I. Observations and Observational Test of Coronal Magnetic Fields

II. High Throughput Multi-Slit Spectropolarimeter

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*Direct observation of coronal **B** is highly relevant to the Science Mission of Solar-C.*

- Coronal magnetic field can be reliably measured
- Coronal ***B*** observations do provide useful information about the solar corona
  - Quantitative observational test of models possible
  - …
  - …
- Space is a very good place for coronal B observations
- Efficient, high-throughput spectropolarimeter design meeting the requirement of Solar-C science mission exists

I. Coronal Magnetic Fields

- **The polarization of forbidden coronal emission lines**
  - *Saturated Hanle Effect*
  - *Coronal Zeeman Effect*
- **Diagnostic capability of Coronal Polarimetry**
  - *What can we measure?*
  - *Ambiguity*
  - *What cannot be measured?*
    - *Complemented by Alfvén Wave Observations*
- **Observational Challenges**
- **What can we learn from Coronal Magnetometry?**
  - *Observational test of coronal magnetic field models*
  - *Reconstruction of 3-D coronal magnetic field structure*
- ***What can be done in space?***

Polarization Mechanism of Forbidden Coronal Emission Lines

The Coronal Zeeman Effect and the Saturated Hanle Effect

The Saturated Hanle Effect

The saturated Hanle effect describes the ***properties of the linear polarization of the coronal emission lines (CELs)*** due to the resonant scattering of the photospheric radiation by the highly ionized atoms in the corona, in the presence of the ***coronal magnetic fields***

- **Linear Polarization (LP)**
  - *LP of the CELs is either **parallel or perpendicular** to the direction of the direction of the coronal magnetic field projected in the plane of the sky.*
  - *Linear polarization is **not sensitive** to the amplitude of the coronal magnetic field.*
- **Circular Polarization (CP) – Zeeman effect**
  - *CP is proportional to the strength of the longitudinal component of the coronal magnetic field.*

The necessary conditions for saturated Hanle effect

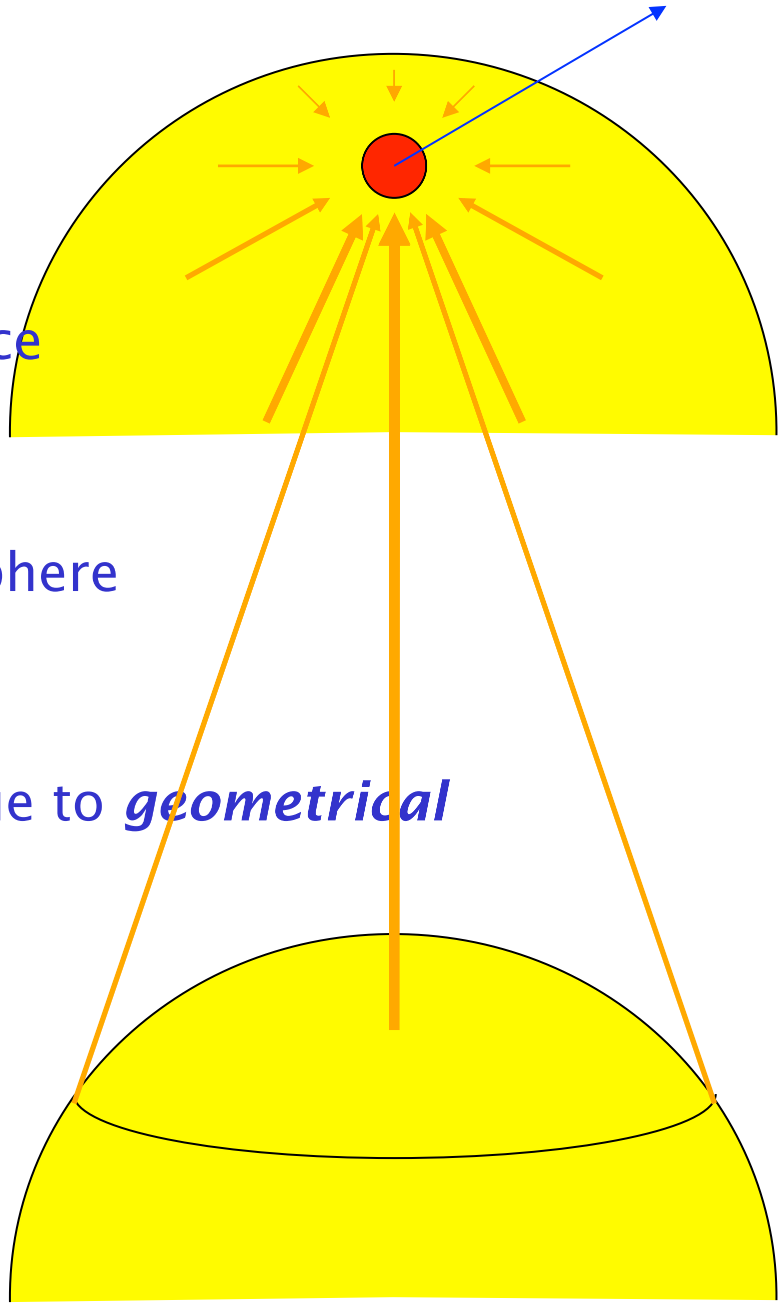
1. *Optically-thin atmosphere* – ***single scattering***
2. *Anisotropic illumination*
3. *'Strong' magnetic field*

The effects

1. *Alignment of LP to* $B_{\perp}$.
2. *Sensitivity of CP to* $B_{\parallel}$.

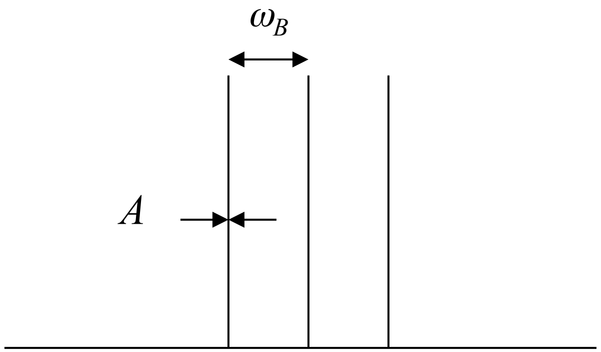
The necessary ingredients:

1. *Optically-thin atmosphere*
2. ***Anisotropic illumination***
   - Prominence/filament/corona
     - Far away from the solar surface
     - Large anisotropy
     - High degree of polarization
   - High photosphere/low chromosphere
     - Close to solar surface
     - Small anisotropy
     - Low degree of polarization due to ***geometrical depolarization***
3. *'Strong' magnetic field*



The necessary ingredients:

1. *Optically thin atmosphere*
2. *Anisotropic illumination*
3. ***'Strong' magnetic field***



$\omega_B >> A$ (Einstein's A coefficient)

- ***The natural line width of the spectral line (in the rest frame of the atom) is proportional to A***
- ***If the Zeeman splitting ω_B is much larger than the natural line width of the spectral line, then there is no coherency between the magnetic substates***

For forbidden transition,

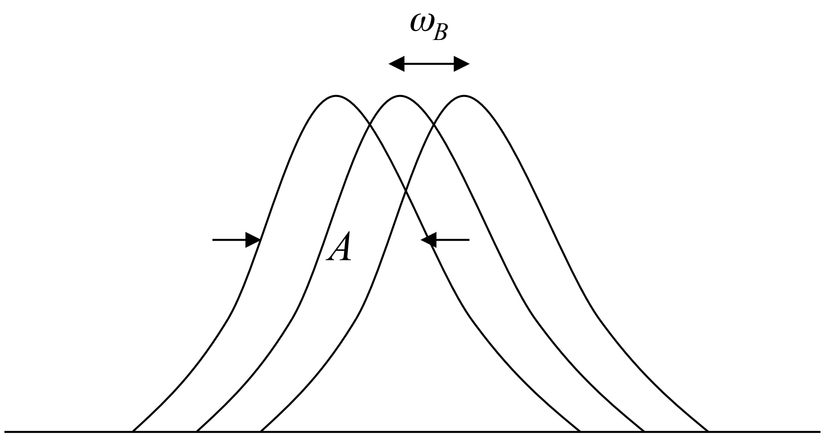
- *$A \approx 10^1$ to 10^2/sec*
- *B_0 ~ **mG** satisfies the strong field condition.*

For permitted lines,

- *$A \approx 10^6$ to 10^8/sec*
- ***B_0 ~ 10 – 100 G, depending on the spectral line***

In comparison…

Weak field regime – Hanle effect



$\omega_B \ll A$

For the permitted lines…

- *Large Einstein's A coefficient → broad natural line widths.*
- ***Strong interference between the magnetic substates***
- *In the upper solar photosphere where there are sufficient anisotropy, the Hanle effect can be used to diagnose weak turbulent magnetic fields.*

Forbidden Lines
(M1 Transition)

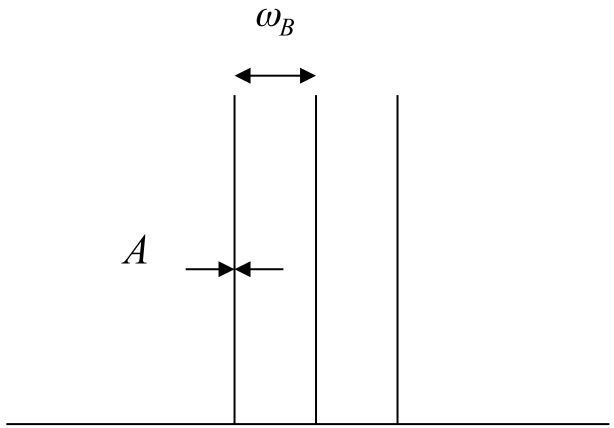
e.g. , Fe XIII 1074.7 nm, Si IX 3934.6 nm for the solar Corona

- Strong field regime:

$$w_B >> A \ (\approx 10^1 \text{ to } 10^2 \text{ sec}^{-1}),$$

- Weak interference between the magnetic substates,
- Incoherent superposition of the magnetic sub-states,

$$|\mathbf{E}|^2 = |\mathbf{E}_{-1}|^2 + |\mathbf{E}_0|^2 + |\mathbf{E}_{+1}|^2$$



Permitted Lines
(E1 Transition)

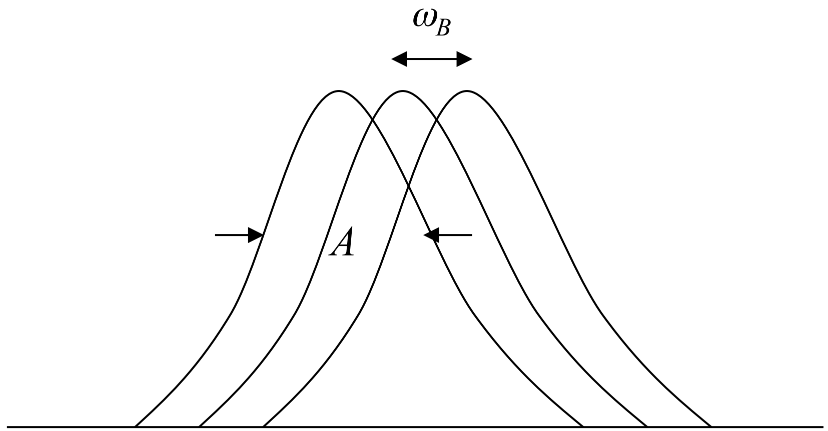
e.g., He I 1083.0 nm, O VI 103.2 nm

- Weak field regime:

$$\omega_B \leq A \ (\approx 10^6 \text{ to } 10^8 \text{ sec}^{-1}),$$

- Strong interference between the magnetic substates,
- Coherent superposition of the magnetic sub-states,

$$|\mathbf{E}|^2 = |\mathbf{E}_{-1} + \mathbf{E}_0 + \mathbf{E}_{+1}|^2$$



Diagnostics Capability of Forbidden Coronal Emission Line Polarimetry

Diagnostic Capabilities of CEL Polarimetry

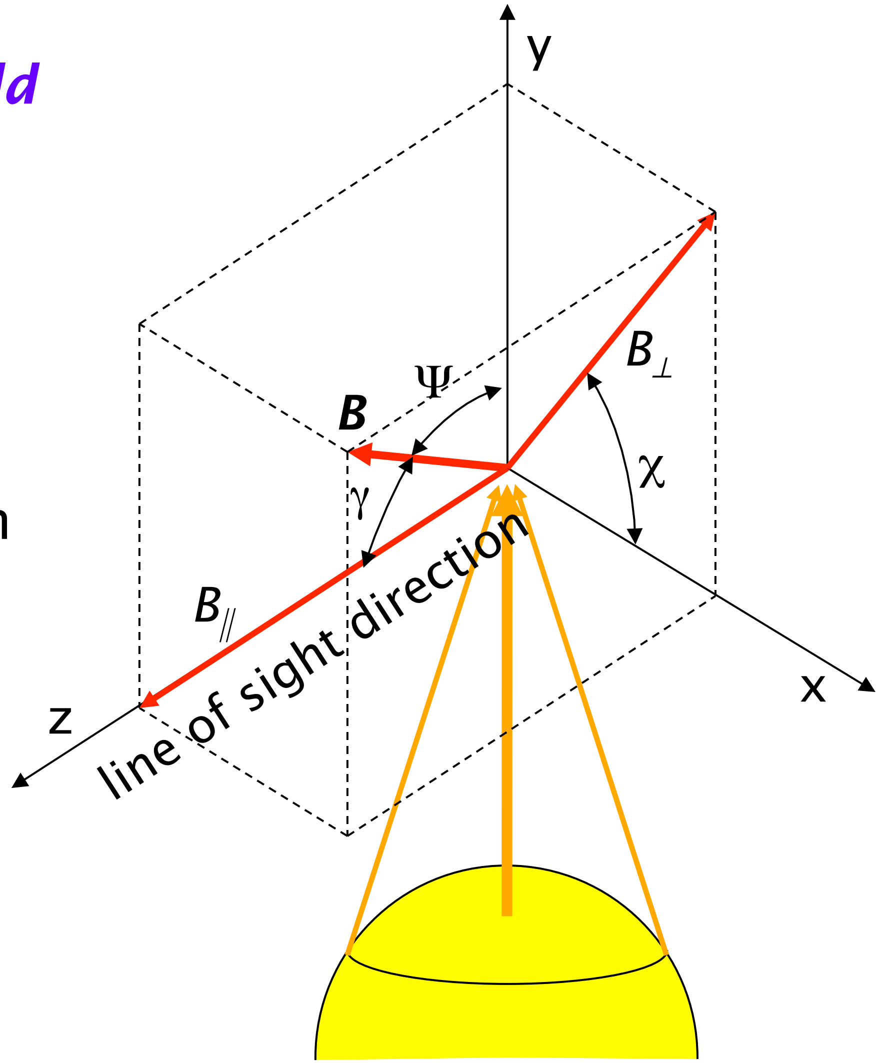
- **Circular Polarization**
  - ***$B_{||}$ – line-of-sight magnetic field strength****…with an alignment effect correction*

- **Linear Polarization**
  - ***χ –Azimuth direction of B***

    Direction of **B** projected in the plane of the sky containing sun center.
  - ***No sensitivity to |B |***

  - ***the van Vleck effect***

    90 degree ambiguity in the azimuth direction of **B**, depending on Ψ

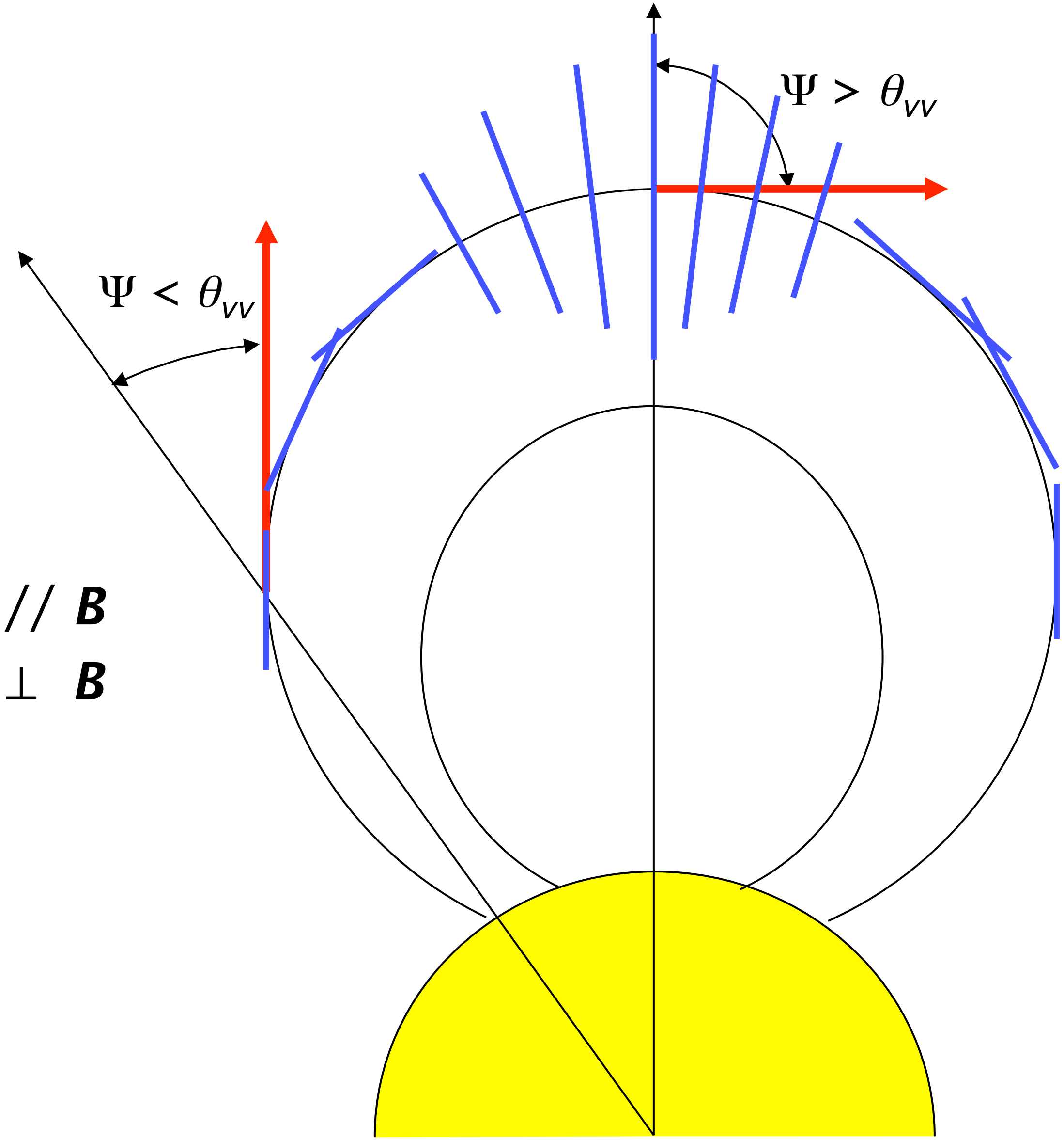


The van Vleck Effect

- *van Vleck Angle*

  θ_{vv} = 54.7 deg

  – $\Psi < \theta_{vv}$, then LP // ***B***
  – $\Psi > \theta_{vv}$, then LP ⊥ ***B***



Alfvén Wave Diagnostics of Corona *B*
Next Talk

Measurement of Alfvén speed yields **transverse coronal |*B* | projected in the POS**

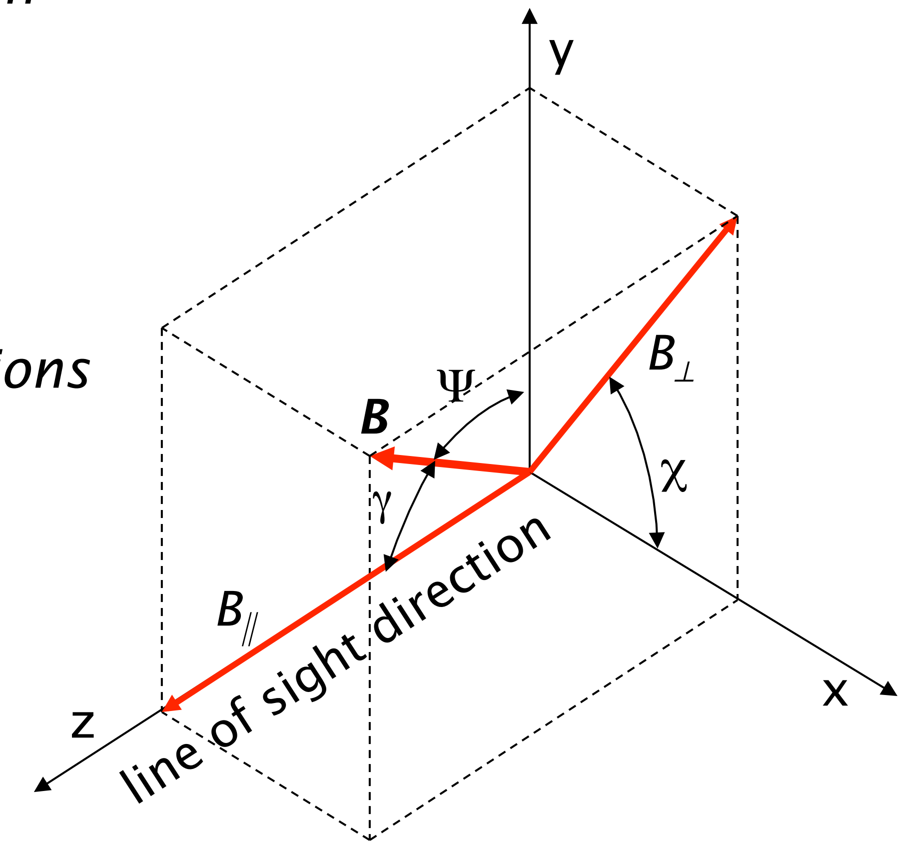
- CEL Doppler measurements
  - ***Sensitive to motion along the line of sight.***
  - Tomczyk et al. 2007

- CEL LP direction oscillation
  - ***Sensitive to motion perpendicular to the line of sight.***
  - Keil et al. (unpublished results)

Vector Coronal Magnetometry

γ {

- **$B_{\parallel}$: Longitudinal |*B* |**
  - *CEL Circulation Polarization*
- **$B_{\perp}$: Tranverse |*B* |**
  Alfvén Waves in
  - *CEL Doppler images*
  - *CEL LP orientation oscillations*
- **χ : Transverse *B* direction**
  - *CEL Linear Polarization*

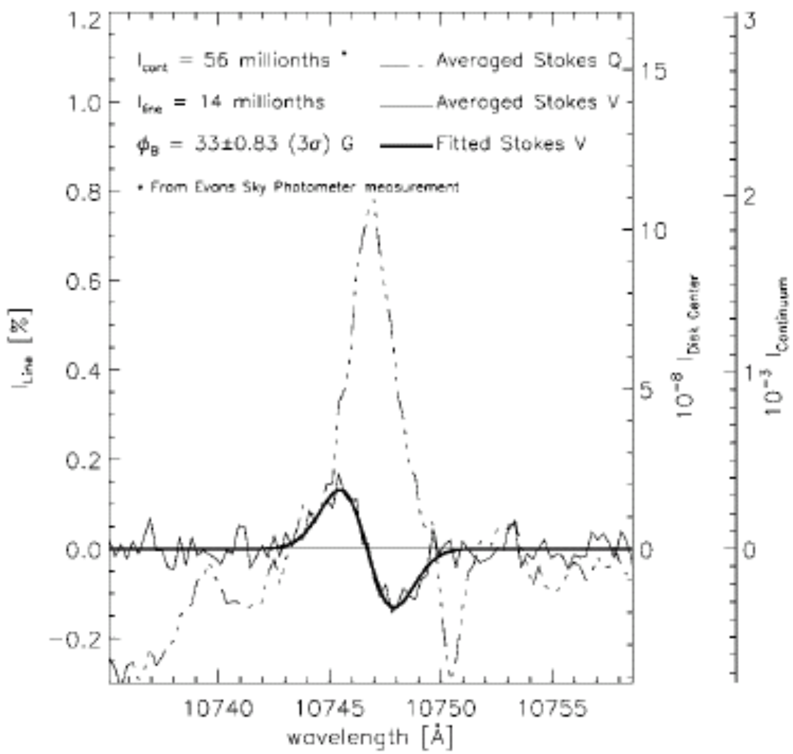


Observational Challenges

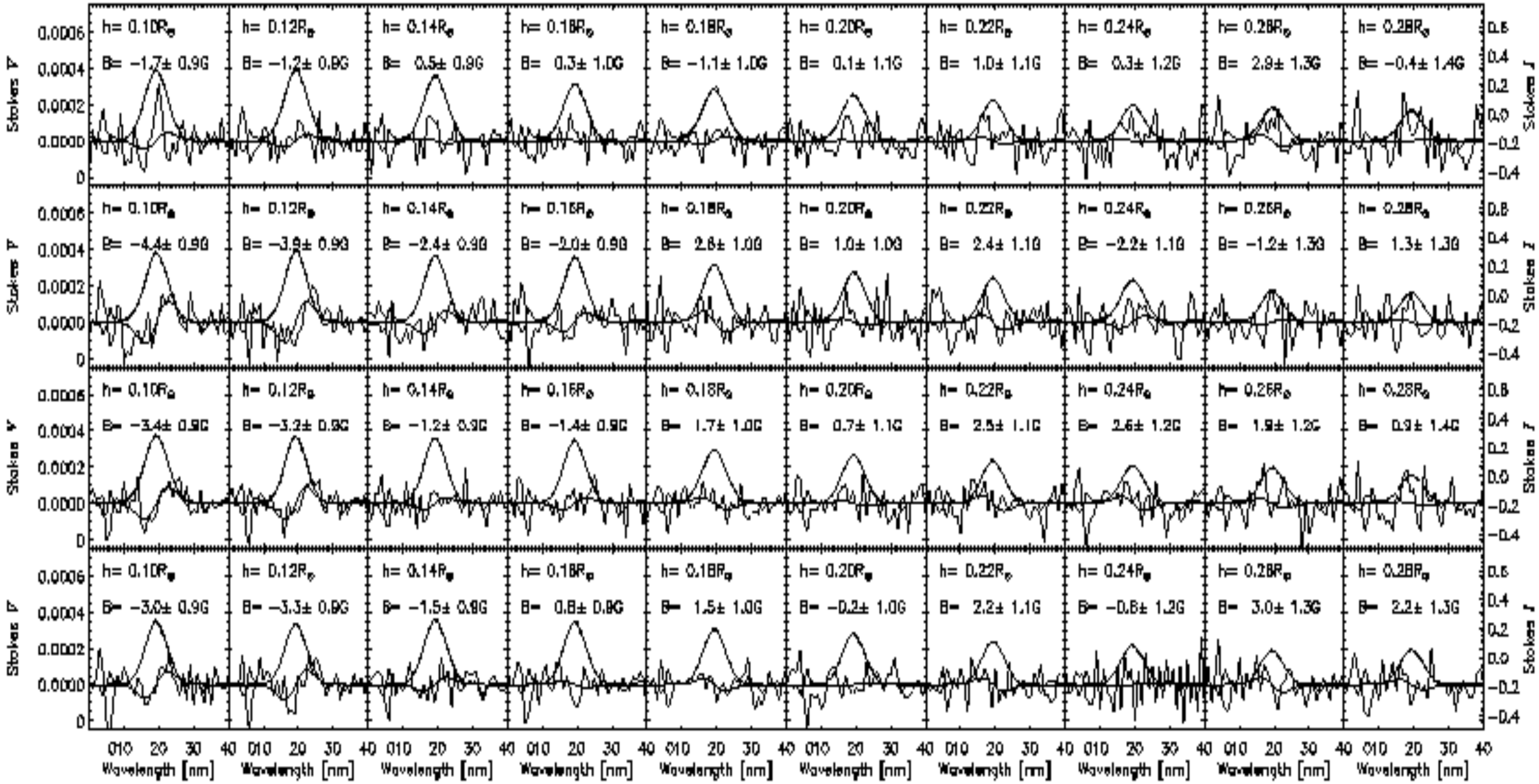
Circular Polarziation

- Best spectral line for coronal ***B*** measurement
  - Fe XIII 1075 nm

- Amplitude of CP
  - Solar Maximum: ~ 10^{-3}
  - Solar Mimumum: ~ 10^{-4}
- With a 50-cm coronagraph on the g
  - 20" pixel
  - ~ 30 × 10^{-6} I_c scattered light
  - ~ 1 hr integration time
  - → **3 G (3 σ) sensitivity @ 1.1 R_{sun}**

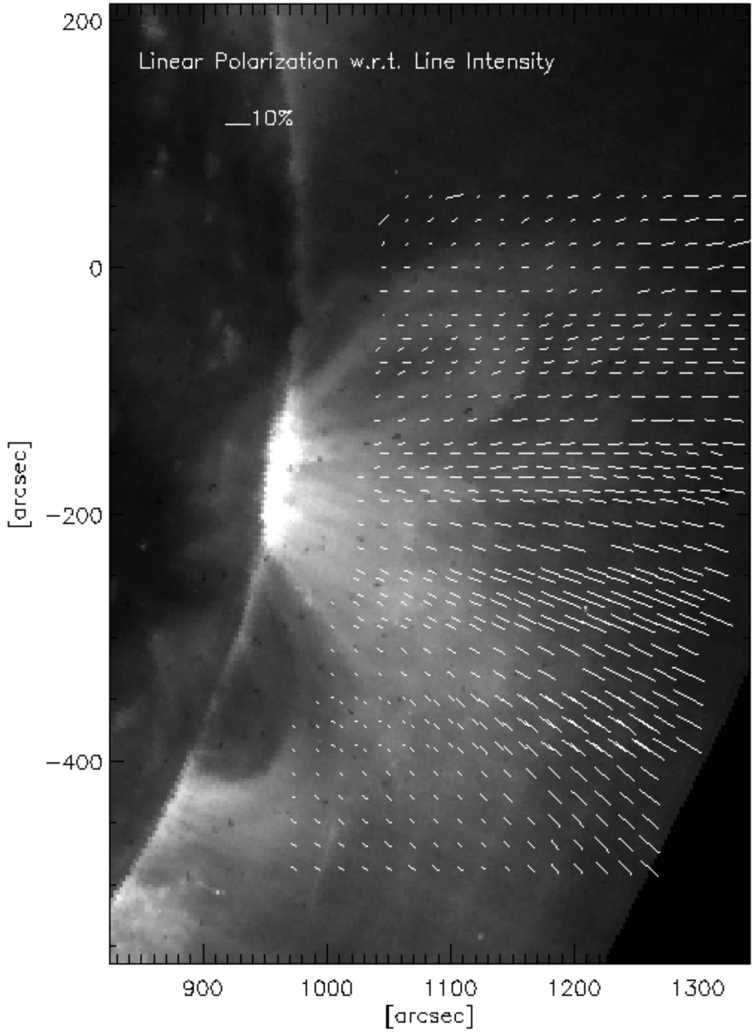


Circular Polarziation, Low Activity Period

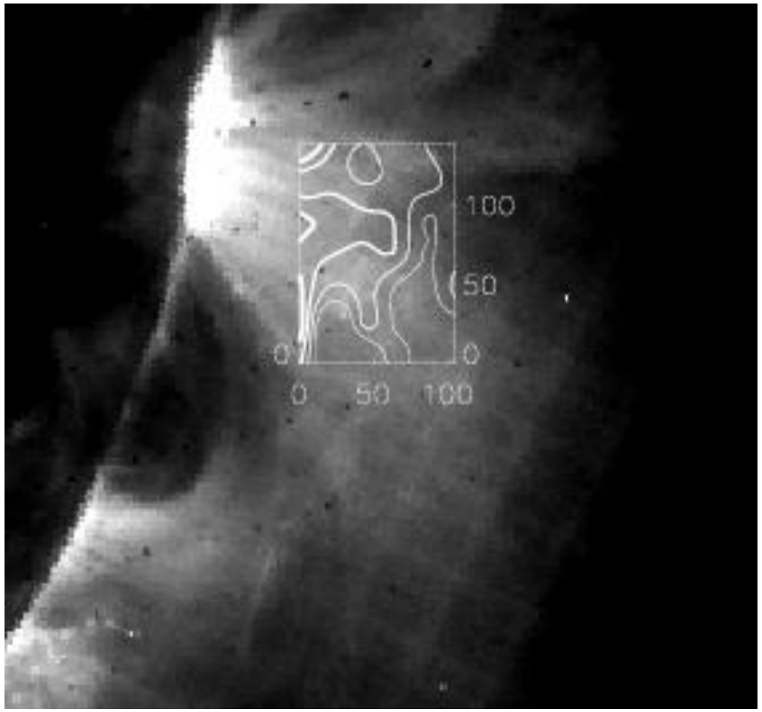


Coronal Magnetogram, April 6, 2004

Transverse field orientation



Longitudinal Field Strength



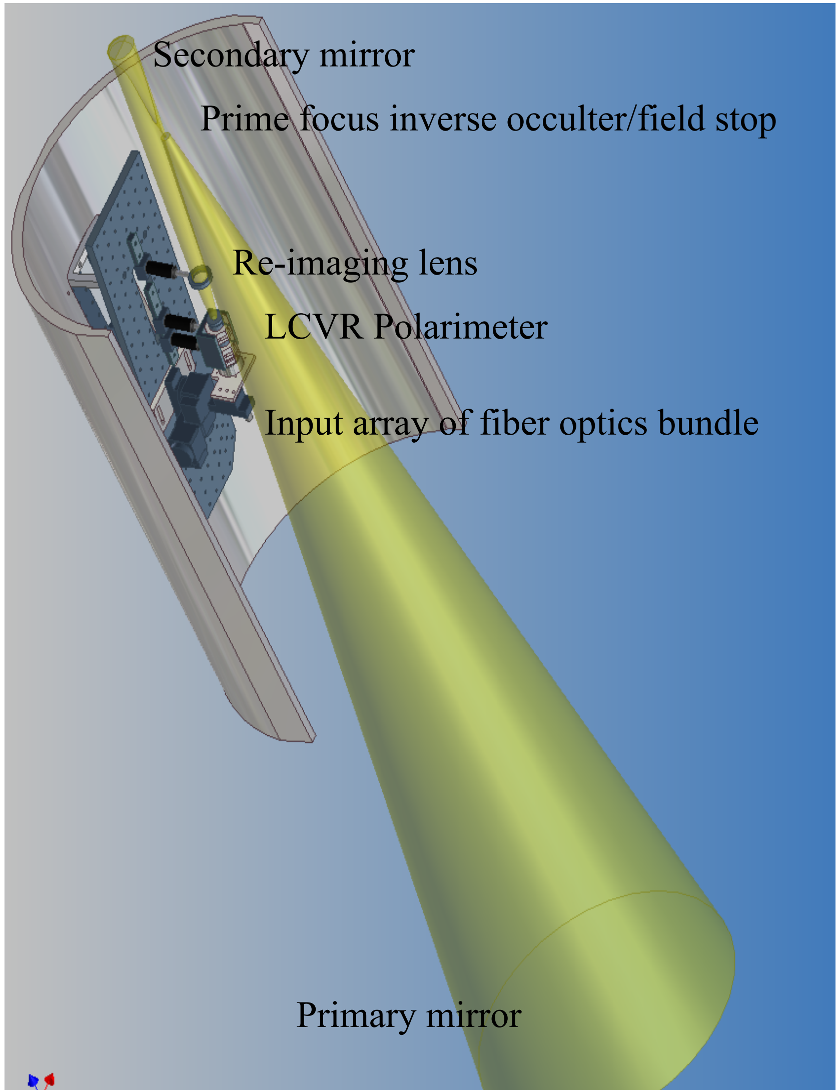
Contour plot of the line-of-sight magnetogram over-plotted on the SOHO/EIT FeXVI 284 A image. The contours are 5G, 3G, and 1G.

SOLARC – Solar Observatory for the Limb and Active Region Coronae – J. R. Kuhn

PI—Jeff Kuhn (IfA)

- 50 cm aperture off-axis gregorian telescope
- No secondary mirror and spider structure in the optical path for coronagraphic performance

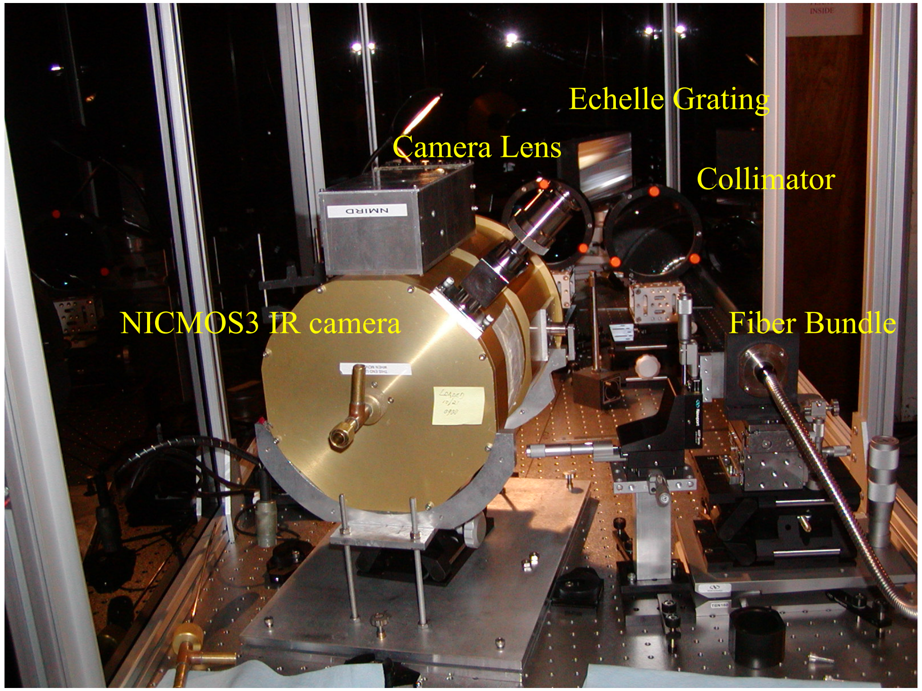
SOLARC and its dome on the summit of Haleakala, Maui.

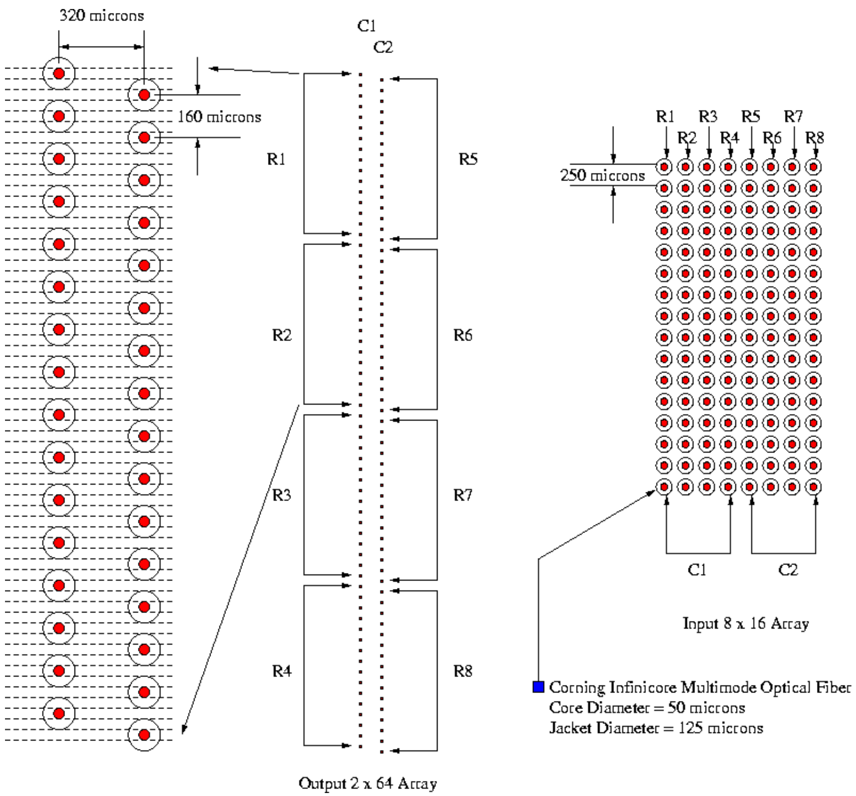


Optical Configuration of SOLARC and OFIS

OFIS: A True Imaging Spectropolarimeter

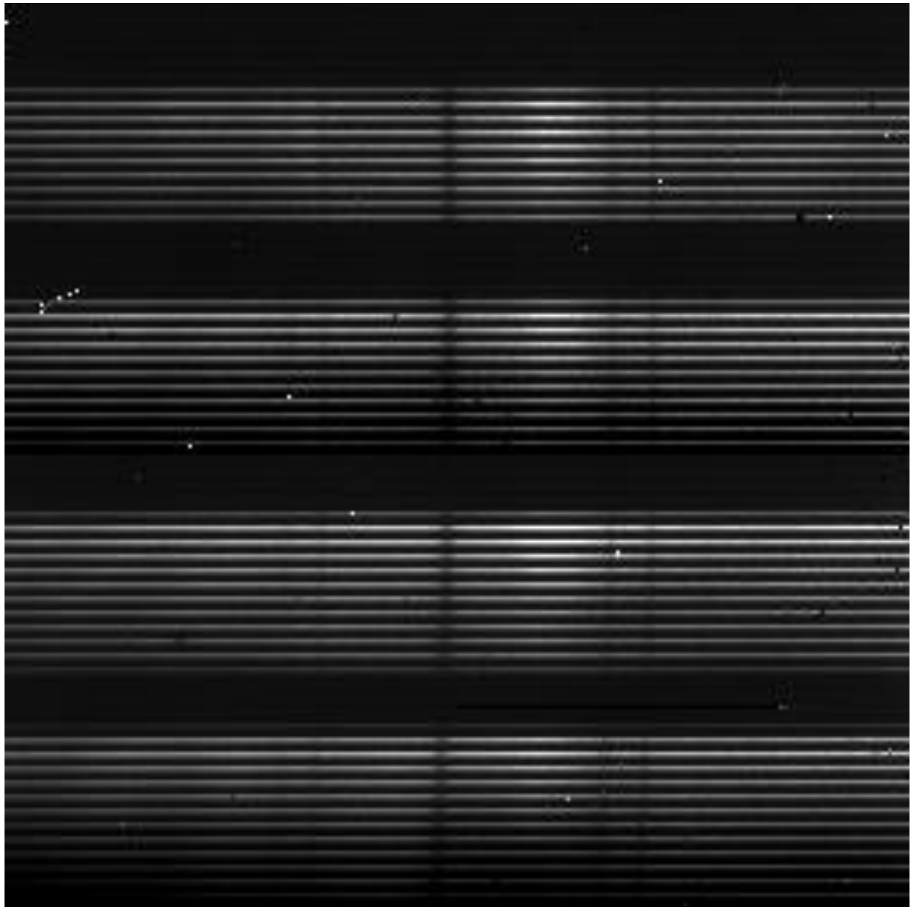
- NICMOS3 IR Camera
- 16 × 8 => 2 × 64 optical fiber-bundle
- 160 × 308 mm, 79 lines/mm echelle grating with 63.5 blaze angle
- f = 800 mm, Φ = 150 mm (F/5.3) collimator and camera lens



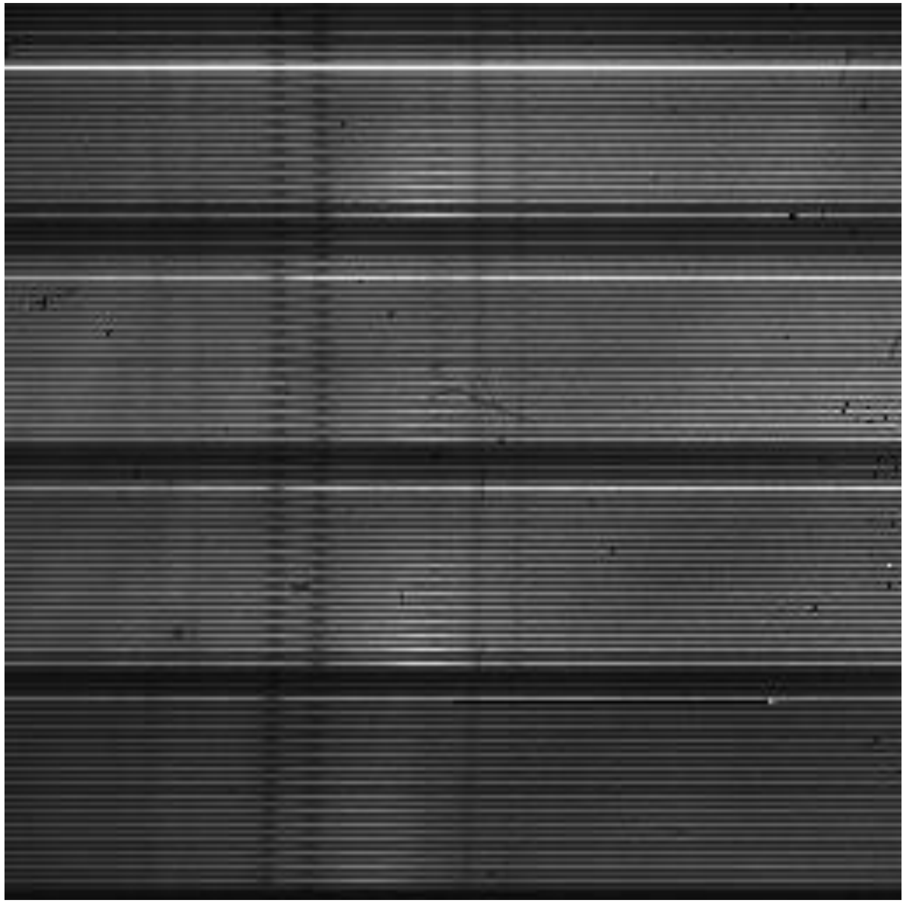


The coherent optical fiber-bundle rearrange the 2-dimensional image sampled by the 16 × 8 input array to two linear array (2 × 64). The two linear arrays act as the slits of the spectrograph, thus allowing for the simultaneous recording of the spectra from all the field points in the 2-D image plane.

Sample CEL Spectra from OFIS



One 64-fiber column illuminated
16 × 4 pixels area coverage

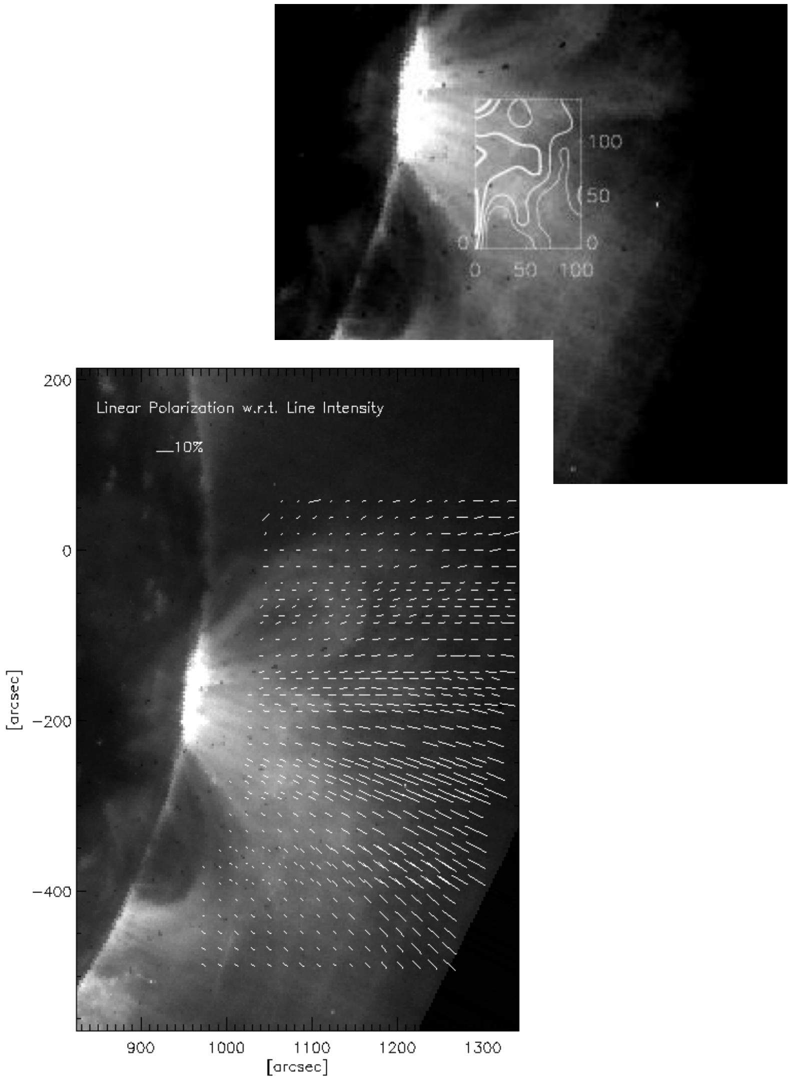


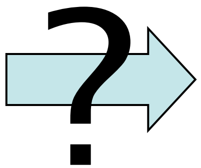
Two 64-fiber columns illuminated
16 × 8 pixels area coverage

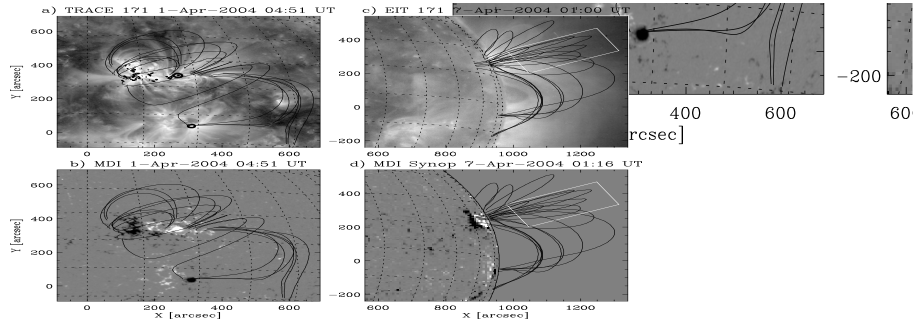
What Can We Learn From Coronal Magnetometry?

1. **Build a Coronal Magnetic Field Model**
2. **Validating Coronal Magnetic Field Model**
3. **…**

Can we build a coronal magnetic field model from the polarimetry data?







The Coronal *B* Inversion Problem

The coronal atmosphere is optically thin

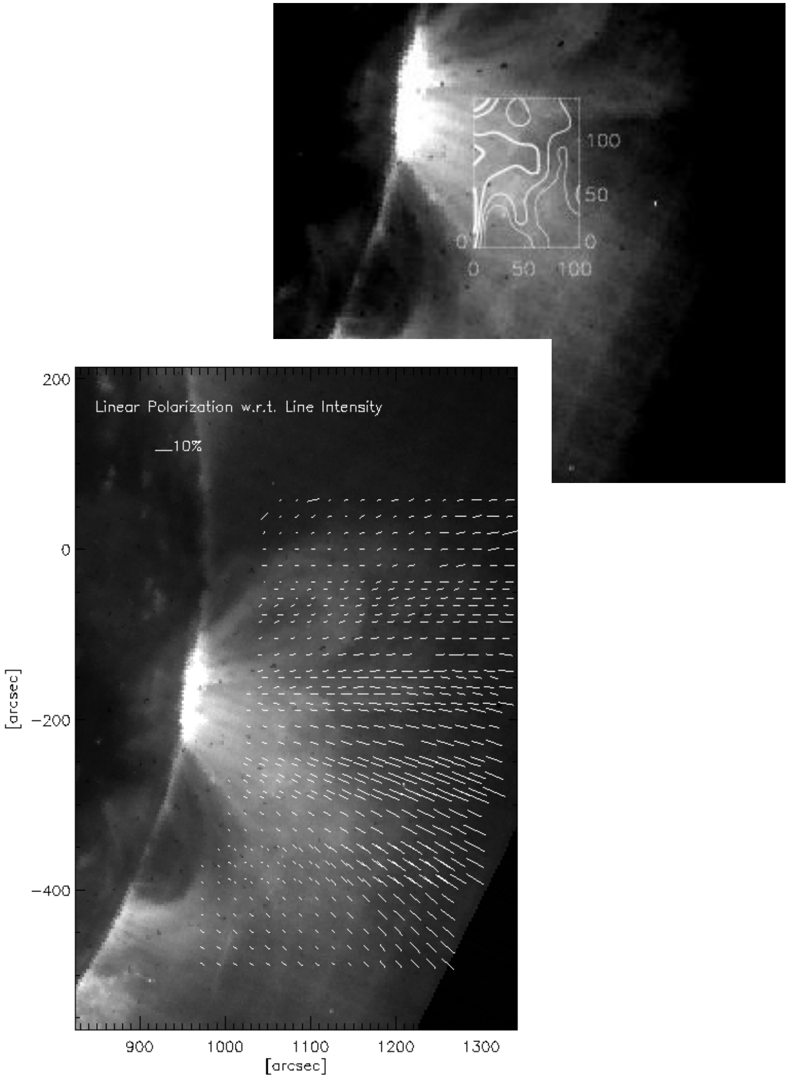
- *The observed coronal polarization signals **may not** originate from a single localized source along the line of sight.*
- *There are many independent parameters in the model, but only a few observables…*

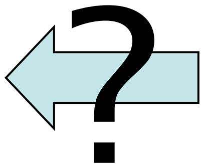
The inversion problem is severely under constrained!

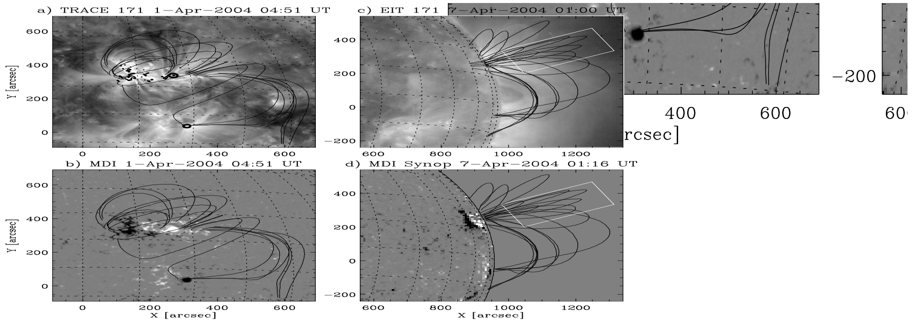
⇒ Currently, there are no tested and reliable inversion methods for the reconstruction of the 3D coronal ***B*** structure using polarization measurements…

⇒ Vector tomography looks promising…

Can we build a coronal magnetic field model and reproduce the polarimetry data?







Forward Modeling…

- **Yes! In principle**…

  If we know the 3-dimensional

  - *magnetic field **B***
  - *Density n_e*
  - *Temperature T_e*

  structure of the corona, then we can synthesize the LP and CP signals emerging from the observed coronal atmosphere for comparison with the observed polarization signals…

Coronal *B* Extrapolation

In reality…

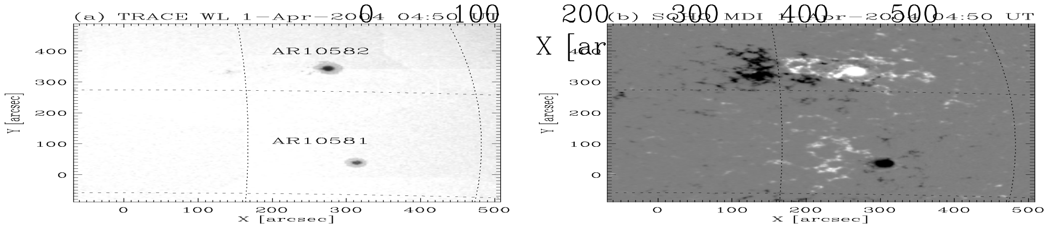
- Extrapolations yield magnetic field configuration only.

  There are no information about n and T.

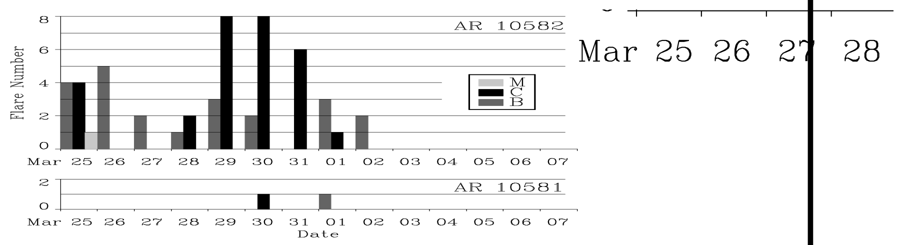
  ⇒ *n and T has to be derived, inferred, assumed, or guessed by other means…*
- The photospheric and coronal observations are not co-temporal…
  - *Uncertainties due to evolution of the active region.*
- Potential and force-free assumption may not be valid at the photosphere.

Testing Potential Field Extrapolation with *SOLARC* Observations

About AR 10581 AND 10582…



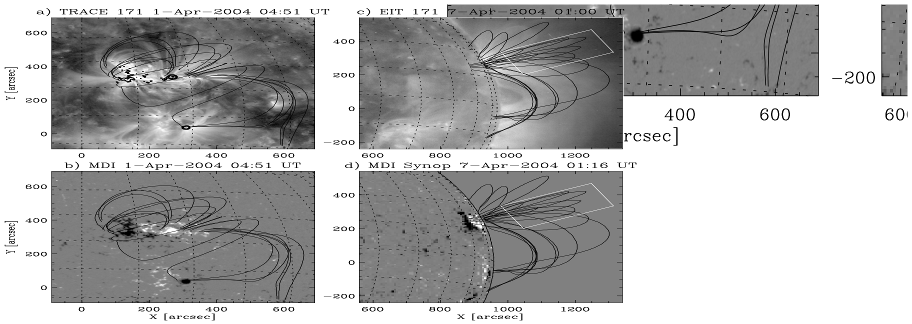
Time of *SOLARC* coronal ***B*** observation

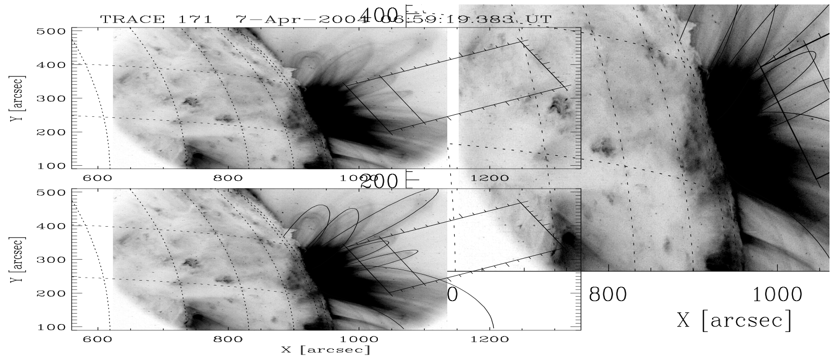


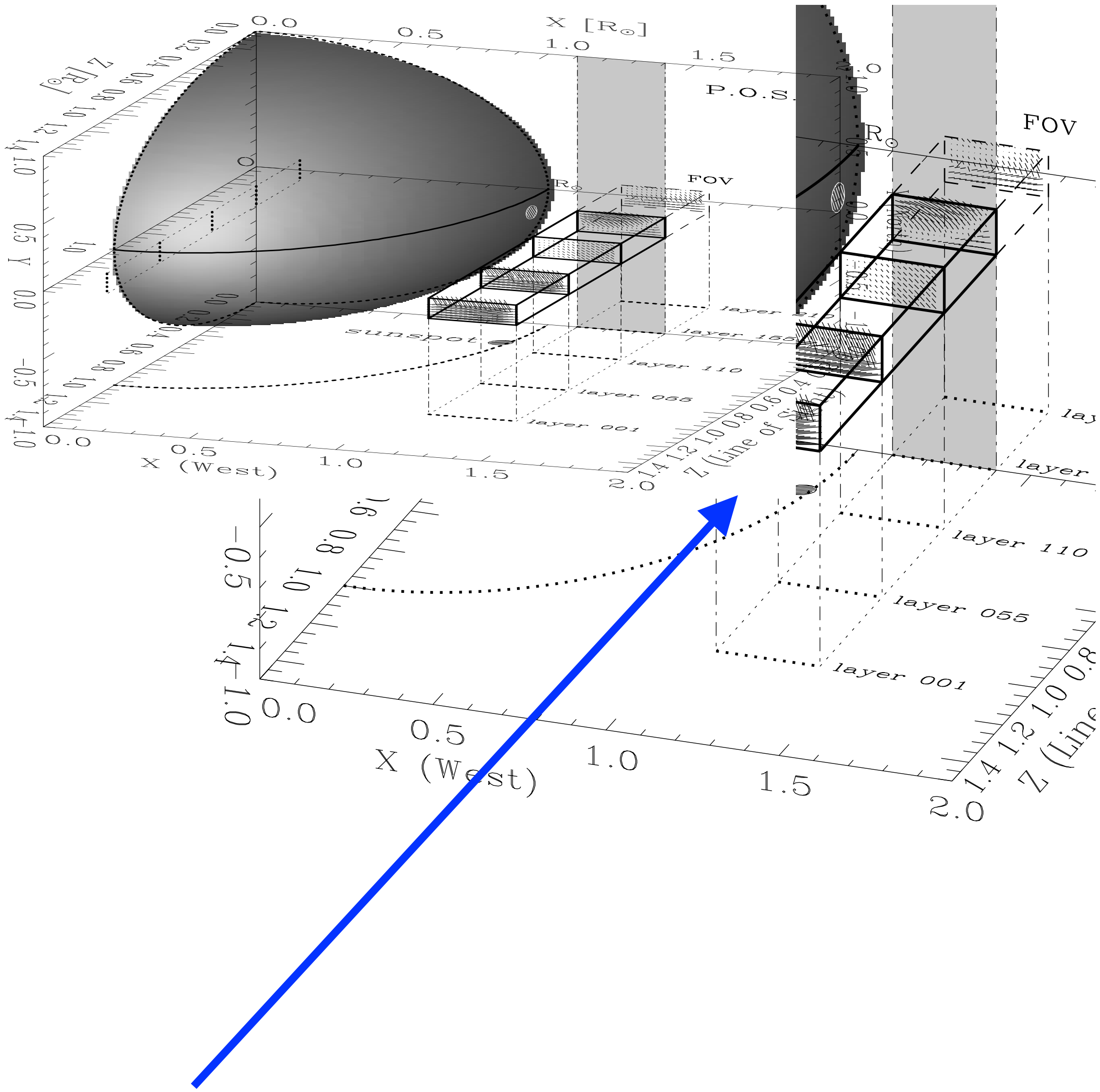
- Flaring activities in AR10582 ceased about 5 days before our coronal ***B*** observation…

  Potential field extrapolation may be OK?

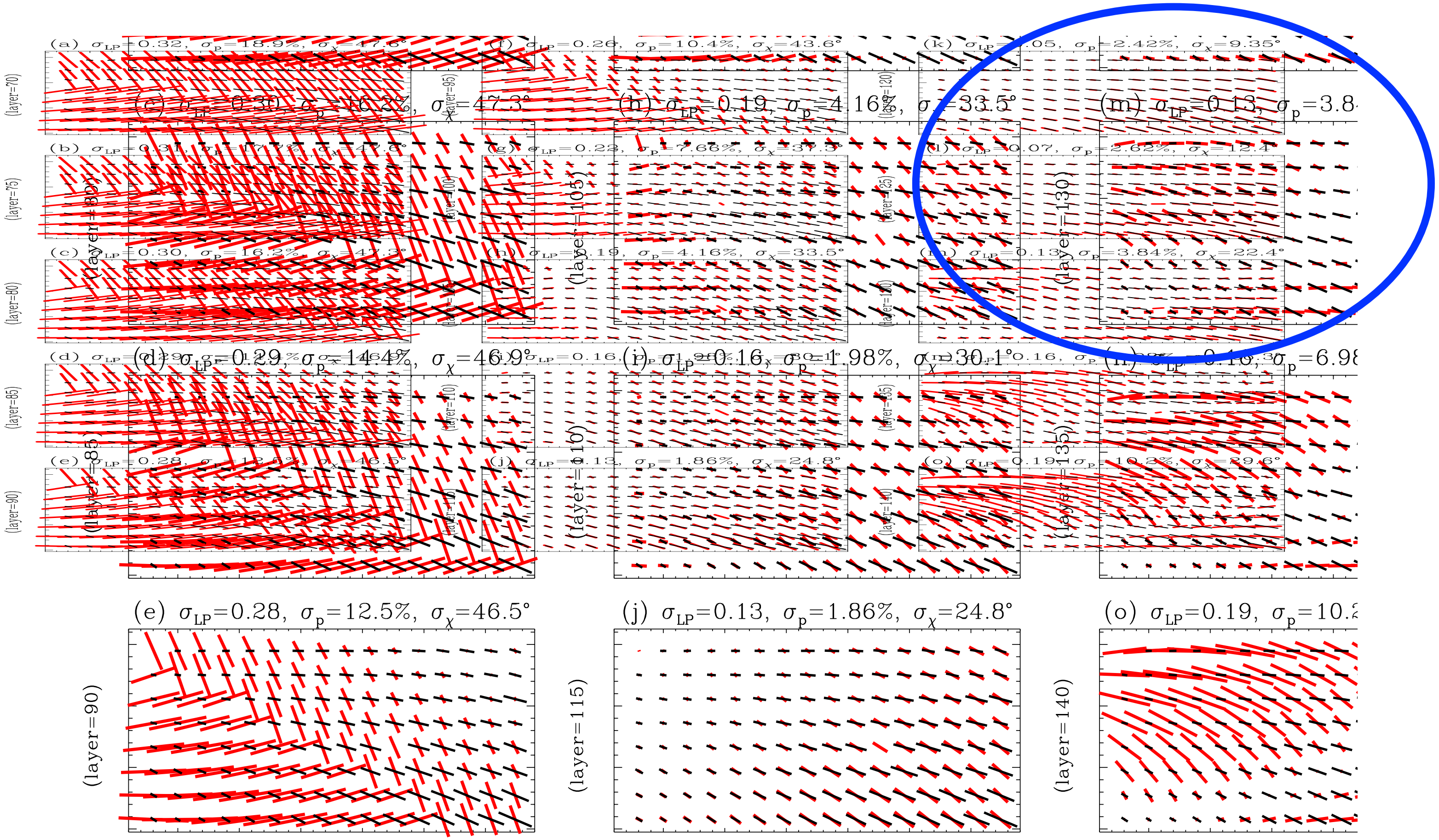
Potential Field Model of AR 10581 and 10582





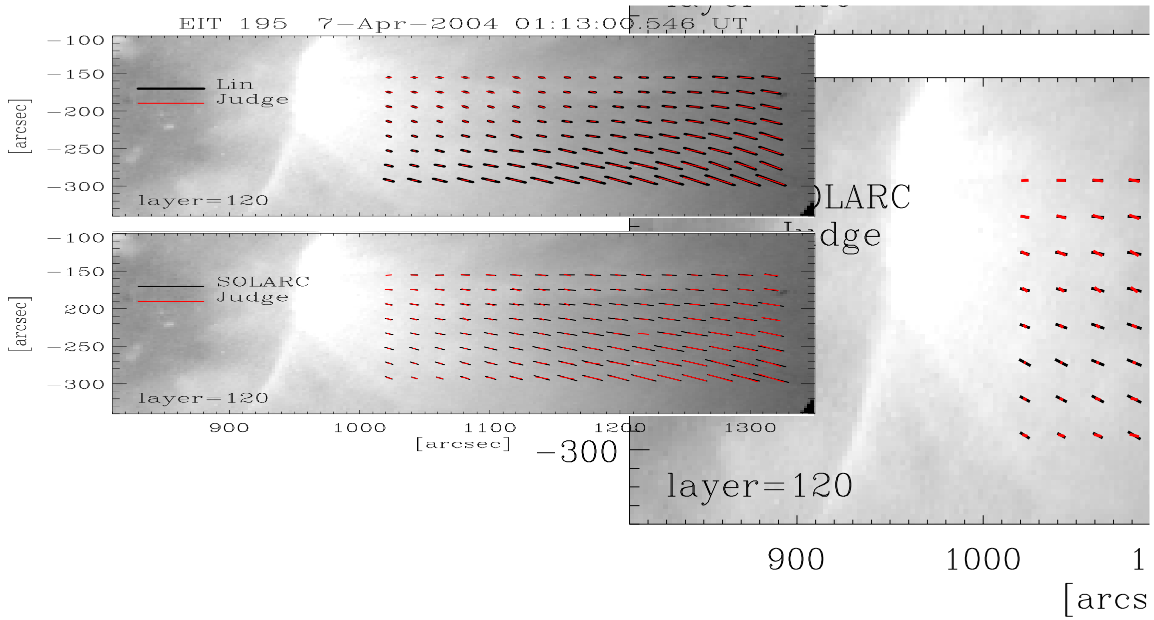


- Since the thickness of the new source function is small, we computed the synthesized LP map as a function of position along the Line of Sight…

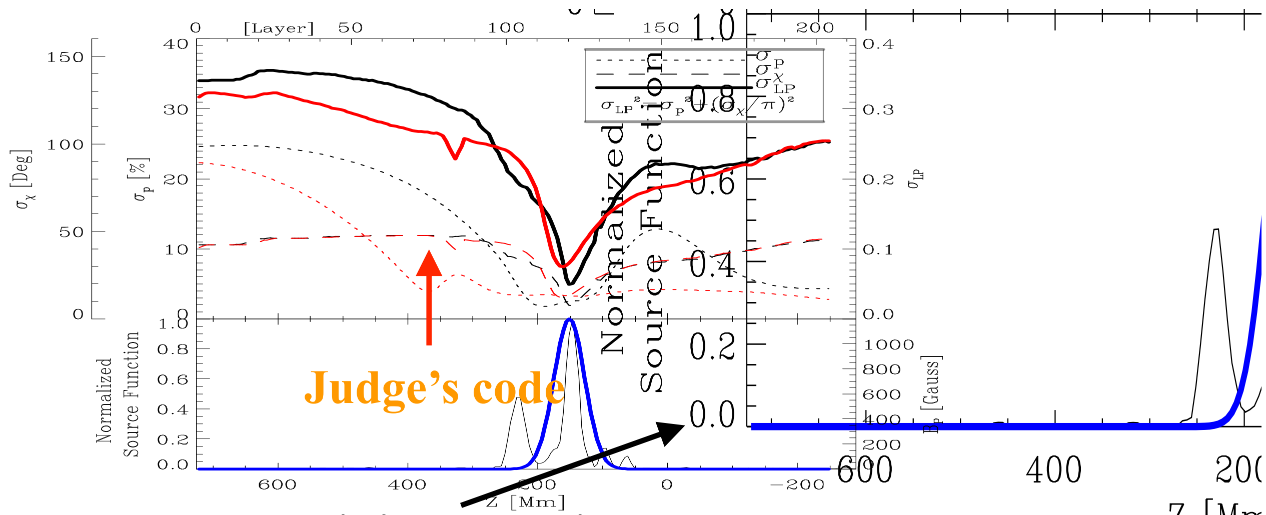


(e) σ_{LP}=0.28, σ_p=12.5%, σ_χ=46.5°
(layer=90)
(j) σ_{LP}=0.13, σ_p=1.86%, σ_χ=24.8°
(layer=115)
(layer=140)

Comparison with Judge's Synthesis Code



- Phil Judge's code includes ***collisional depolarization*** effect…
- We really can't tell which code is better from this comparison. But Judge's code includes more physics…

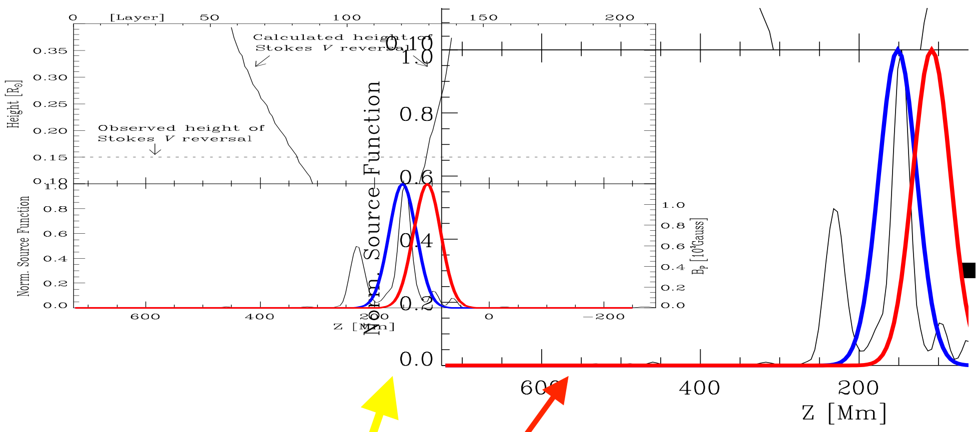


- σ_p: rms error in degree of linear polarization,
- σ_χ: rms error of azimuth angle of LP,
- σ_{LP}: combined rms error of the degree of polarization and the azimuth angle of the LP.

Source function of the best-fit layer

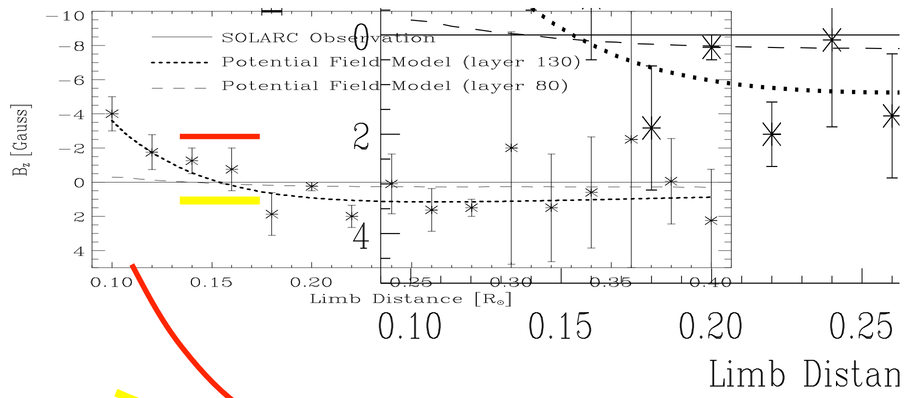
Photospheric B along the LOS

LOS direction

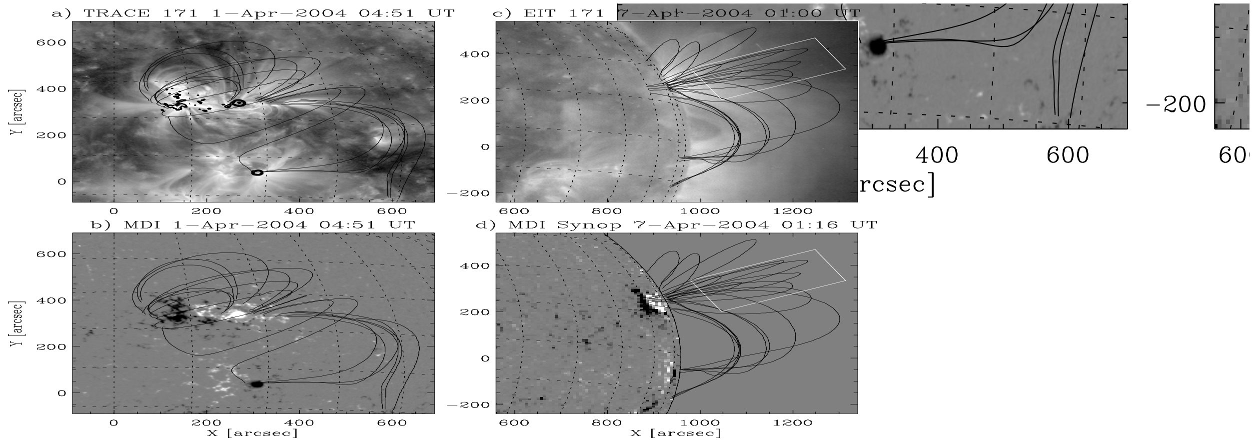


Circular Polarization

- $B_{//}(h)$, the longitudinal B as a function of height h, are calculated for each layer.



- The height of $B_{//}$ reversal agrees with the observed value at two layers.
- $B_{//}(h)$ at layer 130 fits the observed one better.



Source location of the FeXIII 1075 nm CEL…

Is this a coincidences?

NO!

- Two independent parameters
  - the degree of linear polarization, and
  - azimuth angle of linear polarization

  have minimum at about the same location
- Synthesized $B(h)$ matches the observed circular polarization signals at roughly the same location
- The polarization signals originate from the corona above the strongest photospheric magnetic field feature of the AR.

Conclusions

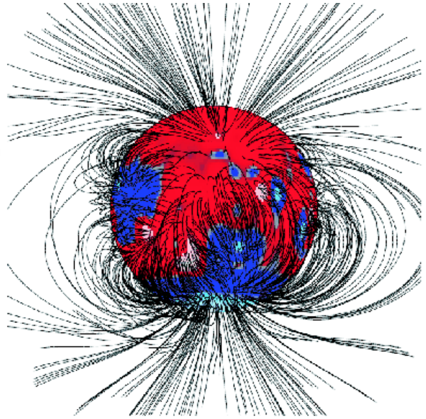
- ***Potential field extrapolation of AR 10582 has reproduced the observed coronal linear and circular polarization maps.***
  - The LP and CP source functions are close to the location of the sunspot of the active region.
  - The locations of the LP and CP source functions are not the exactly the same…
  - **The inferred LP and CP source functions are fairly *localized*!**

⇒ ***Single-source inversion (Judge 2007) might be possible…***

⇒ ***Potential field extrapolation may be a good 0^{th} order approximation for the coronal magnetic field model***

Liu & Lin, 2008, ApJ, 680, 1496

What's Next?


(a)

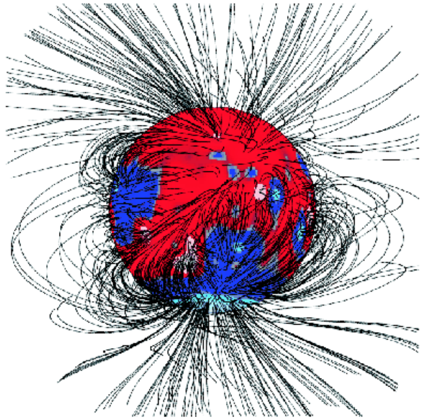
More observations (if the Sun cooperates) and more comparisons with models…

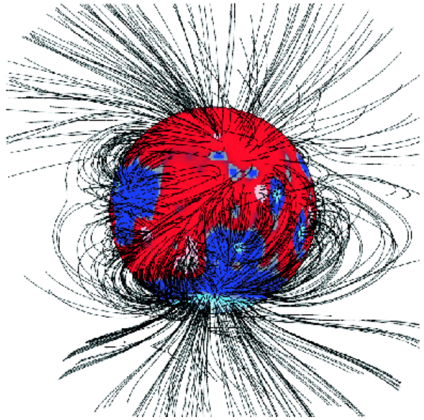
- *Is potential-field extrapolation really OK?*
- *Does force-free extrapolations provide better model?*
- MHD models should come with information about *n* and *T*…

  Collaboration with T. Wieglemann & B. Inhester

  ⇒ Direct comparison can be performed without guessing where the source is located.
- Vector Tomography

  Collaboration with M. Kramar


(b)


(c)

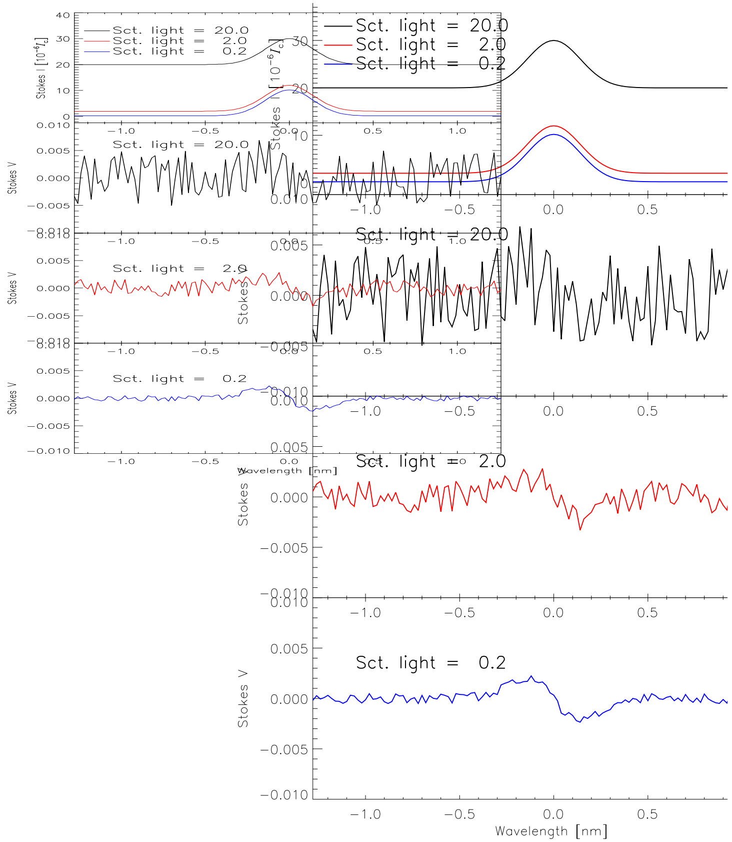
Direct Spectropolarimetry of Coronal *B* can provide important, quantitative constraints for coronal modeling.

What can be done in space?

Background-Limited Observations

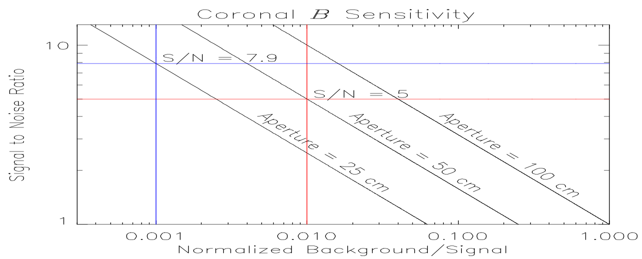
- Coronal ***B*** sensitivity depends on the telescope
  - ***aperture***
  - ***scattered light***
    - ***Instrumental scatter***
    - ***Sky***
- Ground-based coronagraphs are '***dust-limited***'.
  - SOLARC: ~ 25 x 10^{-6} I_{sun} @ 1.25 R_{sun}
  - HAO Mk4: ~ 6 x 10^{-6} I_{sun} @ 1.25 R_{sun}
- **The Space is sky and dust-free**
  - 2 x 10^{-7} I_{sun} for COR1 & COR2 inner field

    Thompson et al., 2005, GSFC internal report
  - 5 x 10^{-7} I_{sun} @ ~1 R_{sun}
    Korendyke & Socker, 1996, Opt. Eng., Vol. 35, 1170



The Coronal Aperture

- **A factor of 100 ($10^{-5} \rightarrow 10^{-7}$ I_c) improvement** in scattered light is possible in the dust-free space environment
  → ***A 25 cm coronagraph with 1 x 10^{-7} I_{sun} scattered light in space is equivalent to a 250 cm telescope on the ground with 1 x 10^{-5} I_{sun} scattered light.***



25-cm Space Coronagraph @ 1 AU Estimated Performance

Assumptions

- *1 x 10^{-7} I_{sun} scattered light*
  - *a factor of 300 improvement from SOLARC*
- *10% system efficiency*

$B_{\parallel}$ (3σ)	20"	~ 1 G in 5 min @ 1.1 R_{sun}
	5"	~ 1.3 G in 60 min @ 1.1 R_{sun}
$B_{\perp}$	S. Tomczyk – Coronal Alfvén Wave, next presentation	
χ	*high resolution and cadence with high sensitivity*	
N_e	Fe XIII 350, 1075, and 1080 nm	
T_e	Fe XVI 530, Fe X 890, and FeXIII 1075 nm	

II. High Throughput Mulit-Slit SpectroPolarimeter

Efficient use of modern large-format focal plane arrays for

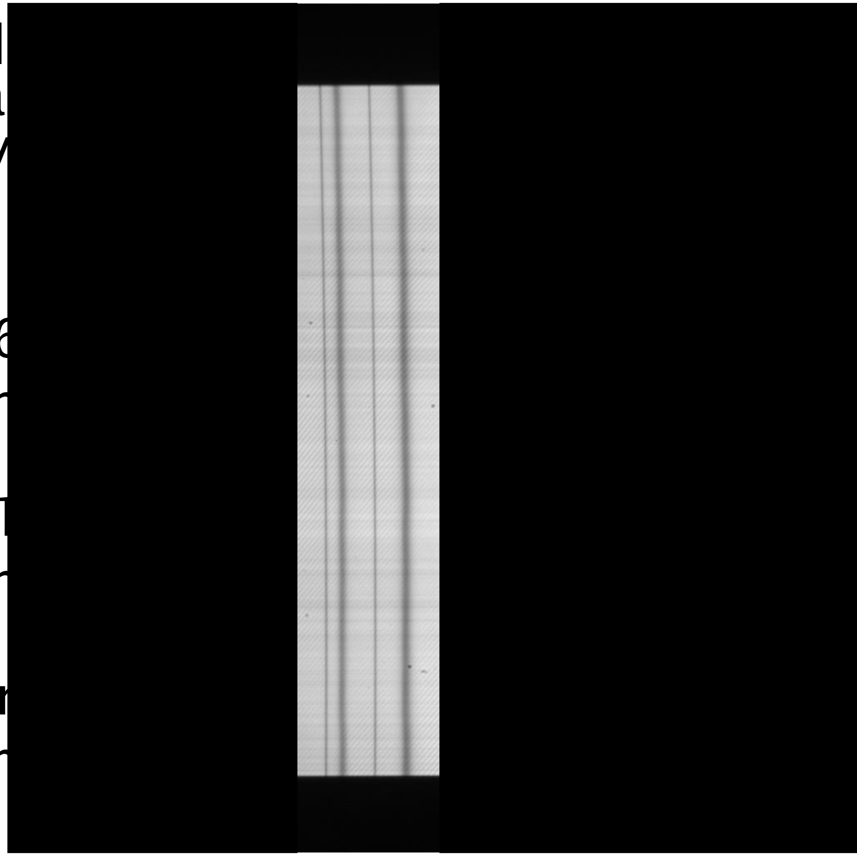
- *Fast Scanning*
- *True-imaging*

- Principle of Multi-Slit Spectropolarimetry
- Current Development
  - FIRS
  - True-imaging spectropolarimeters
    - Conventional fiber-optic array
    - Birefringent Fiber-Optic Image Slicer

Multiple-Slit Spectroscopy and SpectroPolarimetry

In conventional long-slit spectrograph, modern large array detectors are under-utilized, unless we do something different…

Solar spectropol … urement of selected spectra … olution and fidelity, but only …



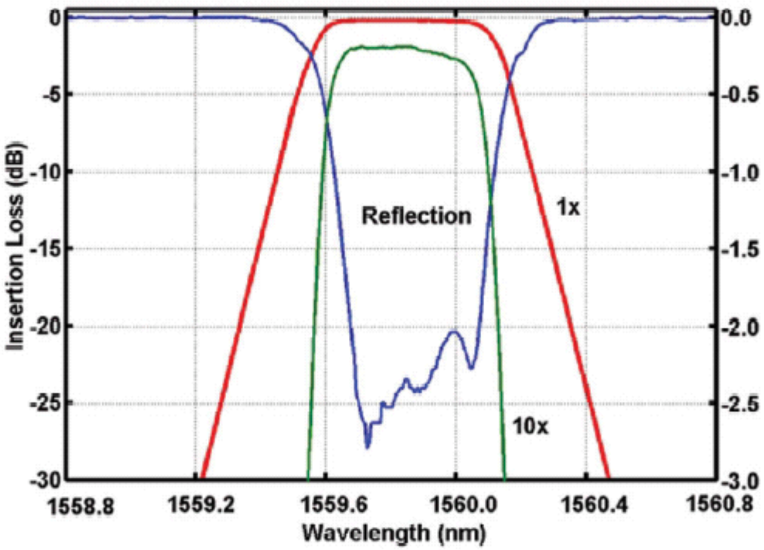
For examples,

- Fe I 630.15/6 …
  - Δλ = 0.2 n … ***s in spectral direction***
- Fe I 1564.8/1 …
  - Δλ = 0.8 n … ***in spectral direction***
- Fe XIII 1075 n …
  - Δλ = 1 nm … ***in spectral direction***

DWDM-Style Filters

- DWDM (Dense Wavelength Division Multiplexing) filters developed for fiber-optic communication are ideal for multi-slit spectroscopy

Product Name	Part Number
100 GHz Regular	10-100-0009-XX

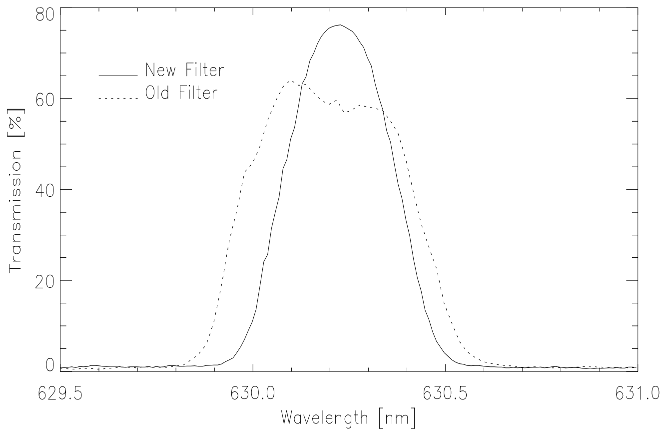


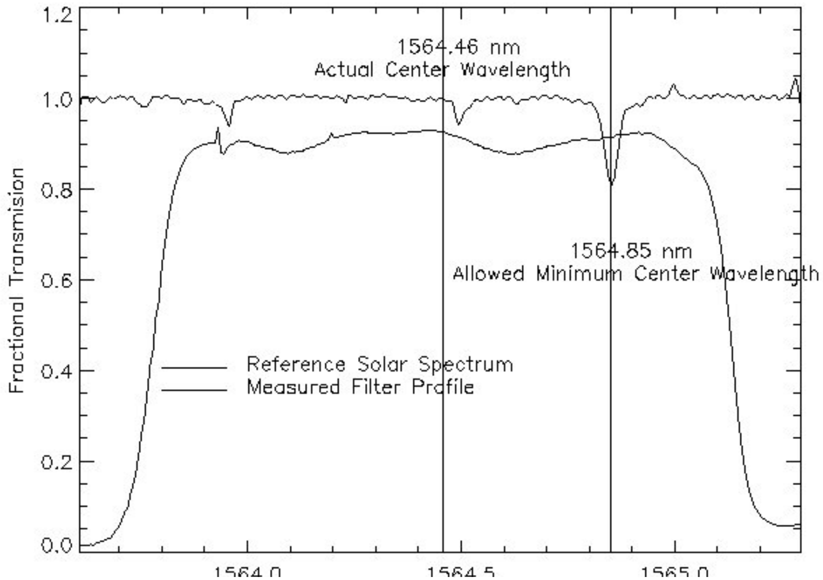
Part Number	Product Name	λ_c (nm)
10-100-0009-19	100 GHz, Ch19	1562.23
10-100-0009-20	100 GHz, Ch20	1561.42
10-100-0009-21	100 GHz, Ch21	1560.61
...	...	...
...	...	...
...	...	...
...	...	...
10-100-0009-60	100 GHz, Ch60	1529.55

Parameter	Unit	Specifications
Operation Wavelength	nm	1500 - 1640
Center Wavelength @ -0.5 dB (λ_c)	nm	ITU
Center Wavelength Tolerance	nm	+ 0.30 ~ + 0.60
Angle of Incidence	degrees	0
Passband	nm	$(\lambda_c - 0.18) \sim (\lambda_c + 0.18)$
-0.5 dB Bandwidth	nm	≥ 0.40
-25 dB Bandwidth	nm	≤ 1.20

Custom 630 nm and 1565 nm DWDM Filters

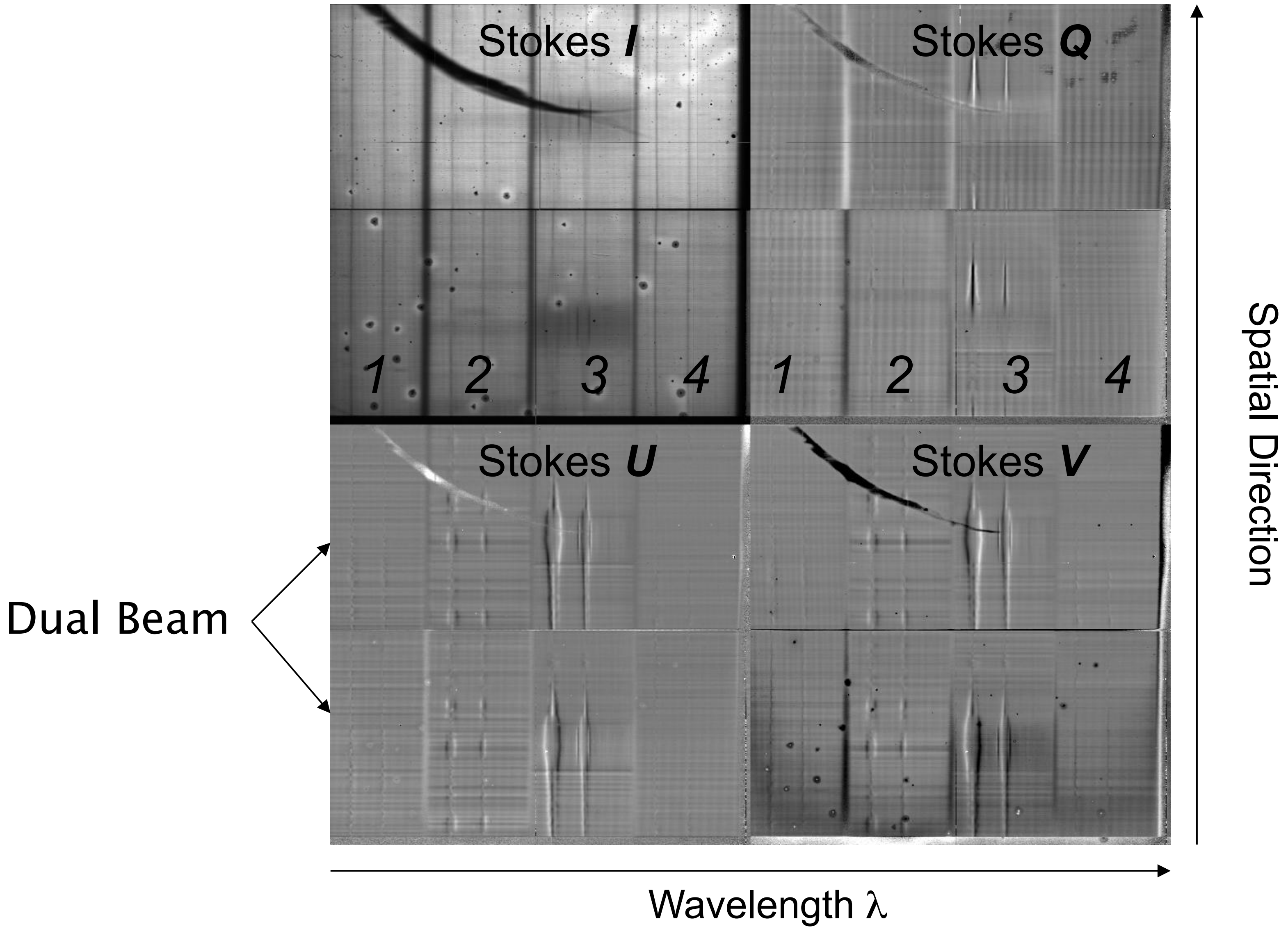
Visible DWDM needs improvements



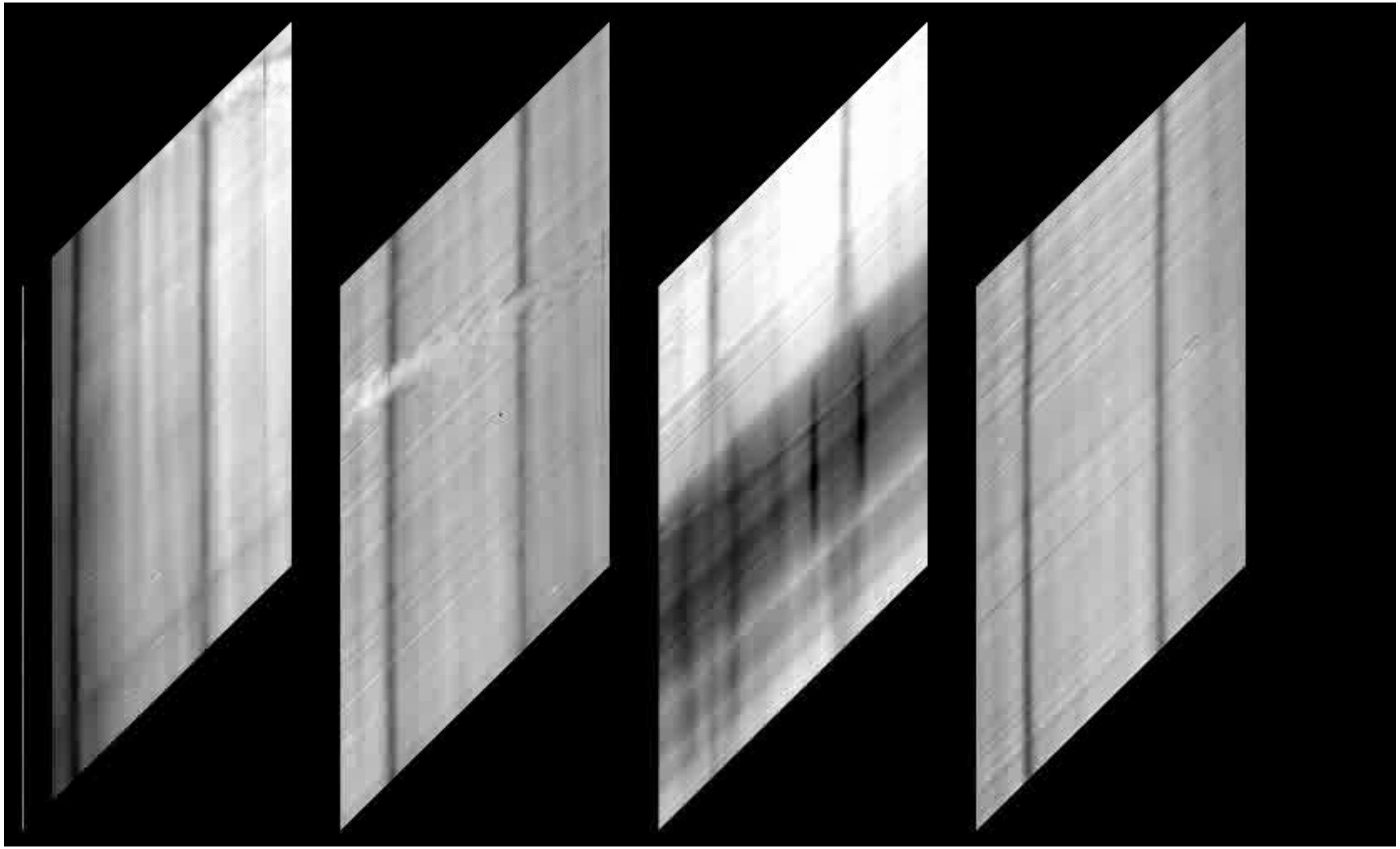


FeI 1565 nm DWDM Filter
Flat top, 90% transmission

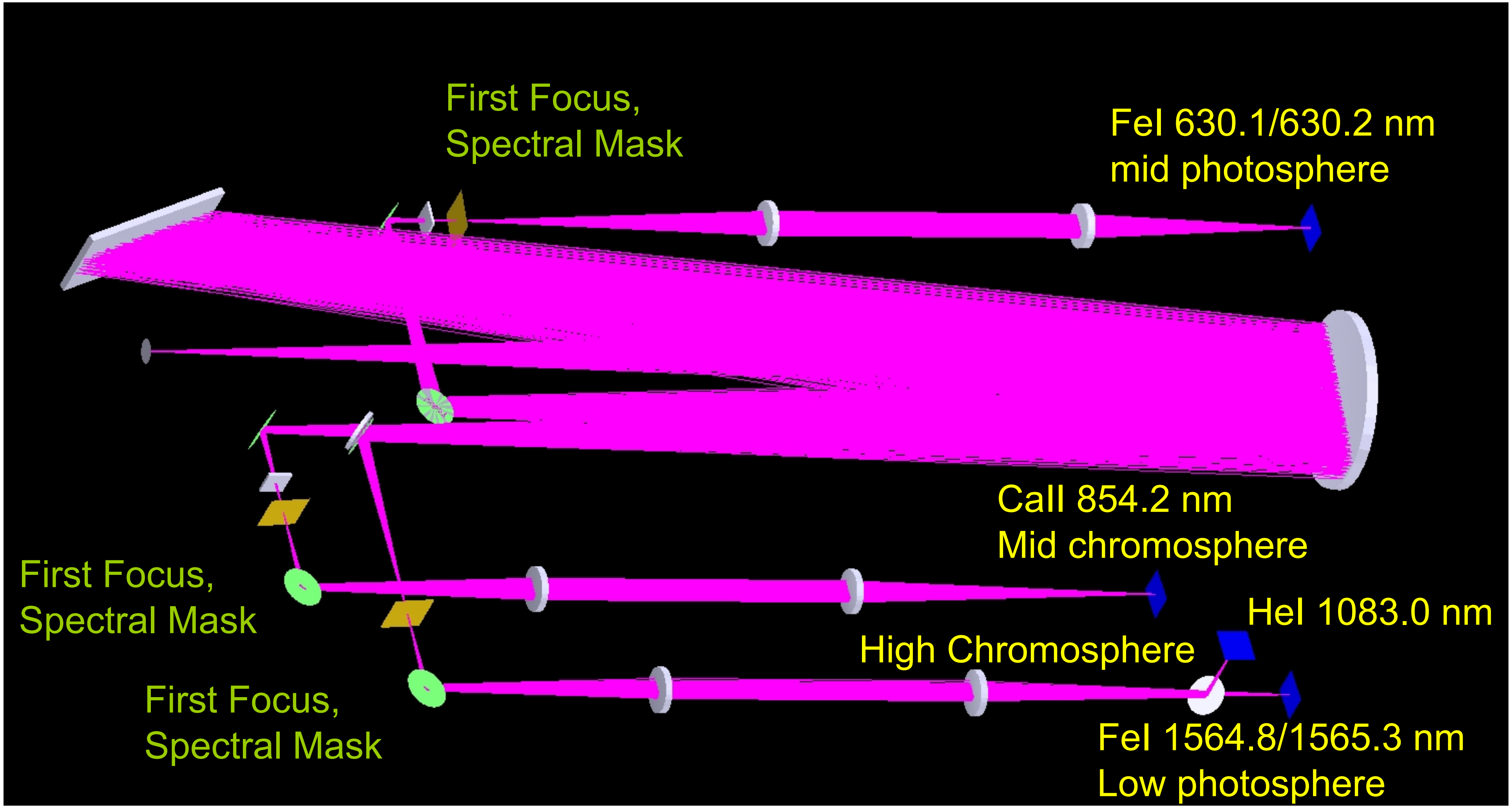
Full-Stokes 4-Slit Spectropolarimetry @ Fe I 1565 nm



Fast 4-Slit Scanning

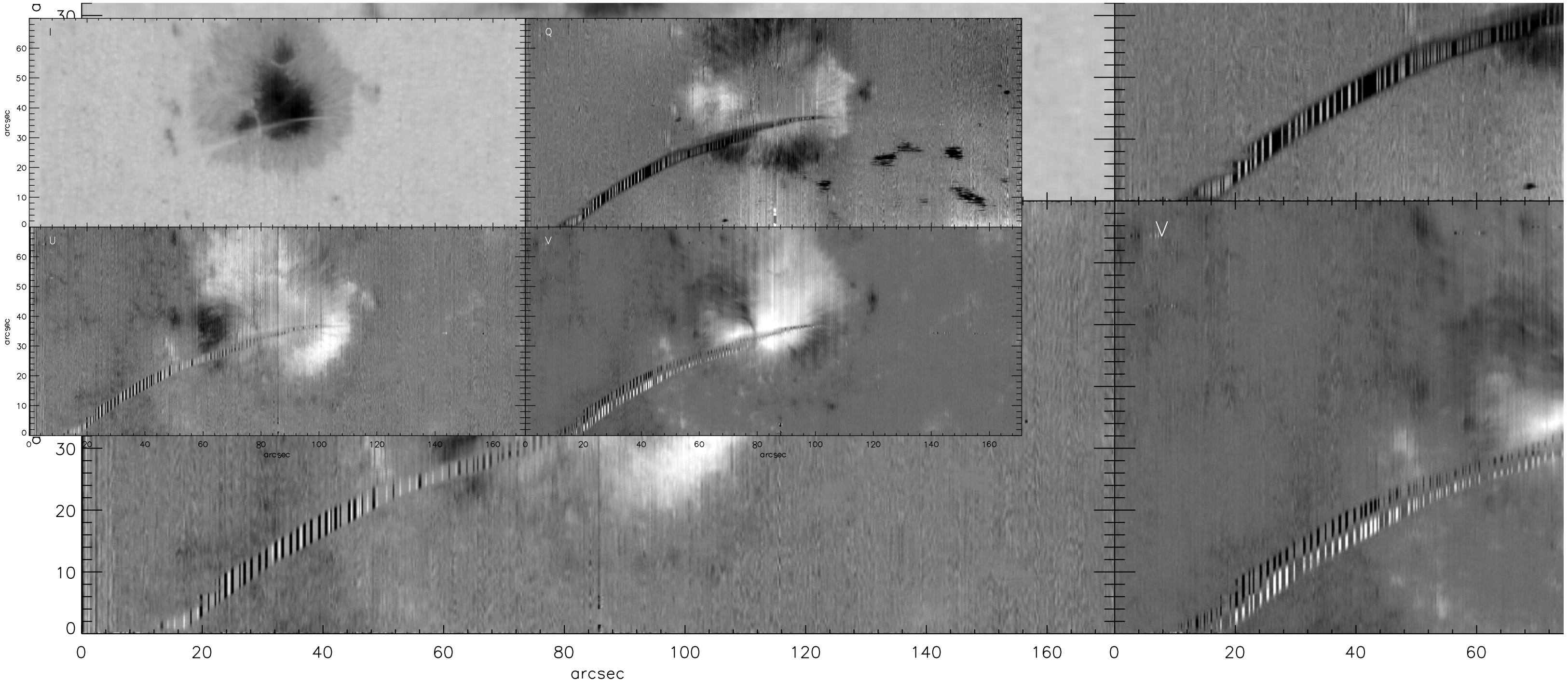


FIRS: The Facility IR Spectropolarimeter for the Dunn Solar Telescope
Up to 4 lines simultaneously



Current FIRS Capabilitis

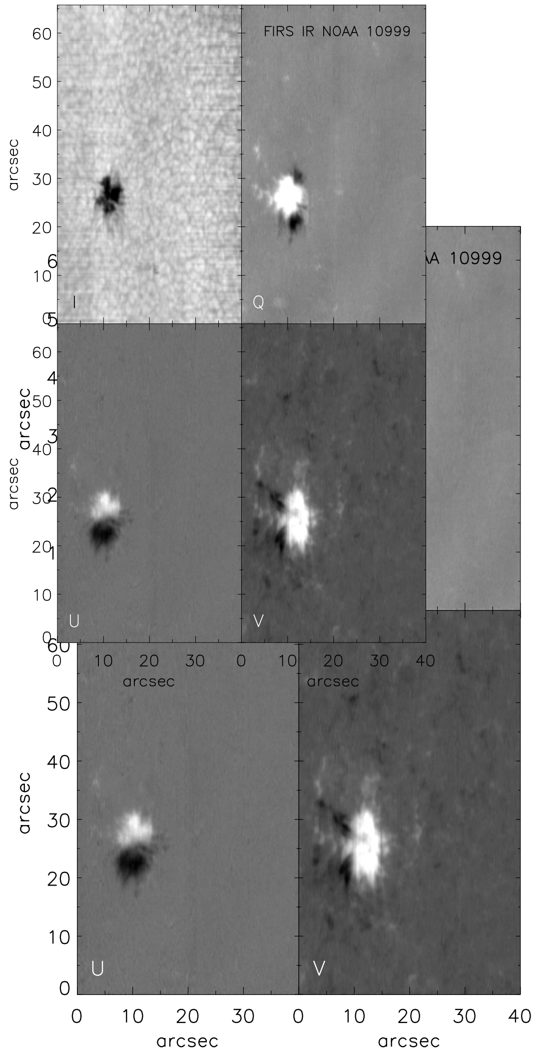
- A complete scan in ~ 10 - 60 minutes (sensitivity dependent)
  - F/36 feed, 150” x 75” coverage now, 150” x 150” in the future
  - F/108 feed, 50” x 25” FOV now, 50” x 50” in the future
- Simultaneous observation of
  - Fe I 630 nm, 1565 nm (FIRS), and CaII 854 nm (IBIS)
  - Fe I 630 nm, He I 1083 nm (FIRS), and CaII 854 nm (IBIS)



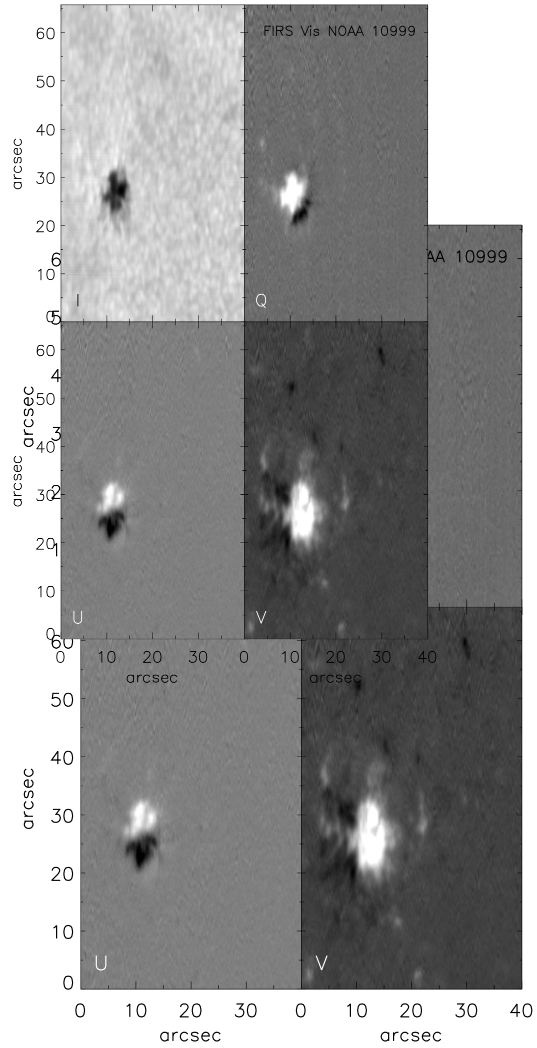
Simultaneous FeI 630 and 1565 nm Observations

- Showing only maps from one slit

Fe I 1565 nm



Fe I 630 nm



Limitations of Multi-Slit Scanning

No speed-up of scan for field smaller than the separation between adjacent slits

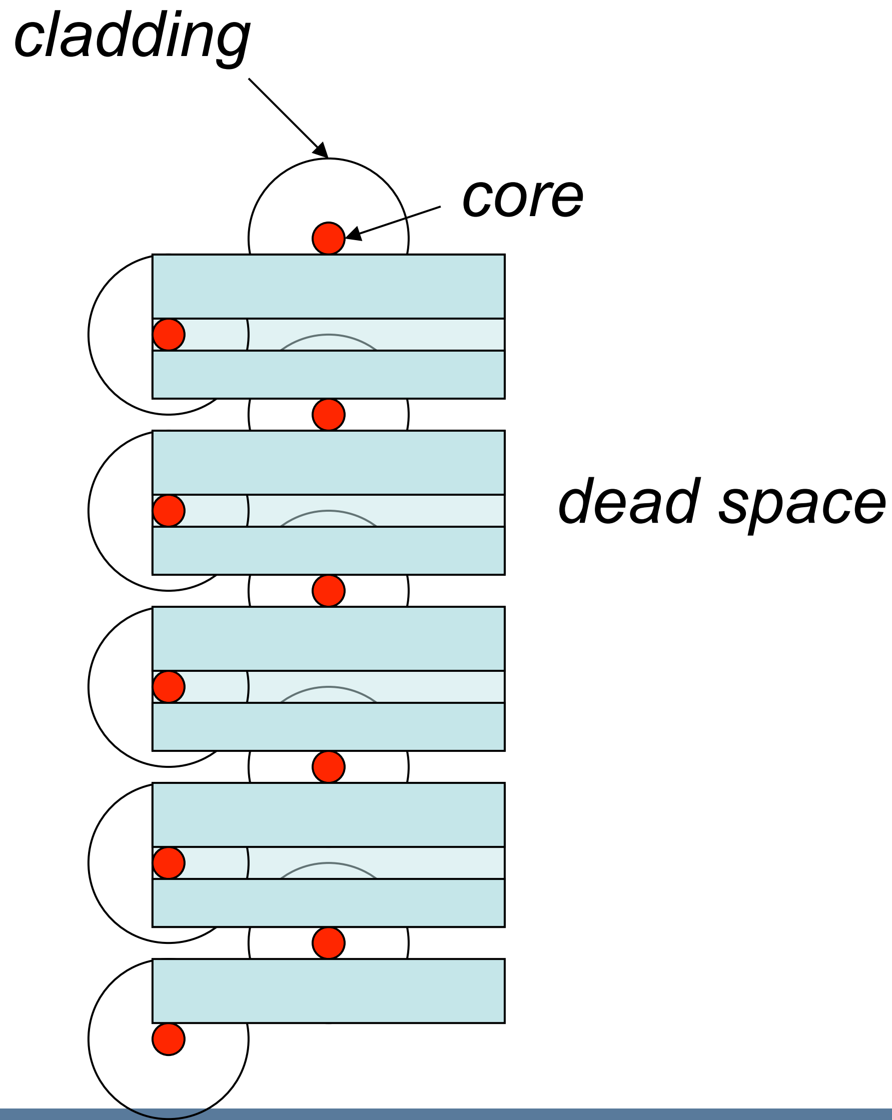
Solutions:

- *Change the plate scale on the slits to scan a smaller FOV with wider slits – e.g. DLSP at Dunn Solar Telescope*
- ***Use True-Imaging Spectropolarimeter***
  - Reflecting Image Slicer – MUSE,
  - Microlens Array – Tiger
  - **Fiber-Optic Integral Field Unit (IFU)** – SOLARC/OFIS, GMOS, VIRUS
    1. *Conventional Optical Fibers*
    2. *Birefringent Rectangular Fiber-Optic Ribbon*

1. Conventional Fiber-Optic IFU

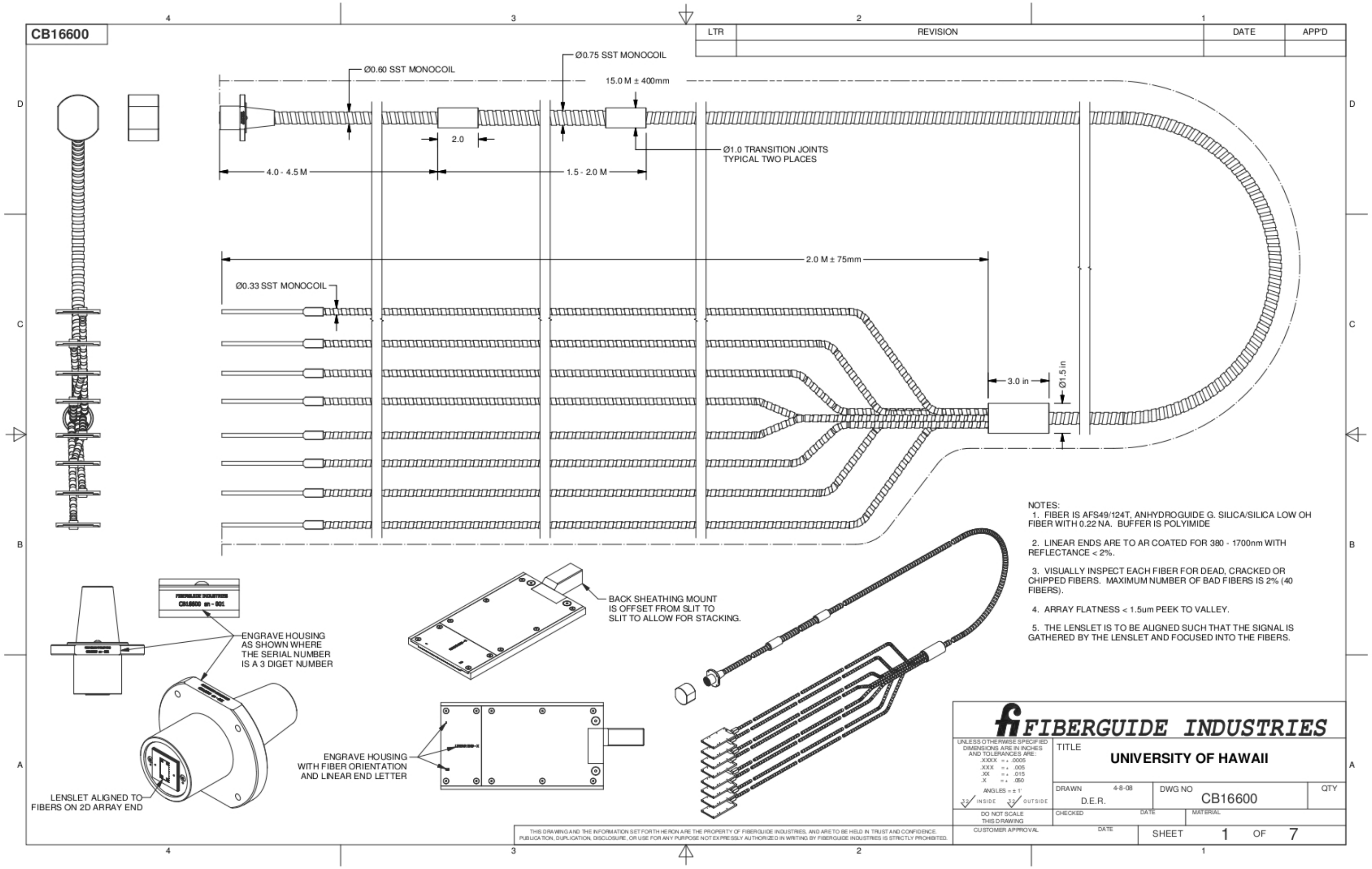
Use standard fused silica low-loss fibers

- The geometry of conventional optical fiber prevents high-density packing necessary for large FOV coverage…
- 50% pixel utilization is possible.



A 64 x 32 – 8 x 256 Coherent Fiber-Optic Array

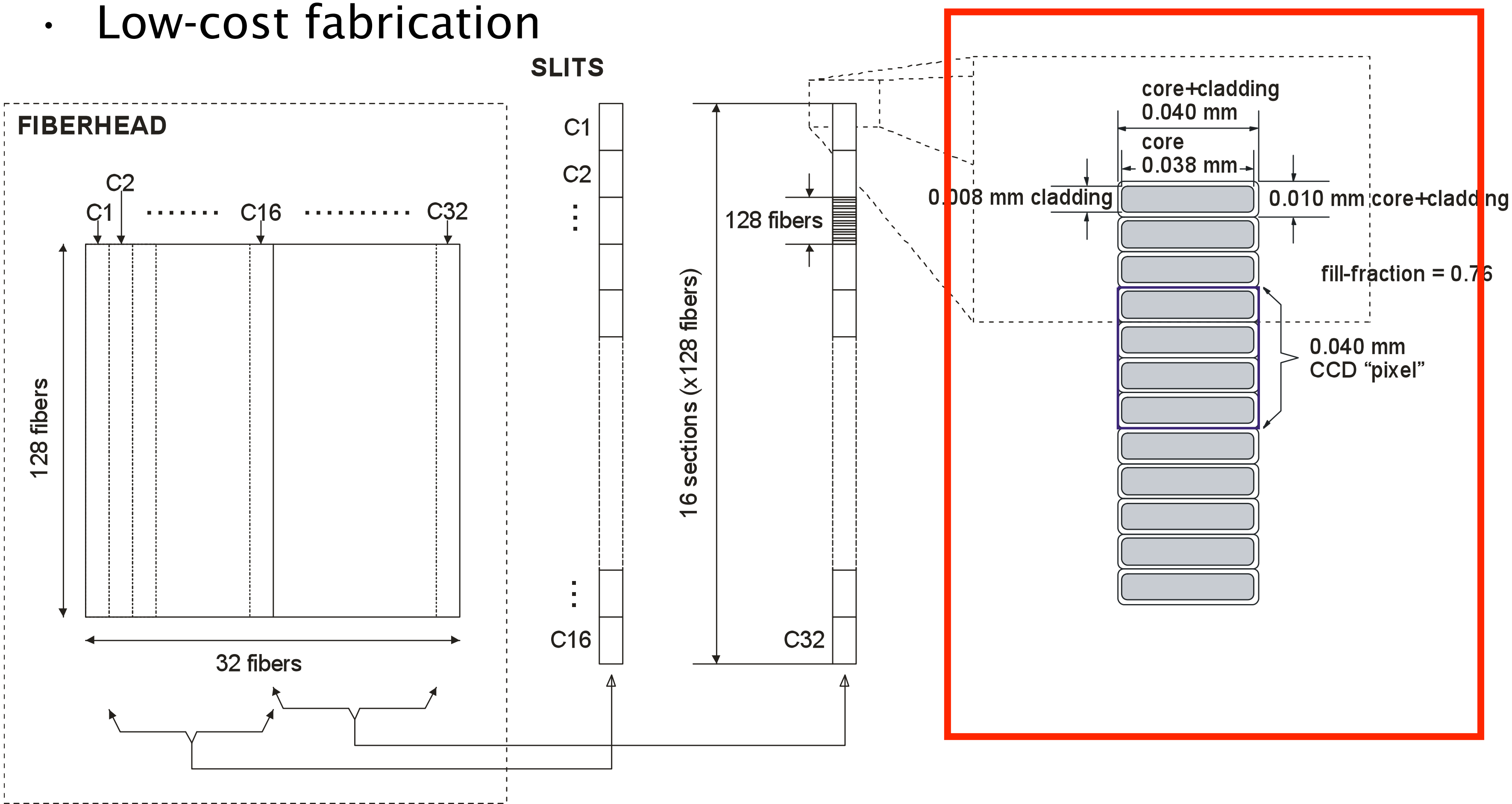
- With new large-format focal plane arrays pushing, it is now possible to build large-format ($10^2 \times 10^2$) true-imaging spectropolarimeters for solar observation



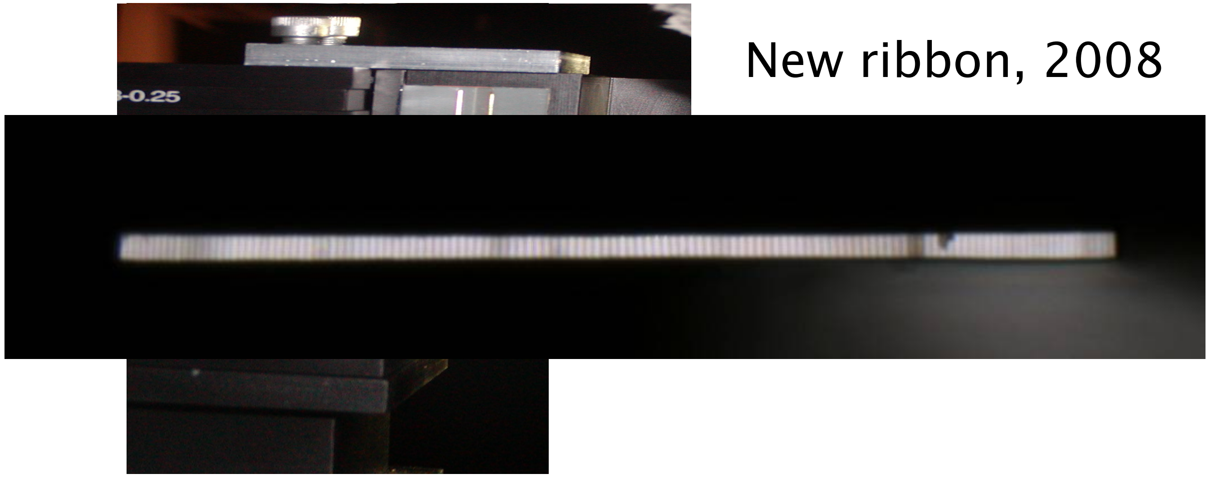
2. Birefringent Fiber-Optic Image Slicer

Fiber-optic ribbon constructed with **rectangular optical fibers**

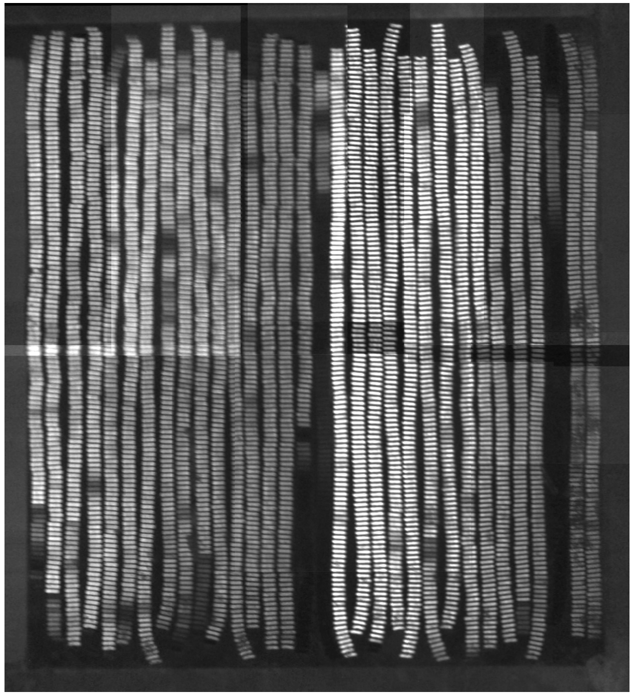
- Linear polarization of the guided waves is preserved – Dual-Beam Polarimetry possible through the fibers
- Low-cost fabrication



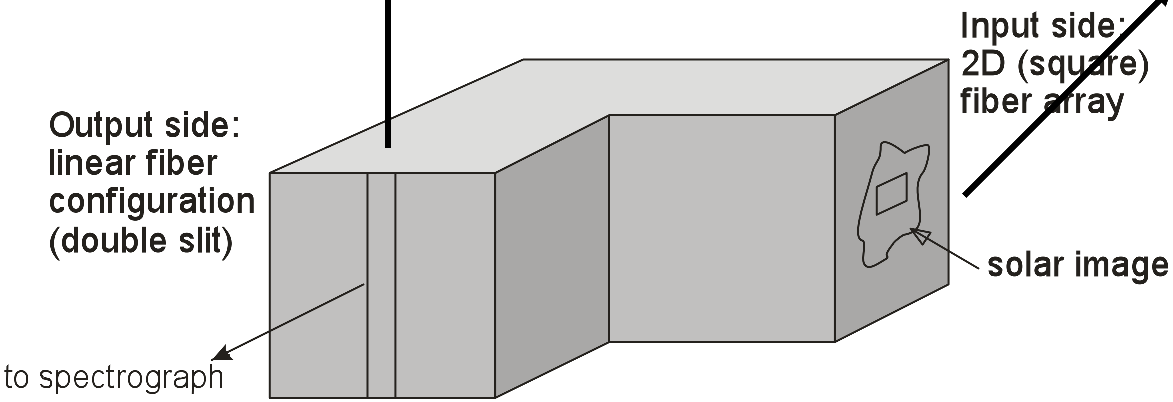
BiFOIS Prototype Input and Output Arrays



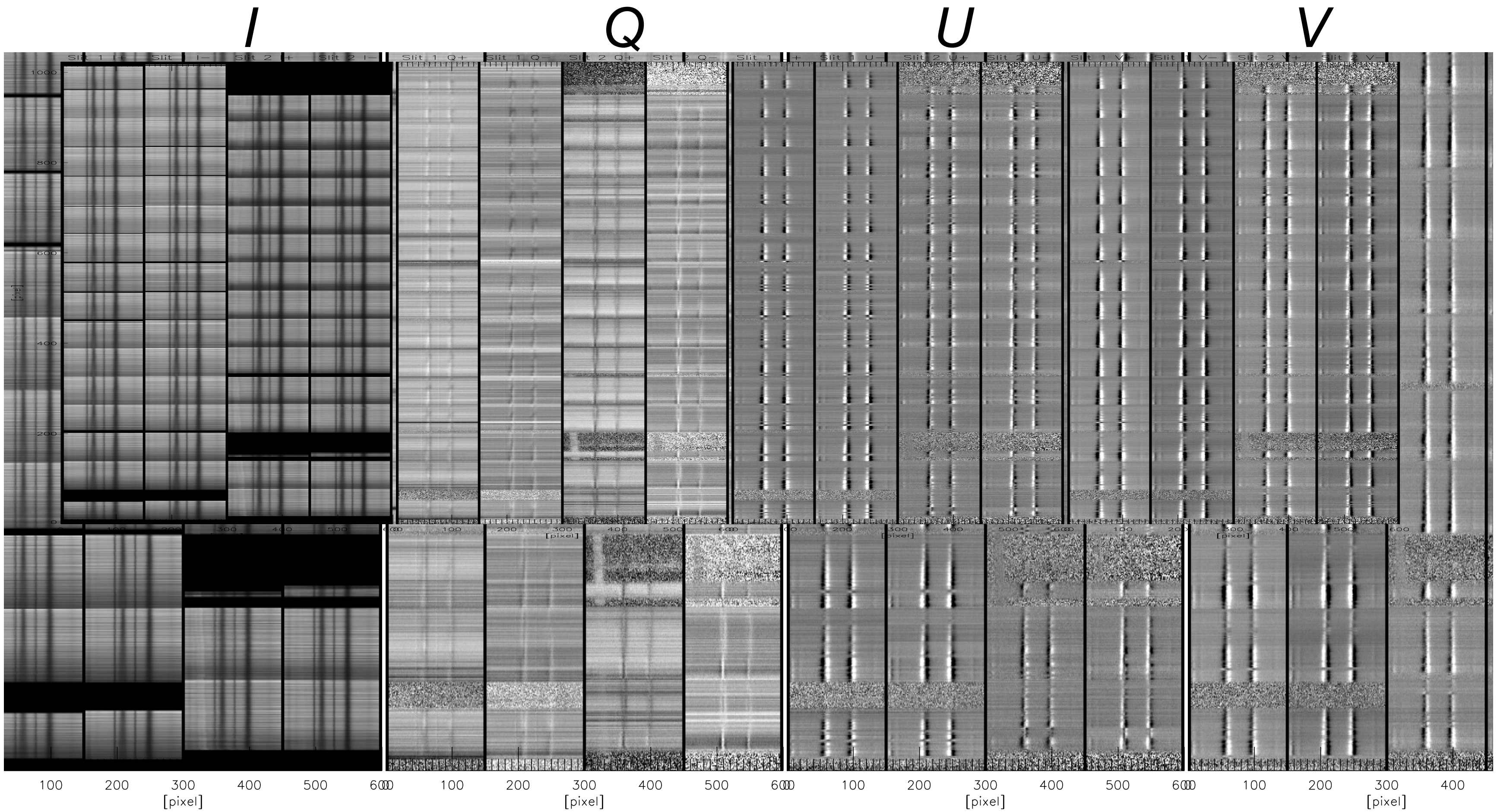
New ribbon, 2008



Output Array:
- 2 x 20.48 mm x 0.04 mm linear array,
- equivalent to two continuous long slits.

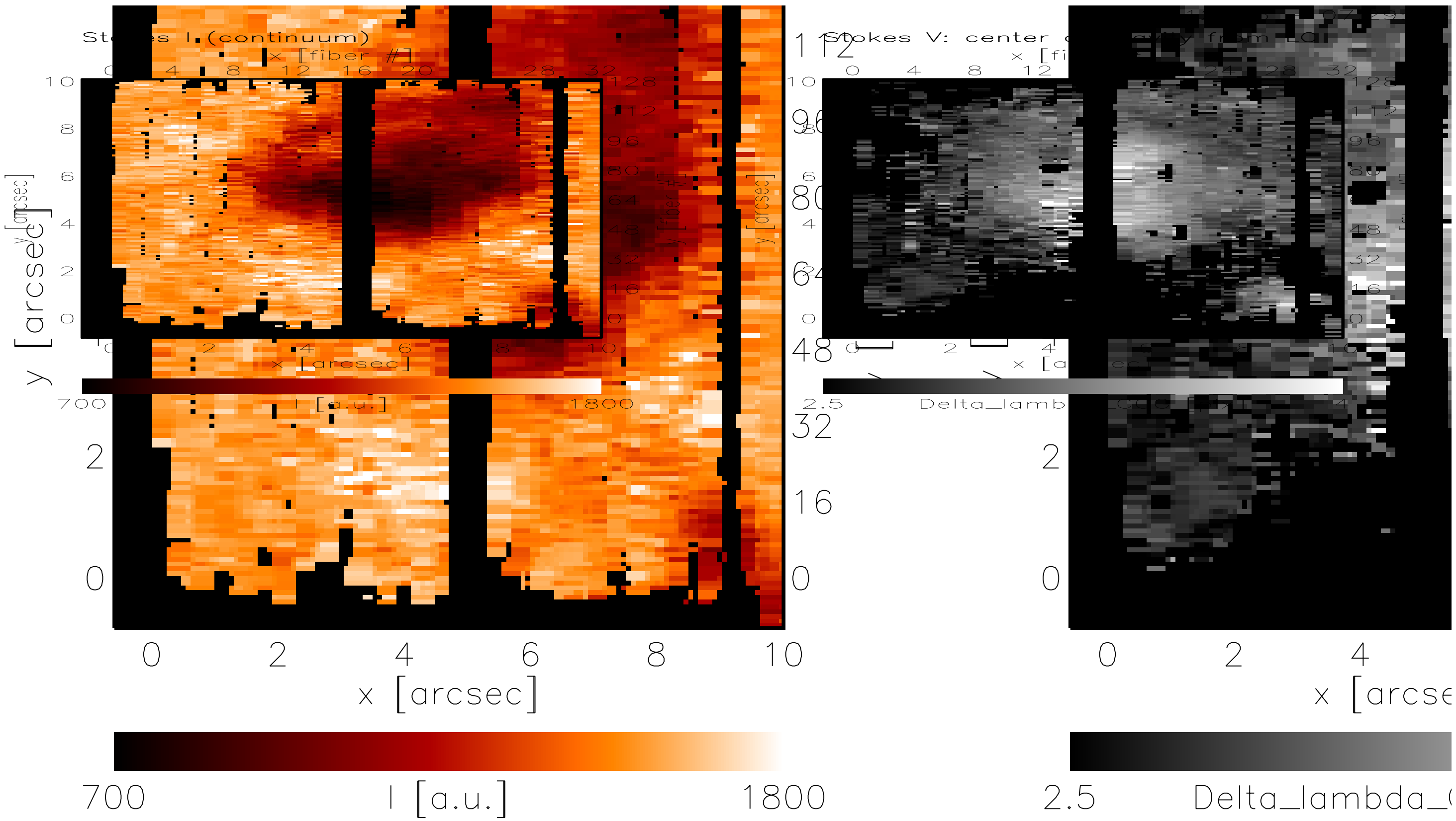


Input Array:
- 32 x 1.280 mm x 0.040 mm ribbons,
- equivalent of 32 x 32 square array with 40 um pixel size.



I
Q
U
V
[pixel]

IRIS Prototype Time Sequence



- 10” x 10” FOV
- 0.3”/pixel spatial sampling with low-order AO
- 10 second time resolution
- 15 minutes

High-Throughput Imaging Spectropolarimeters

- **Fast-scanning multi-slit spectropolarimeter can greatly enhance the temporal resolution of large-area scan**
  - Active region size scan for ~ 10 minutes
- **True-imaging spectropolarimeter can observe a modest field of view with very high temporal resolution**
  - ~10” x 10” with less than 10 sec cadence on solar disk
  - Spectropolarimetry for the solar corona

Both Fast-Scanning and Fiber-Optic Feed Can be Accommodated by a Single Spectrograph.

True-Imaging Multi-Spectral-Line Spectropolarimetry

What can we do with a true-imaging spectropolarimeter that covers a substantial FOV with diffraction-limited performance, and four or five spectral lines simultaneously ?

- Dynamics of the chromosphere
- Small-scale dynamo
- Jets
- Reconnection
- Penumbra filaments
- Dynamics of the filaments
- ???

*Direct observation of coronal **B** is highly relevant to the Science Mission of Solar-C.*

- Coronal magnetic field can be reliably measured
- Coronal ***B*** observations do provide useful information about the solar corona
    - Quantitative observational test of models possible
    - …
    - …
- Space is a very good place for coronal B observations
- Efficient, high-throughput spectropolarimeter design meeting the requirement of Solar-C science mission exists