DYNAMICS OF THE QUIET UPPER SOLAR ATMOSPHERE: PROPAGATING WAVES AND OSCILLATIONS IN THE NETWORK

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ABSTRACT

Simultaneous measurements of the chromospheric He I 584.33 Å, transition region O V 629.73 Å and coronal Mg IX 368.07 Å spectral lines obtained from the Coronal Diagnostic Spectrometer (CDS) in/above the supergranular network near disk center are presented. Temporal evolutions of the spectral parameters were constructed in order to examine the correlations of the spectral line intensities and the Doppler shifts.

Resulted cross-correlation functions were analyzed with a view to describe energy transfer and mass motion in the upper solar atmosphere. The maximum value of the cross-correlation function of the He I and O V line intensities was achieved for the shift + 40 s, i.e. some changes in the O V line intensities lead changes in the He I line intensities. In contrast, cross-correlation function of the Doppler shifts of these lines reached the maximum value for the shift equal to 0 seconds. Cross-correlation function of the O V and Mg IX line intensities revealed multiple maximum values for shifts + 200 s and - 360 s, respectively. This cross-correlation function was found to be influenced by 4.3 mHz oscillations detected in the Mg IX line intensities. No correlation between the Doppler shifts of the O V and Mg IX lines was discovered.

Summarizing we can assume that the non-radiative energy was transported from the transition region down to the chromosphere without any significant mass motion. This can indicate presence of propagating waves in the network of the quiet solar atmosphere. Ambiguity in interpretation of the cross-correlation function of O V and Mg IX line intensities caused the fact that we can not determine if the proposed waves originate in the corona or if they originate in the transition region and spread out simultaneously upward to the corona and downward to the chromosphere.

CDS SLIT POSITION

- CDS slit position in EIT spectroheliograms (He II 304 Å; T $\sim 8 \times 10^4$ K)

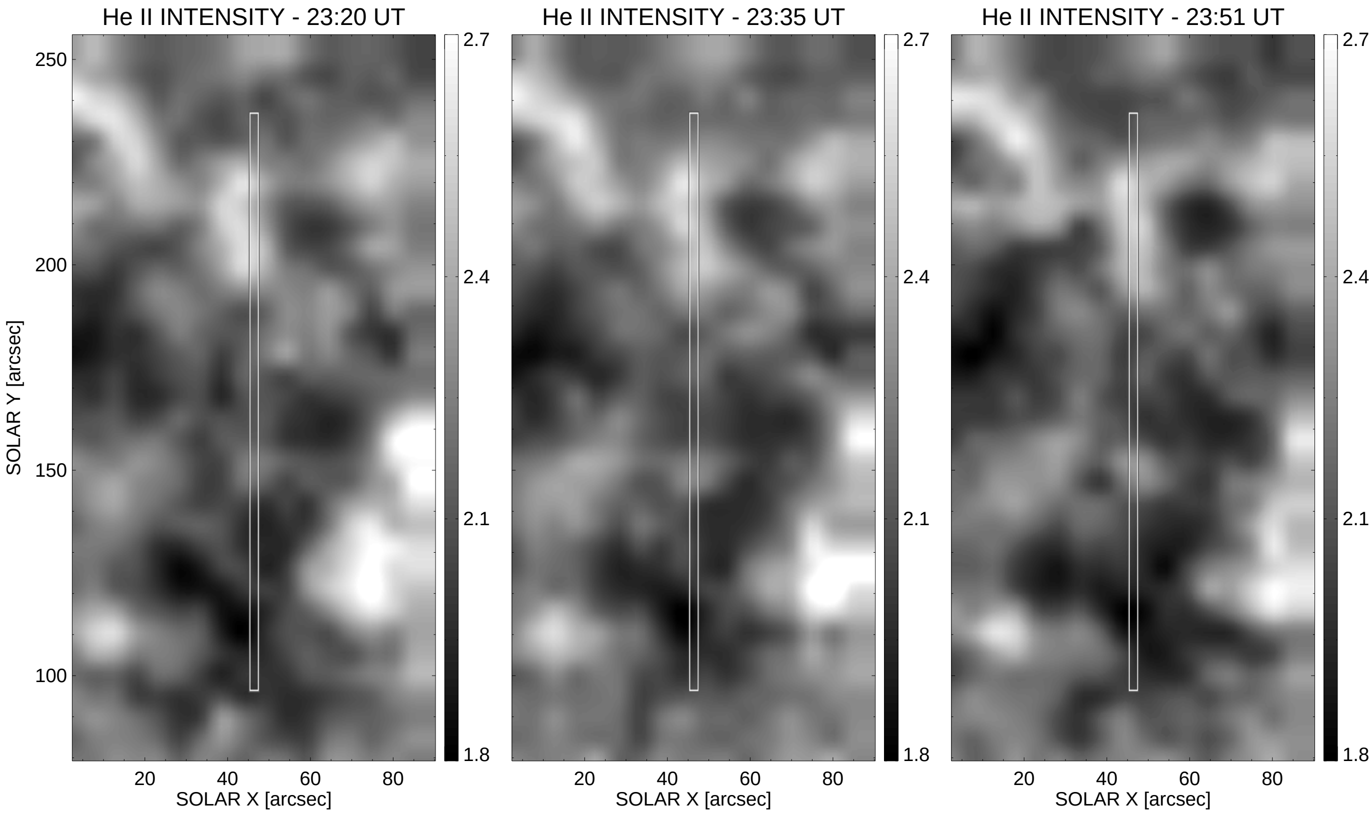


Figure 1: CDS slit position and shapes of the quiet solar network shown in the context images taken with SOHO/EIT instrument in He II 304 Å (log $T_e = 4.9$) spectral line at the beginning (left panel), in the middle (middle panel) and at the end (right panel) of the CDS measurements. The coordinates of the CDS slit center are: x = 46.4"; y = 167.1". The coordinate system is given relative to the disk center. The intensity values given in W $m^{-2}sr^{-1}Å^{-1}$ are displayed in logarithmic scale.

TARGET SELECTION

- **typical network:** so-called part of the supergranular network under study visible as the brightest area in the upper part of the CDS slit (between 111" – 116" along the slit; Fig. 2), which is not influenced by the explosive event detected in the O V spectral line (between 97" – 102"; Fig. 2)

DATA

- instrument: CDS/SOHO NIS spectrometer
  (Harrison, R. A. & CDS team: 1995, Solar Physics 162, 233)
- spectral lines: **He** I **584.33 Å** (2.0×10^4 K)
  O V **629.73 Å** (2.5×10^5 K)
  Mg IX **368.07 Å** (9.3×10^5 K)
- slit: 2" $\times$ 240" oriented in the NS direction
- exposure time: 5 s; telemetry: 4.1 s
- number of exposures: 190; run duration: 1729 s
- observation mode: 'sit-and-stare' $\Rightarrow$ 1D sequence
- 'scanned' 2D area: 141" (NS) $\times$ 4.4" (EW)
- target: quiet solar atmosphere near the disk center
- date / time: May 14, 1998; 23:25 UT - 23:53 UT

DATA REDUCTION

- basic photometry correction of the CDS/NIS spectral data[1]
- data conversion to the physical units
- Mg IX 368.07 Å $\rightarrow$ data binning (4 px. along the slit $\times$ 5 exp.)
- each spectral profile fitted by a Gaussian profile and a linear background $\rightarrow$ I, v_d, χ^2 parameters
- calculation of the zero level of the Doppler shifts
- averaging of I and v_D: $n_y = 4$ pixels $\longrightarrow$ 6.7"
  calculation of the mean values and standard deviations

[1] http://solg2.bnsc.rl.ac.uk/software/uguide/uguide.shtml

2D MAPS

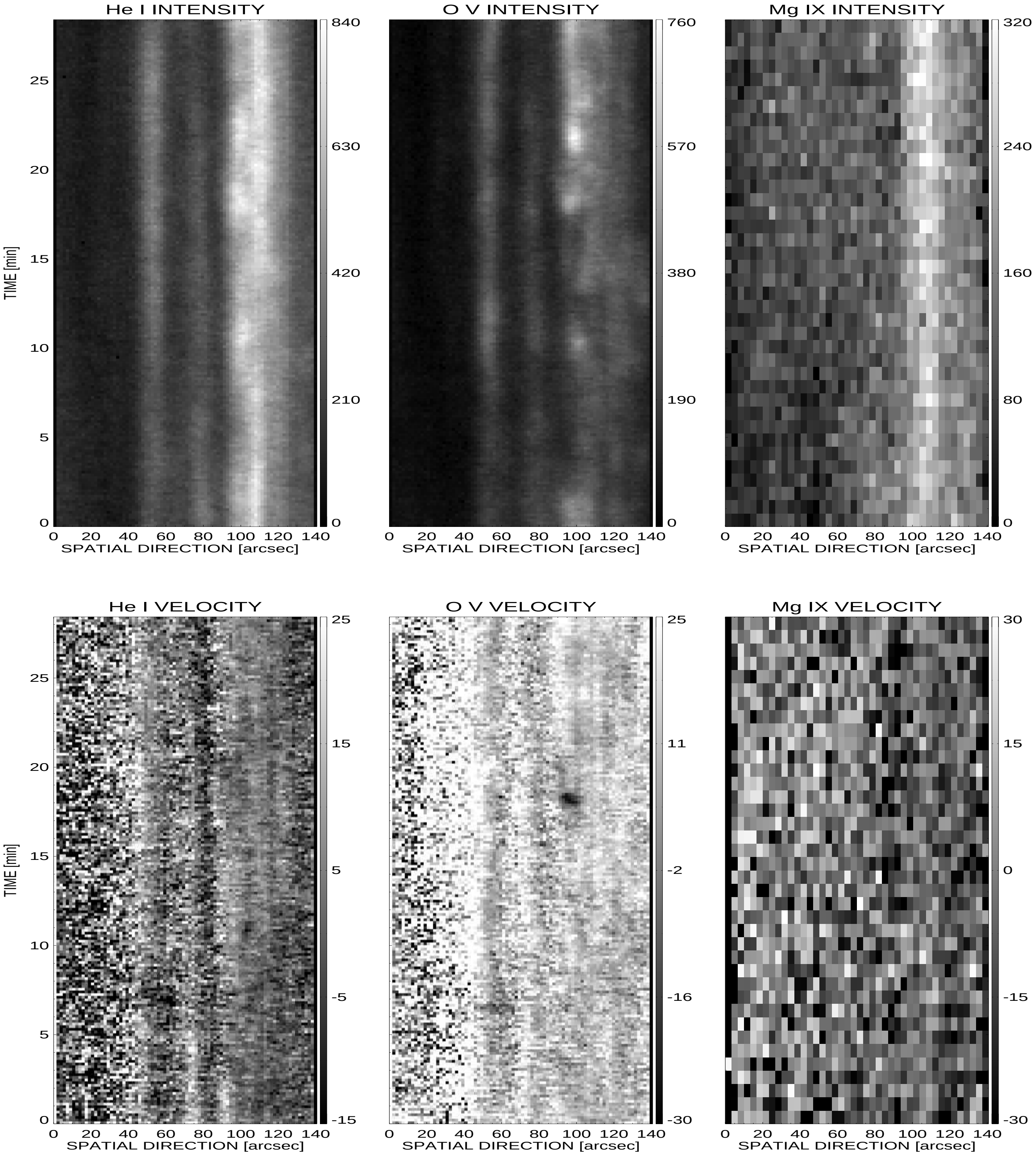
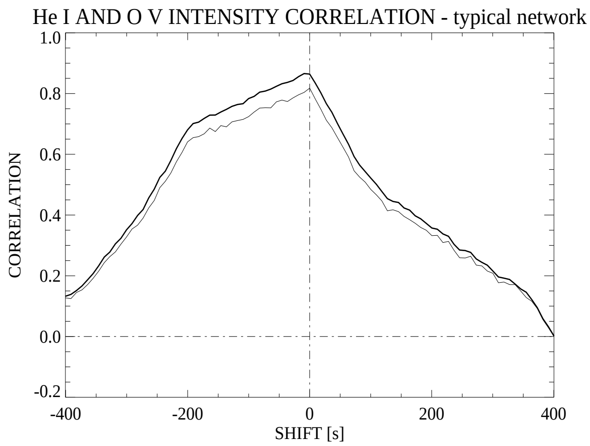


Figure 2: Line intensity (top) and Doppler shift (bottom) 2D time - space maps for the chromospheric He I, transition region O V and coronal Mg IX spectral lines. The studied part of the supergranular network (typical network) is shown in the area between 111" and 116". The horizontal axis gives spatial direction along the slit (solar - y) in arcseconds while the vertical axis describes time in minutes. However the solar rotation was not compensated, therefore the vertical axis presents also the spatial extent of the observed solar features. The intensity values are given in $\mathrm{erg\,cm^{-2}s^{-1}sr^{-1}Å^{-1}}$ and the Doppler shifts in $\mathrm{km\,s^{-1}}$. Positive values of the Doppler shifts correspond to redshift and negative values to blueshift.

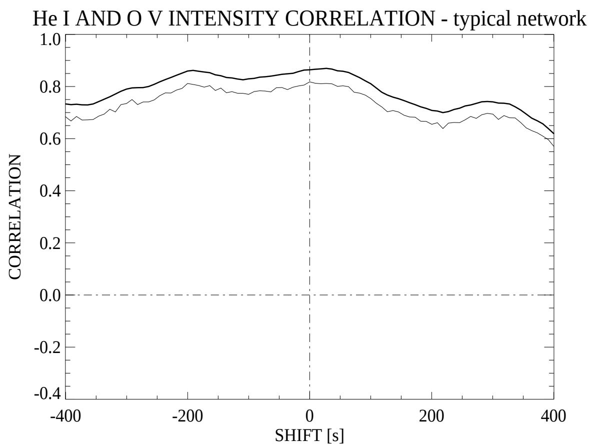
CALCULATION OF THE CROSS-CORRELATION FUNCTION

- for the correct calculation of the cross-correlation function (CCF) of two independent temporal variations (like those on Fig. 3) it is necessary to use the following arithmetic process:

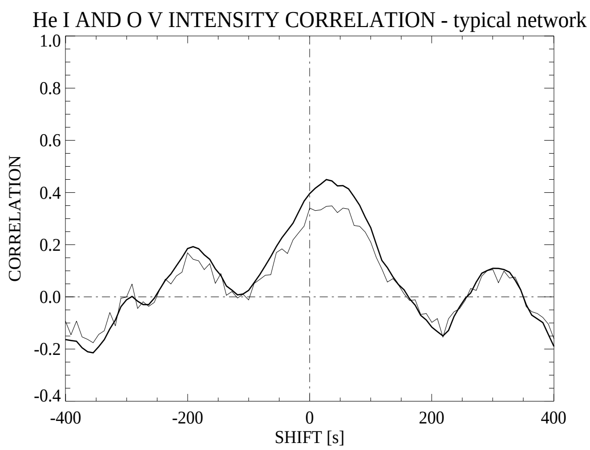
  – CCF calculation using only Pearson's method (PM): asymmetric shape of CCF; hight values for shifts in the interval (-200 s; 0 s) = unreal (see Fig. 3) ⇒ solution: edge data removing (EDR)



  – CCF calculation using PM + EDR: hight values of the CCF in the whole interval = effect of some general trend in the variations (see Fig. 3) ⇒ solution: linear trend removing (LTR)



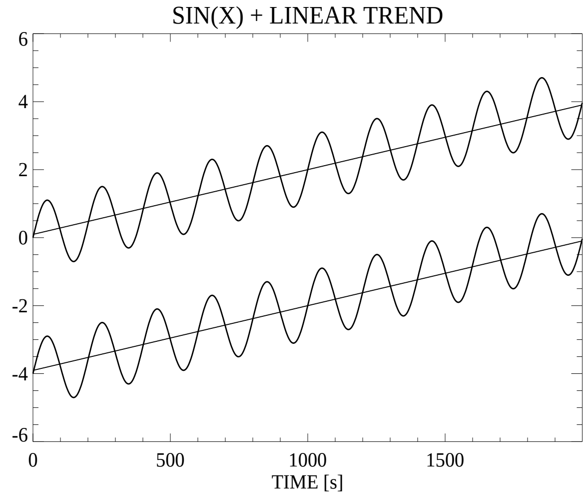
  – CCF calculation using PM + EDR + LTR: correct cross-correlation function ⇒ interpretation: some changes in O V line intensities lead changes in He I line intensities

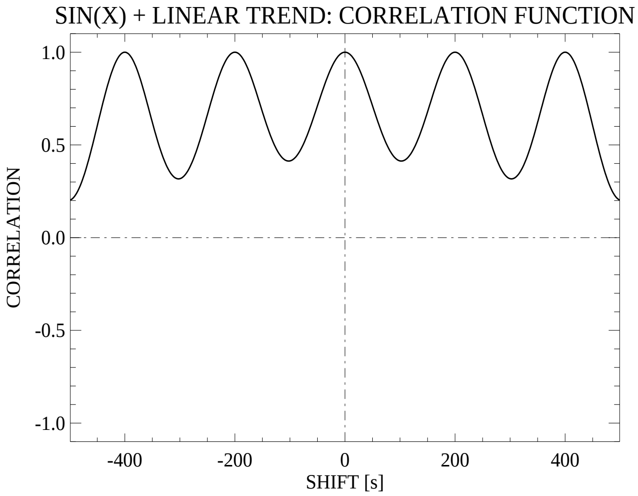


CCF CALCULATION: VERIFICATION OF THE USED METHOD

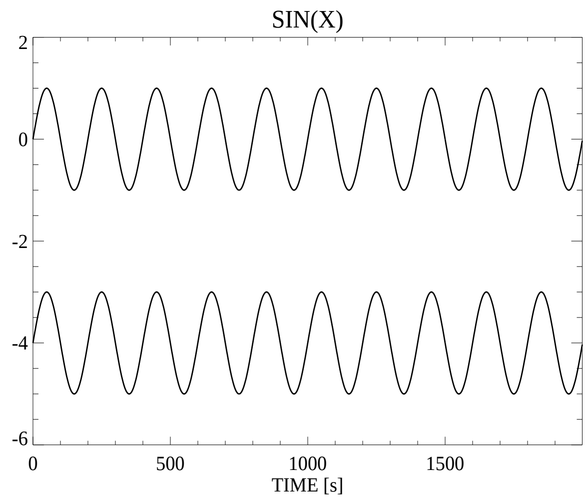
Why is it necessary to remove linear trend from the temporal variations before calculation of the cross-correlation function?

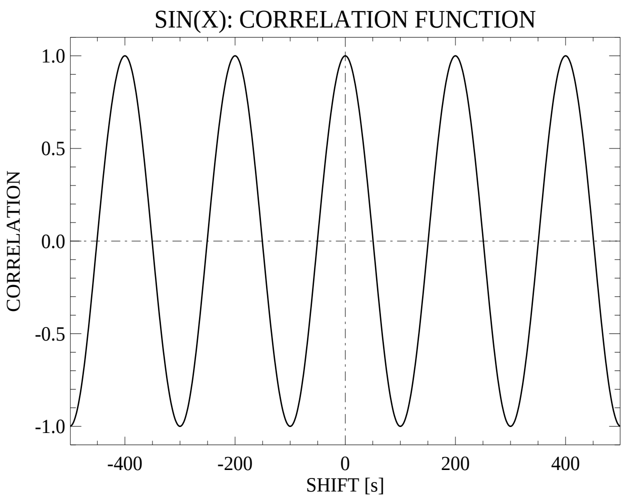
- two ideal sinusoidal functions (period = 200 s) superposed on the linear trend and their cross-correlation function
  - CCF reaches only positive values, i.e. no anti-correlation detected ⇒ unreal cross-correlation function





- two ideal sinusoidal functions (period = 200 s) after removing of the linear trend and their cross-correlation function
  - CCF reaches positive as well as negative values ⇒ expected cross-correlation function with period of 200 s





He I AND O V LINE INTENSITIES

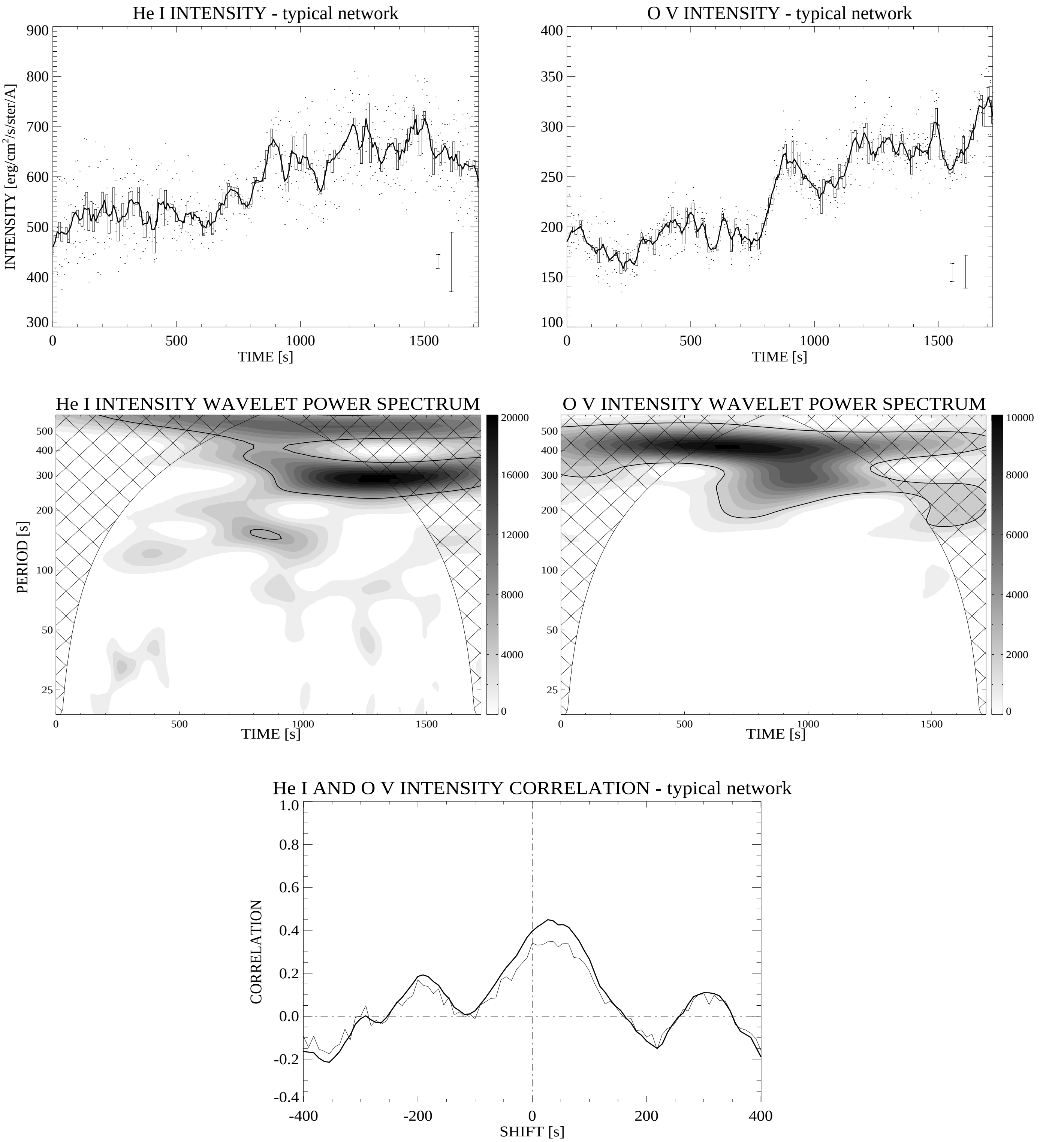


Figure 3: Top: Temporal variations of He I and O V line intensities. The dots show primary data, histograms display the averaged temporal variations of the primary data and the thick lines show the smoothed variations. The error bars show typical square root errors of the primary data (derived from the fitting of the spectral profiles; left error bars) and the mean standard deviations of the primary data from the displayed averaged temporal variations (right error bars). Middle: Wavelet analysis of the temporal variations of He I and O V line intensities. Bottom: Cross-correlation function of He I and O V line intensities. The thin line shows the correlation function of the averaged temporal variations and the thick line shows the correlation function of the smoothed variations.

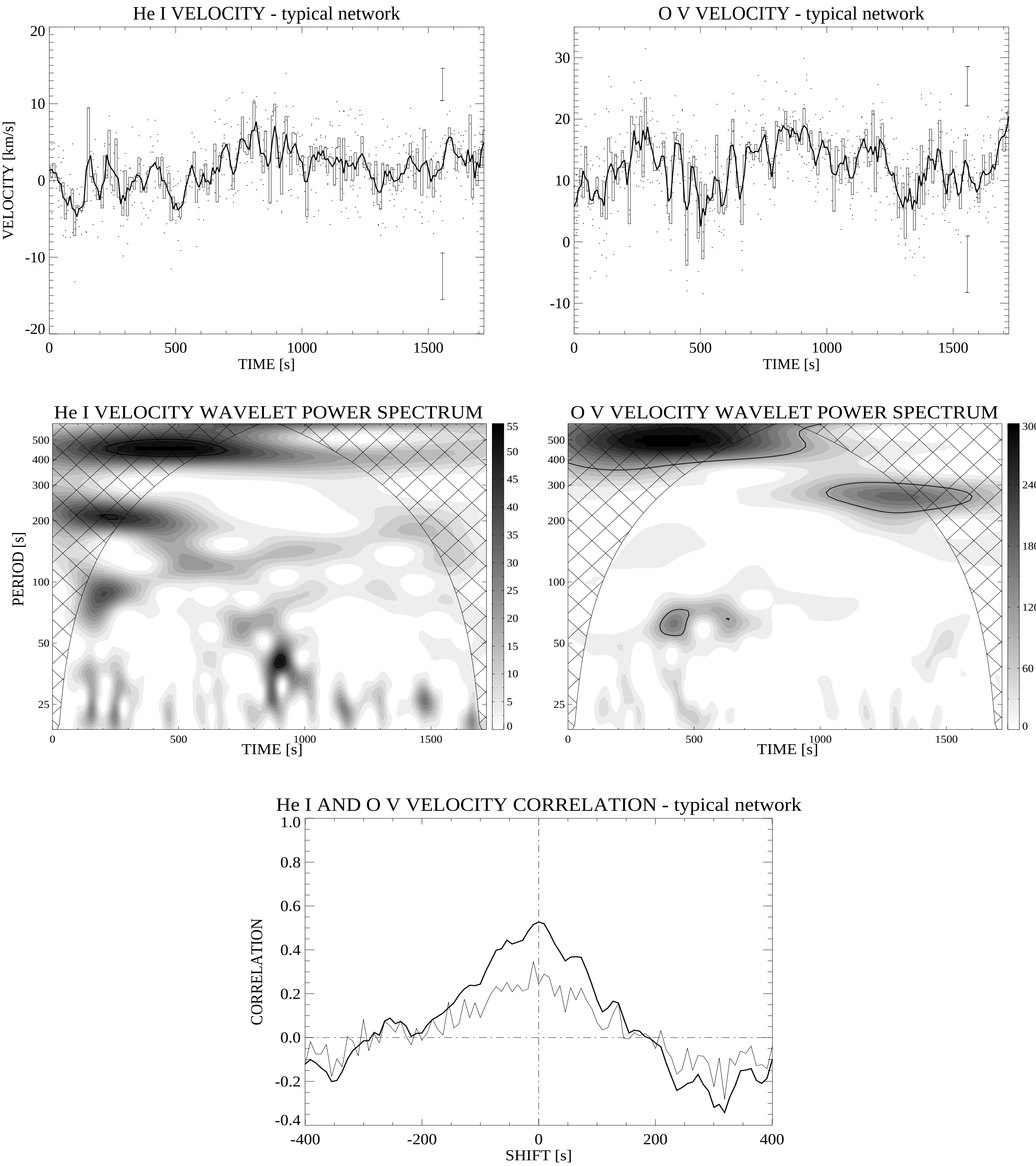


Figure 4: Top: Temporal variations of He I and O V line Doppler shifts. The dots show primary data, histograms display the averaged temporal variations of the primary data and the thick lines show the smoothed variations. The error bars show typical square root errors of the primary data (derived from the fitting of the spectral profiles; top error bars) and the mean standard deviations of the primary data from the displayed averaged temporal variations (bottom error bars). Middle: Wavelet analysis of the temporal variations of He I and O V line Doppler shifts. Bottom: Cross-correlation function of He I and O V line Doppler shifts. The thin line shows the correlation function of the averaged temporal variations and the thick line shows the correlation function of the smoothed variations.

O V AND Mg IX LINE INTENSITIES

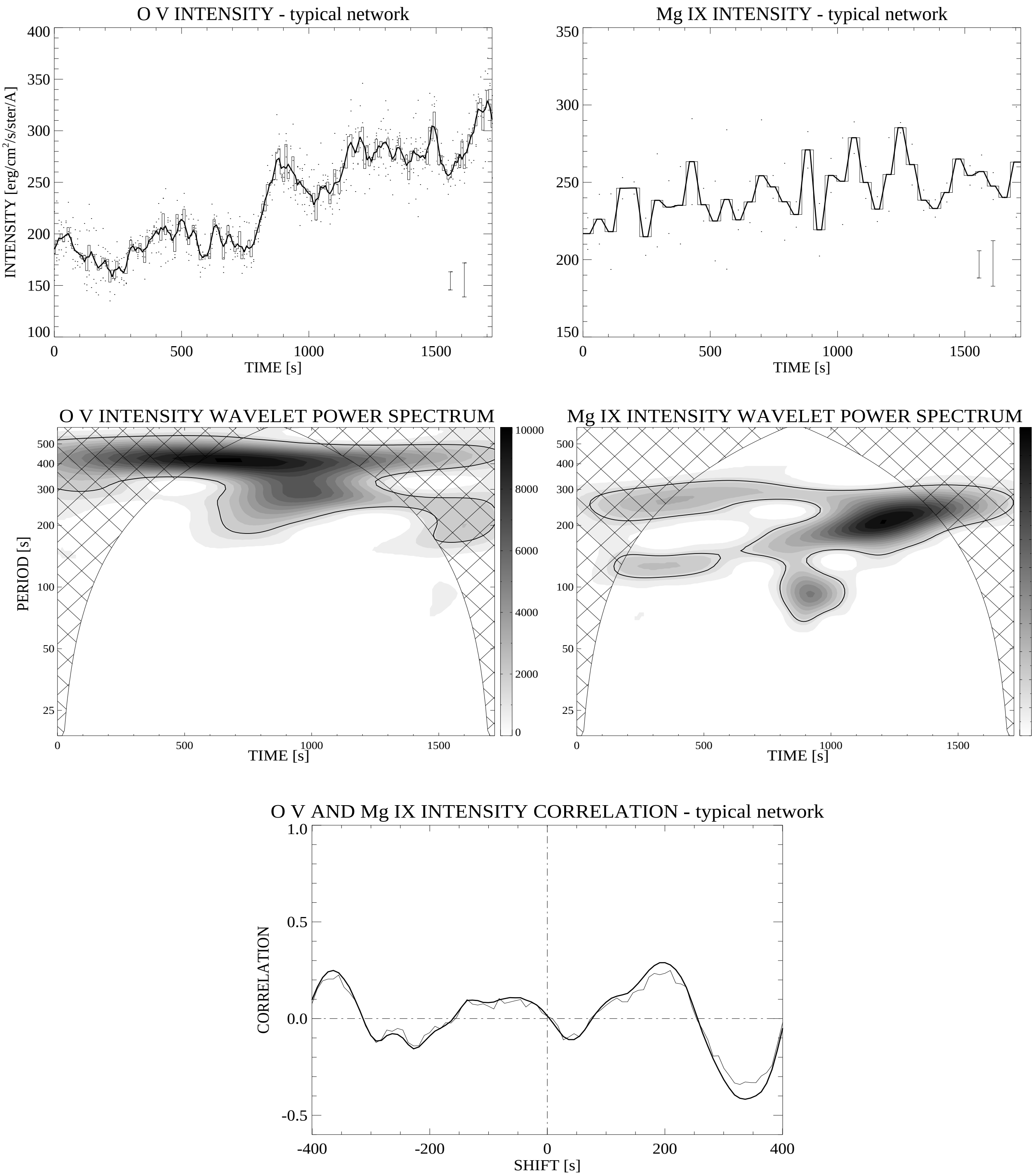


Figure 5: Top: Temporal variations of O V and Mg IX line intensities. The dots show primary data, histograms display the averaged temporal variations of the primary data and the thick lines show the smoothed variations. The error bars show typical square root errors of the primary data (derived from the fitting of the spectral profiles; left error bars) and the mean standard deviations of the primary data from the displayed averaged temporal variations (right error bars). Middle: Wavelet analysis of the temporal variations of O V and Mg IX line intensities. Bottom: Cross-correlation function of O V and Mg IX line intensities. The thin line shows the correlation function of the averaged temporal variations and the thick line shows the correlation function of the smoothed variations.

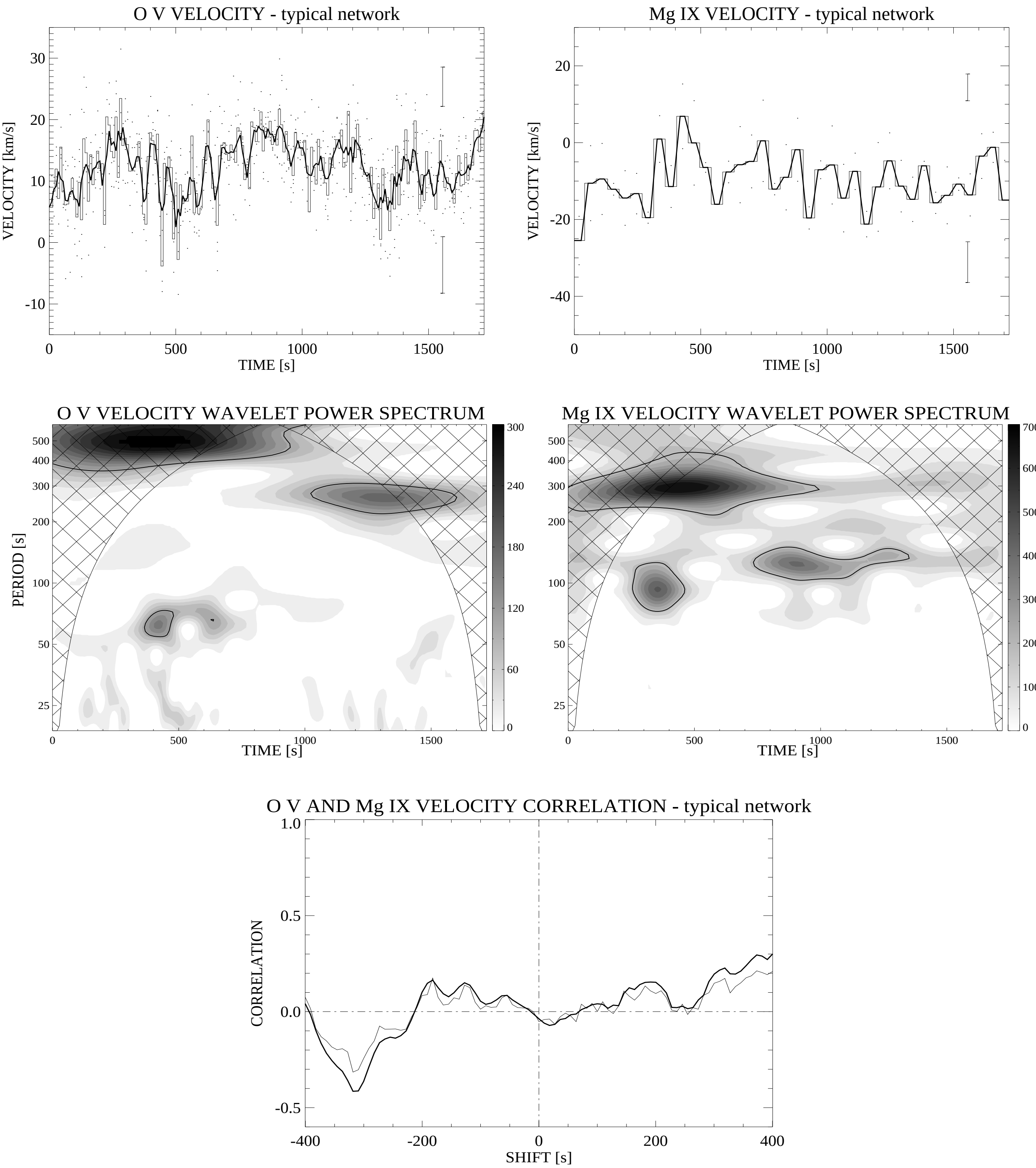


Figure 6: Top: Temporal variations of O V and Mg IX line Doppler shifts. The dots show primary data, histograms display the averaged temporal variations of the primary data and the thick lines show the smoothed variations. The error bars show typical square root errors of the primary data (derived from the fitting of the spectral profiles; top error bars) and the mean standard deviations of the primary data from the displayed averaged temporal variations (bottom error bars). Middle: Wavelet analysis of the temporal variations of O V and Mg IX line Doppler shifts. Bottom: Cross-correlation function of O V and Mg IX line Doppler shifts. The thin line shows the correlation function of the averaged temporal variations and the thick line shows the correlation function of the smoothed variations.

RESULTS

- He I and O V line intensity (Fig. 3):
  - wavelet analysis → He I: $\sim 300\,\mathrm{s} = 3.3\,\mathrm{mHz}$
  - wavelet analysis → O V: $\sim 400\,\mathrm{s} = 2.5\,\mathrm{mHz}$
  - cross-correlation → $\mathrm{CC}_{max} = 0.46$; shift $= +40\,\mathrm{s}$

  ⇒ cross-correlation of two variations with different periods
  ⇒ Is the shift of +40 s only an effect of different periods?
  (see page: cross-correlation of the sinusoidal functions with different periods)

- He I and O V line Doppler shift (Fig. 4):
  - wavelet analysis → He I: $\sim 220\,\mathrm{s} = 4.5\,\mathrm{mHz}$
  - wavelet analysis → O V: $\sim 250\,\mathrm{s} = 4.0\,\mathrm{mHz}$
  - cross-correlation → $\mathrm{CC}_{max} = 0.55$; shift $= 0\,\mathrm{s}$

- O V and Mg IX line intensity (Fig. 5):
  - wavelet analysis → O V: $\sim 400\,\mathrm{s} = 2.5\,\mathrm{mHz}$
  - wavelet analysis → Mg IX: $\sim 230\,\mathrm{s} = 4.3\,\mathrm{mHz}$
  - cross-correlation → CC $= 0.33$; shift $= +200\,\mathrm{s}$
    CC $= 0.24$; shift $= -360\,\mathrm{s}$

  ⇒ multiple maximum of CCF: caused by detected oscillations

- O V and Mg IX line Doppler shift (Fig. 6):
  - wavelet analysis → O V: $\sim 250\,\mathrm{s} = 4.0\,\mathrm{mHz}$
  - wavelet analysis → Mg IX: $\sim 90\,\mathrm{s} = 11.1\,\mathrm{mHz}$
    $\sim 140\,\mathrm{s} = 7.1\,\mathrm{mHz}$
  - cross-correlation → none

CROSS-CORRELATION OF THE SINUSOIDAL FUNCTIONS WITH DIFFERENT PERIODS

- He I and O V line intensity: shift = +40 s → effect of different periods?
- creation of 3 sinusoidal functions with period of 300 s (He I) which reach the first maxima for time lags = -50 s, 0 s, 50 s (real time intervals between first maxima) comparing to other sinusoidal function with period of 400 s (O V) (Fig. 7; left panel)
- calculation of the cross-correlation functions of these variations and determination of the shifts (positions of the maxima of the cross-correlation functions) (Fig. 7, right panel)
- result: positive shifts derived only for positive time lags, i.e. positive shift in cross-correlation function can be interpreted as the real positive time lag between the first maxima ⇒ only when the changes appeared firstly in the variation with period of 300 s (O V)

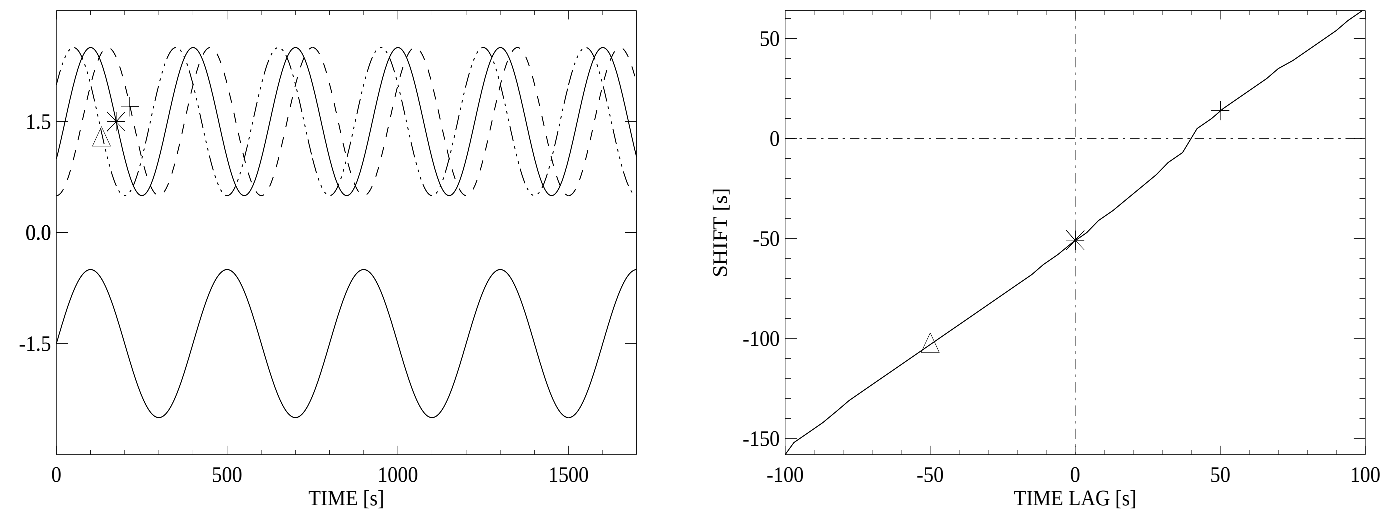
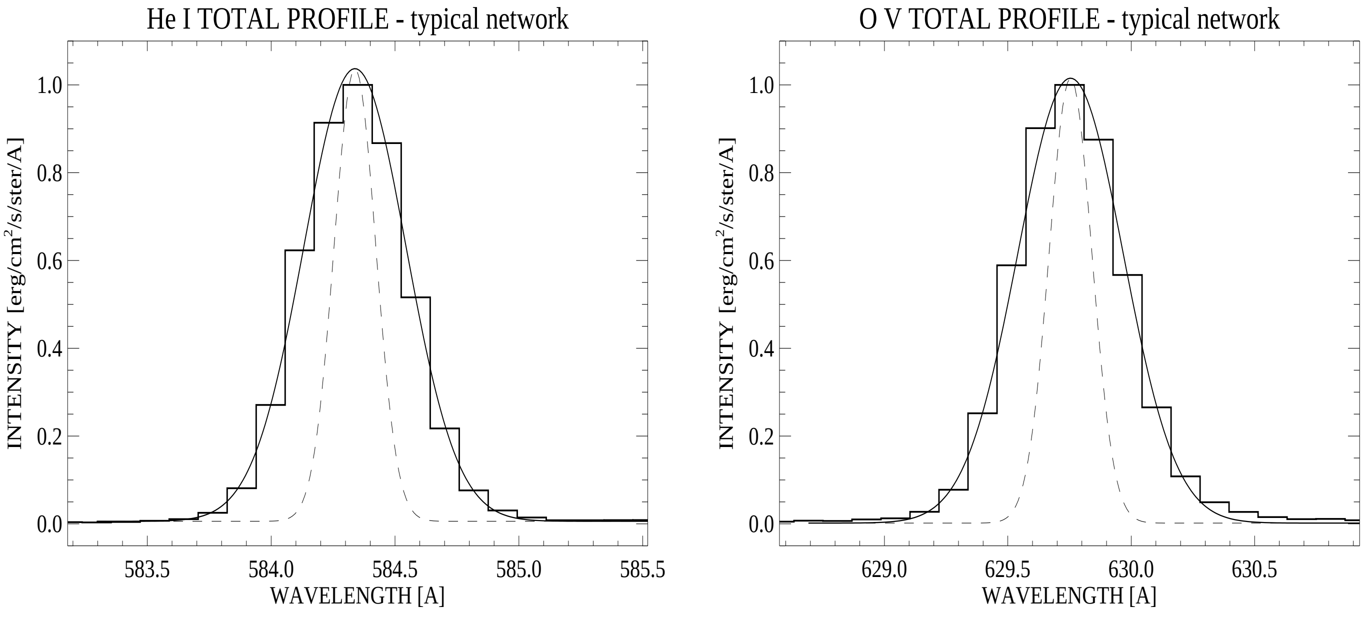


Figure 7: Left: Ideal sinusoidal functions with periods of 300 s (He I) and 400 s (O V). The full lines show sinusoidal functions which reach the first maxima simultaneously. The dashed/dash-dotted line represents the variations with period of 300 s which reaches the first maxima 50 s later/earlier (time lag = +50 s/-50 s) than the variations with the period of 400 s. Right: Shift (position of the maxima of the cross-correlation function) as a function of the time lag (real time interval between first maxima). The marks △, ∗ and + show values of shifts for time lags -50 s (△), 0 s (∗) and 50 s (+).

DISCUSSION (I)

- propagating waves spreading out from the transition region to the chromosphere:
  - He I ∼ O V intensity cross-correlation: shift $\geq +40\,$s
  - He I ∼ O V velocity cross-correlation: shift $= 0\,$s
  - non-radiative energy transfer without mass motion
    $\Rightarrow$ propagating, compressive waves
  - indirect evidence of the propagating waves: dominating non-thermal broadening of the He I and O V line spectral profiles; the non-thermal broadening represents 83 % of the total broadening of the spectral profiles (Fig. 8)



$$\xi_{total} = 0.292 \text{ Å} \qquad \xi_{total} = 0.302 \text{ Å}$$
$$\xi_{therm} = 0.018 \text{ Å} \qquad \xi_{therm} = 0.034 \text{ Å}$$
$$\xi_{instr} = 0.118 \text{ Å} \qquad \xi_{instr} = 0.118 \text{ Å}$$
$$\xi_{nonth} = 0.266 \text{ Å} \qquad \xi_{nonth} = 0.275 \text{ Å}$$

Figure 8: Normalized spectral profiles of the He I and O V lines. The histograms show shapes of the profiles. The thick lines describe single Gaussian fits of the spectral profiles. The dashed lines represent shapes of the spectral profiles without non-thermal broadening. The numbers under panels correspond to the total spectral broadening (ξ_{total}); thermal broadening (ξ_{therm}); instrumental broadening (ξ_{instr}) and non-thermal broadening (ξ_{nonth}) of the He I and O V spectral profiles.

DISCUSSION (II)

- wave source location:
  - O V ∼ Mg IX intensity cross-correlation: multiple maximum shift = +200 s; -360 s
  - O V ∼ Mg IX velocity cross-correlation: no cross-correlation
  - ambiguity in determination of the wave source localization $\Rightarrow$ wave source still uncertain
- reasons of the lower levels of the cross-correlation coefficients:
  - internal structure (He I, O V)
  - data noise (Mg IX)
- model of the quiet solar network atmosphere with proposed propagating waves:

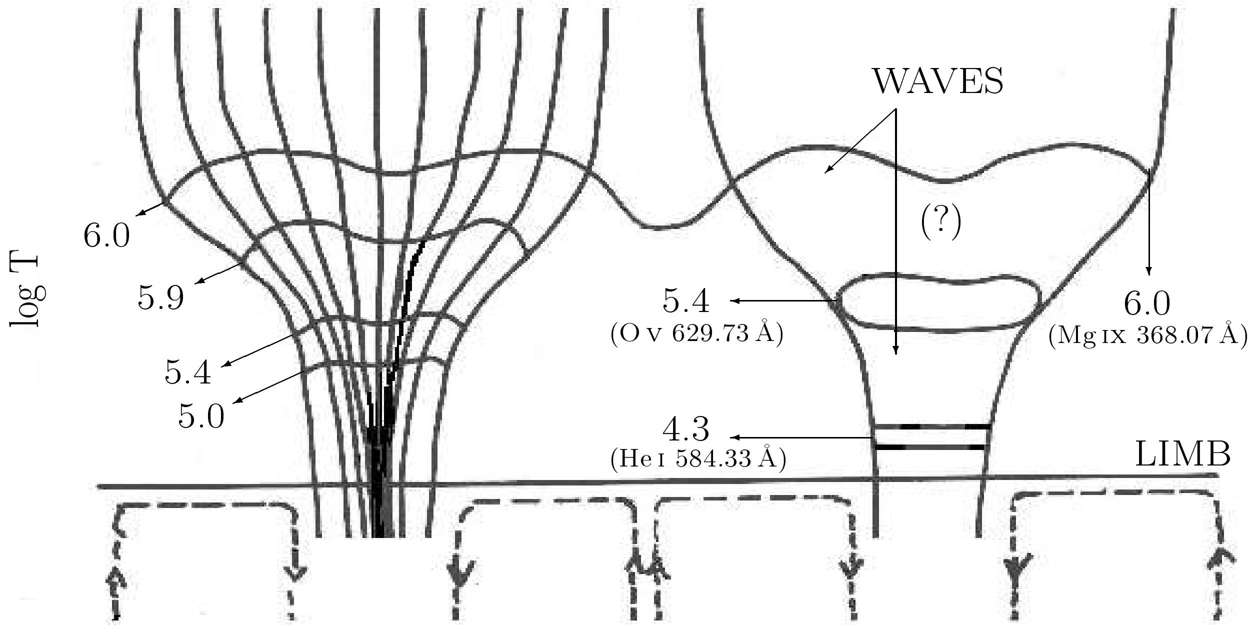


Figure 9: Simple scheme of the proposed model (adopted after Gabriel, A. H.: 1976, Phil. Trans. Roy. Soc. London A281, 339). The magnetic structure of the solar atmosphere and the temperature variation as a function of hight above the limb are shown on the left side. The studied atmospheric layers and proposed waves are shown on the right side. Analysis of the cross-correlation functions of the He I and O V line intensities and Doppler shifts clearly revealed the presence of the downward propagating waves (red color). Ambiguity in interpretation of the cross-correlation function of O V and Mg IX line intensities do not allow us to determine if the proposed waves originate in the corona and consequently affect lower parts of the solar atmosphere or if they originate in the transition region and spread out simultaneously upward to the corona and downward to the chromosphere in the particular network (blue color).

CONCLUSIONS

- necessity of the correct calculation of cross-correlation function of two independent temporal variations
- He I and O V cross-correlations:
  - intensity: shift ≥ 40 s
  - Doppler shift: shift ~ 0 s
  - evidence of the waves: non-thermal broadening of the He I and O V line spectral profiles
  - PROPAGATING WAVES
- O V and Mg IX cross-correlations:
  - O V and Mg IX intensity: ambiguity
  - O V and Mg IX Doppler shift: no cross-correlation
- wave source = uncertain
  - different structures observed in corona?
  - wide contribution function of Mg IX?
- possible source of the waves: nanoflares in corona *(Hansteen, V. et al.: 1996, ASP Conf. Series 111, 116)*
- future verification of results:
  - obtain longer CDS observational runs
  - use more spectral lines

  $\Rightarrow$ JOINT OBSERVING PROGRAM 171

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