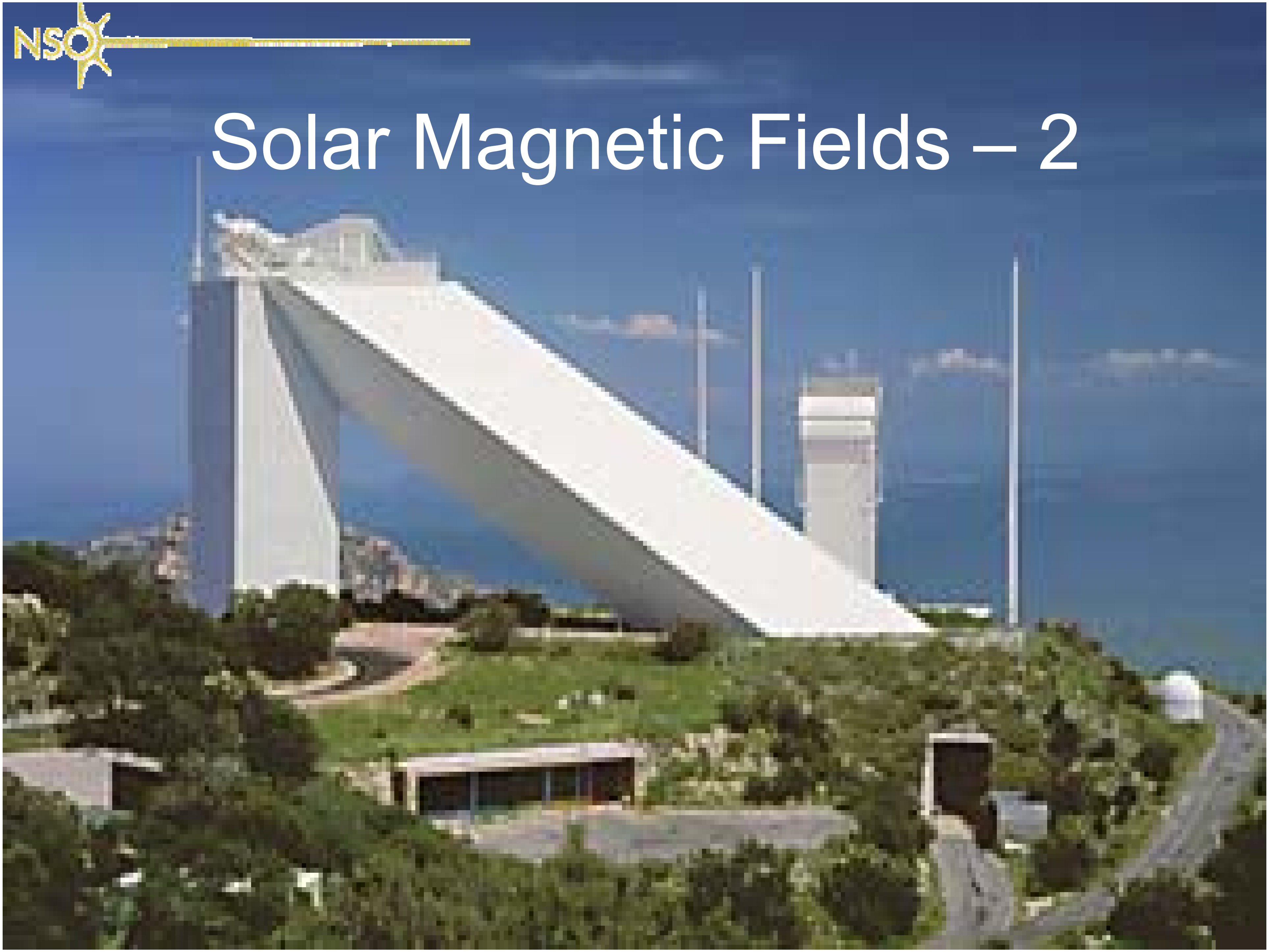
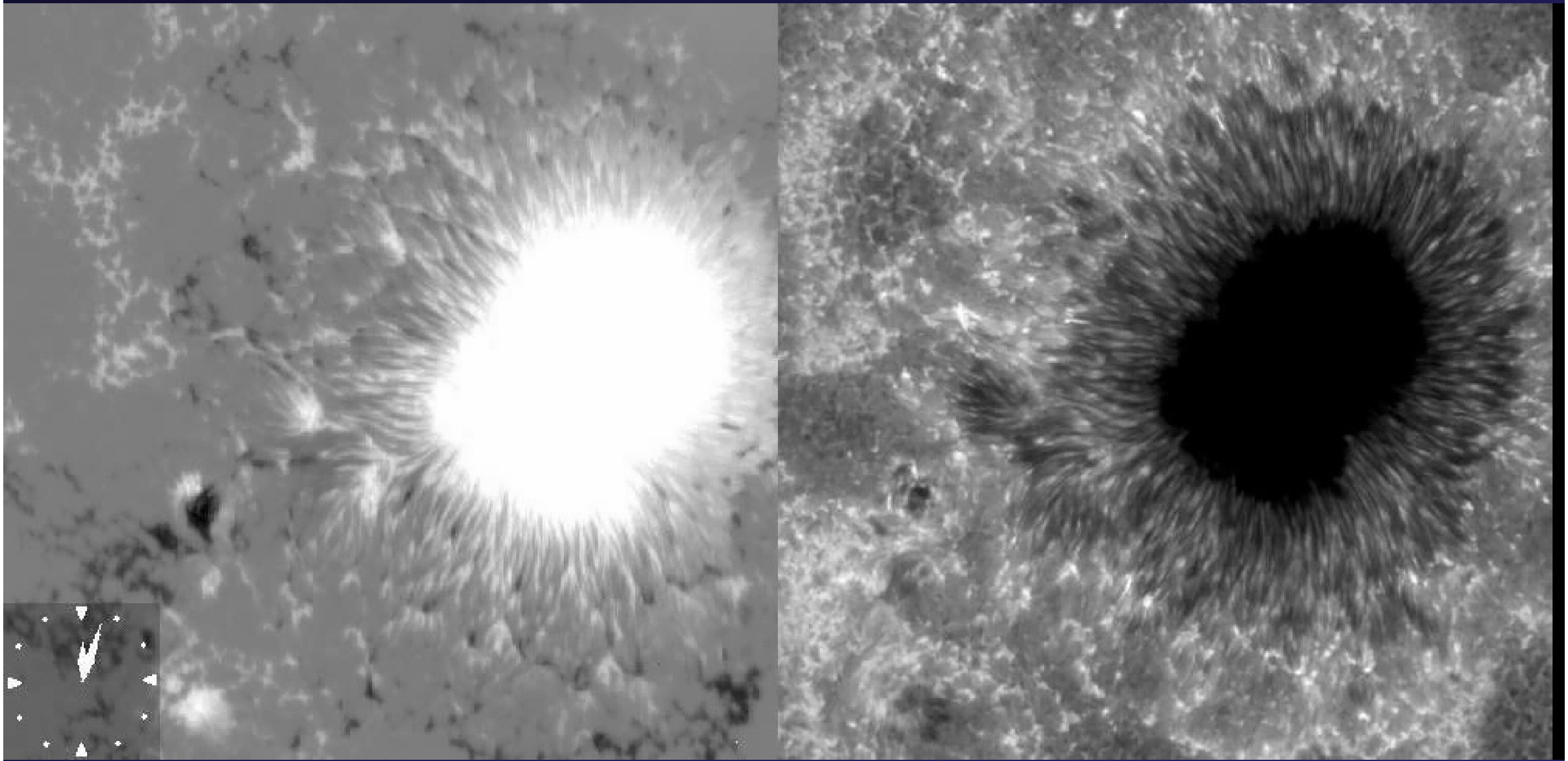
Solar Magnetic Fields – 2

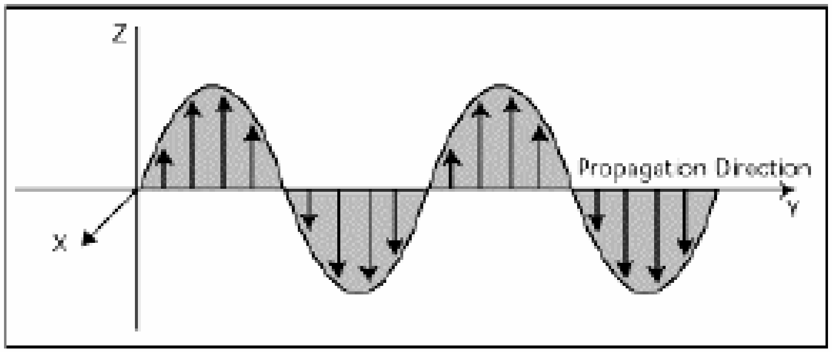


- **Solar Magnetic Fields 2 (12 June)** – An introduction to the instruments and techniques used to remotely measure the solar magnetic field
  - Stokes Vectors
  - Zeeman effect
  - Hanle effect
  - Plans for the Advanced Technology Solar Telescope

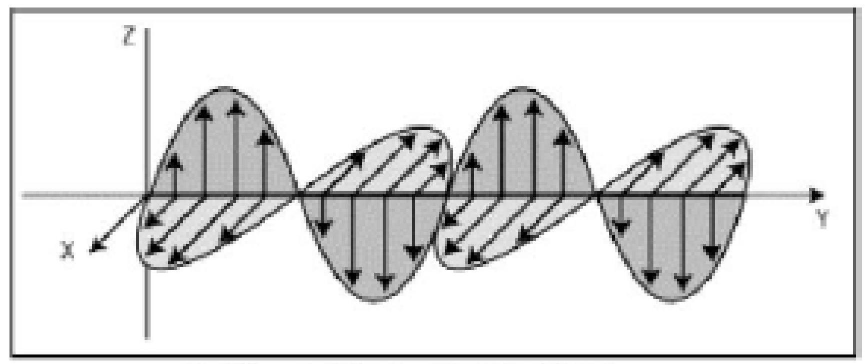


Stokes Vector

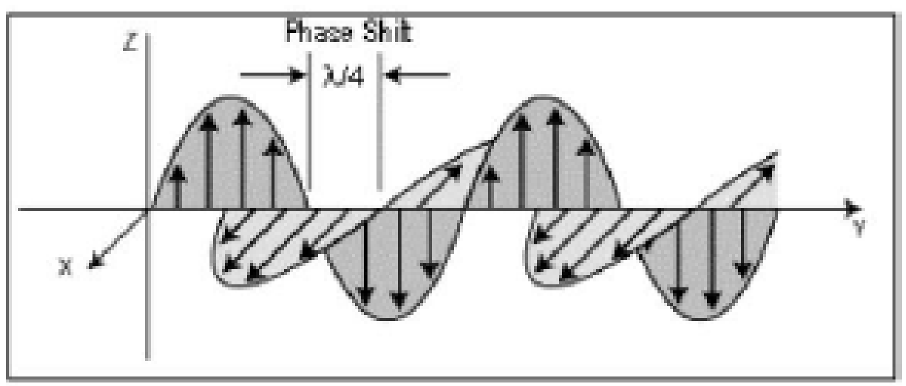
- Any given photon has a particular polarization state, and it can be represented in terms of two linear states and one circular state:



A. Linearly Polarized Light in the Vertical Direction



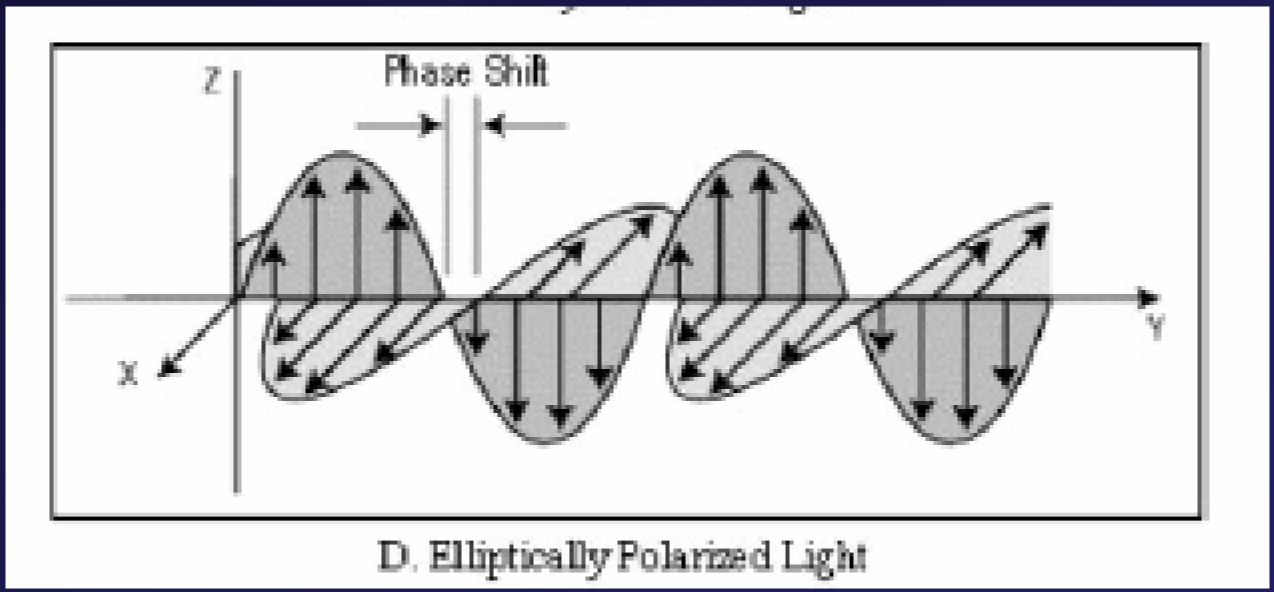
B. Linearly Polarized Light at 45 Degrees



C. Circularly Polarized Light

Stokes Vector

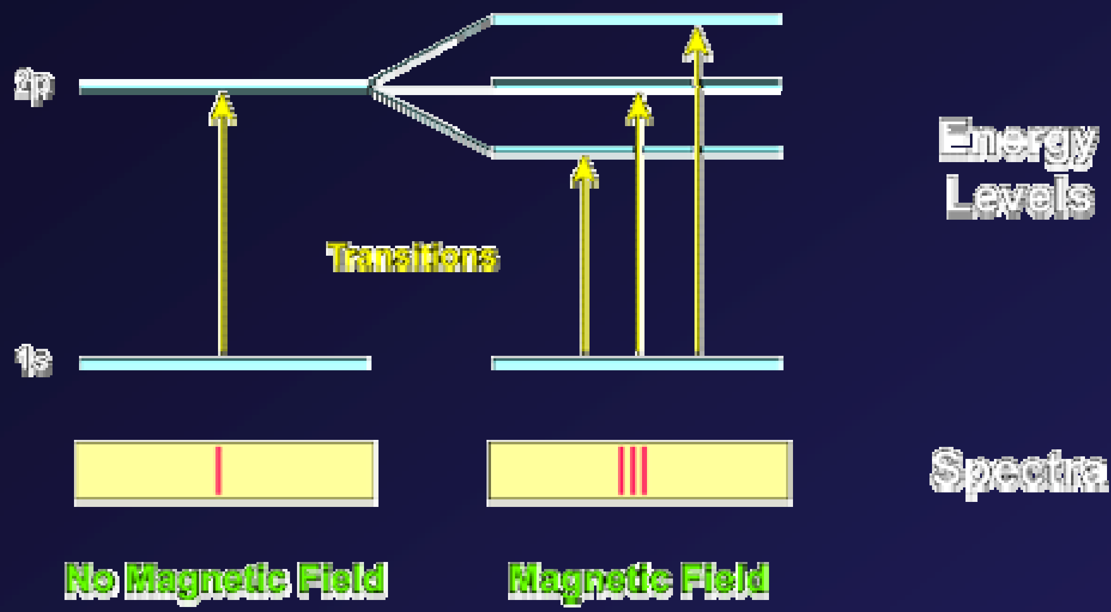
- Any given photon has a particular polarization state, and it can be represented in terms of two linear states and one circular state:



Stokes Vector

- When we observe the Sun we are collecting an ensemble of photons produced incoherently. In the absence of a physical mechanism which produces polarization, the photons will have random polarizations when we measure them, and we call this unpolarized light.
- The Stokes vector has four components: I (unpolarized light), Q and U (linearly polarized) and V (circularly polarized light)
- All polarization states can be decomposed into these four components.
- We can write a vector I=[I,Q,U,V]

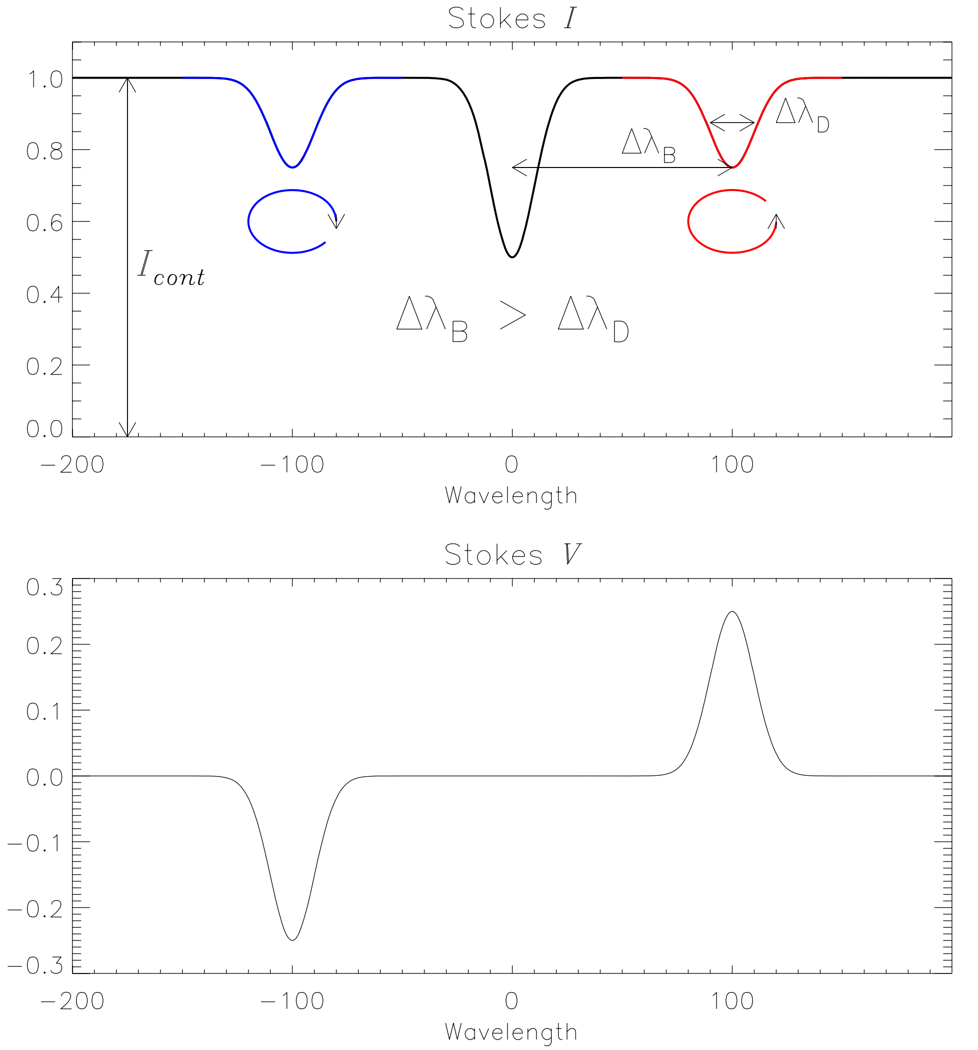
Zeeman Effect



$$\Delta\lambda_B = 4.67\times10^{-7}\, g\lambda^2 B$$

- For magnetic fields 0.1-10,000 G, the electron states of typical photospheric atoms are split into 2l+1 new states separated by a certain energy.
- This energy can be determined by the spin and orbital angular momenta of the electron, which determine a factor called the Lande g factor.

Zeeman Effect



- The split components are also polarized.
- For the simple case of a magnetic field precisely along the line-of-sight to the observer, the two components are circularly polarized.
- The magnetic sensitivity goes as the ratio of $\Delta\lambda_B/\Delta\lambda_D$, which increases with λ, so Fe 1565nm 3 times better than 630.2nm line, Ti 2231nm is even better inside sunspot umbrae.

Zeeman Effect

- In the general case when the magnetic field lies at an angle to the line-of-sight, circular and linear polarization is present in the spectral components of the line.
- When a region of the solar atmosphere is magnetized, the transfer of radiation through that section is different.
- The magnetized atmosphere takes an input of unpolarized (randomly polarized) light and mixes it into different polarization states.

Zeeman Effect

- In the general case when the magnetic field lies at an angle to the line-of-sight, circular and linear polarization is present in the spectral components of the line.
- These spectra are analyzed using the Stokes formalism.
- In terms of radiative transfer, the unpolarized input radiation is modified by a Mueller matrix (a 4x4 matrix) to give a new observed Stokes vector.
- $[I,Q,U,V]_B=M_B[1,0,0,0]$
- This Mueller matrix describes the radiative transfer in the magnetic gas.

Zeeman Effect

standard form of the Stokes transfer equations as

$$-\frac{dI}{dz} = (\kappa_I + \kappa_c)(I - B) + \kappa_Q Q + \kappa_U U + \kappa_V V \,,$$

$$-\frac{dQ}{dz} = \kappa_Q(I - B) + (\kappa_I + \kappa_c)Q + \kappa'_V U - \kappa'_U V \,,$$

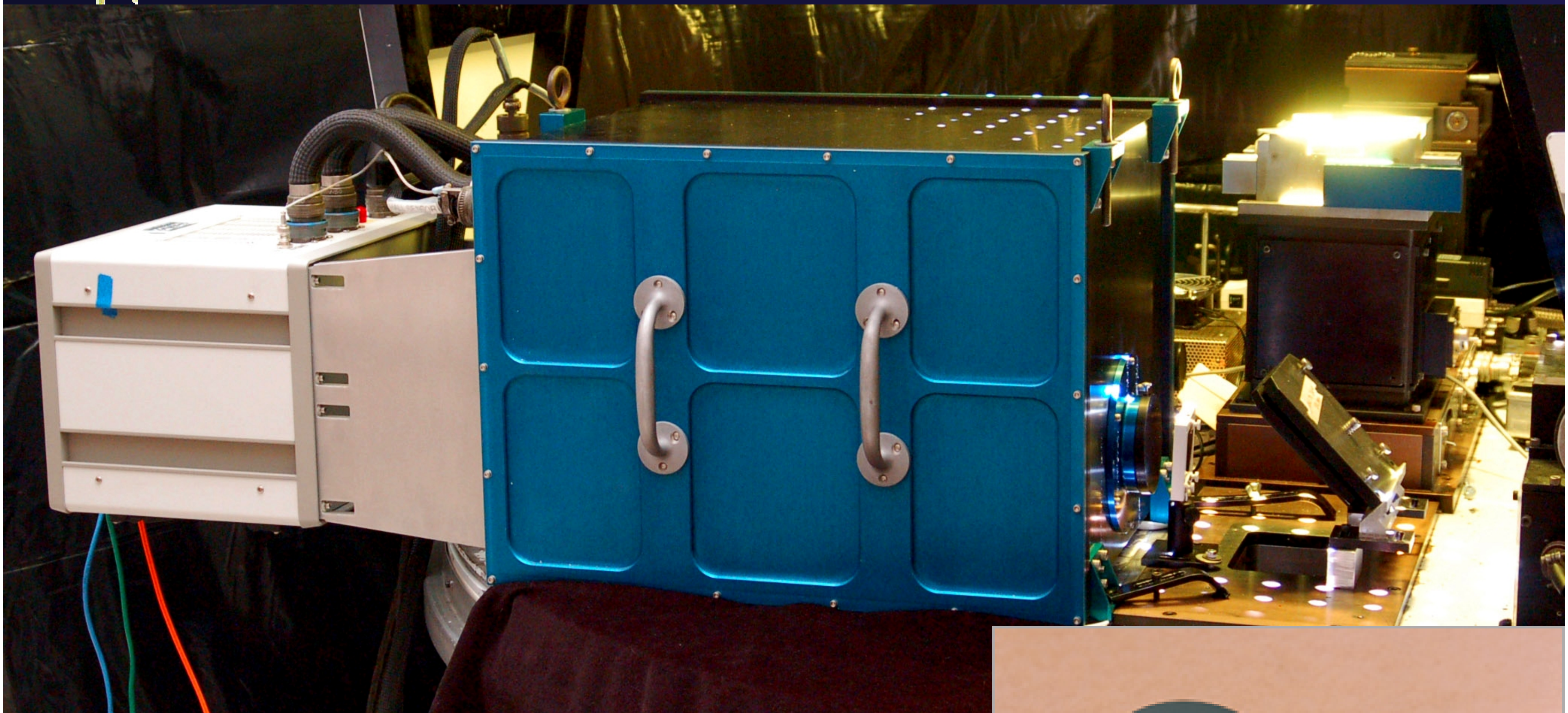
$$-\frac{dU}{dz} = \kappa_U(I - B) - \kappa'_V Q + (\kappa_I + \kappa_c)U + \kappa'_Q V \,,$$

$$-\frac{dV}{dz} = \kappa_V(I - B) + \kappa'_U Q - \kappa'_Q U + (\kappa_I + \kappa_c)V \,,$$

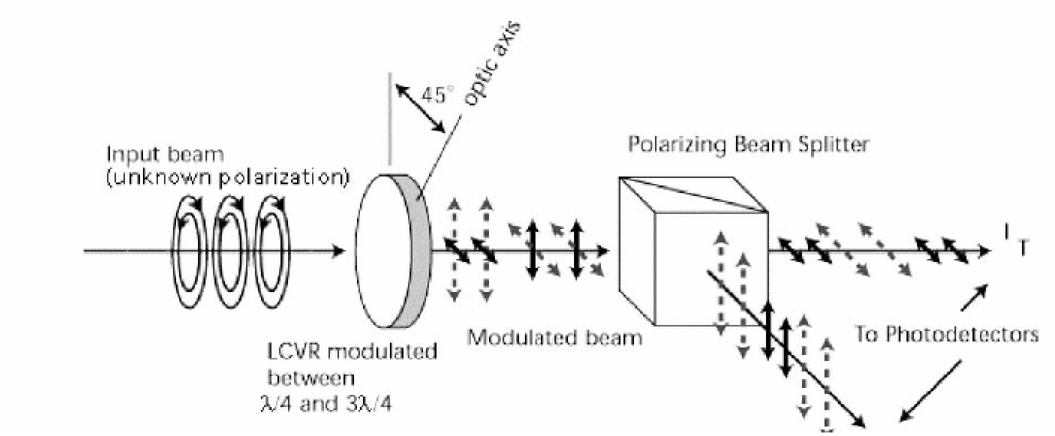
Jefferies, Lites & Skumanich (1989 ApJ 343, 920)

Spectropolarimetry with the NSO Array Camera (NAC)

- A new 1024x1024 InSb array camera is being used at the McMath-Pierce telescope for spectropolarimetry at infrared wavelengths.
- The McM/P is the world's largest telescope (1.6m) and is all-reflecting which allows all infrared wavelengths to be observed (many telescopes with windows or lenses cut off at 2500nm).
- Special polarimetric optics can be purchased and installed in the system; the current optics function from 1000-2500nm, but we have ideas of using other optics out to 5000nm.




VARIABLE RETARDER



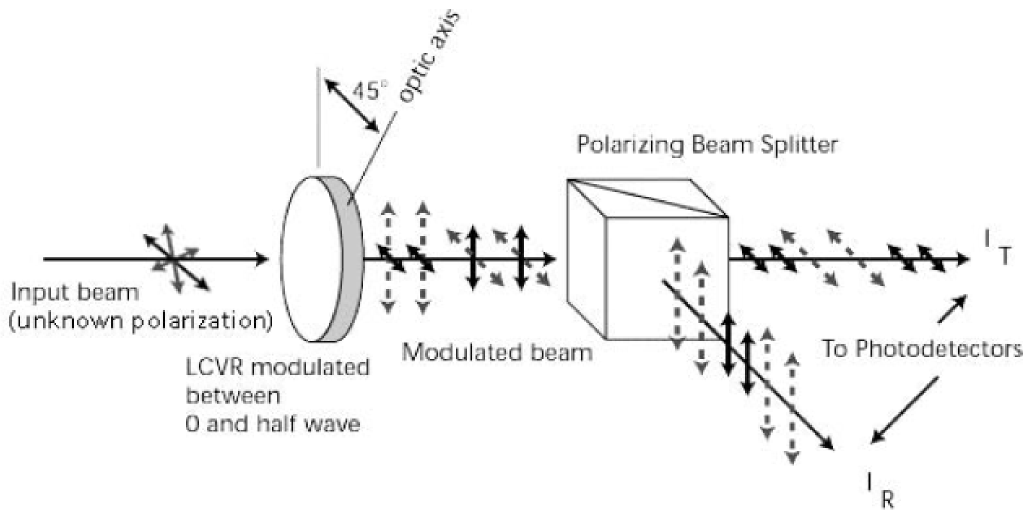


Figure 1: Measurement of the Q-component of the Stokes vector

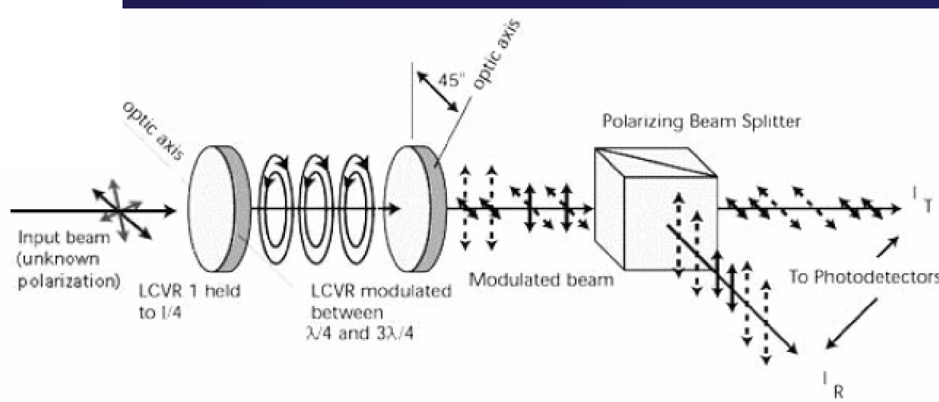
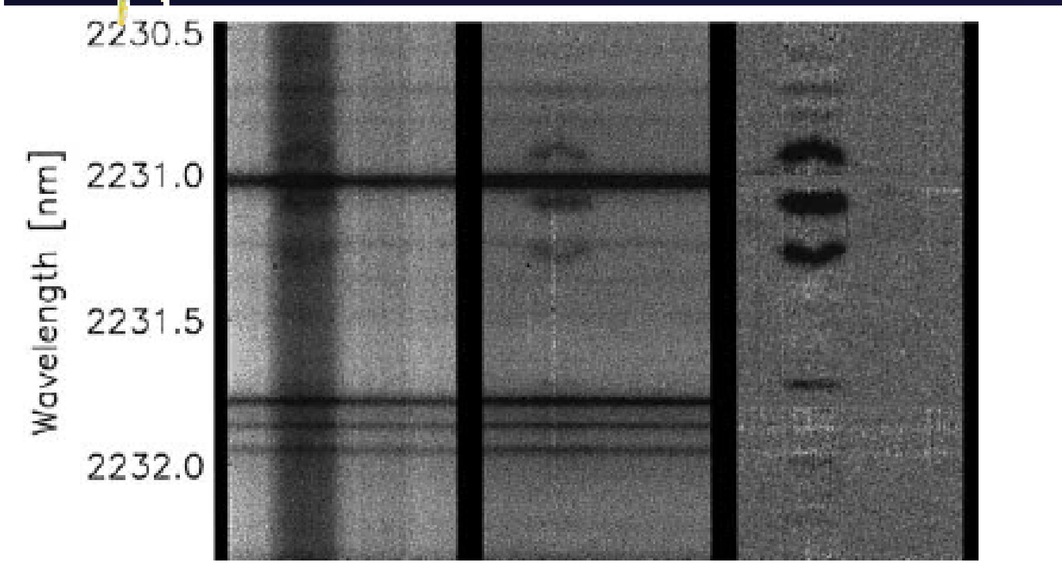
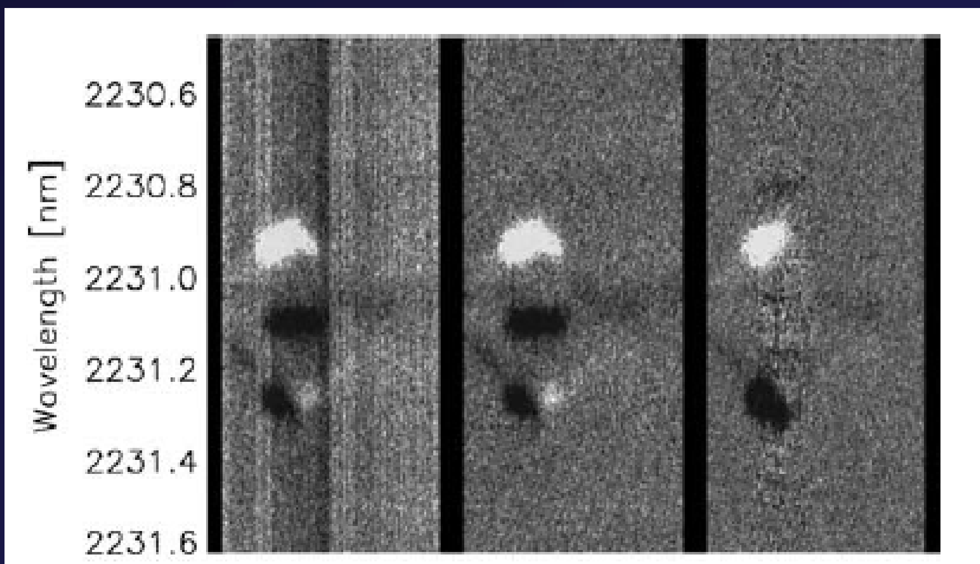
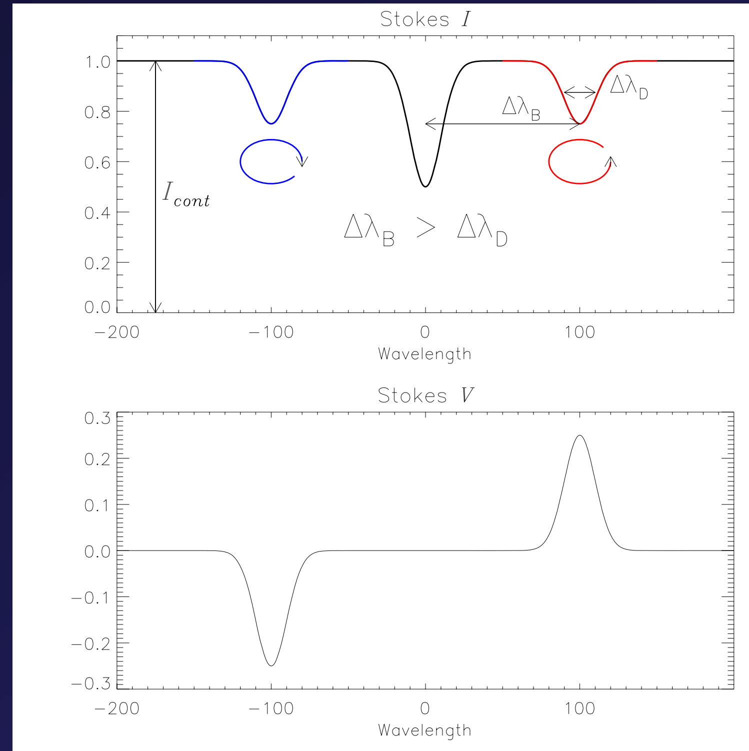


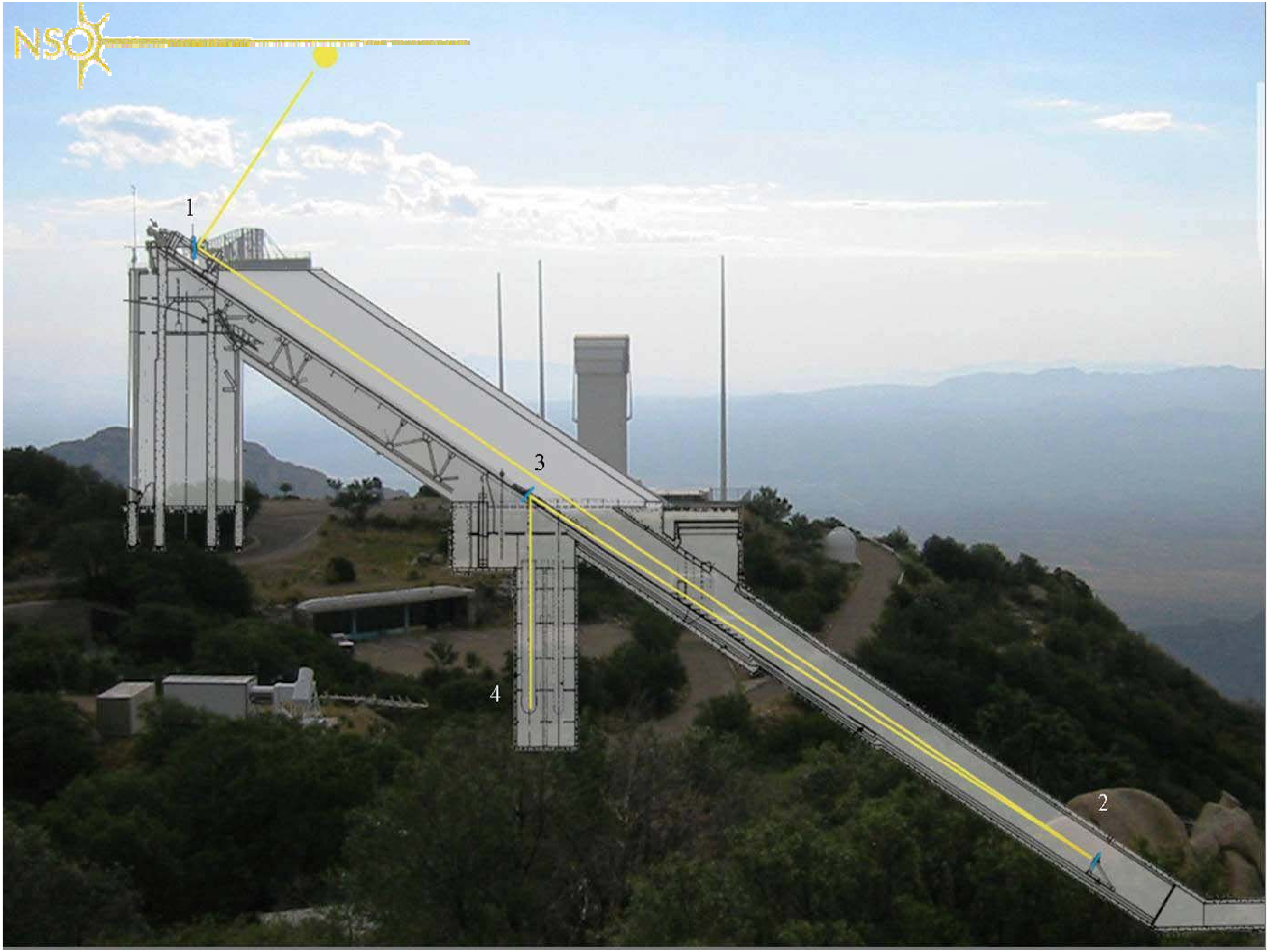
Figure 3: Measurement of the U component of the Stokes vector.







- In real telescopes with reflections, polarized light is modified by the telescope Mueller matrix.



NSO
1
3
4
2

Spectropolarimetry with the NSO Array Camera (NAC)

- There are many ways to remove instrumental polarization; for fully resolved infrared Stokes profiles we can use an indirect method proposed by Kuhn et al. 1994, Solar Physics, v153, p143.
- A more common technique for observations made in the visible (unresolved splitting) assumes the continuum polarization is zero.
- A third technique is to model the telescope Mueller matrix by examining how each optical element modifies the input Stokes vector.
- $[I,Q,U,V]_{obs}=M_3M_2M_1[I,Q,U,V]_{true}$

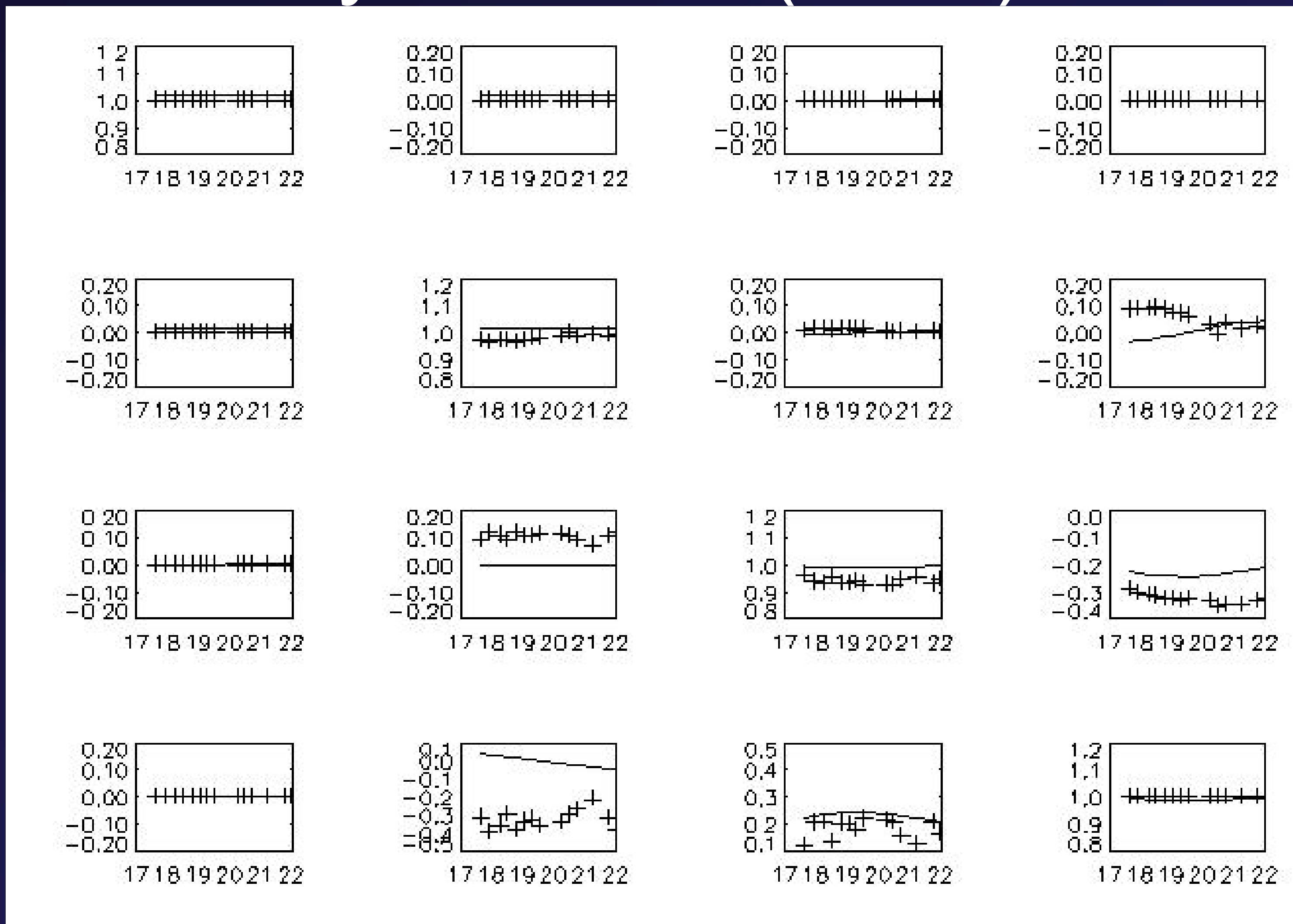
Spectropolarimetry with the NSO Array Camera (NAC)

- Each mirror reflection involves the angle of incidence (changes throughout day) and parameters dealing with the mirror oxide layer (changes slowly over weeks/months)
- A comparison with the model telescope and the indirect correction terms from the Kuhn et al. analysis technique was done with a day of observations.

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

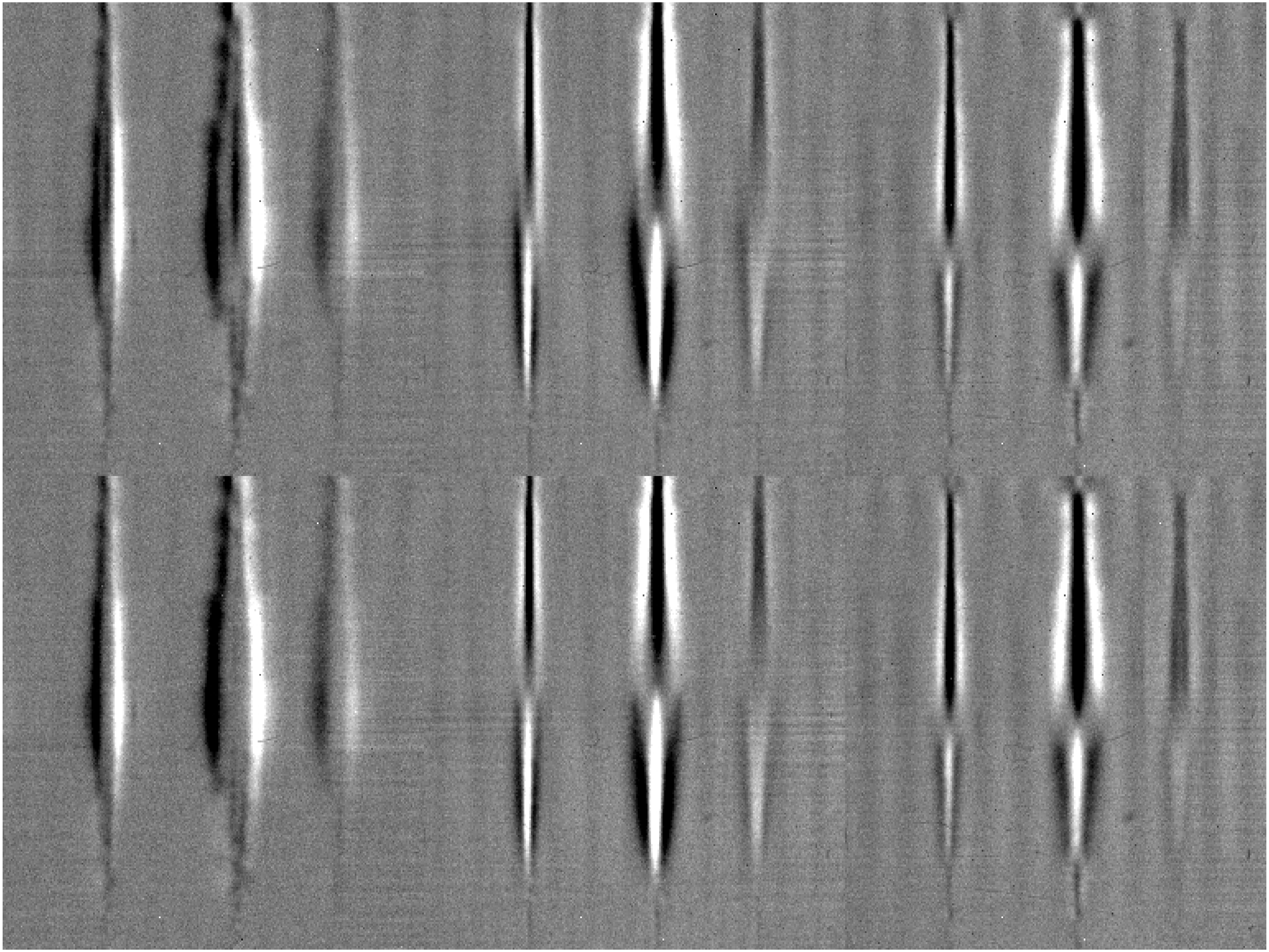
$$M = \frac{1}{2}\begin{bmatrix} 1+\rho^2 & 1-\rho^2 & 0 & 0 \\ 1-\rho^2 & 1+\rho^2 & 0 & 0 \\ 0 & 0 & -2\rho\cos\delta & -2\rho\sin\delta \\ 0 & 0 & 2\rho\sin\delta & -2\rho\cos\delta \end{bmatrix}$$

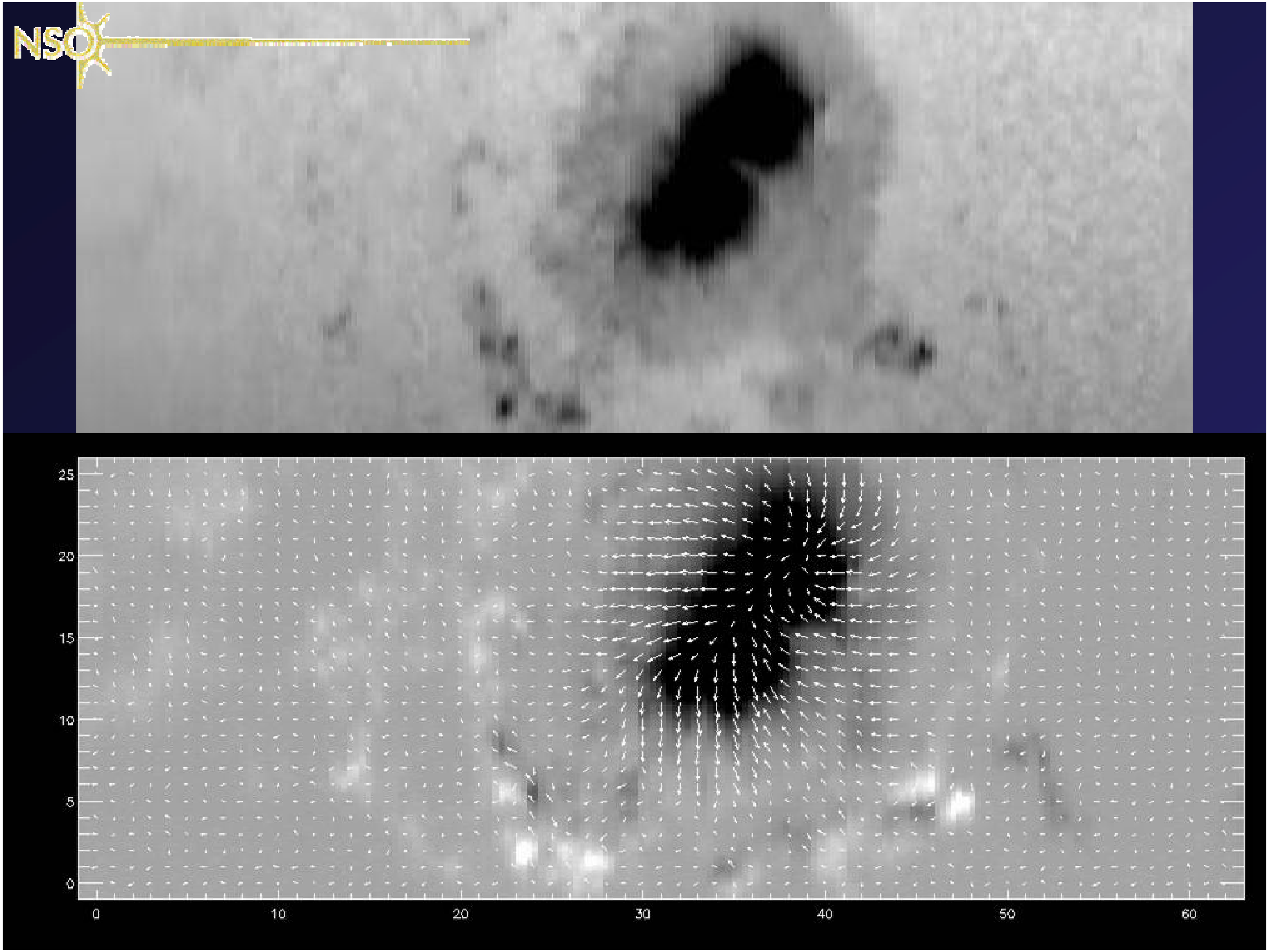
Spectropolarimetry with the NSO Array Camera (NAC)



Zeeman Effect

- It became clear that the model was not properly describing the telescope Mueller matrix, probably due to unknowns in the mirror surfaces.
- However, when the spectra were corrected using the indirect technique derived from one spectral line, all the spectral lines were corrected well, and so we trusted the Kuhn et al. method results.




NSO
25
20
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10
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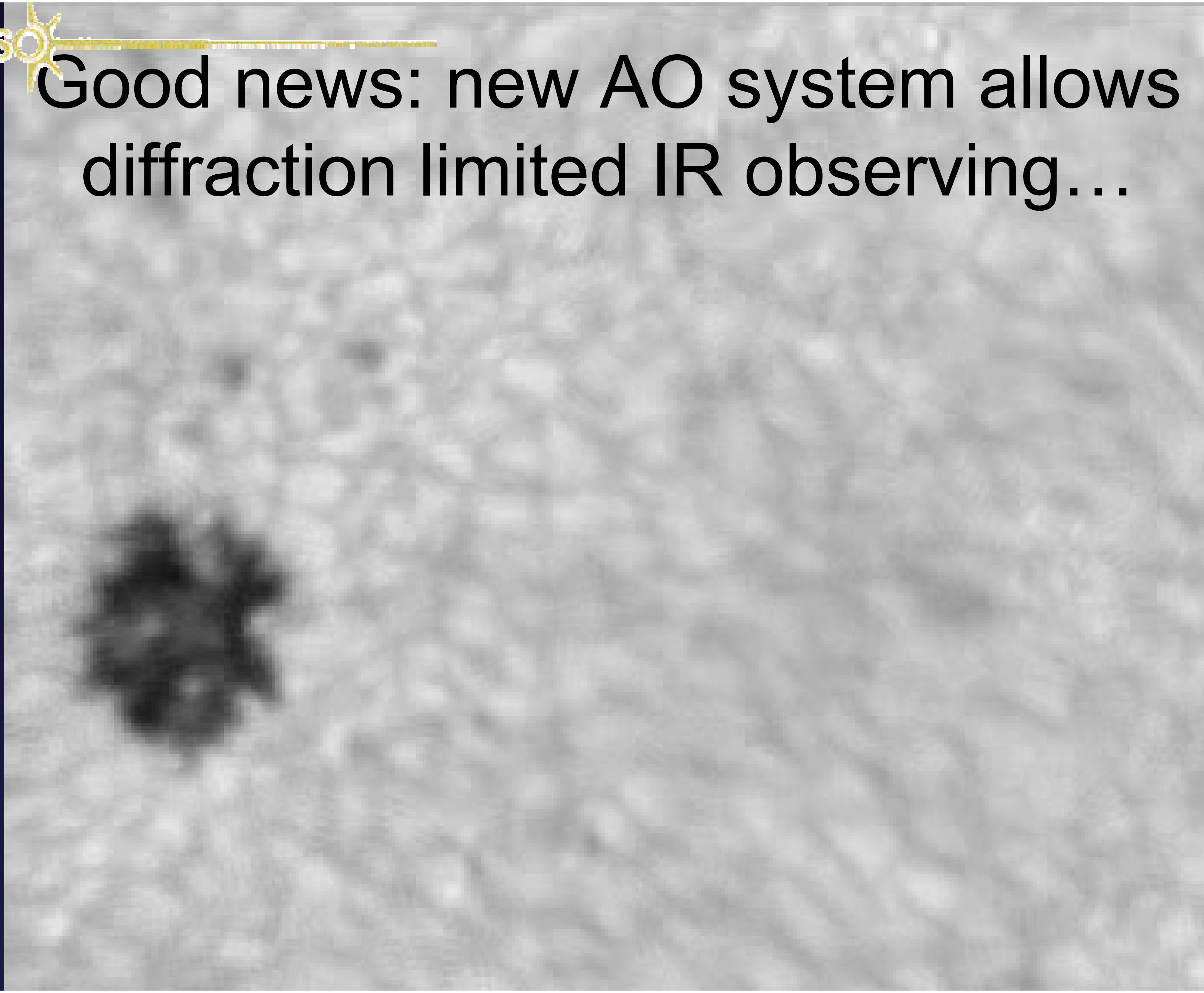
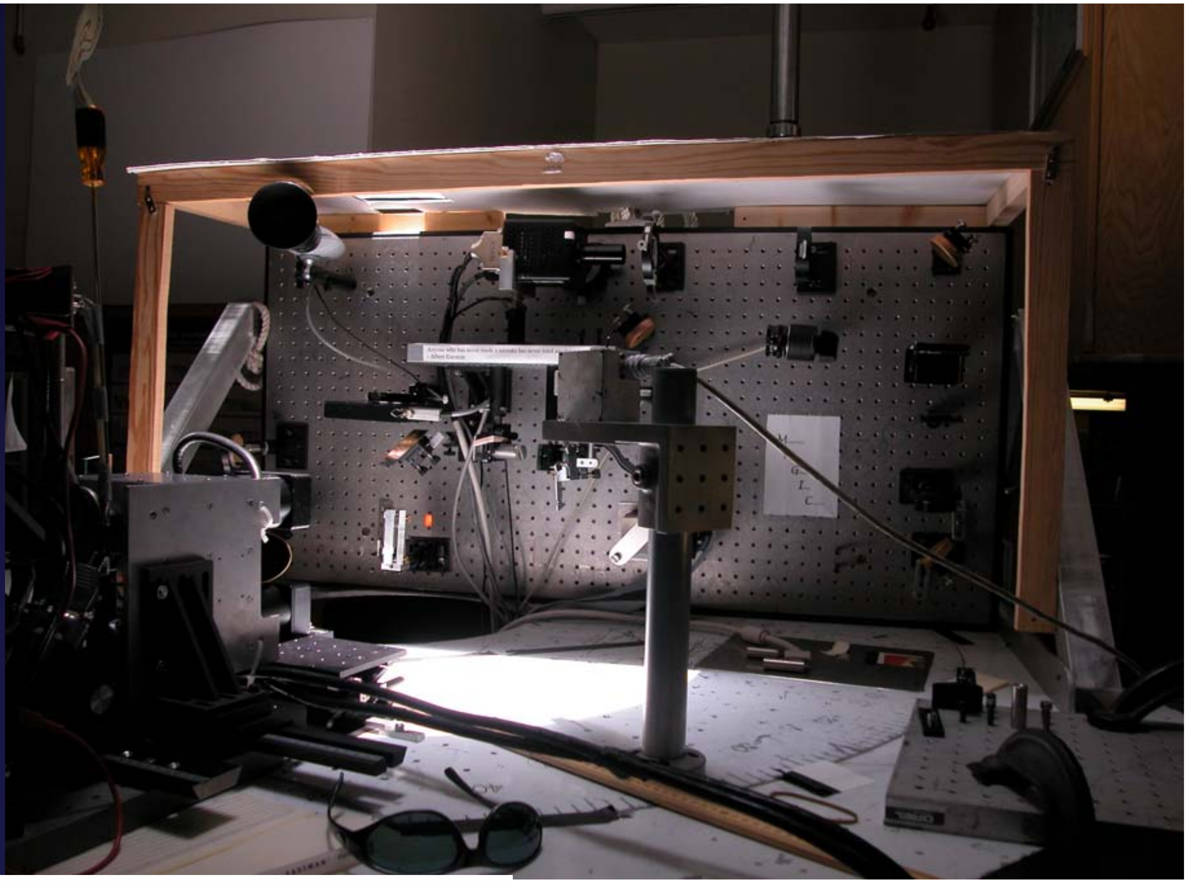
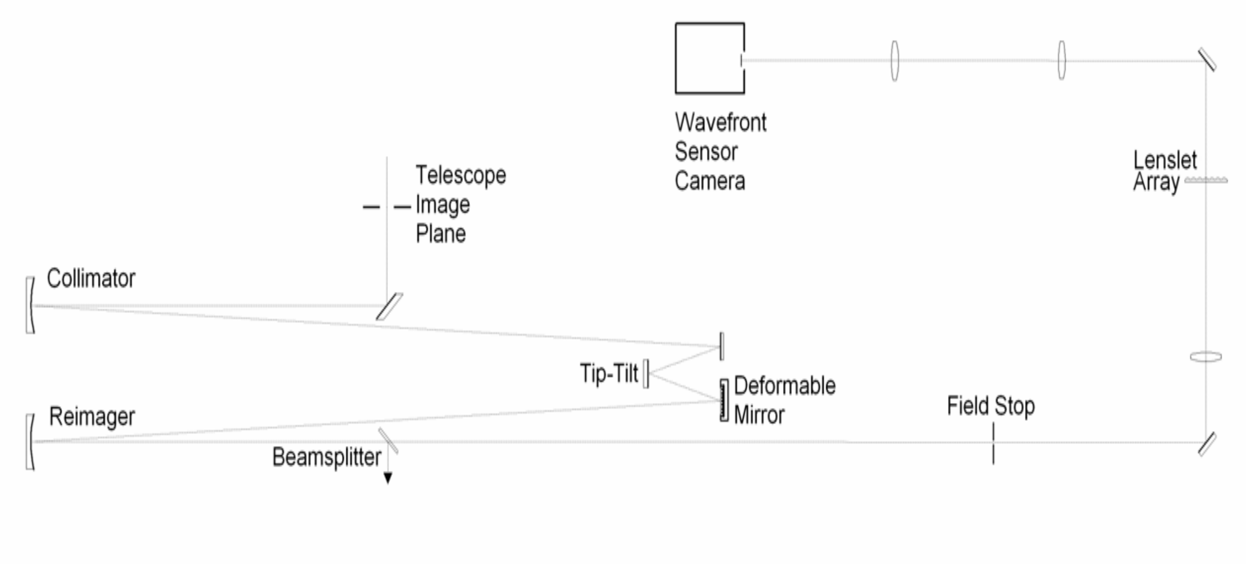
60

Good news: new AO system allows diffraction limited IR observing…



- Bad news: new AO system introduces 7 new reflections…



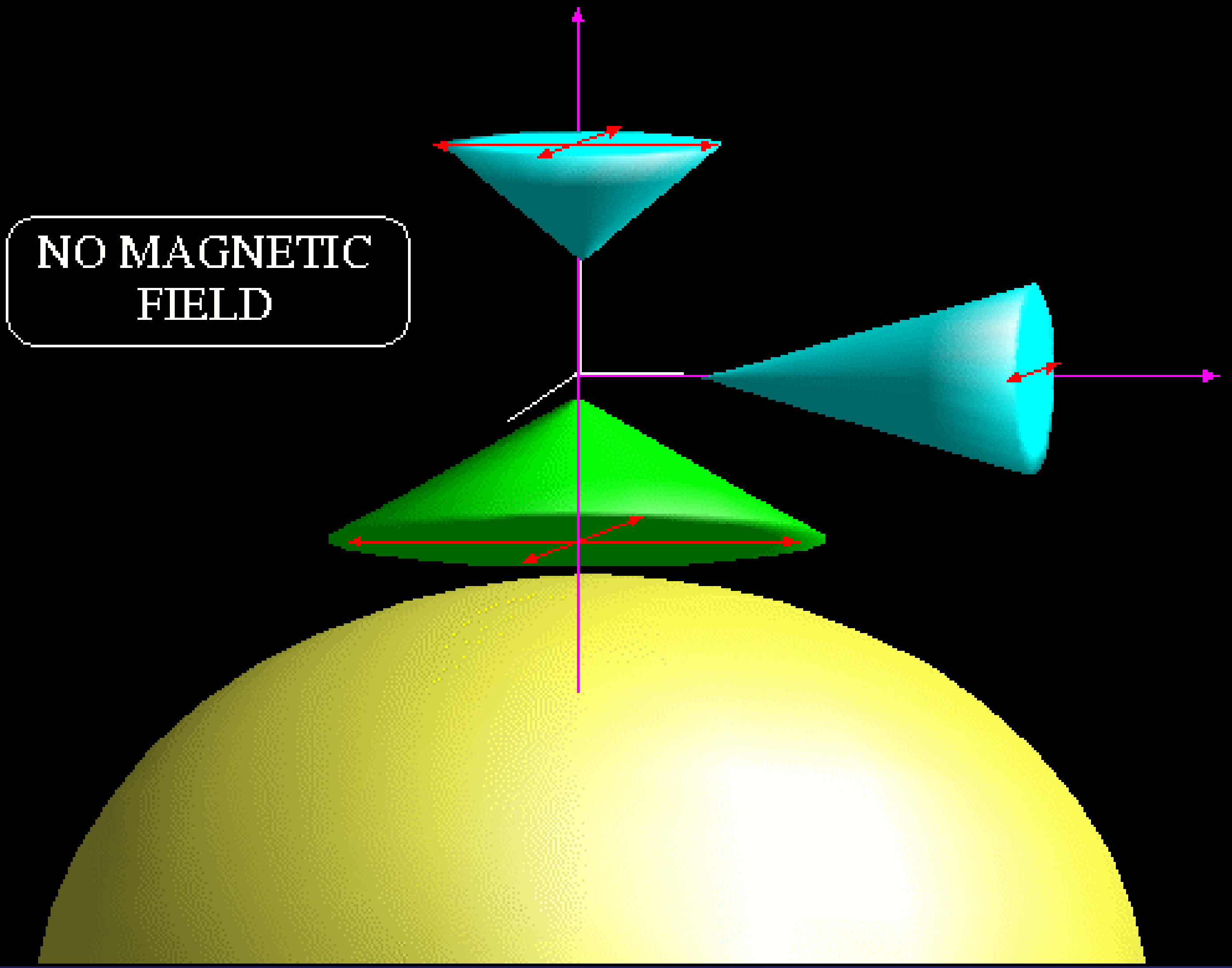


Unresolved Fields and the Hanle Effect

- If the magnetic field on the Sun varies dramatically within the resolution element (ie camera pixel) then the polarization signals may cancel.
- A small-scale unresolved field can be detected by using the Hanle Effect
- The Hanle Effect is a type of scattering polarization.
- The Hanle effect is
  - a decrease in the linear polarization of the scattered radiation compared to no B case
  - a rotation of the polarization azimuth is seen for some geometry

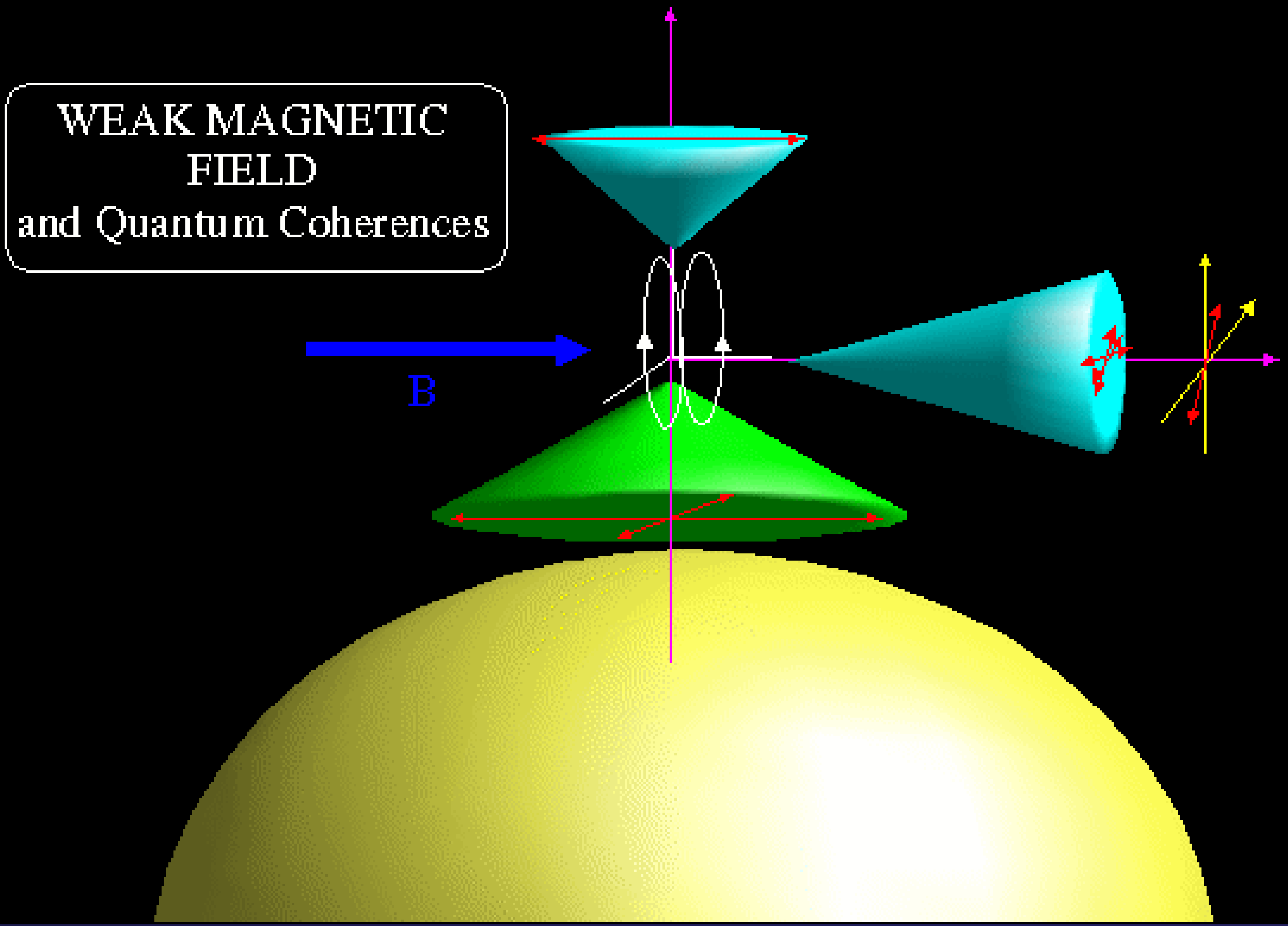
R. Casini

The magnetic signature.
II. The Hanle effect



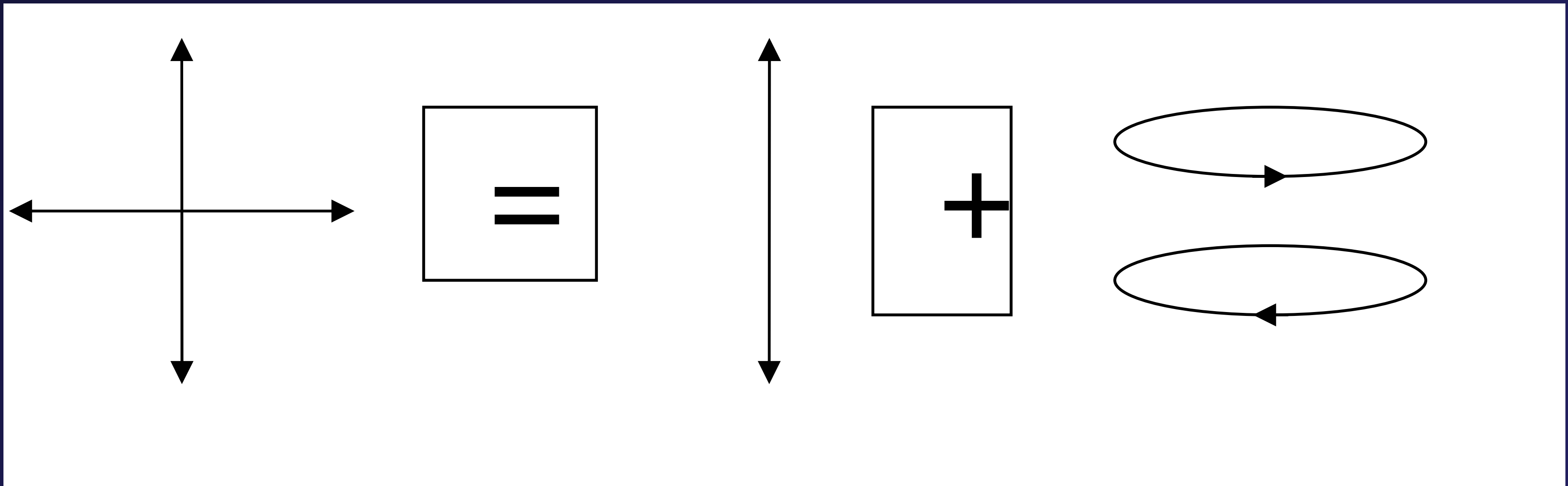
R Casini

The magnetic signature.
II. The Hanle effect



Unresolved Fields and the Hanle Effect

- The Hanle effect can be described with the classical multiple oscillator picture.
- An important idea is that linear oscillators can be decomposed into circular oscillators

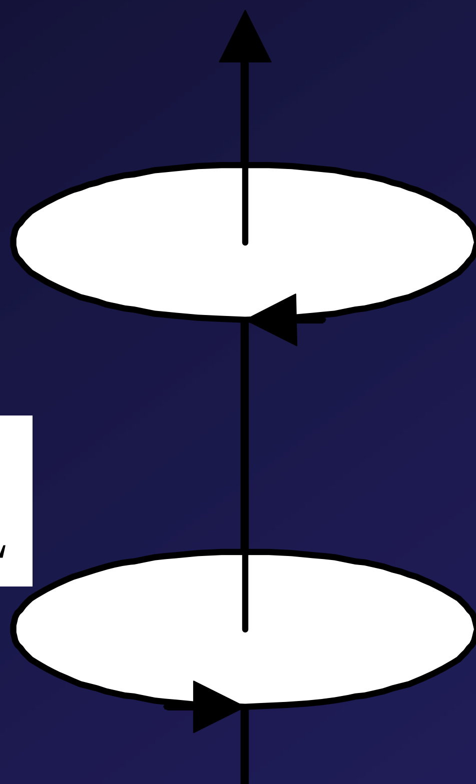


Unresolved Fields and the Hanle Effect

- The frequency of the two circular oscillators must be equal in order to reproduce the linear oscillator.
- A properly oriented magnetic field will alter the frequency of a circular oscillator:
  - Strong magnetic field – large shift (Zeeman)
  - Weak magnetic field – small shift (Hanle)

Unresolved Fields and the Hanle Effect

- This shift is the Larmor frequency:



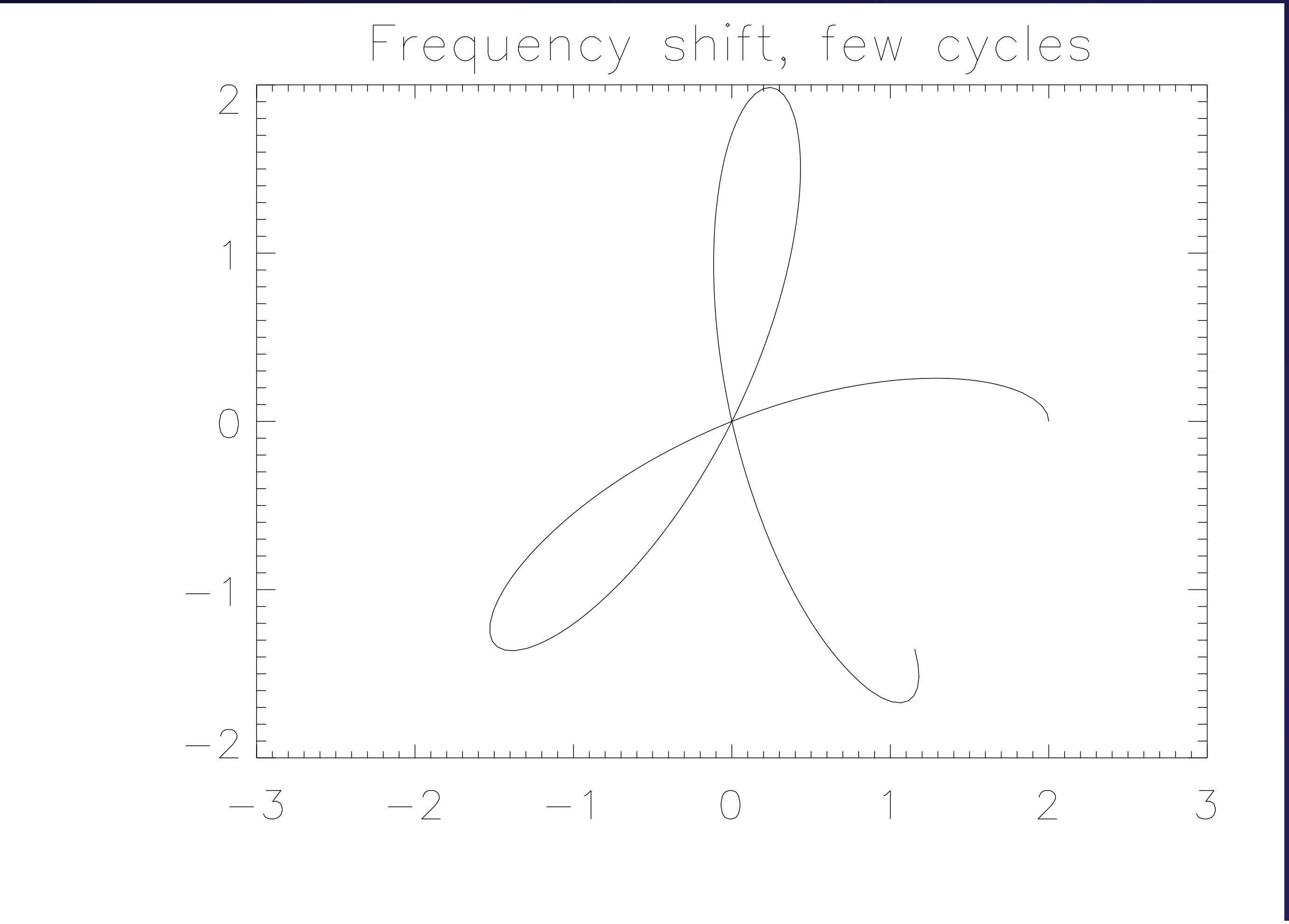
$$\nu = \nu_0 - \nu_L$$

$$\nu = \nu_0 + \nu_L$$

$$\nu_L = \frac{eB}{4\pi mc}$$

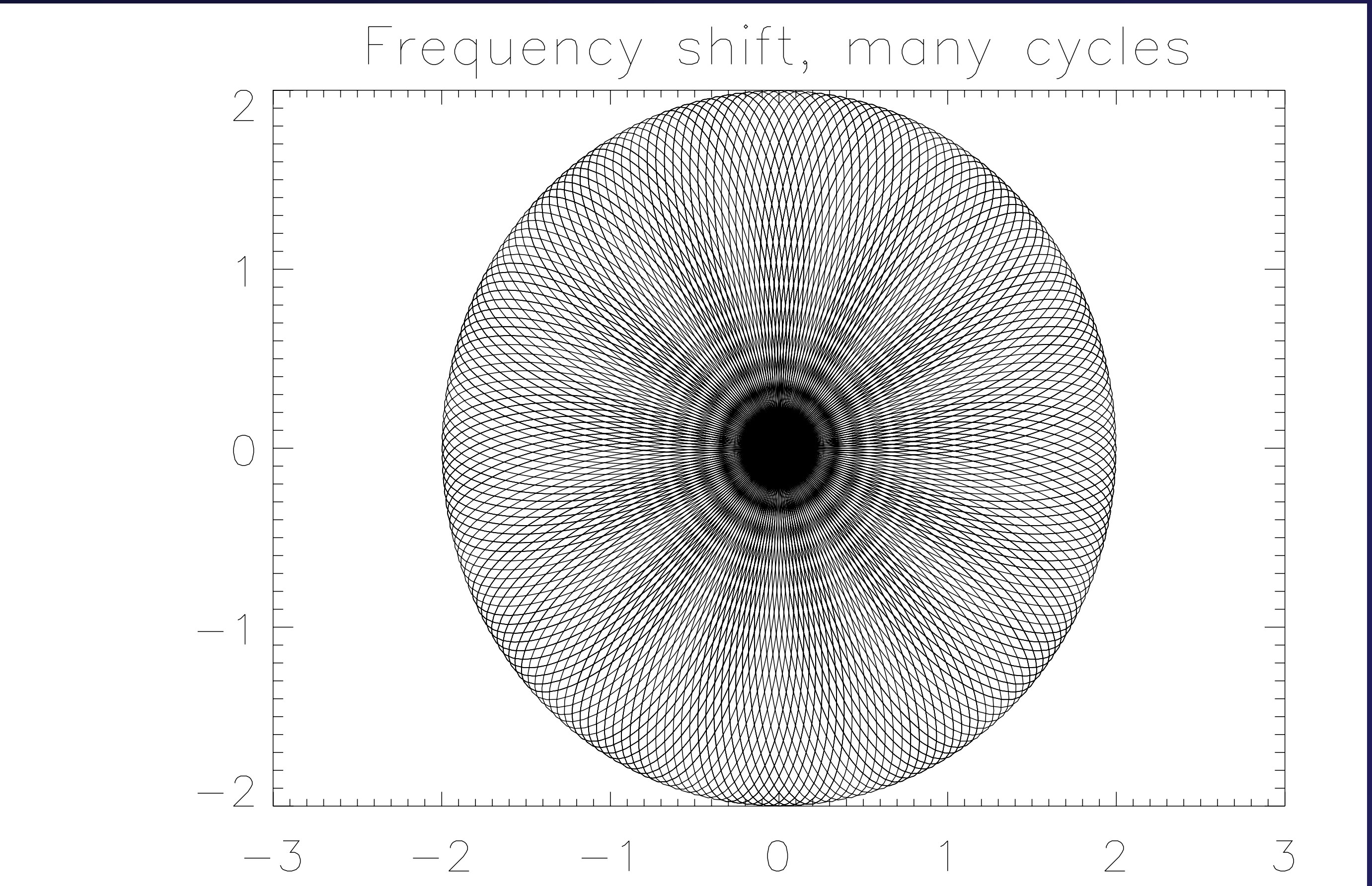
Unresolved Fields and the Hanle Effect

- With shift, direction precesses with time…



Unresolved Fields and the Hanle Effect

- When all directions => total depolarization

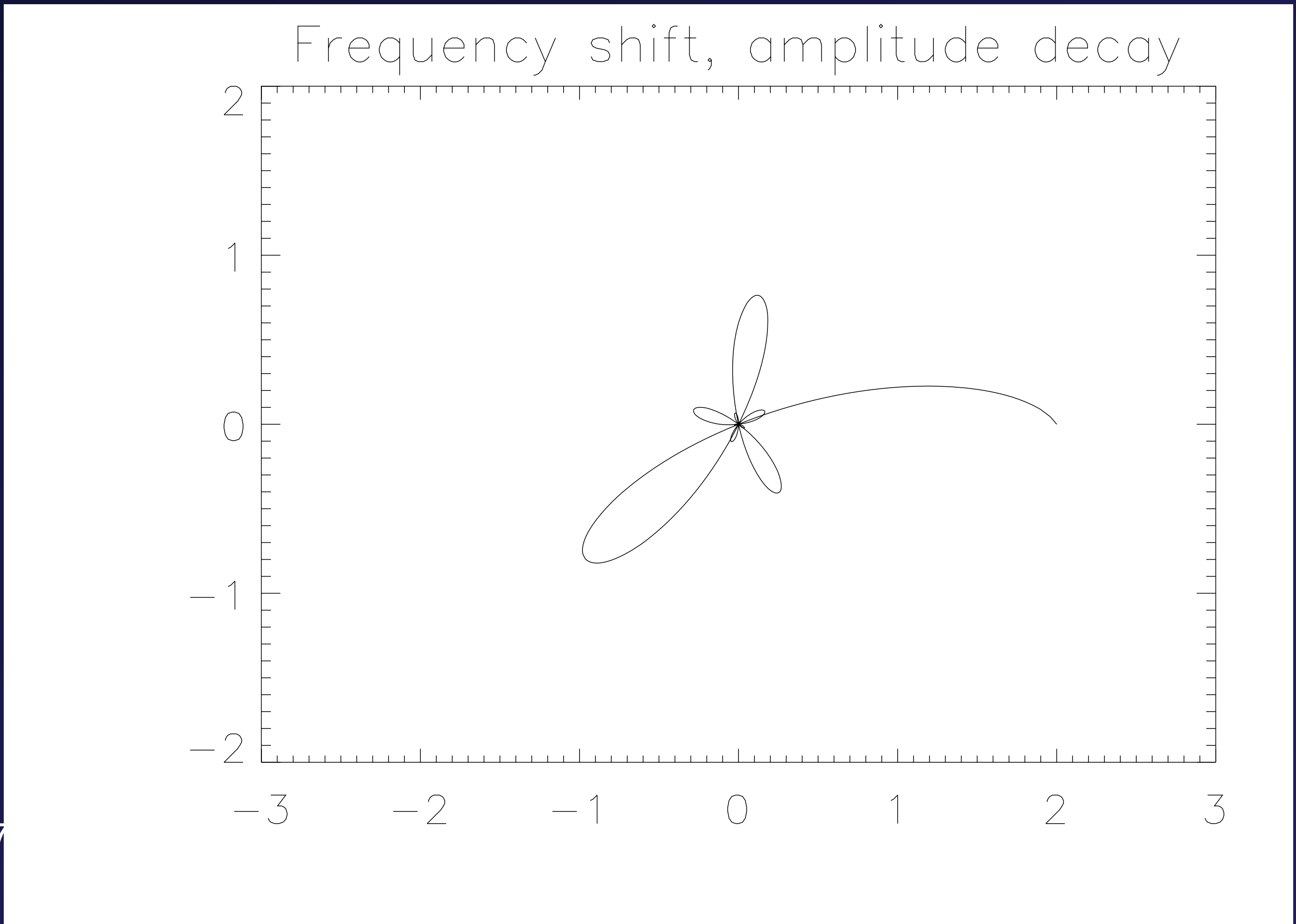


Unresolved Fields and the Hanle Effect

- If the lifetime of the level is much greater than the "precession rate" then the emitted photon can have any polarization azimuth: the signal is completely depolarized.
- However, if the level lifetime is comparable to the rate, then a net polarization change is seen (in total polarization or azimuth).

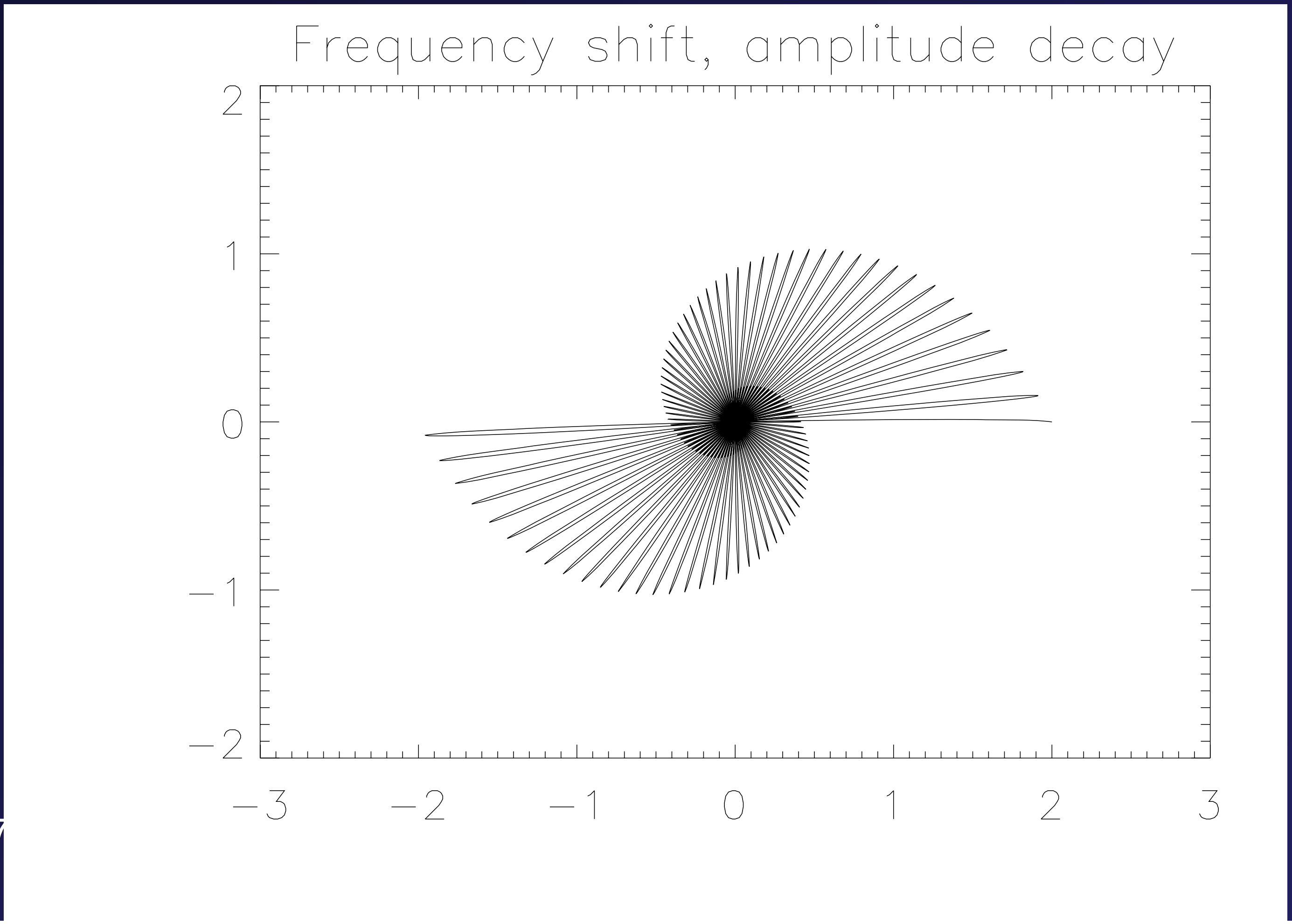
Unresolved Fields and the Hanle Effect

- Net polarization change



Unresolved Fields and the Hanle Effect

- Net polarization change

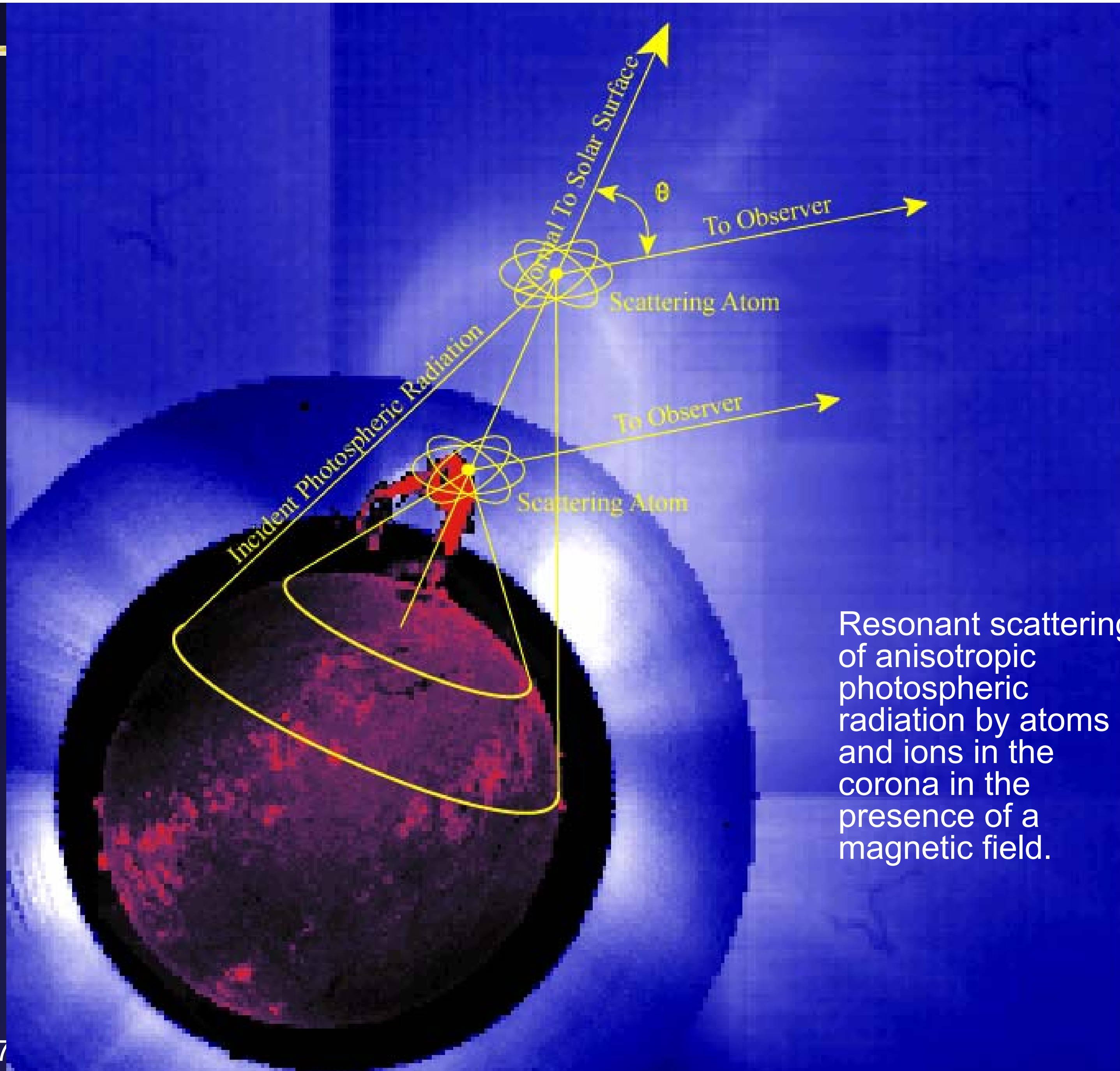


Unresolved Fields and the Hanle Effect

- Investigation of several lines indicate an unresolved weak magnetic field with a strength of about 15G in the upper photosphere (increasing to about 50G in the lower photosphere) which remains undetected with Zeeman studies. (Faurobert & Arnaud, 2003, AA v412 p555)

Coronal Magnetic Fields

- In the corona the lines are very broad and the magnetic field is weak, so the Doppler width is much greater than the Zeeman splitting, even for infrared lines.
- The expected Stokes Zeeman signals are very weak.
- The linear spectra (Q and U) are dominated by the stronger scattering polarization process.
- Work by Lin et al. (also Parker lecture 2007 SPD) represent the leading edge in these measurements.



Composite Image assembled by HAO with data from Solar Maximum Mission and Mauna Loa Solar Observatory

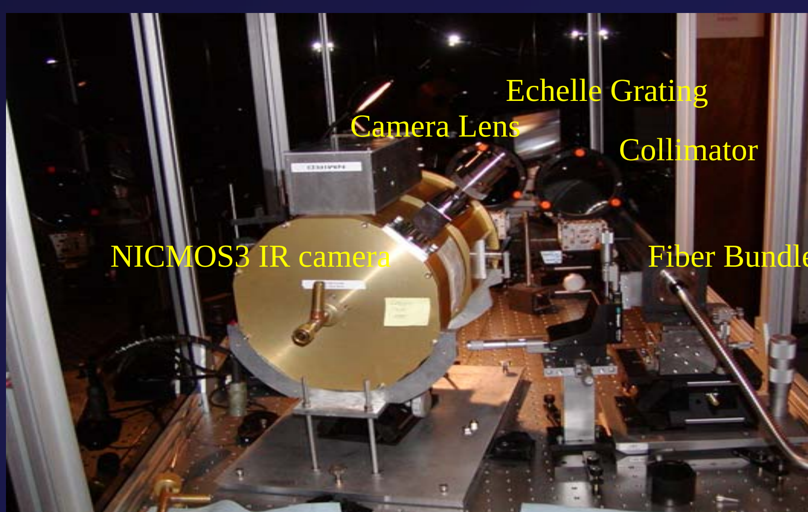
Resonant scattering of anisotropic photospheric radiation by atoms and ions in the corona in the presence of a magnetic field.

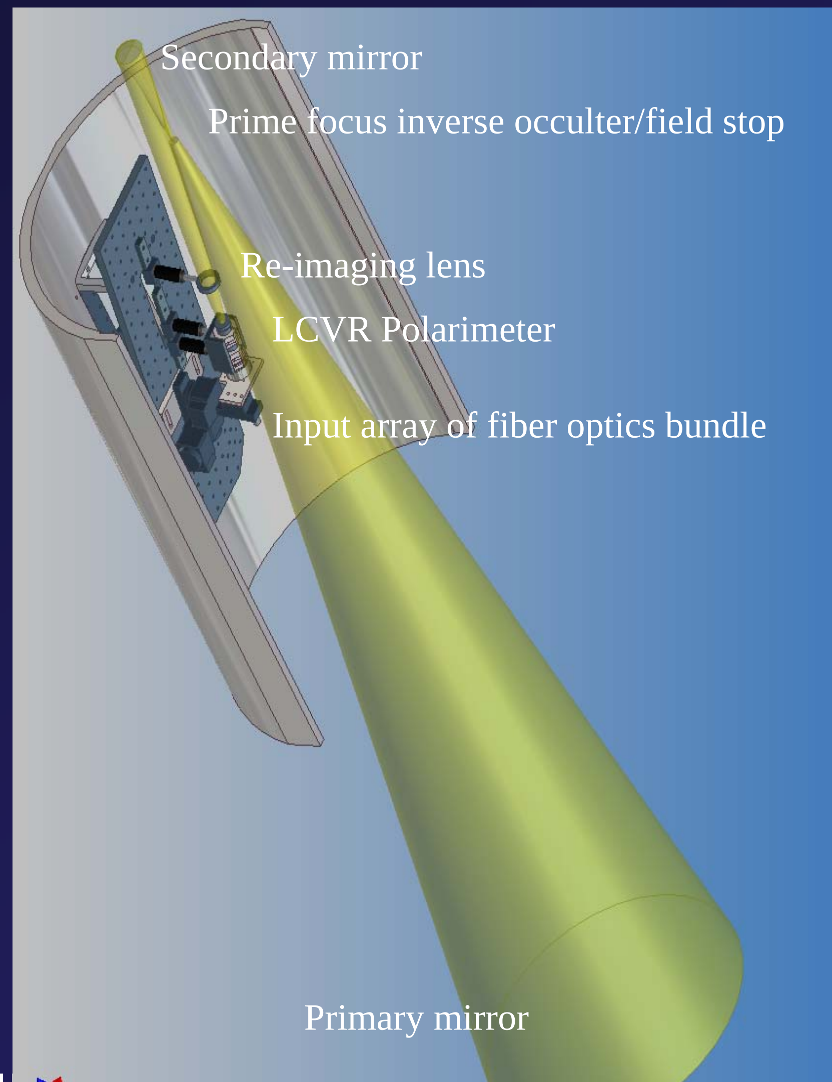
Coronal Magnetic Fields

- **Linear Polarization – Hanle Effect**
  - Orientation of CEL linear polarization maps the orientation of magnetic field projected in the plane-of-sky
  - Not sensitive to the magnetic field strength!
  - Subject to a 90 degree ambiguity (Van Vleck Effect) in field direction.
- **Circular Polarization – Zeeman Effect**
  - Circular polarization of CEL is proportional to the strength of line-of-sight magnetic field
  - The magnetograph formula is modified by an atomic alignment factor that depends on the inclination angle between B and the local vertical direction, and the anisotropy of the incident radiation field.

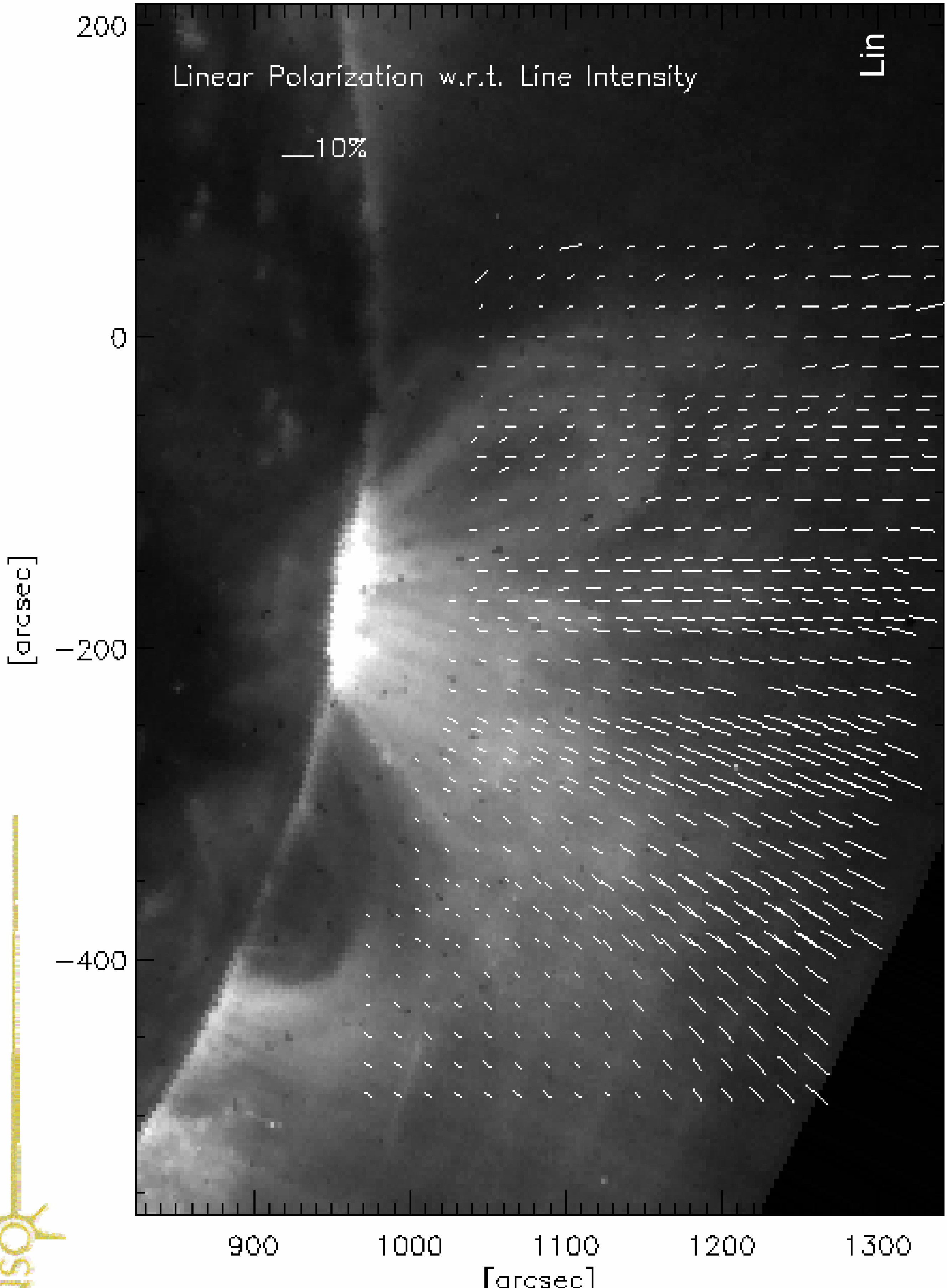
SOLARC and OFIS on Haleakala, Maui

Lin





Optical Configuration of SOLARC and OFIS



Linear Polarization w.r.t. Line Intensity
10%
Lin
200
0
−200
−400
[arcsec]
900
1000
1100
1200
1300
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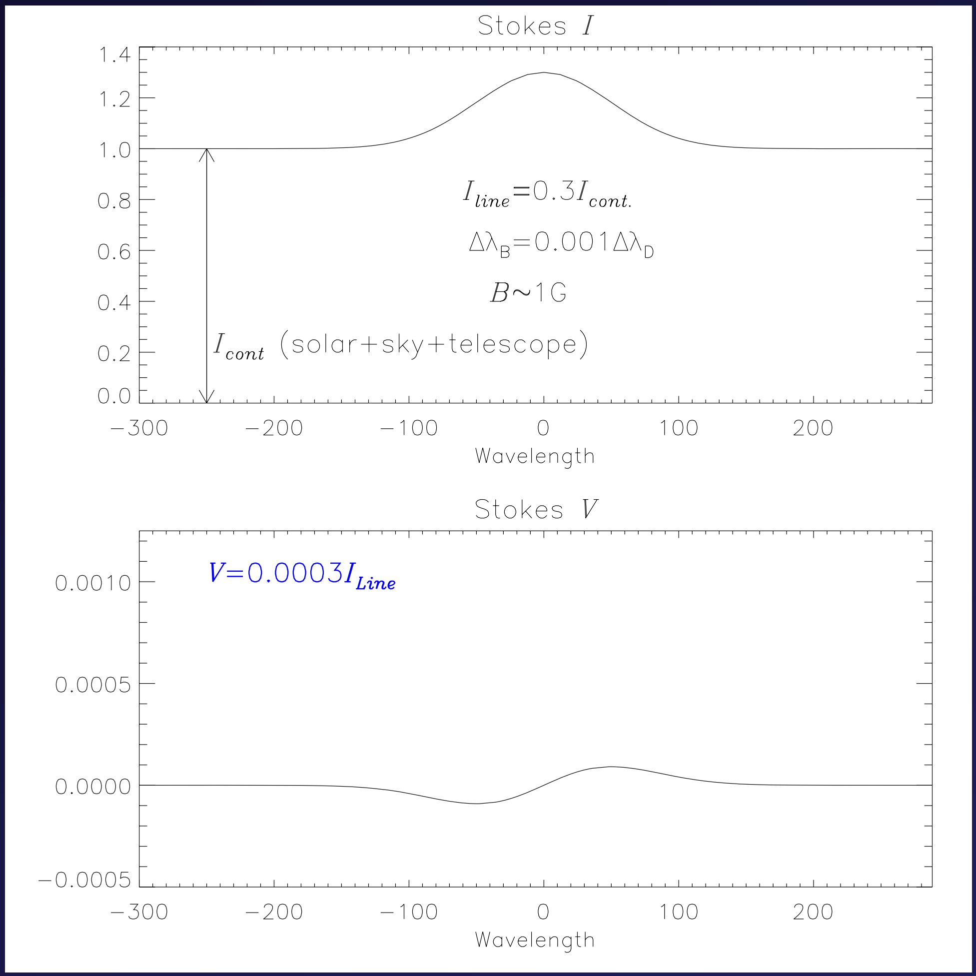
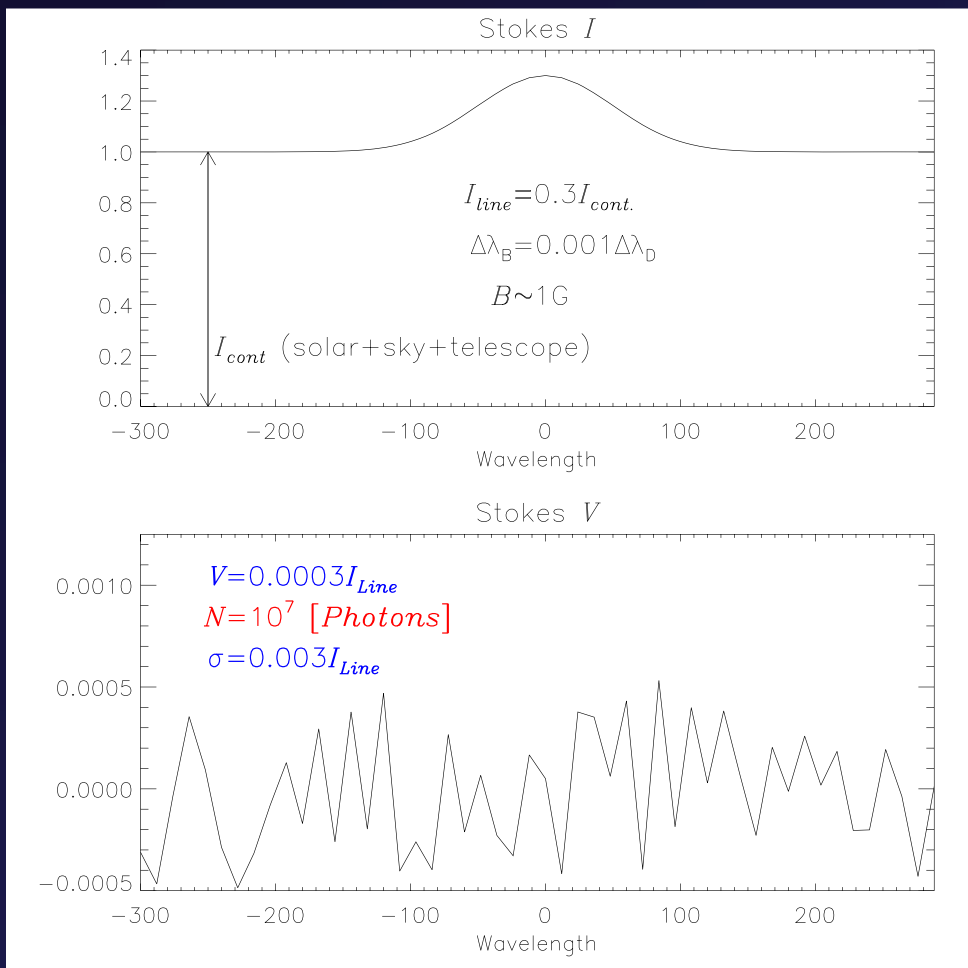
Coronal Magnetic Fields

- **Measurement of the magnetic field strength using Stokes V spectra requires very high signal to noise spectra.**

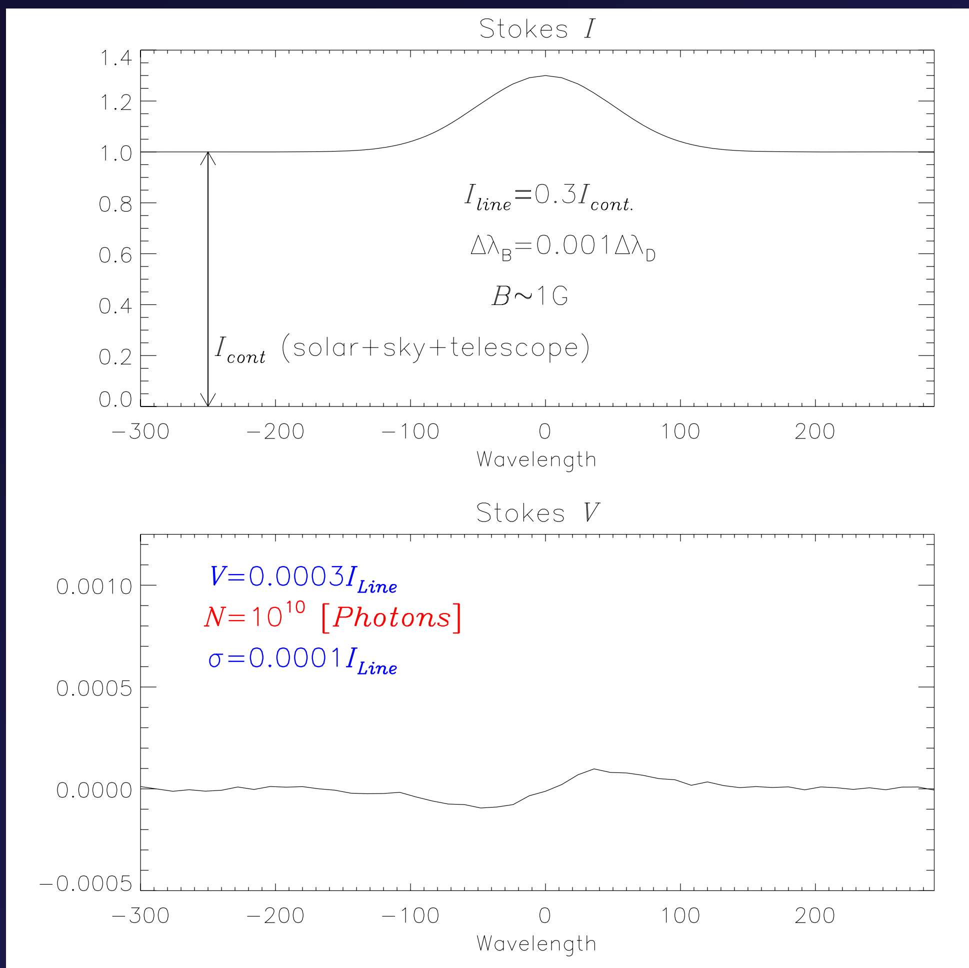
Coronal Magnetic Fields



- In coronal emission-line spectroscopy, the continuum is dominated by telescope scattered light.
- With an "ideal" simulated spectrum, the Stokes V signal is very weak.

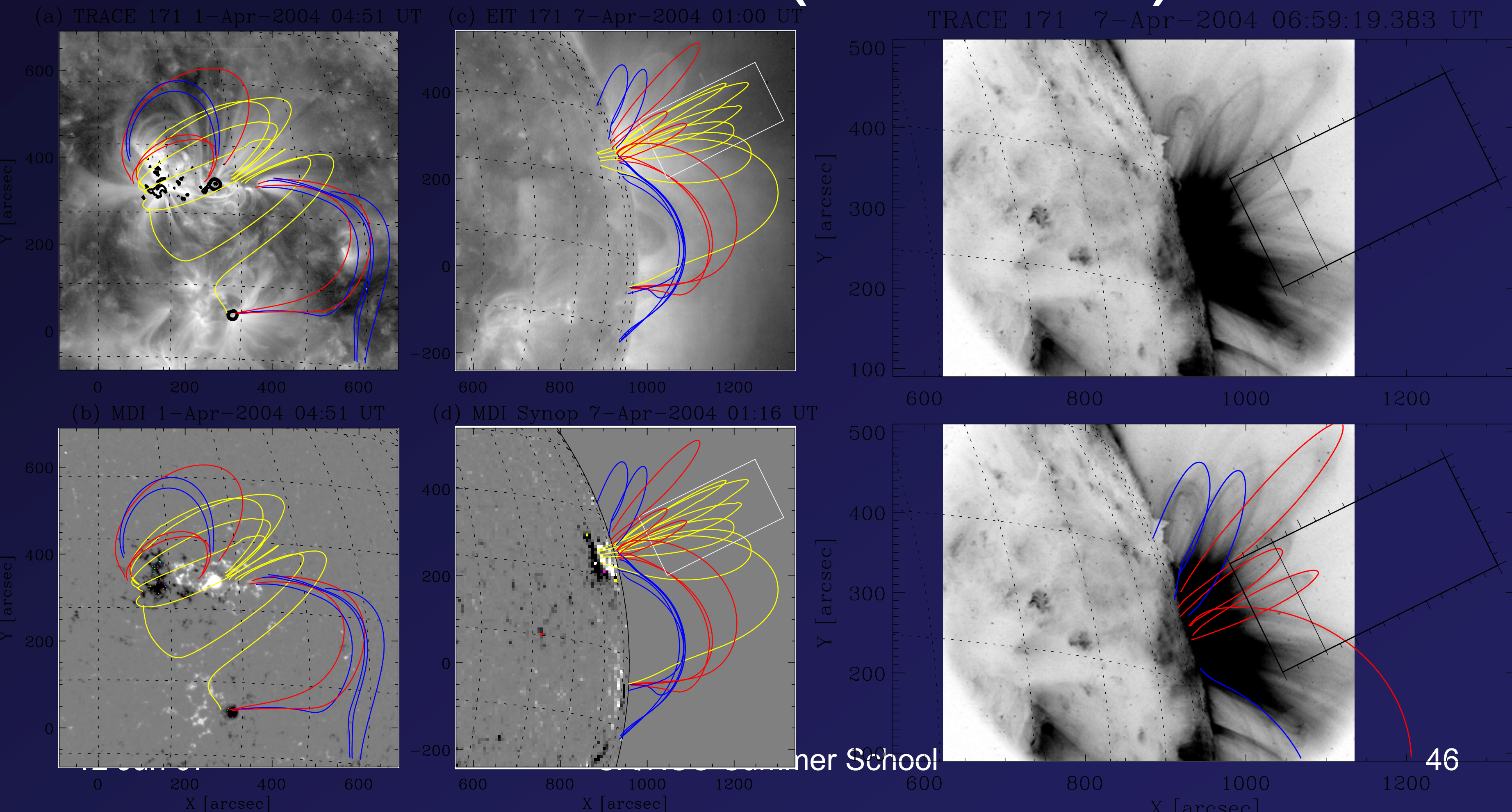


- In the real world, there is noise!
- The “perfect” observed spectrum, one which is completely free of systematic errors, still contains photon noise.
- The photon noise from the scattered light can dominate the Stokes V signal.



- By integrating for enough time to collect enough photons (S/N increases as sqrt(N)), the Stokes V spectrum can be measured.

Potential field Extrapolation of AR 10581 & AR 10582 Observed by SOLARC (Lin et al)



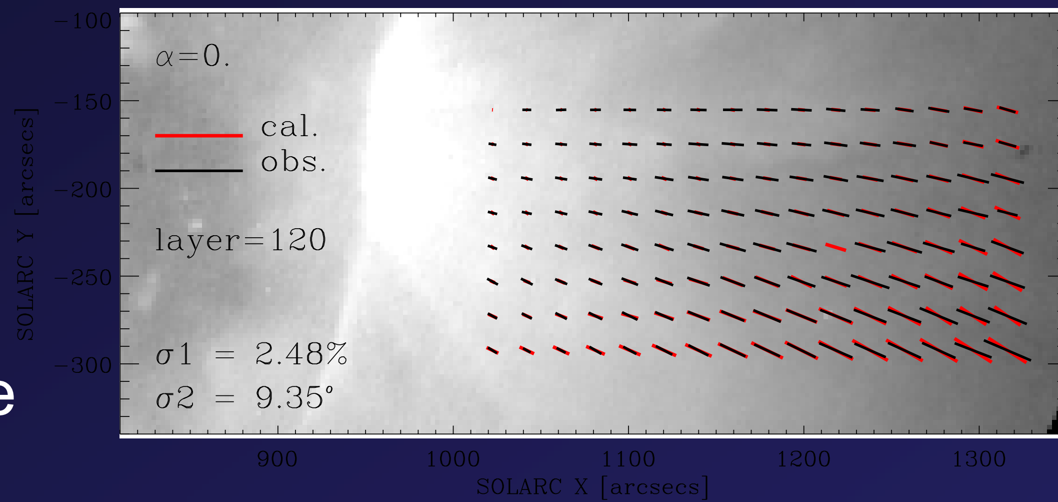
First Observational Test of Coronal Magnetic Field Model

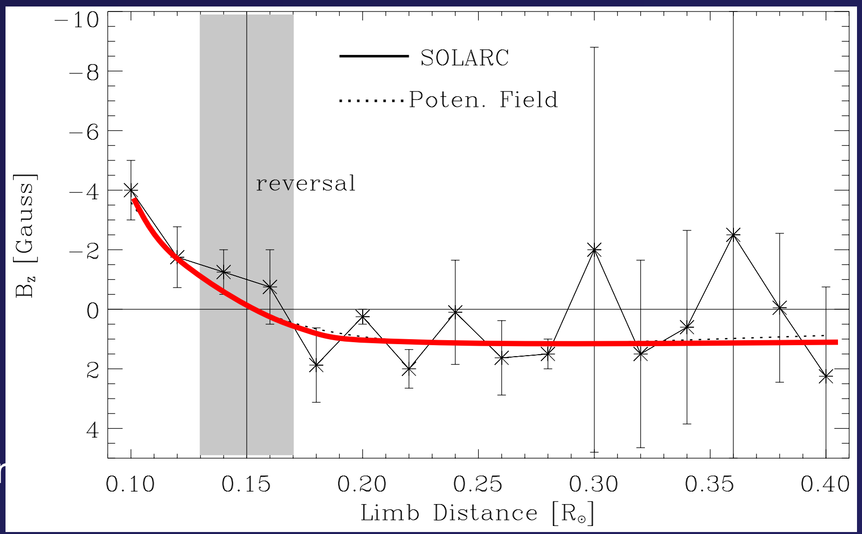
In the case of AR10582…

If we assume that the Fe XIII 1075 nm radiation originates from a (more-or-less) localized source above the sunspot.

See poster in:

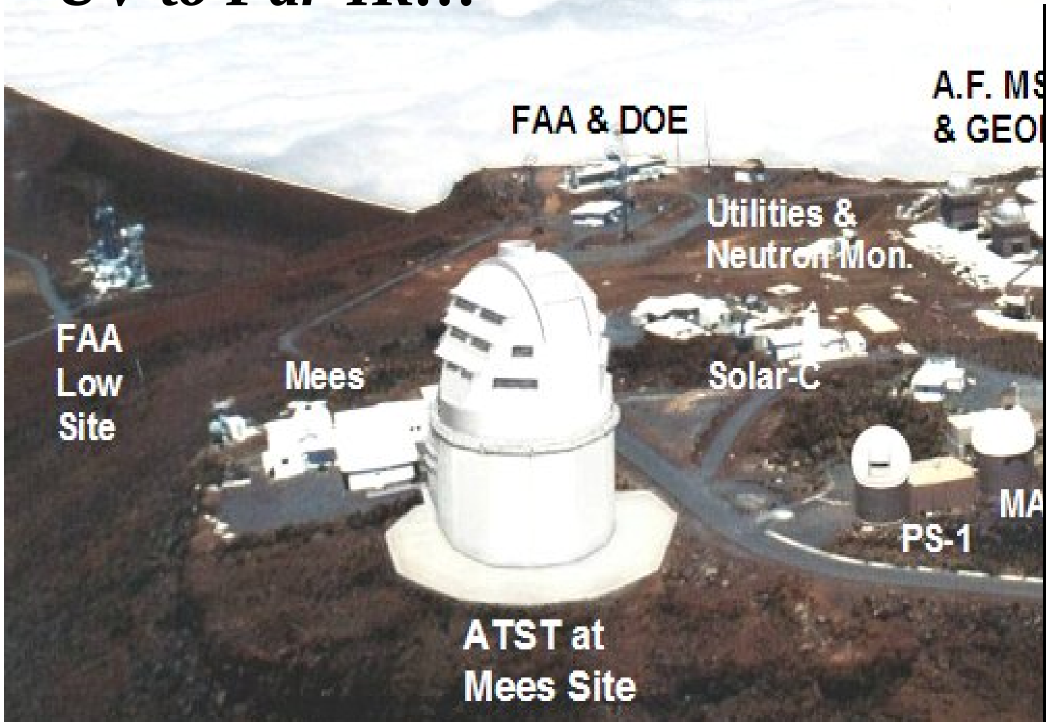
Session 091 *Coronal Magnetic Fields: Observations and Modeling*, Wednesday, May 30, 2007, 10:00 AM, by Y. Liu and H. Lin

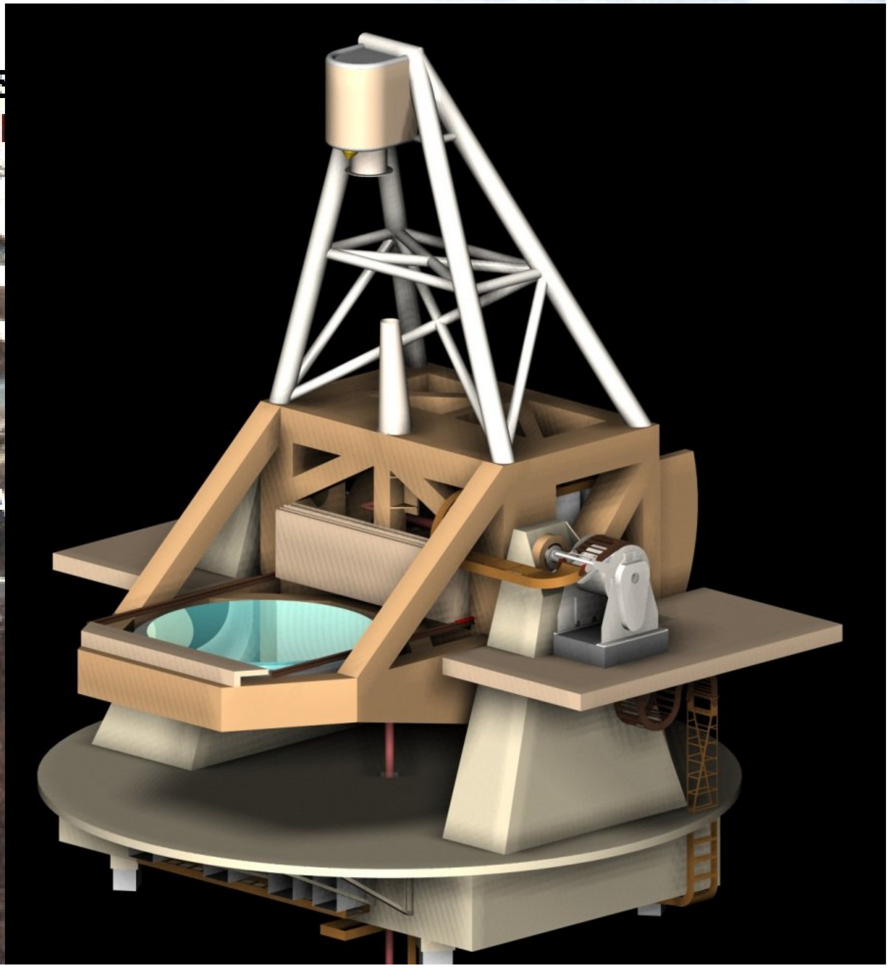




Advanced Technology Solar Telescope on Haleakala, Maui

ATST is a 4-m off-axis coronagraphic telescope designed from the ground up for precision polarimetry with wavelength coverage from UV to Far-IR…



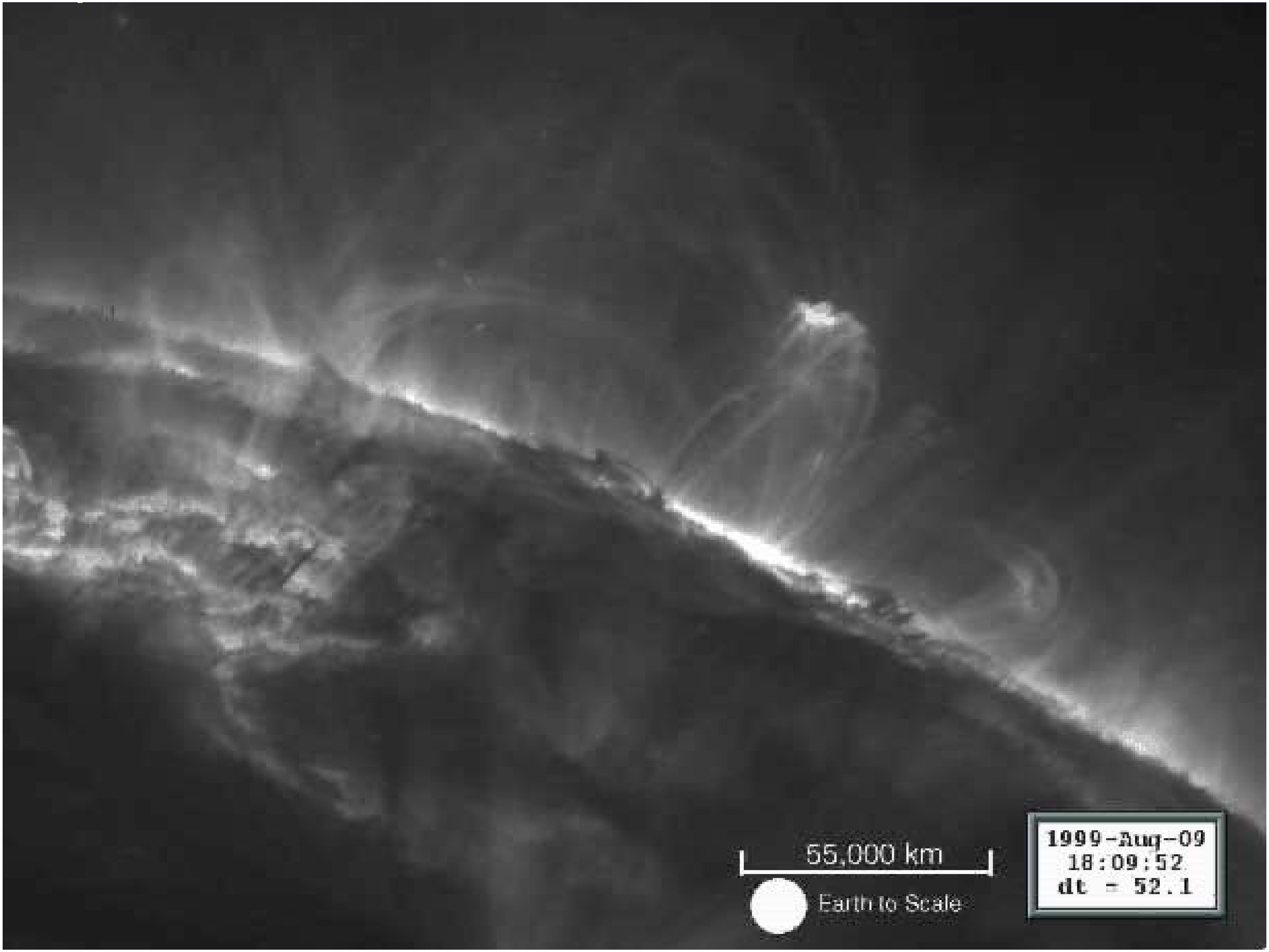


67.00 *What Makes the Advanced Technology Solar Telescope So Advanced?* Kuhn et at.

ATST

- **The ATST will add more photons!**

For a 4m aperture ATST with a mirror roughness of *1.2* nanometers rms with a dust coverage of *0.036%* at a site with a sky brightness of *25* 10^{-6} $B_\odot$ at a wavelength of 1000nm the magnetic sensitivity in a coronal loop with a brightness of *40* millionths at a height of *1.1* $R_\odot$ will be 30^{+30}_{-15} Gauss for a 1 arcsec^2 pixel and an integration time of 1 second.


55,000 km
Earth to Scale
1999-Aug-09
18:09:52
dt = 52.1

Further Reading

- **“Solar Magnetic Fields” – Jan Stenflo**
- **“Solar and Stellar Magnetic Activity” – Schrijver & Zwaan**
- **http://www.astro.uu.nl/~rutten/Astronomy_lecture.html -- Rob Rutten’s lecture notes**

- **References:**
  - **Lin, Parker Lecture SPD 2007, AAS 210, 52.01**
  - **ATST web site: http://atst.nso.edu/**
  - **Roberto Casini's web page (Scattering polarization figures)**
  - **Penn et al. 2004, Solar Physics v222 p61**
  - **Penn et al. 2003, Solar Physics v215, p87**
  - Jefferies, Lites & Skumanich 1989 ApJ v343, 920
  - **Trace movies: http://soi.stanford.edu/results/SolPhys200/Schrijver/index.html**
  - **Hinode data and movies: http://solar-b.nao.ac.jp/latest_e/**
  - **Liu, Y & Lin, H, 2007, AAS 210, 91.05**
  - Meadowlark Optics web page (polarization application notes): http://www.meadowlark.com/products/lcLanding.php