Long-Term Datasets for the Understanding of Solar and Stellar Magnetic Cycles
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Kyiv monitoring program of spectral line variations with the 11-year cycle

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Abstract. Kyiv program of monitoring of long-term variation of solar spectral lines at the horizontal solar telescope of the Main Astronomical Observatory of Ukraine is described. The aim of the program is to clarify the issue how the physical parameters of the quiet solar atmosphere change over the 11-year cycle of solar activity. The diagnostics of the atmospheric variation includes analysis of more than 40 spectral lines of neutral and ionized chemical elements observed at the solar disk and at the limb near north and south poles with high spectral resolution. The results of monitoring show that during 2012–2017 a line core depths and a line full widths at half maximum respond to the cycle modulation of the global unsigned magnetic field of the Sun. Such a correlation can be explained by assuming that temperature gradient of the solar photosphere is growing with solar activity.

Keywords. Sun: atmosphere, line: profiles, line: formation, instrumentation: spectrographs, techniques: spectroscopic

1. Introduction

The first monitoring programs aimed to study changes in spectral lines with 11-year cycle of solar activity started in the mid-fifties of the last century. In particular, Krat & Kokhan (1984) published results of observations of selected spectral lines carried out since 1969. They found that changes in the central line intensities during the 11-year cycle occur within 1%. For many years Livingston & Holweger (1982); Doyle *et al.* (2001); Livingston *et al.* (2007); Livingston *et al.* (2010) monitored chromospheric and photospheric spectral lines, integrated over the full disk (i.e., "the Sun as a star") and some of them for a small circular region near the center of the solar disk. After over 30 years of observations Livingston *et al.* (2007) concluded that the "basal quiet atmosphere is unaffected by cycle magnetism within our observational error". Recently, Danilovic *et al.* (2016) pointed out at a high correlation of the magnitude of solar cycle variations between the full-disk observed and reconstructed change in the Mn I 539.5 nm line parameters. Since 2006 Synoptic Optical Long-term Investigations of the Sun (SOLIS) provides autonomous full-disk spectral, magnetic, and imaging measurements to help understanding solar activity and its effect on the Earth's climate and atmosphere (Keller *et al.* 2003; SOLIS 2018). It should be noted that the Sun as a star monitoring of spectral lines does not allow us to answer the question whether the physical parameters of the quiet solar atmosphere outside active regions change over the 11-year cycle of the solar activity. Kyiv program of long-term monitoring of solar spectral lines variation aims to clarify this question.

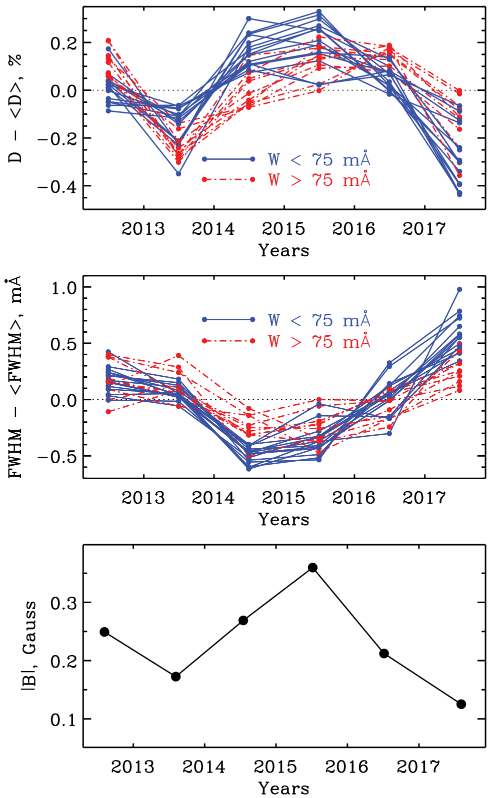

Figure 1. *Top panel:* variations of the line core depth D of the 25 Fe I lines observed over 2012–2017 in the quiet regions of the disk center relatively their mean $\langle D \rangle$ values. *Middle panel:* variations of the line full width at half maximum $FWHM$ relatively their mean $\langle FWHM \rangle$ values for the same observations and the same period of time. Blue solid curves represent the weaker lines with equivalent widths $W < 75$ mÅ. Red dash-dotted curves indicate the stronger lines with $W > 75$ mÅ. *Bottom panel:* the unsigned global magnetic field as measured by Wilcox Solar Observatory over 2012–2017 (*http://wso.stanford.edu/meanfld*). Black circles represent values of the mean field corresponding to each observational season at the telescope ATsU-5.

2. Observations

Our program is based on center-to-limb observations of the quiet Sun obtained with a high ($R = 330\,000$) spectral resolution at the horizontal solar telescope ATsU-5 of the Main Astronomical Observatory of the National Academy of Sciences of Ukraine (see Gurtovenko & Kostik 1989; Kostik & Shchukina 1997; Osipov 2015; Osipov *et al.* 2017). The diagnostics of the solar cycle variation of the quiet solar atmosphere is based on observations of the Hα, Ca II K and more than 40 spectral lines of neutral and ionized chemical elements (C I, Ca I, Cr I, Mn I, Fe I, Fe II, Ti II) in nine spectral regions from 393 nm to 657 nm. The formation heights of these lines cover the photosphere, the temperature minimum and the lower chromosphere. The observing program consists in using the spectrograph in one pass mode. Spectral lines are recorded with a CCD camera with 3326 by 2504 pixels. Since 2012 we perform observations at three positions on the solar disk (center, north and south poles) with the entrance slit height of 2 arcmin and the exposure time in the range of 1–2.5 s. Observational season lasts from March to October. In total, we have 341 days of observations between 2012 and 2017.

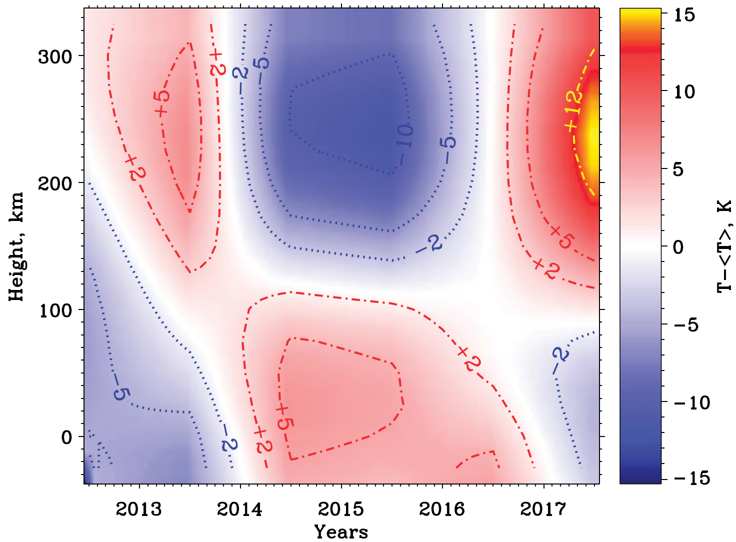

Figure 2. Map of the temperature changes $(T - \langle T \rangle)$ in the quiet regions of the solar photosphere with height and time recovered using observations of the Fe I 537.957 nm line at the ATsU-5 telescope during 2012–2017. Line contours are labeled with their $(T - \langle T \rangle)$-values.

3. Preliminary results

Variations of the line core depths D and the line full widths at half maximum FWHM. The top and the middle panels of Fig. 1 demonstrate variations with time of the $(D - \langle D \rangle)$ and the $(FWHM - \langle FWHM \rangle)$ values of the twenty five Fe I lines obtained for the quiet regions of the solar disk center during observations at the ATsU-5 telescope in 2012–2017. Note, that for each of these lines the $\langle D \rangle$ and $\langle FWHM \rangle$ values represent, respectively, the mean core depth and the mean full width at half maximum obtained by averaging over six observational seasons. Comparison of these variations with annual variations of the unsigned global magnetic field shown in the bottom panel of Fig. 1 indicates that during 2012-2017 the line core depth and full width at half maximum of the solar Fe I lines respond to the cycle modulation of the global unsight magnetic field of the Sun.

Temperature variations of the quiet solar photosphere between 2012 and 2017 were restored by applying the LTE inversion code based on Tikhonov stabilizers (Stodilka 2003) to observations of the Fe I 537.957 nm line at the quiet regions of the solar disk center. Figure 2 shows map of temperature variations $(T - \langle T \rangle)$ with time in photospheric layers between −30 km and +330 km. Note, that the temperature $(\langle T \rangle)$ of each layer represents mean value for the period from 2012 to 2017. Comparing the results shown in the bottom panel of Fig. 1 and Fig. 2 we conclude that the temperature of deep photospheric layers at ascending phase (2012–2015 years) of the 11-year cycle of solar activity is growing. On the contrary, outer layers become cooler. Near the minimum of solar activity (2017 year) we observe opposite effect.

4. Concluding remarks

Our results can be summarized as follows:

• Core depths and full widths at half maximum of the lines in the solar spectrum of quiet areas correlate with the 11-year cycle of solar activity.

- Spectral lines becomes deeper and narrower near the maximum of solar activity and less deep and broader near the minimum.
- Temperature gradient of the solar photosphere is growing with solar activity.

Finally, we conclude that the basal (center disk) quiet atmosphere is affected by cycle magnetism.

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