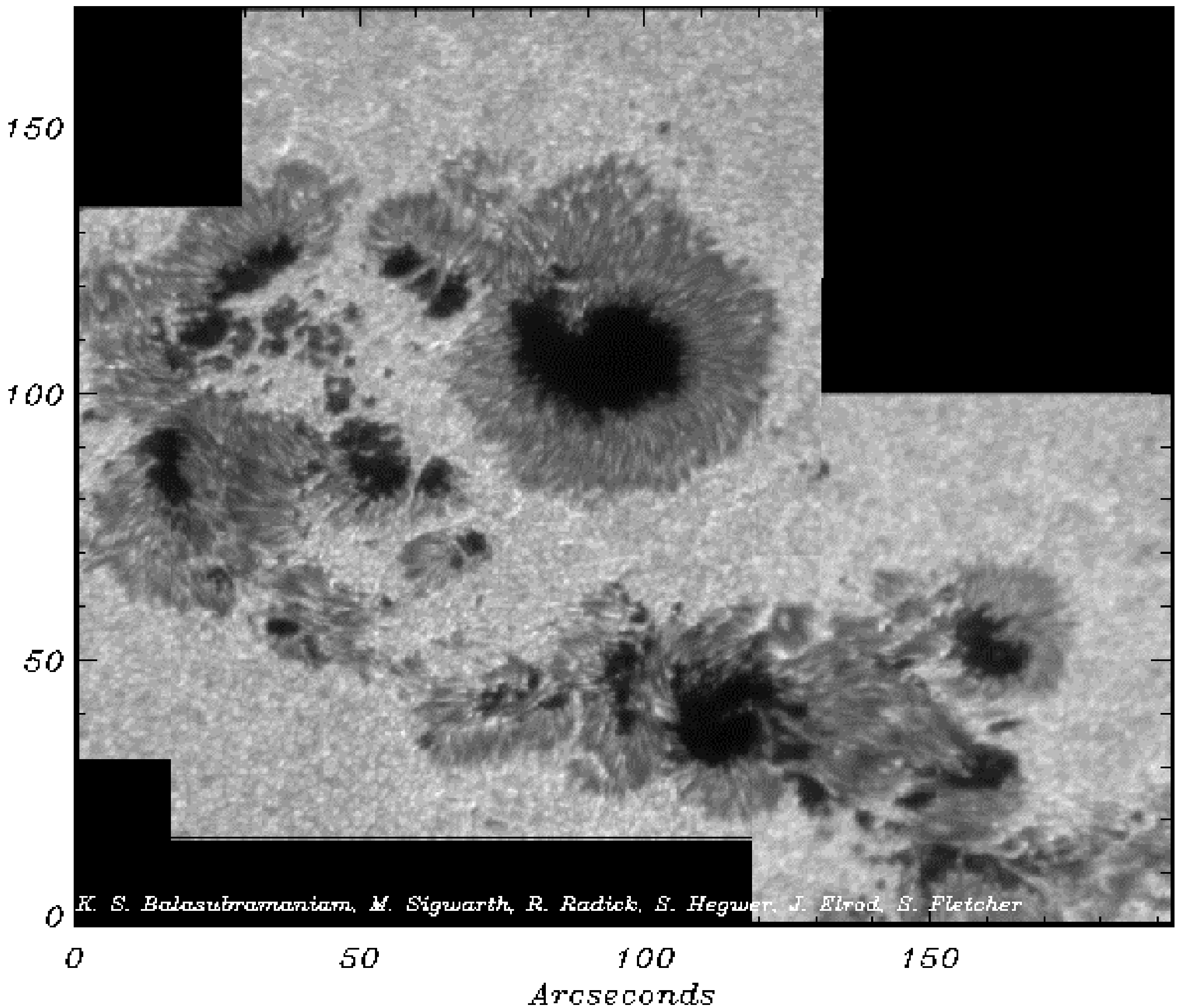
National Solar Observatory
Sacramento Peak
Dunn Solar Telescope, March 27, 2001



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

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?

Solar-B

Table 4: Specifications of the Optical Telescope/Magnetograph

Optical System	Aplanatic Gregorian, 50 cm diameter, F/10.5		
Telescope Tube	CFRP (graphite epoxy), truss structure		
Focal Plane Package	Narrow-band filter	Interference filter	Spectrograph
Objective	Mapping of magnetic and velocity fields	High spatial resolution imaging	High precision magnetic observations
Observing Wavelength	4500–6600 Å	3933, 4305 Å	6203/6303 Å
Wavelength Switch	Rotating waveplate or piezo electric actuator	Filter wheel	—
Spectral Resolution	0.1 Å at 6000 Å	10–20 Å	25 mÅ at 6000 Å
CCD	2048×2048	2048×2048	2048×2048 (TBD)
Pixel Size	$(9\ \mu m)^2$	$(9\ \mu m)^2$	9 μm (TBD)
A/D Converter	10 bit	10 bit	10 bit
Plate Scale	0″.1/pixel	0″.1/pixel	0″.1×25 mÅ/pixel
FOV	$(200'')^2$	$(200'')^2$	150″×0″.2
Standard Exposure	200 msec	0.1–100 msec	300 msec
Time Resolution	10 sec (best)	several sec (best)	100 min/AR
Observing Coverage	Continuous observing in Sun-synchronous orbit.		
Image stabilization	Use attitude control and tip tilt mirror to achieve 0″.02 per 10 sec.		
Changing FOV	Spacecraft attitude control (in addition, tracking of a region using solar rotation is under consideration.)		
CPU	Equivalent of 80C386 for control and on-board processing		
Frame Memory	~30 Mbytes (16 Mbit DRAM)		
Amount of uncompressed data	Data production rate: average–740 kbps, maximum–TBD kbps, total amount of data: 4.4 Gbits per orbit.		
Number of images obtained	About 440 1k × 1k images per orbit.		
Data compression	2×2, 4×4 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		
Size	external: 100 cm × 100 cm × 300 cm		
Weight	goal: 150 kg (maximum system distribution: 200 kg		
Lowest eigen-frequency	15 Hz (assuming that the sub-system requirement is satisfied)		
Moving parts	filer wheel, focus adjustment mechanism, counter wheel (stepping motor) for stabilizing the satellite, shutter (DC motor), tip tilt mirror and scan mirror (piezo electric actuator)		

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

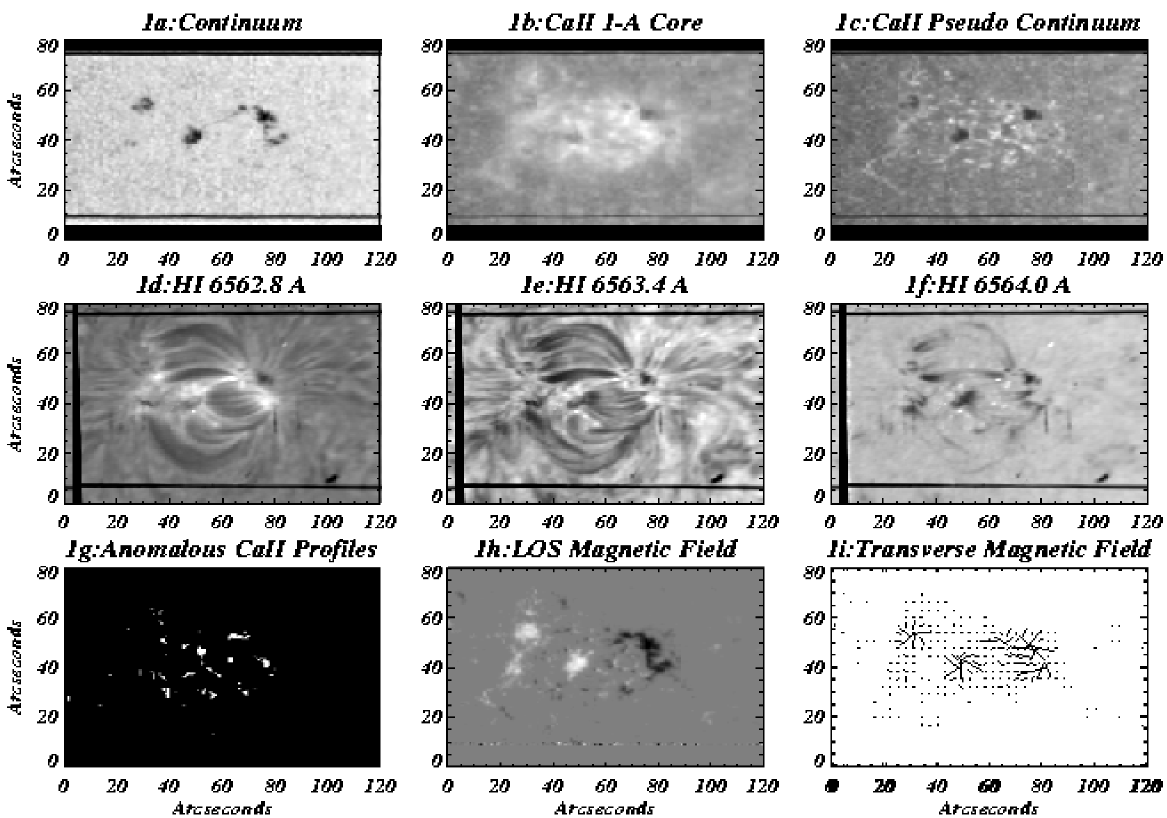
ATST

INSTRUMENT	Spectral		Spatial		Comment
	resolution	coverage	resolution	field	
		nm	arcsec	arcmin	
Filters					
Visible tunable filter	100,000 to 300,000	38-800	0.02	1	
Near-IR tunable filter	100,000 to 300,000	1200-2000	0.08	2	
Thermal IR tunable filter 1	100,000	4800	0.24	5	cryogenic
Thermal IR tunable filter 2	100,000	12000	0.62		cryogenic
Coronal filters	5000-10,000	500-5000	0.1	5	
Spectrographs					
Visible/NIR high-dispersion spectrograph	500,000 to 1,500,000	300-5000	0.05	2	
Thermal IR spectrograph	200,000 to 500,000	3000-12000	0.2	5	cryogenic
Medium dispersion spectrograph	100,000 to 300,000	380-2700	0.02	5	
Polarimeters					
Visible polarimeter	100,000 to 300,000	380-1100	0.05	2	
Near-IR polarimeter	100,000 to 300,000	1000-2500	0.1	2	
12 μm polarimeter	100,000	12,000	1	5	cryogenic
Visible/NIR coronal polarimeter	10,000 to 50,000	500-2000	1	5	
IR coronal polarimeter	10,000 to 50,000	1500-5000	1	5	cryogenic
Detectors					
Visible detectors		350-1100			4k × 4k
Near-IR detectors		1000-5000			2k × 2k
Thermal IR detectors		5000-20000			1k × 1k
Fast chopping detectors		350-1100			2k × 2k
Special Instruments					
Imaging Fourier Transform Spectrometer		300-20000			512 × 512
Bench-mounted nighttime spectrograph	120,000 to 150,000	300-1100			single point
Accessories					
Integral field unit		380-2700	0.05	0.1	
Image de-rotator		300-20000			reflective
Optical benches					
Various optics and optics mounts					

Sunspot structure components

- Pores/Umbra
- Light Bridges
- Penumbra
- Super-penumbra
- Canopy
- _Effects: Flares, Filament eruptions, mass ejections

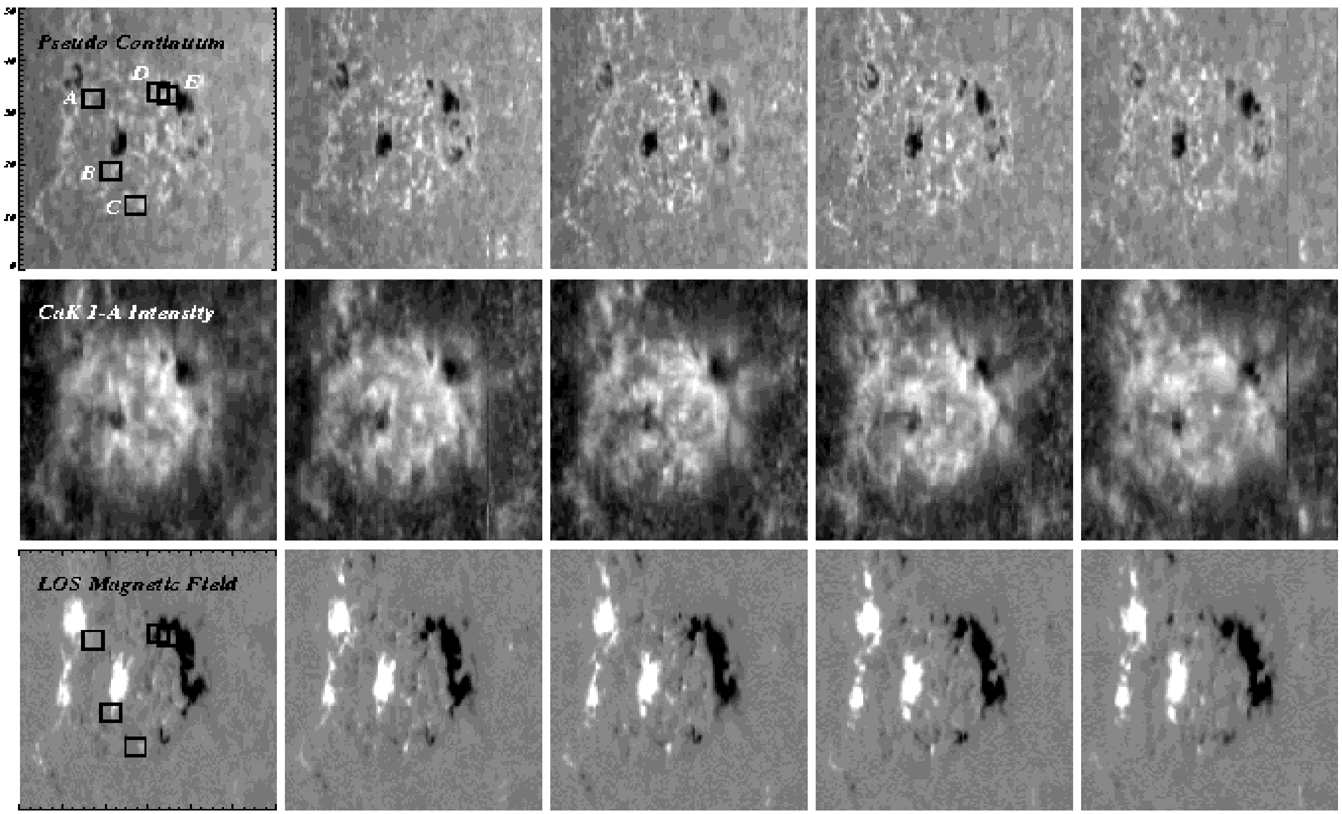
- Pores, Flux Emergence to Sunspots
- Magnetoconvection (Title, Simon and Weiss) and coalition of kilogauss fields (Stenflo)
- Convective collapse (Spruit, Rast) and onset of flux break though the photosphere
- Competition between turbulent and a-w dynamo ? (Chicago, KIS, Lockheed Groups)



K. S. Balasubramaniam (1999)

•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



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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?

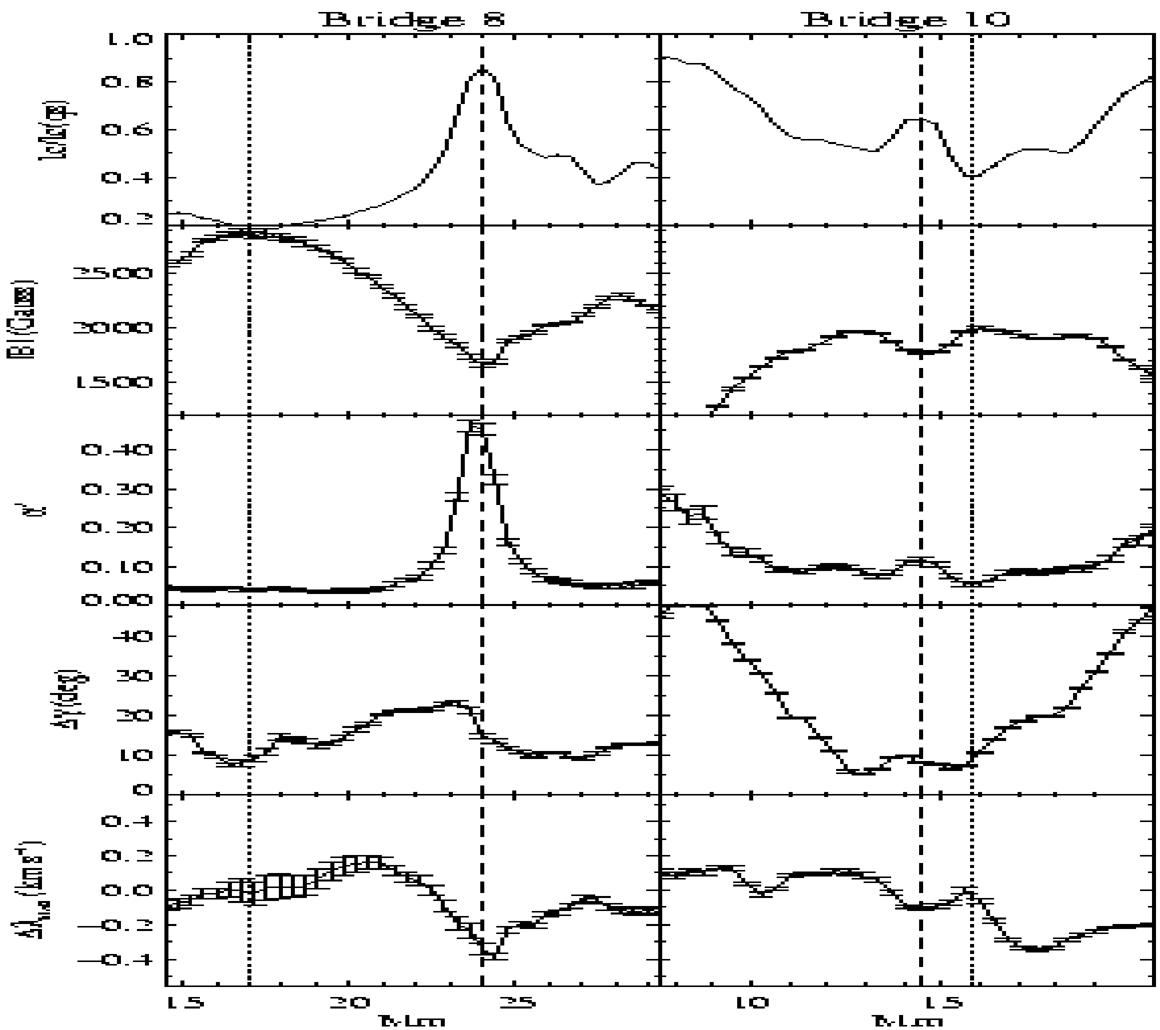
Umbral Dots

- 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<10minutes 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)



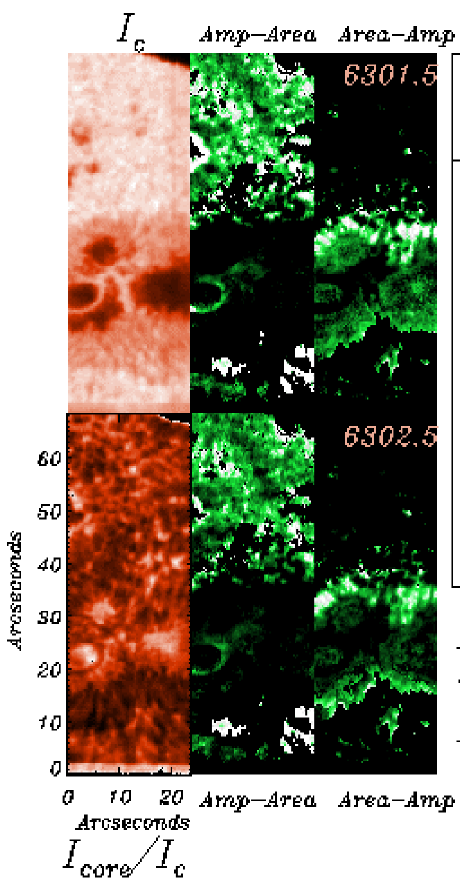
K. D. Leka (1997)

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



	Light Bridges	Penumbral Filaments
Location	Umbra	Penumbra
Magnetic Field	Longitudinal	Inclined
V–Asym.	Larger Amp. Asymmetry	Larger Area Asymmetry
Continuum	Visible	Visible
Line Core	Not Visible	Visible

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

K. Sankara Subramanian 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 7

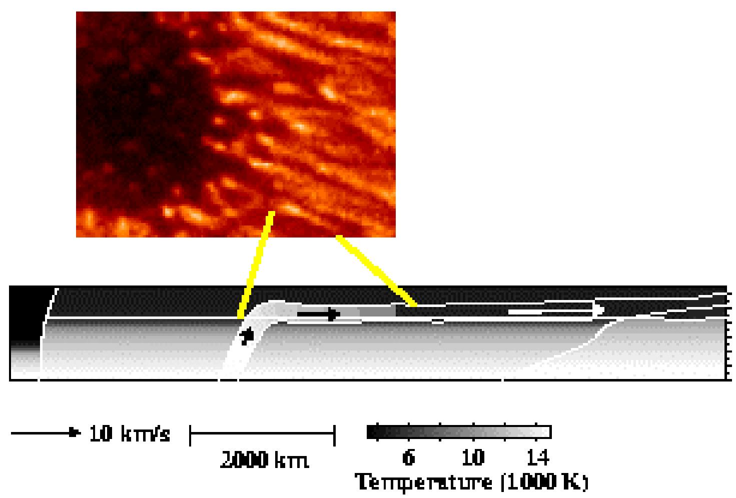


Figure 7. Lower panel: Snapshot of evolution of magnetic flux tube embedded in a model penumbra. While the footpoint (intersection of the tube with the $\tau = 1$ level, black horizontal line) migrates toward the umbra, an upflow within the tube causes a comet-shape like photospheric brightening. The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

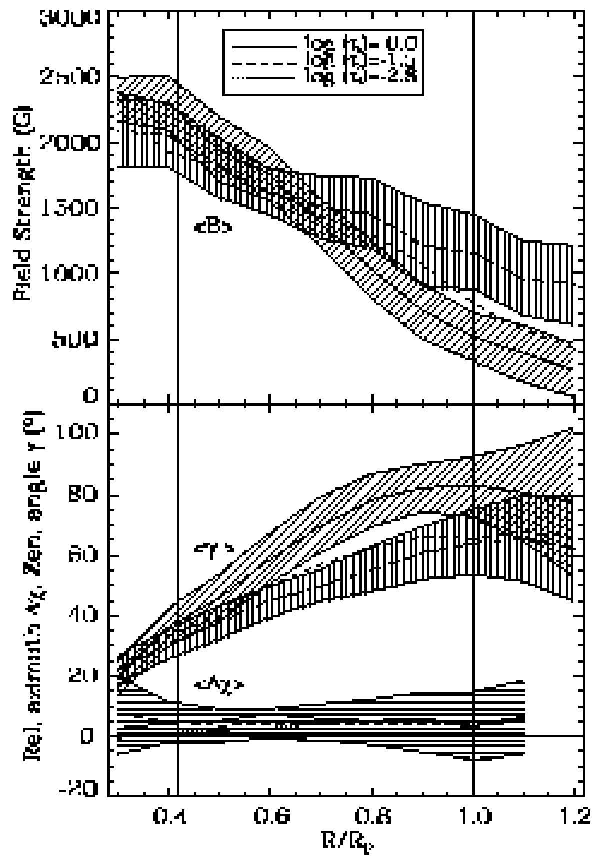


FIG. 9.—Azimuthal averages of B, γ, and $\Delta\chi$ at three optical depths in the atmosphere along several azimuthal paths at given distances from the sunspot center. Vertical lines show the limits of umbra and penumbra. Shaded areas represent the actual rms variations of the parameters, shown in the upper and lower layers for B and γ and at $\log \tau_c = 0$ for $\Delta\chi$.

Westendorp Plaza et al. (2001)

Penumbra

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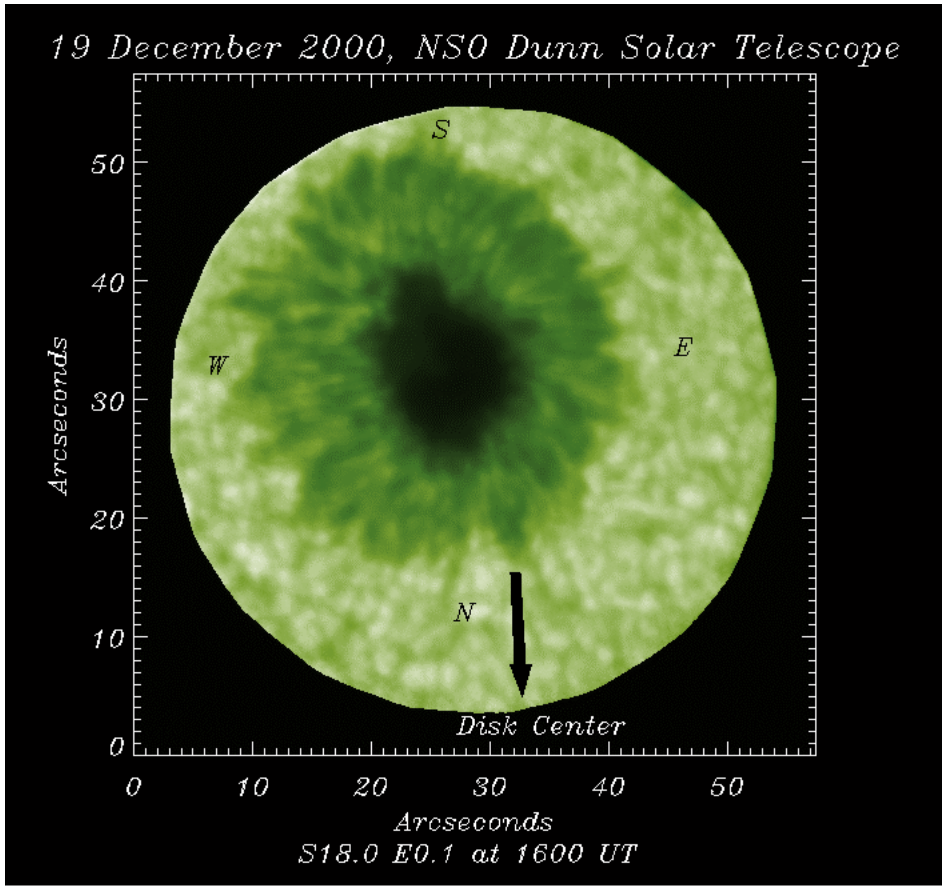
Penumbra thermal and dynamic structures



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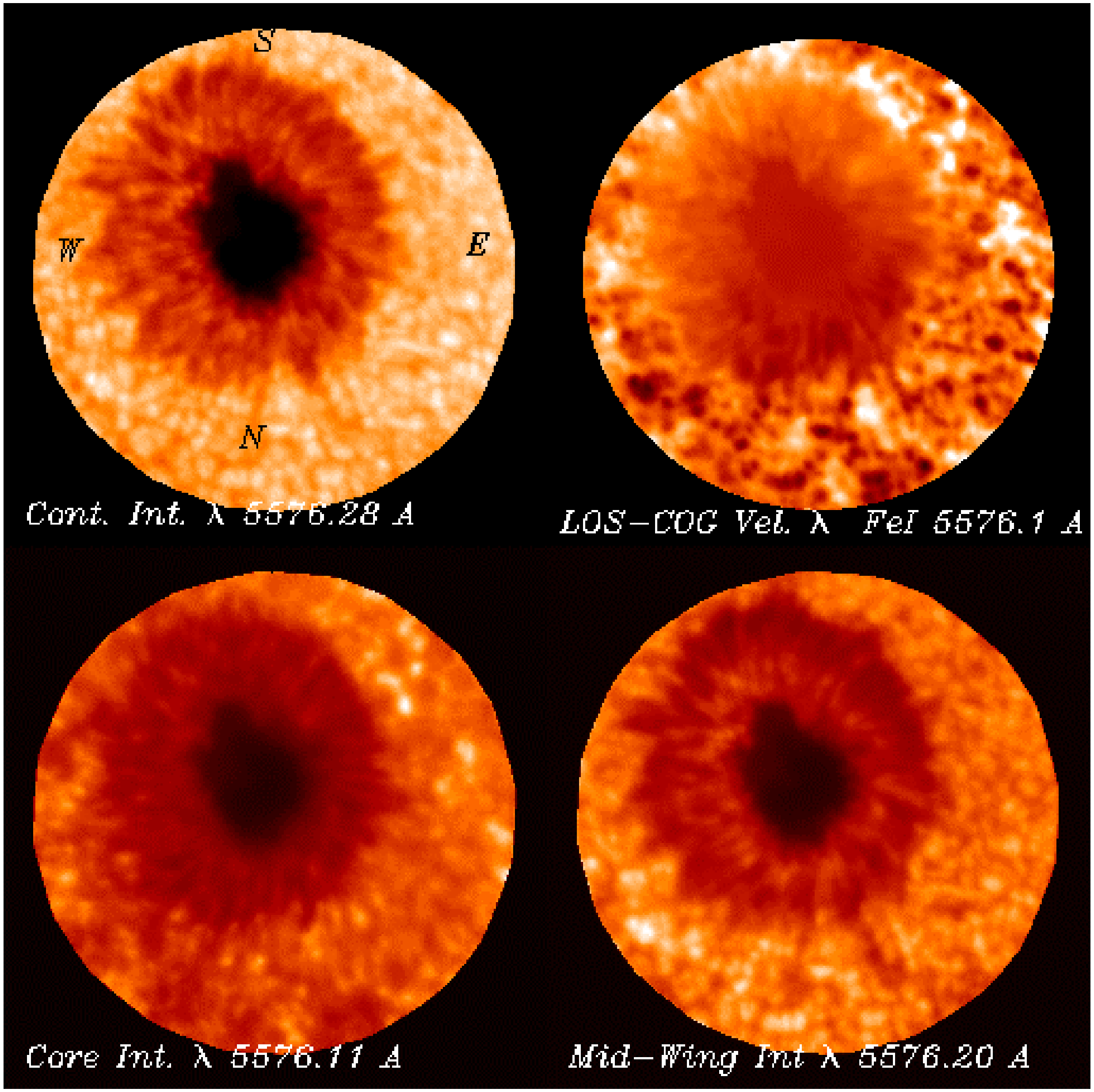
Penumbra thermal and dynamic structures



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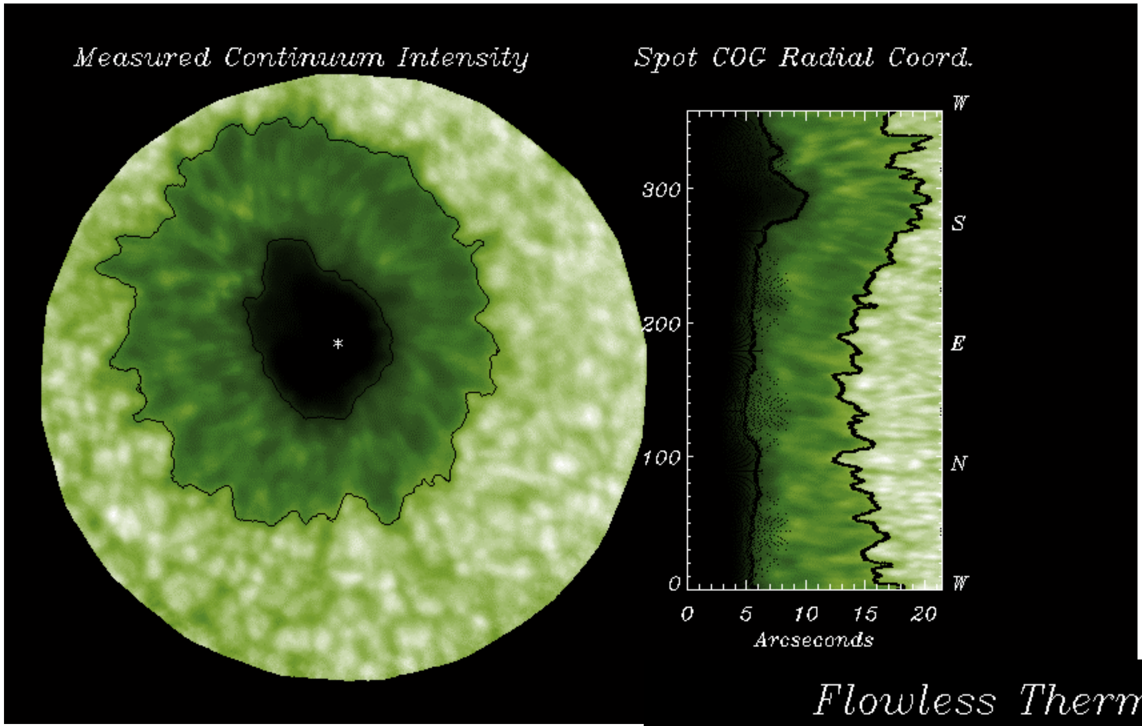
Penumbra thermal structures – Flowless Maps



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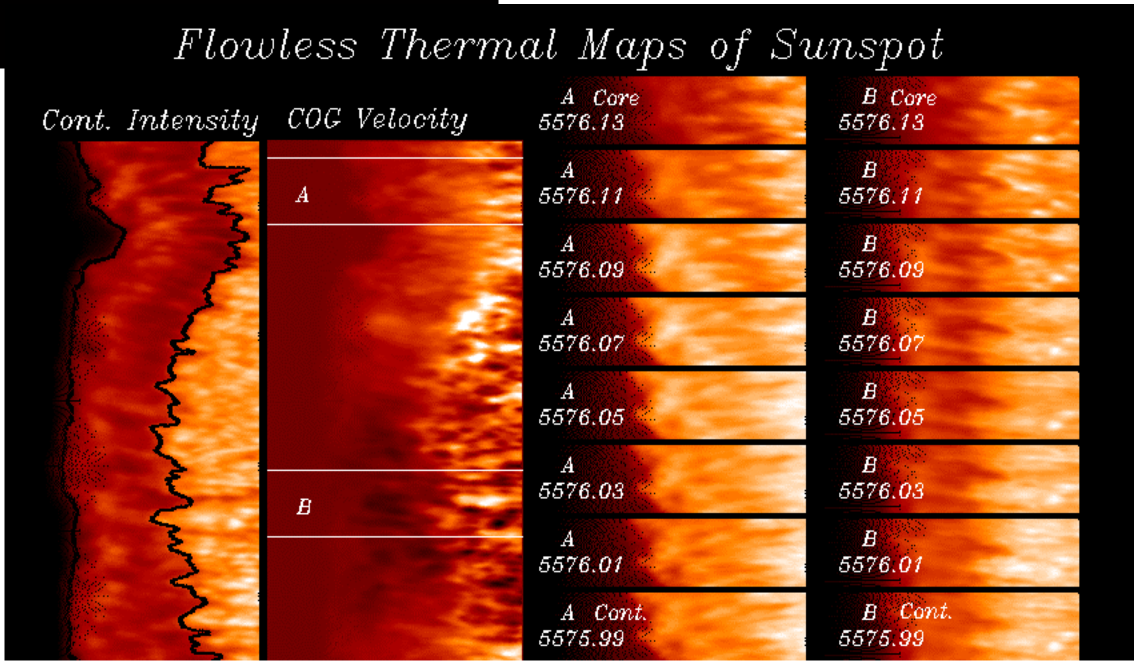
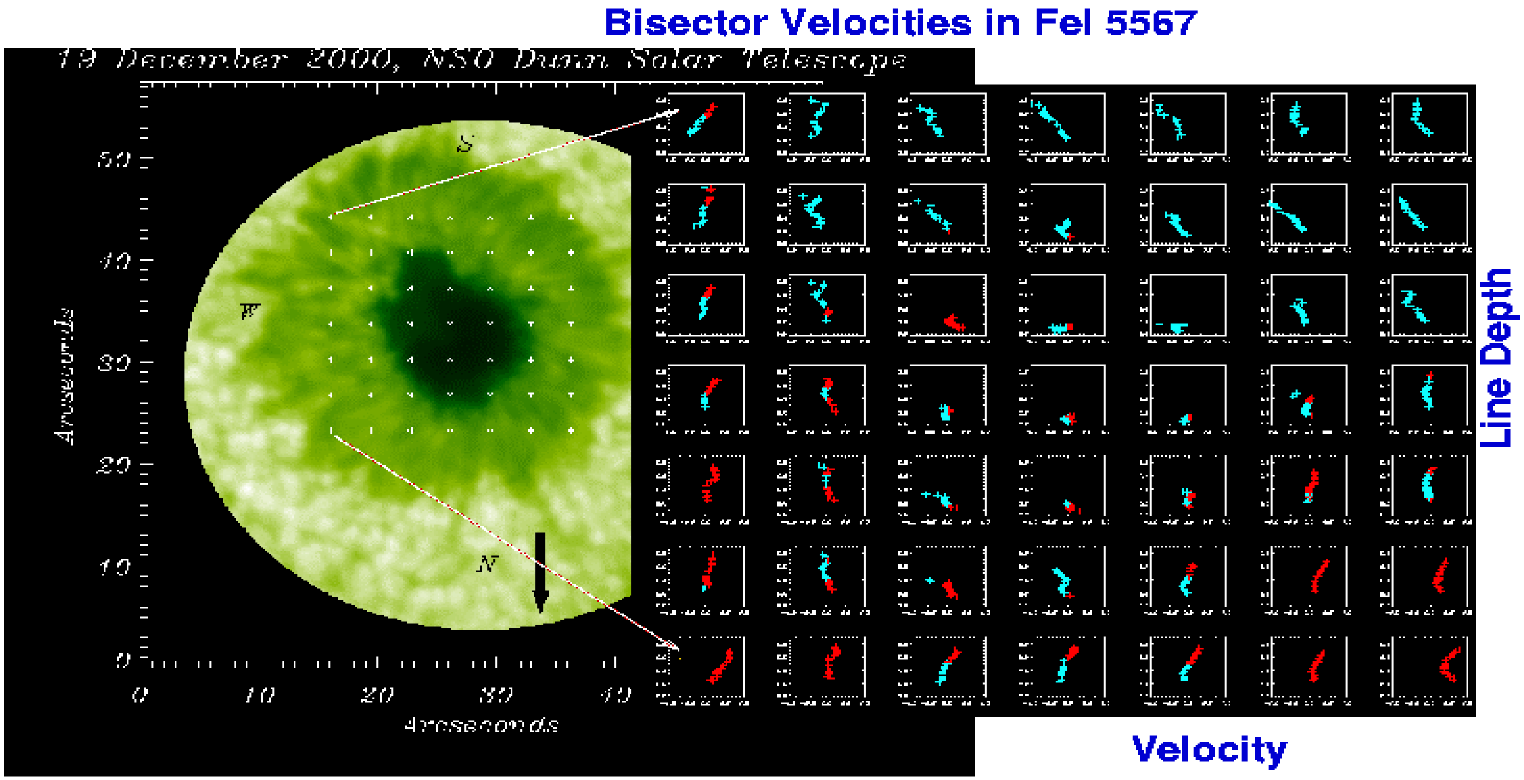


Penumbra dynamical structure
Bisector velocities



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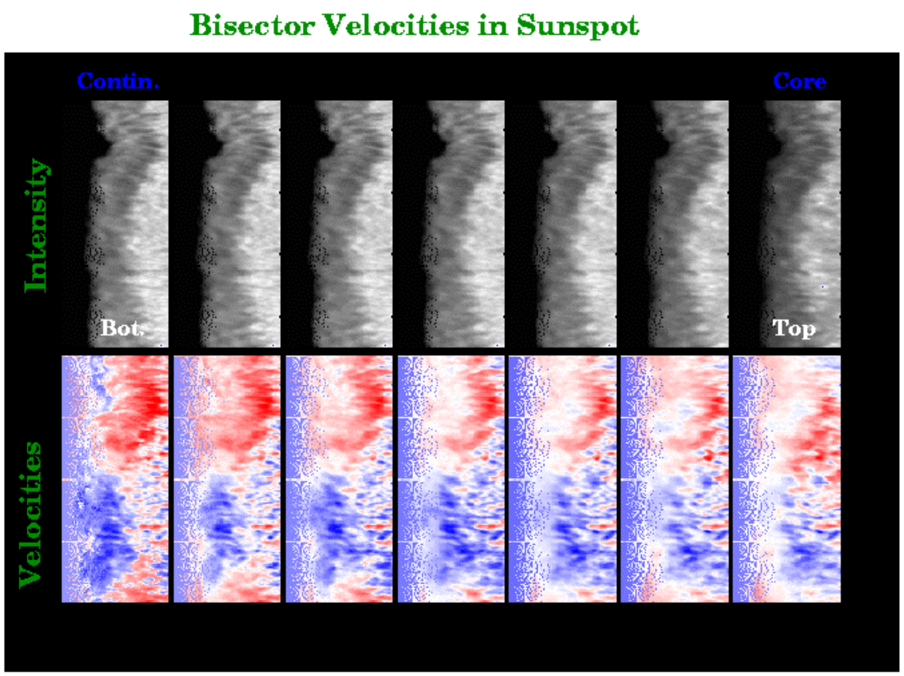
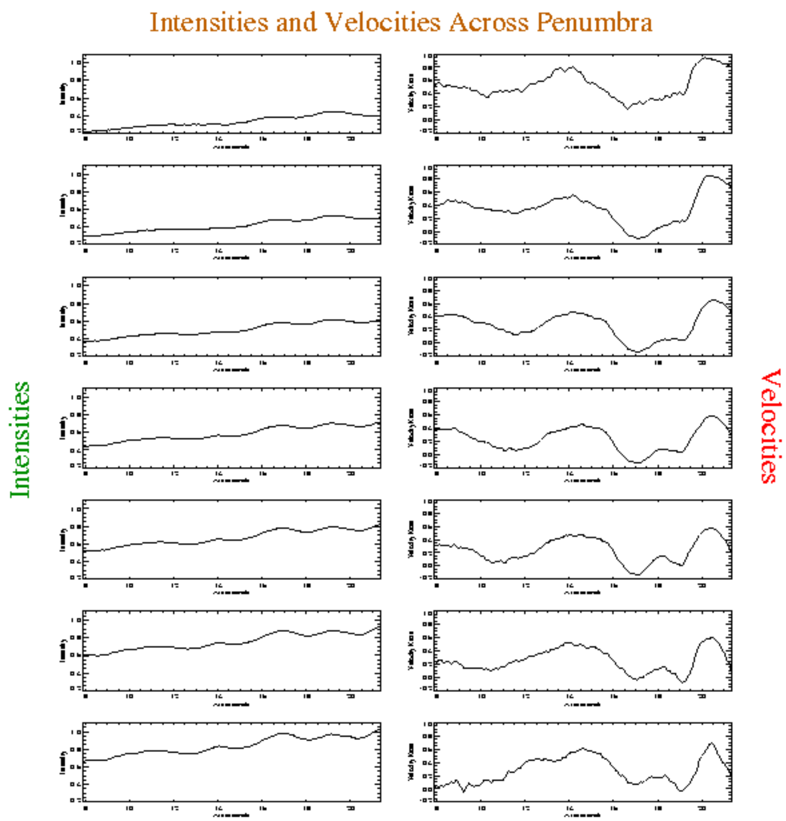
Bisector velocities





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Velocity Span

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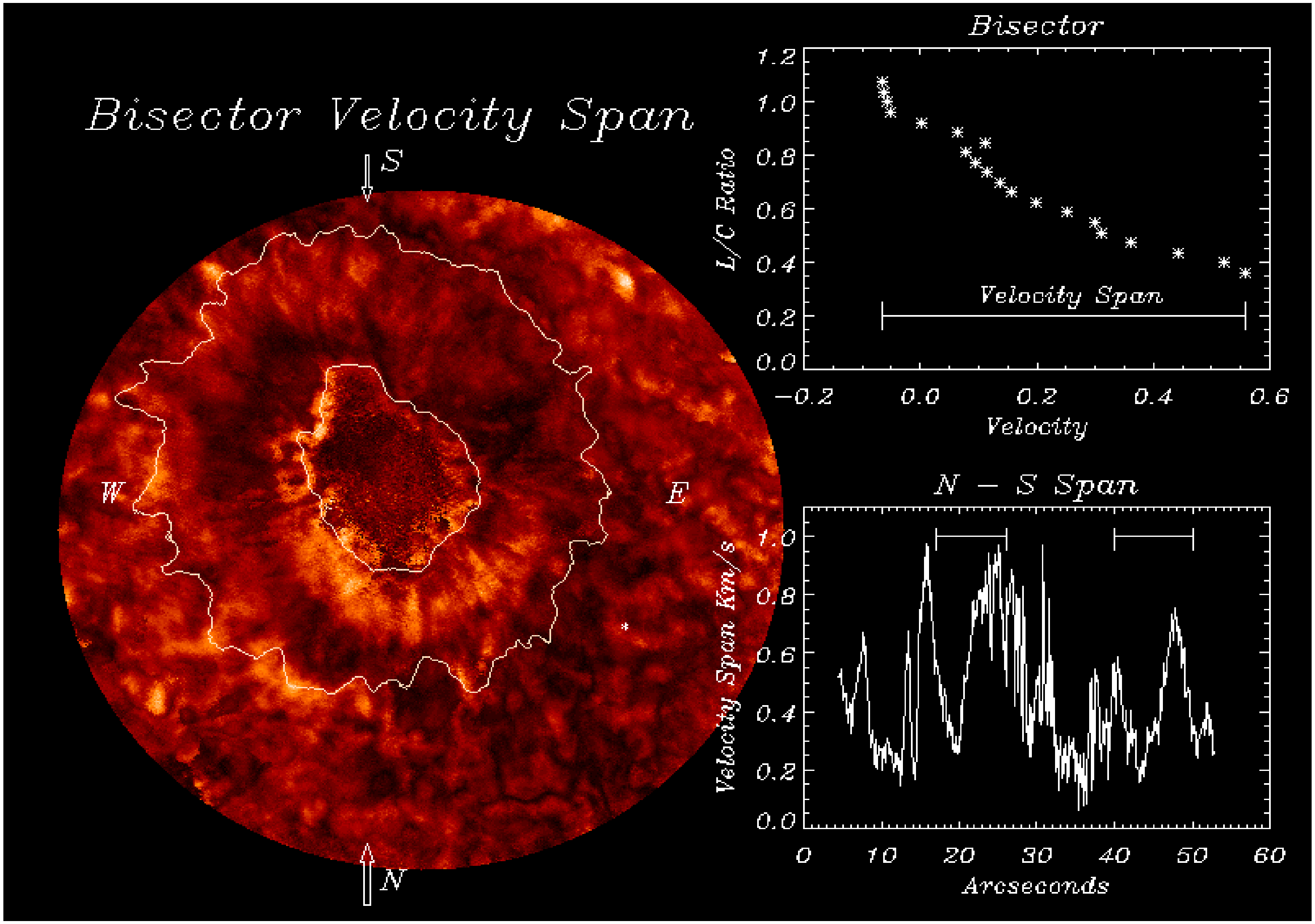
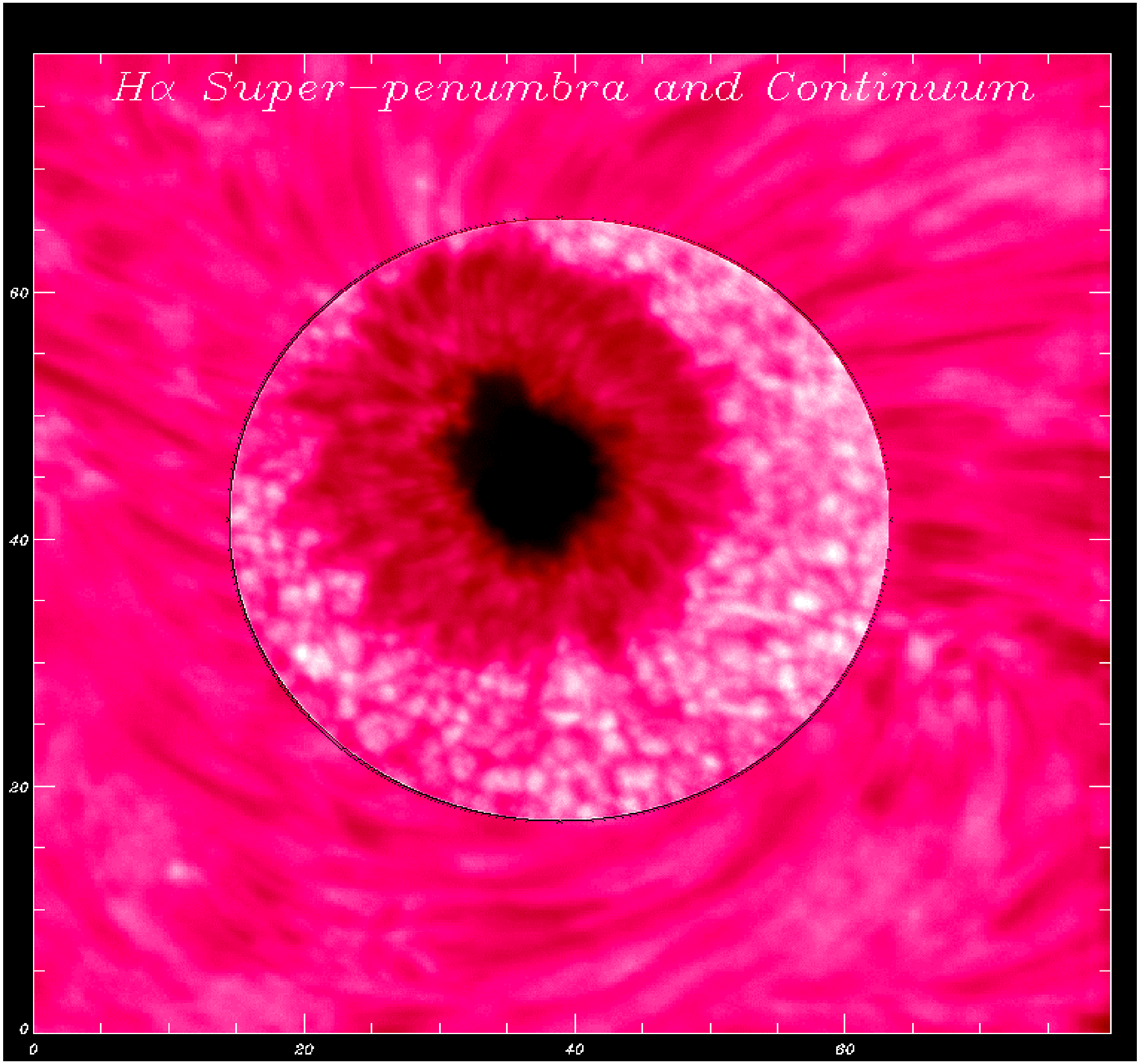


Penumbra…more

- 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).



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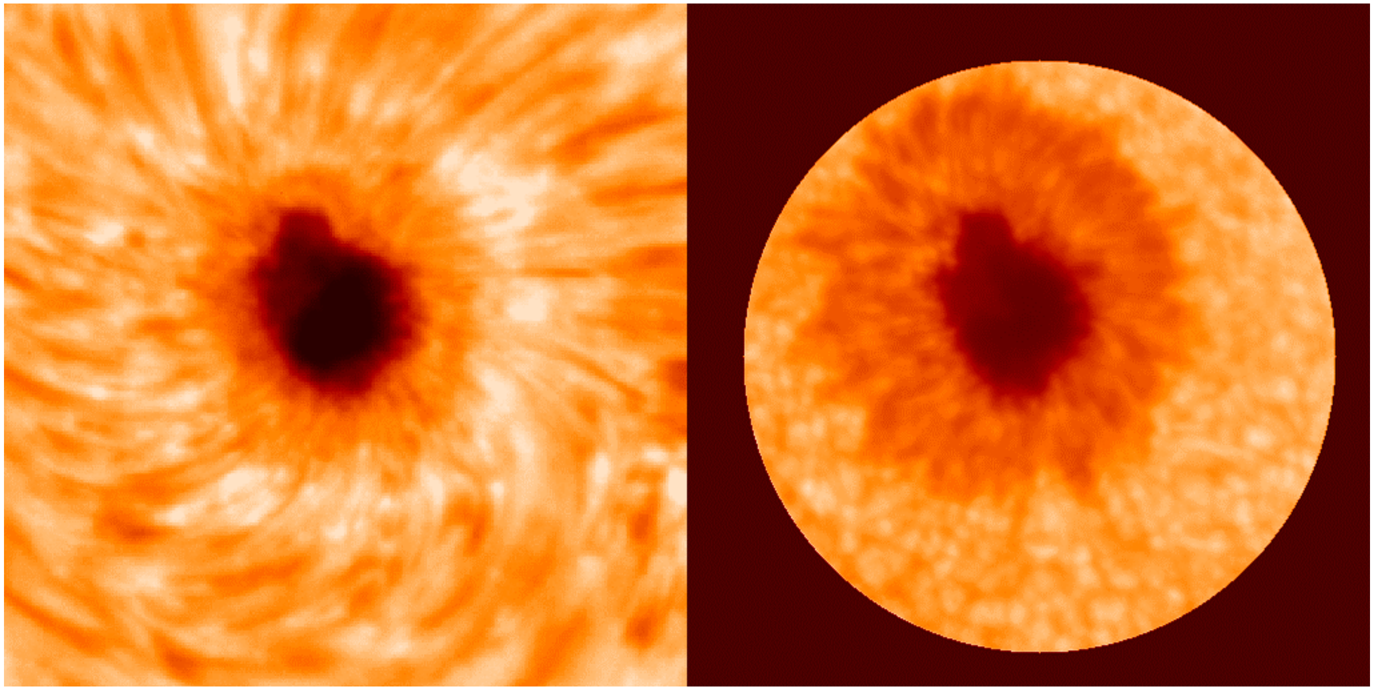
Super-penumbra

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 superpeunumbral flux traceable?



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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

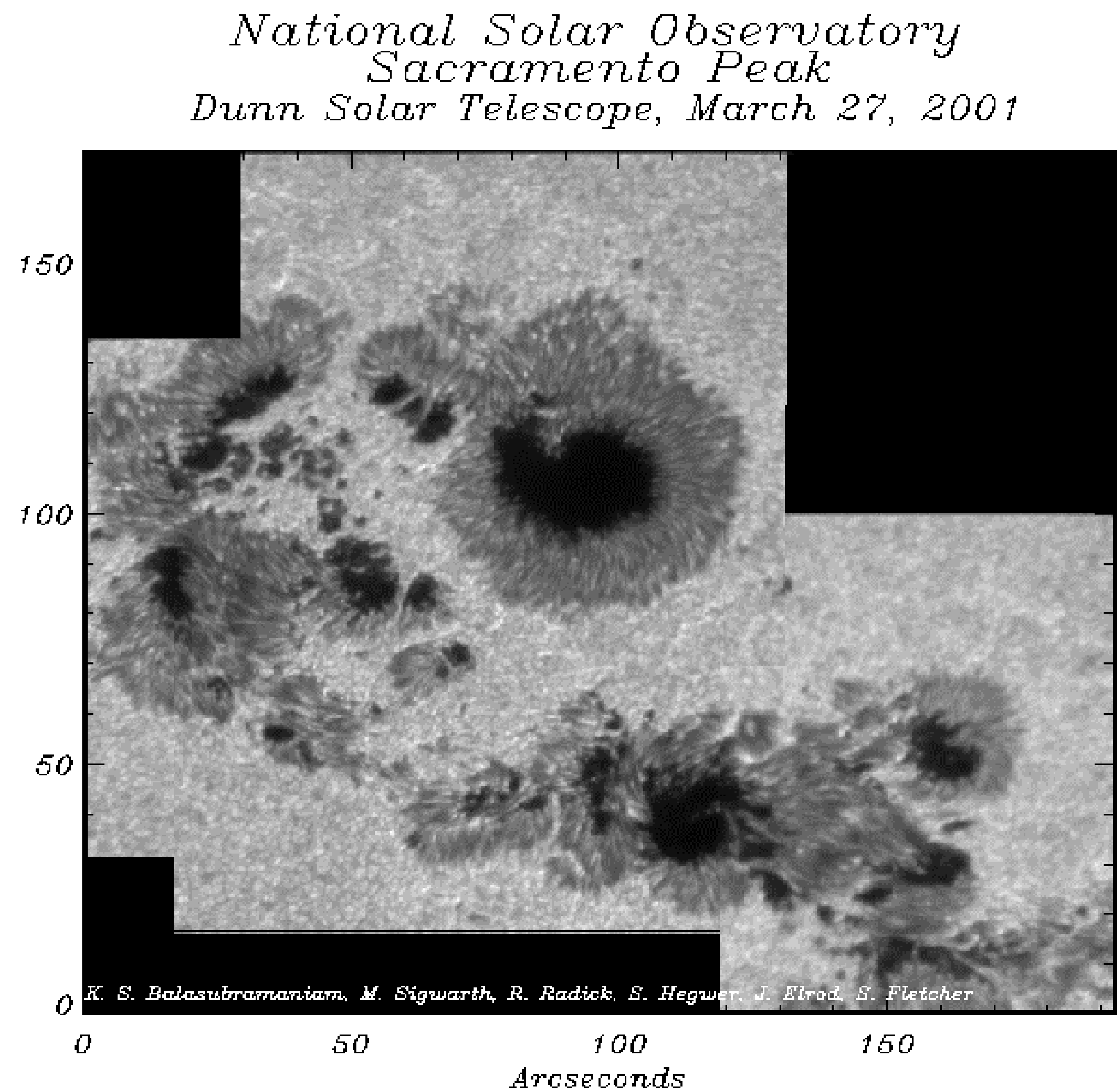
Sunspots…Modeling Issues

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 chromospheric 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.


National Solar Observatory
Sacramento Peak
Dunn Solar Telescope, March 27, 2001
150
100
50
0
50
100
150
Arcseconds
K. S. Balasubramaniam, M. Sigwarth, R. Radick, S. Hegwer, J. Elrod, S. Fletcher