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Results of Spectral Corona Observations in Solar Activity Cycles 17–24

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Abstract—The results of the work of the global observation network are considered, and a comparative analysis of the data of various coronal observatories is performed. The coronal activity index has been reconstructed for the period 1939–2016 based on the data of various observatories in Kislovodsk system. For this purpose, the corona daily intensity maps from the Sacramento Peak and Lomnický Štít observatories according to the Solar-Geophysical Data journal have been digitized; they supplement the data of other observatories. The homogeneity and continuity of the corona observations at the Kislovodsk station, including activity cycle 24, is confirmed. Unfortunately, the only observatory at present that continues observation of the spectral corona in Fe XIV 5303 Å and Fe XIV 6374 Å lines is the Kislovodsk astronomical station Mountain Astronomical Station (MAS) of the Central Astronomical Observatory, Russian Academy of Sciences (Pulkovo). The data on the combined corona in 5303 Å line are analyzed. It is shown that there is a high correlation of the intensity index of green corona with solar radiation measurements in the vacuum UV region. Data on the beginning of the new 25th activity cycle in the corona at high latitudes are presented.

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1. INTRODUCTION

The solar corona light consists of a continuous spectrum (scattering by free electrons), the so-called K-component, and superimposed emission lines (E-component). The difficulty in coronal observation is that the intensity of its emission (even in the brightest regions) is only 10^{-5} of the intensity in the center of the solar disk. Therefore, there were many attempts to observe the solar corona out of eclipses for several decades at the beginning of the 20th century. It first became possible in 1932 for the French explorer Bernard Lio at the Pic du Midi Observatory in the French Pyrenees, at an altitude of 2780 m above sea level. The main obstacle to coronal observation was the high value of scattered light, which is usually two orders of magnitude higher than its brightness. At the same time, it turned out that scattered light significantly decreases with a rise to an altitude of about 2000 m due to the decrease of dust and aerosols in the air. Therefore, an important feature of the coronal station is the choice of observation point, to ensure that it is located above the dust layer and not on the path of dust carried by winds from deserts at high altitude.

Regular out-of-eclipse corona observations started in 1939 at the Arosa Observatory (Switzerland) at an altitude of 2050 m. The organizer of these observations was M. Waldmeier. Observations were initially carried out in the Fe XIV 5303 Å line and later also in the Fe XIV 6374 Å line (Waldmeier, 1957). Regular observations of the coronal lines also began in 1943 in Wendelstein and Zugspiege (FRG) at altitudes of 1840 and 3000 m, respectively, and then in *Climax* (United States, Colorado) at an altitude of 3300 m, the Sacramento Peak (United States, New Mexico), Norikura (Japan), and Lomnický štít (Slovakia) in May 1946 (Sýkora, 1971).

The pioneering role in organizing the first observations of the spectral corona in the USSR belongs to M.N. Gnevyshev (Gnevyshev, 1963). He chose a suitable place in the central part of the Caucasus on the Shat Jad Mas plateau, at an altitude of 2090 meters above sea level. The first images of the coronal lines were obtained in 1950. Regular observations of the corona at the Kislovodsk MAS of Pulkovo observatory RAS began in 1952 (http://solarstation.ru/sun-service/corone). The observation and processing technique of the spectral corona was maintained in 1957 and has been used up to the present. Systematic observations at the MAS are carried out in two lines: 5303 Å and 6374 Å. The large number of observation days and stability of the method of photometric calibration by intensity in the center of the solar disk is the reason for the import-

Table 1. List of coronal stations

Station, designation	Location	State	Latitude (m above sea level)	Instrument for coronal observation	Period of observations
Pic du Midi PM	Pyrenees	France	2860	Spectral coronagraph with white light coronameter (K-corona)	1938–1974
Arosa	the Alps	Switzerland	2050	Spectral coronagraph	1938–1974
Climax	Colorado, Rocky mountains	United States	3500	Large and small spectral coronagraphs	1941–1965
Wendelstein	Wendelstein	Germany	1838	Spectral coronagraph	1941–1948
Kantselhoh	Carinthia	Austria	1900	Spectral coronagraph	1948–1952
Sacramento Peak SP	New Mexico	United States	2760	Large and small spectral coronagraphs with photography and photoelectric recording	1949–1966 1977–2015
Norikura	Prefecture Norikura	Japan	2900	Spectral coronagraph	1950–2009
MAS Kislovodsk	Kislovodsk	USSA, Russia	2100	Spectral coronagraph	1952–present time
Alma-Ata	Western Alatau	USSA, Kazakhstan	2600	Spectrograph with K-coronameter	1954
Meudon	Paris	France	160	K-coronameter, photoelectrical spectrometer	1959
Haleakala	Hawaii	United States	3120	Spectral coronagraph	1963
Lomnický Štít LS	High Tatras	Czechoslovakia, Slovakia	2634	Spectral coronagraph	1964–2009
Ulan Bator		Mongolian People's Republic	1670	Spectral coronagraph	1964
Huancayo		Peru	3313	Spectral coronagraph	1965
Mauna Loa	Hawaii	United States	3378	K-coronameter	1965–present time

ant role of the Kislovodsk Moutain astronomical Station of Pulkovo Observatory in global corona research.

A full list of coronal observatories is presented in Table 1. It should be noted that two coronal observatories are being built in China, but they are not yet in a working state. Unfortunately, observations at the Norikura and Lomnický Štít observatories ceased in 2009, and observations at the Sacramento Peak Observatory ended in September 2015. Thus, at the present time, MAS is the only observatory that continues observations of the spectral corona. Since observations of the corona require special conditions for transparency of the atmosphere, the data of individual stations are supposed to complement each other. In this regard, an important role is played by the method of observation and photometric processing of the corona. The method of measurement in which the brightness of the coronal line is compared with the brightness of a part of the spectrum 1 Å wide at the center of the solar disk is the most complete.

In this paper, the results of the work of the global observational network are considered, and a comparative analysis of the data from various coronal observatories is made. Based on data from different observatories, the coronal activity index was reconstructed for the period 1939–2015 in the Kislovodsk system.

2. CREATION OF A COMBINED SERIES IN THE KISLOVODSK SYSTEM

With the international cooperation of observatories participating in coronal observation and mutually filling in the data gaps in observations, a strict standard of observance is required for all observations. A comparative analysis of data from various observatories was performed earlier (Tlatov et al., 2001). The method for constructing a consolidated series in the Kislovodsk

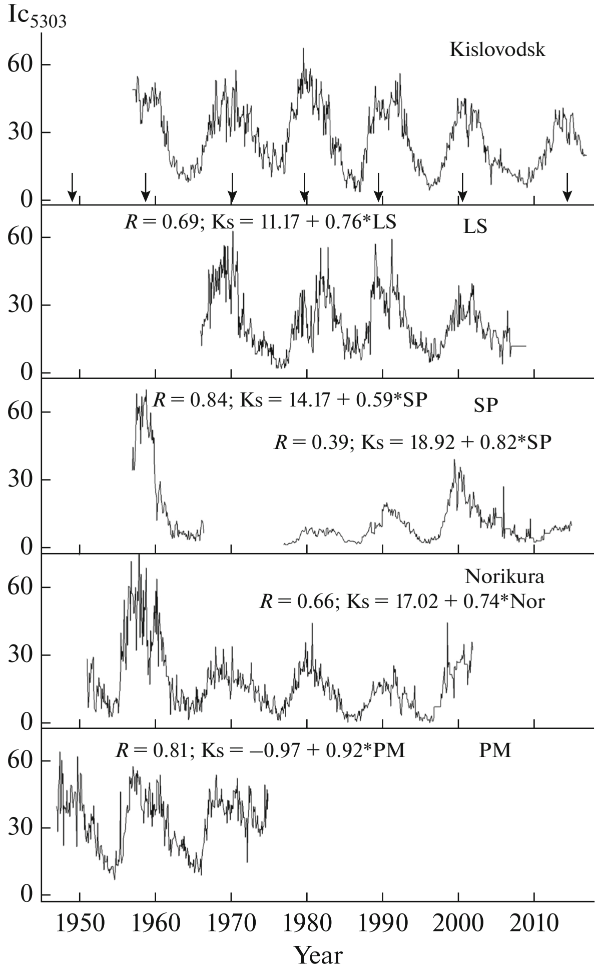

Fig. 1. Variations of coronal intensity index Ic at 5303 Å from observations at the Kislovodsk, Lomnický Štít (LS), Sacramento Peak (SP), Norikura, and Pic du Midi (PM) observatories averaged over a month. The arrows indicate the positions of the activity maxima. The correlation coefficient and the formula for conversion to the Kislovodsk data are presented.

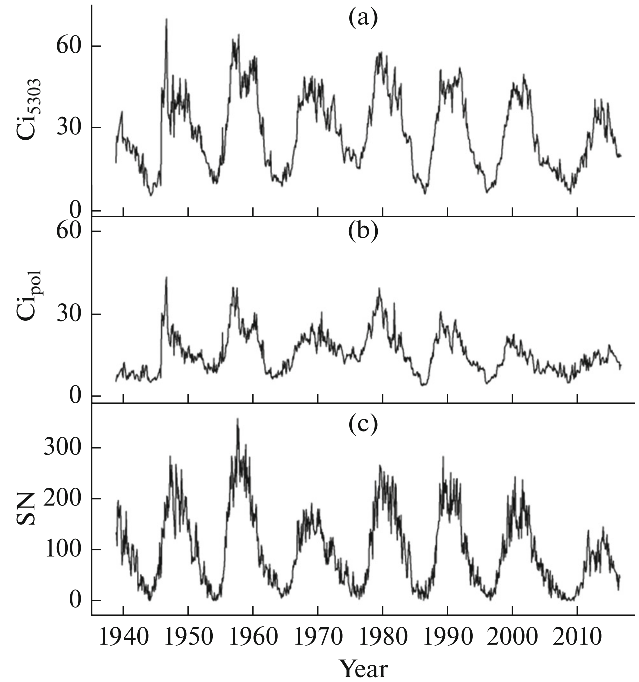

Fig. 2. Variations of the (a) coronal index Ci_{5303} of the combined corona series in the Kislovodsk system in the period 1939–2016, (b) intensity of the polar corona at latitudes $\theta > 50°$ according to the combined series data, (c) sunspot index (SN).

system is described by Tlatov (2006), and the series of the combined corona are presented for the period 1947–2006. This technique is based on filling the missing observation days with data from other stations. Different observatories use observations at different altitudes and apply different calibration methods. To unite the information into one system, the regression relations between Kislovodsk and a particular observatory are used over a period of six months. A new, supplemented version of the combined series is presented in this paper. For this purpose, the daily charts of coronal intensity from the Sacramento Peak Observatory and Lomnický štít (according to the scans of the coronal intensity spectra from the Solar-Geophysical Data journals for the period 1977–2014) were digitized. The scans from the website of the Sacramento Peak Observatory for the period 2012–2015 were also taken into account. To digitize the data, special software was developed to allow processing of the data from daily observations for limb angles from 0 to 360 degrees. Thus, the combined coronal series in line 5303 Å includes data from Kislovodsk (1957–2015), Arosa (1939–1974), Klaimax (1942–1965), Pic du Midi (1947–1974) (PM), Norikura (1947–2009), Lomnický štít (1966–2009) (LS), and Sacramento Peak (1948–1965, 1977–2015) (SP). These data were partially published in the *Quarterly Bulletin of Solar Activity.*

One of the values characterizing the behavior and stability of coronal data may be the coronal index, which is obtained by averaging of the corona data in a given latitude interval for a time of about one month or more. Figure 1 shows the intensity indexes of the solar corona Ic_{5303} for different observatories as compared to Kislovodsk in the solar corona measurement units W/sr. Observations in Kislovodsk have the best stability, that is, the Kislovodsk Corona has the highest correlation coefficient of the coronal index with the index of sunspot activity (Tlatov et al., 2001). This made it possible to create a combined series based only on the data of coronal observations. A combined series of corona in the line 5303 Å was proposed earlier by Rybansky'et al. (2005) in the system of the Lomnický štít observatory. However, because of the poor stability of the LS series, the authors calibrated it using radio emission data (10.7 cm). Thus, this series cannot serve as the basis to obtain coronal indices. Figure 2 presents the monthly

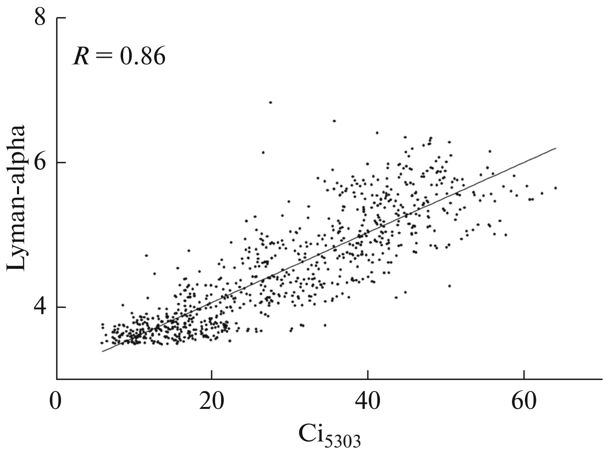

Fig. 3. Comparison of the monthly values of the coronal index Ci_{5303} with the data of the composite UV index in the Lyman-alpha line expressed in units of 10^{11} photons/cm^2 s.

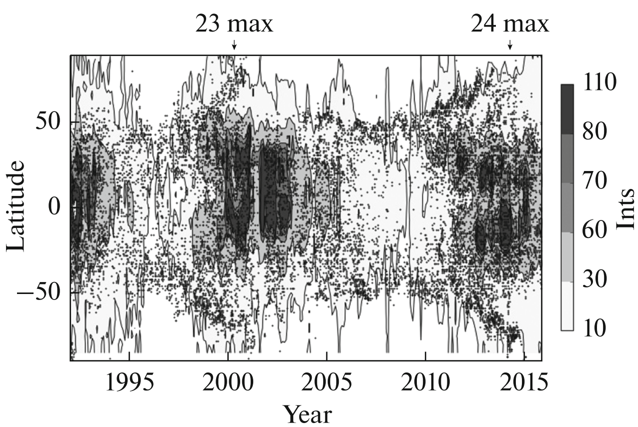

Fig. 4. Latitudinal–temporal diagram of coronal intensity at 5303 Å in the solar activity cycles 23–24. The points show the position of protuberances. The positions of the maxima of the activity cycles are shown.

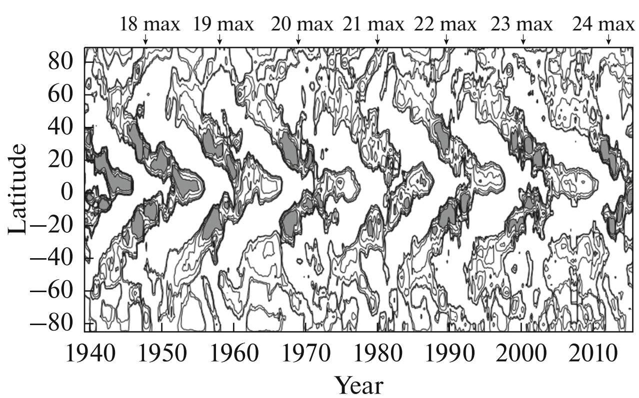

Fig. 5. Latitudinal–temporal diagram of the position of local corona maxima.

averages of the corona series in the Kislovodsk system as compared to the international index of sunspots (SN) (http://sidc.be/silso/). The correlation coefficient between two Ci_{5303} rows and SN spot index is quite high $R = 0.882$.

3. COMBINED SERIES DATA ANALYSIS

The use of the combined corona in line 5303 Å can be useful for the study of solar activity in the UV region at long time intervals and activity at high latitudes, as well as for early diagnostics of solar activity cycles. Thus, Fig. 3 presents a comparison of the spectral corona observation data with the data of the composite emission index in the Lyman-alpha line 126.4 Å (http://lasp.colorado.edu/lisird/lya/). The coronal index shows a high correlation coefficient $R = 0.86$ for the monthly values in the period 1947–2016. This allows us to use the data from spectral corona observations to evaluate the UV and X-ray radiation of the sun, which is necessary for space weather problems.

Since the spectral corona can be observed at all latitudes, this provides a unique opportunity to study long-term variations of the solar activity at high latitudes. Figure 2 shows the index of the polar coronal intensity at latitudes $\theta > 50°$. It can be noted that the intensity of the polar corona decreases starting from the 2nd cycle, and the 24th cycle appears to be the weakest cycle of the coronal intensity at high latitudes.

Figure 4 shows the latitudinal–temporal distribution of coronal intensity in activity cycles 23–24, as well as the distribution of protuberances in this period. It can be noted that the polar branches of intensity of the two types of activity are close in latitude and time.

A latitudinal–temporal diagram of the position of local maxima in the coronal intensity are presented in Fig. 5. Such diagrams are useful for studying extended activity cycles (Altrock, 2014). In this diagram, the beginning of the 25th activity cycle at high latitudes can be noticed near the maximum of cycle 24. The polar branch of cycle 25 is more noticeable in the northern hemisphere than in the southern hemisphere.

We also performed measurements and a comparative analysis of the coronal intensity over the limb of the Sun according to the observations of the SOHO/EIT and SDO/AIA satellites in different spectral lines (Fig. 6). Unfortunately, the data from satellite observations do not have stability over the duration of the whole activity cycle (Oliveira de Silva et al., 2016). Thus, the main peaks in Fig. 6 are visible both on Kislovodsk and AIA data, but the peak amplitude, according to the AIA data, is much higher at the beginning of the cycle than in the decay phase. This is caused by degradation of the AIA telescope matrices. Therefore, their involvement in the creation of the combined long-term series of the corona remains open. However, we can probably use ground-based

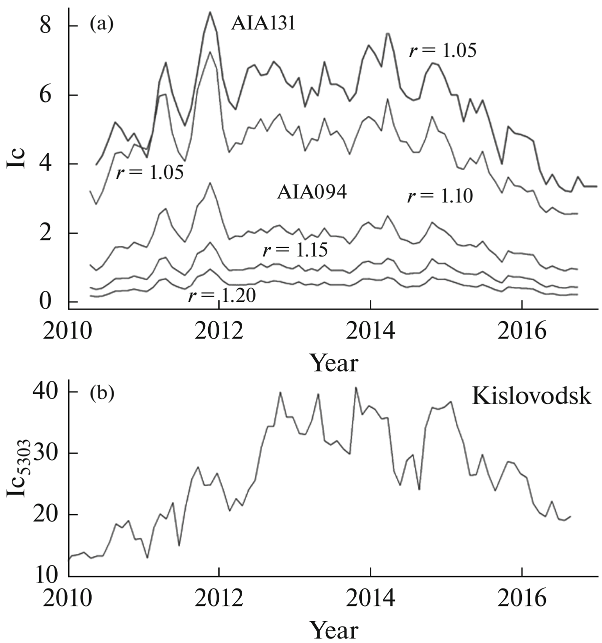

Fig. 6. Variation in the coronal intensity over the limb of the Sun at different altitudes above the limb of the Sun (r = 1.05–1.20 R_o) from observations of the (a) AIA/SDO observatory in 131 Å and 94 Å lines in relative units in comparison with (b) the coronal Kislovodsk index Ic_{5303}.

coronal observations to calibrate the data from satellite coronal observatories.

4. CONCLUSIONS

Spectral corona observations have been going on for about 80 years, which makes this type of synoptic observation one of the longest types of solar observation. The data on the corona make it possible to investigate solar activity at various altitudes. Using this type of observation, precursors of the beginning of solar activity were discovered several years before the appearance of the first spots of the new cycle (Wilson et al., 1988), long-term changes in the temperature of the solar corona (Makarov et al., 2006), and other properties of solar cyclicity. At the moment, observations of the spectral corona are carried out only at the Mountain astronomical Station in Kislovodsk. Therefore, it makes sense to make every effort to maintain this type of solar observation.

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