Velocity Field Diagnostics of the Quiet Sun Using the Lambda-Meter Method: Si I 1082.7 nm line

N.G. Shchukina & R.I. Kostik

Main Astronomical Observatory, National Academy of Sciences
Kyiv, Ukraine

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Why do we analyze the Si I 1082.7 nm line

and

not the another one ?

The spectral region around 10830 Å
is a powerful diagnostic window:
It contains information coming simultaneously from
the chromosphere (the He I 1083.0 nm triplet)
&
from the photosphere (the Si I 1082.7 nm).

Key point:

For the Si I 10827 Å Stokes profiles formed in the quiet solar atmosphere the NLTE effects are important !

(Shchukina et al. 2017, AA, A98).

For today, there are no attempts to apply any NLTE inversion code to this line to determine the 3D structure of the solar magnetic & velocity field in

the quiet solar atmosphere.

METHOD

1. We solve the self-consistent statistical and radiative transfer equations applying our multilevel transfer code (Shchukina & Trujillo Bueno, 2001, ApJ, 550, 970; Shchukina et al. 2017, AA, 603, A98) to the Si I + Si II + Si III model atom.

2. We calculate NLTE intensity *I* profiles for the solar disk center using the 3D model atmosphere with surface and height variations of the

- velocity field,
- magnetic field,
- thermodynamic parameters (density, temperature).

3. Instead of applying the NLTE inversion we apply the lambda-meter technique to the calculated Stokes *I* supposing that they represent "REAL Sun" observations.

4. We compare the recovered "lambda-meter" velocities with the "REAL vertical velocities" of the model atmosphere.

We use a 3D MHD photospheric model resulting from the solar surface dynamo simulations by

M.Rempel

Numerical Simulations of Quiet Sun Magnetism: On the Contribution from a Small-scale Dynamo

2014, ApJ, 789, 132

A vertical unsigned flux density $\langle |B_z| \rangle = 80$ G in the visible surface layers & zero net magnetic flux.

Spatial smearing of the intensity images at the line wavelengths of Si I 1082.7 nm

Intensity *I* images are degraded because of

- seeing (the Earth's atmospheric turbulence described by the Fried parameter R_0),
- light diffraction by the telescope aperture (the finite spatial resolution of the telescope),
- instrumental profile of the spectral filter
- photon noise.

At the moment we ignore last two effects

Lambda-meter technique

Stebbins, R., Goode, P.R.
Waves in the solar photosphere.
Sol.Phys. 1987, 110, 237

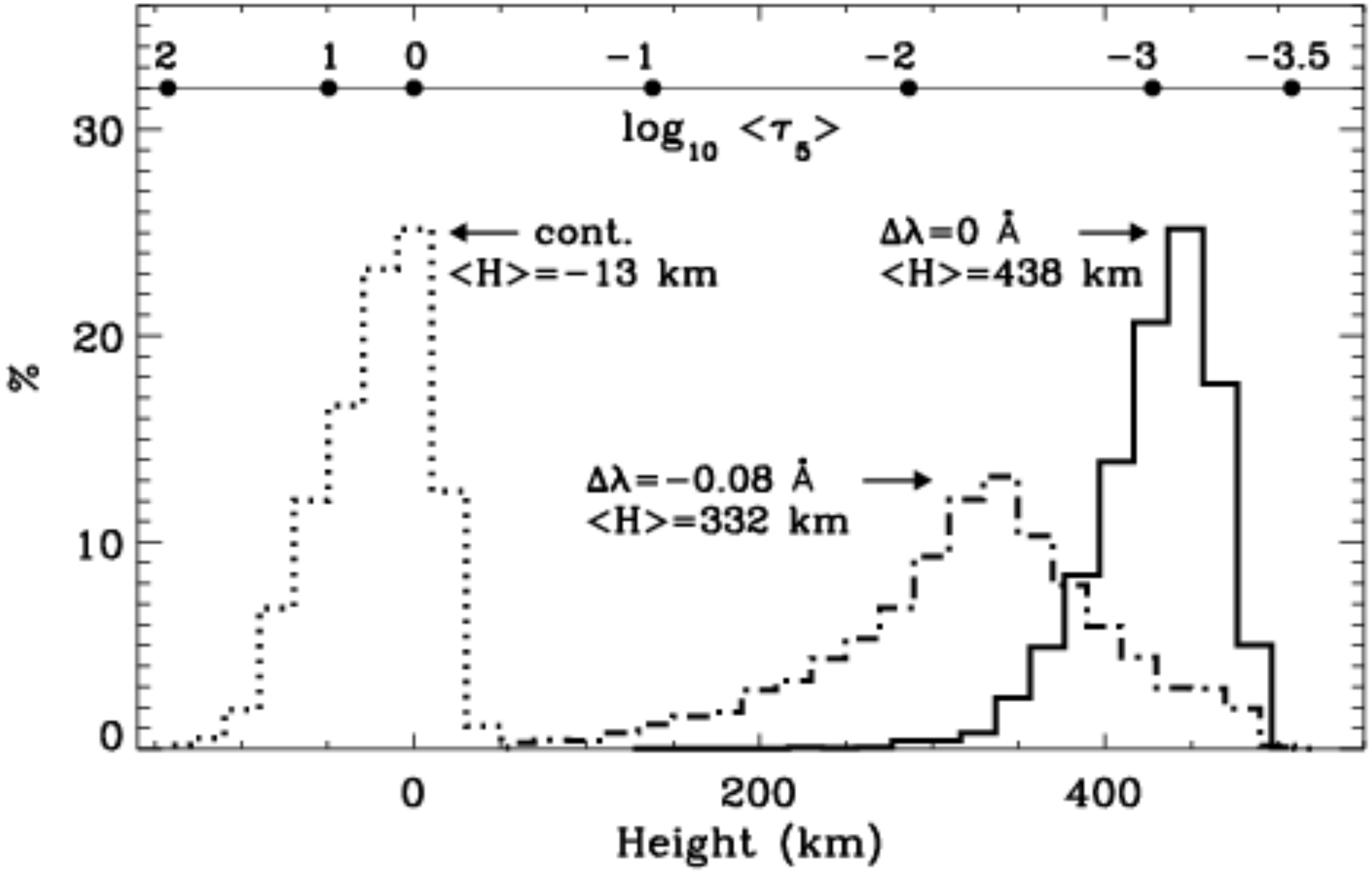
Shchukina N.G., Olshevsky V.L., Khomenko E.V.
AA, 2009, 506, 1393

Idea: to determine the velocity from the shift of the line bisector at the line spectral width $\Delta\lambda_W$

$$V = \Delta\lambda \cdot c/\lambda$$

RESULTS

The formation height of the SiI 1082.7 nm covers the whole photosphere including temperature minimum



Histograms of the NLTE heights of formation calculated at three wavelengths within the Si i 10 82.7 nm line intensity profile.

Eddington-Barbier approximation:

The 3D snapshot velocities are taken at the heights where optical depth at the corresponding wavelength τ(Δλ) equals unity:

$$\tau_{\Delta\lambda} = 1$$

Correlation between Lambda-meter velocities $V_{\lambda M}$

&

"real"(3D model) vertical velocities V_Z

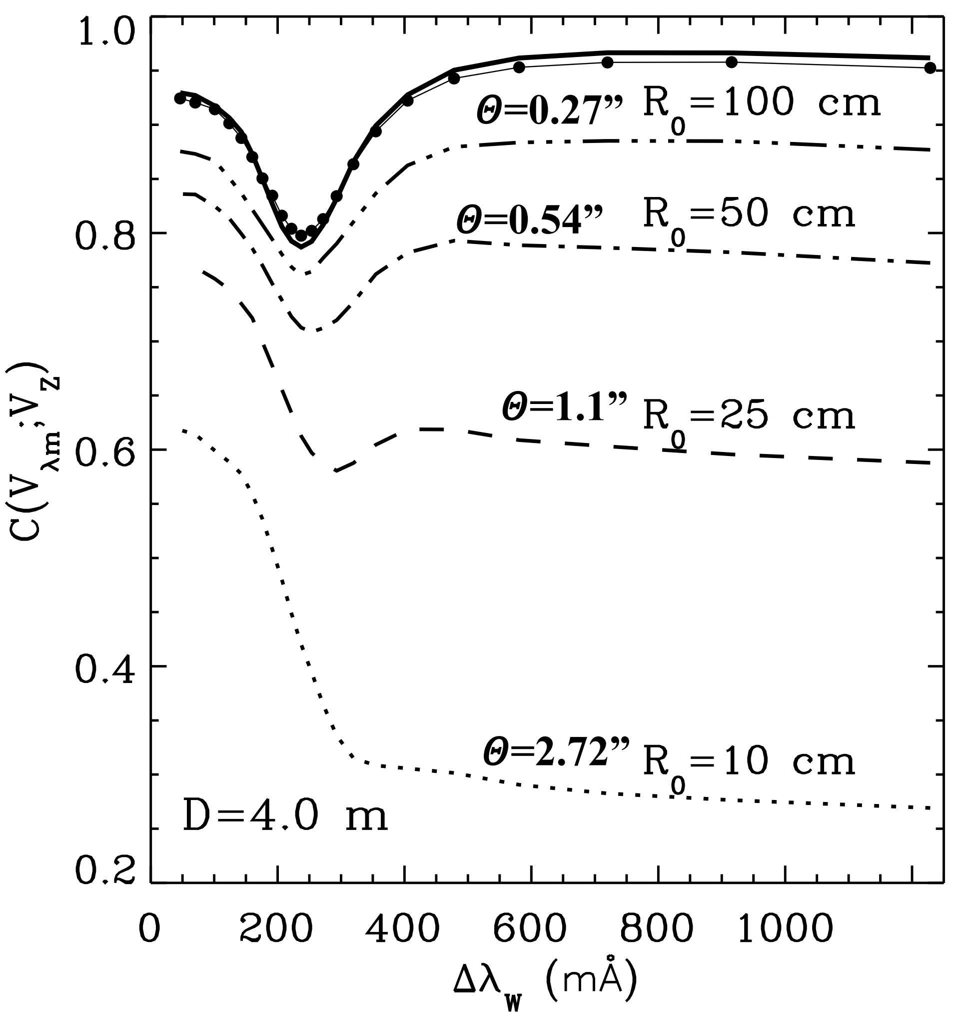
for different spatial resolution Θ

EST/DKIST telescope D=4 m

The spatial resolution Θ is estimated according to the Rayleigh criteria:

$$\Theta(\text{arc sec}) = 206265 \times 1.22\lambda/R_0$$

Fried´s parameter R_0 is the characteristic size of atmospheric turbulence cells



Pearson correlation coefficients $C(V_{\lambda m}; V_Z)$ between $V_{\lambda M}$ & V_Z velocities as a function of the line profile width $\Delta_{\lambda W}$. Each line corresponds to a different value of Fried parameter R_0.
The uppermost solid line: "perfect" (no smearing) observations.
Thin solid line with dots: observations outside the Earth´s atmosphere (the EST/DKIST telescope diffraction limit Θ=0.07").

Observations of the Si I 1082.7 nm on the 4-m telescope outside the Earth's atmosphere (space):

The best agreement between the $V_{\lambda m}$ & V_Z for the space & "perfect" observations.

The ground-based observations (Tenerife), highest spatial resolution Θ=0.27" (Joshi et al. 2016, AA, 596, A18):

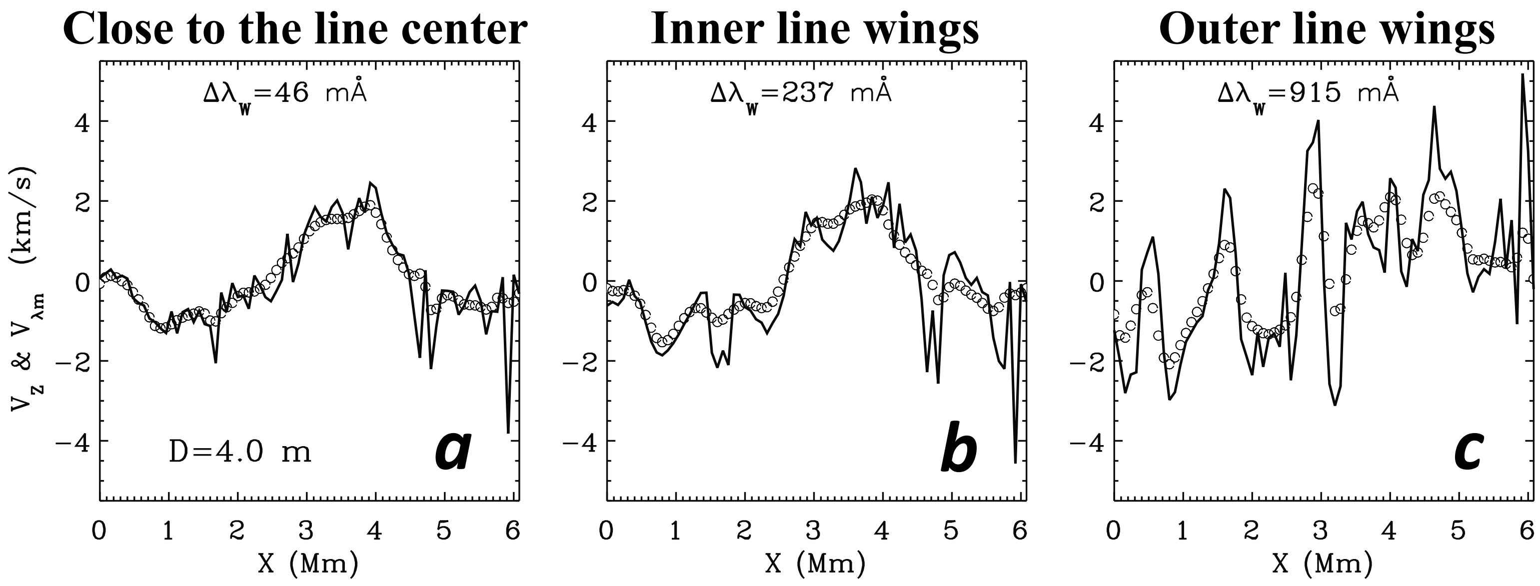
Outer wings & line center: The velocities $V_{\lambda M}$ & V_Z are quite close each other. C(Vλm; VZ) $\gtrsim$ 0.9.

Worse agreement for the inner wings: $C(V_{\lambda m}; V_Z)$ = 0.79.

Poor spatial resolution Θ >1":

Velocity field can be obtained only from the line center.

The "ground-based observations". The spatial resolution Θ = 0.27 arcsec (Fried parameter R0 = 100 cm). EST/DKIST telescope D=4 m



Variations of the lambda-meter velocities $V_{\lambda m}$ (circles) & the "real" vertical velocities V_Z (solid curves) along one of the directions on the surface of the 3D model:
(a) the central part of the Si I 1082.7 nm (line width $\Delta_{\lambda W}$ = 46 mÅ);
(b) inner wings ($\Delta_{\lambda W}$ = 237 mÅ);
(c) Outer wings ($\Delta_{\lambda W}$ = 915 mÅ).

$V_{\lambda m}$ velocities reproduce well large-scale variations of the real velocity field over the solar surface.

However, we underestimate the real velocities, especially in those regions where they are particularly large.

Correlation between Lambda-meter velocities & model vertical velocities

Different spatial resolution Θ

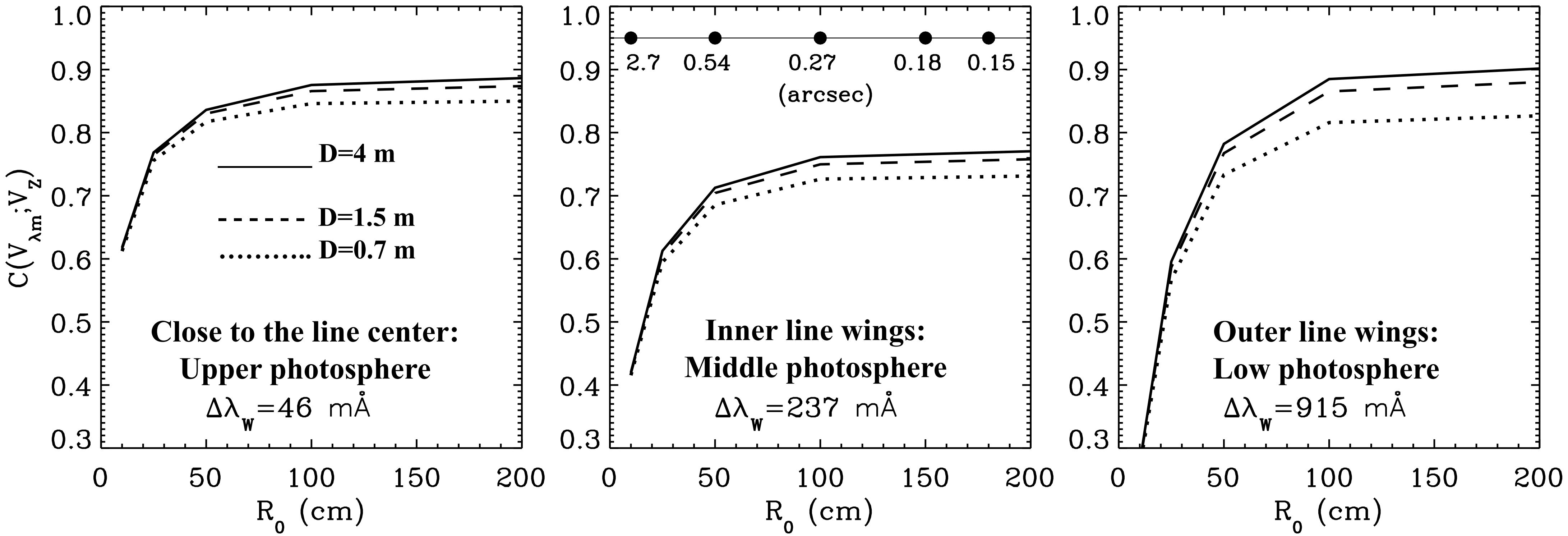
Different Telescopes:

D=4 m (EST),

1.5 m (GREGOR),

0.7 m (VTT)

Correlation coefficients C($V_{\lambda m}$; V_Z) between $V_{\lambda m}$ & V_z velocities as a function of the Fried´s parameter R_0 and the telescope diameter.



For the best spatial resolution of 0.27″ (R0=100 cm) the lambda-meter method gives fairly reliable lower & upper photospheric velocity field. For the middle photosphere, the results are noticeably worse, especially when using smaller telescopes, such as VTT with D=0.7 m.

Under poor seeing conditions (Θ >1″, R0<25 cm) coefficients C($V_{\lambda m}$; V_Z) are low and the same regardless of the diameter of the telescope.

Observations with the 0.7-m diameter telescope (VTT): higher coefficients at the resolution Θ >1″ can be obtained only for the uppermost photosphere. The velocities $V_{\lambda m}$ are noticeably smaller than the real ones.

CONCLUSIONS

I. The lambda-meter technique applied to the Si I 1082.7 nm line gives us a rather good opportunity to "trace" the non-thermal motions along the photosphere.

II. Under poor seeing conditions:

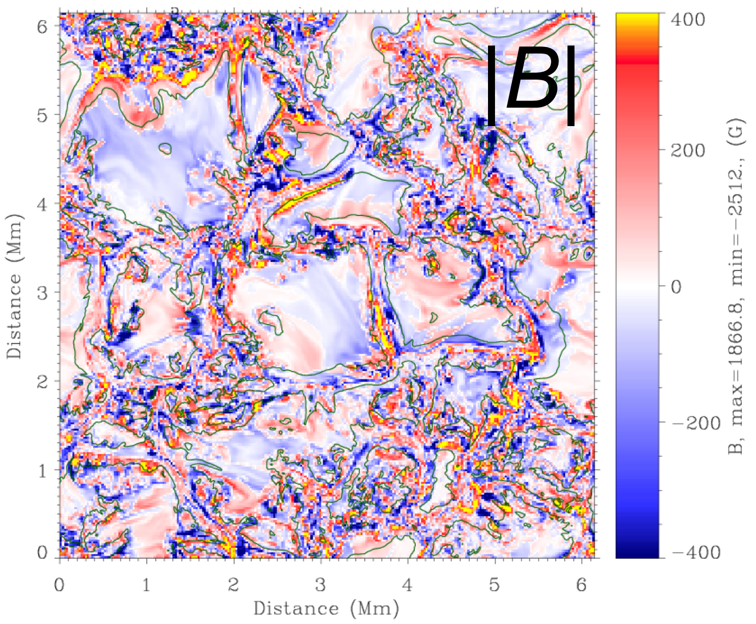
- ❑ We lose information about the strong component of the photospheric velocity field.

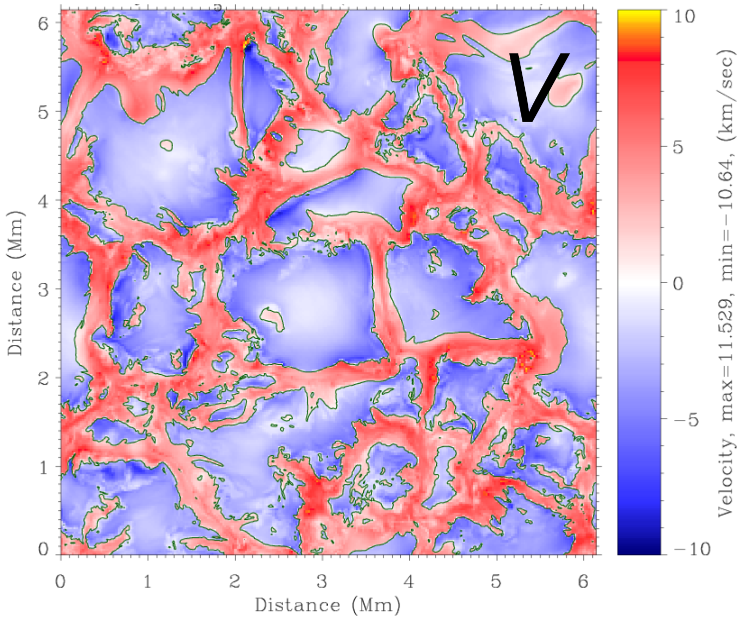
- ❑ The velocities derived from the inner wings of the Si I 1082.7 nm line profiles are more reliable than those for the outer wing.

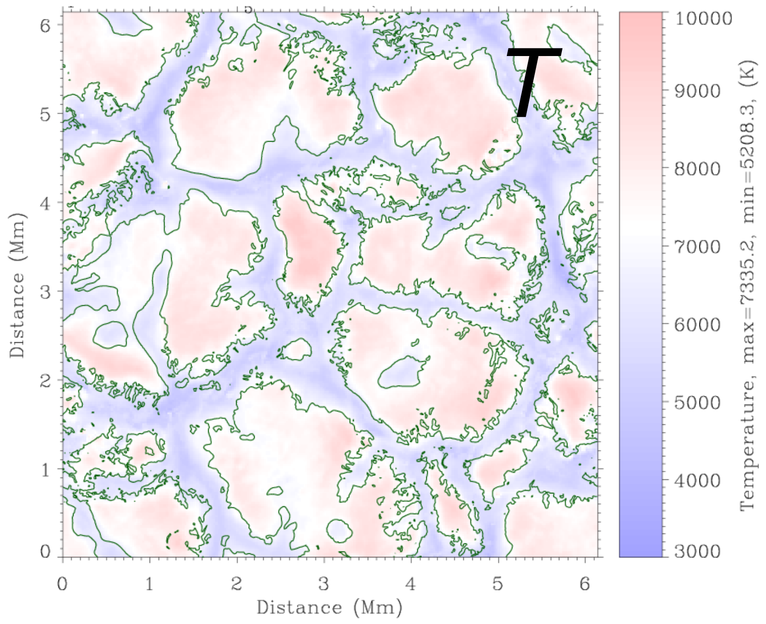
III. Under perfect seeing conditions close to diffraction limit of the telescope it is more reliable to use for determination of the velocities the outer wings of this line.

Thank you
for
your attention

More details







Surface variations of the modulus magnetic field strength *B* (with *Bz* sign), velocity *V* & temperature *T* at continuum level

No. bb=4124 No. bb=6

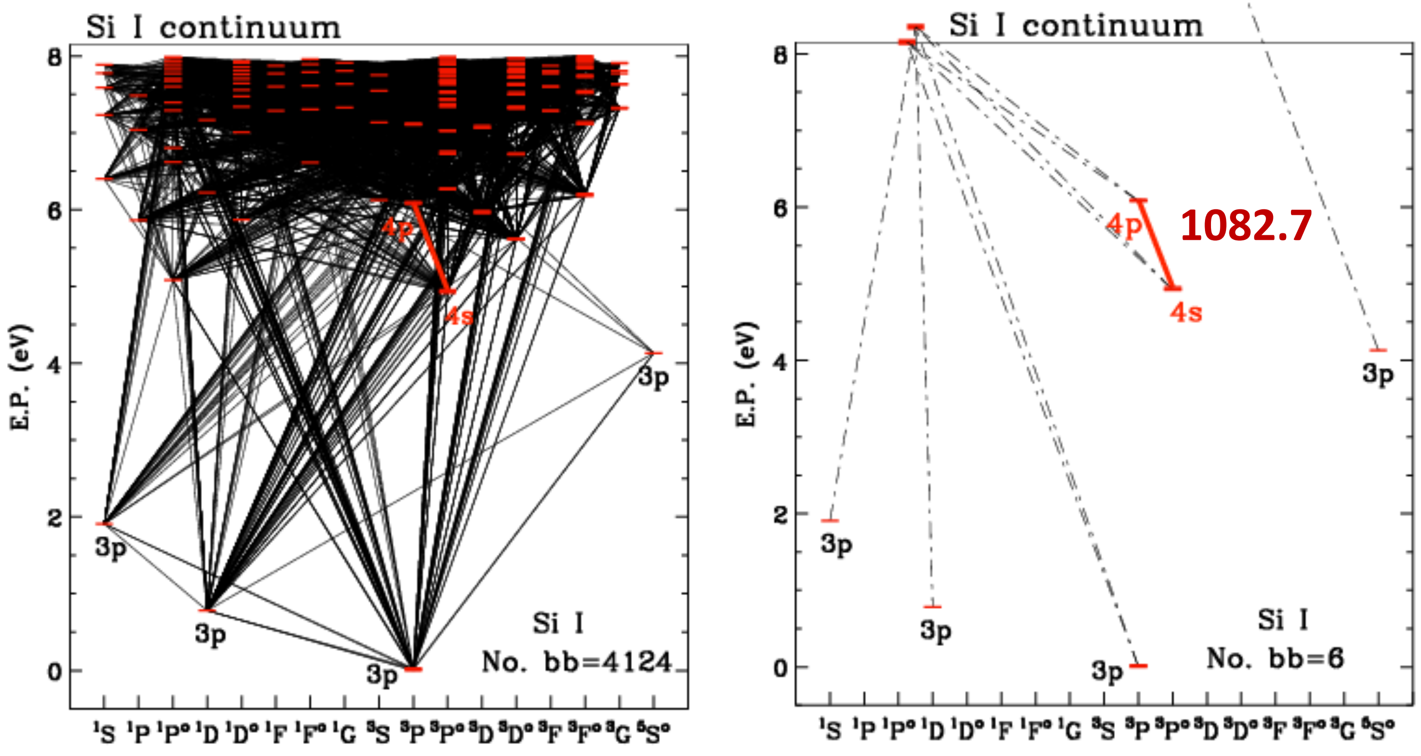


Diagram of the energy levels and radiative transitions for the most comprehensive (Si I 206 levels, Si II 89 levels, Si III ground level, 4708 bb transitions) and the simplest model (Si I 12 levels, Si II 3 levels,Si III ground level, 6 bb transitions) atoms of silicon.

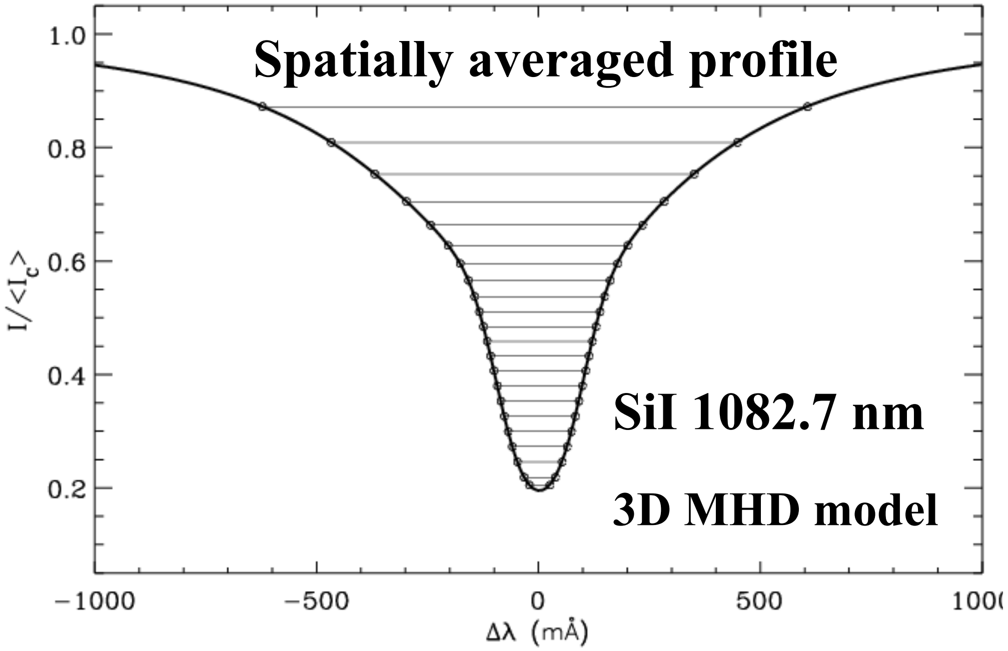
Transition 4s $^3P^o_2$ – 4p $^3P_2$ gives rise to the Si I 10 82.7 nm line.

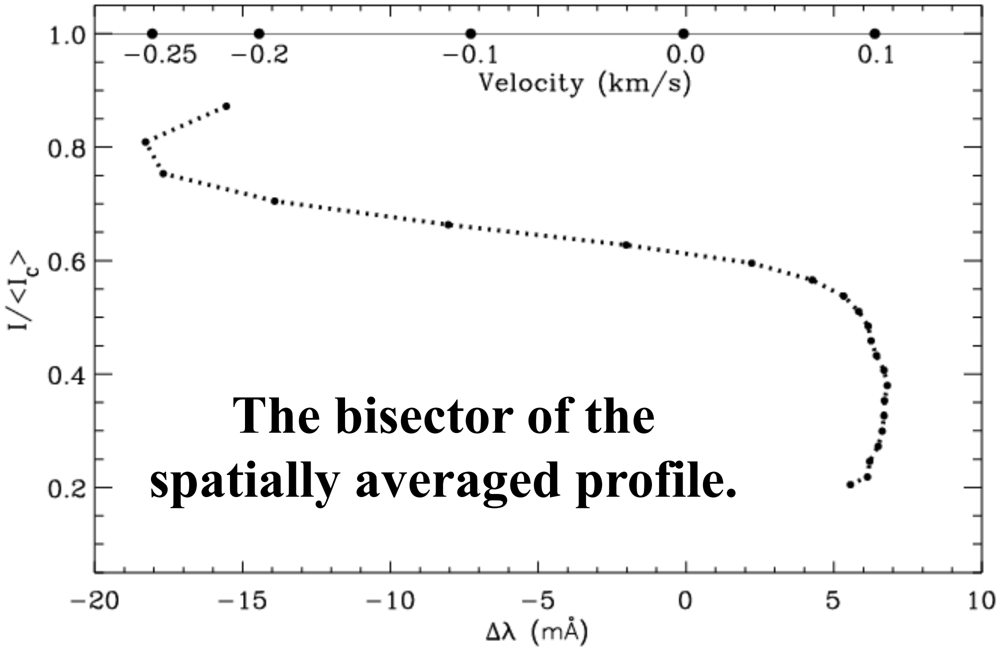
We use of the simplest silicon model atom (right).

It allows a fast and accurate computation of intensity profiles.

The NLTE Stokes profiles calculated using this model atom are very similar to those obtained via the use of the most comprehensive silicon model atom.

N. Shchukina, A. Sukhorukov, J. Trujillo Bueno, 2017, AA, 603, A98

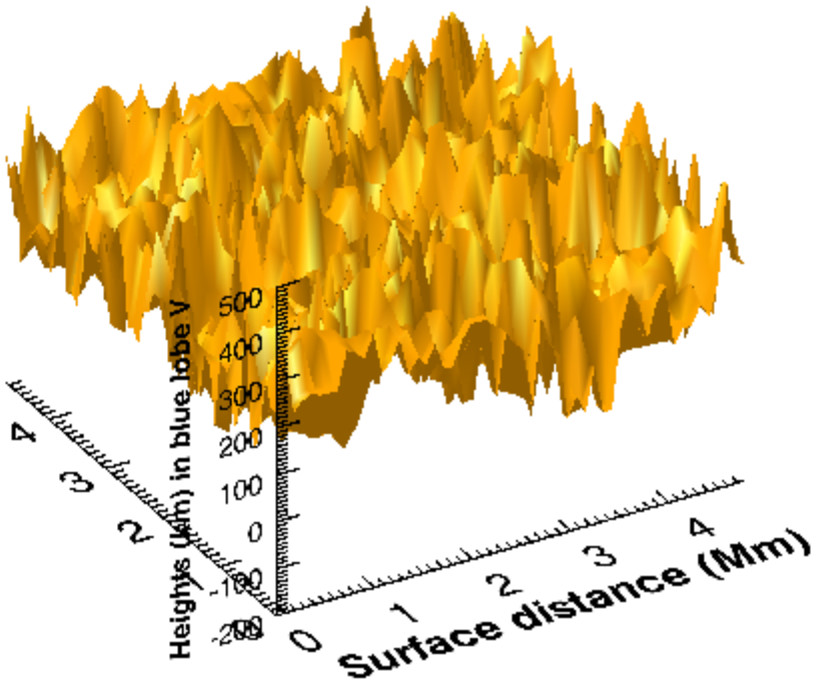




- The line profile depths are specified by a set of profile widths.
- The velocity is defined as the midpoint of the section of the profile having a certain spectral line width
- Optically thin approximation: Intensity profile width is proportional to the width of the line absorption coefficient profile.
- Shift of the line absorption profile is caused by Doppler effect:

$$V = \Delta\lambda \cdot c/\lambda$$

Height of formation of the Si I 1082.7 nm



Eddington-Barbier approximation: heights where $\tau_{\Delta\lambda} = 1$