

Continuous 60-Year Observations of the Spectral Solar Corona at the Mountain Astronomical Station of Pulkovo Observatory

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Received February 16, 2019; revised March 13, 2019; accepted April 25, 2019

Abstract—This paper presents observational series of the spectral solar corona obtained with the Small Lyot Coronagraph deployed in 1948 at the Mountain Astronomical Station of the Central Astronomical Observatory, Russian Academy of Sciences (MAS CAO RAS), near the city of Kislovodsk; this is the only observatory in the world that maintains such large databases (1952–2019) of coronal intensity in the lines $\lambda = 5303 \text{ \AA}$ (Fe XIV) and $\lambda = 6374 \text{ \AA}$ (Fe X). Correlation and regression analysis of data from six solar activity cycles has revealed the homogeneity and stability of continuous series of intensities of the green and red corona.

DOI: 10.1134/S0016793219070168

1. INTRODUCTION

In the autumn of 2018, the Kislovodsk Mountain Astronomical Station of the Central (Pulkovo) Astronomical Observatory of the Russian Academy of Sciences (MAS CAO RAS) turned 70 years old. Systematic observations of the solar corona in the Soviet Union were initiated by Mstislav Nikolaevich Gnevyshev, the founder of the solar station. The history of the station began with a coronagraph based on the design by the French astronomer B. Lyot (lens diameter $d = 200 \text{ mm}$, equivalent focal length $F = 5000 \text{ mm}$); it was manufactured in Germany at the Carl Zeiss optical factory in 1944. After World War II, the coronagraph was brought to the Soviet Union from Jena. At the CAO Academic Council in August 1945, M.N. Gnevyshev requested that the USSR Academy of Sciences bring one of the coronagraphs from Germany. In the autumn of 1948, after the Presidium of the USSR Academy of Sciences granted permission to conduct experimental observations of the solar corona (Minutes no. 3, Section 1, of February 26, 1948), the Zeiss coronagraph was mounted on the Shat-Zhad-Maz plateau (Gnevyshev, 1983). The first images of the green coronal line were taken in February 1950. Continuous observations in two coronal lines $\lambda = 5303 \text{ \AA}$ (Fe XIV) and $\lambda = 6374 \text{ \AA}$ (Fe X) began at the MAS CAO RAS from July 16, 1952 (Gnevyshev and Gnevysheva, 1954). First, a prism spectrograph was constructed and used to obtain the first coronal spectra. A diffraction spectrograph with a diffraction grating of 600 pcs/mm was later installed on the coronagraph. During this period, Gnevyshev developed a stable

photometric system for the observation and processing of coronal lines (Gnevyshev, 1959).

—Each coronal line is photographed with a straight slit of the diffraction spectrograph, which is positioned along the radius in 5° position-angle intervals.

—For standardization, three images of the center of the solar disk are taken through a stepwise attenuator placed on the slit of the spectrograph.

—The line intensity is measured at a distance of $40''$ ($0.04 R_\odot$, where R_\odot is the radius of the Sun) from the solar photosphere.

The intensities of coronal lines (I_{5303} and I_{6374}), which are measured in millionths of energy in a 1 \AA interval of the continuous spectrum of the center of the Sun (in abs. units), are obtained via processing.

In 1967, an international meeting was held at the Pic du Midi Observatory, where the method for observing the solar corona without an eclipse was approved. The XII General Assembly of the International Astronomical Union in Prague recommended it to all observers of the spectral corona of the Sun. The photometric standardization procedure developed by Gnevyshev, which has been used at the Kislovodsk MAS CAO RAS since 1957, ensured the uniformity of the series of coronal line intensities, regardless of weather conditions.

Observations of the solar corona are important, and continuous long-term and stable coronal series have great scientific value for research on the nature of the cyclicity of solar activity and the mechanisms of radiation of the solar corona, which have a great impact on the upper layers of the Earth's atmosphere.

The purpose of this study is to present the coronal series obtained at the MAS CAO RAS and to demonstrate that the patrol observations of the spectral corona initiated by Gnevyshev at the solar station have continued uninterrupted for 60 years in the same system while maintaining the stability and uniformity of the coronal series.

2. SIXTY-YEAR OBSERVATIONS OF THE SOLAR CORONA IN SPECTRAL LINES 5303 Å AND 6374 Å

Until 2005, three observation services were systematically conducted on the Lyot coronagraph: in addition to two coronal lines, prominences in the H α line were observed ($\lambda = 6563$ Å). Aerofilms Isopanochrome Type-17, Type-42, and RF-3 were used for observations. The coronal spectra were processed with the MF-4 microphotometer.

In 2004, the mechanism of the transition of coronal observations from film to digital camera was fine-tuned, and the procedure for computer processing of spectral lines was developed. The spectral lines were processed with the MF-4 microphotometer by computer and compared throughout 2004.

Digital photorecording and computer processing of the spectral corona were introduced in 2005. The coronal spectrum is photographed with a Canon EOS Digital Rebel 600D digital camera.

The second (rearranging) lens was reconstructed in 2009. The works included repolishing of the four optical surfaces and flexible abrasive polishing of 13 optical surfaces, the gluing of elements with OK-72FT optical glue, and other procedures. The spectrograph was also reconstructed and equipped with a new diffraction grating of 1200 pcs/mm.

The clock drive of the coronagraph was modernized and its speed of rotation was accurately adjusted in 2010. The new clock drive mechanism was launched on November 30, 2010. The new clock drive allowed observations to be performed in a shorter period of time, eliminating the need to readjust the telescope guiding. This made it possible to observe the solar corona through small breaks between the clouds.

For the 70-year history of the MAS CAO RAS, 60-year databases of the intensity of two spectral lines, $\lambda = 5303$ Å and $\lambda = 6374$ Å, were created and digitized. Figure 1 shows the time series of the mean monthly intensity values of two coronal lines I_{5303} and I_{6374} , averaged over all positional angles for six solar-activity cycles (1957–2019). A clearer representation of the observational data is given by a latitude–time distribution diagram of the spectral corona. Figure 2 shows the constructed latitude–time distributions of I_{5303} and I_{6374} , the isolines of which were plotted by nonlinear interpolation with a 5° interval in latitude with equal intensity over a month. All solar cycles feature a distinct double-vertex intensity of the emission corona in

the maximum phase; this circumstance was already noted by Gnevyshev (1963).

Although regular observations of the corona began as early as 1952, a stable system of observation and processing has been used from 1957 to the present.

3. STABILITY OF THE SYSTEM OF CORONAL OBSERVATIONS AND PROCESSING

The stability of the system can be analyzed with a comparison of the coronal data and other solar-activity indices, e.g., between the intensity (I_{5303}) of the coronal line $\lambda = 5303$ Å and the Wolf numbers (W). In our study (Tlatov et al., 2001), it was shown that there is a linear relationship between the W number index and I_{5303} . In the period of 1957–2019, the correlation coefficient between I_{5303} and the Wolf number W was $k = 0.89$. There is a regression between the coronal intensity I_{5303} and the Wolf number index W , which can be expressed by the formula

$$I_{5303} = 0.16W + 12.41. \quad (1)$$

Comparative analysis (Tlatov et al., 2001; Guseva, 2013) showed that the coronal series obtained at the MAS CAO RAS had a significantly better correlation between the coronal intensity and sunspot activity than the coronal data series of other observatories. An important feature of the coronal series I_{5303} is the fact that the ratio of the amplitudes in the corona cycles corresponds to the strength of the sunspot cycles.

To test the stability of the system after the transition to digital observations and processing (2005) and the reconstruction of the coronagraph (2009), the relationships between the solar corona line I_{5303} and sunspot activity before and after these periods were examined in detail. Figure 3 shows the coronal series and the variations in the mean monthly Wolf number for solar cycles 23–24, as well as the regression dependences between I_{5303} and W numbers for different periods. The transition to digital observations and processing did not degrade the system of patrol observations of the solar corona. The approximation function for the periods before and after the transition to digital observations is

$$I_{5303} = 0.15W + 12.64 \quad (\text{before 2005}), \quad (2)$$

$$I_{5303} = 0.16W + 11.85 \quad (\text{after 2005}). \quad (3)$$

The correlation coefficient between I_{5303} and W for the previous solar-activity cycles is $k = 0.88$ for cycle 19; $k = 0.85$ for cycle 20 (perhaps, this value of k is due to the limited comparison series for this period, see the next section); $k = 0.89$ for cycle 21; $k = 0.90$ for cycles 22 and 23; and $k = 0.88$ for cycle 24 (the comparison for this period was carried out in conditions of relatively low sunspot activity).

Thus, we can conclude that the system of the spectral corona observations is preserved despite its reconstruction.

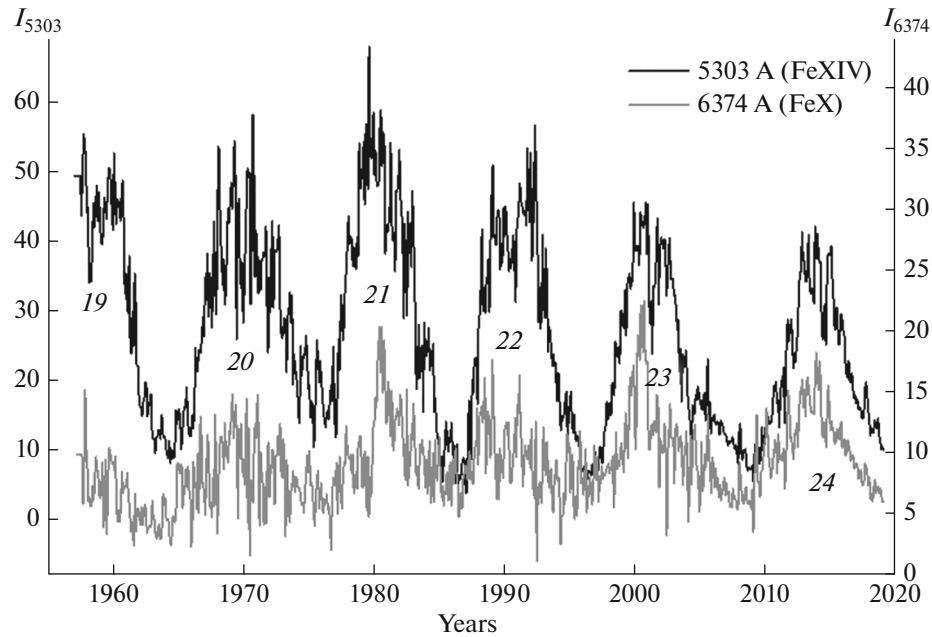


Fig. 1. Time series of the mean monthly intensity of the spectral solar corona in lines $\lambda = 5303 \text{ \AA}$ and $\lambda = 6374 \text{ \AA}$ expressed in absolute coronal units of measurement (one millionth of the radiation from the center of the solar disk in 1 \AA of the continuum adjacent to the line) according to MAS CAO RAS observations.

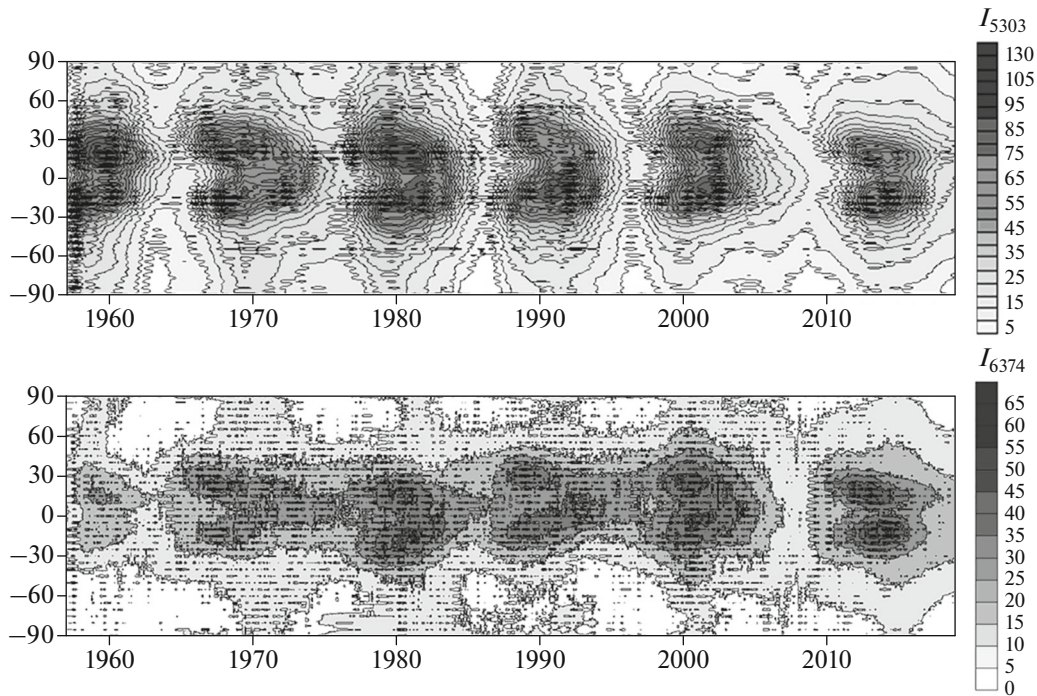


Fig. 2. Latitude–time distributions of intensity of the green I_{5303} (top) and red I_{6374} (bottom) coronal lines expressed in 10^{-6} energy emitted from the center of the solar disk in a 1 \AA interval of the continuum adjacent to the line (in abs. units) according to MAS CAO RAS.

The MAS CAO RAS is currently the only one in the world that has long-term continuous and uniform series of the spectral corona of the Sun (Guseva, 2013).

4. REGULARITY OF CORONAL OBSERVATIONS

The creation of a solar station would not be justified without constant extra-eclipse observations. Figure 4

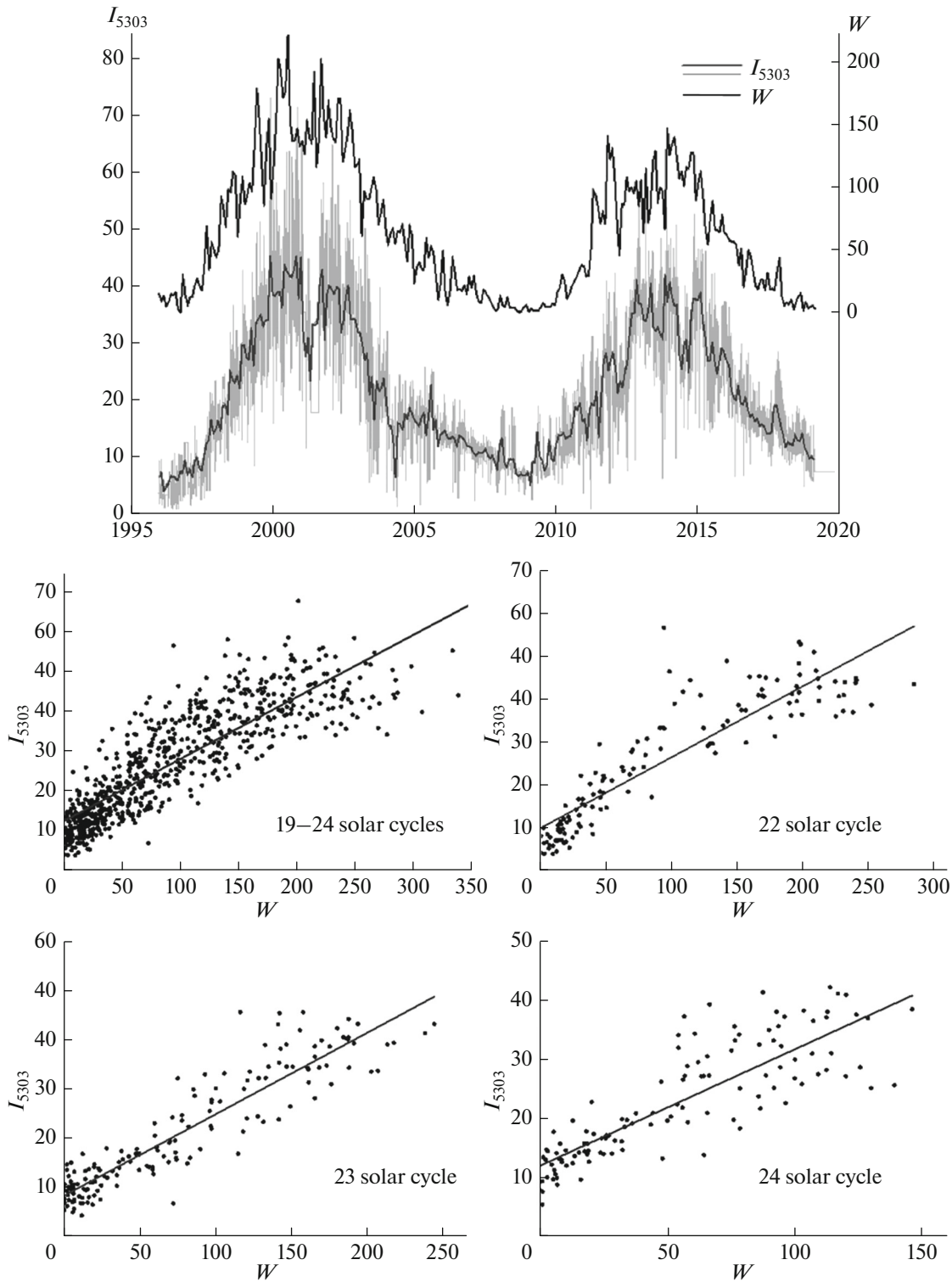


Fig. 3. Variations in the spectral corona (I_{5303} in abs. units) and mean monthly Wolf number (W) for solar cycles 23–24 (top); regression dependences between I_{5303} and W numbers for different periods (bottom).

shows the statistics of the spectral corona observations at the MAS CAO RAS over its entire history. The numbers in this chart show the declines in coronal

observations over the past thirty years, which occurred mainly for technical reasons and not due to bad weather. The reasons were as follows:

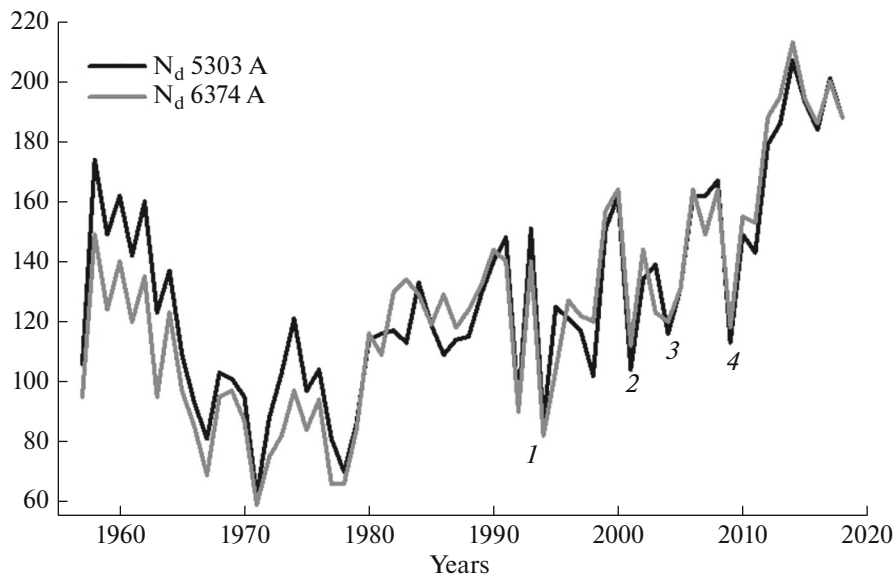


Fig. 4. Variations in the number of days (Nd) of coronal observations per year.

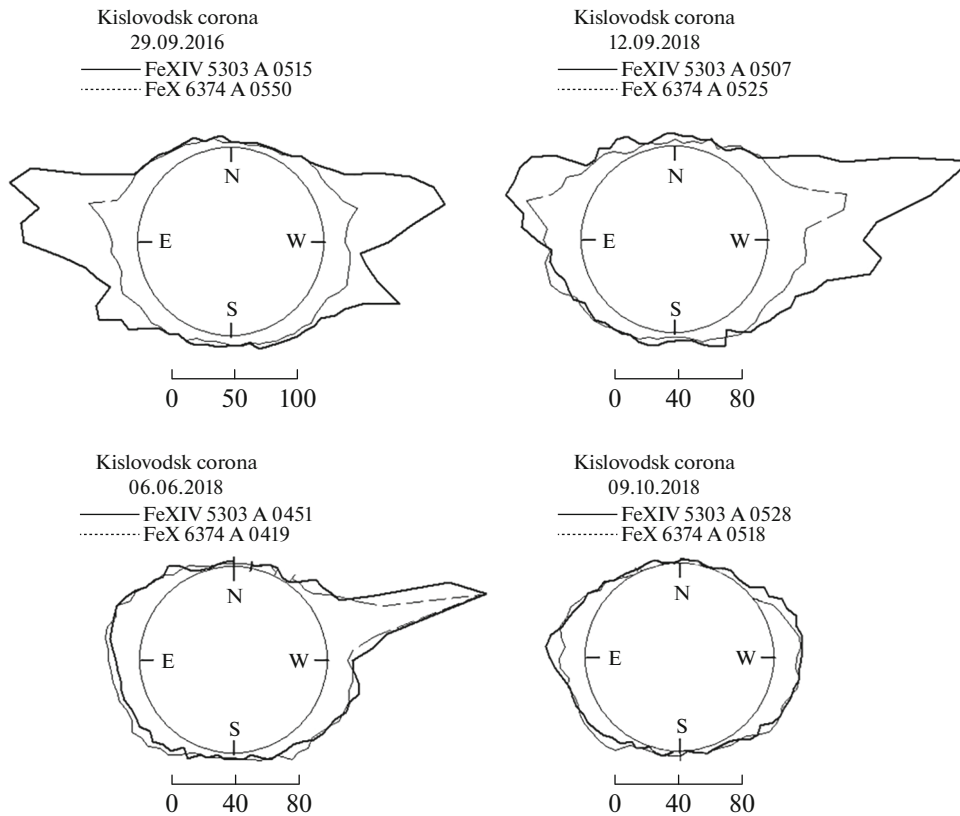


Fig. 5. Daily coronal maps with the intensity measured in absolute coronal units.

1. In the early 1990s, the Small Coronagraph was, unfortunately, operated mostly by only one member of the staff, Kim Gun-Der.

2. In 2001, the coronagraph was completely disassembled, and a general cleaning and relubrication of

all mechanical parts of the telescope was carried out, which took several months.

3. In 2004, there was a problem with the acquisition of aerofilms of the required sensitivity, and their stock was running out. To solve this problem, the transition

from film to digital photorecording was initiated. Coronal observations were carried out for over a year in both modes, with film and a digital camera.

4. As mentioned above, maintenance work to restore the projection lens on the Small Lyot Coronagraph was carried out in 2009.

After the transition to digital photorecording and modernization of the clock drive, the time required for coronal observations decreased greatly (from 40 to 10 min), which had a positive effect on the observational statistics; the number of coronal observations increased to 200 days a year. The Corona Service at the MAS CAO RAS continues to be conducted daily with no holidays or weekends; the sky transparency is monitored throughout the daylight hours.

Regular observations of the spectral corona, combined with the stability of the system for observation and processing of coronal lines, are of primary importance in the global Corona Service.

5. AVAILABILITY OF CORONAL DATA ON THE INTERNET

The data of the spectral corona observations are immediately processed and promptly published on the Internet at the MAS CAO RAS website, www.solarstation.ru. The observation results are used to build daily coronal maps (<http://solarstation.ru/sun-service/corona>), examples of which are shown in Fig. 5. The spectral corona obtained as a result of processing is added to a summary daily map of solar activity (<http://solarstation.ru/archive/>) and to the solar activity map available at the website <http://observethesun.com/>.

The tables of annual coronal reports are presented in the international solar bulletin, "Quarterly Bulletin on Solar Activity" (Japan), at solarwww.mtk.nao.ac.jp/en/wdc/qbsa.html. The summary maps of the solar activity with the intensity of the coronal lines $\lambda = 5303 \text{ \AA}$ and $\lambda = 6374 \text{ \AA}$ can be found in the Pulkovo Bulletin "Solar Data," both in print and in electronic form (<http://www.solarstation.ru>, <http://www.gaoran.ru>).

6. CONCLUSIONS

Systematic coronal observations have been carried out at the MAS CAO RAS since 1952. The creation of such information resources as the database of intensity values of two coronal lines, $\lambda = 5303 \text{ \AA}$ (FeXIV) and $\lambda = 6374 \text{ \AA}$ (FeX), was noted among others as the most important result according to the Scientific Council on Astronomy of the Physical Sciences Division of the Russian Academy of Sciences, the Interdisciplinary Sun–Earth Council, and the Russian Academy of Sci-

ences in 2008. The study of the intensity of emission coronal lines is of great interest for research on the physical processes in the solar atmosphere and makes it possible to investigate solar activity at different altitudes. It allows one to estimate the distribution of temperature, concentration, and turbulent velocities in the corona. In the global Corona Service, MAS CAO RAS has the longest and most stable observational series of the spectral solar corona in two coronal lines. The coronal data are unique in that the observations of the spectral corona are carried out from the world's only functioning ground-based Lyot coronagraph. The coronal observations initiated by Gnevyshev have been uninterruptedly continued for 60 years, and they retain their scientific value. The author has contributed to these coronal observations from the end of 1995 to the present.

The results of the spectral corona observations remain important; they serve as the basis for the analysis and prediction of solar activity and processes in interplanetary space (solar–terrestrial relations).

FUNDING

The work is supported by the Russian Foundation for Basic Research, project no. 18-02-00098 and programs of the Presidium of the Russian Academy of Sciences.

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Translated by M. Chubarova