Model studies of the solar limb shape variation with wavelength within the PICARD project.

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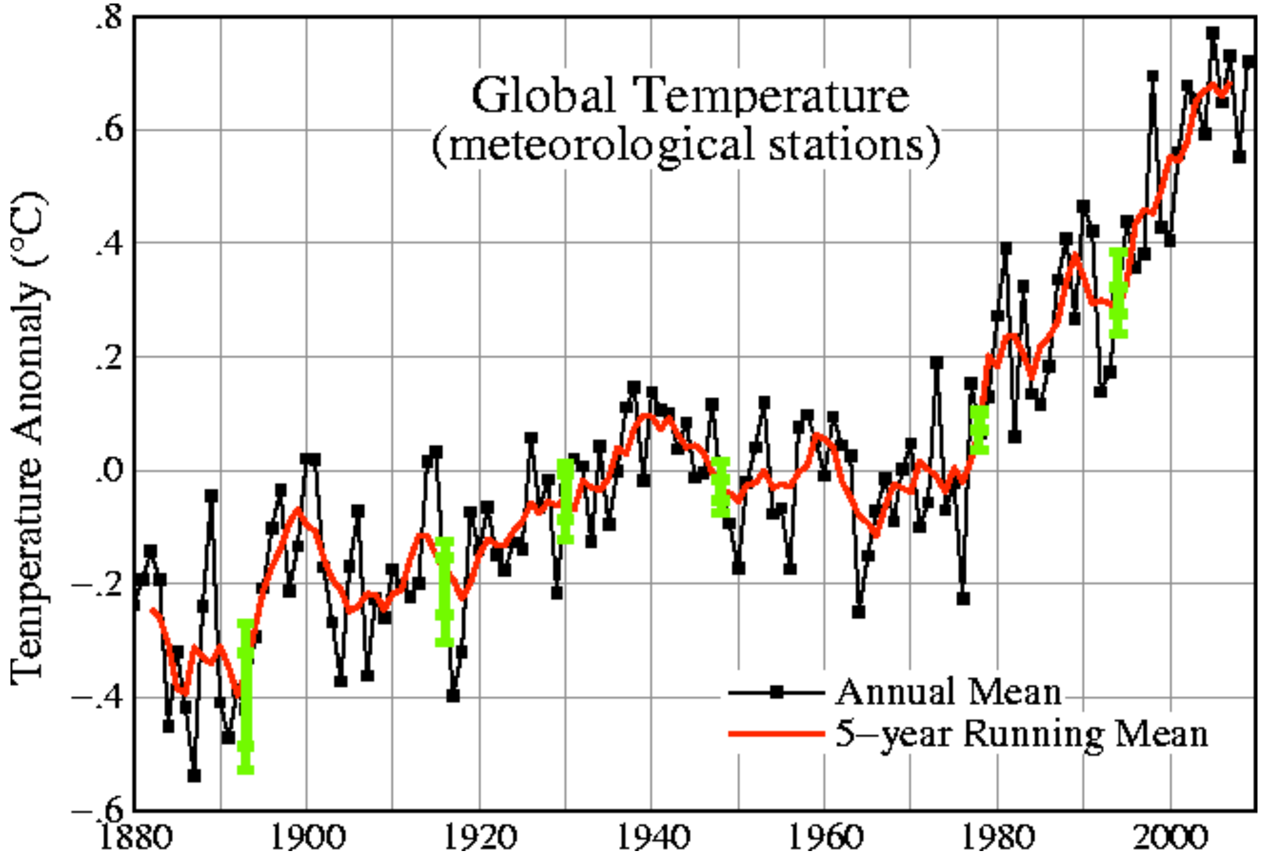
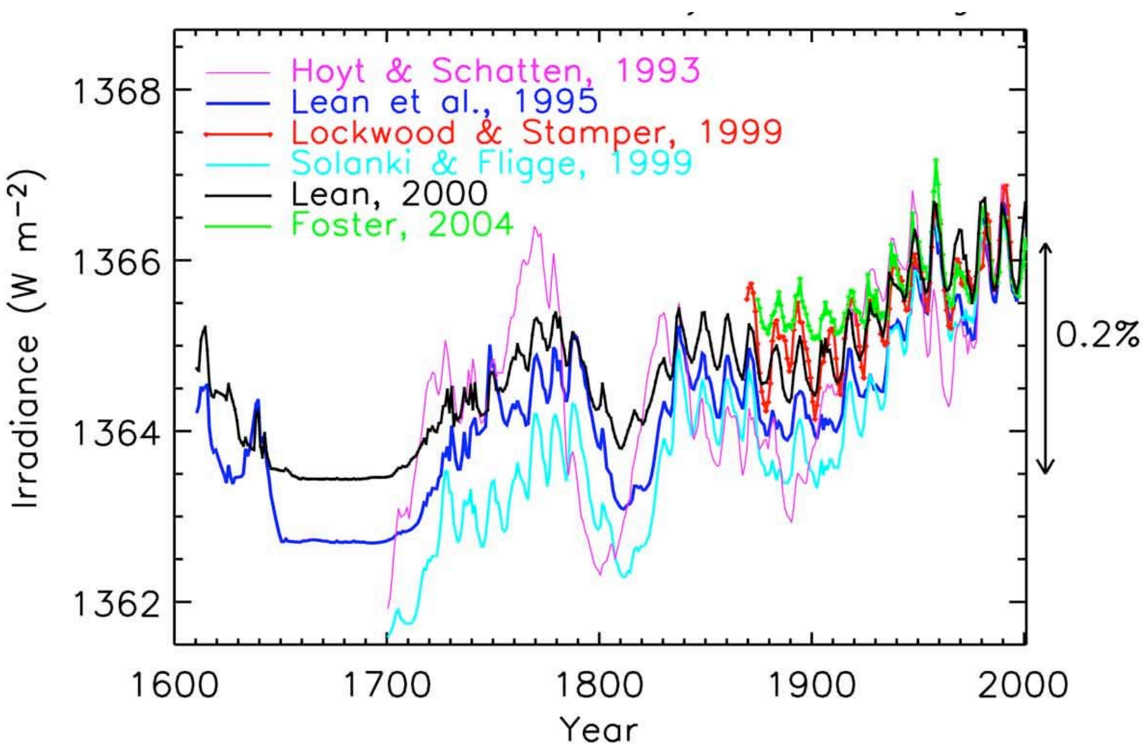
Motivation: the climate is changing



- Can we separate natural from anthropogenic forcing?
- Can we quantify?
- Can we clearly attrtibute?

For climate studies we need to reconstruct luminosity variability back in time AND we need to be able to forecast



Reconstructions are based on different hypothesis and different data sets.

Reconstructions disagree at certain periods and disagreements increase towards the past.

PICARD

- PICARD measurements will allow us to test the hypothesis:

$$W = d\ln R / d\ln L$$

Furthermore, the centre to limb variation, the limb shape and its variability with wavelength can provide important insights to test solar atmosphere models

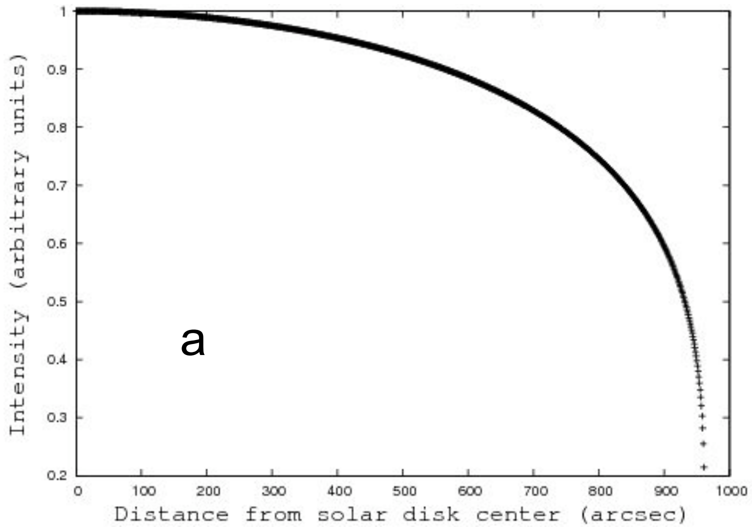
Solar Centre to Limb Variation (CLV)

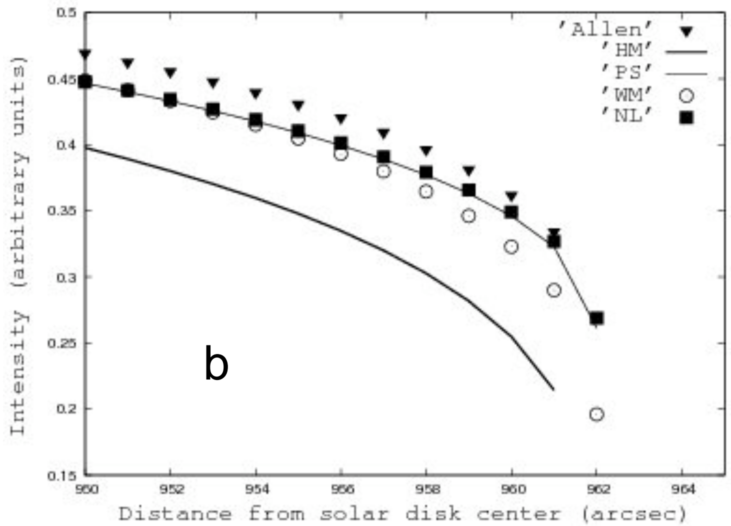
- CLV contains information about the solar photosphere that can not be derived from observations of the disk centre
  - At the limb the optical depth of the solar atmosphere steeply decreases and becomes optically tin resulting in a drop of emerged intensity over the entire solar spectrum
  - The CLV is an important characteristic to constrain/test models.

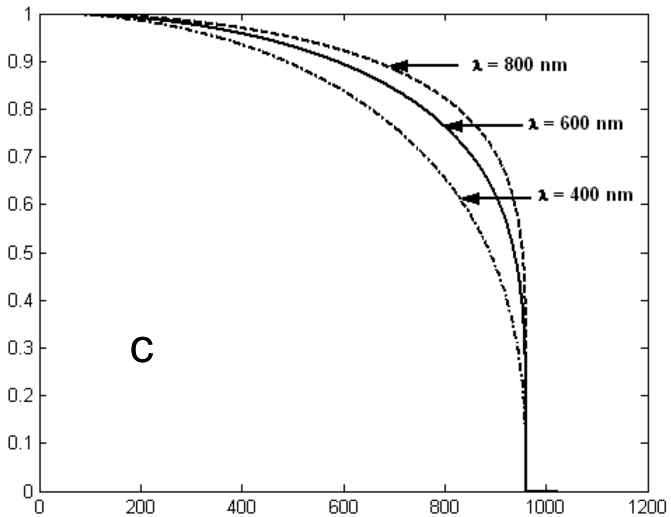
Solar limb measurements

Authors	Acronym	Pupil (cm)	Wavelength (nm)	Time Period	S/M
Allen, 1973	A73	unknown	200-10000	01/52-12/61	M
Pierce and Slaughter, 1977	PS77	152	303.327-729.675	03/74-01/75	S
Pierce, Slaughter & Weinberger, 1977	PSW77	152	740.46-2401.80	Fall/74, 06/75-08/75 03//76-06/75	S
Walter & Mitchell, 1981	WM81	61	299.71-565.65	08, 09 /75	S
Neckel & Labs, 1994	NL94	152/159	303.3-1089.9	01/86-12/90	S
Hestroffer & Magnan, 1998	HM98	152/159	303.327-2401.80	0174-12/90	M

Solar limb measurements







a. left up panel: Solar limb profiles for λ=559.95 nm according to HM98 (solid line), PS77 (thin line), and NL 94(squares). The A73 (triangles) and WM81 (open circles) measurements are given at 600 nm, and 565.65 nm, respectively.

b. right up panel: a close up of a.

c. lower panel: Intensity solar limb profiles calculated using HM98 model for different wavelengths.

Solar models (1/6)

The VAL81 (Vernazza at al, 1981) solar atmosphere model:

Consists of 6 solar atmosphere models corresponding to different brightness components of the solar atmosphere, ranging from dark cell centers to very bright network elements. Based on Skylab measurements of the quiet Sun.

Solar models (2/6)

The FCH09 solar atmosphere model:

- *Developed by Fontenla et al. (2009), consists of a semi-empirical model including inter-granular cells, network lanes, enhanced network, plage and faculae. Include the lower and upper chromosphere as well as the transition region. Non-LTE is considered. For the transition region and corona, the level populations are calculated as optically thin.*
- *In this work the limb profiles are calculated using the FCH09 atmosphere and the Solar Radiation Physical Model (SRPM) System that includes spherical symmetry.*

Solar models (3/6)

The PHOENIX model:

Consists of a theoretical multi-purpose one dimensional stellar atmospheric model and spectral synthesis that solves the radiative transfer equation under spherical symmetry and horizontal homogeneous atmospheric layers (Hauschildt and Baron, 1999).

Includes the complete line lists of Kurucz (1992), as well as continuous transitions, from many atoms, ions and diatomic molecules with the extinction computed under the approximation of local thermodynamic equilibrium (LTE).

The continuous photo-ionization opacity from metals is computed with the cross sectional data of Reilman and Manson (1979) or those compiled by Mathisen (1984).

PHOENIX computes the atmospheric structure in pure radiative/convective thermal equilibrium, and does not reproduce the chromospheric and coronal heating of the outer atmosphere exhibited in the Sun.

PHOENIX models applied to the Sun, represent the photosphere below the temperature minimum (Tmin) in the quiet Sun conditions.

To facilitate comparison with the Mein model, we are using a Phoenix model computed in LTE with line opacity neglected.

Solar models (4/6)

The Code for Solar Irradiance model (COSI):

- *COSI (Haberreiter et al. 2008a, b; Shapiro et al 2009) calculates the solar spectral irradiance from a given temperature and density structure and given composition.*
- *COSI calculates the NLTE populations for 61 ions and 114 energy levels by solving the radiative transport equations simultaneously with the equations for statistical equilibrium. The model accounts for the elements from hydrogen to zinc.*
- *The radiative transfer equation is solved in spherical symmetry.*

Solar Models (5/6)

The Mein model: quiet Sun conditions:

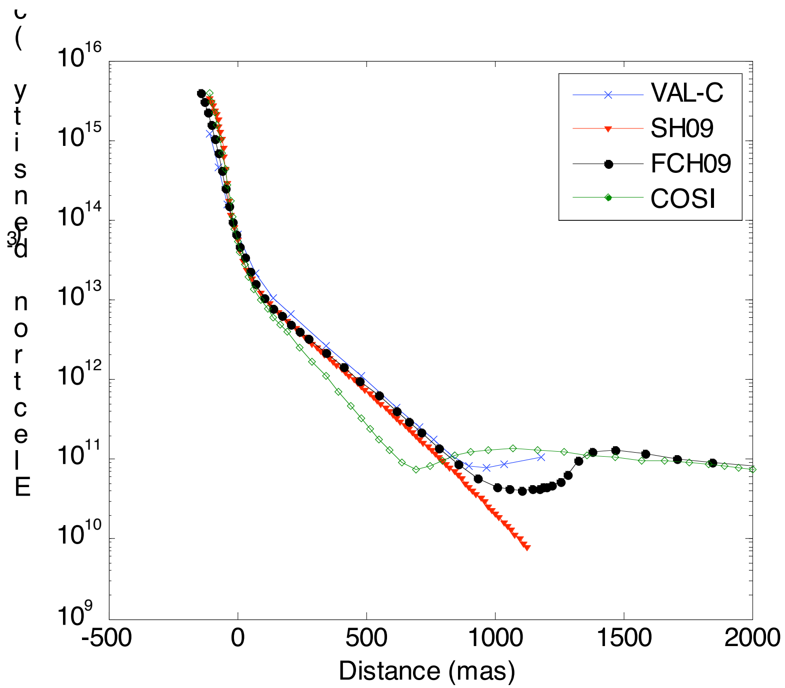
- *Consists of a radiative transfer model that uses a 1D atmosphere structure, a given set of opacities, with a spherical symmetry approach to calculate the intensity $I(\lambda)$ as a function of wavelength.*
- *The integration of the transfer equation is performed over a number of slabs of the solar atmosphere crossed by the line of sight:*

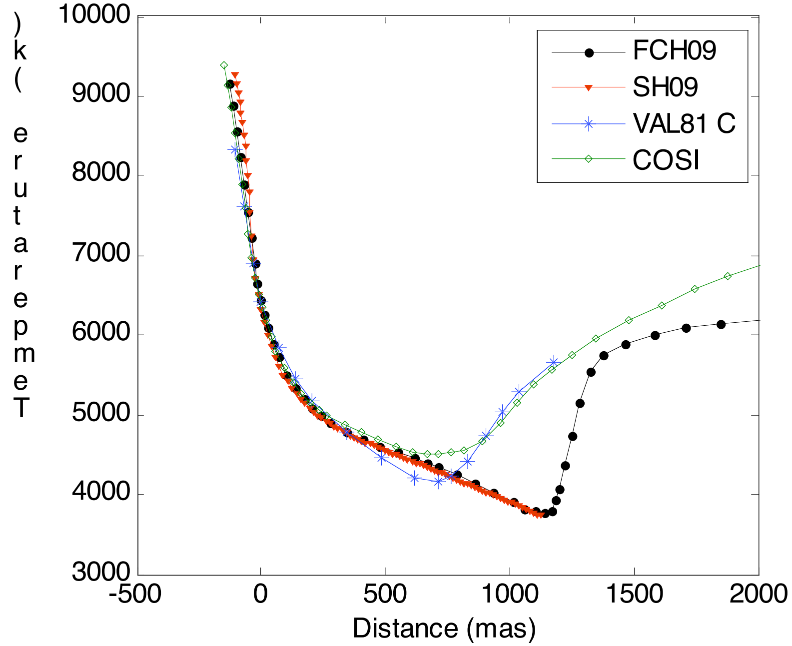
$$I(\nu) = \int S(z) \exp(-\tau\nu(z))\, k\nu(z)\, dz$$

where z is the distance along the line of sight, S(z) the source function and $k\nu(z)$ the absorption coefficient at position z. The optical depth $t\nu(z)$ is defined by $\int k\nu(z')\, dz'$, with z' between 0 and z.

- *The Mein model assumes local thermodynamic equilibrium (LTE) and represents the source function S(z) by the Planck function.*
- *The limb profiles are calculated using atmospheric temperature, density of neutral hydrogen, electron density, and density of protons covering at least the region from -70 km to 800 km with respect to $\tau_{500}=1$.*

Solar atmosphere models (6/6)





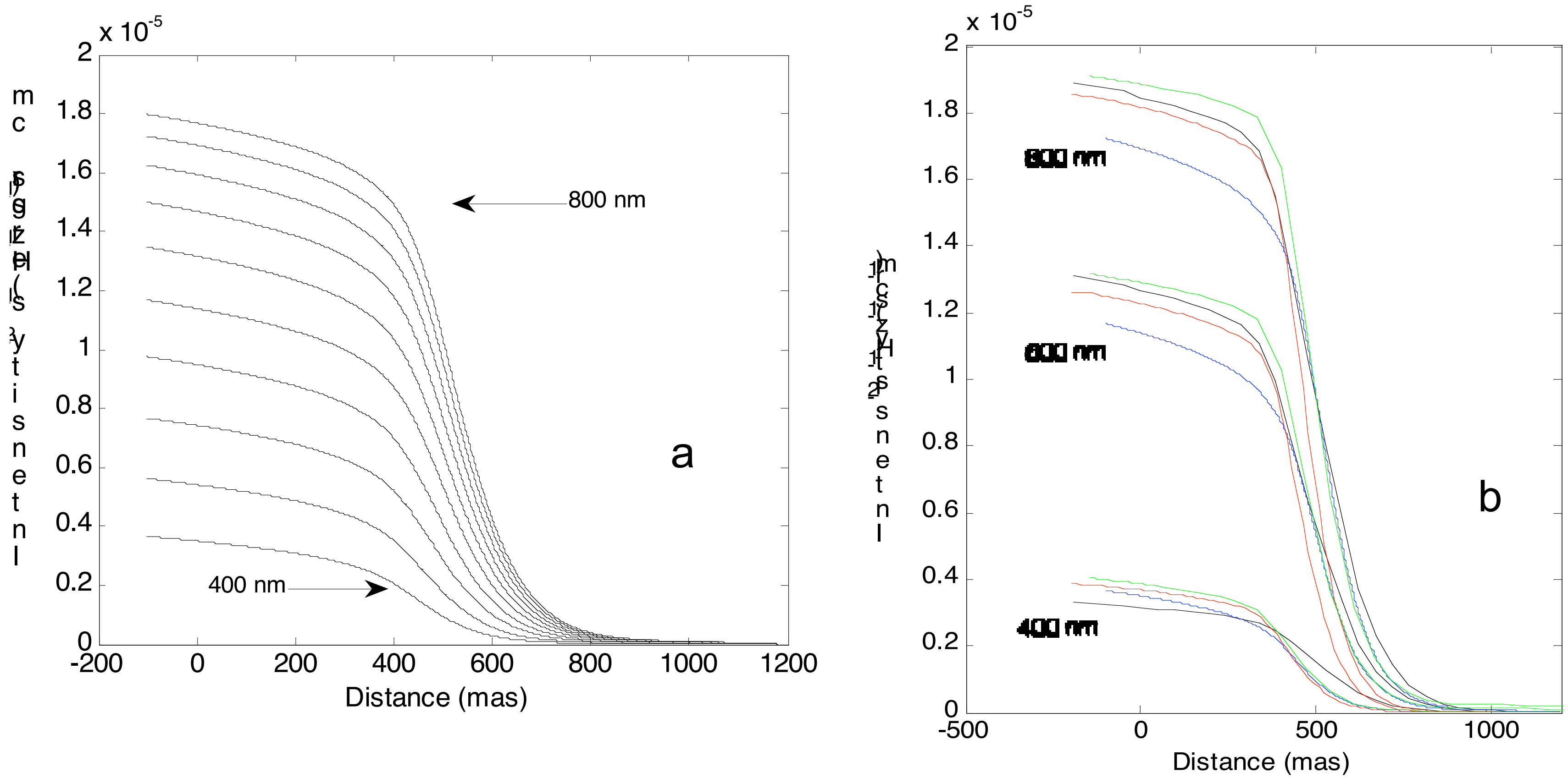
VAL-C, SH09, FCH09, and COSI (quiet Sun) solar atmosphere temperatures and electron density.

Limb shape and inflection point position calculated using different models

Model simulations:

code	Atmosphere	Opacities	normalization (nm)	Reference inflection point (mas)
Mein	VAL81 C	Straka 2006	400	444.
Mein	SH09	Straka 2006	400	420.
Mein	FCH09	Straka 2006	400	439.
Mein	FCH09	FCH09	400	454.
SH09	SH09	SH09	400	636.
FCH09	FCH09	FCH09	450 *	433.
COSI	COSI	COSI	400	432.

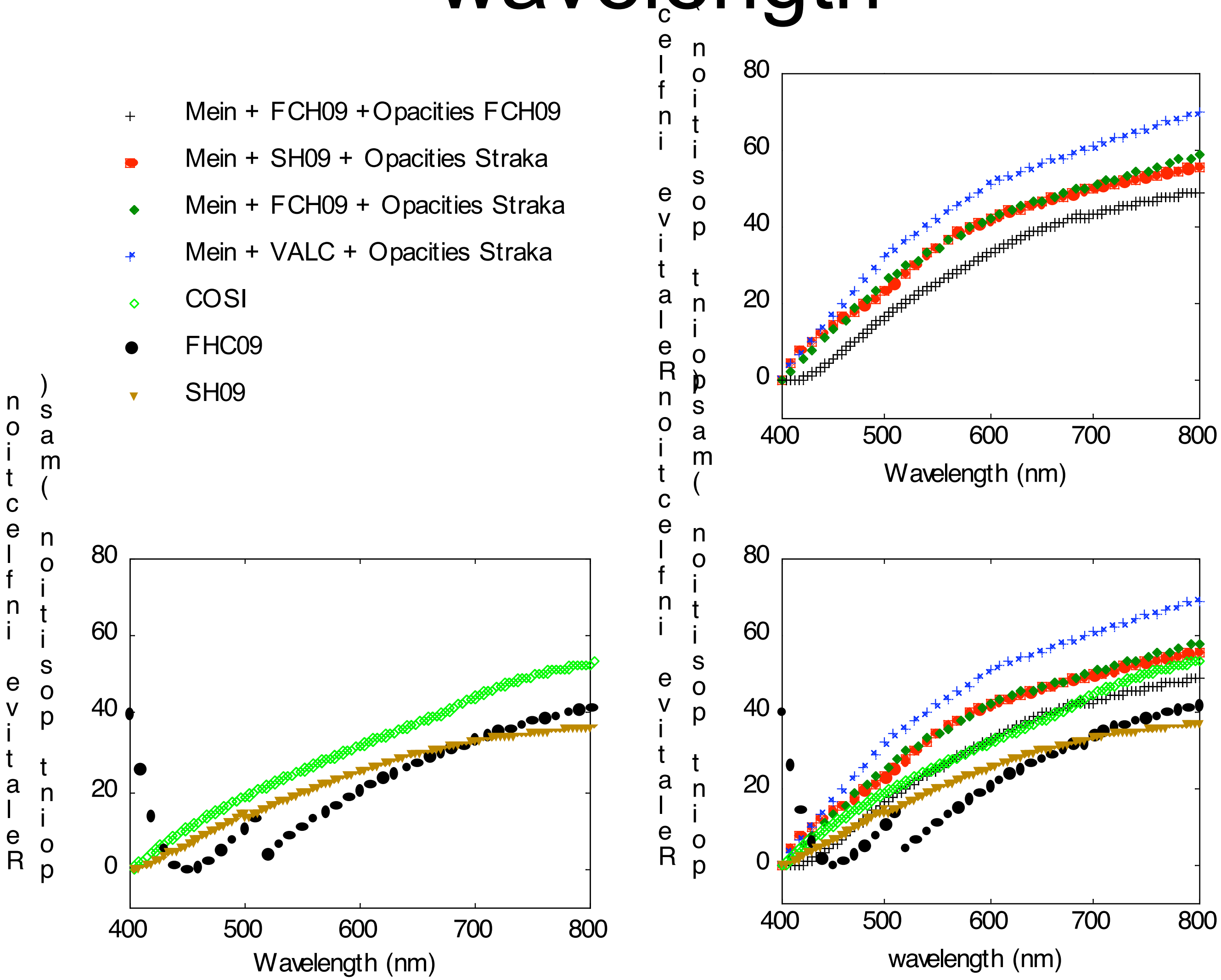
Solar limb calculations



a. Left panel: variation of the limb shape with wavelength using VALC atmosphere and Mein model;

b. Right panel: Limb shape for three wavelengths predicted by SH09 (red curve), FCH09 (back curve), VAL-C (blue curve), and COSI (green curve).

Variation of the inflection point with wavelength



Summary

- We looked in detail at the properties of several solar atmosphere models. For example, certain models represents the chromosphere while other models do not include this representation.
- The position of the inflection point is wavelength dependent and the slope of this variation is different for each model since it depends on the temperature, electron density and opacities in a complex way. Furthermore, it also depends on the radiative transfer assumptions (LTE or non LTE).
- The SODISM/PICARD data will allow us to validate the solar atmosphere structures as a function of the activity cycle.