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Dynamics of the solar photosphere and chromosphere derived from high-resolution Fe I and Ca II K spectra(*)

K. Brčeková(1), A. Hanslmeier(2), A. Kučera(1), J. Rybák(1) and H. Wöhl(3)

(1) *Astronomical Institute of the Slovak Academy of Sciences - 05960 Tatranská Lomnica Slovakia*
(2) *Institut für Geophysik, Astrophysik und Meteorologie - Universitätsplatz 5 8010 Graz, Austria*
(3) *Kiepenheuer-Institut für Sonnenphysik - Schöneckstr. 6, 79104 Freiburg, Germany*

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Summary. — The analysis of high-resolution spectra of the Fe I (522.5 nm, 557.6 nm) and Ca II K (393.3 nm) lines in the solar photosphere and chromosphere is presented. A dynamic coupling of the photosphere and chromosphere was determined from the ratios of both the photospheric and chromospheric line characteristics. All results are discussed for quiet and plage regions. It is found that in the plage region the mean values of K1, K2, K3 intensities in Ca II K are increased 2, 5 and 6 times, respectively, as compared to the quiet region. The mean values of Fe I line core intensities increased in plage only 1.32 and 1.64 times for the magnetic non-sensitive and magnetic sensitive line, respectively. The ranges of Fe I core intensity values are larger for the magnetic sensitive line than for the magnetic non-sensitive line.

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1. – Introduction

Solar spectra with high spatial and spectral resolution are a good tool to diagnose the physical conditions in the solar atmosphere. To achieve this aim, it is important to choose suitable spectral lines which are formed at appropriate heights in the solar atmosphere. We selected two photosperic Fe I lines—557.6 nm and 522.5 nm, the former is pure dynamic, the latter is magnetic sensitive. To investigate the connection between different layers of the solar photosphere in different levels of activity, we included the

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TABLE I. – *The parameters of spectral lines.*

line	Wavelength (nm)	Height of line core formation (km)	Landé factor g_{eff}
Fe I	522.55	~ 370	2.5
Fe I	557.61	~ 370	0.0
Ca II K	393.36	~ 1500	1.17

Ca II K line. This line is widely used as a probe of the solar chromosphere dynamics due to its core variability.

2. – Observations and data reduction

The Vacuum Tower Telescope (Observatório del Teide, Tenerife) was used to obtain the high-resolution spectra analysed in this work. The spectra were taken on June 1, 1993 in regions with different levels of solar activity. The spectra of three spectral regions were taken simultaneously at each position on the solar disc. The main parameters of the spectral lines used are listed in table I. The exposure time was 0.2 s for Fe I lines and 2 s for Ca II K line, respectively. The spectra were taken with 1024×1024 pixels CCD cameras with a binning of 2. The final reduced spectra are 512×512 pixels with the spatial resolution $0.17''$ along the slit and the spectral resolution 3.5×10^{-4} nm per pixel for Fe I lines and 2.6×10^{-4} nm per pixel for Ca II K line. The spectrograph slit was 150 μm wide and it was adjusted to be parallel with the meridian. The characteristics of the used spectra are listed in table II. The data were reduced using IDL software: the dark current subtraction was applied and a special procedure was applied to remove the flat field [1]. To compare images taken at different wavelengths, it was necessary to eliminate the influence of the atmospheric refraction. With regard to the fact that the slit was parallel to the meridian it was done by shifting images along the slit relative to each other. The shift was assigned as a position of the maximum correlation coefficients between the intensity fluctuations along the slit in the centers of Fe I lines and in the Ca II K line wing. After this basic reduction the FFT noise depression, elimination of the continuum trend and calibration of the spectra to the real atlas continuum were done.

3. – Spectral characteristics

We used Doppler velocities (v_{d}) and intensities in the centers of Fe I lines (I_0), the integrated intensity in the Ca II K line (a 1 Å interval with midpoint in the line center) and intensities at the K1, K2 and K3 positions in the Ca II K line, where the following relations were applied: $I(\text{K1}) = [I(\text{K1r}) + I(\text{K1v})]/2$ and $I(\text{K2}) = [I(\text{K2r}) + I(\text{K2v})]/2$.

In the Ca II K spectrum of the quiet region genuine quiet scans were selected applying

TABLE II. – *Characteristics of the spectra used.*

Number	Time (UT)	Disc location	Level of activity
1	08:01:01	$\mu \sim 1$	quiet
2	08:28:31	$0.97 > \mu > 0.77$	plage

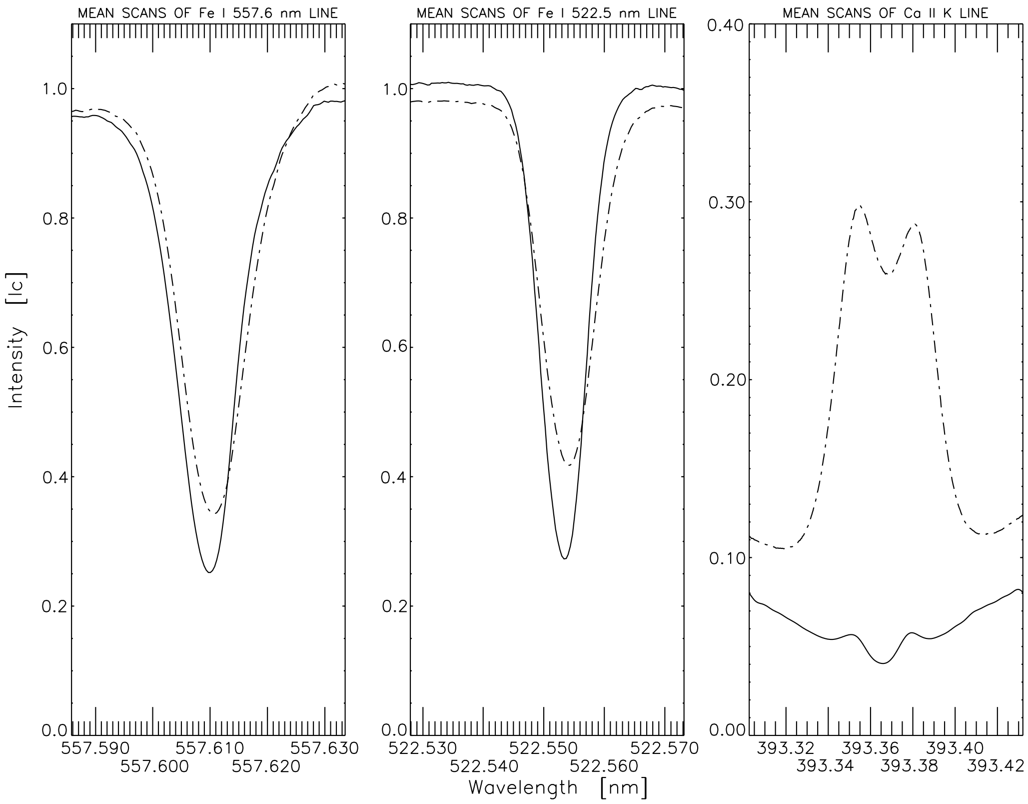

Fig. 1. – Mean scans (from selected scans only) of all investigated lines for both levels of activity. Solid lines stand for quiet, dash-dotted lines for plage, respectively.

the condition $I_{\max} < 0.07 I_C$, where $I_{\max}$ is the maximum intensity in particular scans. In [2] was found that enhanced chromospheric Ca II K emission can be produced by wave motion driven by the photospheric pistons. Using our condition we selected all scans which were not influenced by pistons at the moment of exposure. As "plageous" we understand the Ca II K scans with $I_{\max} > 0.25 I_C$. Only the Ca II K spectral scans meeting these constraints were used in our investigations together with corresponding scans from the Fe I lines spectra (quiet region—64 scans, plage—202 scans). Figure 1 shows averaged spectral profiles (mean scans) of all three spectral lines.

4. – Results and discussion

The properties of the photosphere were derived from the ratios of Fe I line characteristics. It is obvious that the correlations between intensities and velocities are similar for both the Fe I lines (fig. 2). Due to the presence of magnetic fields the amplitudes of the intensity variations of magnetic sensitive Fe I 522.5 nm line are larger in plage regions (indicated by diamonds in fig. 2). Maybe the different values of the magnetic field occur through the active region and this caused the larger intensity dispersion. In the quiet photosphere the intensity I_0 in Fe I is of about 0.25 I_C for both lines, the value being the same for the whole range of velocities. This is not consistent with findings of [3]

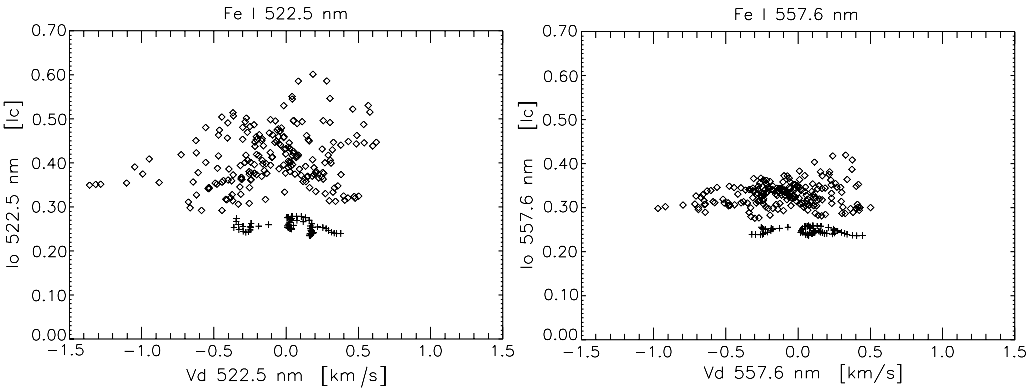

Fig. 2. – The dependences of the intensities on the velocities in the centers of Fe I lines for quiet (+) and plage (⋄). Up-flows have negative velocities.

(see fig. 3 in their work) where the correlation of the intensity I_0 of Fe I 557.6 nm with the velocity v_{d} of Fe I 557.6 nm is evident. The lack of this feature in our analysis is probably due to the fact that we have analysed the granular and intergranular patterns together, while [3] distinguished between these two structures. More we selected only those scans which are related only to the moments of the "really quiet" atmosphere not influenced by pistons. In the quiet photosphere the positive (down-flow) velocities are slightly prevailing. In the photosphere under the plage we can see a shift of the core intensities to higher values. The intensities I_0 never fall below a fixed limit $0.27 I_C$, *i.e.* the photosphere under the plage is heated to a higher temperature when compared to the quiet region.

The velocities in the photosphere under the plage are found to lie within a larger interval than is the case for a quiet region. This interval exhibits an increase when one goes to the negative velocities. Greater negative velocities tend to have smaller dispersion in the intensity values. The largest range of intensities is seen in scans featuring the maximum positive velocities. This trend is more conspicuous in non-magnetic Fe I 557.6 nm line, but it can be traced in Fe I 522.5 nm as well. Thus we conclude that this

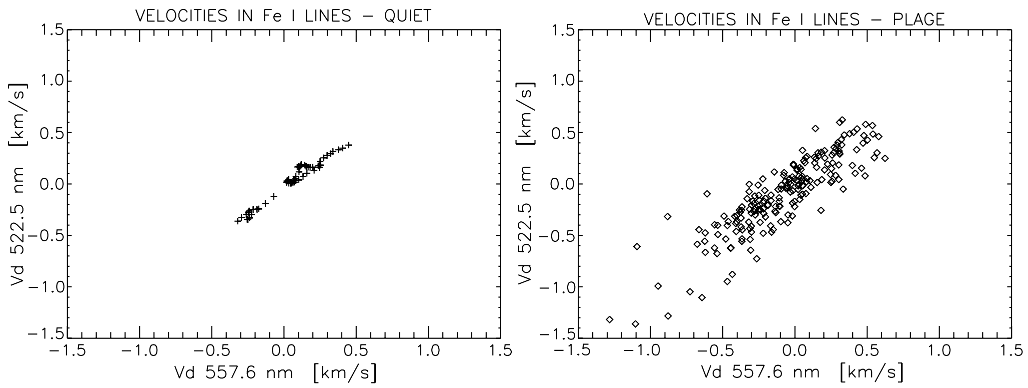

Fig. 3. – The dependences of the velocities in the centers of Fe I lines.

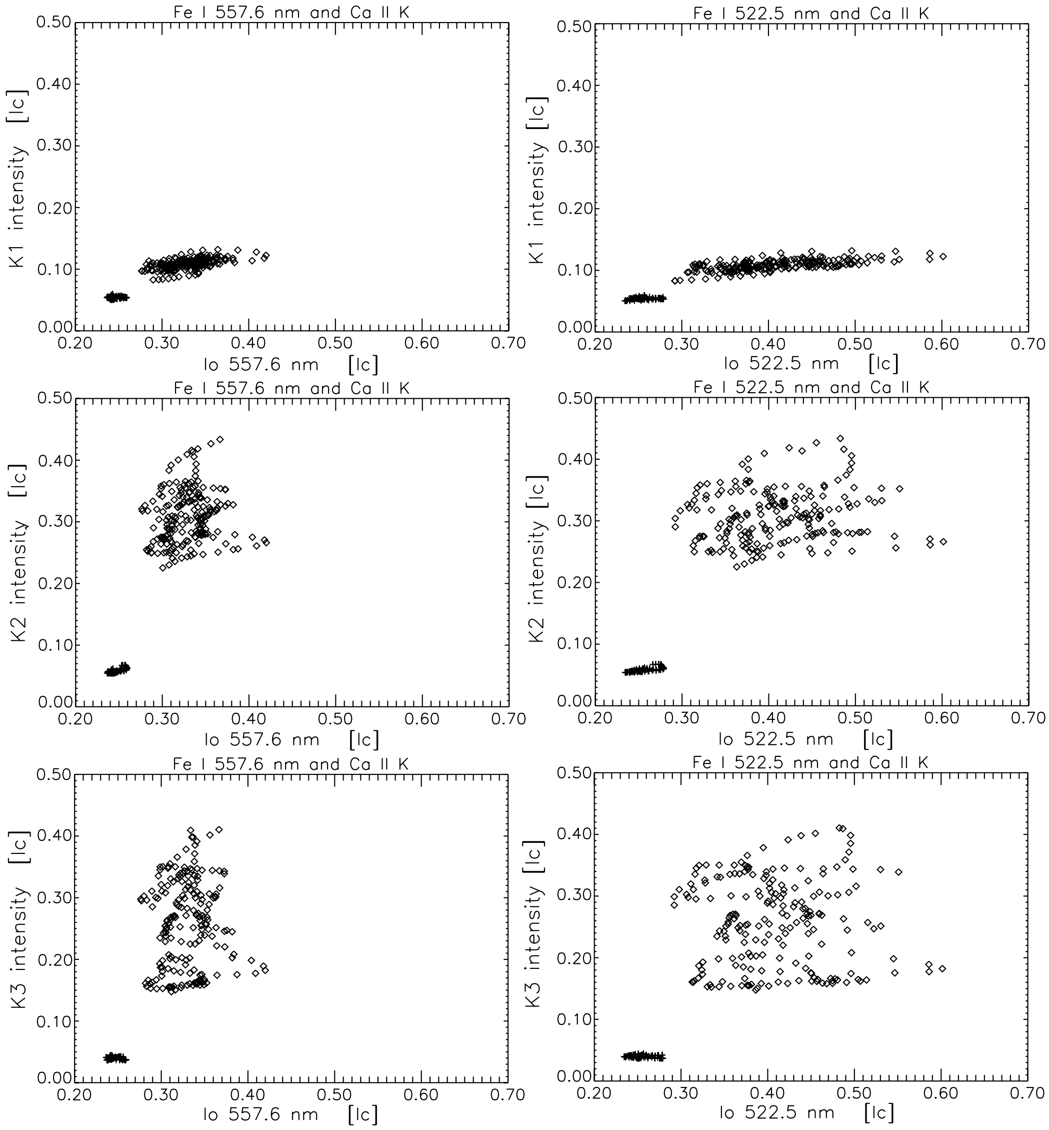

Fig. 4. – The ratios of the intensities in Ca II K line against the Fe I line core intensities.

trend has its probable origin in the dynamic properties of the atmosphere and it maps the different conditions of up-flowing and down-flowing plasma in the granulation.

Figure 3 shows the ratios of the velocities in both photospheric lines under the quiet and plageous atmosphere separately. The dependence is the same in both levels of activity. The range of values in the quiet region is slightly different from [3]. Their range of velocities in the positive values (up to 0.5 km/s) is the same as ours, but in the negative velocities they report the values up to -0.63 km/s and our values amount to -0.3 km/s only. This discrepancy can be a consequence of the choice of strictly quiet-atmosphere region and the fact that our data were not corrected for oscillatory fluctuations unlike [3].

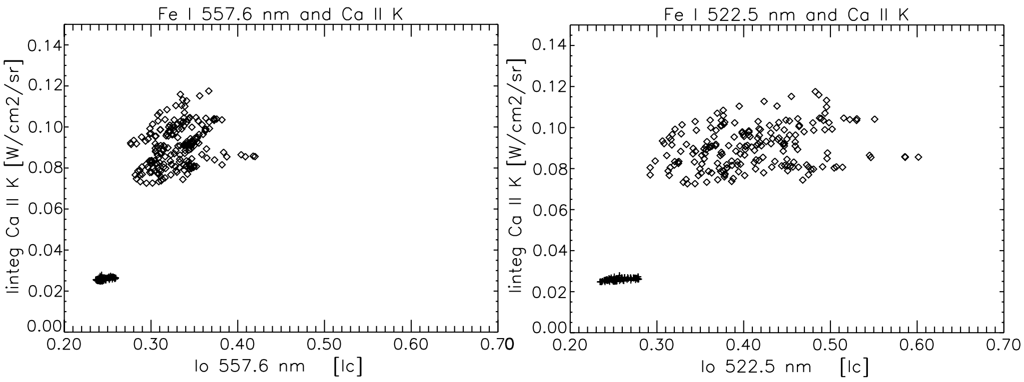

Fig. 5. – The ratios of the integrated intensities in Ca II K against the intensities in the centers of Fe I lines.

The range of values in the photosphere under the plage is larger, mostly in negative values and exhibits a greater dispersion as well.

The coupling of the photosphere and chromosphere is demonstrated by the ratios of characteristics in fig. 4. There is no link between the K1, K3 intensities and those of Fe I in quiet region. It seems as if the quiet photosphere and chromosphere did not affect each other, but we can see a coupling effect between K2 and Fe I core intensities. The K2 intensities slightly increase with increasing Fe I intensities (in both lines). We also investigated the intensities in K2v and K2r separately, but almost no difference in the dependence was found. In the region of plage all intensities increased significantly. The mean values of K1, K2, K3 intensities increased 2, 5 and 6 times, respectively, according to the quiet region. The mean values of Fe I line core intensities increased too but only 1.32 and 1.64 times for the magnetic non-sensitive and magnetic sensitive line, respectively. The ranges of Fe I intensity values are larger for the magnetic sensitive line than for the magnetic non-sensitive line. The dependence on the Fe I intensity is apparent just in the K1 intensity, because the K1 minimum in the Ca II K line is formed in the heights around 500 km, relatively close to the height of the formation of the photospheric lines (370 km). The most intensive increase of Ca II K intensities in plage is found in K2 (5 times) and K3 (6 times), which are formed in a higher atmosphere and are considered as indicators of the chromospheric activity.

The dependence of the Ca II K integrated intensity on the intensity in Fe I lines (fig. 5) has nearly the same shape as in fig. 4 for the K2 peak. This means that the integrated intensity is mostly influenced by the K2 intensity. Our values of the integrated intensities are smaller in quiet region and larger in plage than those found in [4].

The derived relations of the photospheric and chromospheric line characteristics can be used as the check of the available semi-empirical 1D hydrostatic models of the solar plage atmosphere [5-7]. Our selection of the typical quiet and plage scans can be a good tool for verification of these basic models.

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