Bull. Spec. Astrophys. Obs., 2001, 51

A peculiar source in the structure of the active region AR 8108 from observations with RATAN-600

N.G. Peterova[a], **B.I. Ryabov**[b], **S.Kh. Tokhchukova**[c]

[a] St.-Petersburg Department of SAO RAS
[b] Ventspils International Radioastronomical Centre, Riga
[c] Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 369167, Russia

Received December 20, 2000; accepted March 24, 2001.

Abstract. Analysis is presented of the radio emission from the active region (AR) AR 8108 (November 1997) in which, by numerous indications, powerful flare events were to occur, but have not been revealed in observations. For over 4 days in this AR there was observed an extraordinary detail identified with one of the bases of a streamer originating in the delta-configuration of the photospheric magnetic field. It has been proposed that it is exactly through this streamer that the excess energy of the AR magnetic field was "draining" gradually for several days, which explains the lack of intense short-time events in the form of flares. Spectral and polarizational characteristics of the radio emission of the source associated with the coronal streamer have been obtained in cm range for the first time. They point to the fact that the peculiar detail is an optically thin source of thermal bremsstrahlung in the cm range. The derived spectrum and the degree of circular polarization of the peculiar emission source have made it possible to estimate values of electron temperature, electron number density and magnetic field intensity at heights $h \leq 2 \cdot 10^9$ cm, which appeared to be equal to $T_e = 2.0 \div 2.5 \cdot 10^6$ K, $N_e = 7 \cdot 10^9$ cm^{-3} and $H = 50$ G, respectively.

Key words: radio emission of the Sun — forecast of solar flares — peculiar source — coronal streamer

1. Introduction

Many indications characteristic of a flare-expected(?) active region (AR) are known at present.

1. It has been noticed (see the survey by Martin, 1980) that emergence of a new magnetic flux and complication of the magnetic field structure, especially formation of a delta configuration, cause flares.

2. Flares occur more frequently in ARs whose semi-major axis is strongly inclined to the solar equatorial plane.

3. Beginning with the papers by Severny (Moreton and Severny, 1968) it has been noted that the regions of generation of powerful events are associated with locations of strong vertical currents in ARs.

4. Increased flare activity is characteristic also of ARs where movement of spots, vortex processes, disappearance of filaments etc are observed.

On the basis of observations in the radio range, two principal ways have been proposed, which allow one to judge of the possibility of emergence of major flares:
— investigation of characteristics of sources of the S-component (Tanaka–Enome's(?) criterion) (Tanaka, Enome, 1975, Korobchuk, Peterova, 1980) and
— investigation of fluctuations of the solar radio emission (Kobrin et al., 1978).

It has been established over the last few years that in the structure of flare-active ARs there appear the so-called peculiar details associated (Vatrushin, Korzhavin, 1989) with coronal arches above the bend of the neutral line. The enumerated features available from observations in a wide range of electromagnetic radiation make it possible to forecast major flare events. Justification of these forecasts, however, is not high enough. Cases are not infrequent where a major flare arises in a seemingly "quiet" AR and vice versa. In this paper we examine such a case is AR 8108, which has not produced intense flares suspected according to a number of indications. It turned out that its activity manifested itself in a different form — as coronal mass ejections (CME) at previous revolutions, and two long-lived large coronal streamers.

Streamers belong to one of the most picturesque structures of the middle and low corona owing to their specific hemlet-like shape. They have been known from sketches of the white corona obtained during solar eclipses and have so far been well studied (see the survey of Koutchmy, Livshits, 1997). The beginning of observations in the soft X-rays (Cheng et al., 1994) opened up strong possibilities of studying this fascinating structure. One can observe presently the lower part of these objects not only at the limb but also on the disk of the Sun. It has been established now that coronal streamers are large-scale and stable arch-shaped structures that extend into the corona to a height of 2–3 solar radii and existing sometimes during several revolutions. The arch of a streamer consists of (1) a base, (2) a lower part ($\sim 10^5$ km), which is termed a hemlet-like loop at the top of which there is often a cusp-shaped brightening and, at last, (3) an upper part strongly extended in a form of threads or a beam possibly reaching the Earth's orbit. It has been noticed that the axis of a coronal streamer is generally inclined to the solar equator (up to 60°), the inclination being larger in the period of solar cycle minimum. The inclination angle is affected by other large-scale magnetic structures that surround the streamer. All this can be well illustrated by the case under investigation, AR 8108, the larger streamer of which extends in the direction of another AR located in the southern hemisphere (Fig. 1).

marked pointed streamer

The properties of coronal streamers known from observations can be advantageously simulated. Model calculations show that the magnetic field of a streamer can be represented as a closed-type arch structure embeded in an opened field envelope. For a "quiet" streamer, these fields are separated by a thin current layer ~ 500 km thick, which narrows to 10 cm during a flare (Pneuman, 1972; Somov, 1992). According to the model, the plasma density of the coronal streamer is by an order of magnitude higher than the background values, while its temperature is lower than the background temperature ($\sim 1 \div 1.5 \cdot 10^6$ K).

The streamer is supposed to originate as a consequence of rise of hot plasma which "inflates a bubble" extending it upwards. This results in reconnection of the magnetic field and formation of a current layer (Schultz, 1994). Coronal streamers are considered to be responsible for the slow component of the solar wind and ejection of solar magnetic fields into the interplanetary space.

Observations of coronal streamers in the radio range were chiefly made at metre and decametre wavelengths (Lantos et al., 1987, 1992) with the Nancay and Clark Lake radio heliographs, i.e. the observations referred to the upper part of the streamers. In this range (metres–decametres) a spectrum of brightness temperatures has been obtained. The analysis of this spectrum within the frames of a thermal bremsstrahlung mechanism of emission has shown that the temperature inside the streamer is by 10–30 % higher than that outside. It has been found that radio outbursts of type III are observed near a cusp, which confirms the existence of a current layer inside the streamer. To explain the results of observations at long wavelengths, model calculations have been performed (Chiuderi-Drago, 1994) which show that the existing models of streamers need to be modified.

2. Description of AR 8108

The active region AR 8108 (heliolatitude 19.5° N, central meridian passage (CMP) 20.1 XI) was observed in the Carrington(?) revolution No.1929 and had an area of $\sim$ 300 ???. It was characterized by a complicated magnetic field structure at the photosphere level and was noted for considerable dynamics. In the leader(head?) part of the group of spots a delta configuration of the magnetic field was noted, which was particularly distinct on 17–21 XI. The magnetic field in the spots that constituted the delta configuration had an about twofold difference in intensity (1150 G of N polarity and 750 G of S on 19 XI). The trailer part of the group, in which the spots alternatively merged together (16 XI, 21–23 XI) and fragmented, was not stable either. In the interspot space emergence was in progress of a new magnetic flux coincident in magnetic field polarity with the field of the leader spot. At the photosphere level, formation of a new spot in the interspot space was recorded on 21 XI. On the images of AR 8108 in soft X-rays two coronal streamers located in orthogonal planes were visible during the entire observing period (Fig. 1). One of them had a vertical orientation, whereas the axis of the other was strongly inclined to the solar equator and extended in the S–E direction by more than 500 thousand kilometres. This huge streamer rested with one end on different polarity spots of the delta-configuration magnetic field near the leader spot. The brightest part of the X-ray loops at the base of the coronal streamer formed a narrow strip of $\sim$ 20 thousand kilometres in extent. In the previous revolution, No.1928, several CMEs (19 X, 1 XI (Dere et al., 1999), 23 X) were observed which coincided in location with the AR 8108 coordinates to an accuracy of 15–20°. In the next revolution, just before(?) the solar disk, the two streamers were observed in the AR. Proceeding from the law found by Sterling et al. (2000) these streamers can be assumed to be a consequence of halo-type CMEs. As has already been noted, weak flare activity is characteristic of the active region AR 8108. Only one flare (15 XI) reached an intensity of 1N. During the rest of the days weak flares of magnitude SF were recorded. This description is consistent with the characteristics of AR 8108 given in the papers by Canfield et al. (1999), Gibson et al. (1999), in which it is included in the list of 23 active regions of 1997 selected for studying the so-called sigmoid structures — precursors of CMEs (Rust, Kumar, 1996) observed in the soft X-rays and ultraviolet. The AR under investigation has also been observed with the radio telescope VLA (Willson, 1998).

RATAN-600 with

3. Observations and data processing

The observations of AR 8108 have been made at the radio telescope RATAN-600 with the aid of the Panoramic Analyzer of Spectrum (PAS) (Bogod et al., 1993) in the range 1.8–15.4 cm with a resolution of $15'' \times 13'5 - 131'' \times 101'$, respectively. Fig. 2 shows the brightness distributions in the intensity channel at the wavelength 3.21 cm during two days, 19 XI and 21 XI. The dashed curves present the division of the Local Source (LS) of radio emission into individual components using the Gauss analysis. From the RATAN-600 observations, details of three types have been isolated (1) details A, B and C — these are bright compact sources related to the major spots of the group, A and B are the leader and trailer spots, respectively, C is a new spot formed between them on 21 XI (Fig. 2); (2) detail H is the halo, an extended source of size of the whole AR that is associated with its magnetosphere, at the top of which emitting plasma is held; (3) detail X — a peculiar source that we identify with the bright part of the loops at the base of the coronal streamer, $\sim$ 20 thousand kilometres in extent.

4. Results of observations

The flux spectra, brightness temperatures and degree of polarization have been obtained for all the selected details. For three days, 19–21 XI, they have been averaged and are displayed in Fig. 3. ¿From these characteristics one can judge of the nature of each detail of the LS. The most obvious is the origin of detail A — this is acyclotron radiation of the coronal plasma in the strong magnetic field of the leader spot. This is evidenced by the detail size, $\approx 30''$, which is close to the size of the penumbra of the corresponding spot, as well as by the character of the spectra of fluxes with a peak at 5–7 cm. The degree of circular polarization of radiation from detail A was most likely higher than that measured at RATAN-600 ($\approx 30\,\%$). Its reduction is due to partial compensation of radiation from different-polarity sources above the delta-configuration of the leader spot in the beam of this instrument???. The brightness temperature of radiation of detail A was somewhat higher than typical coronal values, and it reached $3\cdot 10^6$ K at a wavelength of $\approx$ 7 cm, i.e. the presence of the magnetic field delta configuration was accompanied by additional heating of the atmosphere above it.

For detail B the bremsstrahlung radiation plays an important role, apart from the cyclotron radiation. The characteristic features of this detail: a great size, $\approx 60''$, a low brightness temperature as compared to that of detail A, growth of the degree of polarization with wavelength increase. The distinctions of detail B are due to the fact that, in contrast to detail A that is located above a large solar spot, detail B is a superposition of sources above minor spots and pores, distributed in the trailer part of the group of spots.

Detail C is interesting for its dynamics, since it is not common that one has an opportunity of tracing birth of a spot right on the disk. At the photosphere level the spot appears on 21 XI and then its area grows. Radio emission of the source becomes appreciable 24 hours earlier, however on the first day its radiation is nonpolarized. Next day there appears noticeable circular polarization, the intensity of radiation rising at the same time as well. It is noteworthy that the sign of polarization for detail C on 21 XI corresponds to excess of ordinary wave throughout the whole range 2–7 cm. A complex relationship between polarization and wavelength is noted on 22 XI: O-mode at 2 cm, E-mode at 3 cm, zero polarization at 4 cm, O-mode again at 7 cm. Most likely, this points to a complicated temperature distribution in the corona above the spot being formed . The influence of transversal magnetic fields (Bogod et al., 1993)is hardly the case since the polarization sign for details A and B in that period (21–22 XI) corresponded consistently to excess of an inordinary wave over the entire wavelength range.

In detail H (halo) as is often the case, a considerable part ($\approx 50\,\%$) of radiation from the AR was concentrated. By the character of the spectrum, the AR 8108 halo can be classified as typical (Peterova, 1994). The flux spectrum flat in short waves (to 3 cm) and with a slightly increasing slope at higher wavelengths is their distinguishing feature. The degree of polarization of detail H is insignificant ($< 5\,\%$), the brightness temperature of radiation ($3\cdot 10^5$ K at the wavelength 7 cm) is higher than normal for this type of LS components.

The radiation of detail X is characterized by a flat flux spectrum over the whole wavelength range (1.7–7 cm) and slight polarization ($< 5\,\%$). As to the contribution to the total flux of radio emission ($\approx$ 0.8 solar units of radio emission flux (s.f.u.)), it compared unfavourably with the rest of the details. However, in radio brightness it approached(resembled?) the brightest spotted detail A. The radio emission characteristics of detail X, namely, the flat flux spectrum, $F(\nu) = const$, as well as the quadratic rise of the radio brightness spectrum, $T_B \sim \lambda^2 (\lambda > 2\,\mathrm{cm})$, and the linear rise in degree of polarization with increasing wavelength $p \sim \lambda$, (15 cm$> \lambda >$2 cm) suggest that this was an optically thin in the cm range source

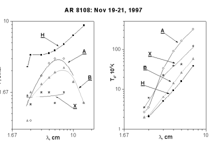

Figure 1: *Flux density and brightness temperature spectra of AR 8108 details. Details A and B identified with spots have spectra characteristic of cyclotron radiation with some addition of bremsstrahlung in the case of B. The spectrum of detail H is nonthermal, typical of halo. Detail X, identified with streamer, has a flat flux spectrum characteritic of thermal bremsstrahlung.*

of bremsstrahlung. Based on this assumption, estimate its parameters — plasma density N and magnetic field intensity B.

For thermal bremsstrahlung of an optically thin source of size Δs, being at a coronal temperature T and having a brightness temperature of radiation T_B at a frequency ν, we have the relation (Akhmedov et al., 1982):

$$T_B \approx 0.2 \times N^2 \times \Delta s \times \nu^{-2} \times T^{-1/2}. \qquad (1)$$

At $\Delta s = 2{\cdot}10^9$ cm, $T_B = 1.2{\cdot}10^6$ K, $\nu = 4.3{\cdot}10^9$ Hz ($\lambda = 7$ cm), $T = 2.0 \div 2.5 \cdot 10^6$ K, obtain $N = 7 \cdot 10^9$ cm^{-3}.

For the module of the magnetic field longitudinal component B_l of a source having at a wavelength λ a degree of circular polarization p, relation is (Gelfreikh, 1982):

$$B_l \approx 54. \times \lambda^{-1} \times p. \qquad (2)$$

At $\lambda = 4$ cm and $p = 4\%$ $B_l \sim 50$ Oe. Note that this magnetic field intensity has been derived for a height $h < 2 \cdot 10^9$ cm at the base of the coronal streamer.

The gas-kinetic–to–magnetic pressure ratio β in the source is

$$\beta \approx \frac{8\pi \times N \times k \times T}{B^2} \sim 0.02, \qquad (3)$$

(here $k = 1.38 \cdot 10^{-16}$ erg·degr^{-1} is Boltzman's constant).

The gas-kinetic–to–magnetic pressure ratio is not at variance with the values expected at these heights. It should be noted that to evaluate characteristic velocities of plasma motions in the inspected part of the streamer, one can possibly use the CDS (Coronal Diagnostic Spectrometer) data of the SOHO spacecraft.

In conclusion we provide an estimate of flare activity of AR 8108 and its activity as CMEs. The former two components of Tanaka–Enome's criterion have turned out be close to the cut-off values: (1) the density of the radio flux from the whole AR at 3 cm $F^I(3\,\text{cm}) \sim 7$ s.f.u. (which is a little less than the limiting value, 10 s.f.u.); (2) the flux ratio $F^I(3\text{ cm})/F^I(10\text{ cm}) = 0.7$ (i.e. ~ 1). A forecast derived from the third criterion would be negative: the AR 8108 image in polarized light at 3 cm had an S-shape, which is far from the flare-expected P-shape. As a whole, one may consider Tanaka–Enome's criterion to be justified in this case — AR 8108 did not actually produce intense flares. However, care should be used to draw this conclusion, allowing for the closeness of two components of the criterion to the limiting values. The activity in the form of CMEs was also weak. According to Canfield (2000) the erruptive growth of the coronal loop system in AR 8108 (19 XI at 21:54 UT) turned out inadequate to destroy even only one of the two streamers; on the contrary, their soft X-ray radiation became more contrasty.

5. Discussion of results

The basic peculiarity of AR 8108 that requires explanation is its weak activity, which is at variance with the magnetic field structure (a clearly defined delta configuration) and the vigorous dynamics of development of this active region (emergence of a new magnetic flux).

According to van Driel-Gesztelyi et al. (1999), Green et al. (2000), the intensity and duration of flares drop when major CME events are present. However, in the case in question, both kinds of activity were faint. Our investigation has shown that additional heating of the coronal plasma occurred in this AR. The duration (days) of this process was much longer than that of flares or CME (minutes or hours), while the intensity, on the contrary, was much at a disadvantage in relation to them. Indeed, as can be seen from the results of observations, the active region under investigation was of enhanced (as compared to the statistical average) radiation brightness. Apparently, the enhanced brightness is indicative of the presence of a certain amount of high-temperature plasma preserved for a long time comparable with that of existence of the AR itself. This additional heating showed itself in both the low corona, in the region of strong magnetic fields (nuclear component of the LS), and high up in the corona at the top of the magnetosphere (halo of the LS). Besides, in the structure of the LS there was detected a long-lived (> 4 days) bright source identified with the lower part of one of the streamers. The appearance of the streamer from the X-ray observations strongly resembled that of the postflare streamers: in that period, a brightening was noted over the entire surface (or its individual parts) that separated the opened and closed field of the streamer.

An evident source heating the coronal plasma above AR 8108 was the delta-configuration of the magnetic field — it is exactly from there that the brightest irradiation of the streamer comes. Physical conditions in the AR were such that excess energy of the complex (non-potential) magnetic field was released not as an explosion, but in a gradual manner. It can be assumed that slow (as compared to flares or CMEs) outflow of accumulated energy occurred through the two coronal streamers, which maintains their post-flare appearance for several days.

Peculiar details of the LS structure similar to detail X represent a comparatively new class of objects. This name was introduced in the paper by Vatrushin, Korzhavin (1989) and stuck to the objects, which would be more correctly termed as unidentified. Part of them were identified with bent portions of the neutral line of the total magnetic field of flare-active ARs above which arcades of low coronal loops containing heated (up to 10^7 K) plasma are hypothetically located. The radiation of these objects was interpreted as synchrotron at gyrofrequency harmonics (Akhmedov et al., 1987, Peterova et al., 1997). The peculiar source that we have detected in the structure of the weakly active AR 8108 has a different identification. It is related genetically to a very intense coronal loop having an open-configuration magnetic field. Despite the fact that the nature of this object (thermal bremsstrahlung) is different from that of the peculiar details mentioned above, the conclusion made by other authors that the presence of peculiar details in the LS structure is an indication of enhanced energy release in the AR is generally corroborated. The result obtained in the studies of AR 8108 allows a preliminary inference to be made that from the parameters of the peculiar details in the given AR one can suggest what path will be followed by the events in the given active region. If the radiation of the peculiar sources is characterized by a steep flux spectrum (synchrotron radiation, explosive events (in the form of flare) are then to be expected. If the peculiar source has a flat spectrum (thermal bremsstrahlung), the activity will proceed in a much slower manner, in the form that can be termed a sluggish flare.

Acknowledgements. The authors thank V.M. Bogod for useful discussion. The work was supported through grants of INTAS RFBR 97-1088, RFBR 99-02-16403, Latvian Council on Science 96.129, and also grant No.181 "INTAS CALL 2000".

References

Akhmedov Sh.B., Bogod V.M., Borovik V.N., Wilson R.F., Gel'freikh G.B., Dikij V.N., Korzhavin A.N., Lang K.R., Petrov Z.E., 1987, Astrofiz. Issled. (Izv.SAO), **25**, 105

Bogod V.M., Abramov-Maksimov V.E., Dikij V.N., Vatrushin S.M., Tsvetkov S.V., 1993, Preprint SAO No.84, St.-Petersburg

Bogod V.M., Gelfreikh G.B., Ryabov B.I., Hafizov S.R., in: ASP Conference Series, 1993, **46**, 302

Gel'freikh G.B., 1982, in: Dinamika tokovykh slojov i fizika solnechnoj aktivnosti, 1982, Riga, "Znanie", 116

Peterova N.G., Golovko A.A., Stojanova M.N., 1997, Astron. Zh., **74**, No.3, 466

Canfield R.C., 2000 (private communication with Gibson S.E.: Internet http://www.damtp.cam.ac.uk/user/sg273/AR8108/ar8108.html)

Canfield R.C., Hudson H.S., McKenzie D.E., 1999, Geophys. Res. Letters, **26**, No.6, 627

Cheng C.-C. and SXT/Yohkoh Team, 1994, in Space Sience Reviews, **70**, 273

Chiuderi-Drago F., 1994, Space Science Reviews, **70**, 279

Dere K.P., Brueckner G.E., Hovard R.A., Michels D.J., Delaboudininiere J.P., 1999, Astrophys. J., **516**, 465

Gibson S.E., Mason H.E., Pike C.D., Young P.R., 1999, in: Proceed. of the 8th SOHO Workshop, ESA publications

Green L.M., Harra L.K., Matthews S.A., Culhane J.L., 2000, Solar Phys. (submitted)

Kobrin M.M., Korshunov A.I., Arbusov S.I., Pakhomov V.V., Fridman V.M. and Tikhomirov Yu.V., 1978, Solar Phys., **56**, 359

Korobchuk O.V., Peterova N.G., 1980, in: Prognozirovanie solnechnykh vspyshek i ikh posledstvij (ser. Radioizluchenie Solntsa, vyp.5, LSU Press, L., 102

Koutchmy S., Livshits M., 1992, Space Sci. Rev., **61**, 393

Lantos P., Alissandrakis C.E., Gergely T., Kundu M.R., 1987, Solar Phys., **112**, 325

Lantos P., Alissandrakis C.E., Rigaud D., 1992, Solar Phys., **137**, 225

Martin Sara F., 1980, Solar Phys., **68**, 217

Moreton G.E., Severny A.B., 1968, Solar Phys., **3**, 282

Peterova N.G., 1994, Bull. Spec. Astrophys. Obs., **38**, 133

Pneuman G.W., 1972, Solar Phys., **23**, 223

Rust D.M., Kumar A., 1996, Astrophys. J., **464**, 199

Schultz C.G., 1994, Space Sci. Rev., **70**, 233

Somov B.V., Physical Processes in Solar Flares, 1992, Kluwer Academic Publ., Dordrecht, London

Sterling A.S., Hudson H.S., Thompson B.J., Zarro D.M., 2000, Astrophys. J., **532**, 628

Tanaka H., Enome S., 1975, Solar Phys., **40**, 123

Tanaka H., Kakinuma T., 1964, Rep. Ionosph. Space Res. Japan, **18**, 32

van Driel-Gesztelyi L., Mandrini C.H., Thompson B., Plunkett S., Aulanier G., Dimoulin P., Schmieder B., de Forest C., 1999, in: 3rd Advances in Solar Physics Euroconference: Magnetic Fields and Oscillations, ASP Conf. Series, **184**, 302

Vatrushin S.M., Korzhavin A.N., 1989, in: Fizika solnechnoj plazmy, M., "Nauka", 100

Willson R.F., 1998, in: Proceed. of an International Meeting, Guadeloupe, France, 23-26 Feb., Publ.Paris, ESA SP-421, 349.