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Microwave Radiation of Solar Active Regions before X Flares according to the RATAN-600 Observations in 2011

V. E. Abramov-Maximov[a], V. N. Borovik[a], and L. V. Opeikina[b]

[a]*Central (Pulkovo) Astronomical Observatory (GAO), Russian Academy of Sciences, Pulkovskoe sh. 65, St. Petersburg, 196140*

[b]*Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz, Karachai-Cherkessian Republic, 369167 Russia*

e-mail: beam@mail.ru, vnborovik@mail.ru, lvo@sao.ru

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Abstract—The evolution of the microwave radiation from four active regions, where strong X-ray flares (X-class,GOES) occurred in 2011, has been studied. Daily multiwavelength RATAN-600 radio observations of the Sun in the 1.6–8.0 cm range have been used. It has been indicated that the radiosource above the photospheric magnetic field neutral line (above the region with the maximal convergence of the fields opposite in sign) becomes predominant in the structure of the active region microwave radiation one to two days before a powerful flare as in the eruptive events previously studied with RATAN-600. The appearance of such a radiosource possibly reflects the current sheet formation in the corona above the active region. The energy necessary for a flare is stored in the magnetic field of active region, which can be considered as a factor for predicting a powerful flare.

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INTRODUCTION

The development of modern technologies and telecommunications makes space weather predictions more urgent. The methods for predicting solar activity geoeffective manifestations are based on the detection of the preparation criteria for these manifestations in different solar radiation ranges. Solar activity is most effective in the solar corona, where the energy in the active region (AR) magnetic field is accumulated and released, short-wavelength electromagnetic radiation is generated, particle fluxes are formed and accelerated, and coronal mass ejections (CMEs) and shocks are generated. Coronal ARs can be observed against a background of the solar disk independently of the weather conditions in radioemission and onboard satellites in the X-ray and UV ranges.

Great experience in predicting powerful (geoeffective) flares has been accumulated. For example, Ishkov (1998) considered methods of short-term prediction (the lead time is one to three days) and warning (the lead time is 0–24 h) of flares. The methods for predicting flares based on the heliographic criterion of AR potential flare activity, analysis of radiosources in the corona above the magnetic field neutral line, and estimation of free magnetic energy in ARs were developed at the Institute of Solar–Terrestrial Physics (see (Smol'kov et al., 2011) and references therein). The Tanaka–Enome criterion, based on an analysis of integral AR radioemission characteristics according to medium-resolution observations, was developed and physically explained (Borisevich et al., 2006).

To reveal the factor for predicting powerful flares, it seems important to study the specific features of the AR microwave radiation before flares based on routine radio observations of the Sun. This work analyzes the radioemission of several ARs, where X flares occurred in 2011, based on daily multiwavelength solar observations with the RATAN-600 radiotelescope with a high spatial resolution (17'' × 13' at 2.0 cm). When the Sun passed through a fixed antenna beam, the solar radioemission in the 1.6–8.0 cm range was simultaneously measured, at many wavelengths using a new spectral-polarization complex (Bogod and Tokhchukova, 2010). Attention was mainly paid to the analysis of the AR radioemission spectral characteristics. A method for processing solar scans obtained with RATAN-600 (Akhmedov et al., 1987; Korzhavin et al., 2010) was used to separate the radiosource above an AR into components and determine the component parameters identified with individual AR parts. Data on the circular polarization channels were used to control the correlation of scans with sunspot groups on the solar disk (Fig. 1).

The aim of this work is to study the AR evolution and reveal the specific features of microwave radiation, which indicate that a powerful flare is prepared. The GOES satellite registered eight X flares in 2011. We selected for analysis the flares of February 15, March 9, August 9, and September 6 and 7, 2011, which occurred in ARs NOAA 11158, 11166, 11263,

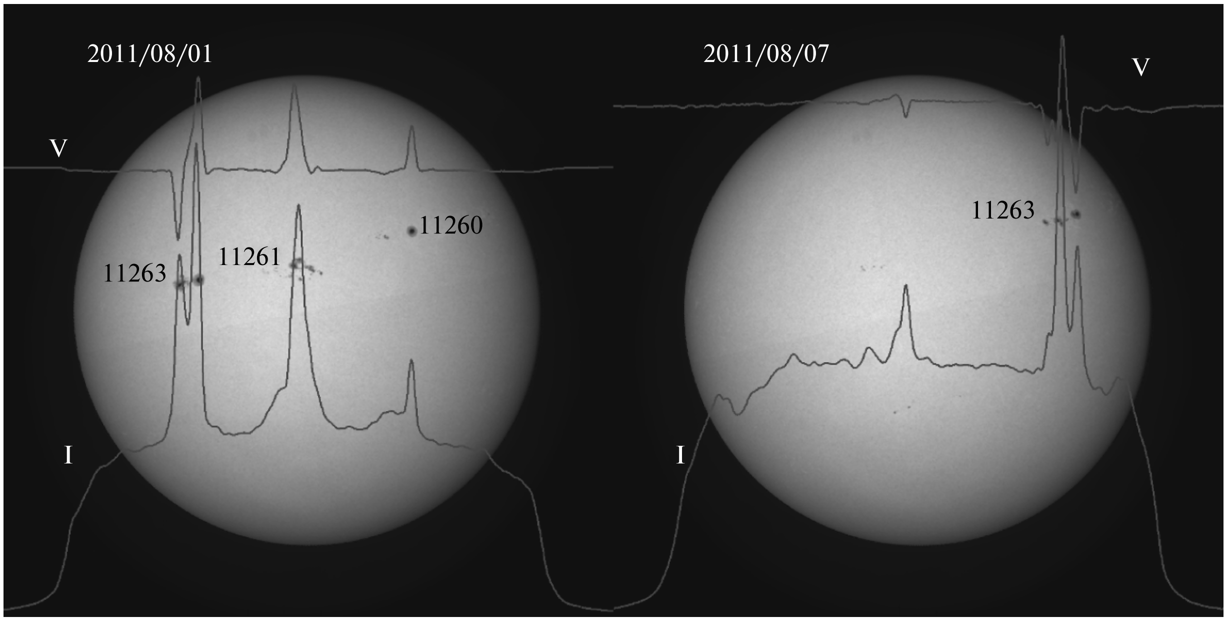


Fig. 1. Solar scans (RATAN-600) at a wavelength of 3.0 cm in the intensity (Stokes parameter I) and circular polarization (Stokes parameter V) channels for August 1 and 7, 2011, superposed on solar disk images (SDO/AIA).

and 11283, respectively. The evolution of NOAA 11302 before the X1.4 (September 22, 2011) and X1.9 (September 24, 2011) flares was not studied since the flares occurred when this AR was near the eastern solar limb. We did not study NOAA 11339 before the X1.9 flare (November 3, 2011) because there were no solar radio observations.

OBSERVATIONAL DATA

X6.9 flare in NOAA 11263 (August 9, 2011)

Figure 2a indicates that the X6.9 flare was accompanied by an energetic proton flux. NOAA 11263 appeared on the disk on July 27, 2011, and had a bipolar structure during several days. According to the SDO (Solar Dynamics Observatory) data and sunspot magnetic field maps obtained at ground-based observatories, new sunspots of different polarity were registered in the group beginning from August 2. New magnetic fields emerged up to August 9. The photospheric magnetic field gradient in the AR was maximal on August 7. This is confirmed by two adjacent sunspots of opposite polarity (S2600 and N2600) at the group center (see Fig. 2b) according to the Mount Wilson Observatory (MWO) data.

Before August 8, many C flares were registered in the studied region (GOES). An M3.5 flare occurred at 1800 UT on August 8, and M2.5 (at 0319 UT) and X6.9 (at 0748 UT) flares were registered on August 9. The solar record fragments (RATAN-600) related to NOAA 11263 at several wavelengths are compared with the AR image (SDO/AIA) and SDO/HMI) in Fig. 2b. The values of the sunspot magnetic fields are presented according to the MWO data. It is clear that the local radiosource indicated that the sunspot group was bipolar at all wavelengths on August 1–6 and included two main components identified with the leading and tail sunspots. Component A related to the leading sunspot dominated in this case, and a new source (P), which was projected on the inversion line of the photospheric magnetic field at the AR center, became the predominant component on August 7 (two days before the X6.9 flare).

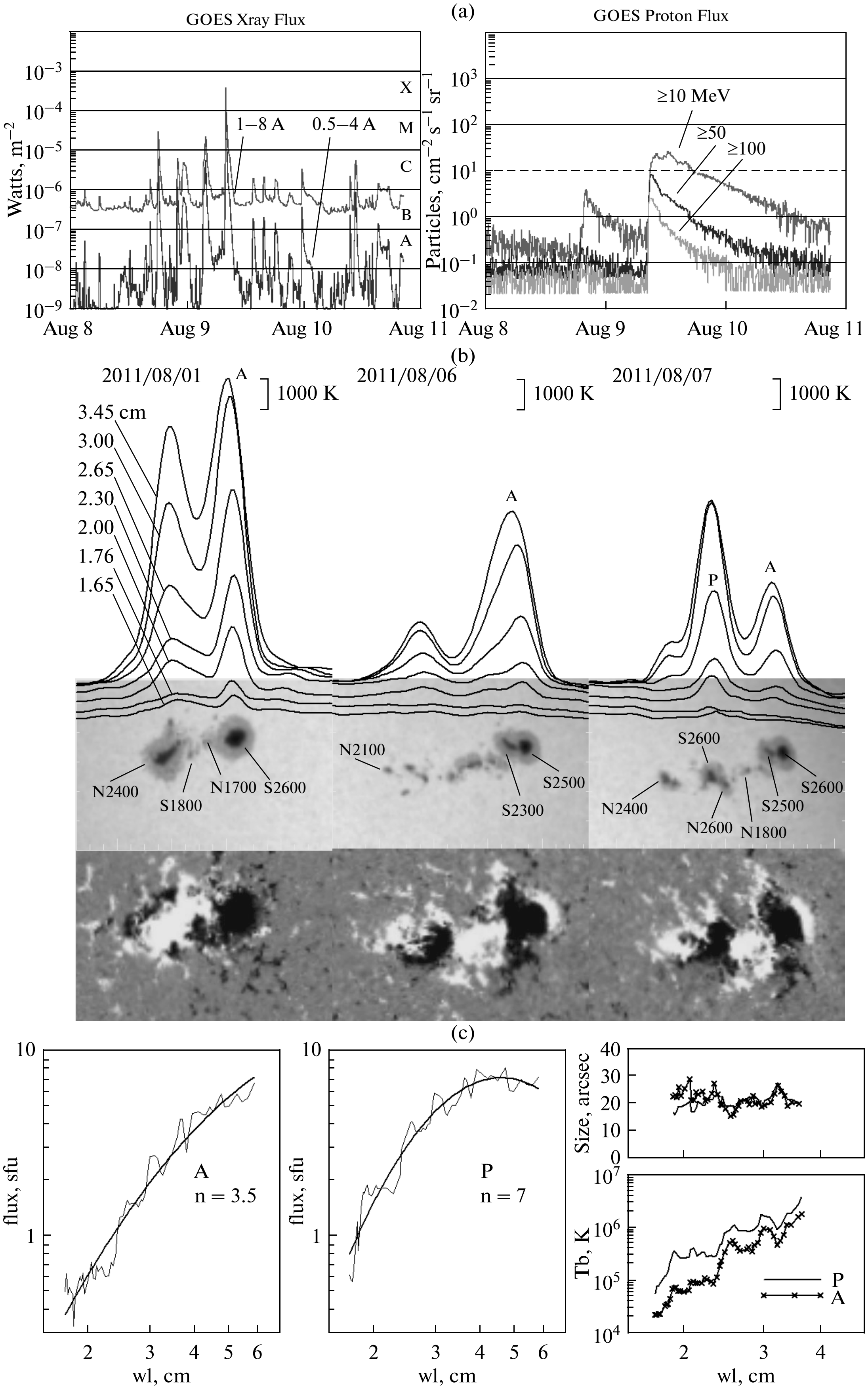
The flux density spectra of these sources are given in Fig. 2c. It is clear that spectral index n, reflecting the spectral tilt, of source P is larger than that of source A. The spectra of the sizes and brightness temperatures of these sources are also given. In the short-wave range part, the brightness temperature (Tb) of source P is higher than that of source A and accounts for several MK at waves longer than 3 cm.

X1.5 Flare in NOAA 11166 (March 9, 2011)

Figure 3a indicates that the X1.5 flare in NOAA 11166 (March 9, 2011) did not cause a considerable

Fig. 2. (a) Solar X-ray and proton fluxes (GOES) for August 8–11, 2011. (b) Comparison of solar scan fragments (RATAN-600), related to NOAA 11263, at several wavelengths with the AR image (SDO/AIA (at 0900 UT) and SDO/HMI). The values of the sunspot magnetic fields are presented according to the MWO data. (c) The spectra of the flux density, sizes, and brightness temperatures of sources A and P (August 7, 2011).

(a)


GOES Xray Flux
GOES Proton Flux
Watts, m^{-2}
X
M
C
B
A
1–8 A
0.5–4 A
Particles, cm^{-2} s^{-1} sr^{-1}
≥10 MeV
≥50
≥100
Aug 8
Aug 9
Aug 10
Aug 11
(b)
2011/08/01
2011/08/06
2011/08/07
1000 K
3.45 cm
3.00
2.65
2.30
2.00
1.76
1.65
A
P
N2400
S1800
N1700
S2600
N2100
S2300
S2500
S2600
N2600
N1800
(c)
flux, sfu
A
n = 3.5
P
n = 7
wl, cm
Size, arcsec
Tb, K
P
A

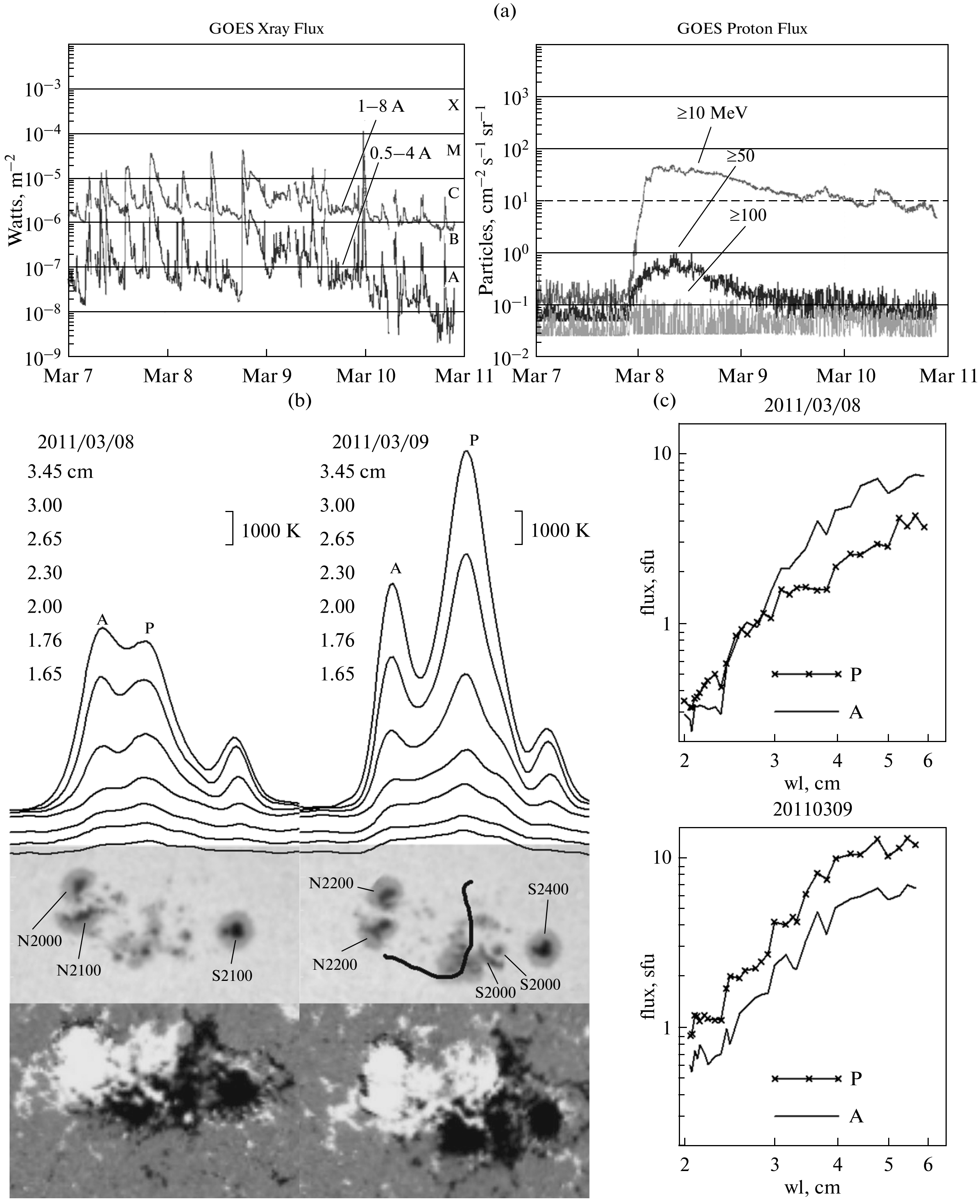


Fig. 3. (a) Solar X-ray and proton fluxes (GOES) for March 8–11, 2011. (b) Comparison of solar scan fragments (RATAN-600) at several wavelengths with the NOAA 11166 image (SDO). The values of the sunspot magnetic fields are presented according to the MWO data. The filament position (according to the GAS GAO observations) is schematically shown on the group image of March 9. (c) The spectra of the radiosource flux densities above the group tail part (A) and neutral line (P) for March 8 and 9, 2011.

increase in the proton flux against the background of an increased total proton flux caused by the M flares that occurred on the previous days in NOAA 11164 and 11165.

NOAA 11166 appeared from the solar limb on March 3. The sunspot group was initially a bipolar structure with a large leading sunspot and a fragmented tail part. New magnetic fields of different polarity emerged as the group developed. The solar record fragments (RATAN-600) at several wavelengths are compared with AR 11166 images for March 8 and 9 in Fig. 3b. The values of the sunspot magnetic fields are presented according to the MWO data. The group image on March 9 schematically shows the position of the filament, separating the fields of opposite polarity, which is drawn according to the observations at the Mountain Astronomical Station (GAS GAO). Three components were distinguished in the structure of the radiosource above the AR on March 8; in this case, the sources above the group tail (A) and center (P) were comparable in value. At the same time, source P above the neutral line became predominant on March 9 (14 h before the X flare). Figure 3c indicates that the intensity of the source above the neutral line (P) before the flare on March 9 became three times as high as the day before (March 8).

X2.1 and X1.8 Flares in NOAA 11283 (September 6 and 7, 2011)

M5.3 (0135) and X2.1 (2232) flares occurred in NOAA 11283 on September 6 and X1.8 (2232) on September 7. The first two flares caused an increase in the proton flux (Fig. 4a).

The sunspot group that appeared on the limb on September 3 was bipolar. Figure 4b indicates that a sunspot of polarity N appeared on September 5 in the northwestern group part among S-polarity sunspots (according to the Crimean Astrophysical Observatory (CrAO) data). On September 6, the magnetic field gradient on the photosphere increased after the emergence of new N-polarity sunspots in the same region. This affected the AR microwave radiation (Fig. 4b). A new radio source associated with δ-configuration developed in the region on September 5. Its radiation increased considerably on the next day (before the X2.1 flare on September 6) and remained at the same level on September 7 before the X1.8 flare, which is illustrated by the spectra of the radioemission flux density of this source for September 5–7 shown in Fig. 4c.

Flare of February 15, 2011, in NOAA 11158

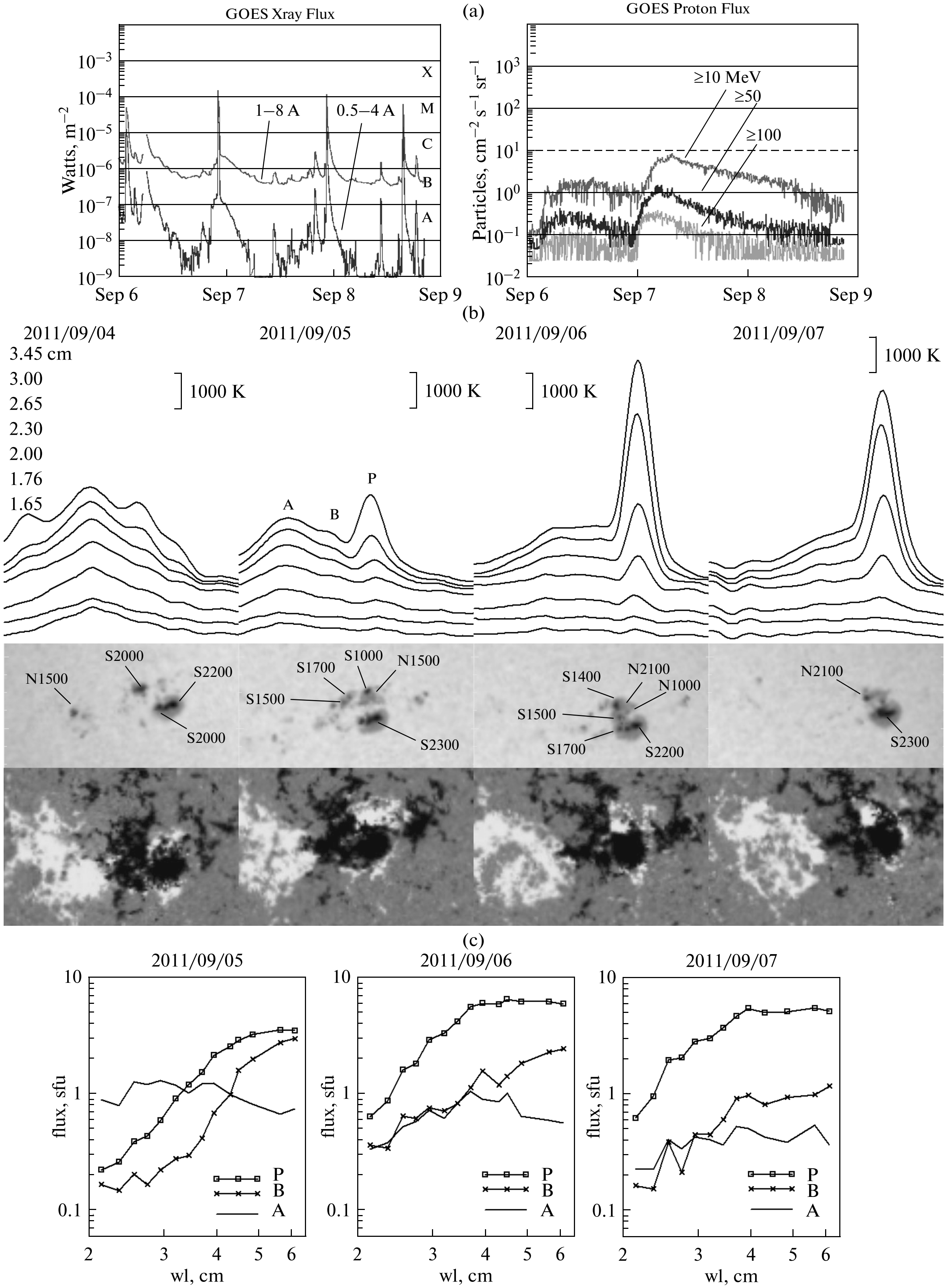
To make the list of eruptive events in 2001 more complete, we illustrate here a study of NOAA 11158, where the X2.2 flare occurred on February 15 and was accompanied by an increase in the proton flux (Fig. 5a). The development of this eruptive event was considered in detail in several works (see Borovik et al., 2012 and references therein).

The emergence of a new magnetic field and a sunspot shear motion on February 14 (a day before the X flare) resulted in the maximal gradient of photospheric magnetic fields in the AR. A new radiosource above the area with the maximal convergence of the fields of opposite polarity was registered on that day in the microwave radiation. Figure 5b, taken from (Borovik et al., 2012), presents the spectra of the radiosource flux density above the group center for February 13–15, which were affected by the appearance of a new component above the δ-configuration region on February 14.

CONCLUSIONS

We studied most X flares that occurred on the Sun in 2011, as well as the evolution of NOAA 11158, 11166, 11263, and 11283 and their microwave radiation during several days before the X flares.

A complex analysis of the eruptive events, performed using solar observations in different energy channels, indicated that an eruptive process followed the formation of a region with a high gradient of the photospheric magnetic field one to two days before a powerful flare in all considered cases. This resulted from the emergence of new magnetic fields and/or sunspot shear motions. We compared the development of ARs and their magnetic structures on the photosphere with the AR microwave radiation evolution based on daily multiwave solar observations in the microwave range, performed using the RATAN-600 radiotelescope with a high spatial resolution. We established that an increase in the gradient of the magnetic field on the photosphere was accompanied by the development of a radioemission source above the neutral line, which is usually registered in developed ARs (Shibasaki et al., 2011; Bogod et al., 2012). This source became predominant in the AR radioemission structure one to two days before a strong flare. The parameters of the developed radiosource make it possible to consider it among the so-called "peculiar" sources (PSs), which were for the first time detected in the flaring active groups in the 1970s–1980s in solar eclipse observations and with the RATAN-600 radio telescope (see references in (Borovik et al., 2012)). Researchers use PSs in order to diagnose regions with a high energy release at altitudes of about 10000–15000 km in the corona. Vatrushin and Korzhavin (1989) indicated that the PS radioemission can be interpreted as a gyrosynchrotron emission from the region of anomalous energy release with a subrelativistic plasma ($T = 10^7$–10^8 K and Ne ~ 10^{10} cm^{-3}) in moderate magnetic fields. Such conditions are antici-



(a)
GOES Xray Flux
Watts, m^{-2}
1–8 A
0.5–4 A
X
M
C
B
A
Sep 6
Sep 7
Sep 8
Sep 9
GOES Proton Flux
Particles, cm^{-2} s^{-1} sr^{-1}
≥10 MeV
≥50
≥100
(b)
2011/09/04
2011/09/05
2011/09/06
2011/09/07
3.45 cm
3.00
2.65
2.30
2.00
1.76
1.65
1000 K
A
B
P
N1500
S2000
S2200
S1700
S1000
S1500
S2300
S1400
N2100
N1000
S2200
(c)
flux, sfu
wl, cm
P
B
A

Fig. 4. (a) Solar X-ray and proton fluxes (GOES) for September 6–9, 2011. (b) Comparison of solar scan fragments (RATAN-600) at several wavelengths with an NOAA 11283 image (SDO). The values of the sunspot magnetic fields are presented according to the CrAO and MWO data. (c) The spectra of the flux densities for the radiosource A, B, and P components above NOAA 11283 on September 5–7, 2011.

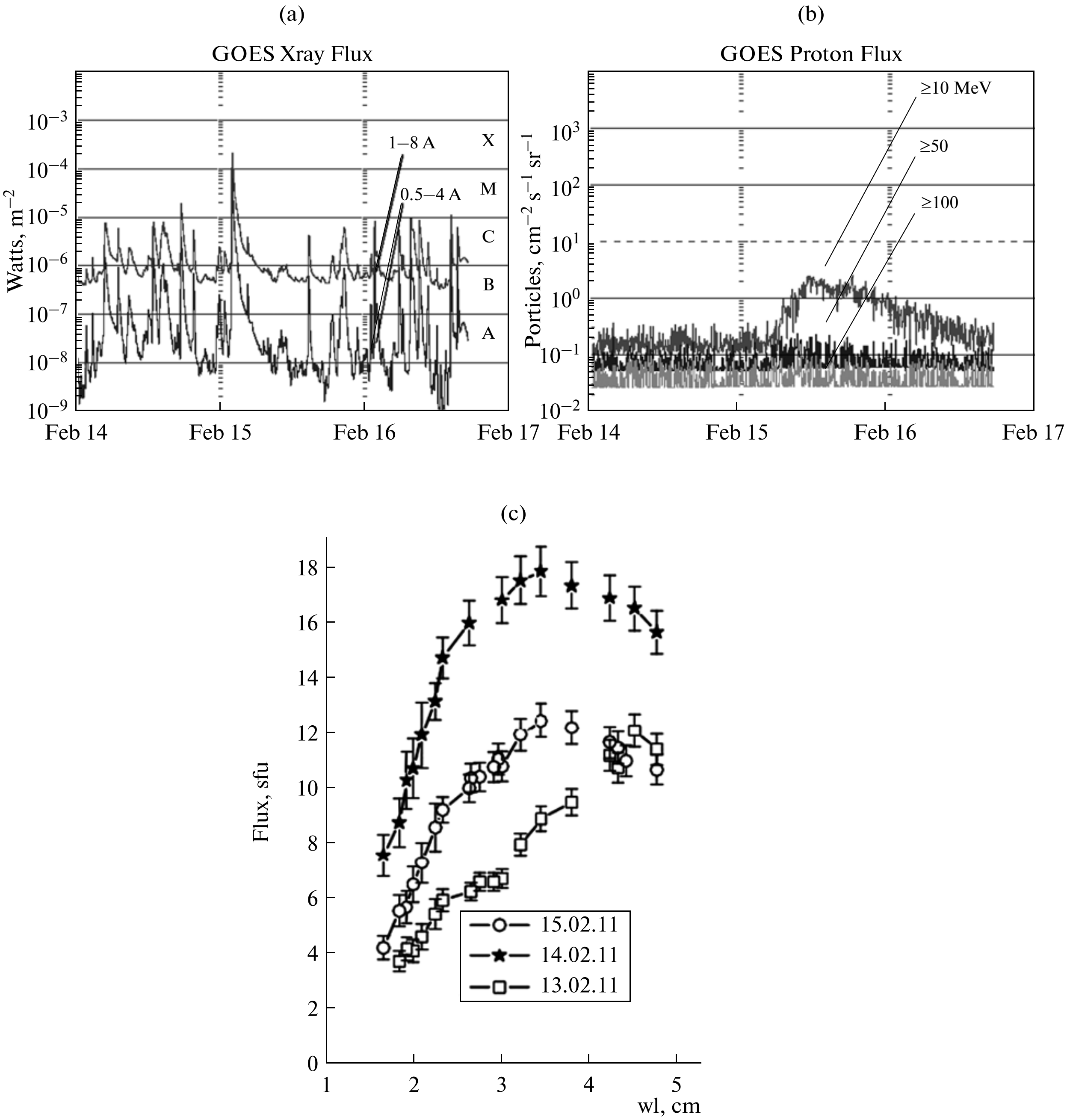


Fig. 5. (a) Solar X-ray and proton fluxes (GOES) on February 14–17, 2011. (b) The spectra of the radiosource flux densities above the central part of the group in NOAA 11158 according to the RATAN-600 observations on February 13–15 (from (Borovik et al., 2012)).

pated in models of high-temperature current sheets (Somov, 1986). The possibility that a current sheet is formed in the corona above an AR, which has a magnetic field where the energy necessary for a flare is stored, agrees with the 3D MHD modeling performed using the photospheric state characteristics before a flare in (Podgorny and Podgorny, 2012).

Thus, early detections of a predominant source above the photospheric magnetic field neutral line in the structure of the AR microwave radiation, performed based on routine solar radio observations, can be used as a prognostic criterion for powerful flares.

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