Astronomical and Astrophysical Transactions (*AApTr*), 2019, Vol. 31, Issue 3, pp. 389–398,
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Diagnostic complex of solar activity based on small radiotelescopes of the Sun service KRIM

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Received 1 October, 2018

The radio astronomical diagnostic complex of solar activity, created on the basis of the radio telescope RT-22 and three small radio telescopes united in the Sun Service KRIM located in coordinates longitude 33° 59′ 30″ latitude 44° 23′ 52″, conducts simultaneous observations in the wavelength range from 8 mm to 1.2 m in the monitoring mode and alerts. The Sun Service KRIM registered a series of strong outbreaks in the Sun in September 2017, when it was at a minimum of its activity. The information obtained by radio telescopes correlates well with data from other terrestrial and satellite observatories such as RSTN and GOES. Correlation coefficients are calculated and scattering diagrams for X-ray class flares 9.3 and 2.2 are constructed. The information from the radio telescopes of the Sun Service KRIM allows them to be used for daily monitoring of solar activity, further processing of data obtained in the course of scientific research, short-term forecast of space weather and analysis of its infuence on the Earth.

Keywords: Sun, radio telescope, radio emission, flash, correlation coefficient, X-ray class

1 Introduction

The sun is very dynamic and plays a key role in the entire solar system. On the surface of the Sun, there are constant physical processes associated with the release of energy. During solar flares a lot of energy is released and this occurs particularly in the sunspot area. The study of solar activity is of undoubted interest in connection with its influence on a number of geophysical phenomena and on the ecological situation on Earth. Solar flares are extremely powerful explosions in the solar atmosphere. They are found near sunspots, usually along the line of separation (neutral line) between regions with oppositely directed magnetic fields. Physically, the outbreak is a reaction of the solar atmosphere to a sudden rapid process of energy release, probably of magnetic origin. The response affects mainly the chromosphere and the crown (Miroshnichenko, 2011). The perturbation caused by a solar flare is accompanied by the formation of radio emission. Solar radio emission is studied in a wide range,

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beginning with millimeter waves and ending with waves of length 15–20 m. From the side, the long wavelength range is limited by the increase in the opacity of the ionosphere with increasing wavelength, while the reception of millimeter waves is difficult due to the absorption of radio waves by molecules of O_2 and H_2O in the Earth's atmosphere (Zheleznyakov, 1958).

Energetic protons invade our atmosphere after large flares, and the delay varies from tens of minutes to several days. The energy of proton fluxes is greater than the energy of radio bursts. However, the synchronism of proton streams and radio bursts and a certain similarity in their structure means that we are dealing with a common source. Thus, radio bursts have become a remarkable indicator of the relationship between solar and terrestrial disturbances. Radio emission at different wavelengths is an indicator of physical conditions at different heights in the solar corona. The flux of radio emission from the Sun with changes in activity varies in tens and thousands of times, so its properties are a very sensitive indicator of solar events. Observations of the flux of radio waves at several wavelengths are the basis for the diagnosis of flares. From all these data, it is possible to form a model of an explosion, to determine the moment of the arrival of a corpuscular stream to Earth and to estimate the expected scale of geophysical perturbations.

2 Experimental setup and methodology

In the radio astronomy laboratory of the Crimean Astrophysical Observatory, the Sun Service KRIM operates on the basis of radio telescopes RT-22, RT-3, RT-2 and RT-M. Small radio telescopes are equipped with radiometers for six discrete wavelengths ranging from 3 cm to 1.09 m. The solar radiometric complex RT-22 CrAO contains receivers for wavelengths of 8 and 13 mm and polarimeters for waves 2.0, 2.3, 2.8 and 3.5 cm. The data of daily radio monitoring with solar activity are stored in real time in digital form and are exposed to the world solar service that includes 14 ground-based observatories in cooperation with orbital observatories.

The RT-2 radio telescope is a parallactic rotating device with an electric drive clockwise, on which a parabolic mirror 2.5 m in diameter with combined irradiators at wavelengths of 3 and 5 cm (frequencies of 10 and 6 GHz) is mounted, and is placed in a 6-m radio-transparent dome. Modulation direct-gain radiometers are built on the basis of low-noise microwave (ultra-high frequency) amplifiers. At a wavelength of 3 cm, the beamwidth is $1^\circ\ 15'$, and at a wavelength of 5 cm – $1^\circ\ 45'$. The bandwidth of each channel is 40 MHz, the time constant is 1 s. RT-2 receives radiation in the centimeter wavelength range in order to obtain information about the processes occurring in the lower chromosphere of the Sun.

The RT-3 radio telescope is a parallactic rotating device with an electric drive clockwise, on which a parabolic mirror with a diameter of 3 m with combined irradiators is fixed to wavelengths of 10 and 12 cm (frequencies 2.5 and 2.85 GHz). It is placed in a radio-transparent dome with a diameter of 6 m to protect against weather events, which significantly improves the quality and stability of the data. The width of the antenna pattern is 2.30°–2.50°. This ensures the reception of a radio emission from the entire surface of the Sun. The bandwidth of each channel is 40 MHz, the minimum time constant is 10 ms, the signal is digitally recorded with a sampling rate

of 1 Hz in standby mode and 100 Hz during a burst of radio emission. The telescope collects information on the physical states in the energy release region of the solar flares – the upper chromosphere and the lower corona.

The RT-M radio telescope is equipped with a 4×4-m antenna mounted on a parallactic mount with an electric drive clockwise. It is a kind of in-phase grating consisting of 16 elements. The antenna has a bandwidth of 250 to 350 MHz. The beamwidth is 11°, the bandwidth of each channel is 300 kHz, the minimum time constant is 1.25 ms, the continuous dynamic range is –30 dB, digital signal recording occurs at a frequency of 400 Hz.

For the registration of coronal radiation, an e-Callisto radio spectrograph is installed, which operates in the frequency range from 275 to 327 MHz (wavelengths from 0.9 to 1.09 m). Regular monitoring in automatic mode (without the participation of an operator) is conducted on it, with the transfer of the received data every 15 minutes to the Central database in Zurich to provide on-line diagnostics of solar flares.

Dynamic spectrograph makes it possible to record the dependence of radiation intensity on frequency and time. Spectral observations give a classification of bursts, based on well-defined features of radio emission, such as the velocity drift frequency, the width of the bands of individual burst details, and the structure of the harmonics. These burst characteristics are significant because they are related to the physical properties of the source.

The data obtained in the radio telescope RT-M in the form of dynamic spectra provide valuable information for studying various events in the solar corona such as flares, coronal mass ejections. Such data are useful for determining the physical phenomena responsible for the acceleration of particles on the Sun (Volvach, 2016).

3 Observations of flare activity in September 2017

As of September 2017, there was a 24 cycle of minimum solar activity. From 4 to 10 September, through the western half of the visible sun disk, the active region NOAA 12673 (according to NOAA (National Oceanographic and Atmospheric Administration)), was increasing its area and supporting very active beta-gamma-delta magnetic groups. According to SWPC (Space Weather Prediction Center), 54 flares of class C, 26 flares of class M, 4 flares of class X were recorded in this region (Fig. 1, Fig. 2).

The Sun service KRIM observed these outbursts using the radio telescopes at centimeter, decimeter and meter wave bands.

On September 6, 2017, from 11:50 to 13:00 UT, the radio telescope RT-M of the Sun Service KRIM recorded a powerful radio burst at 275 MHz and 327 MHz (Fig. 3). Radio burst has reached the max at 12:02 UT.

At the same time, the satellites GOES 15 (Geostationary operational satellite for the study of the surrounding space) and GOES 14 also observed a powerful X-ray flash (the eighth largest in strength in the last 20 years). It was assigned X-ray class X9.3. This outbreak occurred in area of the Sun – NOAA 12673, located in heliographic coordinates S09 W34. In order to characterize the solar flare activity, in addition to radio emission, it is convenient to use the value of the X-ray flux, since during the flare its intensity can increase by several orders of magnitude. The NOAA also has a space

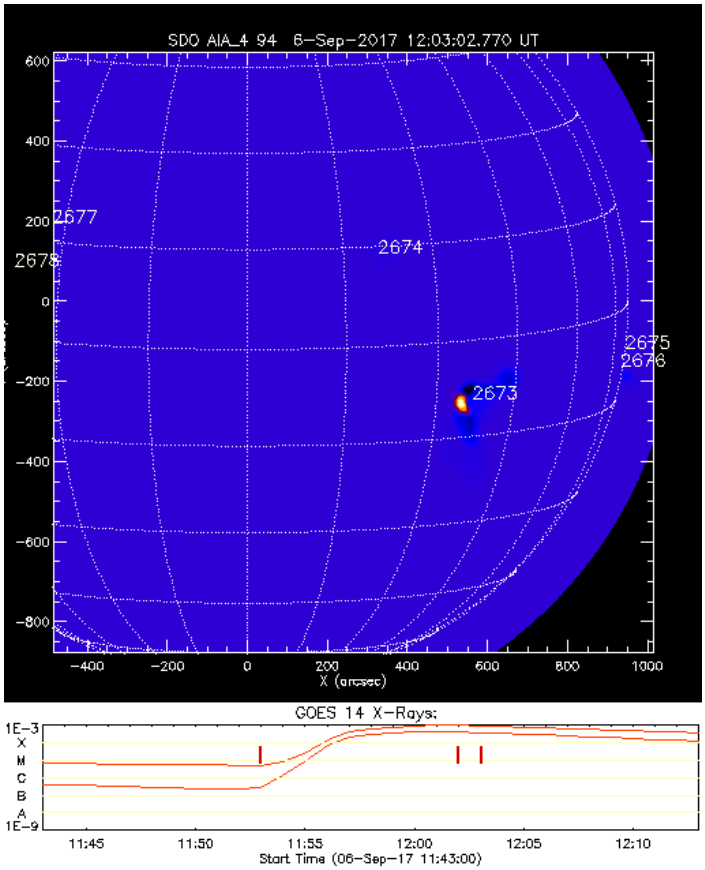


Figure 1 Active regions on the Sun map 06.09.17 according to SDO (Solar Dynamic Observatory), below is a graph showing the X-ray value measured by the Geostationary Operational Environmental Satellites (GOES).

weather scale for evaluating the effects of solar bursts on the radio communication on Earth and Earth's orbit. This flash is assigned class R3 – strong Radio Blackout occurred on 6 September from Region NOAA 12673 at 0910 UT after X-ray class X2.2 burst. This leads to the disconnection of radio communication and the absence of RF communication, which mainly affects the frequency band from 3 to 30 MHz. There were also irregularities in the operation of navigation equipment operating at low frequencies, which lasted about an hour (https://www.swpc.noaa.gov).

A powerful flare was preceded by a weaker one with the X-ray class X2.2, it was also recorded in the centimeter wave band by the Sun's KRIM service with the RT-2 and RT-3 radio telescopes (Fig. 4, Fig. 5). This outbreak occurred in the same area of the Sun – NOAA 12673, located in heliographic coordinates S08 W32.

Figure 6 shows the time variation in X-ray values measured by GOES, which clearly demonstrates the presence of an increase in intensity corresponding to two bursts. The first flare occurred at 09:10 UT and was assigned X-ray class X2.2. The power of the first burst is more than 10^{-4} mW/m^2. The second burst of X-ray class

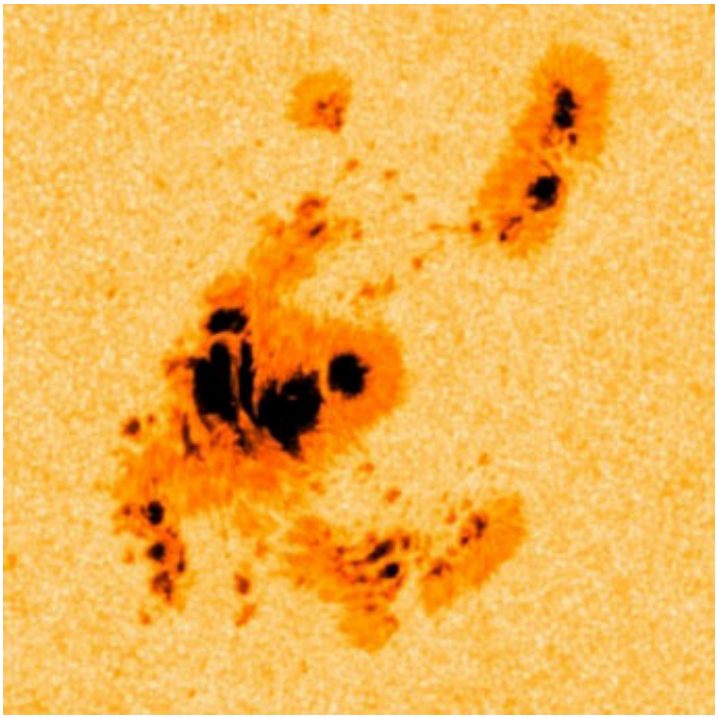


Figure 2 A region of sunspots located in the active region NOAA 12673 (according to HMI NASA SDO). HMI observes the full solar disk at 6173 angstroms with a resolution of 1 arcsecond. This wavelength is great for viewing visible sunspot formations.

X9.3 occurred at 12:02. The power of the second burst is 10^{-3} mW/m^2. Both events coincided in time with the registered radio telescopes of the Sun Service KRIM radio bursts.

According to the SWPC burst of X-ray class X9.3 caused the formation of a type IV radio burst, followed by the formation of a type II radio wave burst propagating at a shock wave velocity of 1969 km/s, generated at the shock front (https://www.swpc.noaa.gov). Varieties of types of radio bursts can be determined by analyzing the data obtained by the radio telescope RT-M (Fig. 7). A powerful surge reached a maximum value at 12:02 UT and a series of bursts continued to be fixed by the equipment until 13:00 UT, when there was an automatic shutdown of the equipment. Observations in the field of radio waves at low frequency are the most informative tool for predicting the effects of solar flares. Spectral observations give a classification of bursts, based on well-defined features of radio emission, for example, at the velocity drift frequency, the width of the bands of individual burst details, and the structures of the harmonics. These burst characteristics are significant because they are related to the physical properties of the source.

According to the Space Weather Forecasting Center (SWPC), the radio telescopes of the observatories Learmonth (Western Australia) and San-Vito (Italy) belonging to the US Air Force meteorological service on September 6, 2017 recorded radio bursts

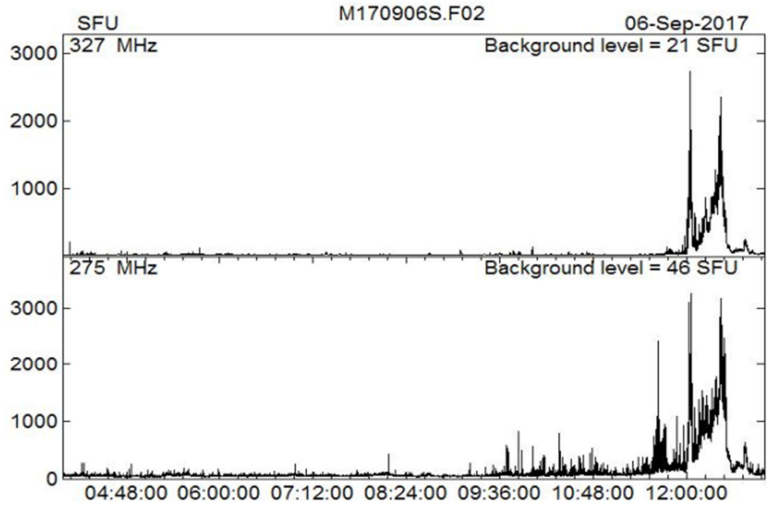


Figure 3 Spectral fluxes of radio emission registered by RT-M. The chart clearly shows a strong radio burst that occurred at 12:02 UT with a power of 3260 SFU at 275 MHz and 2733 SFU at 327 MHz.

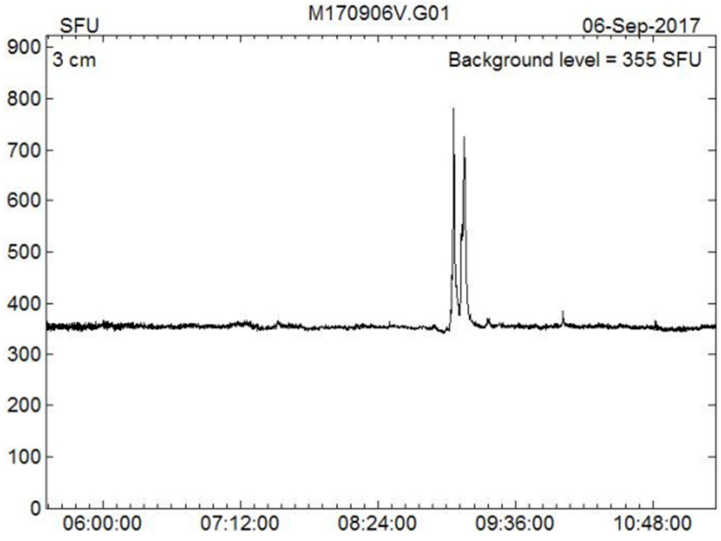


Figure 4 Spectral flux of radio emission registered by RT-2 at a frequency of 10 GHz. The graph clearly shows that a strong radio burst occurred at 09:10 UT with a power of 691 SFU.

at frequencies of 245 MHz, 410 MHz, 2695 MHz, 4995 MHz, 8800 MHz and 15400 MHz. The radio emission level of the X-ray flare X9.3 corresponded to 14,000 SFU at a frequency of 2650 MHz and 3200 SFU at a frequency of 245 MHz. According to SWPC data, the level of the radio emission of the X2.2 flash at a wavelength of 10.7

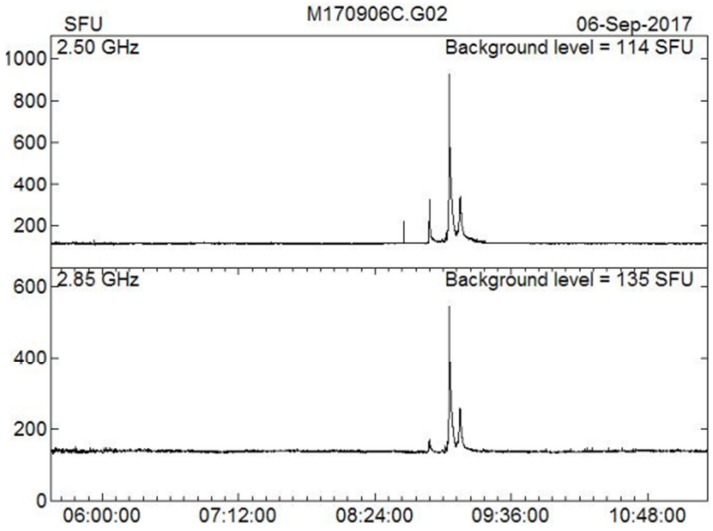


Figure 5 Spectral fluxes of radio emission registered by RT-3 at a frequency of 2.5 GHz and 2.85 GHz. The graph clearly shows that a strong radio burst occurred at 09:10 UT with a power of 691 SFU at 2.5 GHz and 578 SFU 2.85 GHz.

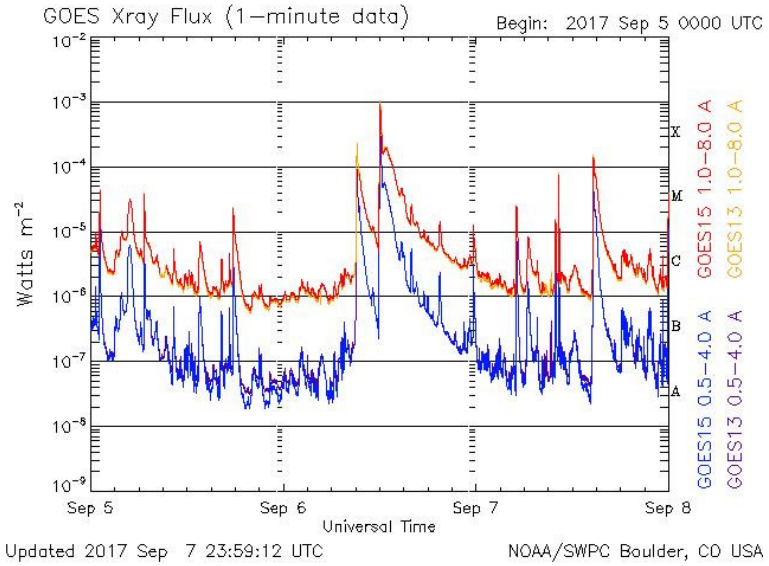


Figure 6 The time variation in X-ray values measured by geostationary operational environmental satellites (GOES).

cm corresponded to 410 SFU by https://www.swpc.noaa.gov.

The radio bursts obtained by the KRIM solar radio telescopes correlate well with them. The correlation coefficients are calculated and scattering diagrams for the

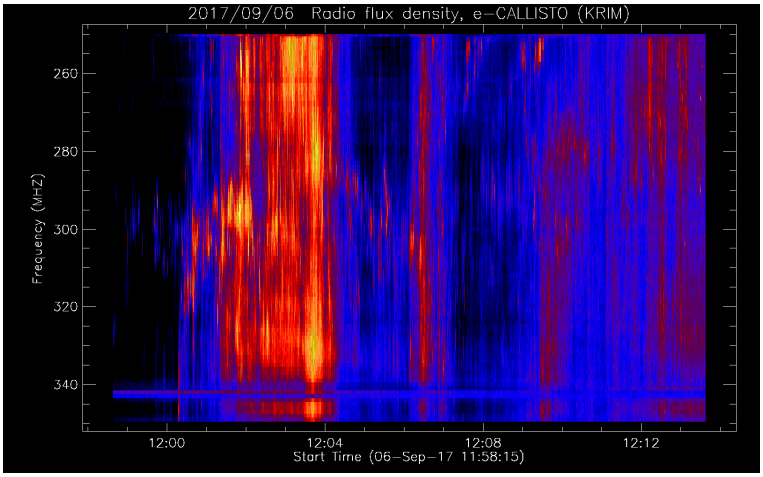


Figure 7 Dynamic radio emission spectra X9.3 recorded by RT-M equipped with a spectrometer Callisto. Type IV radio bursts.

X-ray flares X9.3 and X2.2 are constructed. The value of the Pearson correlation coefficient $R = 0.912581520917723$ shows a strong positive relationship between the spectral flux density in the SFU measured at frequency 245 MHz in the San Vito radio observatory and the spectral flux density in the SFU measured at frequency 275 MHz by the Sun KRIM service during the flash X-ray class X9.3 occurred on September 6, 2017. The value of the Pearson correlation coefficient $R = 0.849343706$ shows a strong positive relationship between the values of the spectral flux density in the SFU measured at a frequency of 8800 MHz in the Learmonth radio observatory and the spectral flux density in the SFU measured at frequency 10,000 MHz by the Sun KRM service during the flash X2.2 on September 6, 2017.

Conclusions

Thus, the received and reliably confirmed information from the radio telescopes Sun service KRIM can be used for daily monitoring of solar activity. Daily data on the state of solar activity allow us to assess the radiation situation in the vicinity of the Earth, predict the stability of radio communications, the reliability of navigation systems, remote monitoring and control, and are the basis for studying physical conditions in the solar corona, which makes it possible to improve the accuracy of the forecast of solar activity. The data received by radio telescopes of the Sun Service KRIM in the form of a graphic representation are placed in the archive on the web-site and replenished daily after the end of daytime observations.

Acknowledgements

We acknowledge the support from the Presidium of the Russian Academy of Sciences (program KP19-270).

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