Sunspots
Now, Solar-B/ATST, and Beyond

K. S. Balasubramaniam

National Solar Observatory
Why Study Sunspots?

- Ramification of thermal and dynamic interaction between convection and magnetic fields.
- Signature and tracers of the solar a-w dynamo.
- Balance between convection driven material flows and magnetic field guided flows.
- Spectral line formation in a magnetically dominated atmosphere.
- Magneto hydrodynamic basis for magnetic-field to heat conversion
- Flare eruptions significantly at the periphery of sunspots, exceptional white-light flares, extending to the umbra.
- Understanding of potential and sheared magnetic geometries, potential basis for comparison with turbulent dynamo
Instruments Now:

Imaging: 0.2 – 5 arcsecond spatial resolution
Spectroscopic: 0.4 – 2 arcsecond spatial sampling depending on instrument

  15 – 60 mA spectral resolution
  (spectromagnetographs, vector polarimeters)

 Imaging Spectroscopy:

  20 – 500 mA filters
  (Tunable filters, magnetographs, imaging polarimeters)

Field-of-View: 2 – 5 arcminutes with raster scanning/spectral tuning

 Exceptions – Full-disk magnetographs, SOHO/MDI
Solar-B

Solar B:
  Imaging: 0.25 arcsecond resolution, 0.1 arcsecond sampling
  Spectroscopic: 0.16 arcsecond spatial sampling (?)
  25 mA spectral resolution (?)
  (Vector polarimeter)

Imaging spectroscopy:
  >0.1A filters
  (Tunable filters, magnetographs)

Field-of-view: 3 – 5 arcminutes
  Only photospheric magnetic fields

Temporal cadence: sub-seconds for imaging, 50-100 minutes for AR vector magnetograms

Temporal coverage: >24 hours continuous for given active region?
<table>
<thead>
<tr>
<th>Optical System Telescope Tube</th>
<th>Aplanatic: Gregorian, 50 cm diameter, F/10.5 CFRP (graphite epoxy), truss structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Plane Package Objective</td>
<td>Narrow-band filter Mapping of magnetic and velocity fields</td>
</tr>
<tr>
<td></td>
<td>Interference filter High spatial resolution imaging</td>
</tr>
<tr>
<td>Observing Wavelength Wavelength Switch</td>
<td>1500–6600 Å Rotating waveplate or piezo electric actuator</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>0.1 Å at 6000 Å 10–20 Å</td>
</tr>
<tr>
<td>CCD</td>
<td>2048×2048 (9 μm)² 10-bit.</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>2048×2048 (9 μm)² 10 bit.</td>
</tr>
<tr>
<td>A/D Converter</td>
<td>9 μm (TBD)</td>
</tr>
<tr>
<td>Plate Scale</td>
<td>0′′1/pixel (200″)²</td>
</tr>
<tr>
<td>FOV</td>
<td>0′′1/pixel (200″)²</td>
</tr>
<tr>
<td>Standard Exposure</td>
<td>0.1–100 ms and 0′′1×25 ms/pixel</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>100 ms (best)</td>
</tr>
<tr>
<td></td>
<td>100 ms/25 ms (best)</td>
</tr>
<tr>
<td>Observing Coverage</td>
<td>Continuous observing in Sun-synchronous orbit</td>
</tr>
<tr>
<td>Image stabilisation</td>
<td>Use attitude control and tip-tilt mirror to achieve 0′′02 per 10 sec.</td>
</tr>
<tr>
<td>Changing FOV</td>
<td>Spacelab attitude control (in addition, tracking of a region using solar rotation is under consideration.)</td>
</tr>
<tr>
<td>CPU</td>
<td>Equivalent of 80C386 for control and on-board processing</td>
</tr>
<tr>
<td>Frame Memory</td>
<td>~30 Mbytes (16 Mbit DRAM)</td>
</tr>
<tr>
<td>Amount of uncompressed data</td>
<td>Data production rate: average<del>749 kbps, maximum</del>TBD kbps, total amount of data: 4.4 Gbits per orbit.</td>
</tr>
<tr>
<td>Number of images obtained</td>
<td>About 440 1k × 1k images per orbit.</td>
</tr>
<tr>
<td>Data compression</td>
<td>2×2, 4×1 CCD on-chip pixel summation, bit compression with consideration of photon noise, reduction of the amount of data by using partial-frame mode, DPCM and JPEG compressions by DP</td>
</tr>
<tr>
<td>Size</td>
<td>external: 100 cm × 100 cm × 300 cm</td>
</tr>
<tr>
<td>Weight</td>
<td>goal: 150 kg (maximum system distribution: 200 kg)</td>
</tr>
<tr>
<td>Lowest eigen-frequency Mowing parts</td>
<td>15 Hz (assuming that the sub-system requirement is satisfied)</td>
</tr>
<tr>
<td></td>
<td>filter wheel, focus adjustment mechanism, counter wheel (stepping motor) for stabilising the satellite, shutter (DC motor), tip tilt mirror and scan mirror (piezo electric actuator)</td>
</tr>
</tbody>
</table>
ATST

- Resol. 0.03 arcseconds with AO
- FOV: AO - 20 arcseconds FOV – present AO
- Multi-conjugate AO: 2 arcminute FOV
- FOV – general: 5 arcminutes
- Temporal Coverage: >2 hrs <10 hours
<table>
<thead>
<tr>
<th><strong>INSTRUMENT</strong></th>
<th><strong>Spectral resolution</strong></th>
<th><strong>Spectral coverage</strong></th>
<th><strong>Spatial resolution</strong></th>
<th><strong>Spatial field</strong></th>
<th><strong>Comment</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible tunable filter</td>
<td>100,000 to 300,000</td>
<td>38-800</td>
<td>0.02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Near-IR tunable filter</td>
<td>100,000 to 300,000</td>
<td>1200-2000</td>
<td>0.08</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Thermal IR tunable filter 1</td>
<td>100,000</td>
<td>4800</td>
<td>0.24</td>
<td>5</td>
<td>cryogenic</td>
</tr>
<tr>
<td>Thermal IR tunable filter 2</td>
<td>100,000</td>
<td>1200</td>
<td>0.62</td>
<td>5</td>
<td>cryogenic</td>
</tr>
<tr>
<td>Coronal filters</td>
<td>5000-10,000</td>
<td>500-5000</td>
<td>0.1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Spectrographs</td>
<td></td>
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<tr>
<td>Visible/IR high-dispersion spectrograph</td>
<td>300,000 to 1,500,000</td>
<td>300-5000</td>
<td>0.05</td>
<td>2</td>
<td></td>
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<tr>
<td>Thermal IR spectrograph</td>
<td>200,000 to 500,000</td>
<td>3000-12,000</td>
<td>0.2</td>
<td>5</td>
<td>cryogenic</td>
</tr>
<tr>
<td>Medium dispersion spectrograph</td>
<td>100,000 to 300,000</td>
<td>380-2700</td>
<td>0.02</td>
<td>5</td>
<td></td>
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<tr>
<td>Polarimeters</td>
<td></td>
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<tr>
<td>Visible polarimeter</td>
<td>100,000 to 300,000</td>
<td>380-1100</td>
<td>0.05</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Near-IR polarimeter</td>
<td>100,000 to 300,000</td>
<td>1000-2500</td>
<td>0.1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>12 μm polarimeter</td>
<td>100,000</td>
<td>12,000</td>
<td>1</td>
<td>5</td>
<td>cryogenic</td>
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<tr>
<td>Visible/IR coronal polarimeter</td>
<td>10,000 to 50,000</td>
<td>500-2000</td>
<td>1</td>
<td>5</td>
<td>cryogenic</td>
</tr>
<tr>
<td>IR coronal polarimeter</td>
<td>10,000 to 50,000</td>
<td>1500-5000</td>
<td>1</td>
<td>5</td>
<td>cryogenic</td>
</tr>
<tr>
<td>Detectors</td>
<td></td>
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<tr>
<td>Visible detectors</td>
<td>350-1100</td>
<td></td>
<td>4k × 4k</td>
<td></td>
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<tr>
<td>Near-IR detectors</td>
<td>1000-5000</td>
<td></td>
<td>2k × 2k</td>
<td></td>
<td></td>
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<tr>
<td>Thermal IR detectors</td>
<td>5000-20000</td>
<td></td>
<td>1k × 1k</td>
<td></td>
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<tr>
<td>Fast chopping detectors</td>
<td>350-1100</td>
<td></td>
<td>2k × 2k</td>
<td></td>
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<tr>
<td>Special Instruments</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Imaging Fourier Transform Spectrometer</td>
<td>300-20000</td>
<td></td>
<td>512 × 512</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bench-mounted nighttime spectrograph</td>
<td>120,000 to 150,000</td>
<td>300-1100</td>
<td></td>
<td>single point</td>
<td></td>
</tr>
<tr>
<td>Accessory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integral field unit</td>
<td>380-2700</td>
<td>0.05</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image de-rotator</td>
<td>300-20000</td>
<td></td>
<td></td>
<td>reflective</td>
<td></td>
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<tr>
<td>Optical benches</td>
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<td></td>
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<tr>
<td>Various optics and optics mounts</td>
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</tbody>
</table>
Sunspot structure components

- Pores/Umbra
- Light Bridges
- Penumbra
- Super-penumbra
- Canopy

_Effects: Flares, Filament eruptions, mass ejections_
- Pores, Flux Emergence to Sunspots
- Magnetoconvection (Title, Simon and Weiss) and coalition of kilogauss fields (Stenflo)
- Convective collapse (Spruit, Rast) and onset of flux break though the photosphere
- Competition between turbulent and a-w dynamo? (Chicago, KIS, Lockheed Groups)
• Pores, Flux Emergence…..cont

• Onset of penumbral formation (necessary?) and siphon flows (Montesinos & Thomas 1997)
Answers/Solutions to these questions will be addressed by Solar-B, ATST

K. S. Balasubramaniam (2001)
Pores, Umbra

Brightness-to-magnetic field strength ratio of pores (Mugalach et al. 1994) similar to mature spots (Kopp & Rabin 1992), strongly linear in the deepest layers.

Pore downflow velocities strongly drop with height (Keil et al. 1999)

Hot walls with different magnetic topology (Pizzo 1996),

Umbral magnetic fields locally vertical, strong gradients, field strengths rapidly falling with height (Westendorp Plaza et al. 2001a,b).

Flux shedding of pores (Keil et al. 1999) - formation of penumbra?
Umbral Dots

- Umbral dots: hot weakly magnetized convecting plasma amidst darker strong magnetized regions. (Degenhardt & Lites 1993)
- Brighter umbral dots near penumbral boundary, no definitive lifetimes, lifetimes < 10 minutes represent 2/3 population (Sobotka, Brandt & Simon 1997)
- Magnetic field strengths slightly lower than background umbra (Tritschler & Schmidt 1997)
Light Bridges
Oscillatory magnetoconvection responsible for the formation of light bridges (Rimmele 1997)
Intrusion of convective material into an otherwise stable spot (Leka 1997)

K. D. Leka (1997)
Umbra/Light Bridges
At 1.6 microns, field strength reduced by ~1000G relative to umbra, presence of currents (Ruedi, Solanki, Livingston 1995)

**V-Asymmetries in Light Bridges and Penumbral Filaments**

Data taken on Jul. 24, 1999 with DST, ASP and AO

<table>
<thead>
<tr>
<th></th>
<th>Light Bridges</th>
<th>Penumbral Filaments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Umbra</td>
<td>Penumbra</td>
</tr>
<tr>
<td><strong>Magnetic Field</strong></td>
<td>Longitudinal</td>
<td>Inclined</td>
</tr>
<tr>
<td><strong>V-Asym.</strong></td>
<td>Larger Amp. Asymmetry</td>
<td>Larger Area Asymmetry</td>
</tr>
<tr>
<td><strong>Continuum</strong></td>
<td>Visible</td>
<td>Visible</td>
</tr>
<tr>
<td><strong>Line Core</strong></td>
<td>Not Visible</td>
<td>Visible</td>
</tr>
</tbody>
</table>

Formation Height of Light Bridges is deeper compared to that of the Penumbral Filaments.

K. Sankara Subramaniam and Thomas Rimmele (2001)
Penumbra

- Evershed effect driven by siphon flows
- Evidence of azimuthal fluctuation of magnetic field inclination (Title et al. 1993, Rimmele 1995)
- Inclination fluctuations correlated with field fluctuations (Lites et al. 1993, Stanchfield et al. 1997)
- Penumbral magnetic field structured into horizontal magnetic tubes in a vertical background (Solanki & Montovan 1993)
- Field strength in outer penumbra increases height by 500G and inclination decreases by 30 deg, explained by unresolved tubes using the uncombed model (Martinez Pillet 2000)
Penumbra

- Penumbral structure mostly produced by inclinations rather than strength of the magnetic field (10% variation) (Wiehr 2001). Bright penumbral structures moving towards the umbra are rising flux tubes as suggested by Schlichenmaier, Jahn, Schmidt (1998)

![Small-Scale Flow Field in Penumbra](image)

Figure 7. Lower panel: Snapshot of evolution of magnetic flux tube embedded in a model penumbra. While the footpoint (intersection of the tube with the $\tau = 1$ level, black horizontal line) migrates toward the umbra, an upflow within the tube causes a comet-shape like photospheric brightening. The hot flow bends horizontal, cools radiatively in the photosphere and forms the dimmer tail, very much like it is observed (upper panel). The grey arrows represent the temperature, the arrows within the tube represent the flow velocity.

R. Schlichenmaier (2001)
Penumbra

- Evershed flow concentrated in elevated channels – using Stokes SIR techniques (Westendorp Plaza 2001a,b)
- All over the penumbra azimuthal angle increases with depth. Magnetic field is larger in the bottom layers of inner penumbra, larger in the higher layers of outer penumbra
- Middle penumbra is where a new family of flux tubes rise interlaced horizontally and vertically
Fig. 9 — Azimuthal averages of \( B \), \( \psi \), and \( \Delta \) at three optical depths in the atmosphere along several azimuthal paths at given distances from the umbral center. Vertical lines show the limits of umbra and penumbra. Shaded areas represent the actual rms variations of the parameters, shown in the upper and lower layers for \( B \) and \( \psi \) and at \( \log \tau = 0 \) for \( \Delta \).

Westendorp Plaza et al. (2001)
Penumbra

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- All over the penumbra azimuthal angle increases with depth. Magnetic field is larger in the bottom layers of inner penumbra, larger in the higher layers of outer penumbra
- Middle penumbra is where a new family of flux tubes rise interlaced horizontally and vertically
Penumbra thermal and dynamic structures

K. S. Balasubramaniam (2001)
Penumbra thermal and dynamic structures

K. S. Balasubramaniam (2001)
Penumbra thermal structures – Flowless Maps

K. S. Balasubramaniam (2001)
Penumbra dynamical structure
Bisector velocities

Bisector Velocities in Fel 5567

K. S. Balasubramaniam (2001)
Bisector velocities

K. S. Balasubramaniam (2001)
Velocity Span

K. S. Balasubramaniam (2001)
Penumbra...more

- Tree-trunk analogue
- Branches of trees run along the length of trunk, branches pointing upward propagating outward of trunk
- Magnetic tubes more fibrous on the periphery of spots (similar to Westendorp Plaza et al.) additional flux rising in mid-penumbra.
- Penumbral temperatures cooler in the deeper layers, nearly same in outer layers (similar to Westendorp Plaza et al.)
Super-penumbral canopy

- Magnetic canopies (Giovanelli & Jones 1982)
- Magnetic volume fills outside the penumbra while photosphere is largely field-free (Lites 1997, del Toro Iniesta 1997)
- 3-6” from penumbra boundary, magnetic canopy is about 150-300km above the quiet sun, inclined 15-45deg. to horizontal, further away canopy field is almost horizontal at 300-400Km (Adams et al. 1993)
- Magnetic field beyond penumbral boundary is 200-300 Km higher than the penumbra. Far outer edge of penumbra shows polarity changes in the deepest layers (Westendorp Plaza 2001a,b).
Ha Super-penumbra and Continuum

K. S. Balasubramaniam (2001)
Super-penumbra

Why are the superpenumbral filaments twisted only beyond the boundary of the penumbra?
Is the bright ring at the penumbra-superpenumbra interface a signature of flux cancellation?
Is the photospheric magnetic edges of the return superpenumbral flux traceable?

K. S. Balasubramaniam (2001)
Sunspots..Related Issues

- Sunspots and Flares (Samis, Tang and Zirin 2000)
- Convergent flows in the periphery of delta spots (Lites 2001)
- Faraday rotation (Hagyard et al. 2000) and Faraday-Voigt effects, we can probe the deeper layers for magnetic shear, with a combination of SIR techniques
- Nature of the sub-photospheric magnetic structure (Zirker) before it erupts. Local magnetic helioseismology of the evolution of the subsurface structure (Braun, Duvall, Lindsey et al) if there is sufficient depth resolution.-
What understanding about sunspots be achieved with Solar-B and ATST?

• Dynamics/structure and formation of pores, umbral dots, light-bridges, penumbral filaments, formation and dynamics.
• Evolution of spots within a FOV of about 3-4 arcminutes
• Piece-wise understanding of structures
What understanding about sunspots needs to be addressed beyond Solar-B and ATST?

- **Large-scale (5-8) arcminutes continuous magnetic field evolution at 0.1 – 0.2 arcsecond resolution.**
- Local high resolution magnetic helioseismology over time-scales of days.
- **Multi-line vector polarimetry imaging/spectroscopy in a number of lines that span the photosphere and chromosphere**
Sunspots…Modeling Issues

What modeling efforts are necessary to characterize the combined magnetic, thermodynamic and height structure of sunspots thought the solar atmosphere, of entire sunspot groups.

- Can such models, if designed, help to predict where energy release of pent-up energy would occur?
- For example, why are some flares white light flares and most others chromospheretic flares?
- Realistic radiative transfer efforts to resolve the sub-structure height of non-LTE spectral lines, in particular.
Beyond Solar-B and ATST Space Based Telescope

- Need for multi-spectral/imaging full-spectra magnetograph covering spectral lines FeI 6302.5, CaII 8542, HI 6563, FeI 15648, CI 1548/1510
- 0.1 arcsecond resolution,
- 6-8 arcminutes FOV
  - 2 FOV scales: small FOV, large FOV
- 4096x4096 multi-wavelength detectors.