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VARIATIONS IN FRACTAL CHARACTERISTICS OF A SOLAR PROTON EVENT

This joint research work is devoted to quantitative radio diagnostics of flare and proton events based on their radio bursts near the end of the 24th solar activity cycle. Observations were carried out on the 12 – meter radio telescope of the Institute of Ionosphere of the Republic of Kazakhstan at frequencies f=1 and f=3 GHz. Studies have shown that three flare events: B 6.2/~X 2.4, 01.09.2014; M 2.7, 21.06.2015 and M 7.9, 25.06.2015, fully meet the proton criteria. The intersection point of radio emissions of dual-frequency (1 and 3 GHz) solar proton events determines the zero time of the beginning of their pulses and gradual phases. In the first – pulse phase, electrons predominate, and in the second – the phase of gradual increase in the number of protons. The acceleration of electrons in the "first" phase during solar flares is 4-8 min.; the acceleration of electrons and protons in the "second" phase varies in the range of 10-46 min. The time-intensity profiles we built and the values of the Herest index we found allow us to follow the dynamics of the combustion events we studied. This allows us to evaluate the habituation events both qualitatively and quantitatively.

Thus, the values of radio data obtained as a result of applying the method to these three proton events quite correctly reflect phenomena that differ from each other in their characteristics, both in the scale of observation and in the energy of the spectra.

Key words: radio emission – solar electron and proton events – solar flares – radio diagnostics.

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Күн протон оқиғасының фракталдық сипаттамаларының өзгеруі

Бұл бірлескен зерттеу жұмысы күн белсенділігінің 24-ші циклінің соңындағы радиожарылулар негізінде алау мен протон оқиғаларының сандық радиодиагностикасына арналған. Бақылау Қазақстан Республикасының Ионосфера институтының 12 метрлік радиотелескопында f=1 және f=3 ГГц жиіліктерінде жүргізілді. Зерттеулер көрсеткендей, үш алау оқиғасы: B 6.2/~X 2.4, 09.01.2014; M 2.7, 21.06.2015 және M 7.9, 25.06.2015, протон критерийлеріне толық сәйкес келеді. Қос жиілікті (1 және 3 ГГц) күн протонының оқиғаларының радиосәулеленуінің қиылысу нүктесі олардың импульстерінің және біртіндеп фазаларының басталуының нөлдік уақытын анықтайды. Біріншісінде – импульстік фазада электрондар басым, ал екіншісінде – протондар санының біртіндеп көбею фазасы. Күннің жарылуы кезінде «бірінші» фазадағы электрондардың үдеуі 4-8 мин.; электрондар мен протондардың «екінші» фазадағы үдеуі 10-46 мин аралығында өзгереді. Біз жасаған уақыт қарқындылығы профильдері және біз тапқан Герест индексінің мәндері біз зерттеген жану оқиғаларының динамикасын қадағалауға мүмкіндік береді. Бұл бізге дағдылану оқиғаларын сапалық және сандық тұрғыдан бағалауға мүмкіндік береді.

Осылайша, радиомәліметтердің мәндері осы үш протон оқиғасына әдісті қолдану нәтижесінде бақылау масштабында да, спектрдің энергиясында да бір-бірінен сипаттамалары бойынша ерекшеленетін құбылыстарды өте дұрыс көрсетеді.

Түйін сөздер: радиосәулелену – күн электроны және протондық құбылыстар – күн алаулары – радиодиагностика.

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Вариации фрактальных характеристик солнечного протонного события

Совместная исследовательская работа посвящена количественной радиодиагностике вспышечных и протонных событий по их радиовсплескам вблизи конца 24-го цикла солнечной активности. Наблюдения проводились на 12-метровом радиотелескопе Института ионосферы Республики Казахстан на частотах f=1 и f=3 ГГц. Исследования показали, что три вспышки: B 6.2/~X 2.4, 01.09.2014 г.; M 2.7 от 21.06.2015 и M 7.9 от 25.06.2015 полностью соответствуют протонным критериям. Точка пересечения радиоизлучений двухчастотных (1 и 3 ГГц) солнечных протонных событий определяет нулевое время начала их импульсов и постепенных фаз. В первой – импульсной фазе преобладают электроны, а во второй – фаза постепенного увеличения числа протонов. Ускорение электронов на «первой» фазе во время солнечных вспышек составляет 4-8 мин.; ускорение электронов и протонов на «второй» фазе варьируется в пределах 10-46 мин. Построенные нами временные профили и найденные значения индекса Хереста позволяют проследить за динамикой изученных нами событий горения. Это позволяет оценить события привыкания как качественно, так и количественно.

Таким образом, значения радиоданных, полученных в результате применения метода к этим трем протонным событиям, вполне правильно отражают явления, отличающиеся друг от друга по своим характеристикам, как по масштабу наблюдения, так и по энергии спектров.

Ключевые слова: радиоизлучение – солнечные электронные и протонные события – солнечные вспышки – радиодиагностика.

Introduction

For more than 60 years, specialists have been arguing heatedly about the formation and diagnosis of proton events in the Sun. Information dedicated to the mentioned problem is reflected chronologically [1,2]. Recently, revolutionary advances have been made in the field of means and methods for radio diagnostics of solar flares. These achievements remain relevant in the creation of broadband (~10 MHz ÷ 100 GHz) radio spectrographs, radio heliographs, as well as through the development of software systems for high-speed calculation of observational data obtained in the microwave range.

The interaction of accelerated particles with the Sun's atmosphere and its magnetic fields results in radio, hard X-rays and gamma rays, which are used to diagnose solar flares [3].

Among the issues of observation in the microwave diapason – the correct selection of the signs of prognostic-diagnostic parameters during the generation of strong solar flares, excitation by shock waves, and the presence of accelerated electrons and protons in interplanetary space occupy an important place. Multi-wavelength observations provide extensive information about the quiet solar atmosphere and various processes occurring in it.

At the same time, their mutual comparison with observations made in other ranges allows researchers to understand the various processes occurring in the Sun and to obtain invaluable conclusions about their effects on the Earth's environment. Starting from [4, 5], there is evidence that the flare can be divided into two phases, apparently, different acceleration mechanisms operate.

The diagnosis of solar flares is studied mainly on the basis of observational data carried out in 3 areas: a) solar cosmic ray (SCR) [6, 7]; b) microwave radiation [8, 9]; c) measurements outside the atmosphere [10, 11]. Until now, the prognostic and diagnostic potential of radio observations of the Sun has not been fully exploited due to the lack of radio heliographs with high temporal, spatial and spectral resolution [12].

The advantage of studying solar activity in the radio range lies mainly in the following facts:

1. The Earth's atmosphere has less influence on the signal we receive;

2. Observation in the range 1 ÷ 3 GHz, it is possible to obtain information from the solar chromosphere layer to the upper layers of the corona;

3. Observing in a very wide range of 3 ÷ 24 GHz allows one to localize various structures in the solar atmosphere, including active regions, filaments and coronal holes;

4. The production of radio telescopes is cost-effective compared to extra-atmospheric observation technologies and optical devices, and others.

In the interplanetary medium, powerful flare events are considered effective candidates for sources of solar protons and electrons. Space weather disturbances caused by solar activity can pose a threat to various sectors of human activity and human health.

In this work, the main goal is to find out which parameters of solar eruptive events and SPEs have the highest correlation.

Thus, in order to increase the efficiency of diagnosis of strong proton events occurring in the Sun, we used their observational data obtained in different (λ=10.7 and 27.8 cm) microwave ranges and fractal dimension values [13, 14]. The method we use is based on the parameters of the intensity of solar flares at frequencies f=1÷3 GHz and the dynamics of the fractal structure H_t. It also reflects the number of accelerated particles arriving at the Earth, as well as the number of protons with energy E≥10 MeV. In other words, the observed proton flux is usually characterized by an $I(\geq E) \sim E^{-\alpha}$ (here α ~1÷4) power-law energy spectrum [8, 13].

In the 1st section, the relevance of radio diagnostics of the ignition events occurring in the Sun in the microwave range, and in the 2nd section, the preparation of observational data and their mathematical processing are reflected. In the 3rd section, the relationships between various parameters of solar flares (power of the intensity stream, heliowaves in which they occur, configuration of spot regions and duration of flares) and the growth of the proton stream were discussed. Section 4 describes the main scientific results.

Experimental data and its processing

Processing of observational data was carried out using both fractal analysis and direct viewing of signal recordings. As observational material, we used 7-isolated solar bursts observed in 2014÷2020 on the RT-12 radio telescope in Ionosphere Institute of Kazakhstan Republic. Figure 1(1a,1b,1c,1d,1e,1f,1j) shows the time profiles of flare events at f=3 GHz for the indicated years. Discretization step Δt=5 sec. Based on the time profiles carried out in the work, it is clear that the signal records have a maximum with a high confidence probability (more than 90%) at periods of 20÷350 seconds, which, however, vary significantly from implementation to implementation.

If we visually look at the time profiles of intensity (Fig. 1(1a,1b,1c,1d,1e,1f,1j)), compiled by us based on flare events in different years on the Sun, we can note the following similarities and differences:

I. General images of time profiles of solar flare intensity differ from each other.

II. Pulsations with different periods and drifts are present in all solar flare profiles and in all phases (rise, maximum and decay).

III. Pulsations with shorter periods and drifts are mainly detected in the increasing phases of solar flares.

IV. The decay phases are dominated by pulsations with long periods and drifts (compared to the rise and maximum phases) of the 7 solar flares studied.

In Fig. 2(2a, 2b, 2c), shown the time profiles of the intensity of three strong proton events, which we constructed at two frequencies (f = 1 and 3 GHz) consisting of a pulsed and gradual phase. The time between the sharp approach or intersection of intensity lines reflecting their dynamics from the starting point t_0 of each proton event indicates the duration of the $t_{imp.}$ – impulse phase. The time from the intersection of intensity lines to the end of proton events characterizes the duration of the $t_{grad.}$ – gradual phase.

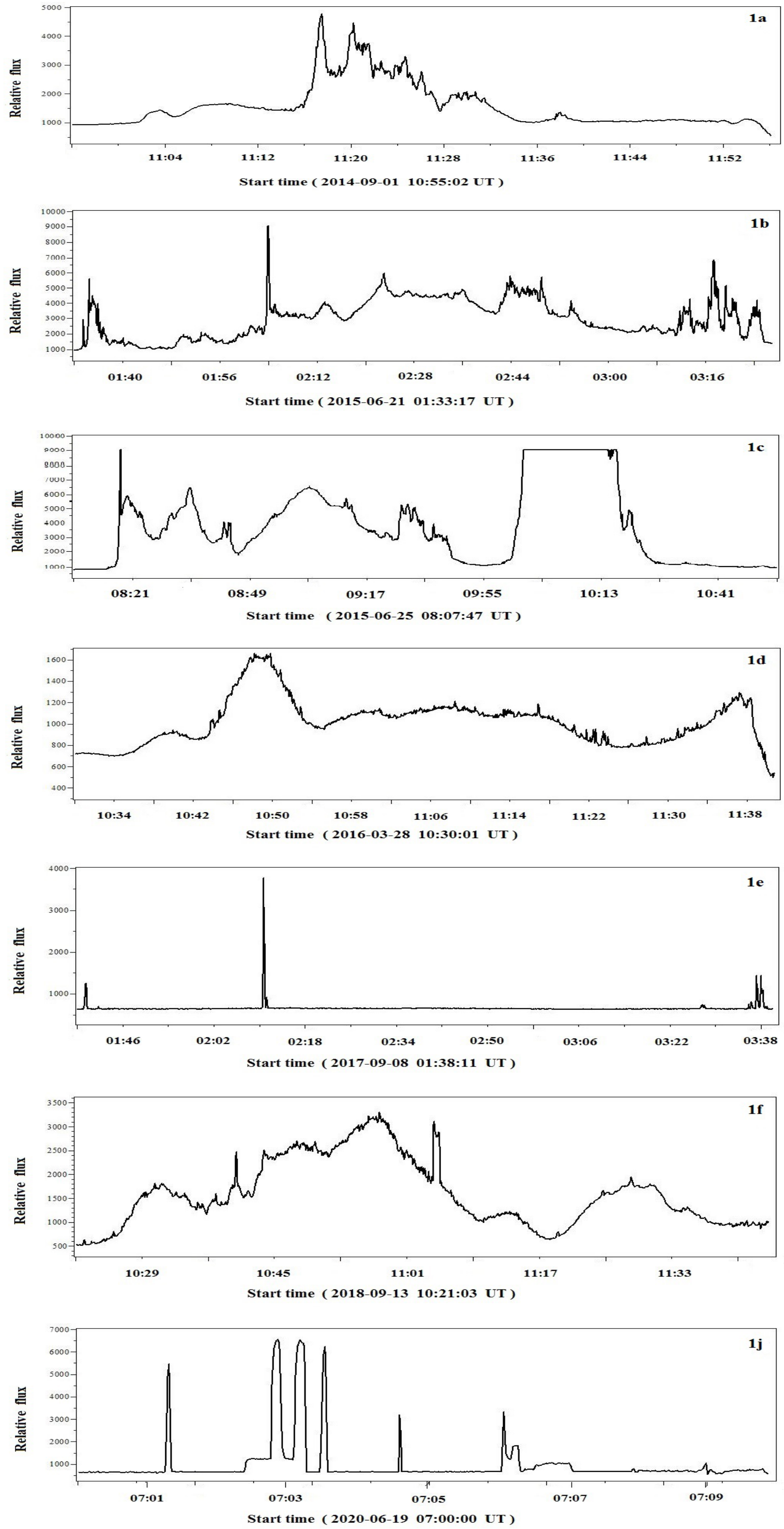

Figure 1 – Time profiles: 7-solar flares observed in 2014÷2020 on RT-12 in the microwave range λ=10.7 cm in Ionosphere Institute of Kazakhstan Republic

Table 1 – The estimates of the Herest exponent and the degree of the fractal dimension

Date (at the time of events)	Herest exponent H_t	Fractal dimension D_t
01.09.2014 (10:55:02 – 11:57:42 UT)	0.792	1.207
21.06.2015 (01:33:17 – 03:33:18 UT)	0.812	1.187
25.06.2015 (08:07:47 – 10:58:19 UT)	0.771	1.228
28.03.2016 (10:30:01 – 11:43:47 UT)	0.787	1.212
08.09.2017 (01:38:11 – 03:45:22 UT)	0.583	1.416
13.09.2018 (10:21:03 – 11:47:25 UT)	0.810	1.189
19.06.2020 (07:00:00 – 07:09:49 UT)	0.687	1.312

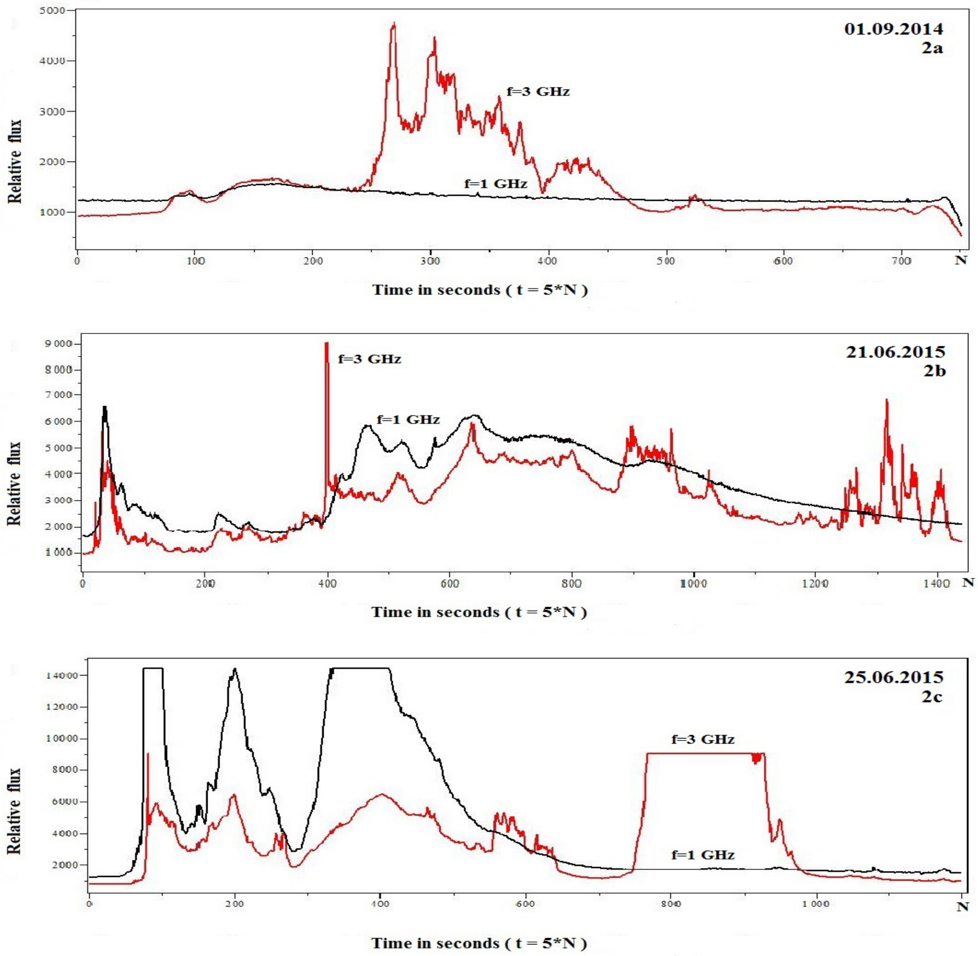

Figure 2 – Time profiles: 3 solar proton events observed simultaneously by the RT-12 radio telescope at frequencies f = 1 and 3 GHz.

Table 2 – Shown are estimates of the Heresty index and the degree of Fractal dimension of solar proton events observed simultaneously by the RT-12 radio telescope at frequencies f=1 and 3 GHz

Date (proton event time)	Herest exponent H_t		Fractal dimension D_t	
	f = 3 ГГц	f = 1 ГГц	f = 3 ГГц	f = 1 ГГц
01.09.2014 (10:55:02 – 11:57:42 UT)	0.792	0.779	1.207	1.200
21.06.2015 (01:33:17 – 03:33:18 UT)	0.812	0.834	1.187	1.165
25.06.2015 (08:07:47 – 10:58:19 UT)	0.771	0.818	1.228	1.181

Discussion

Using Yu. I. Logachev's catalog data for 2011÷2020 solar activity, the dependence of the measured increases in solar microwave radiation on disturbances on the Sun was studied. It is shown that the efficiency of recording on Earth increases in microwave radiation caused by the acceleration of protons in the chromosphere and corona depends on the power of the solar flare and its position on the solar disk.

According to this catalog, there are 54 proton events with a quasi-maximal energy of $80 < E_{qt} < 5000$ MeV in the 24th cycle of solar activity in 2010÷2017 [15]. Of these proton events, 40 (~76%) occur in and around sunspot regions located at favorable solar longitudes of 40–88° W. The main reason for this is that proton transport at other heliolongitudes occurs transversely to the magnetic field lines, which makes it difficult to increase the microwave flux in interplanetary space and the solar corona.

In this work, the fractal research method is based on the idea that the development of turbulence associated with flare events in the solar atmosphere demonstrates self-similarity at different scales. A higher Hurst exponent means that the data is more stable and has long-term dependency. Based on this tables, it can be seen that is the H_t – Herest exponent and D_t - degree of the Fractal dimension, respectively equal to $0.5 < H_t \leq 1$ and $1 < D_t < 1.5$. These estimates obtained show that, chaoticity is replaced by smoother chaoticity during solar flares. More precisely, chaoticity turns into non-stationary quasi-periodic beats [13]. In Table 1, it can be seen that most of the ignitions we studied have a higher value of the H_t – Hurst indicator.

The diversity of the number of pulses in the impulsive and gradual phases of these plots varies depending on the dynamics of the proton event and the resolution of the radio telescope. In other words, the number of pulses depends on the number of events occurring simultaneously in the spots and in the general areas of the spots and in the immediate vicinity of them.

Conclusions

Based on the above, the following main conclusions can be drawn:

1. The intensity and time profiles we have constructed for numerous solar flares and proton events allow us to trace the dynamics of events (pulse – the "first" phase and gradual – the "second" phase).
2. The point of intersection of radio emissions of dual-frequency (1 and 3 GHz) solar proton events determines the zero times of the beginning of their pulse and gradual phases. The study of proton events has shown that for a more accurate determination of zero phase onset times, it is more expedient to use radio spectrographic and radio heliographic measurements in a wide range of 0.05÷150 GHz.
3. The acceleration of electrons in the "first" phase during solar flares is 2 ÷ 6 minutes; the acceleration of electrons and protons in the "second" phase varies in the range of 8 ÷ 35 min.
4. It is shown that the increase in the number of protons depends on the flow power, the duration of microwave flares and the heliolongitude at which the event occurs.
5. The results of the study showed that for proton events the criterion is fulfilled – $F_{10.7} / F_{27.8} > 0.8$, similar to the Tanaka-Enome criterion – $F_3 / F_8 > 0.8$. The effectiveness of this criterion depends on the intensity of the 11-year cycle of solar activity and the intensity of its next cycle.

Thus, the values of radio data obtained as a result of applying the method to these three proton events quite correctly reflect phenomena that differ from each other in their characteristics, both in the scale of observation and in the energy of the spectra.

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