Non-LTE modelling of active filaments observed in the Hα line using the 2D flux-tube model

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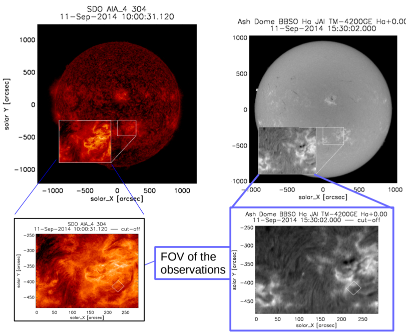
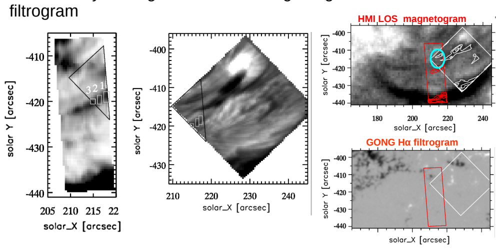
ABSTRACT. We present development, current state and plans for future improvements of our non-LTE 2D flux-tube model. The model is used for simulations of spectroscopic observations in the Hα line of small-scale filaments in active regions, arc filaments and filaments in state of activation. We assume that filaments of these types are composed of flux-tubes located in the transition region and/or corona and relatively cool plasma can flow along these flux-tubes with various velocities. The flux-tube system is approximated in the model by a 2D horizontal slab where its finite dimensions form its cross section and the infinite dimension is parallel to the solar surface. The isothermal and isobaric slab is irradiated from the bottom and sides and the non-LTE radiative transfer in the 2D geometry is solved using the MALI numerical technique. The orientation of plasma flows in the slab is defined by the azimuth and inclination angles. The influence of different plasma flow velocities on the emerging radiation from the slab can be regulated using filling factors. The model was already successfully applied to several filament Hα line spectroscopic observations made with the echelle spectrograph at the Vacuum Tower Telescope (VTT) and the IBIS interferometer at the Dunn Solar Telescope. In further development of the model we also plan to introduce fine structures in 2D geometry composed of individual flux-tubes and variation of the temperature and pressure within each flux-tube.

Mini-filament observed in the active region NOAA 12159 with VTT on 11Sep2014

The solar chromosphere displays a wide variety of filamentary structures with a typical length ranging from 60 up to 600 Mm (Tandberg-Hanssen 1995). During our observing campaign that took place in autumn 2014 at Vacuum Tower Telescope we focused on small-scale and very dynamical filamentary structures (lengths below 60 Mm) occurring at periphery of active regions which were called by Denker & Tritschler (2009) as "mini-filaments". We obtained multi-spectral and spectropolarimetric observations of a mini-filament with its Hα spectral imagery to infer its magnetic and thermodynamic structure by the non-LTE modelling (Schwartz et al. 2016).



Left: The slit-reconstructed monochromatic image of the target area in the center of the red component of the HeI 10830 Å triplet observed by the TIP 1 polarimeter with Echelle spectrograph. The scanning ran from 09:56:28 UT to 10:04 UT. *Middle:* intensity map of the Hα line center of the target taken by the TESOS interferometer at 10:01 UT. The black lines identify a triangular overlap area of TIP 1 and TESOS FOVs. White lines mark three rectangular segments at the mini-filament selected for an analysis. *Right:* HMI LOS magnetogram and GONG Hα filtrogram



Except of the HeI spectropolarimetric observations, the spectrograph made also spectral observation in the CaI 8552 Å line

Fitting the Hα profiles from the three areas (marked by numbers 1 – 3 in the HeI 10830 Å intensity map) using a simple cloud model inversion (constant source function, e.g. Beckers 1964) led to estimation of very large temperatures non-realistic for hydrogen and.

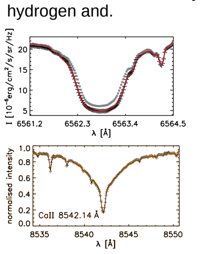


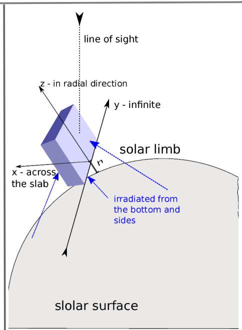
Table 1 Cloud model parameters of selected segments of a small active region filament inferred from the TESOS Hα observations. The unit of the source function S is 10^{-6} erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}. The symbols T, $\Delta\lambda_D$, τ_{6563}, v_{LOS}, and v_{MT} correspond to the temperature, the Doppler width, the cloud optical thickness in the Hα line center, the line of sight velocity, and the microturbulence, respectively.

Parameter	Seg. 1	Seg. 2	Seg. 3
S	2.55 - 4.71	2.92 - 3.68	2.98 - 3.52
T [kK]	34.2 - 49.1	31.8 - 39.7	20.3 - 31.8
$\Delta\lambda_D$ [Å]	0.53 - 0.63	0.53 - 0.63	0.45 - 0.54
τ_{6563}	0.41 - 0.78	0.42 - 0.77	0.62 - 0.87
v_{LOS} [km s^{-1}]	-1.1 - $+2.4$	-4.7 - $+0.5$	-3.5 - -2.1
v_{MT} [km s^{-1}]	3.7 - 6.0	4.6 - 14.4	6.7 - 11.9

too high temperatures, nonrealistic listic for filaments, moreover hydrogen is totally ionized at such temperatures!!!

Thus, a so-called flux-tubes non-LTE model based on 2D RTE solver of Heinzel & Anzer was prepared to be able to fit such deep and broad Hα observed at the filament. In the model, filament is – assumed as a system of flux-tubes – is approximated by isobaric and isothermal slab:

– It is assumed that the mini-filament is composed of multiple flux-tubes bes placed one above another and plasma of the filament is flowing inside them along the magnetic field.
– The model is simplified – a system of flux-tubes is approximated by the isothermal and isobaric 2D slab of a box-like cross-section with two finite dimensions – vertical Z and across the filament X.
– the dimension Y along the filament is infinite and inclined by an angle of 18° from the direction to the solar West (only for this filament, for other filaments it can be different)
– The width of the dark structure of the mini-filament of 1000 km was measured in the Hα center intensity map and was used as the X dimension of the slab. The vertical height (Z-dimension) together with



temperature and with temperature and plasma pressure were taken as free parameters ters of the model. The slab is irradiated at its bottom and sides from the solar surface ce and it is situated in the height h above it.
– the radiative transfer in the 2D model is solved using the short-characteristics method (Kunasz & Auer,1988) together with the Multilevel Accelerated Lambda iterations (MALI) (Rybicki & Hummer 1991). The 2D numerical code used is described in Heinzel&Anzer (2001) and was accordingly modified to account for a filament geometry.
– the statistical equilibrium was calculated for a 5-level plus continuum hydrogen atom. The formal solution of the radiative transfer was made along the LOS at μ=0.87 corresponding to the position of the mini-filament on the solar disc. It is assumed that plasma flows along the flux-tubes, and this flow is oriented along the filament dark structure. The angle of the flow inclination from the vertical Z is taken as a free parameter. We assumed that very broad Hα profiles observed at the mini-filament can be emitted only by a system of multiple flux-tubes in which plasma is flowing with different, even opposite, velocities. We approximated such a system of fluxtubes by two isothermal and isobaric 2D slabs with opposite plasma-flow velocities contributing to emerging radiation by a filling factor of 0.5.
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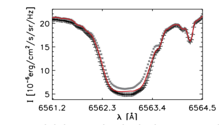
– assuming that plasma flows along the magnetic field, inclination (angle θ_V) of the velocity vector measured from the vertical (Z-axis) is determined by the magnetic field inclination which can be obtained from inversion of spectropolarimetric observations of the HeI infra-red triplet.

Due to very low signal in the HeI 10830 Å polarisation signal it was not possible to infer the magnetic field vector, only LOS Velocities of few km/s were obtained by inversion of intensity profiles using the HAZEL code (Asensio Ramos et al. 2008). Then inclination angle was taken as a free parameter of the flux-tube non-LTE model for the Hα profile fitting.

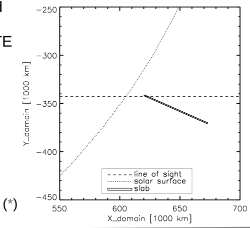
Table 2 Parameters of a small active region filament inferred by the 2D NLTE modeling of the Hα profiles observed by TESOS. The inclination is an angle between local vertical and fluxtubes comprised in the slab. Mass density and hydrogen ionization degree are shown in Fig. C.

height of slab base	9 000 – 13 000 km
slab width	1 000 km
vertical thickness of slab	60 000 km
inclination	90 – 100°
temperature	9 000 K
pressure	0.12 dyn cm^{-2}
flow velocity	±25 km s^{-1}
microturbulence	5 – 13 km s^{-1}

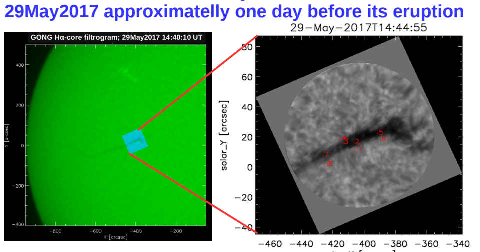
An example of fitting of very broad broad Hα observed profiles by a synthetic obtained with the non-LTE model



Observed (+), synthetic (—), QS profile (*)

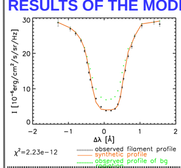


A filament observed in Hα by DST/IBIS interferometer on 29May2017 approximatelly one day before its eruption

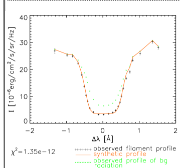


Observations of IBIS between 14:00 – 15:30 UT used for the NLTE modelling. Model similar to that used for the 11Sep2014 filament, but only one macroscopic plasma flow taken (one macroscopic velocity as a model input parameter) while unresolved flows within the slab are represented by the velocity of microturbulence as an input parameter of the model. Avg profiles from 4 areas at the filament were modelled and profiles from close-by QS areas were taken as background irradiation of the slab. No information about the magn. field => inclination of the flux-tubes not known => only LOS velocity as a model input parameter.

RESULTS OF THE MODELLING:

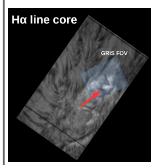


shallower and narrower asymmetric profiles at SE and N-central parts of the filament
– lower temperatures (7000 – 9000 K), high gas pressure (0.23 – 0.25 dyn/cm^2)
– large downflow velocities (LOS component of 4 – 6 km/s)
– large plasma densities ranging from 1×10^{-13} to 7×10^{-13} g/cm^3
– low ionization degree of H (up to 0.4)

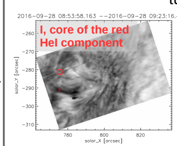


deeper and broader symmetric profiles at NW and S-central parts of the filament
– higher temperatures (11000 – 13000 K), lower but still rather high gas pressure (0.13 – 0.17 dyn/cm^2)
– small downflow velocities (below 1 km/s)
– lower plasma densities ranging from 9×10^{-14} to 1×10^{-13} g/cm^3
– more of ionized H (ionization degree of 0.7 – 0.8)

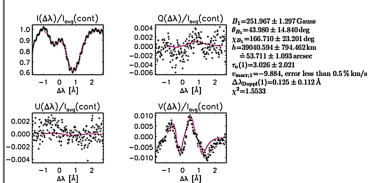
An arc filament observed by in full-Stokes in the HeI IR triplet by GRIS/GREGOR and spectroscopically in Hα at VTT 28Sep2016



Non-LTE modelling of the filament in Hα – in preparation:
– the GRIS spectropolarimetric data reduced by a new reduction pipe-line.
– improved non-LTE 2D slab model – realistic fine structure with different plasma flows (no limitations of the slab width due to RTE numerics)
– introducing temperature structure within individual flux-tubes



S/N ratio of polarization signal of the HeI 10830 Å triplet high enough to obtain reliably vector of the magnetic field using the HAZEL inversion code. Inclination of the magnetic field == inclination of the flux-tubes --> used as one of the input parameters of the non-LTE model in modelling of the Hα profiles



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Poster

1. Fundamental physical processes and modeling

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