ISSN 0016-7932, Geomagnetism and Aeronomy, 2012, Vol. 52, No. 8, pp. 1032–1043. © Pleiades Publishing, Ltd., 2012.

Local Maximum in the Microwave Spectrum of Solar Active Regions as a Factor in Predicting Powerful Flares

V. N. Borovik[a], I. Yu. Grigor'eva[a], and A. N. Korzhavin[b]

[a] *Main Astronomical Observatory, Russian Academy of Sciences, Pulkovo, St. Petersburg, 196140, Russia*

[b] *St. Petersburg Branch, Special Astronomical Observatory, Russian Academy of Sciences, St. Petersburg, Russia*

e-mail: vnborovik@mail.ru

Received March 3, 2012

Abstract—We discuss the results of a study of microwave radiation from three flare-active regions—NOAA 10300, 10930, and 11158—with powerful eruptive events (X-class flares and coronal mass ejections) recorded on July 15, 2002; December 13, 2006; and February 15, 2011, when the regions were in the central part of the disk. There exists evidence of a δ-configuration in the structure of the photospheric magnetic field formed one or two days prior to the eruptive process as a result of the emergence of a new magnetic flux and shifting movements of the sunspots and accompanied by changes in the spectral characteristics of the microwave radiation of the active regions (ARs), which suggests the development of a peculiar radio source. The analysis of these regions continues a series of studies of eruptive events carried out at RATAN-600 in the 1980s–1990s and gives a reason to conclude that early detections of peculiar sources in the microwave radiation of ARs, which are essentially areas of high energy release in the solar atmosphere, can be used as a factor in predicting powerful eruptive (geoeffective) processes on the Sun.

DOI: 10.1134/S001679321208004X

1. INTRODUCTION

Understanding the nature of solar eruptive processes and finding the origin of flares is one of the most important tasks of plasma heliophysics. Currently, a lot of attention is paid to the integrated study of manifestations of solar activity and their effects on space weather and the Earth's atmosphere. To understand the nature of energetic geoeffective events, such as powerful flares and coronal mass ejections, and to be able to predict them, it is extremely important to have early-stage observations of transient processes on the disk. The source of these data are ground-based observations in the H_α line with a high temporal and spatial resolution, satellite images of the solar disk in the X-ray and UV ranges, and solar magnetograms acquired by spacecraft and ground-based observatories.

Ground-based solar radio astronomy studies in a wide range of radiowaves provide information on the structure of the solar atmosphere and the development of physical processes over a large range of altitudes, which cannot be duplicated by other methods. Microwave observations with a high spatial resolution, as well as spectral and polarization analysis, allow one to understand the nature of radio emission processes, determine the parameters of thermal plasma and nonthermal electrons, and measure the magnetic field in the upper chromosphere–lower corona, i.e., in those regions of the solar atmosphere that accommodate the evolution of the main preflare phenomena reflecting the transfer and accumulation of energy prior to a transient explosive energy release.

Regular multiwavelength observations of the Sun in a wide microwave range have been carried out with a RATAN-600 Radio Telescope since 1974. This instrument has a unique combination of design features and equipment that enables the investigation of both undisturbed solar atmosphere and complex transient phenomena (Bogod, 2007).

An analysis of the eruptive (geoeffective) events of February 3–5, 1980; July 12–17, 1982; April 24, 1985; and November 2, 1992, based on spectral and polarization observations of the Sun with the RATAN-600 telescope revealed compact peculiar radio sources (PS's) in the structure of the microwave radiation of flare-active regions with a δ-configuration of the sunspot magnetic field. The PS radiation often dominated over that of other features of these regions at 2–4 cm wavelengths. The PS positions were projected onto the polarity separation line of the photospheric magnetic field in the area with the densest clustering of spot umbrae with different signs of the magnetic field (Akhmedov et al., 1986; Borovik et al., 1987; Borovik et al., 1989; Borovik et al., 2006).

PS's were first discovered by A.N. Korzhavin during observations of the solar eclipse on March 7, 1970, in Cuba (Quinones et al., 1975). Subsequent observations of solar eclipses confirmed the presence of PS's in the microwave radiation of flare-active regions (see, e.g., (Akhmedov et al., 1982)).

The typical dimensions of PS's (10–30") correspond to a radio source of a linear size of about 10 000 km and suggest that PS radio emission is generated in an area that is associated with the peaks of compact coronal arches in the area of interactions between the old and new magnetic fluxes. PS's have a high brightness temperature (up to 10 MK) at 4 cm wavelength. Their flux spectrum has a maximum at a 3–4 cm wavelength, and their spectral index at shorter wavelengths can in some cases be as high as 10. The degree of circular polarization is 10–30%, which is less than the typical values for spot sources. The above listed observational characteristics of PS's are unique and can hardly be interpreted as usual well-studied components of the radio emission of an AR.

Some scientists suggested that these sources represent a new type of astrophysical objects on the Sun. Currently, radio observations of the Sun using the world's largest radio astronomical instruments have confirmed that PS's are a typical component of the microwave radiation of ARs (Shibasaki et al., 2011).

As shown by Vatrushin and Korzhavin (1989), the characteristics of PS's can be interpreted within the framework of the magnetobremsstrahlung or gyrosynchrotron radiation of a region of anomalous energy release containing subrelativistic plasma with $T = 10^7$–T^8 K and electron density of the order of 10^{10} cm^{-3} in moderate magnetic fields. These conditions are expected in the currently analyzed models of current sheets that can be surrounded by plasma with densities of about 10^{10} cm^{-3}.

The high brightness temperature of PS's suggests that the energy coming from underneath the photospheric layers might be released in these areas. Their connection with complex magnetic structures indicates that this energy release is associated with magnetic field reconnections, which lead to plasma heating. It is obvious that an early detection of PS's in the structure of the radio emission of ARs can be used as a prognostic criterion in devising physically substantiated methods to predict strong solar flares.

The purpose of this study is to continue the investigation into the evolution of microwave radiation from flare-active regions using the RATAN-600 data and the results of solar observations in different energy ranges carried out with modern highly sensitive instruments onboard satellites and at ground-based observatories. We present the results of an analysis of three powerful (geoeffective) eruptive events (X-class flares (GOES) and the associated coronal mass ejections (CMEs)) that have occurred on the Sun over the last decade (on July 15, 2002; December 13, 2006; and February 15, 2011) in NOAA ARs 10030, 10930, and 11158, respectively, and study the evolution of microwave radiation from these regions prior to the eruptive processes. For analyzing the eruptive events, data from the SOHO, TRACE, Hinode, and SDO satellites were used.

2. OBSERVATION RESULTS OF THE ERUPTIVE EVENTS

In the study periods (July 2002, December 2006, and February 2011), daily solar observations with RATAN-600 were carried out at the southern sector of the radio telescope, which was operating in combination with a flat periscope mirror in monitoring mode (Tokhchukova, 2011). The observations were made in the meridian (~09 UT) and, in some cases, in additional azimuths. When the Sun was passing through a fixed diagram, the antennas were recording radio emission simultaneously at a large number of wavelengths (more than 20) and analyzing the circular polarization. The dimensions of the antenna diagram were 17" × 13" at a 2-cm wavelength. The observations in July 2002 used a panoramic spectrum analyzer (PSA), and those in 2006–2011 used a wide-range spectral and polarization complex of a high resolution (SPCHR) (Bogod, 2007). The data were processed using the software developed by Garaimov (1997).

The fluxes from the radio sources detected in one-dimensional solar scans were calibrated using the RATAN-600 observations of standards (the moon and the Crab Nebula); solar observations with the Large Pulkovo Radio Telescope (LPRT), Siberian Solar Radio Telescope (SSRT), and Nobeyama Radio Heliograph (NoRH); and measurements of integral solar radio fluxes with a Nobeyama Polarimeter (NoRP).

2.1. X3.0 Flare of July 15, 2002, in NOAA Active Region 10030

The NOAA 10030 sunspot group emerged from behind the limb on July 10, 2002. Its area was growing rapidly. Thus, in the period from July 11 to 15, when the AR approached the central part of the solar disk, its area doubled and reached almost 1000 msh. The AR was characterized by a high level of flare activity. In the period from July 11 to 18, the GOES observations detected two X-class flares, six M-class flares, and 33 C-class flares.

An eruptive event (a two-component X3.0/3B flare and two successive coronal mass ejections (CMEs) associated with filament eruptions) (Harra et al., 2005) occurred on July 15, 2002, when the AR was in the center of the disk. According to the GOES data, the flare began at 1959 UT, peaked at 2008 UT, and ended at 2014 UT. The flare caused a strong solar proton flux, which was detected on July 16 in a geostationary orbit (GOES 10) and in a low-altitude orbit in the polar caps at an altitude of 350 km (Coronas-F) (Myagkova et al., 2007).

This transient phenomenon has been studied from various perspectives by many researchers, e.g., (Liu et al., 2003; Brown et al., 2003; Gary and Moore, 2004; Harra et al., 2005; Shakhovskaya et al., 2006; Knyazeva et al., 2011).

On July 15, when the eruptive event occurred, the AR had a complex magnetic pattern. Liu et al. (2003) note that, as seen in the H_α images of the solar disk, the AR was dominated by a large-scale system of loops connecting head and tail spots of opposite polarity. Another system of small-scale loops was concentrated near the northwestern part of the group's central positive-polarity spot surrounded by small spots and pores of negative polarity. An eruptive process, which was caused by a release of a twisted magnetic flux rope, began to develop precisely in this area (Liu et al., 2003). The central-spot rotation and shifting motions in the AR resulted in the development of powerful flare episodes (Brown et al., 2003; Gary and Moore, 2004; Harra et al., 2005).

The changes in the structure of the photospheric magnetic field of AR 10030 over a few days prior to the X3.0 flare (July 15) were analyzed to show that on July 13–14 a δ-configuration formed as a result of the emergence of a new negative-polarity magnetic field near the northern boundary of the penumbra of the central positive-polarity spot. In Fig. 1b (the magnetogram for July 14), the newly emerged field is marked with a white arrow. The formation of a δ-configuration in the AR one day prior to the flare event can also be seen on maps of the spots' magnetic fields obtained from solar observations at ground-based observatories.

Figure 1 shows magnetograms of NOAA AR 10030 for July 13, 14, and 15, according to the SOHO/MDI data (http://soi.stanford.edu/production/time_range.html). In the July 14 magnetogram (Fig. 1b), the newly emerged magnetic field of negative polarity is marked with a white arrow. Figures 1d–1f show fragments of solar magnetic field maps built at the Kourovka Astronomical Observatory, Urals University (http://www.gao.spb.ru). On the map for July 14, 2002 (Fig. 1e), the formation of a δ-configuration is confirmed by the appearance of a spot with field 23S near the northern part of the central spot with a field of opposite polarity (35N). Figure 1g shows an outline of a magnetic field map for AR 10030 made at the Mount Wilson Observatory (http://obs.astro.ucla.edu/intro.html). Here the evidence for a δ-configuration is the appearance of a spot with field V20 near the northern boundary of the penumbra of the central spot with field 26R.

The microwave radio emission of NOAA AR 10030 in the period July 13–17, 2002, was studied from the results of daily multiwavelength observations of the Sun with RATAN-600 and an analysis of the circular polarization at a number of wavelengths in the range 1.8–5.0 cm. A sample of recordings of a local radio source identified with NOAA 10300 at a 2.1-cm wavelength is shown in Fig. 2a, where solar scan fragments in the intensity channel (*I*) and polarization channel (*V*) are superimposed on an image of the sunspot group (SOHO/MDI, Intensity). The evolution of the radio source in the period July 13–15, 2002, is depicted in Figs. 2b–2d, which show fragments of solar scans at wavelengths of 1.8, 2.3, 3.2, 4.1, and 5.0 cm (intensity channel *I*) that are identified with NOAA 10300. The scans are arranged from bottom to top in order of increasing wavelength. It is evident that, prior to the flare, the short centimeter wavelengths were dominated by the radio source component associated with the central part of the sunspot group.

We analyzed the evolution of the flux density spectra for this source in the period July 13–16. Figure 3 shows the flux density spectra of the central dominant radio source from the observational data for July 13–15. There is a noticeable change in the pattern of the spectrum on July 14, compared to the one recorded on the previous day: at short wavelengths, the slope of the spectrum increases and a local maximum appears at ~3.0 cm. Such a change in the spectrum can be interpreted as evidence of the appearance of a peculiar microwave source above the area with a δ-configuration that formed on July 13–14. The observed spectrum of the microwave source above the central sunspot group is the result of a superposition of two spectra: the spectrum of the thermal gyro-resonance emission from a spot source, which increases uniformly with the wavelength in the microwave range, and the spectrum of a PS, which has a steeper slope at short centimeter wavelengths and a maximum at ~3 cm (Vatrushin and Korzhavin, 1989). Note that the eruptive process, which was caused by a release of a twisted magnetic flux rope, began to develop precisely in the area with the δ-configuration (Liu et al., 2003).

2.2. X3.4 Flare of December 13, 2006, in Active Region 10930

Although a cycle minimum was predicted for the end of 2006, this period saw the development of a set of solar activity phenomena, with a large-spot AR being the main component during four revolutions. In December, this AR (NOAA 10930) was observed to produce a series of flares: four X-class flares (according to the GOES classification), two of which (on December 13 and 14, 2006) were the first flares of this class that were observed with new instruments—an X-ray telescope (XRT) and a solar optical telescope (SOT)—on board the *Hinode* satellite. In addition, observations of the flares were carried out by the SOHO and TRACE satellites.

A geoeffective X3.4/4B flare occurred two days after the AR passed the central meridian, which made it possible to study in detail the dynamics of the sun-

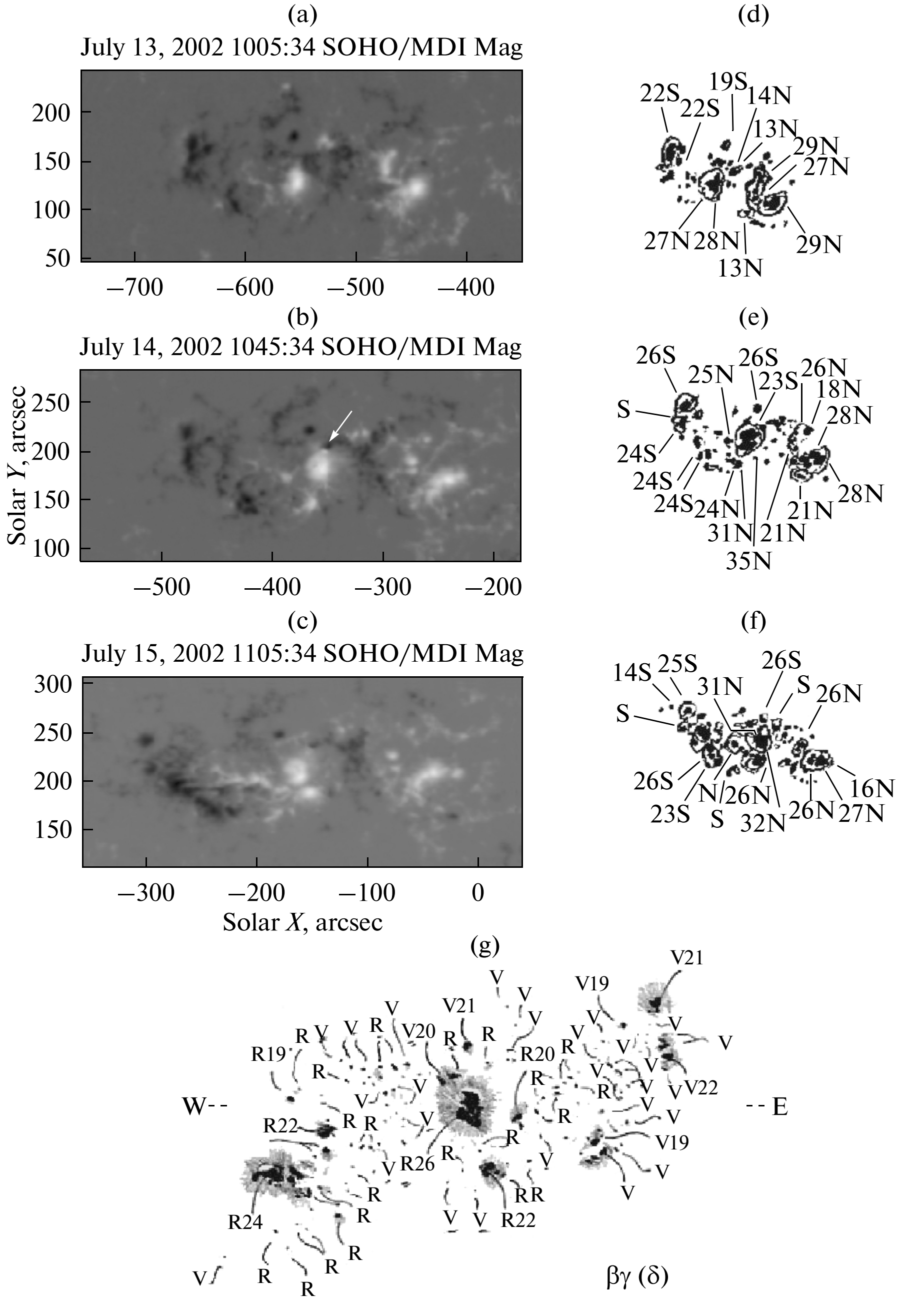

Fig. 1. Images of the magnetic field of NOAA AR 10300 on July 13, 14, and 15, 2002: (a–c) magnetograms (SOHO/MDI); the white arrow in Fig. 1b shows the newly emerged magnetic field of negative polarity; (d–f) maps of magnetic fields (Kourovka Astronomical Observatory, Ural); and (g) sketch of a magnetic field map for July 14, 2002 (Mount Wilson Observatory).

spots and the changes in the structure of the photospheric magnetic field over a few days prior to the flare and compare them with observations in the microwave range. According to the GOES data, the X3.4/4B flare began at 0214 UT, peaked at 0240 UT, and ended at about 0900 UT. The flare was accompanied by a flux of high-energy protons of different energies (over 100 MeV) and caused a number of geoeffective phenomena (Murav'eva et al., 2007).

According to the GOES data, after a series of flares on December 5–7, the flare activity at NOAA 10930 was virtually over. According to the data of the SOHO, TRACE, and *Hinode* satellites (Kubo et al., 2007b), in the period December 8–14, in this compact group, which mainly consisted of a large negative-polarity spot of 600–900 msh, the observations detected the appearance and further development of a new magnetic flux, which was essentially an area of the field

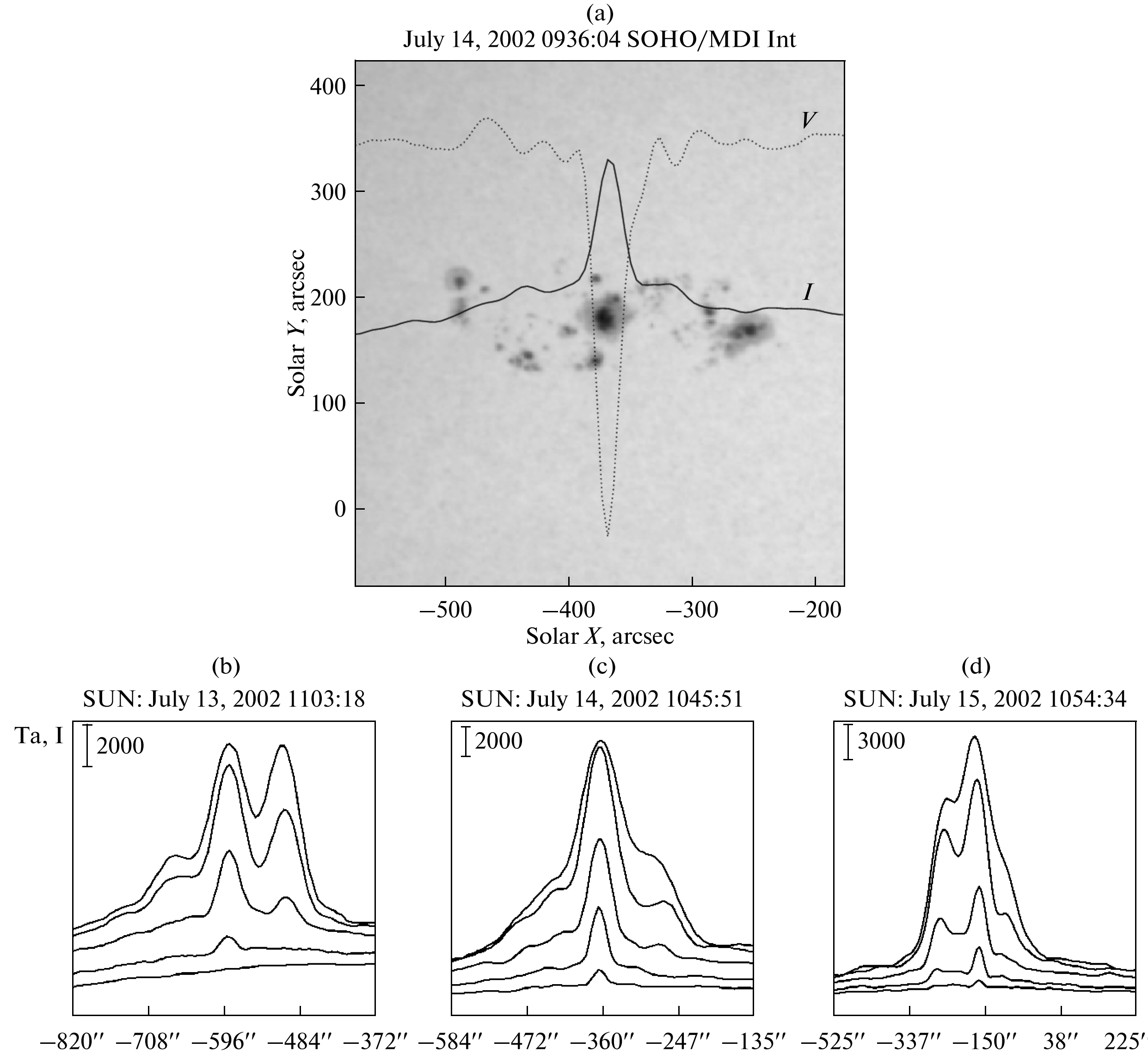

Fig. 2. Evolution of the microwave radiation of NOAA AR 10300 on July 13, 14, and 15, 2002: (a) fragments of solar scans (RATAN-600) at a 2.1-cm wavelength in the intensity (*I*) and polarization (*V*) channels superimposed on an image of NOAA 10300 (SOHO/MDI, Intensity); (b–d) fragments of solar scans at wavelengths of 1.8, 2.3, 3.2, 4.1, and 5.0 cm (intensity channel *I*) that were identified with NOAA 10300 for July 13, 14, and 15, 2002. The scans are arranged from bottom to top in order of increasing wavelength. The vertical segment in the upper left corner of the panels shows the scale of the vertical axis (antenna temperature is in degrees Kelvin). The horizontal axis shows the distance from the center of the Sun in seconds of arc.

with small spots of opposite polarity within the penumbra of the main spot (δ-configuration). The evolution of NOAA 10930 in the period December 9–14, 2006, is depicted in Fig. 4, which shows images of the spots in white light based on the data of the TRACE satellite (http://trace.lmsal.com/trace_cat.html).

A number of studies have investigated various aspects of this AR that were observed a few days and immediately before the flare: the emergence of a new magnetic field (Kubo et al., 2007a; Yazev and Savinkin, 2007; Golovko and Salakhutdinova, 2012), counterclockwise rotation of the main spot and the surrounding elements and shifting motions in the AR (Su et al., 2008; Magara and Tsuneta, 2008), changes in the distances between magnetic tubes in the photosphere and corona (intermittency) (Abramenko et al., 2008), coronal mass ejections (Liu et al., 2008), soft X-ray and EUV radiation of coronal loops (Harra et al., 2009), etc. The main findings of these studies were confined to the fact that the main cause of the flare was the rotation and the eastward shift of the emerged spots. The interaction between multiage loop systems in the magnetic field facilitated the generation of powerful flares. The X3.4 flare occurred where the main negative-polarity spot was interacting with newly emerged positive-polarity spots. Nonthermal processes in the atmosphere of the AR increased a day before the flare.

The evolution of the microwave radiation of NOAA 10930 over a few days prior to the flare on December 13, 2006, was investigated based on RATAN-600 observations; the first results were published in (Borovik et al., 2007).

In the study period, the solar microwave radio emission was recorded daily with RATAN-600 at a number of wavelengths in the range 1.8–5.0 cm when the Sun passed through the fixed antenna diagram in seven azimuths. It should be noted that the conditions for observing the AR with RATAN-600 were extremely favorable because this region was the only one on the disk during this period (Fig. 5a). This eliminated a number of methodological problems associated with the identification of the local source on the scan, specification of its coordinate, flux calibration, etc. A sample recording of the Sun at a 3.2-cm wavelength on December 12, 2006, in the intensity and polarization channels is shown in Fig. 5b.

We compared the radio flux spectra of the source identified with AR 10930 obtained from RATAN meridian observations for several consecutive days before and after the flare. The resulting spectra are shown in Fig. 6. To construct the spectra, we used data for 12 wavelengths in the range 1.9–5.0 cm. The spectra for December 8–11 refer to the period of the emergence and development of a new magnetic flux of positive polarity within the penumbra of the main negative-polarity spot (δ-configuration), which is reflected in the shape of the spectra. The pattern of these spectra with a local maximum at ~3 cm can be interpreted as the result of the superposition of two spectra—that of a radio source associated with the main spot of the group (this spectrum increases with the wavelength) and that of a PS with a maximum at 3 cm. The conclusion about the decisive role of a PS in the formation of the spectrum of the microwave emission flux of AR 10930 prior to the flare of December 13 was also made from solar observations at the LPRT with a moderate spatial resolution at 2.7-, 3.2-, 4.5-, and 6.2-cm wavelengths (Borisevich et al., 2007).

Noteworthy is the significantly different pattern of the December 12 spectrum obtained from the RATAN-600 observations 17 hours prior to the flare. Its dramatic increase with the wavelength may be assumed to reflect an increase in nonthermal processes that began on December 11 after 21 UT and lasted until 12 UT on December 12. These processes were detected with a highly sensitive EIS (EUV Imaging Spectrometer) spectrometer on board *Hinode* from the broadening of the profiles of the spectral EUV-lines

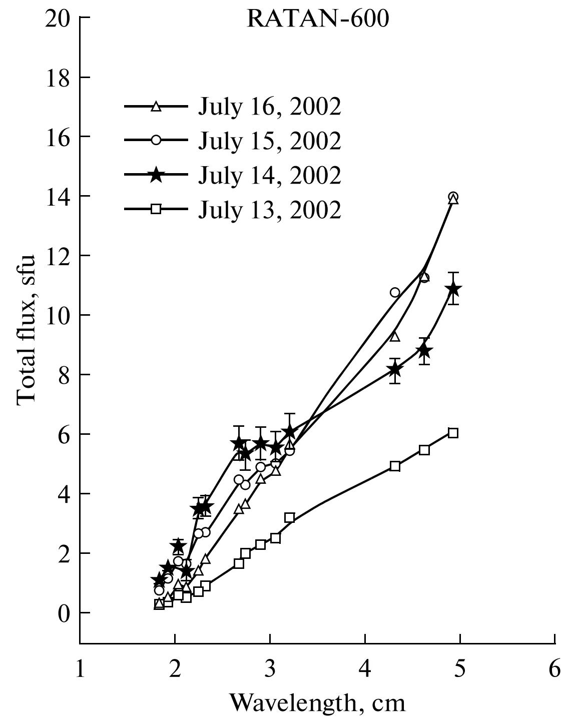

Fig. 3. Flux density spectra of the dominant local source of NOAA 10300 for July 13–16.

(Harra et al., 2008). The spectra in Fig. 5b show that, on the days following the X3.4 flare, no PS radiation effects were observed and the shape of the spectra was consistent with the dominating emission from the spot source associated with the main spot of the group.

2.3. Flare of February 15, 2011, in NOAA Active Region 11158

This flare was the first X-class flare in the growth phase of solar cycle 24, which was studied with a new instrument—a helioseismic and magnetic imager (HMI)—on board the SDO (Solar Dynamics Observatory).

NOAA AR 11158 appeared on the disk on February 10 and began to develop quickly: when the sunspot group was in the central part of the disk (February15–17), its area exceeded 600 msh. At first, the group had a simple bipolar β-configuration. As a result of the emergence of new magnetic fields, shifting motions of sunspots, and convergence of fields of opposite polarity, by February 14, the AR transformed into a complex magnetic entity (βγδ-configuration). A sigmoid shape of coronal loops along the neutral line of the photospheric magnetic field was recorded in soft X-rays and EUV rays prior to the flare, which indicates the formation of a magnetic flux rope and is a precondition for an eruptive process (Zharkov et al., 2011).

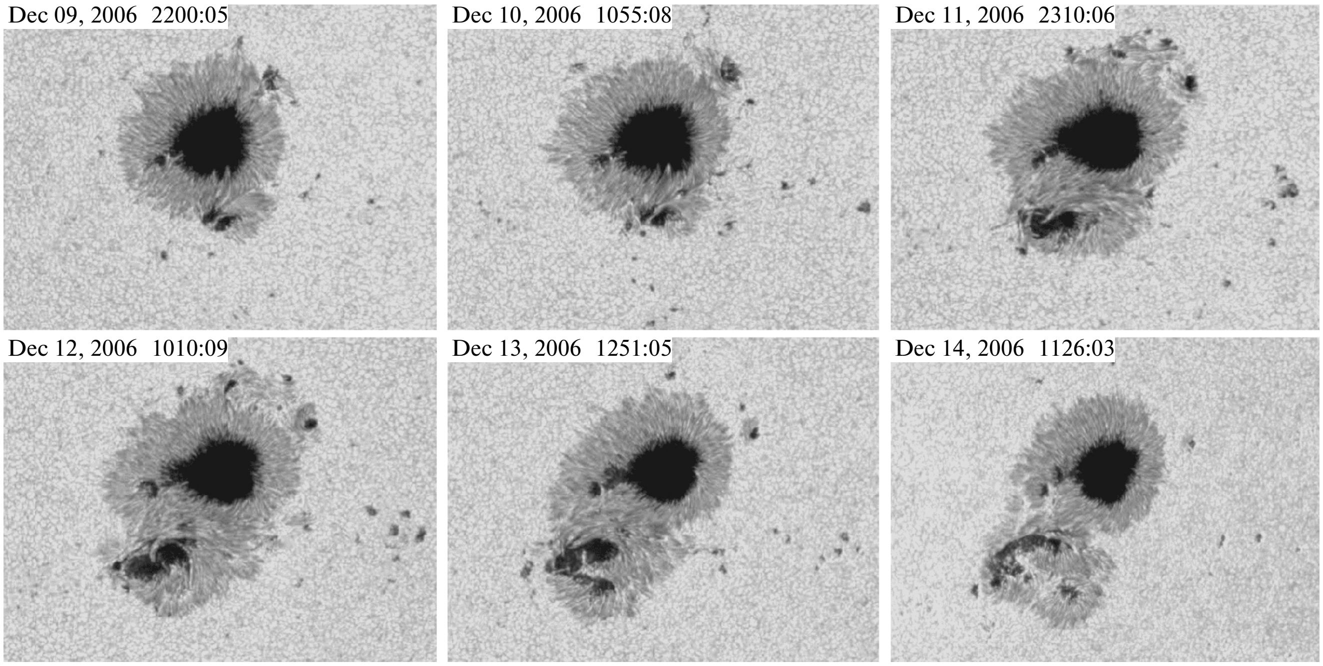

Fig. 4. Evolution of NOAA AR 10930 in the period December 9–14, 2006 (TRACE/WL).

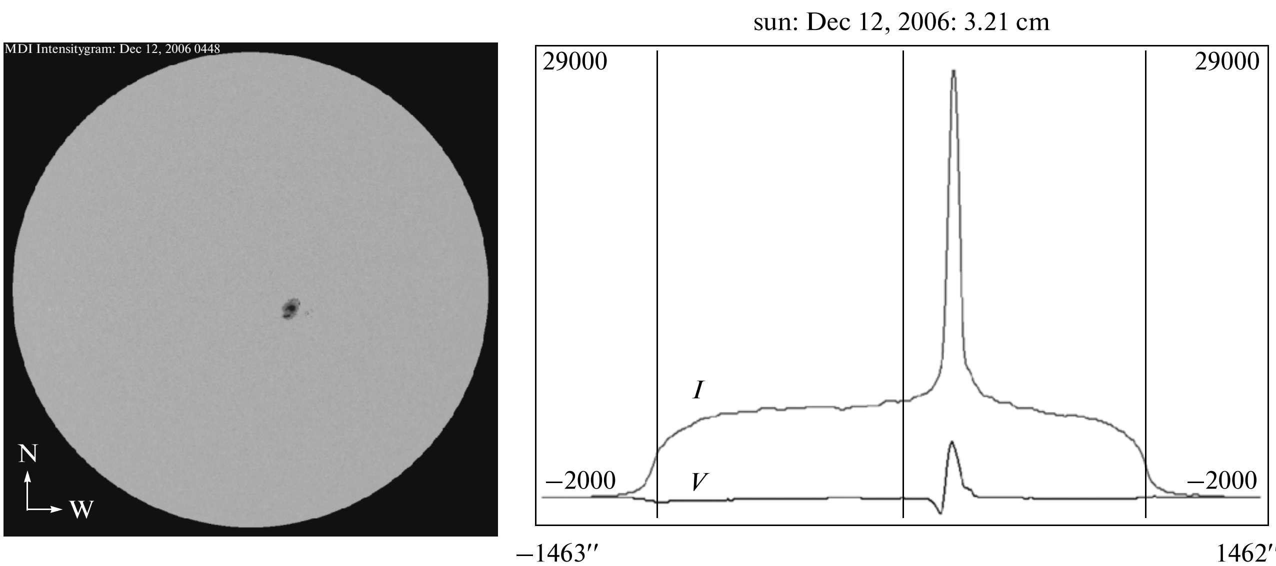

Fig. 5. Left panel: an image of the solar disk (SOHO/MDI, Intensity) on December 12, 2006. Right panel: a solar scan (RATAN-600) at a 3.2-cm wavelength in the intensity (I) and polarization (V) channels on December 12; the vertical lines show the boundaries of the Sun's optical disk.

While AR 11158 was moving across the disk, it produced several C-class flares and five M-class flares (according to the GOES classification). On February 15, there was an X2.2 flare in the group (it began at 0144 UT, peaked at 0156 UT, and ended at 0206 UT). In white-light images (SDO/HMI), it had a typical two-ribbon structure. Ribbons were located on either side of the neutral line of magnetic field in the photosphere (Maurya et al., 2011). The flare was accompanied by a coronal mass ejection (CME) that flew out in the direction of the Earth and was registered by LASCO C2 at 0224. At this point, the velocity of the

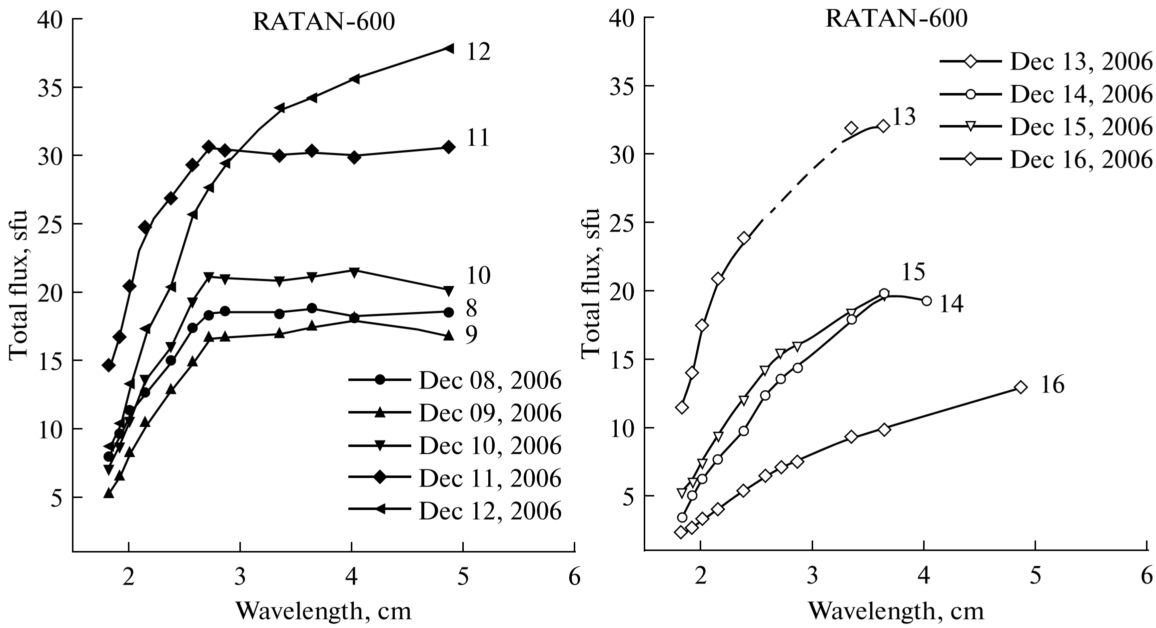

Fig. 6. Flux density spectra of a local radio source associated with NOAA 10930 from RATAN-600 observations on December 8–16, 2006.

CME in the sky plane was 274–469 km s^{-1} (Zharkov et el., 2011).

The X2.2 flare of February 15 is notable because it caused a strong gelioseismic response—a sunquake (Kosovichev, 2011). The white arrows in the magnetogram of AR 11158 on February 15 (Fig. 7c) indicate the two areas of the photosphere where the strongest impacts of the X2.2 flare were detected (according to Fig. 1 in (Kosovichev, 2011)). However, the center of the sunquake was impact *1*, which occurred at the periphery of the penumbra of the central spot in a moderate magnetic field (~400 G), unlike more severe impact *2*, which was detected near the neutral line, where the photospheric magnetic field strength was ~2000 G.

The evolution of AR 11158 before the X2.2 flare can be seen in Fig. 7, which shows magnetograms of this active region for February 13, 14, and 15 obtained from the SDO/HMI observations (http://jsoc.stanford.edu/ajax/lookdata.html). The magnetograms show shifting movements of the spots, i.e., movements of positive-polarity spots with respect to stable negative-polarity spots in the center of the AR. The maximum gradient of the photospheric magnetic fields was observed on February 14, i.e., the day before the X2.2 flare, when a δ-configuration formed in the group (Kosovichev, 2011; Zharkov et al., 2011).

The evolution of AR 11158 microwave radiation prior to the X2.2 flare can be seen in Figs. 7a–7f. Figure 7 (on the left-hand side) shows fragments of solar scans obtained with RATAN-600 at a 2.1-cm wavelength in the intensity (*I*) and polarization (*V*) channels, which are superimposed on the AR 11158 magnetogram (SDO/HMI). On the right-hand side, there are fragments of solar scans in the intensity (*I*) channel at wavelengths of 1.8, 2.3, 3.2, 4.1, and 5.0 cm.

The favorable position of the group, which was stretched along the equator in the central part of the solar disk, allowed one to reliably identify individual components of the microwave radiation source with individual parts of the AR. During three days—on February 13–15—the radio source associated with the central part of the AR dominated at shorter wavelengths of the studied range. As seen in Figs. 7b and 7e, on February 14, an additional *B* component, which had not been observed the day before, was recorded in the source. It can be identified with the area of the maximum gradient of magnetic fields in the magnetogram. The most powerful focus of the X2.2 flare "impact *2*" was detected precisely in this part of the AR (near the polarity division line of the photospheric fields).

It is evident from Fig. 7e that the flux from the newly emerged *B* component is increasing with wavelength faster than the flux from component *A*. This is illustrated in Fig. 8 (left panel), which shows the wavelength dependent variations in the antenna temperature of the *A* and *B* components of the local radio source above AR 11158.

The emergence of a new component, *B*, on February 14 affected the spectral pattern of the integral flux from the dominant source identified with the central part of the group. Figure 8 (right panel) shows the integrated flux density spectra for this source from

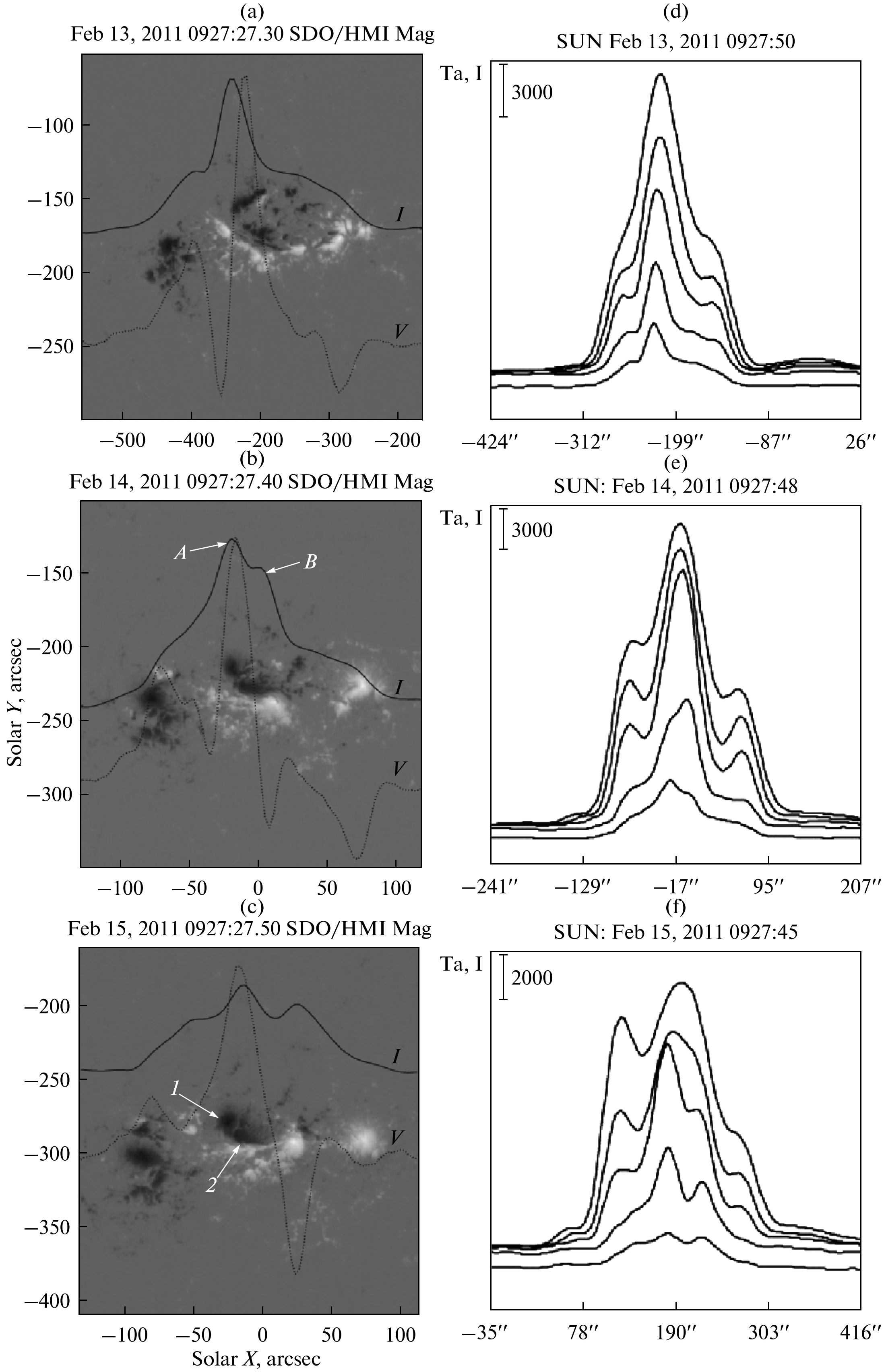
(a)
Feb 13, 2011 0927:27.30 SDO/HMI Mag
−100
−150
−200
−250
−500 −400 −200 −300 −200
I
V
(d)
SUN Feb 13, 2011 0927:50
Ta, I
3000
−424″ −312″ −199″ −87″ 26″
(b)
Feb 14, 2011 0927:27.40 SDO/HMI Mag
A
B
Solar Y, arcsec
−150
−200
−250
−300
−100 −50 0 50 100
I
V
(e)
SUN: Feb 14, 2011 0927:48
Ta, I
3000
−241″ −129″ −17″ 95″ 207″
(c)
Feb 15, 2011 0927:27.50 SDO/HMI Mag
−200
−250
−300
−350
−400
1
2
I
V
−100 −50 0 50 100
Solar X, arcsec
(f)
SUN: Feb 15, 2011 0927:45
Ta, I
2000
−35″ 78″ 190″ 303″ 416″

Fig. 7. Evolution of NOAA AR 11158 and its microwave radiation on February 13, 14, and 15, 2011: (a–c) fragments of solar scans (RATAN-600) at a 2.1-cm wavelength in the intensity (*I*) and polarization (*V*) channels superimposed on magnetograms of the AR (SDO/MDI); (d–f) fragments of solar scans (intensity channel *I*) at wavelengths of 1.8, 2.3, 3.2, 4.1, and 5.0 cm, which were identified with NOAA 11158. The scans are arranged from bottom to top in order of increasing wavelength. The vertical segment in the upper left corner of Figs. 7d–7f shows the scale of the vertical axis (antenna temperature is in degrees Kelvin); the horizontal axis shows the distance from the center of the Sun in seconds of arc.

observations on February 13–15. On February 14 (the day before the powerful flare), the slope of the spectrum increased at short wavelengths of the centimeter range and a local maximum appeared at ~3–4 cm. These changes in the spectrum can be attributed to the development of a new (peculiar) source above the area with a δ-configuration, the flux of which joined the radio emission from the source above the central part of the group, observed on the previous day.

3. CONCLUSIONS

We have studied three solar eruptive events, including a powerful X-class flare and coronal mass ejections (CMEs), that occurred on July 15, 2002; December 13, 2006; and February 15, 2011 in NOAA active regions 10300, 10930, and 11158, when these regions were in the central part of the Sun's disk. This made it possible to investigate the dynamics of the ARs over a few days prior to the eruptive process.

A comprehensive analysis of these events using solar observations in different energy ranges carried out with highly sensitive instruments onboard the SOHO, TRACE, *Hinode,* and SDO satellites and at ground-based observatories has shown that, in all three cases, the eruptive process (strong flare) was preceded (one or two days prior to the event) by the formation of a δ-configuration in the AR photospheric magnetic field. This was a result of both the emergence of a new magnetic field and shifting movements of the sunspots. The foci of the future powerful X-class flares and CME eruption were recorded precisely in the areas with a δ-configuration (tight arrangement of the umbrae of sunspots with theopposite sign of the magnetic field).

The dynamics of the active regions and their magnetic structures in the photosphere was compared with

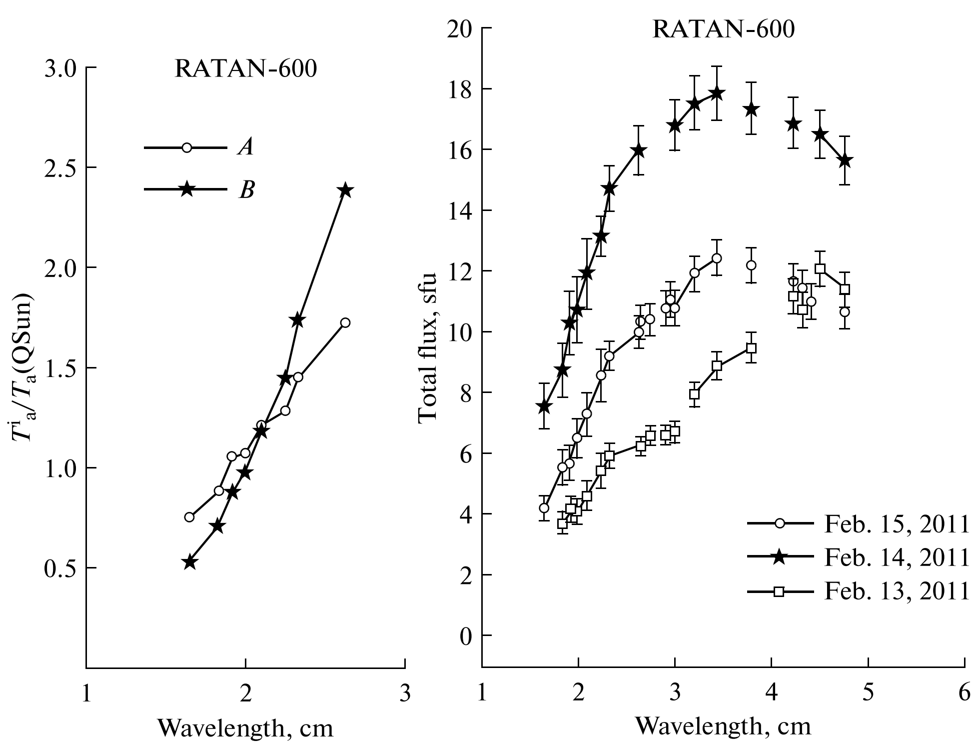

Fig. 8. Left panel: wavelength-dependent changes in the antenna temperature of components of a local source above AR 11158: *A* is the component associated with the central part of the sunspot group; *B* is the new component above the area with the maximum gradient of the photospheric magnetic field. The antenna temperature of *A* and *B* is measured in relative units (fractions of the antenna temperature of a quiet Sun). Right panel: flux density spectra of the dominant radio source identified with AR 11158; the spectra were obtained from RATAN-600 observations on February 13, 14, and 15.

the evolution of their microwave radiation. We used the results of daily multiwavelength spectral and polarization observations of the Sun in the microwave range with a high spatial resolution at RATAN-600. It was found that the formation of a magnetic structure with a δ-configuration in the photosphere was consistent to an accuracy of a day with changes in the spectrum of the dominant local microwave radio source that was identified with the AR. The detected changes in the spectrum of the radio source flux (spectrum steepening, i.e., an increase in the growth rate of the flux with a wavelength of 2–5 cm, and the emergence of a local maximum at 3 cm) provide evidence of the development of a microwave PS above the area with a δ-configuration that formed one or two days before the flare.

The results of the above analysis of the eruptive events in NOAA ARs 10300, 10930, and 11158 in 2002, 2006, and 2011 put the latter on a par with the active regions producing powerful (proton) flares, which were studied at RATAN-600 in the 1980s–1990s. It is concluded that early detection of peculiar sources (areas of high and long-term energy release in the solar atmosphere) in the microwave radiation of ARs by characteristic changes in the spectra (increased steepness in the range 2–5 cm and the emergence of a local maximum at a ~3-cm wavelength) can be used as a prognostic criterion in predicting powerful eruptive (geoeffective) events on the Sun.

ACKNOWLEDGMENTS

We thank the staff of the solar radio astronomy research group of SAO for carrying out regular solar observations at RATAN-600. We are also grateful to Prof. M.A. Livshits for useful discussions and to the reviewer for helpful comments. This work was supported by the Ministry of Education and Science (GK 16.518.11.7062 and 16.552.11.7028) and partially supported by the Presidium of the Russian Academy of Sciences (N P-22) and by grant N Sh-3645.2010.2.

REFERENCES

Abramenko, V., Yurchishyn, V., and Wang, H., Intermittency in the Photosphere and Corona above an Active Region, *Astrophys. J. Lett.*, 2008, vol. 681, pp. 1669–1676.

Akhmedov, Sh.B, et al., Results of Observations of Solar Eclipse that Occurred on July 31, 1981, *Issled. Geomagn. Aeron. Fiz. Solntsa*, 1982, no. 62, pp. 172–180.

Akhmedov, Sh., Borovik, V., Gelfreikh, G., et al., Structure of Solar Active Region from RATAN-600 and VLA Observations, *Astrophys. J. Lett.*, 1986, vol. 301, no. 1, pp. 460–464.

Bogod, V.M., Studying the Solar Atmosphere Based on the RATAN-600 Multiwave Solar Observations, *Trudy Vserossiiskoi konferentsii, SAO RAN* (Proc. All-Russia Conference SAO RAN), N. Arkhyz, 2006, pp. 2–26.

Borisevich, T.P., Venger, A.P., Zverev, Yu.K., et al., Characteristics of the Long-Lived Active Region Based on the BPR Observations in November 2006–February 2007, *Trudy XI Pulkovskoi konferentsii po fizike Solntsa* (Proc. 11th Pulkovo Conference on Solar Physics), St. Petersburg, 2007, pp. 63–66.

Borovik, V.N., Vatrushin, S.M., and Korzhavin, A.N., Radio Characteristics of the Active Region Related to Proton Flare of April 24, 1985, Based on the RATAN-600 Observations, *Astrofiz. Issled. Izv. SAO*, 1987, vol. 28, pp. 123–131.

Borovik, V.N., Drake, N.A., Korzhavin, A.N., and Plotnikov, V.M., Evolution and Structure of Flare-Active Region HR 16631 (February 1980) Based on the RATAN-600 Observations, *Kinematika Fiz. Nebesnykh Tel*, 1989, vol. 5, no. 1, pp. 63–67.

Borovik, V.N., Grechnev, V.V., Abramov-Maksimov, V.E., et al., RATAN-600 Multiwave Observations of Coronal Loops after the Flare of November 2, 1992, *Trudy Vseross. Konferentsii* (Proc. All-Russia Conference), Troitsk, 2006, Obridko, V.N. and Zaitsev, V.V., Eds., pp. 41–47.

Borovik, V.N., Abramov-Maksimov, V.E., Grigor'eva, I.Yu., et al., Evolution of AR 10930, Related to the X 3.4/4V Geoeffective Flare of December 13, 2006, Based on the Microwave Observations, *Trudy XI Pulkovskoi konferentsii* (Proc. 11th Pulkovo Conference), St. Petersburg, 2007, pp. 67–68.

Brown, D.S., Nightingale, R.W., Alexander, D., et al., Observations of Rotating Sunspots from TRACE, *Sol. Phys.*, 2003, vol. 216, no. 1, pp. 79–108.

Garaimov, V.I., Processing of Univariate Data Sets in OC Windows, *Preprint of SAO*, Nizhnii Arkhyz, 1997, no. 127T.

Gary, G. and Moore, L., Eruption of a Multiple-Turn Helical Magnetic Flux Tube in a Large Flare Evidence for External and Internal Reconnection That Fits the Breakout Model of Solar Magnetic Eruptions, *Astrophys. J. Lett.,* 2004, vol. 611, no. 1, pp. 545–556.

Golovko, A.A. and Salakhutdinova, I.I., Fractal Properties of Active Regions, *Astron. Zh.*, 2012, vol. 89, no. 5, pp. 1–7.

Harra, L., Demoulin, P., Mandrini, C., et al., Flows in the Solar Atmosphere Due to Eruptions on the 15 July 2002, *Astron. Astrophys.*, 2005, vol. 438, no. 3, pp. 1099–1106.

Harra, L., Williams, D., Wallace, A., et al., Coronal Nonthermal Velocity Following Helicity Injection before an X-Class Flare, *Astrophys. J. Lett.*, 2009, vol. 691, pp. L99–L102.

Kinenes, H.A., Korzhavin, A.N., Peterova, N.G., and Santos, H., Observations of Solar Eclipse of March 7, 1970 with the GRS Polarimeter at the 4.5 cm Wavelength in Havana, *Soln. Dannye*, 1975, no. 3, pp. 87–96.

Knyazeva, I.S., Makarenko, N.G., and Livshits, M.A., Detecting the Effect of a New Magnetic Field Emergence from the SOHO/MDI Magnetogram Topology, *Astron. Zh.*, 2011, vol. 88, no. 5, pp. 503–512.

Kosovichev, A.G., Helioseismic Response to X2.2 Solar Flare of February 15, 2011, *Astrophys. J. Lett.*, 2011, vol. 734, pp. L15–L25.

Kubo, M., Ichimoto, K., Shimizu, T., et al., Formation of Moving Magnetic Features and Penumbral Fields with Hinode/SOT, *PASJ*, 2007a, vol. 59, pp. 607–S612.

Kubo, M., Yokoyama, T., Katsukawa, Y., et al., Hinode Observations of a Vector Magnetic Field Change Associated with a Flare on 2006 December 13, *PASJ*, 2007b, vol. 59, pp. 779–S784.

Liu, Yu., Jiang, Y., Ji, H., Zhang, H., and Wang, H., Observational Evidence of a Magnetic Flux Rope Eruption Associated with the X3 Flare on 2002 July 15, *Astrophys. J. Lett.*, 2003, vol. 593, pp. L137–L140.

Magara, T. and Tsuneta, S., Hinode's Observational Results on the Saturation of Magnetic Helicity Injected into the Solar Atmosphere and Its Relation to the Occurrence of a Solar Flare, *PASJ*, 2008, vol. 60, pp. 1181–1189.

Maurya, R., Vemareddy, P., and Ambastha, A., Velocity and Magnetic Transition Driven by the X2.2 White-Light Flare of 2011 February 15 in NOAA 11158, *Astrophys. J. Lett.*, 2012, vol. 747, p. 134M–162M.

Murav'eva, E.A., Myagkova, I.N., and Yushkov, B.Yu., Protons of Solar Flares in December 2006, *Trudy VAK-2007* (Proc. VAK-2007), Kazan, 2007, pp. 148–150.

Myagkova, I.N., Kuznetsov, S.N., Kurt, V.G., et al., X-Ray, γ-Emission and Energetic Particles in Near-Earth Space as Measured by CORONAS-F Satellite: From Maximum to Minimum of the Last Solar Cycle, *Adv. Space Res.,* 2007, vol. 40, no. 12, pp. 1929–1934.

Shakhovskaya, A.N., Livshits, M.F., and Chertok, I.M., Role of Plasma Ejections in Development of Powerful Solar Flares, *Astron. Rep.*, 2006, vol. T. 59, pp. 1013–1025.

Shibasaki, K., Alissandrakis, C., and Pohjolainen, S., Radio Emission of the Quiet Sun and Active Regions, *Sol. Phys.*, 2011, vol. 273, no. 2, pp. 309–337.

Su, Y., Golub, L., Van Ballegooijen, et al., Evolution of the Sheared Magnetic Fields of Two X-Class Flares Observed by Hinode/XRT, *PASJ*, 2007, vol. 59, pp. 785–S791.

Tokhchukova, S.Kh., RATAN-600 Radio Telescope in the 24th Solar Activity Cycle. IV. Information System for RATAN-600 Solar Observations, *Astrophys. Bull.*, 2011, vol. 66, no. 3, pp. 379–388.

Vatrushin, S.M. and Korzhavin, A.N., Peculiar Radio Sources in Solar Flare-Active Regions and Their Possible Relation to Current Sheets, *Trudy 6-go seminara "Fizika solnechnoi plazmy"* (Proc. 6th Seminar "Solar Plasma Physics"), Somov, B.V. and Fomichev, V.V., Eds., Moscow, 1989, pp. 100–106.

Yazev, S.A. and Savinkin, M.Yu., The Last Discharge of Cycle 23 (Events in November 2006–February 2007), *Trudy VAK-2007* (Proc. VAK-2007), Kazan, 2007, pp. 173–175.

Zharkov, S., Green, L., Matthews, S., and Zharkova, V., February 15, 2011: Sun-Quakes Produced by Flux Rope Eruption, *Astrophys. J. Lett.*, 2011, vol. 741, no. 2, pp. L35–L50.