Introduction to Solar Radiative Transfer
III Solar Observations

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Overview

- I Basic Radiative Transfer
  Intensity, emission, absorption, source function, optical depth, transfer equation
- II Detailed Radiative Processes
  Spectral lines, radiative transitions, collisions, continuum processes, Saha-Boltzmann, polarization, Non-LTE radiative transfer
- III Observations of Solar Radiation
  Solar telescopes, spectroscopy, polarimetry

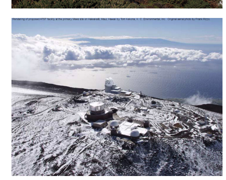
Are solar telescopes special?

- Solar telescopes need to deal with daytime seeing and Sun-generated heat
- The Sun has been observed with telescopes for centuries. To make progress requires both new instruments as well flexible instruments that allow custom setups
- Solar observations are event driven, on time scales of minutes to weeks, again requiring instrument flexibility

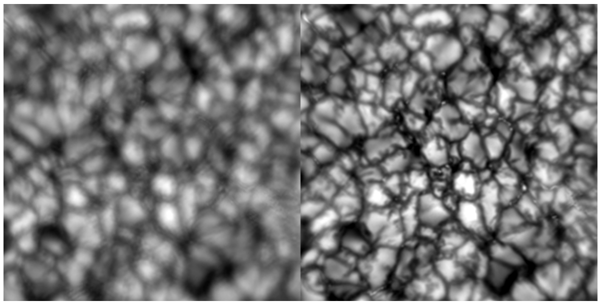
How do we deal with day-time seeing?

Sacramento Peak Observatory

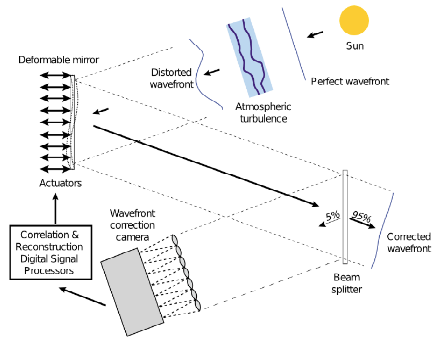
Other telescopes find good places too



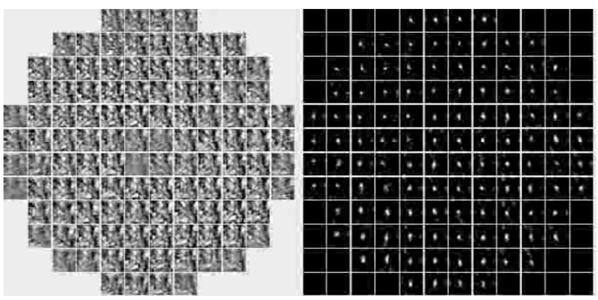
Solar adaptive optics



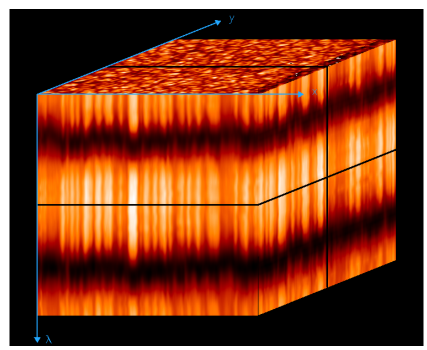
Schematics of solar adaptive optics



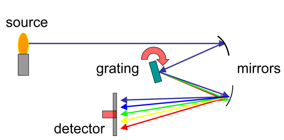
Shack–Hartmann wavefront sensor

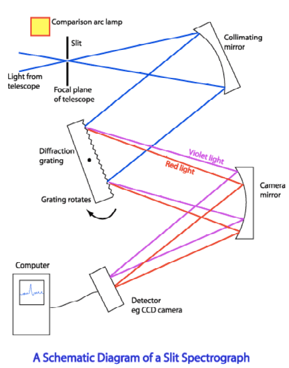


Spectroscopy

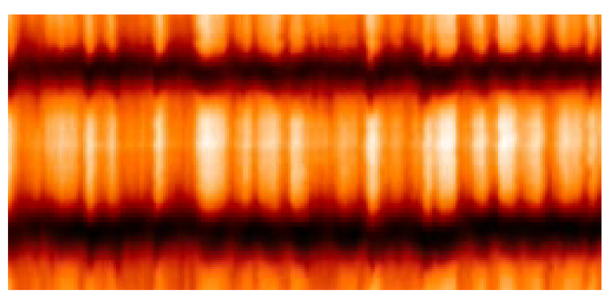


Slit spectrograph

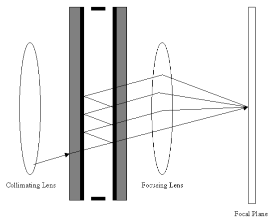


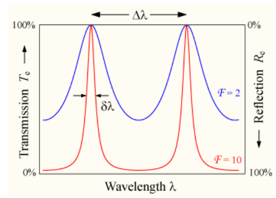


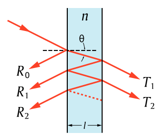
Slit spectrograph observations



Fabry–Perot spectrometer



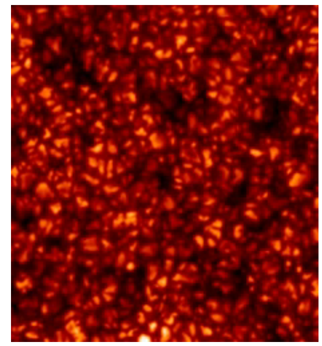




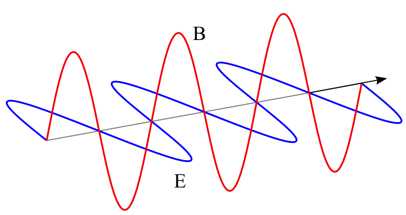
$$\delta = \frac{2\pi}{\lambda} 2nl\cos(\theta)$$

$$T = \frac{1}{1 + F\sin^2(\delta/2)}; \qquad F = \frac{4R}{(1-R)^2}$$

Two-dimensional spectrometer observations



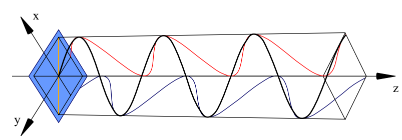
A plane electromagnetic wave



$$E(\vec{r}, t) = (A\sin(kz - \omega t), 0, 0)$$
$$B(\vec{r}, t) = (0, A\sin(kz - \omega t), 0)$$

General description of polarized light

$$E(\vec{r}, t) = (A_x\cos(kz - \omega t), A_y\cos(kz - \omega t + \phi), 0)$$



Linear Polarization:

$$A_x = A_y$$
$$\phi = 0$$

General description of polarized light

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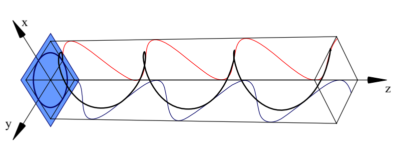
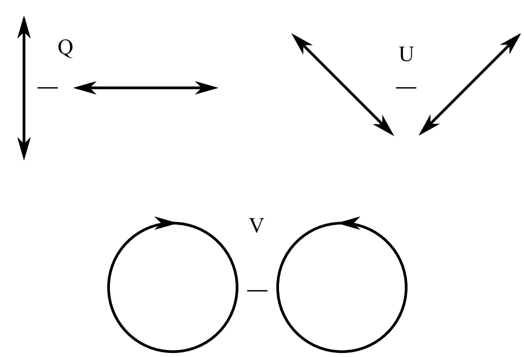


Circular Polarization:

$$A_x = A_y$$
$$\phi = 90$$

Stokes parameters



Stokes parameters related to polarized plane wave

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} A_x^2 + A_y^2 \\ A_x^2 - A_y^2 \\ 2A_xA_y\cos(\phi) \\ 2A_xA_y\sin(\phi) \end{pmatrix}$$

Partially polarized light

- Most sources of electromagnetic radiation contain a large number of atoms or molecules that emit light. The orientation of the electric fields produced by these emitters may not be correlated, in which case the light is said to be unpolarized
- If there is partial correlation between the emitters, the light is partially polarized
- Partially polarized light can be descripbed as the superposition of a completely unpolarized component, and a completely polarized one
- Degree of polarization:

$$P \equiv \left(\frac{Q^2 + U^2 + V^2}{I^2} \right)^{1/2}$$

Stokes parameters give full description of polarized radiation field

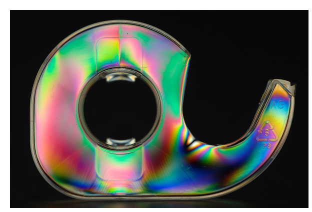
- The 4-element Stokes vector $S = (I, Q, U, V)$ give a full description of the intensity and polarization state of the radiation field
- Interactions of the polarized radiation field with material can be described through 4×4 matrices, the so-called Müller matrices M.

$$S_{\text{out}} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{\text{out}} = M \cdot S_{\text{in}} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \cdot \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{\text{in}}$$

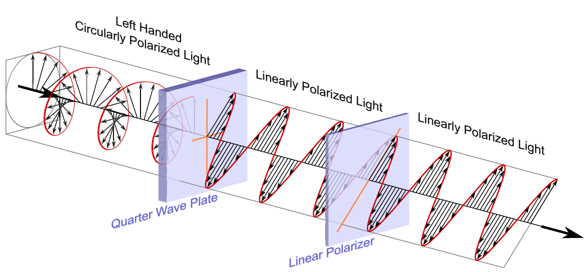
- Based on constraints that follow from the process it describes the Müller matrix M has 16 elements, of which only 7 are independent

Polarization altering materials

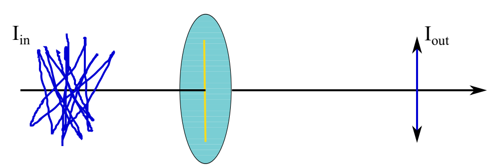
- Birefringent: Media in which the two modes accrue a differential propagation delay. Example: wave plate
- Dichroic: Media in which the amplitude of waves propagating in one of the modes is reduced. Example: polarizer



Linear polarizer and quarter-wave plate



Müller matrix for a linear polarizer



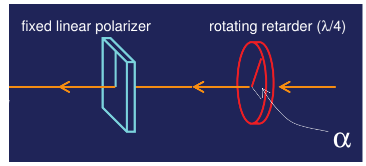
$$S_{\text{out}} = \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} I \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} I/2 \\ I/2 \\ 0 \\ 0 \end{pmatrix}$$

Müller matrix for a quarter waveplate at ± 45 degrees

$$S_{\mathrm{out}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \mp 1 \\ 0 & 0 & 1 & 0 \\ 0 & \pm 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ \pm 1 \end{pmatrix}$$

Modulation optics

Optical system whose Mueller matrix can be (strongly) varied upon changing a set of control parameters.

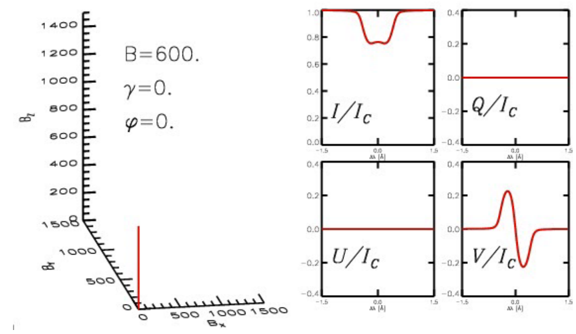


$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{\mathrm{out}} = \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix} \left[\overline{I} + \cos^2(2\alpha)\overline{Q} + \sin(2\alpha)\cos(2\alpha)\overline{U} + \sin(2\alpha)\overline{V}\right]$$

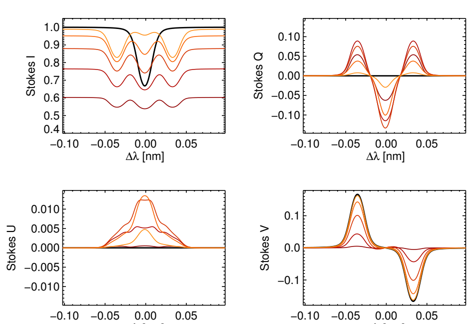
Polarimetric calibration of instrument and telescope

- The light path through a telescope typically includes oblique reflections, which introduce linear polarization and retardance (from the mirror coatings), and passage through windows, which may induce birefringence.
- Ideally one would like to use a calibration package (which produces known polarization states) in front of the telescope. But such large scale polarizing optics does not exist
- Instead, therefore a theoretical expression for the Mueller matrixes of all individual optical elements forming the telescope is used (given the geometry the light path, complex refractive indexes of the mirrors, specific retardances of the windows, etc.). One can use this Mueller matrix to correct the measurements

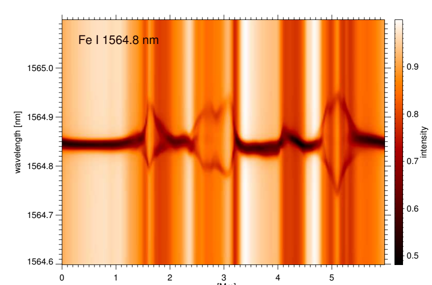
Variation of the Stokes parameters with properties of B



Stokes profiles of the Fe I 1564.8 nm line at different angles



Stokes profiles of the Fe I 1564.8 nm in magneto-convection

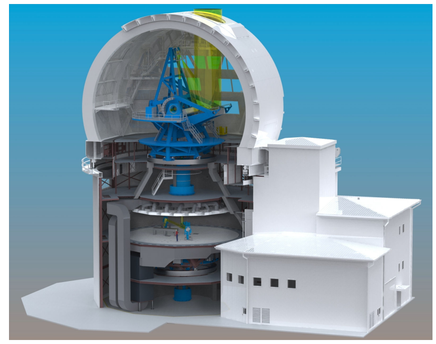


$$\Delta\lambda = \left(\frac{e}{4\pi mc}\right) g_{\mathrm{L}} \lambda_0^2 B_{\mathrm{LOS}}$$

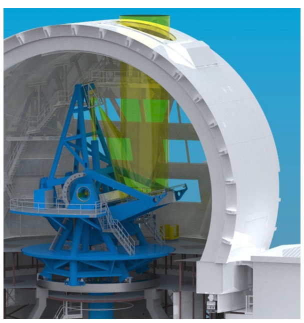
why do we want a bigger telescope?

- Better spatial resolution: $R = 1.22\frac{D}{\lambda}$. For a telescope like the DST ($D = 0.76\text{m}$) $R = 0.166''$.
- Bigger light bucket. Per resolution element the rate of photons is the same (for a resolved object), but for the same resolution the bigger telescope catches D^2 more photons. Important for polarization.
- With higher photon rates better temporal resolution becomes possible.

ATST



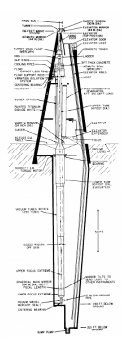
ATST an important part of the future of solar physics



- ATST will be a 4-meter off-axis Gregorian telescope
- Very high order Adaptive Optics system
- Dome with vents, forced ventilation
- Dome, primary and heat stop cooled
- Instrumentation and polarimetry integrated part of design
- Wide wavelength range (300–5000 nm)

End Part III

Schematics of the Dunn Solar Telescope



- Tall to stick out above the seeing layer
- Long focal length, not to concentrate heat
- Inner tube vacuum or fill with helium to preserve image quality

DST on Sacramento Peak