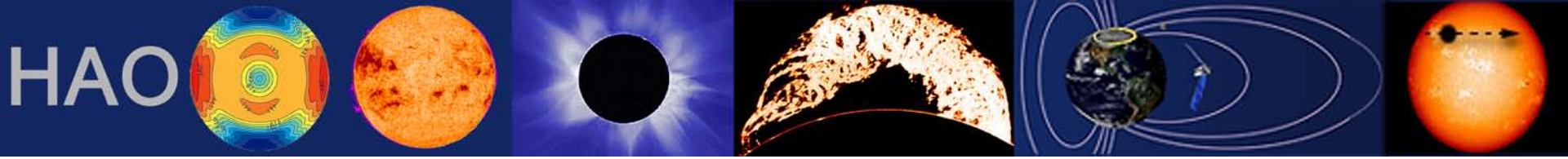


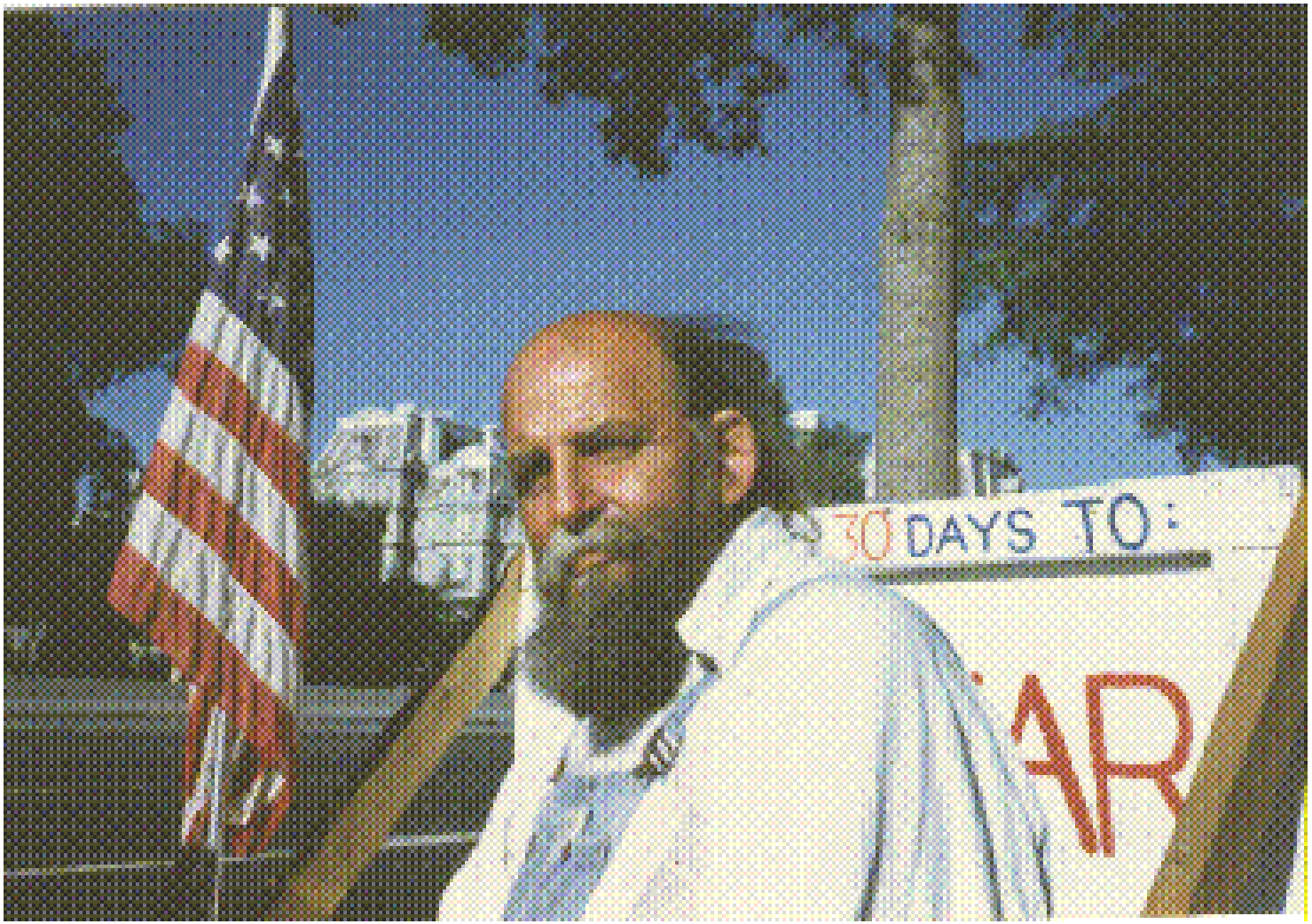
Spectro-Polarimetry at Sac Peak: A Personal Retrospective and Reminiscence

Bruce W. Lites
High Altitude Observatory
National Center for Atmospheric Research

"Last" Sac Peak Workshop
August, 2017

Dr. Jack Evans (1909 – 1999)
Dr. Harlow Shapley

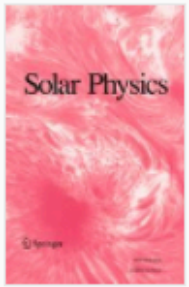
Charles Hyder (1930 – 2004)



First Group Sac Peak Summer Students: 1969
(Woodstock, 1st Moon Landing)

- **Doug Brown**
- **Doug Hoyt**
- **Bruce Lites**
- **Francoise Magnant**
- **Dan McNamara**
- **Molly Woodruff**

Images from slides of peak from tower, me on bike,
Dick Dunn on sailboat



Solar Physics

September 1970, Volume 14, Issue 1, pp 147–156

Hα Doppler brightening and Lyman-α Doppler dimming in moving Hα prominences

Authors | Authors and affiliations

Charles L. Hyder, Bruce W. Lites

Article

Received: 11 February 1970

DOI: 10.1007/BF00240170

Cite this article as:
Hyder, C.L. & Lites, B.W. Sol Phys (1970) 14: 147. doi:10.1007/BF00240170

Lites & Hyder 1970, Sol Phys **14**, 147

Primary use of Spectro-Polarimetry: Solar Magnetic Fields

Early Spectro-Polarimetry at Sac Peak: KELP, Stokes I & II

K Emission Line Polarimeter (KELP)

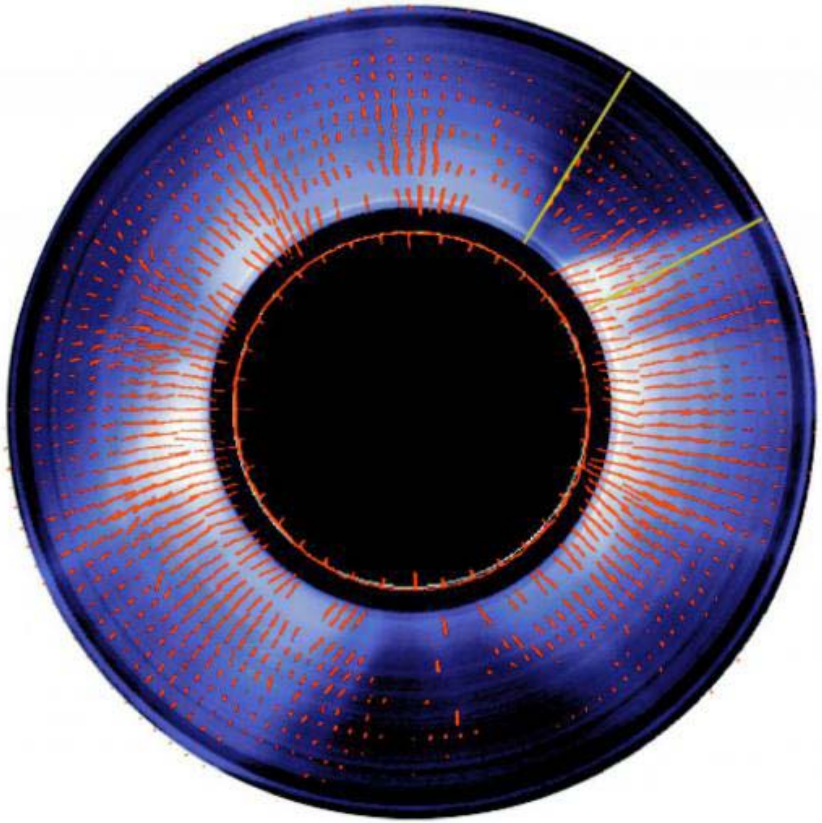
- 1974 – 198??
- Orientation of coronal polarization -> field orientation

Stokes I

- 1975? – 1979
- Single-aperture measurement
- Dual-beam, rapid modulation
- Wavelength-scanning

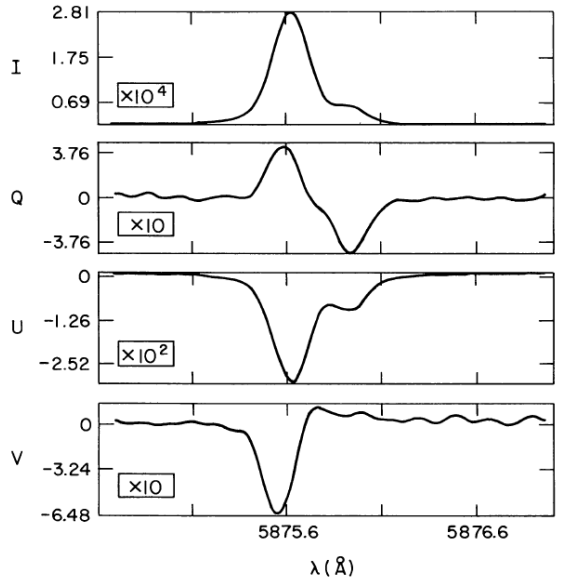
Stokes II

- 1979 – 1980
- Single-aperture measurement
- Dual-beam, rapid modulation
- Linear diode array: simultaneous spectral coverage at one spatial position

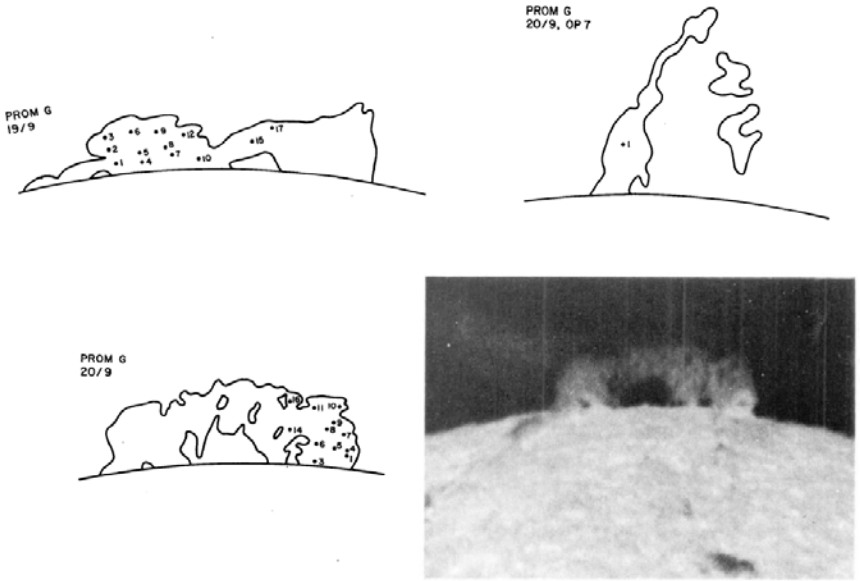


Full Stokes Spectro-Polarimetry with Stokes I

1. **House & Smart 1982 – first systematic full-Stokes spectro-polarimetric observations of He I D_3 multiplet in prominences**



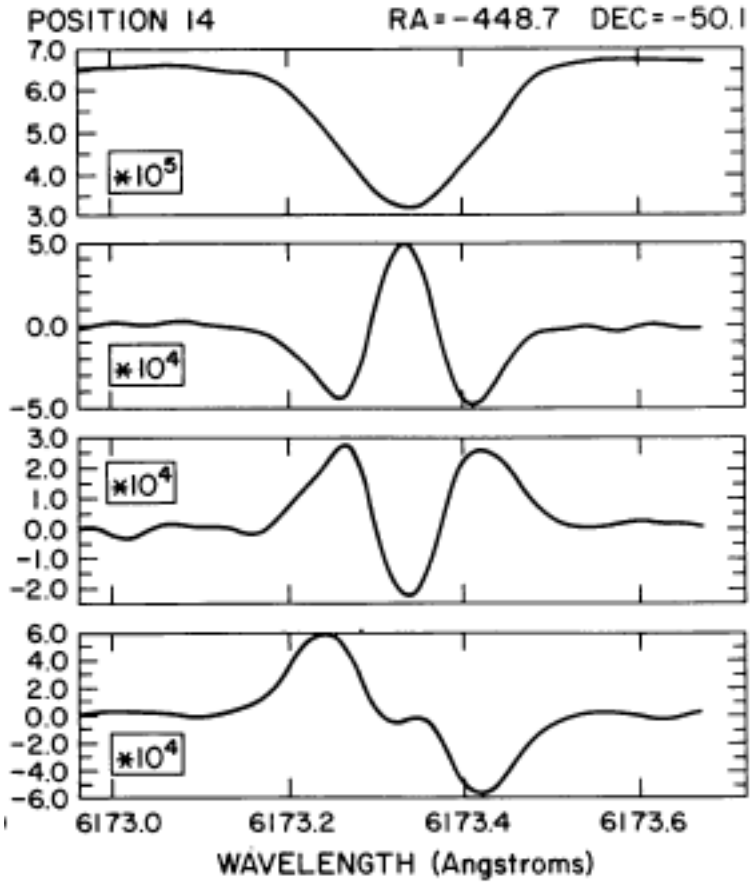
Landi degl'Innocenti 1982, fig. 1

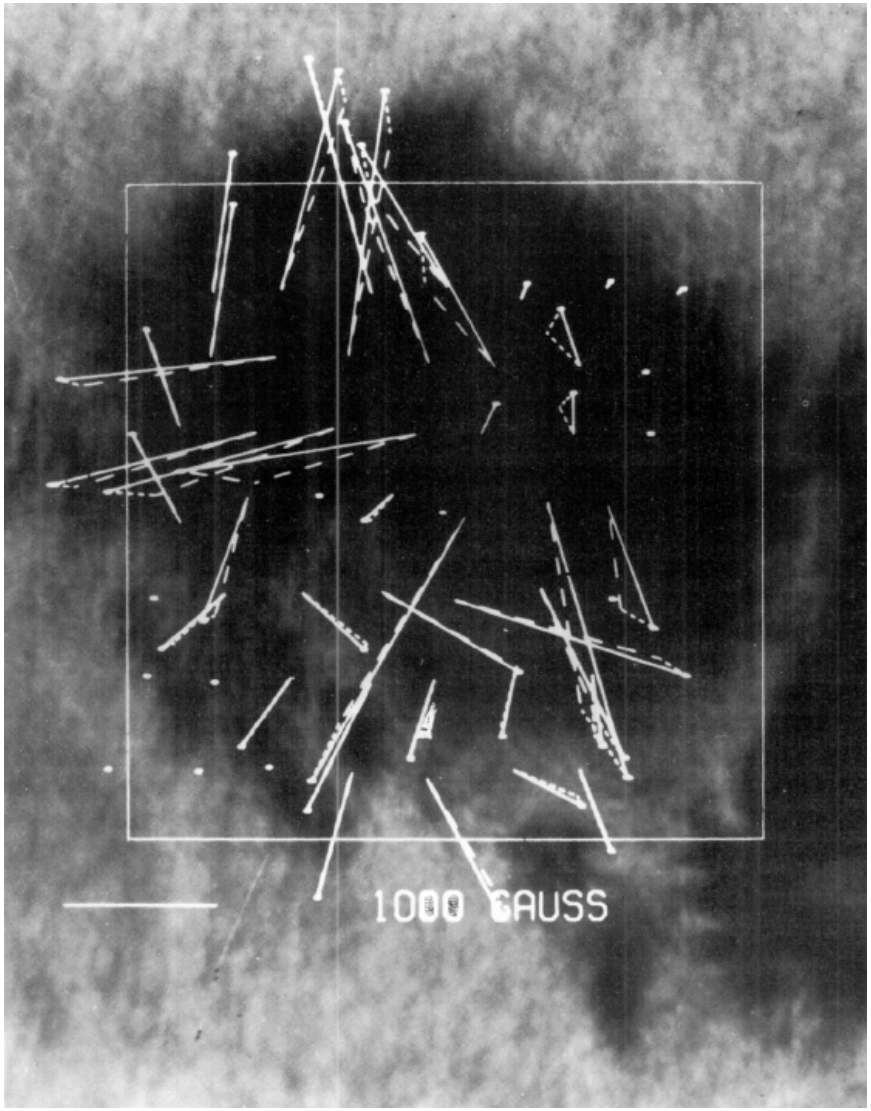


Athay et al. 1983, fig. 2

1. **Landi degl'Innocenti 1982**
   - **Density matrix quantum treatment**
   - **Derive Hanle effect on Stokes *V* in addition to *Q, U***
   - **Gaussian fits to profiles**
   - **Inversion code developed for *Q/I, U/I* only, *V* used as consistency check**
2. **Athay et al. 1983, Querfeld et al. 1985**
   - **Used analysis of Landi degl'Innocenti (1982) and Bommier et al. (1981)**
   - **Found horizontal fields**
   - **Ambiguity – difficulty in determining if inverse or normal polarity fields**

HAO Stokes I Observations of a Sunspot

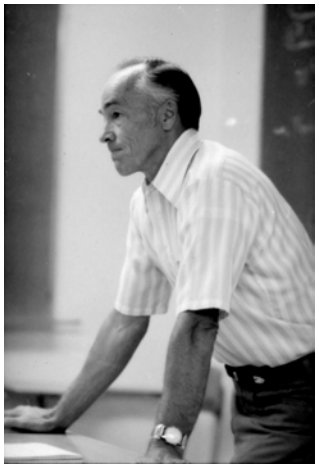





Jack Thomas
Bruce Lites
FALLOUT

My mid-80's Entry into Spectro-Polarimetry:

- **The analysis procedures were either too simplistic, or in the case of "inversions" the results were not stable**



- **R. Grant Athay (had been my thesis advisor) suggested in the early 1980s that I attempt to include magneto-optical effects (Faraday rotation) into the "inversion" procedure of Auer, Heasley, and House (1977)**

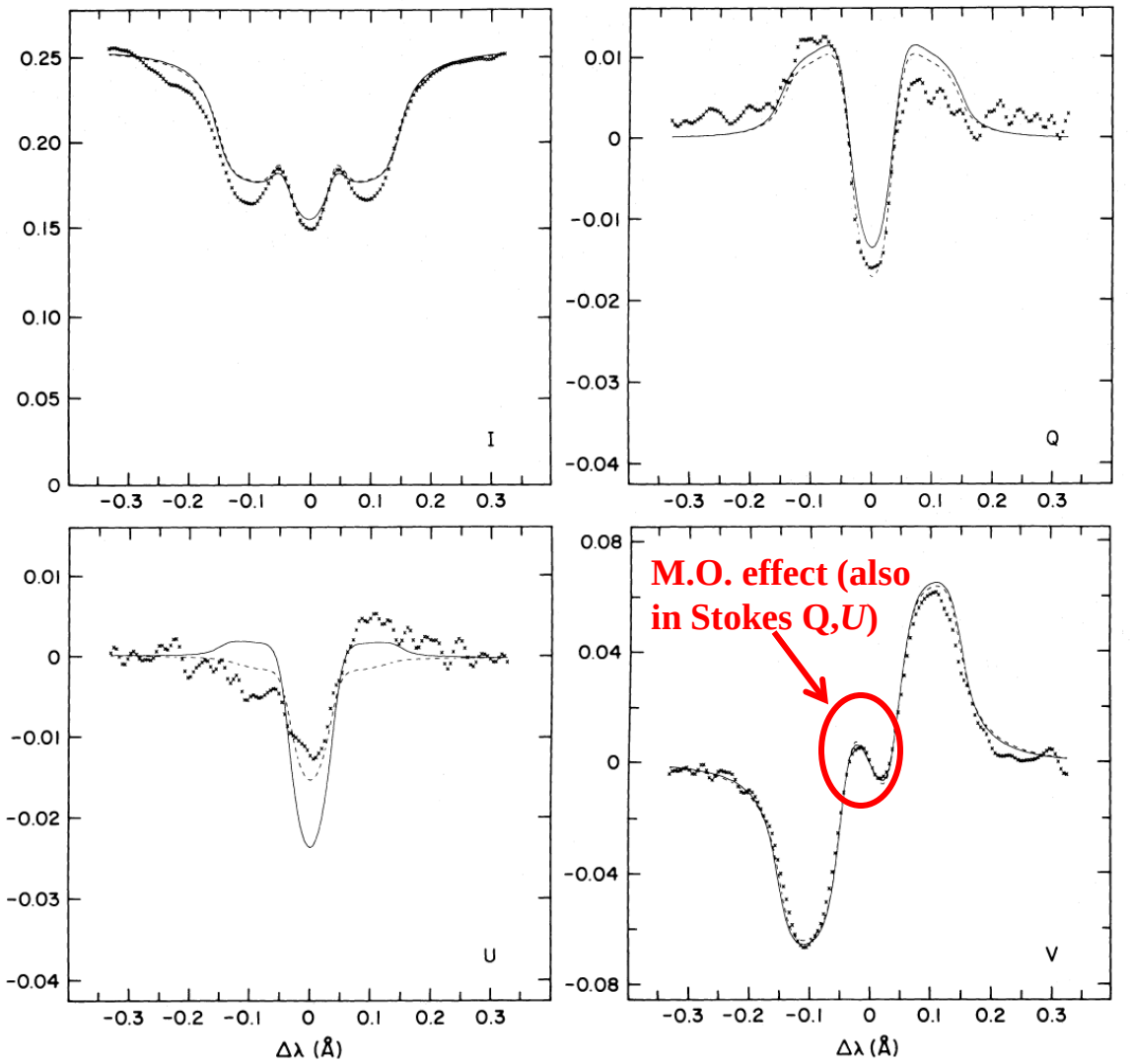
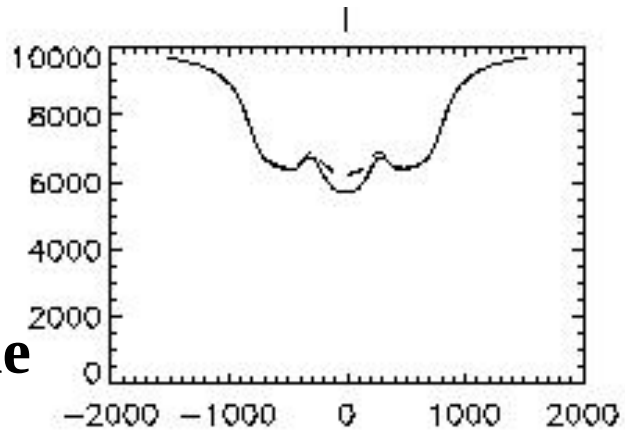


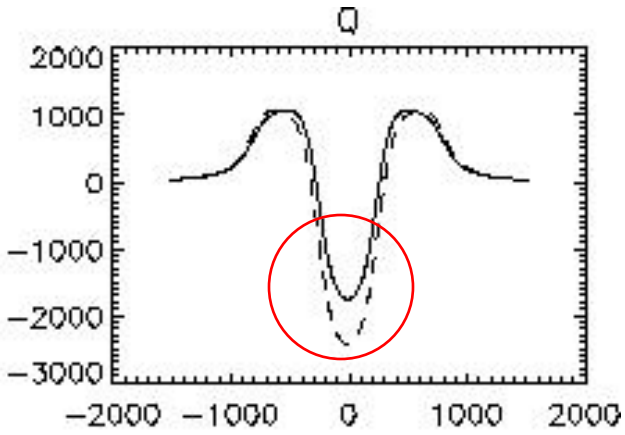
FIG. 3.—Comparison of Fe I λ6173 observations (*crosses*) and the theoretical fit with MO and (μB_1, a, χ) with ($a = 0.2$, $\chi = 7.04$) (row 5 of Table 1, *solid lines*) and with (a, χ) free (row 6 of Table 1, *dashed lines*). See Fig. 1 for additional details.

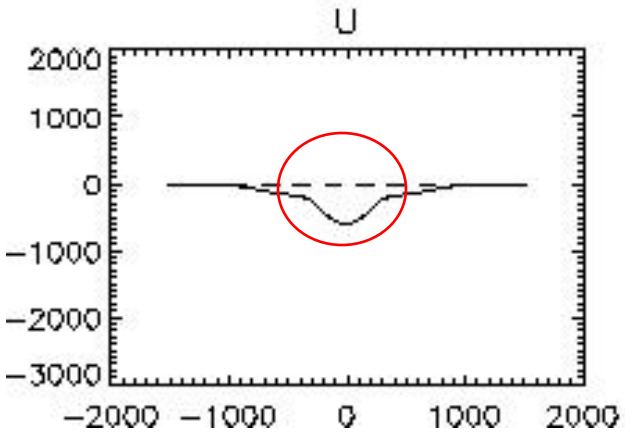
Skumanich & Lites 1987, ApJ **322**, 473

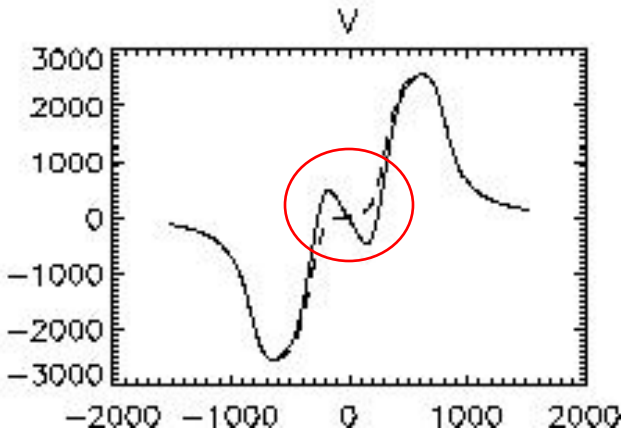
Theoretical Profiles with and without Magneto-Optical Effect

Magneto-optical effect (Faraday Rotation) is proportional to the optical depth



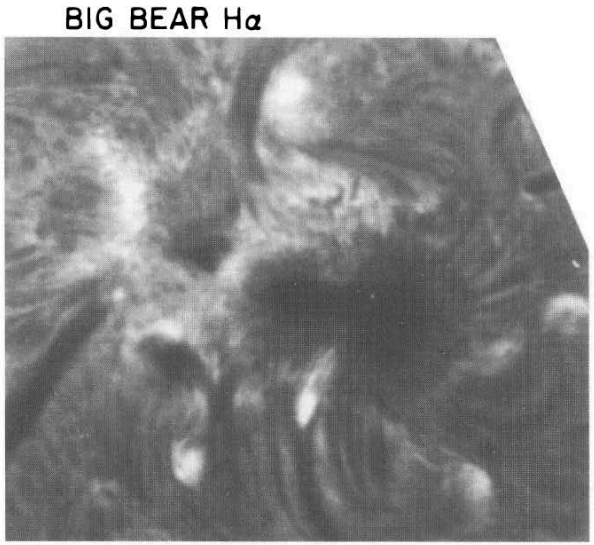






Inversion code applied to Stokes II observations of large sunspots

- **Addition of magneto-optical effect, and other improvements, resulted in an "inversion" procedure that finally yielded believable values for the magnetic field vector for Stokes II data**



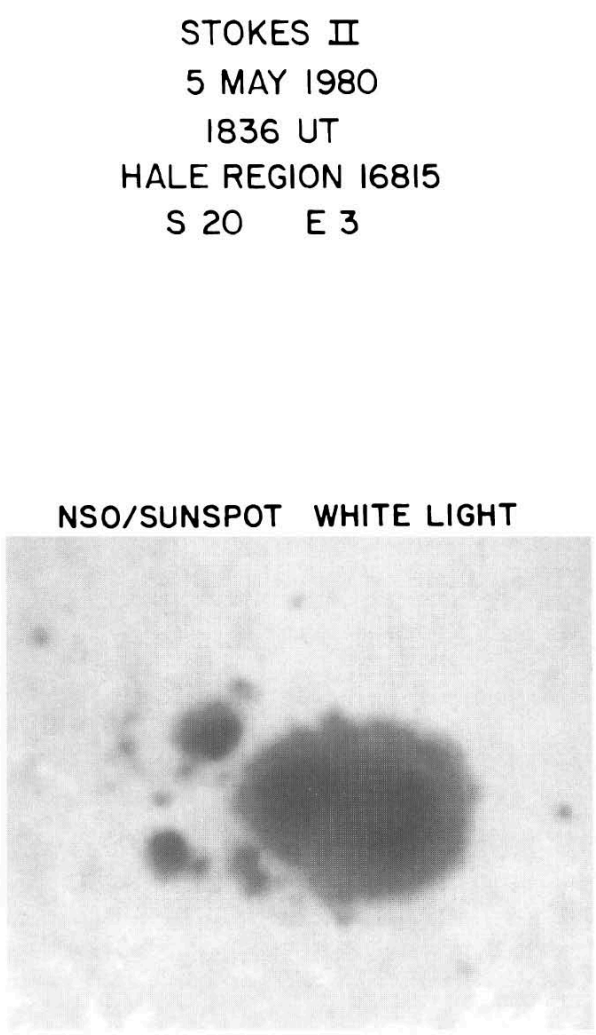


FIG. 3.—Same as Fig. 2, but for 1980 May 5 active region

LITES AND SKUMANICH (*see* **348**, 751)

Lites & Skumanich 1990, ApJ **348**, 747

Toward Comprehensive Sensing of the Magnetic Field:

- **The Advanced Stokes Polarimeter (1991 – 2007?)**

The Stokes Consortium:

A “Stokes Consortium” was formed of interested parties, including:

- **HAO**
- **National Solar Observatory (NSO)**
- **University of Hawaii**
- **University of Sydney (Australia)**
- **Astrophysical Observatory of Arcetri (Italy)**

Deliberations began on how to build the instrument:

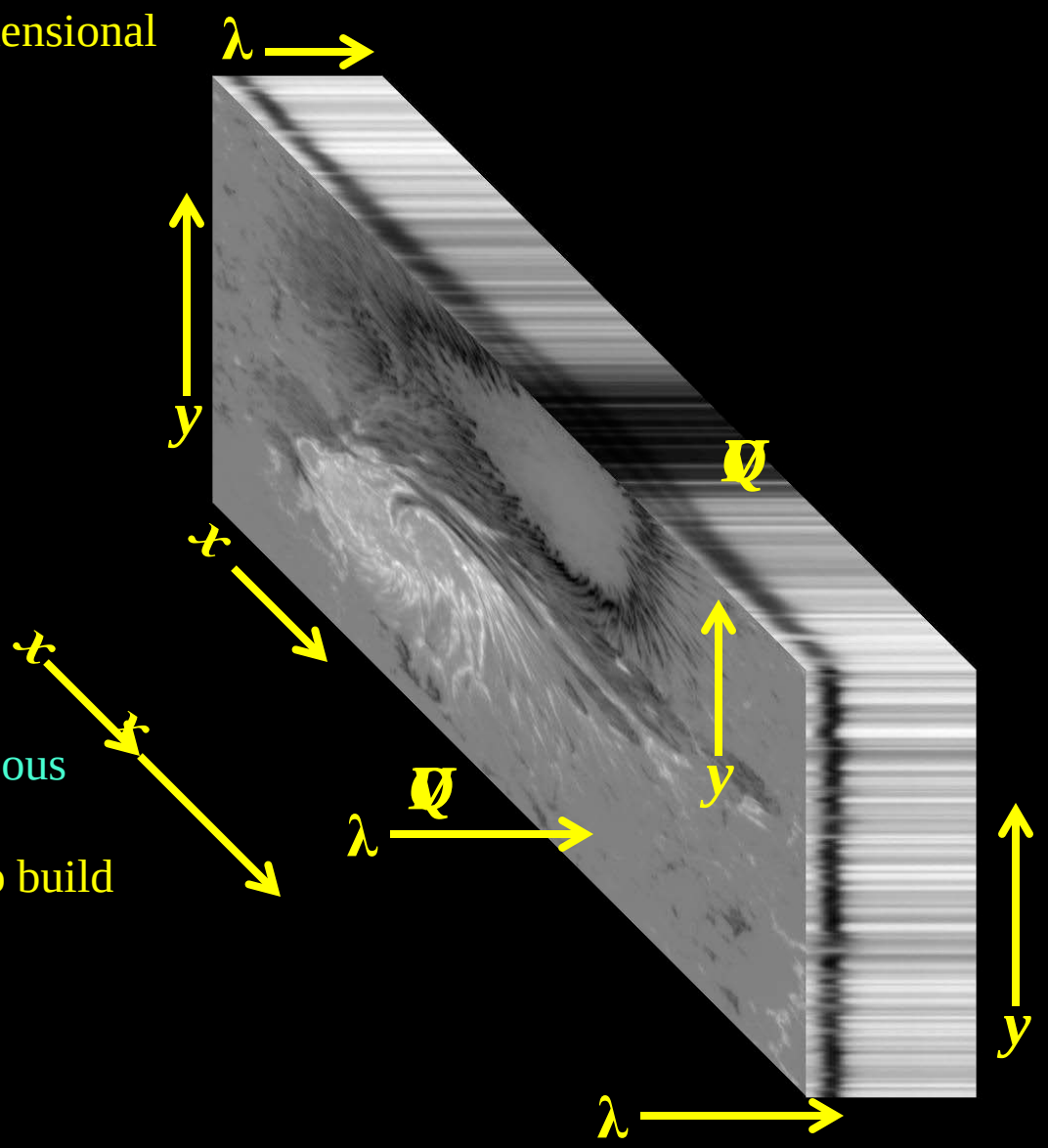
- **Would an existing facility be used, or would a new facility be built?**
- **Would wavelength discrimination be accomplished by a filtergraphic or spectrographic means?**
- **What would be the focus science targets (active regions, scattering polarization, ….)?**

5-Dimensional Data Hyper Cube [*x, y, λ, Polarization, time*]

- Polarization usually multiplexed in time: reduces the cube to 3 dimensions [*x,y,λ*]
- Limited by detectors that are 2-dimensional

- Spectrographic observations: simultaneous imaging of [*y, λ*]
- Spectrograph slit steps temporally across the solar image in the *x*-direction

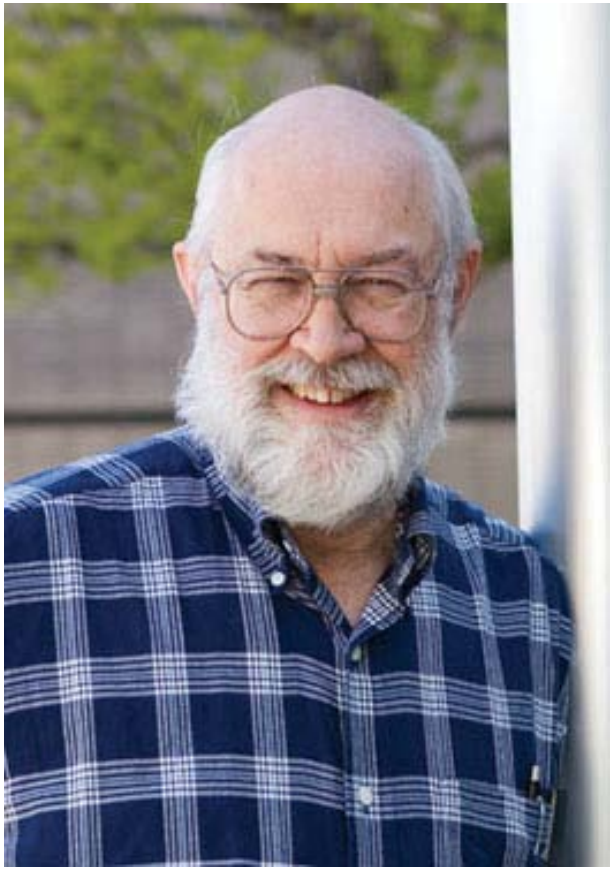
- Filtergraph observations: simultaneous imaging of [x, *y*]
- Filter tunes in λ at separate times to build up cube



A New Instrument for Solar Spectro-Polarimetry

The Stokes Consortium deliberated possible instrument configurations

- **Imaging instruments were in favor**
- **Recognized that only a spectrographic instrument yielded uncompromised Stokes profiles**
- **A new facility of the scale needed was beyond the possibility of funding**
- **HAO/NSO committed to hardware development**
- **Decision to focus on solar active region science**
- **Instrumentation deployed at the Sac Peak Vacuum Tower Telescope (later the Dunn Solar Telescope)**
- **In the end, Peter Gilman, then director of HAO, made some hard choices to fully fund the ADVANCED STOKES POLARIMETER (ASP) at HAO**



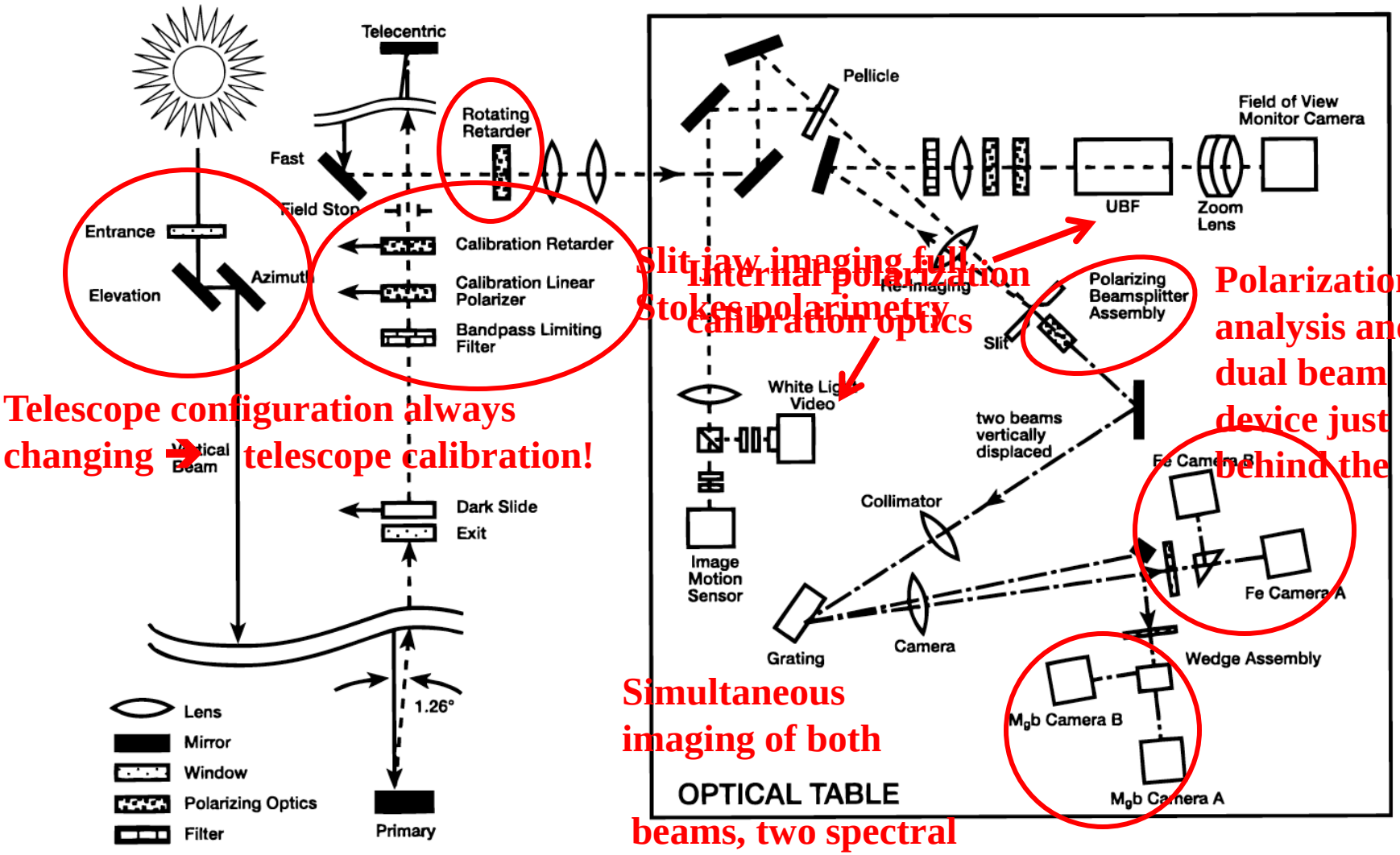
Peter Gilman

The Advanced Stokes Polarimeter (ASP)

- First instrument that combined the following attributes:
  - Simultaneous, spectrally-resolved *I*, *Q*, *U*, *V* profiles
  - Spectral imaging with 2-D detectors
  - High frame rate (at least for that era: late 1980's): 60 Hz
  - Dual-beam polarimetry
  - Image-frame demodulation
  - High resolution capability at a large solar telescope (DST at Sac Peak, NSO)
  - Rapid image motion compensation ("tip-tilt mirror")

Dunn Solar Telescope (DST), National Solar Observatory, Sunspot, NM USA

The Advanced Stokes Polarimeter



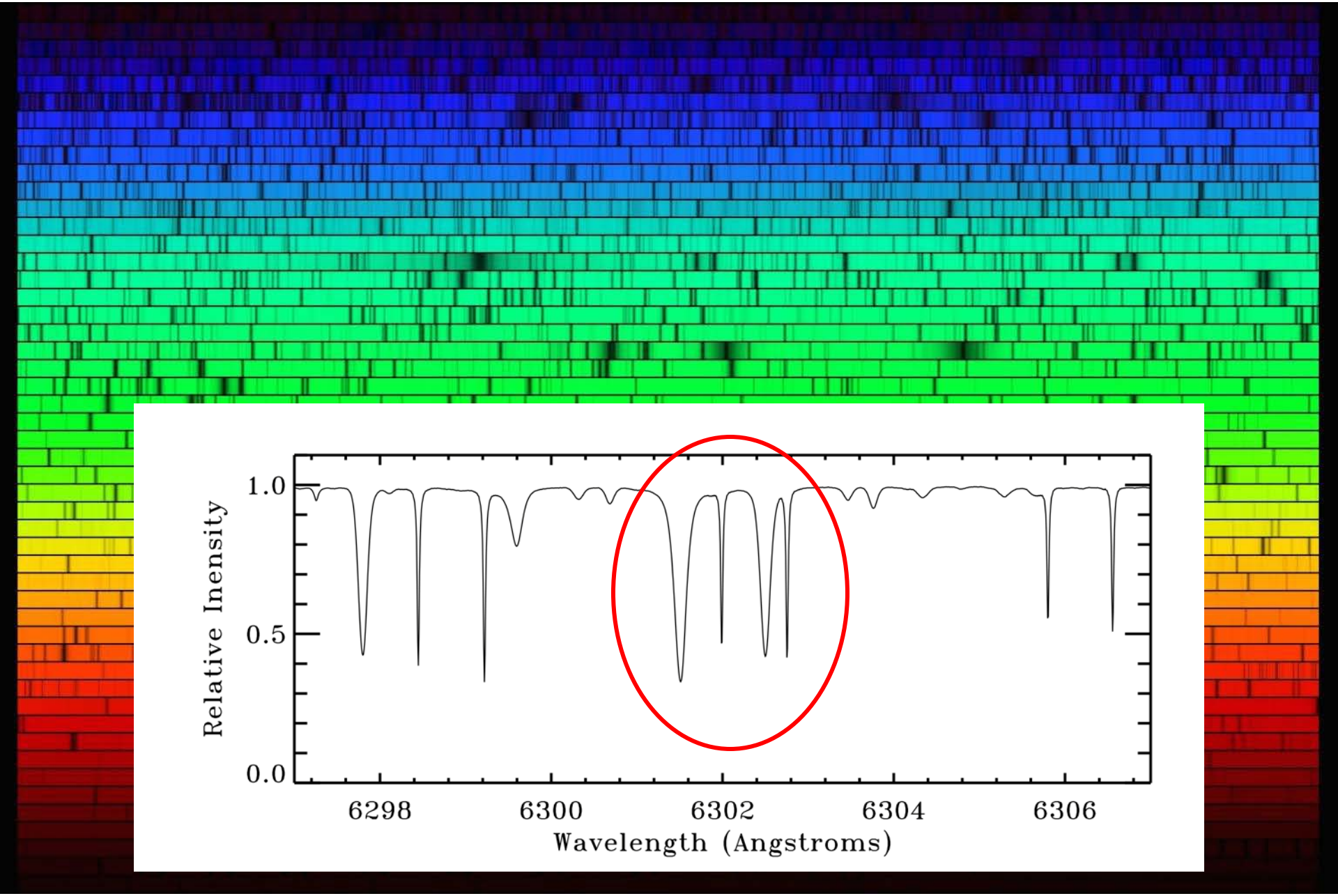
Slit jaw imaging full Stokes polarimetry

Internal polarization calibration optics

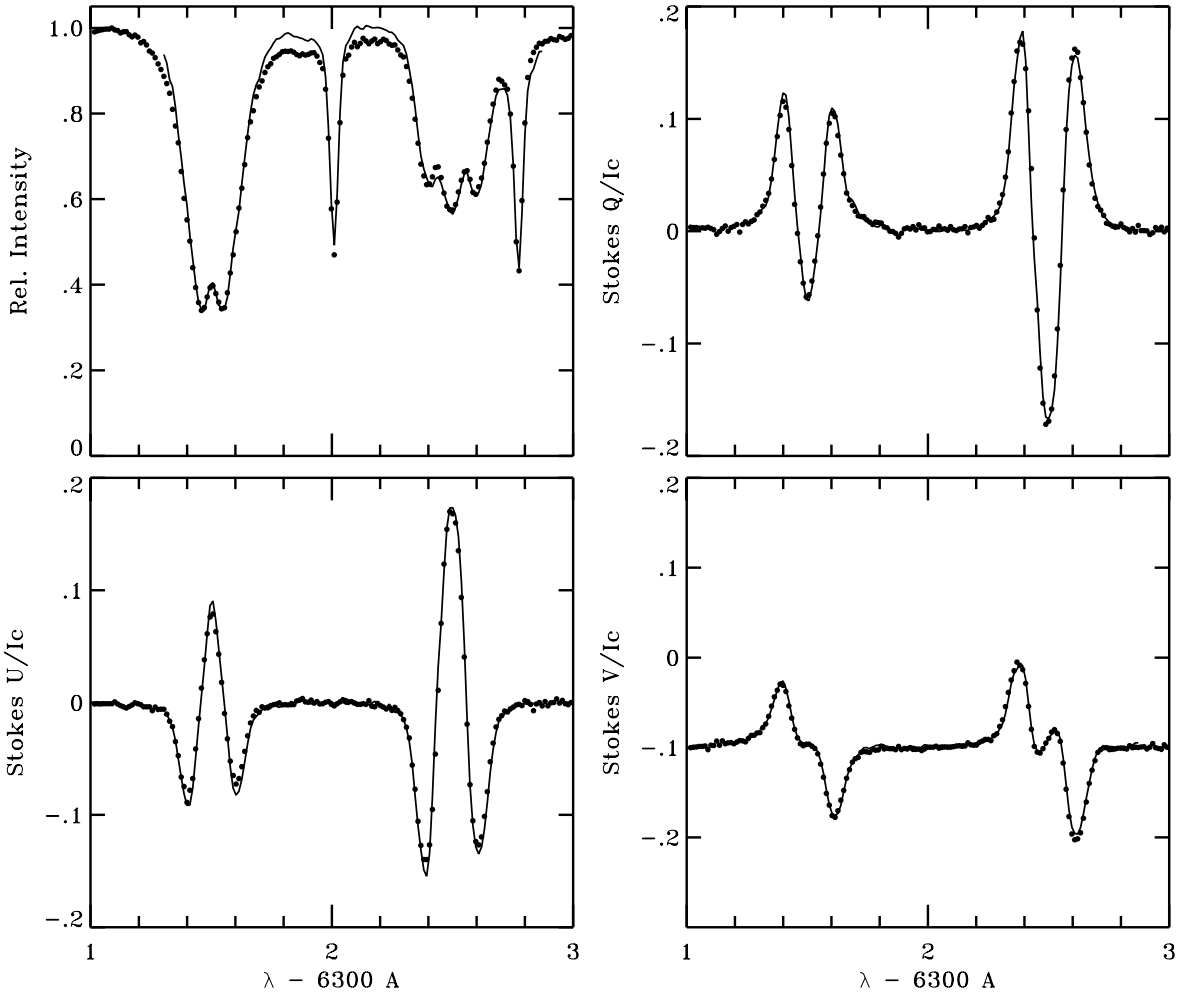
Polarization analysis and dual beam device just behind the slit

Telescope configuration always changing → telescope calibration!

Simultaneous imaging of both beams, two spectral regions


Relative Inensity
1.0
0.5
0.0
6298
6300
6302
6304
6306
Wavelength (Angstroms)

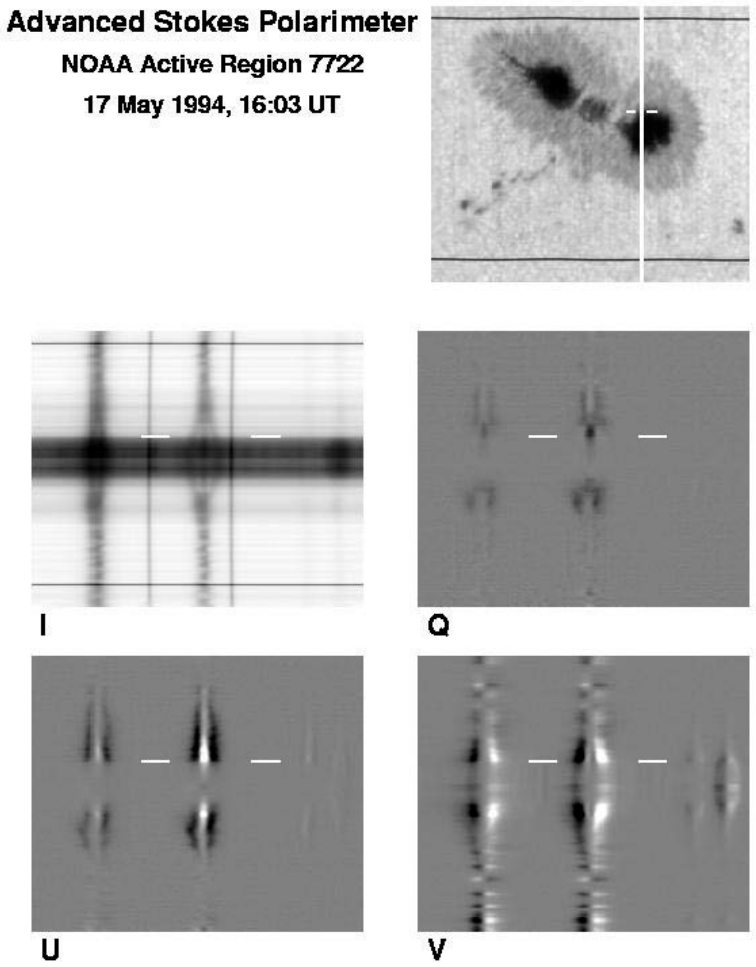
Details of *shapes* of spectral profiles in polarization contain information on the *strength and orientation* of the magnetic field vector in the solar atmosphere – *SPECTRO-POLARIMETRY*:

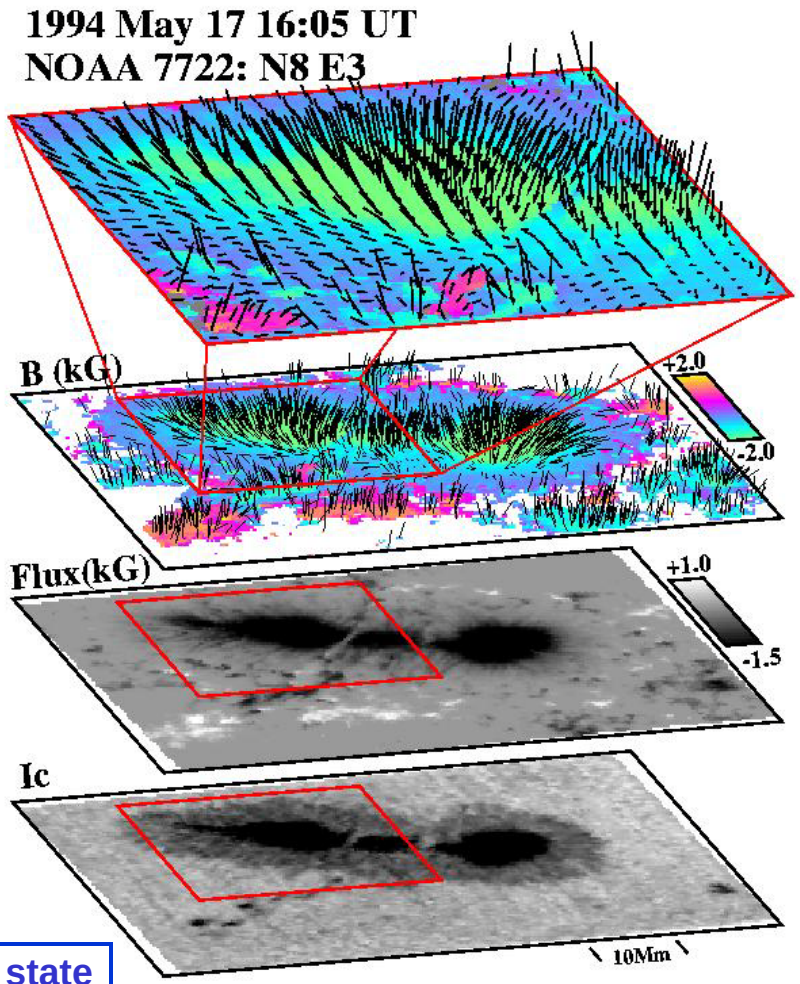


Polarization Measurements

Zeeman Effect

Inferred Vector Magnetic Field

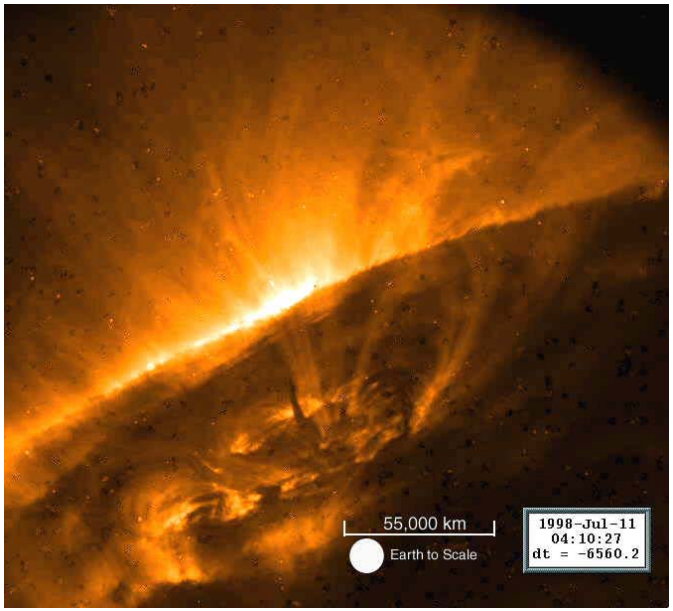




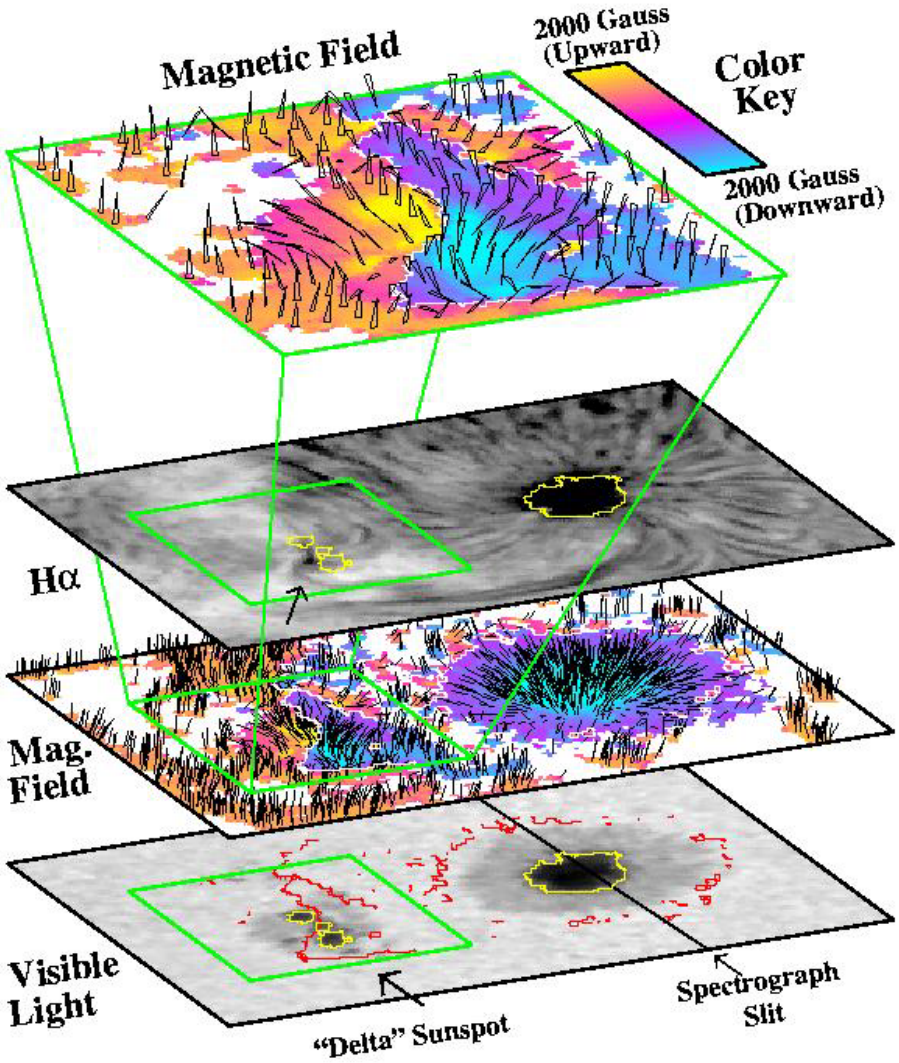
The Stokes 4-vector $\{I, Q, U, V\}^T$ describes the complete state of polarization of light

ASP Science Example: Observed signatures of emerging flux ropes in the solar photosphere

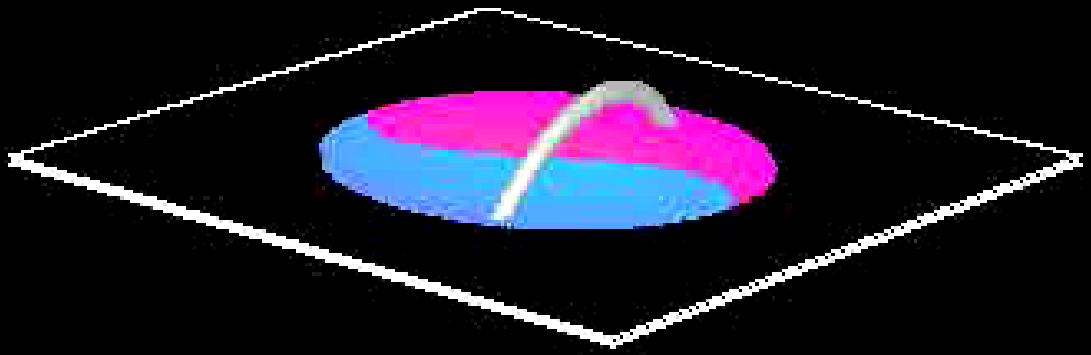
Most coronal mass ejections are associated with erupting flux ropes



Photospheric vector magnetic fields suggest a rising, closed toroidal flux system

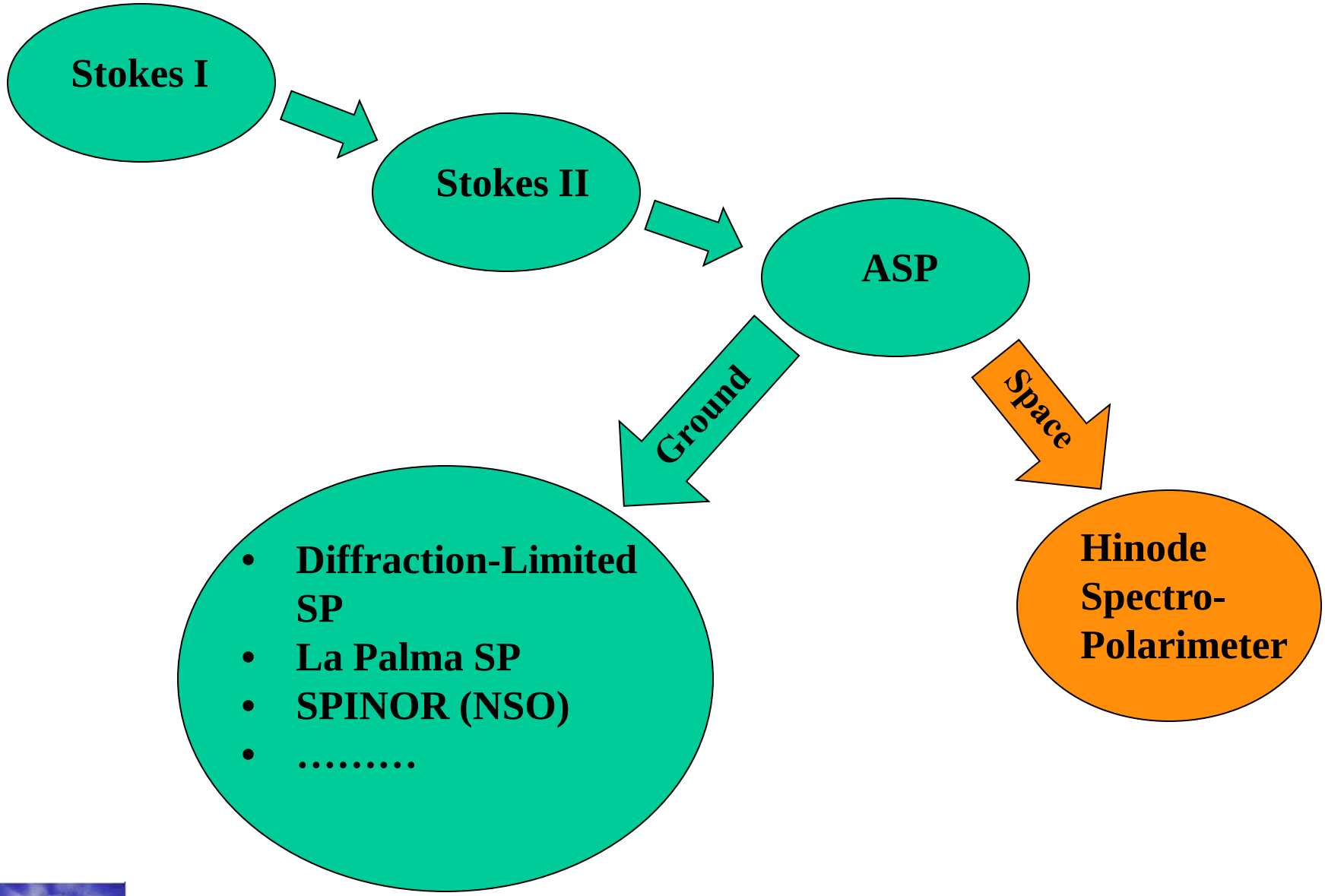


Animation of emergence of a theoretical closed flux system of toroidal topology



Theoretical Model:
BC Low

Sac Peak Heritage of Modern Spectro-Polarimetry



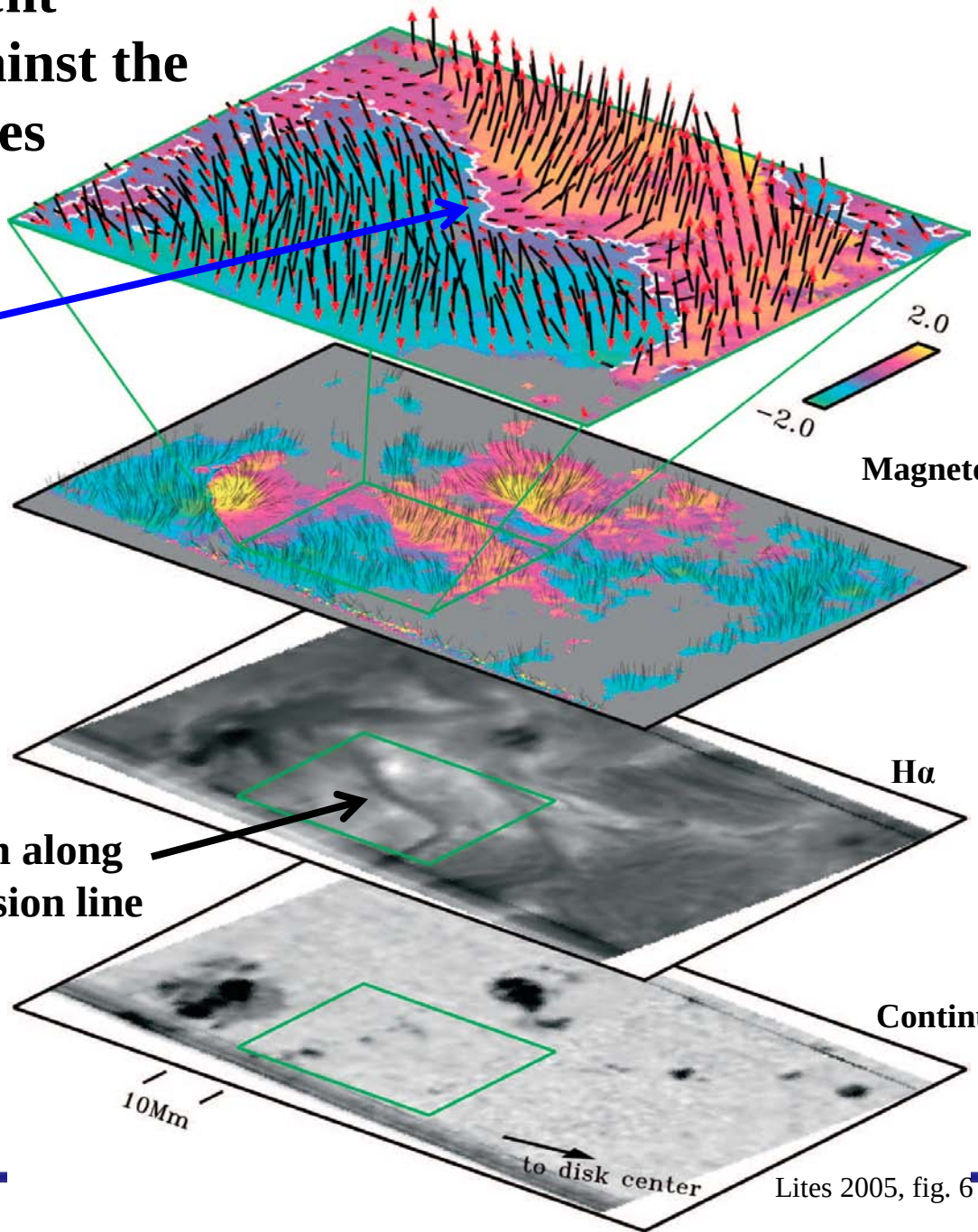

M
20
M
OS

My Sac Peak History

1961 or 1962: Visit from Charlie Hyder at my home in Albuquerque
Spring 1963: Day visit to Sac Peak, hosted by Jack Evans
Summer 1969: Among first group of Sac Peak Summer Students
1977-8: Visiting Observer: measurements of oscillatory phase delays, MDA
1980-1984: Staff at Sac Peak
1983-1984: My initial foray into Spectro-Polarimetry
1985-1987: Visiting observer, sunspot dynamics with MDA?
1986?-1991: Development of Advanced Stokes Polarimeter, deployed in late 1991
1990's: Many observing runs with ASP
Feb 2000: Concept Model Solar-B Spectro-Polarimeter, verify the design and compare head-to-head with ASP
????: DLSP

Active Region Filament (prominence seen against the disk), Advanced Stokes Polarimeter

Vector magnetogram demonstrates inverse configuration of field near polarity inversion line below prominence

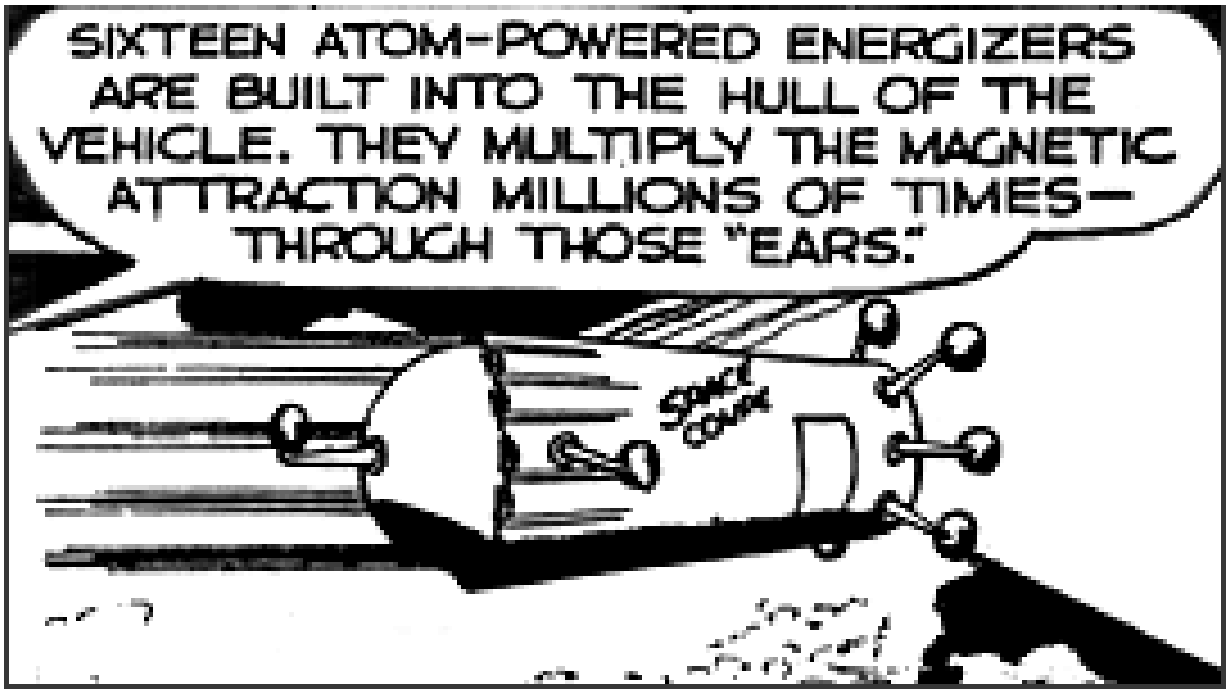


Filament in H seen along AR polarity inversion line

Lites 2005, fig. 6

"The nation that controls magnetism will control the universe"

-- purportedly from Dick Tracy Comic Strip September 1962 in reference to the "space coupe":



(…….I could not find the quote in a review of the Dick Tracy comics "space coupe" series published in the Chicago Tribune in September 1962……)

A more academic rationale:

"If the sun didn't have a magnetic field, then it would be as boring a star as most astronomers think it is."

-- Attributed to Robert B. Leighton on various occasions in the 1960's, quote above as recalled by R. Noyes

(most sources, but not all, attribute this quote to Leighton. Versions with varied wording have been reported; there appears to be no written or standard version)

Stokes I – Quantitative, Precision Measurements of Spectrally-Resolved Stokes Profiles

- HAO scientists (House, Querfeld, ….) recognized the advantages of:
  - Spectrally-resolved Stokes polarization profiles
  - High polarimetric sensitivity
  - Instrumental design to minimize spurious weak polarization signals
- They also recognized the broad range of science problems that could be addressed with a flexible, precision polarimeter

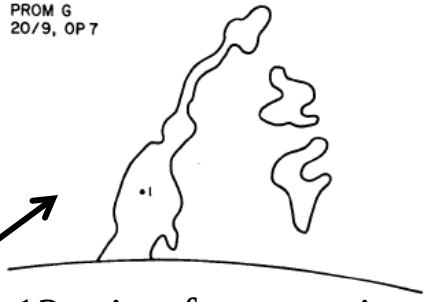
HAO Stokes Polarimeter ("Stokes I")

- Implemented at Sac Peak Big Dome
- Wavelength-scanning full Stokes polarization measurements
- Flexible wavelength 390 – 700 nm
- Single-point detectors
- Very high sensitivity to polarization
- Modest spatial resolution
- Crude spatial sampling
- Operated 1975 – 1979

HAO Stokes I Observations of Prominences

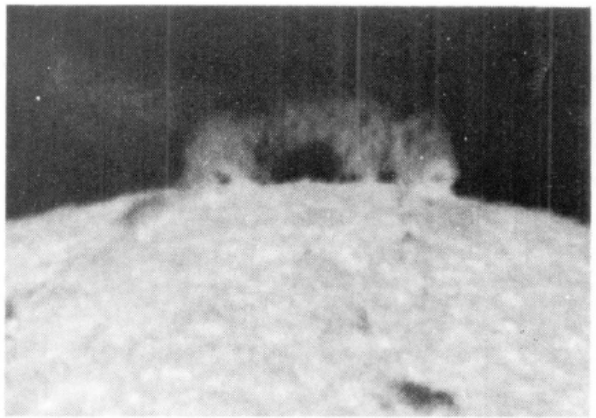
- Observations in He I D_3 line
- Hanle effect analysis (not Zeeman): scattering polarization in weak magnetic field
- Theoretical and observational work by House, Smartt, Landi degl'Innocenti, Athay, Bommier, Querfeld
- High polarimetric sensitivity of Stokes I instrument permitted meaningful analysis of weak polarization

- Analysis of many prominences indicated largely horizontal fields
- Some hint of inverse polarity
- Ultimate goal toward which we still strive: ***magnetic conditions leading to prominence eruption***



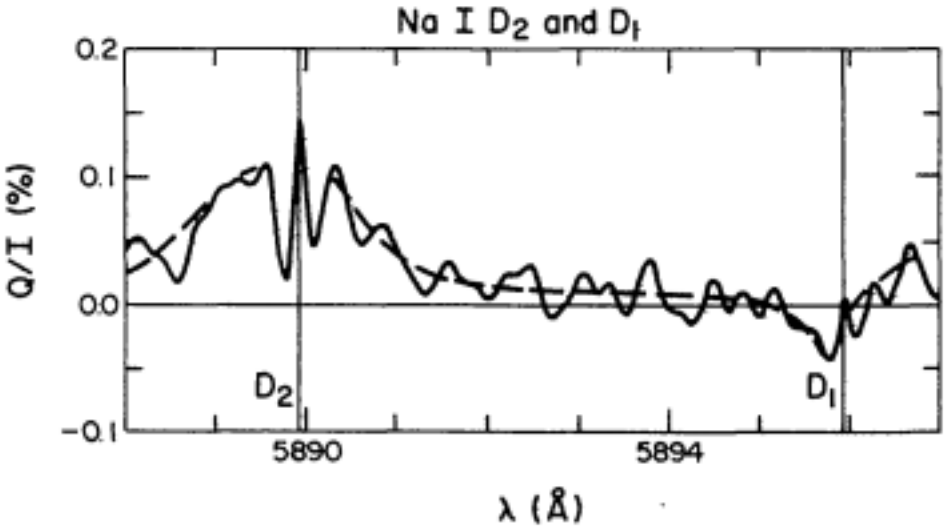
12 min after eruption

2 hr before eruption



- **Although the Stokes I and II instruments produced limited scientific results*, the data from these instruments spurred advances in instrumentation, data analysis, interpretation, and theory associated with the polarization in the solar spectrum***

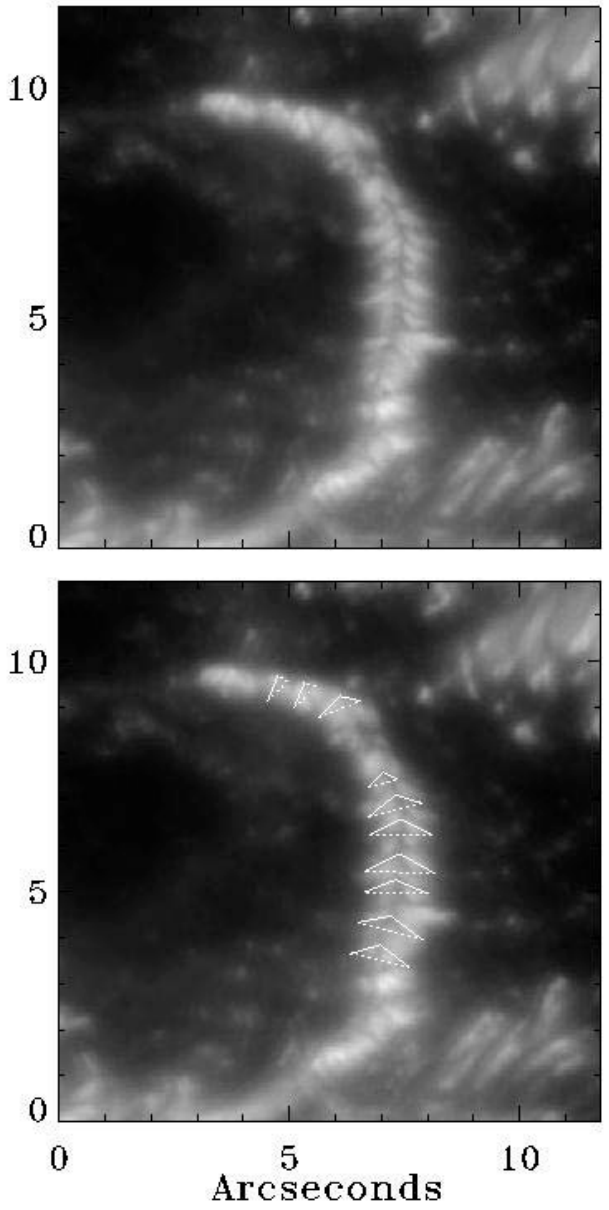
-- e.g. the first systematic center-limb observations in 1978 of non-magnetic resonance line polarization (the "Second Solar Spectrum") by J. O. Stenflo:

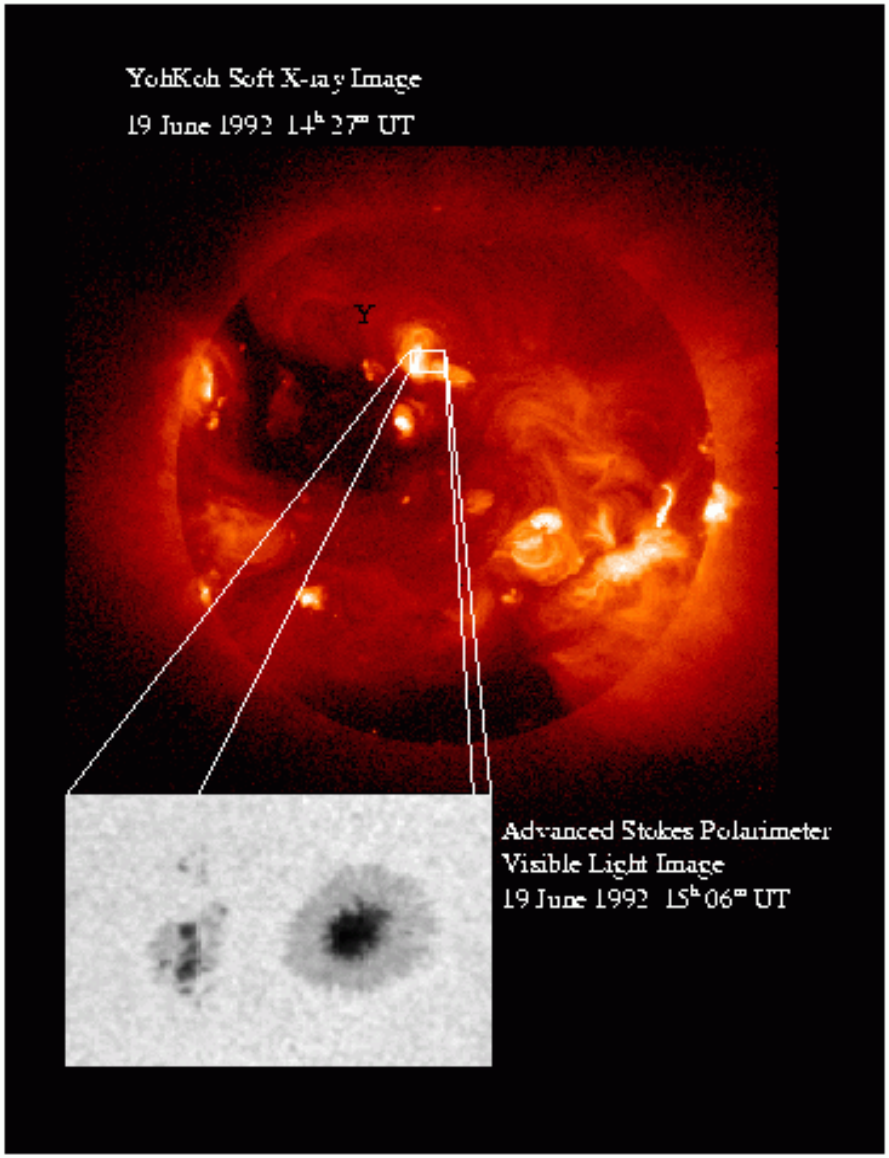


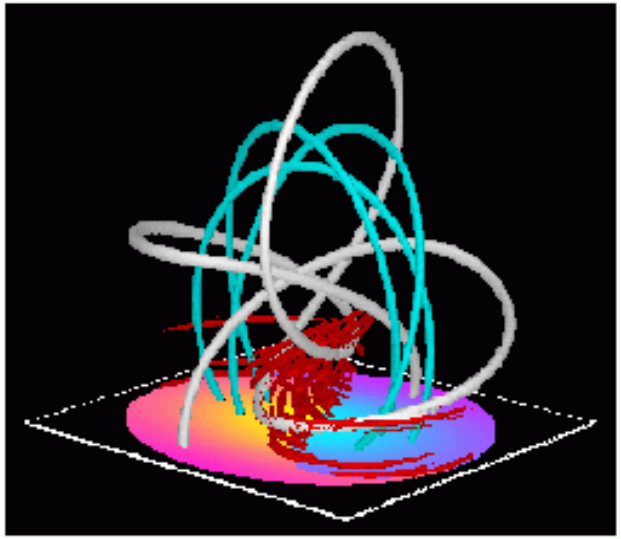
Swedish Solar Observatory

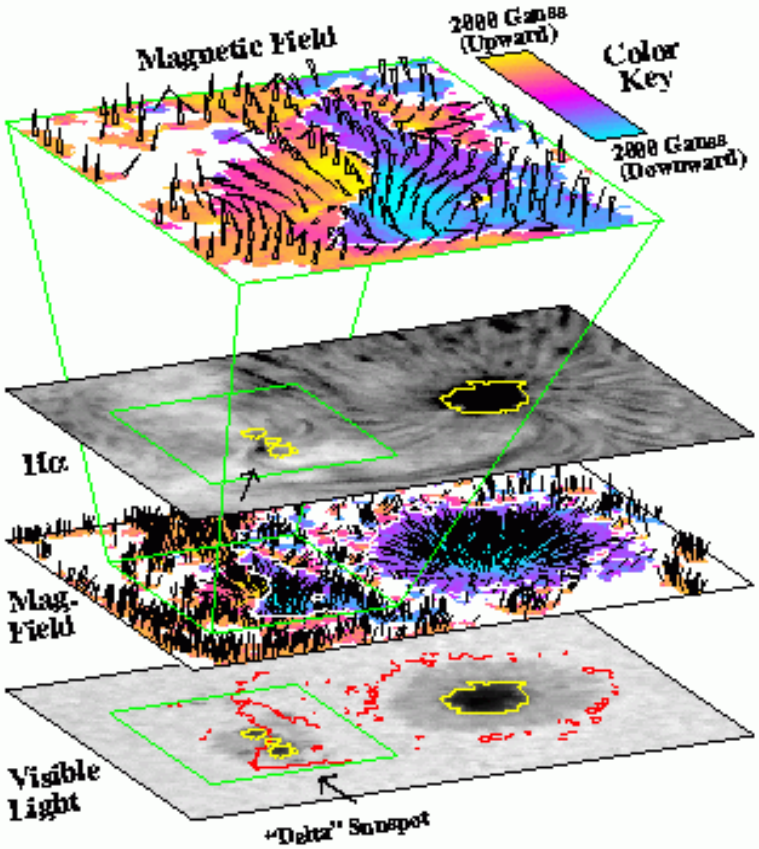
- **Segmented structure with ridge is clearly visible in this light bridge as well**
- **Similar physical heights: 200-400 km**

(to limb)

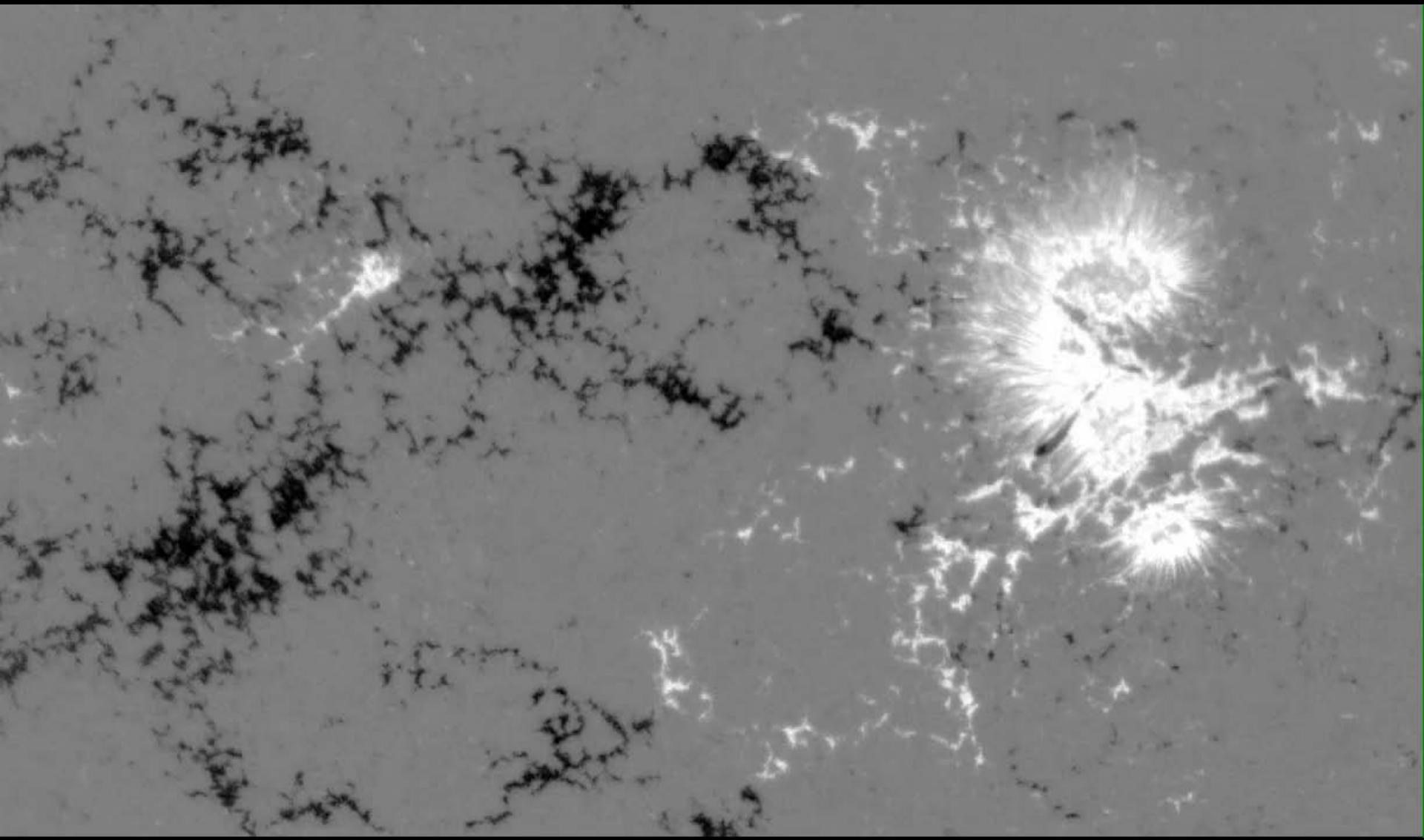



YohKoh Soft X-ray Image
19 June 1992 14h 27m UT
Y
Advanced Stokes Polarimeter
Visible Light Image
19 June 1992 15h 06m UT




Magnetic Field
2000 Gauss (Upward)
Color Key
2000 Gauss (Downward)
Hα
Mag. Field
Visible Light
"Delta" Sunspot

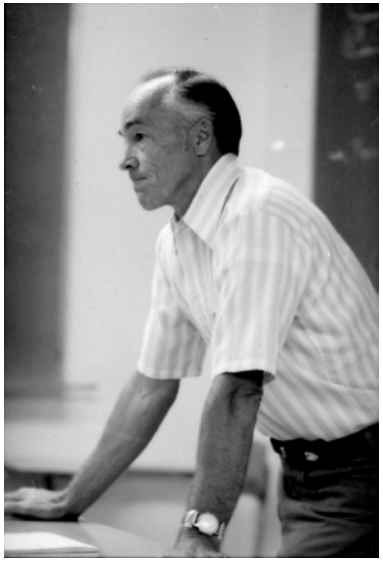
Hinode SOT Line-of-Sight Magnetogram Movie, 1-2 December 2006



At this time I entered the field of solar polarimetry:

- **The analysis procedures were either too simplistic, or in the case of "inversions" the results were not stable**
- **R. Grant Athay (had been my thesis advisor) suggested in the early 1980s that I attempt to include magneto-optical effects (Faraday rotation) into the "inversion" procedure of Auer, Heasley, and House (1977)**

- **Addition of magneto-optical effect, and other improvements, resulted in an "inversion" procedure that finally yielded reliable values for the magnetic field vector for Stokes II data**



Grant Athay