  - Primary: Al
  - SAC: LLNL enhanced Ag/Al

- **Find pol:**
  - < 0.1% 4' dia FOV
  - ~0.2% at 8' dia
  - Field effect > track effect
  - spec: correctable to < 0.04%

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SALT Prime Focus Imaging Spectrograph

- **dual beam UV – NIR spectroscopy (320 nm – 1.7 μm).**
- **8 arcmin FOV.** Slitmasks and long slit.
- **all refractive; 150 mm beam.**

**Visible beam commissioning in late 2004.**

- **Spectroscopy/ polarimetry with Volume Phase Holographic ("VPH") gratings 320 – 900 nm.**
  - spectrograph/ detector efficiency 60% peak; 30% @ 320 nm
  - $R = 600 - 5300$ (1.25 arcsec slit – median seeing+telescope) $R -> 10,000$ (0.5 arcsec)

- **Dual etalon Fabry-Perot spectroscopy/ polarimetry 430 – 860 nm.**
  - $R = 2500$, "bullseye“ 3 arcmin;
  - $R = 13,000$, 1.5 arcmin
Imaging VPH Grating Spectropolarimetry

Volume Phase Holographic Grating

Beam-splitter

Wave-plate

NGC 7027

Fabry-Perot Imaging Spectropolarimetry

Fabry-Perot Etalons

Na D

NGC 7027

Aug 27, 2002 SPIE Polarimetry in Astronomy

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Polarimetry - Beamsplitter

- Calcite Wollaston Beamsplitter in collimated beam after grating
- Mosaic of 9 calcite prisms in framework
- Split +/- 45 deg polarizations ~ 5 deg => 4 arcmin at detector into two half-fields “O” and “E”

Polarimetry - Waveplates

- Pancharatnam superachromatic waveplates: stack of 6 very thin retarders
- In collimator after field lens (to minimize diameter)
- ½ and ¼ waves from 320 – 1.7 microns
- very large SALT etendue (aperture x FOV) limits performance of waveplates in UV – reduced efficiency; sensitivity to pupil
Waveplate efficiency

- Pancharatnam modified for off-axis performance
- Overall polarimetric efficiency reduced, but still > 98% (halfwave), 94% (quarterwave)
- Pupil shape sensitivity not significant for halfwave
- Quarterwave more sensitive to pupil effects, due to manufacturing limits on element thickness

Far Ultraviolet SpectroPolarimeter (FUSP)

- Wavelengths 105 – 150 nm
  - 1st polarimetry below Lyα
- Resolution $\lambda/\Delta\lambda = 1800$
  (0.05 nm; 180 km/sec)
  - aperture 20” (50 cm)
  - stressed LiF waveplate
  - diamond brewster-reflection polarization analyzer
  - spherical holographic grating
- Sounding Rocket in development:
  - two-stage rocket, apogee 400 km
  - science time 400 sec
- Scheduled first launch: 2003
FUSP Spectropolarimeter

Zero-Order Sensor
Fold Mirror
Correcting Lens
Diamond Brewster Mirror
Rotating LiF Waveplate
Spectrometer Detector
Grating

FUSP Polarimetric Optics

- **LiF Waveplate**
  - 12 mm square, 1.5 mm thick
  - 15 lbs pressure on side => ½ wave at 125 nm
  - absorption edge 105 nm
  - rotated in 11.25 deg steps
- **Diamond brewster**
  - 10 mm square, 0.5 mm thick CVD diamond
  - angle 72.5 deg
  - FOV 12x17 arcmin
**FUV Spectropolarimetry of ζ Ori**

- Hanle Effect simulation: dipole field embedded in spherical wind
- Note lower Hanle field lines appear first
- 3 G detectable with FUSP...

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**Summary**

- High spectral resolution linear spectropolarimetry potentially very powerful if we can get enough photons
  - polarimetric tomography
  - magnetic diagnostics
- Visible: SALT 11m
  - $R = 1000 – 5000$ imaging grating spectropolarimetry
  - $R = 300 – 13000$ imaging Fabry-Perot spectropolarimetry
- VUV: FUSP 0.5m sounding rocket
  - $R = 1800, 105 – 145$ nm
  - First polarimetry below Ly$\alpha$
Backups

PFIS Polarimetric Modes

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**Atomic Scattering Diagnostics**

- Line scattering (fluorescence), no field
  \[ \sigma = \text{monochromatic} \approx 10^{-18} \text{ cm}^2 \]
  \[ I(\theta) = E_1 I_e(\theta) + (1 - E_1) I_{iso} \]
  \[ p(\theta) = \frac{3}{4} E_1 \sin^2 \theta / (1 - \frac{1}{4} E_1 + \frac{3}{4} E_1 \cos^2 \theta) \]

  \( E_1 \) is the "polarizability", comes from QM, a function of \( J_i, \Delta J_i, \Delta J_f \).

- B-field modifies polarizability
  \[ \Rightarrow \text{Diagnostics. Circumstellar application:} \]
  - \( \tau \ll 1; \text{ point illuminator} \)
  - Resonance fluorescence (ground state) emission

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**Imaging High Resolution Polarimetry of Nebulae**

Magnetic Realignment pilot project:
- spatially resolved nebulae with atomic resonance scattering. Na D in:

- **Planetary Nebulae**
  - Fluorescent NaD seen in 5 PN's by Dinerstein, et al 1995
  - PN magnetic field geometry used to explain PN bipolar geometry
  - Sensitive to \( B < 1 \mu \text{G} \)
  - Resolve expansion profile (R > 10,000) to isolate 90° scattering at line center
  - Requires large telescope: \( \sim 50 \text{ R 20 arcsec nebula} \)