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Long-term monitoring of spectral line variations with the 11-year cycle. Quiet Sun

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The monitoring program of long-term variation of selected solar spectral lines is described. The aim of the program is to study how the physical parameters of the quiet solar atmosphere change over the last solar cycle 24. The research is based on high spectral resolution observations of the quiet Sun using the Ernest Gurtovenko horizontal solar telescope of the Main Astronomical Observatory of the National Academy of Sciences of Ukraine. Since 2012 the observations are performed daily, when the weather conditions allow. We found that the line core depths and full widths at half maximum of the Fe I solar spectral lines correlate with the cycle modulation of the total unsigned magnetic field and the Wolf numbers of the Sun. The behaviour of these line parameters can be explained by variations of the temperature of the quiet photosphere during the 11-year cycle.

Keywords: Solar instrumentation, observations, spectral lines, solar magnetic field, solar cycle variations

1 Introduction

In recent decades the countries of the civilised world are increasingly concerned about global warming and its multiple effects, including global average air and ocean temperature increase, widespread melting of glaciers, rising global average sea level, more frequent extreme weather events like hurricanes, tsunami, heat waves, expansion of deserts etc. There is a widespread belief that most of the global warming since the mid-20th century is likely to be due to human activities. However, it should be borne in mind that the Sun could be another important driver of Earth's climate system change. There are many indications of both monotonous and cyclic variations of the Sun in different timescales, such as the 11-year cycle, secular and millennial changes,

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as well as evolutionary changes on the scale of the order of 10^8 years. Without studying these variations it is impossible to understand the causes of global warming and to predict its impact on the Earth's climate, biosphere, social and economical systems.

Of particular interest in this sense are long-term (for decades) variations of the outer layers of the Sun, including the photosphere, chromosphere and corona. At present, such variations are particularly poorly understood. To evaluate them, long-term monitoring of the solar atmosphere is needed. An important source of information on these variations are the solar spectral lines.

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. A review of some of them is published by Atroshchenko et al. (1991). Many of these programs are based on the observations whose duration does not exceed one or two years (see, e.g., Cavallini et al. 1986, and references therein). As an exception, it is necessary to mention results of observations of selected spectral lines carried out between 1969 and 1979 by Krat & Kokhan (1984). They found that changes in the central line intensities during the 11-year cycle occur within 1%. Another example is the long-term observations of Livingston and his colleagues. Namely, many years Livingston & Holweger (1982), Doyle et al. (2001), Livingston et al. (2007), Livingston et al. (2010) observed chromospheric (Hα, Ca II K & H, CN 3883 Å, Ca I 8542 Å, He I 10830 Å) and photospheric (Fe I 5379.5 Å, C I 5380.32 Å, and Ti II 5381.02 Å) 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 5395 Å line parameters. Since 2006 Synoptic Optical Long-term Investigations of the Sun (SOLIS) provide 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" observations (SOLIS, 2018; Livingston et al., 1982, 2007, 2010; Danilovic et al., 2016) do not allow us to answer the question whether the physical parameters of the quiet solar atmosphere outside active regions vary over the 11-year cycle of the solar activity and if so, how large are these variations. The solution to this problem is faced with serious challenges. First of all, it happens because during such observations variations of the quiet component of the solar atmosphere can not be separated from variations, caused by contributions from active regions (sunspots, flashes, plages, etc.). Our program of long-term monitoring of solar spectral lines aims to answer the question posed above.

2 Observations

We are monitoring variations of the spectral lines during Cycle 24 of solar activity using observations of the quiet Sun obtained with high (R = 330 000) spectral resolution at the horizontal solar telescope of the Main Astronomical Observatory of the National Academy of Sciences of Ukraine. The telescope is located near Kyiv.

It was set into operation in 1966 and upgraded in 2011. The main contribution to its implementation and design in the sixties was made by Ernest Gurtovenko. Now the telescope is named in his honor. A description of the telescope can be found in Gurtovenko & Kostik (1989), Kostik & Shchukina (1997) and Osipov (2015).

The main telescope characteristics are: a 440 mm coelostat and additional mirrors, a 440-mm main mirror with a focal length of 17.5 m. The telescope designed for low scattered light has a spectrograph which can be used both in single and double pass mode. The spectrograph collimator and camera 500-mm mirror has a focal length of 7 m. Currently, the telescope is equipped with a CCD camera having set-point cooling to -40° C below ambient temperature. Its array (17.96×13.52 mm) has 3326×2504 pixels at 5.4 microns. A ruled area of the grating is 140×150 mm with 600 lines per mm. The instrumental profile of the spectrograph in the fourth order measured at 6328 Å using a helium-neon laser has a half width of 19 – 21 mÅ.

The diagnostics of the solar cycle variation of the quiet solar atmosphere is based on the observations of the Hα, Ca II K & H 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 3930 Å to 6570 Å. The formation heights of these lines cover the large portion of the photosphere, the temperature minimum and the lower chromosphere (see Fig. 1).

We perform observations at three positions on the solar disk (center, north and south poles) with the entrance slit height of 2 arc min. To reduce seeing effects we use, as a rule, a short exposure time in the range of 1–2.5 s. The observing program consists of using the spectrograph in single pass mode. According to Osipov et al. (2017) such a scheme makes it possible to measure line bisectors with an accuracy

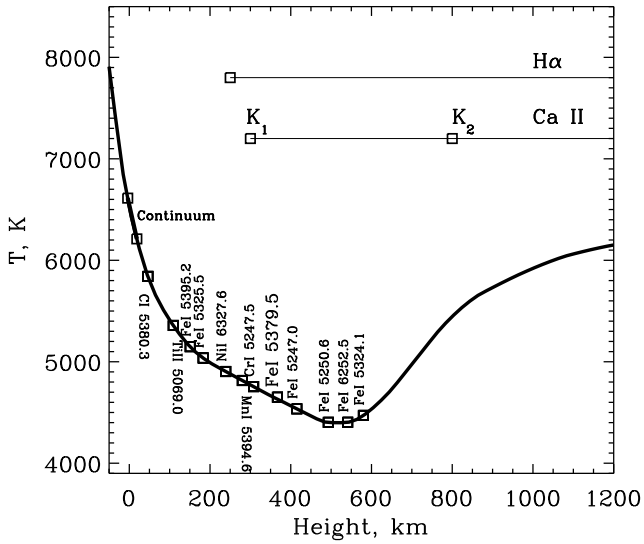


Figure 1 Unit optical depth for cores of various lines and continua (squares and horizontal lines) in the solar atmosphere. The solid curve shows the variation with height of the temperature in the MACKKL (Maltby et al., 1986) model.

higher than that of Liège (Delbouille et al. 1973) and FTS (Neckel & Labs, 1984; Neckel, 1999) atlases.

We perform monitoring daily, when the weather conditions allow. The observational season lasts from March to October. In total, we have about 460 days of observations between 2012 and 2019. We started these observations at the final stage of the ascending phase of Cycle 24 near a "double-peaked" solar maximum. Observations obtained after 2015 belong to the descending phase of this cycle. Monitoring of 2019 can be considered most likely as performed near its minimum.

We have developed a special methodology and instrumentation that allow us to record the spectral lines on long time scales with a high precision metrological stability. Among them are:

- Unique spectrograph calibration system. It makes it possible to measure the instrumental profile several times during the observation day. Note that on other telescopes this is usually done no more than once per year.
- Accounting for partial signal coherence and for changing the instrumental profile when switching to another wavelength. This is not done on any similar telescope.
- Unique thermal protection system, namely, closed type spectrograph and dual airbag in the walls of the telescope building. As a result, the LOS velocities inside of the spectrograph are surprisingly small being in the range of 4–5 m/s for exposure time of 2 s (Osipov, 2014).

Due to high spectral resolution and long-term metrological stability, the Ernest Gurtovenko telescope turns out to be the scientific tool best adapted for monitoring of the quiet Sun. Using this telescope we can detect variations of the spectral line central depth about 0.1%, variations of the line half-width less than 0.2 mÅ, and the variations of the line bisector less than 5 m/s.

3 Results

In this study, we present results of our monitoring program using observations at the solar disk centre of eighteen Fe I lines of different strength. We divided these lines into two groups. The first one contains stronger lines with equivalent widths W more than 75 mÅ. In the second group we included weaker lines whose equivalent widths are below this value. The weaker lines are formed in the deeper layers of the solar photosphere, i.e., between the lower and middle photosphere, while the formation region of the stronger line covers usually the whole photosphere.

3.1 Variations of the line parameters

We analyse two parameters of the observed Fe I spectral lines which could be the indicators of the temperature variation of the solar atmosphere. They are a line core depth D and a line full width at half maximum $FWHM$. The top and middle panels of Fig. 2 show temporal variations of these parameters over 2012–2019. Note that filled circles shown in this figure represent averaging over each annual observing season, while the vertical lines are 95% confidence intervals for random errors.

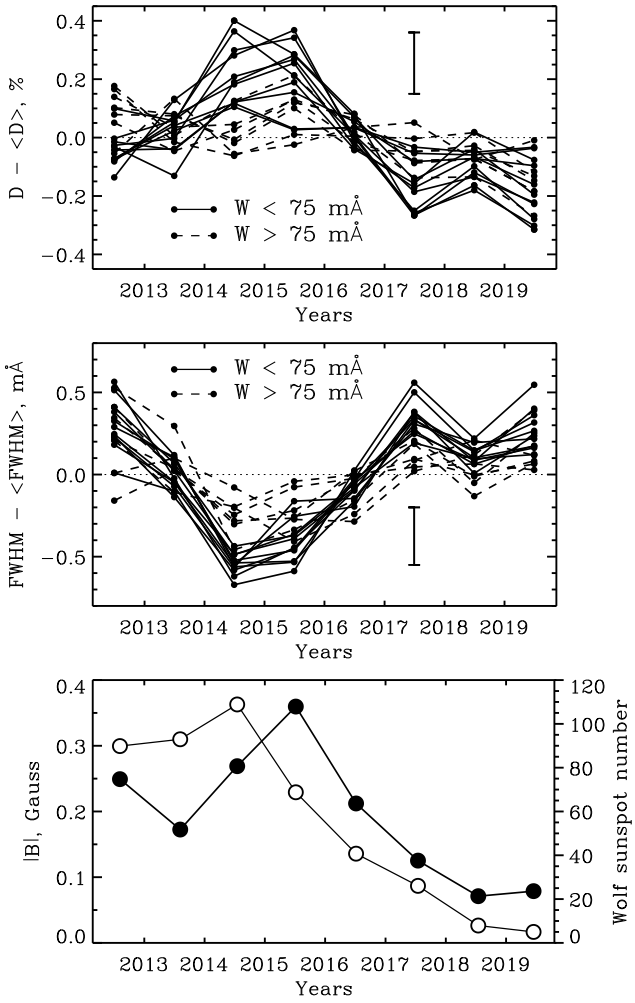


Figure 2 *Top panel:* variations of the line core depth D of eighteen Fe I lines observed over 2012–2019 in the quiet regions of the disk centre relative to their mean $\langle D \rangle$ values. *Middle panel:* variations of the line full width at half maximum $FWHM$ relative to their mean $\langle FWHM \rangle$ values for the same observations and the same period of time. Solid curves represent the weaker lines with equivalent widths $W < 75$ mÅ. Dashed curves indicate the stronger lines with $W > 75$ mÅ. *Bottom panel:* the unsigned global magnetic field (filled circles and solid curve) as measured by Wilcox Solar Observatory over 2012–2019 (*http://wso.stanford.edu/meanfld*) and Wolf sunspot numbers (open circles and solid curve) taken from *http://sidc.be/silso/datafiles*. Circles represent values of the mean field corresponding to each observational season at the Ernest Gurtovenko telescope.

We measured the line core depths D and the line full widths at half maximum $FWHM$ relative to their mean $\langle D \rangle$ and $\langle FWHM \rangle$ values, respectively. These mean values were calculated by averaging over eight observational seasons. As one can see, the variations of the Fe I line core depths and the full line widths at half maximum

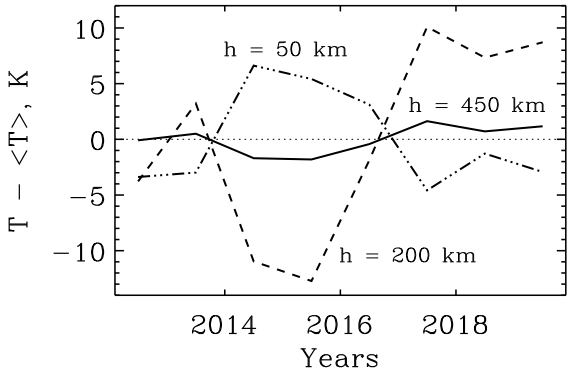


Figure 3 Variations of the temperature over 2012–2019 in three layers of the solar atmosphere. The mean heights h of these layers are shown close to each of the curves.

are rather small. For the line depths they are within a few tenths of a percent. The amplitudes of the FWHM variations are below 1 mÅ.

We compared the variations of D and $FWHM$ values during 2012–2019 with the solar global unsigned magnetic field $|H|$ and the Wolf sunspot numbers for the same period of time. To this end, we calculated mean values of magnetic field and Wolf numbers for each of eight observational seasons at the Ernest Gurtovenko telescope and plotted them against corresponding years in the bottom panel of Fig. 2 (see filled and open circles, respectively).

A comparison of results in this figure shows that during 2012–2019 the Fe I line parameters respond to the variations of the unsigned global magnetic field and the Wolf sunspot numbers. Such a response is more pronounced for weaker Fe I lines. Stronger lines are less sensitive to variations in the solar activity.

Generally, most of the weaker Fe I lines become notably deep when the global magnetic field of the Sun reaches a maximum. At the same time, the full widths $FWHM$ of the weaker lines correlate better with the Wolf sunspot numbers. As these numbers increase, the weaker Fe I lines are narrowing more and more. Their full widths $FWHM$ reach minimum when the Wolf numbers approach the peak values. Interestingly, this happens before the weaker lines become most deep. This time lag for the line depths ranges from a few months to one year.

Qualitatively, the behaviour of the D and $FWHM$ parameters can be explained by assuming that during the maximum of the 11-year solar activity deep layers of the quiet photosphere become hotter. Consequently, the line wing and local continuum intensities grow and, as a result, the Fe I lines become deeper and narrower.

3.2 Temperature variations of the quiet solar photosphere

In order to quantify the changes in temperature in the quiet photosphere over 2012–2019 we apply the LTE (Local Thermodynamical Equilibrium) inversion code based on Tikhonov stabilizers. The code developed by Stodilka (2003) makes it possible to recover the map of the temperature changes $T-\langle T\rangle$ of the quiet solar atmosphere with height and time using monitoring observations of spectral lines (see, e.g., Shchukina

et al.). To this end, we used Fe I 5379.58 Å line with equivalent width $W \approx 64$ mÅ whose formation region covers most of the solar photosphere (see Fig. 1). Variations of the temperature $T - \langle T \rangle$ with time in three photospheric layers restored using this code are shown in Fig. 3. Here $\langle T \rangle$ is the mean temperature of the layer over eight seasons of our monitoring. As can be seen the range of temperature variations is about ± 10 K. At the same time the temperature changes of the upper photosphere are much smaller.

From comparison of the results shown in Fig. 3 and Fig. 2 (bottom panel) we conclude that the temperature of deep photospheric layers at the final stage of the ascending phase of Cycle 24 (i.e. near the "double-peaked" solar maximum in 2012–2015) is growing. Maximum heating of these layers happens when the Wolf numbers reach their peak values. Then in the descending phase a gradual decrease in the temperature occurs.

On the contrary, middle photospheric layers at heights of about 200 km gradually cool down as solar activity rises. Maximum cooling, in fact, coincides in time with the maximum value of the global magnetic field of the Sun. Interestingly, this phenomenon lags by about a year from the maximum heating of deep photospheric layers. With a decrease in solar activity, the middle quiet photosphere warms up little by little. Near the minimum of solar cycle (2019 year) it turns out to be noticeably hotter than the average for 8 years of our monitoring of the quiet solar atmosphere.

4 Conclusions

The high precision metrological stability on long time scales of the Ernest Gurtovenko telescope allows us to measure the slightest temporal changes of the solar spectral line parameters. Thanks to this, we found that during 2012–2019 the parameters of eighteen Fe I lines respond to the variations of the unsigned global magnetic field and the Wolf sunspot numbers. Our results can be summarized as follows:

- Core depths and full widths at half maximum of the Fe I lines in the solar spectrum of quiet solar photosphere correlate with the 11-year cycle of solar activity.
- Fe I lines become 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.

Unlike Livingston et al. (2007) we finally conclude the quiet (basal) photosphere is affected by solar cycle magnetism.

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