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Peculiarities of Long-Wave Radio Bursts from Solar Flares Preceding Strong Geomagnetic Storms

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Abstract—Radio bursts in the frequency range of 100–1500 kHz, recorded in 1997–2000 on the *INTERBALL-1* satellite during the solar flares preceding the strong geomagnetic storms with $D_{st} < -100$ nT, are analyzed in this paper. The observed long-wave III-type radio bursts of solar origin at frequencies of 1460 and 780 kHz were characterized by large values of the flux $S_f = 10^{-15}$–10^{-17} W/m^2 Hz and duration longer than 10 min. The rapid frequency drift of a modulated radio burst continued up to a frequency of 250 kHz, which testified that the exciting agent (a beam of energetic electrons) propagated from the Sun to the Earth. All such flares were characterized by the appearance of halo coronal mass ejections, observed by the LASCO/*SOHO*, and by the presence of a southward B_z-component of the IMF, measured on the *ACE* and *WIND* spacecraft. In addition, shortly after radio bursts, the *INTERBALL-1* satellite has recorded the fluxes of energetic electrons with $E > 40$ keV.

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INTRODUCTION

The study of active solar phenomena preceding strong magnetospheric disturbances is of great theoretical and practical interest. Numerous investigations are devoted to the analysis of geoeffectiveness of solar events, and various aspects of solar-terrestrial links are studied in them. The issues of origin, development, and forecasting of geomagnetic storms were discussed in detail in many publications (see, for example, reviews [1–5] and references therein).

In situ measurements in the interplanetary medium have shown that geomagnetic storms are mainly associated with the interplanetary magnetic field (IMF) oriented in the southern direction, i.e., with $B_z < 0$ [6, 7]. In the conventional quasistationary solar wind the magnetic field vector is located in the ecliptic plane, and such a wind does not contain any considerable and durable B_z-component of the IMF that would be sufficient for exciting a magnetic storm. And only some disturbed types of solar wind streams, first of all such as magnetic clouds (MC) and interplanetary coronal mass ejections (ICME), being a continuation of coronal mass ejections (CME) on the Sun into the interplanetary medium, as well as the CIR (Corotating Interaction Region—compression regions at the boundary of slow and fast solar wind stream from a coronal hole), can contain a large and durable B_z-component of the IMF, including that of southern orientation, which results in the magnetic storm development [8–15]. We do not consider here the data of CIR-related observations and analyze only the sequence of events: CME – magnetic cloud – geomagnetic storm. This issue is quite important from the viewpoint of geoeffectiveness of solar events, and it is widely discussed in the literature.

A good correlation between the flares and CMEs is observed for strong solar flares [16]. The geoeffectiveness of CMEs directed to the Earth is studied in detail in a number of publications [see 1–3, 9, 14, 17]. In particular, in paper [18] it is specially emphasized that the magnetic storm intensity depends on the presence of a fast halo coronal transient, as well as on the presence of a southward component $B_z < 0$, as it was already mentioned above. In addition, it was noticed that CMEs, accompanied by the type II bursts, may occur to be geoeffective [19].

However, as statistical investigations have shown, the geoeffectiveness of events, i.e., their correlation with magnetic storms is low and does not exceed 50% both for solar flares and for halo coronal mass ejections (see [9, 14, 20, 21]). By this reason, some authors consider additional parameters, which, being taken into account, would allow them to improve forecasts of geomagnetic storms.

For improving the forecasts of geomagnetic storms, it was proposed to take into account, along with the solar wind properties and halo coronal transient, also the flux of solar protons with $E > 10$ MeV; in this case the probability of appearance of a strong geomagnetic storm increases up to 85% [22].

In papers [9, 23] it was also stated that additional accounting for arrival of energetic protons to the Earth increases the forecasting reliability and can be used as a magnetic storm precursor.

From the prognostic viewpoint, of interest is the conclusion that the enhancement of a flux of energetic ions (protons), observed at the libration point L_1 by the EPAM/*ACE* in the solar wind, can also be a precursor of a geomagnetic storm some hours prior to its onset [24].

The disturbances in the interplanetary medium, propagating toward the Earth, are known to be determined by solar flares. As a rule, the strong geomagnetic storms are related with chromospheric flares which are characterized by high energy release in various energy ranges, judging by the fluxes of X-ray, microwave, and optical radiation, as well as by the fluxes of energetic particles.

In studying the geoeffectiveness of solar flares, of especial interest are the long-wave radio bursts of solar origin. The electrons with energy $E > 40$–60 keV, accelerated in the expansion phase of a flare, are known to propagate along the open magnetic field lines and to generate, at the plasma frequency, bursts of hectometric radio emission in the interplanetary medium at distances from $r > 8\ R_s$ (R_s is the radius of the Sun) up to the Earth's orbit [25].

The analysis of results of observation of hectometric radio bursts over a long period is presented in a series of papers (see, e.g., [26]).

In particular, the properties of hectometric type III radio bursts and their interrelation with solar electron events are discussed in review [27].

The fluxes of energetic particles generating radio emission are known to propagate along the IMF lines over the Parker spiral. They are observed near the Earth with a delay of a few tens of minutes relative to the main phase of a flare, while the solar plasma flows in the solar wind which cause the geomagnetic storm development propagate with CME, MC, and shock wave in almost radial direction and come to the Earth for a time of 2–5 days. Therefore, it seems important to analyze the hectometric radio bursts, observed near the Earth, as possible precursors of geomagnetic storms.

The purpose of our investigation is to study the peculiarities of long-wave radio bursts observed by satellites from the viewpoint of geoeffectiveness of solar flares.

ANALYSIS OF OBSERVATIONAL DATA

We have studied radio bursts in the frequency range of 100–1500 kHz, recorded on the *INTERBALL-1* satellite during strong solar flares in 1997–2000. Observations of radio emission were carried out by means of the multichannel AKR-X radiometer in the frequency channels of 1501, 1463, 749, 500, 252, and 100 kHz. The sensitivity threshold of a receiver corresponded to the flux $S_f = 10^{-19}$ W/m^2 Hz. The most powerful bursts had amplitudes of about 10^{-15} to -10^{-16} W/m^2 Hz. Some examples of most typical radio bursts were presented in [28].

In this work we have analyzed the type III radio bursts, which were characterized by fast drift in frequency. For illustration, the figure presents as an example the time profiles of type III bursts for the events of July 14, 2000 (a) and of May 3, 1998 (b).

The flux amplitude at all frequencies was modulated with the period $T = 120$ s, which was stipulated by changing orientation of the instrument because of satellite rotation relative to its axis directed to the Sun. The presence of modulation for type III bursts implies that the radio emission source has finite dimensions, being displaced with the drift velocity, and, consequently, it reflects the motion of a disturbing agent (a beam of energetic electrons) that generates the radio burst in the interplanetary medium. It is characteristic that for the majority of bursts the amplitude modulation is observed down to 252 kHz, and it is important to note that energetic electrons were recorded in all these events.

From all recorded bursts we have selected the most powerful in amplitude and longest in time; and these bursts were juxtaposed with solar flares. As a rule, these bursts were identified with the flares of importance X and M located predominantly to the west of the central meridian.

Further, with the purpose of revealing the peculiarities of long-wave radio bursts during geoeffective flares, we separated the events on the Sun preceding the development of powerful geomagnetic storms. We have selected geomagnetic storms with the values of parameter D_{st} from –67 nT to –320 nT. Such strong storms are known to be rather rarely observed and constitute about 7% of the total number of geomagnetic storms [9].

The list of events we have analyzed is presented in the Table. It contains the data about the long-wave radio bursts observed on the *INTERBALL-1* satellite. The data for chromospheric flares were taken from (http://www.sec.noaa.gov/ftpdir/indices). In addition, the table marks the facts of observation of coronal transients on the LASCO/*SOHO* (http://cdaw.gsfc.nasa.gov/CME_list) and hectometric type II + IV radio bursts recorded by the WAVE/*WIND* in the frequency range of 1–16 MHz (http://lep694.gsfc.nasa.gov/waves/waves.html) (+).

The Table indicates also the events with energetic electrons according to the data of EPAM/*ACE* (http://sd-www.jhuapl.edu/ACE/EPAM), 3PD/*WIND* (http://sprg.ssl.berkley,edu/~krucker/electron_event_list_short.html), and DOK/*INTERBALL-1*.

Finally, the table contains the data on the properties of the geomagnetic storms related to analyzed events. The storm observation dates, the minimum values of D_{st} index (http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/dstl/f/fds.html), and the maximum values of index A_p (http://www.sel.noaa.gov/ftpdir/indices/old_indices/) are tabulated. In addition, the values of the southward B_z-com-

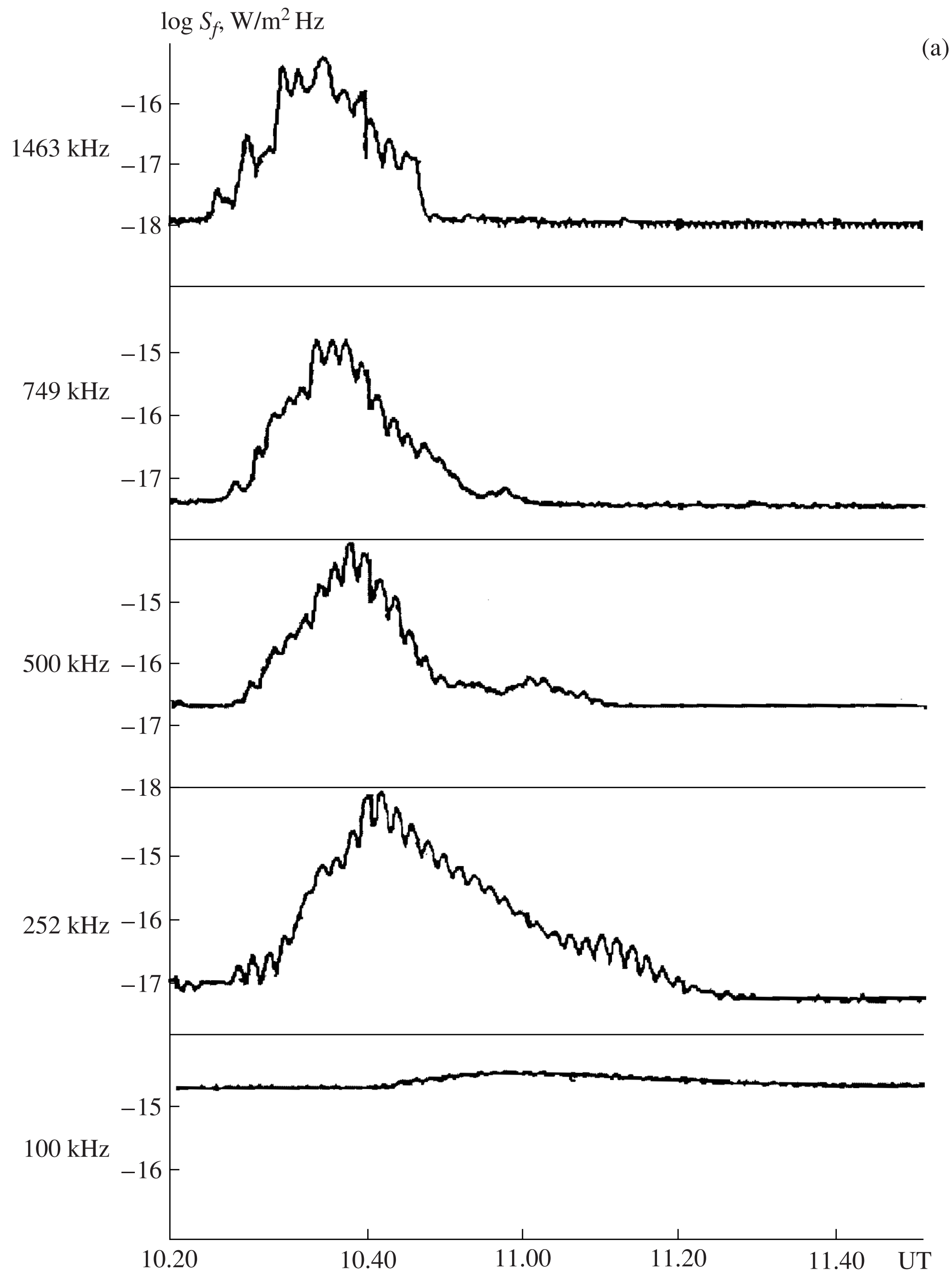

Figure.

ponent are presented for each storm. The majority of the events included in the Table is discussed in connection with comprehensive studying the solar-terrestrial links during some special active periods (see http://pwg.gsfc.nasa.gov/ istp/event/).

RESULTS OF DATA ANALYSIS

It follows from the analysis of hectometric radio bursts presented in the Table that all, without exception, bursts in the range of 100–1500 kHz, which preceded strong geomagnetic storms, were associated with strong chromospheric flares. Judging by the active phenomena in various ranges, including X-ray, microwave, and optical radiation, as well as fluxes of energetic particles, these flares were characterized by high energy release. In addition, the flares were accompanied by halo coronal transients and by magnetic clouds (IN). It should be noted that the active regions, in which the flares were developed, possessed complicated magnetic field structure, which is typical for flare-active regions, and were located in the range of longitudes from 26 E

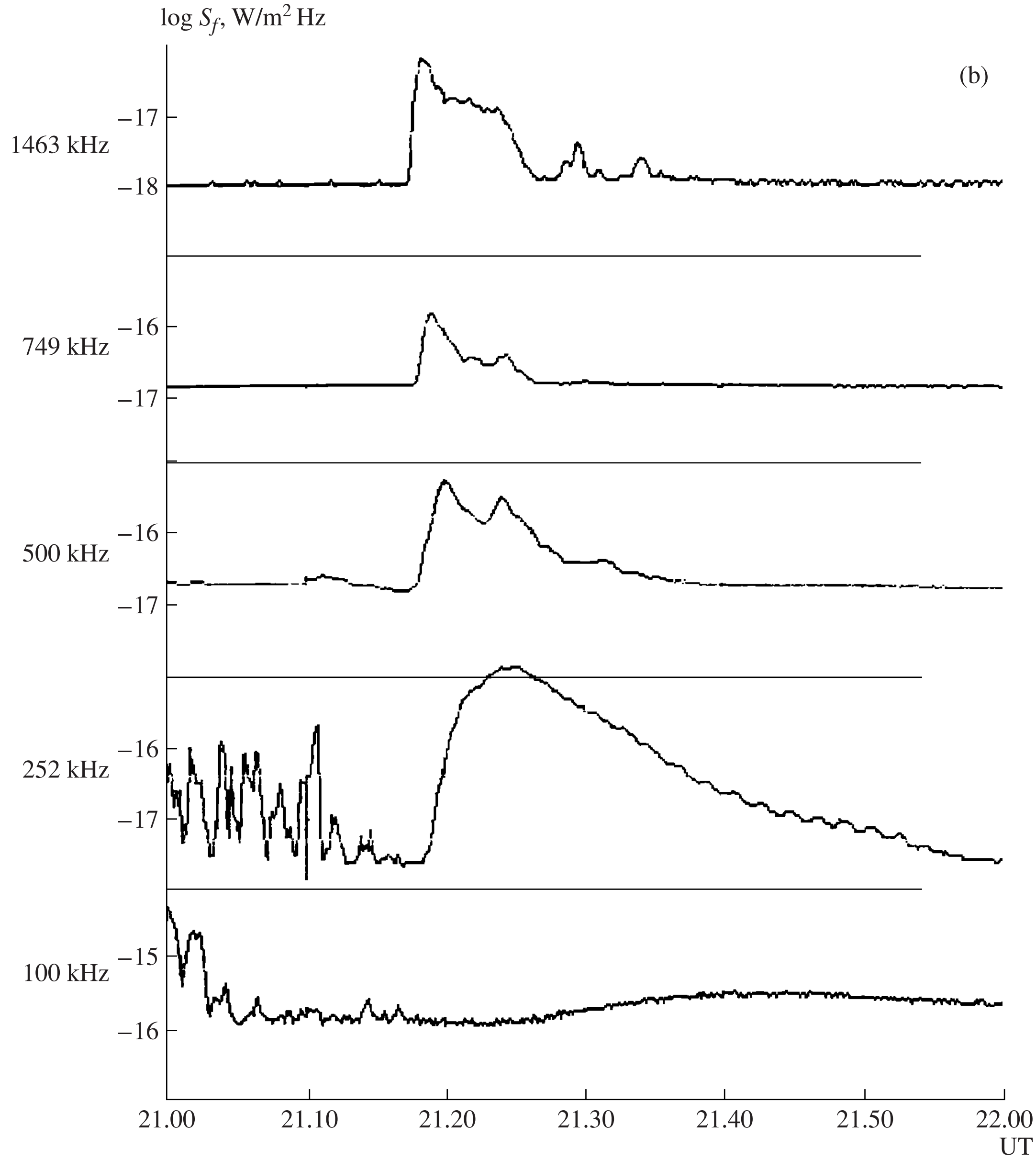

Figure. (Contd.)

to 66 W. Besides, it follows from the analysis of synoptic maps that these groups of sunspots were parts of the complexes of interrelated active regions extended in longitude, which determined the structure of the large-scale photospheric and coronal magnetic field. It is characteristic that all radio bursts of a long-wave range were distinct by a considerable flux amplitude $S_f = 10^{-17}$ to 10^{-15} W/m^2 Hz at the frequency of 1460 kHz. In addition, the duration of radio bursts was no shorter than 10–15 min at frequencies of 1460 and 780 kHz. On the contrary, for the majority of observed bursts their duration was usually 2–5 times shorter. Some of these bursts were identified with weak flares of C importance, and the radio emission fluxes did not exceed 10^{-18} W/m^2 Hz.

The analyzed long-wave radio bursts were characterized by fast drift in frequency, which is typical for type III bursts, and, as a rule, they represented a continuation of type III bursts of meter range, observed in the frequency range of 200–800 MHz in the solar corona.

It is characteristic that all, without exception, bursts were modulated in amplitude. And this modulation was observed up to the frequency of 252 kHz, and for strong flares it was rather long, more than 20–40 minutes. This fact implies that energetic electrons, generating a radio

Table

	Radio bursts at freguency 1460 kHz				Flares				Radio/CME		Geomagnetic storm				*WIND*	*ACE/WIND*
	Date	UT_{on}, h, m	dt, min	S_f, W/m^{2}Hz	Importance	coordinates	AR no.	UT_{max} h, m	Type		Date	D_{st}, nT	A_p	B_z	II + IV	electrons
1.	Nov. 4. 97	05.57	18	$8 \cdot 10^{-17}$	X2.1/2B	14S,33W	8100	05.58	II, IV	+	Nov. 6. 97	–110	45	–11	+	+
	Nov. 6. 97	11.53	19	$5 \cdot 10^{-16}$	X9.4/2B	18S, 63W	8100	11.55	IV	+					+	+
2.	May 2. 98	13.38	20	10^{-15}	X1.1/3B	15S, 15W	8210	13.42	IV	++	May 4. 98	–205	101	–35	+	+
	May 3. 98	21.18	18	10^{-17}	M 1.4/1B	15S, 28W	8210	21.18	IV		May 5. 98	–138			+	+/+
	May 6. 98	08.04	>20	10^{-16}	X2.7/1N	11S, 65W	8210	08.09	III,IV	+	May 9. 98	–67		–6	+	+/+
3.	Aug. 24. 98	22.05	25	$3 \cdot 10^{-17}$	X1/3B	30N,7E	8307	22.12	II,III,IV	+	Aug. 26.98	–155	144	–15		
4.	Sept. 23. 98	22.46	5	10^{-16}	C2.2	1N,4W	8340	22.46	II, IV	+	Sept. 25.98	–233	167	–18	+	
		07.02	4	$2 \cdot 10^{-18}$	M7/3B	18N, 9E	8340	07.13	III, IV	+					+	
5.	Oct. 20. 99	09.27	6	10^{-17}	C2.2/SF	14S, 78E	8739	09.29	III							
		05.56	16	10^{-17}	M 1.7/F	10N,48W	8731	06.02	II,III	+	Oct. 22.99	–220	144	–27	+	
6.	Feb. 8. 00	08.52	20	10^{-16}	M1.3/1B	25N, 26E	8858	08.58	II,III	+	Feb. 10–16.00	–109	52			
	Feb. 9. 00	19.30	10	$6 \cdot 10^{-17}$	C 7.4/2F	17S, 40W	8853	19.39		+	(Feb. 12–max)			–18		
7.	Apr. 4. 00	15.17	2	10^{-16}	C9.7/F	6N,66W	8933	15.34	IV							+
		16.38	5	10^{-17}	–					+	Apr. 6–9. 00	–320	150	–28	+	
8.	May 23. 00	06.03	20	$8 \cdot 10^{-16}$	C1.5	–	–	06.09	III						+	+
		12.46	14	$6 \cdot 10^{-16}$	C3	22N,37W	9002									
		20.42	13	$8 \cdot 10^{-17}$	C 9.5/1F	22N, 43W	9002	20.53	III	+	May 24–25. 00	–147	133	–21		
9.	June 6. 00	15.10	35	$6 \cdot 10^{-16}$	X2.3/3B	20N,13E	9026	15.25	II,IV	+	June 8. 00	–85	53	–7	+	
10.	July 14. 00	10.20	28	$3 \cdot 10^{-16}$	X5.7/3B	22N,7W	9077	10.26	II, IV	+	July 15–17. 00	–300	152	–15	+	+/+
11.	Sept. 12. 00	11.45	25	$2 \cdot 17^{-17}$	M1.1/2N	17S, 9W	9158	12.15	II, III	+	Sept. 17–19. 00					
	Sept. 15. 00	14.33	25	10^{-16}	M2.0/1N	2N,7E	9165	14.35	III	+	Sept. 17–19. 00	–177	136	–25	+	+/+
12.	Oct. 2. 00	02.47	12	$1 \cdot 10^{-17}$	C 4.1	9S, 7E	9176	02.57	III		Oct. 3–6. 00					
		19.56	12	$8 \cdot 10^{-17}$	C 8.4	9S, 0E	9176	0.04	III, V		Oct. 5. 00	–172	129	–30		

burst at frequency of 252 kHz, have reached a distance of about 0.7 AU (according to the model of [25]).

Of special interest is the fact that in all our cases with modulated radio bursts the solar electron events were observed by the EPAM/*ACE* and DOK/*INTERBALL-1*.

DISCUSSION OF RESULTS

It should be noted that the data obtained on the *INTERBALL-1* satellite were mainly on type III bursts. Observation of type II bursts, associated with the shock wave propagation, was complicated due to the circumstance that the AKR-X radiometer had a narrow frequency band (100–1500 kHz), and, in addition, the AKR-radiation of magnetospheric origin that was recorded in the 100–250 kHz and 500 kHz ranges is amplified during geomagnetic storms.

The dynamic WAVE/*WIND* spectra in the frequency range of 40 kHz–16 MHz clearly show that, along with intense type III bursts generated by fluxes of energetic solar electrons, the type II and SA radio bursts took place, caused by shock wave propagation in the outer corona and interplanetary medium.

In the table of hectometric type III bursts, observed on the *INTERBALL-1* satellite, there are facts of observation of type II + IV bursts according to the WAVE/*WIND* data, which implies the presence of shock waves in the interplanetary medium during our events.

Characteristic is the fact that virtually all long-wave radio bursts were observed during intensifications of the fluxes of energetic electrons. These solar electron events were recorded on the EPAM/*ACE*, 3DP/*WIND*, and, partially, on the DOK*INTERBALL-1* satellite (see Table).

For some events, earlier we have obtained from the *INTERBALL-1* data the estimates of delay times for the arrival of energetic electrons with $E = 40–300$ keV to the Earth. (These electrons were accelerated in the explosive phase of flares and generated the type III radio burst in the interplanetary medium). This delay time was equal to a value of no less than 15–30 min [29]. However, it should be noted that this estimate relates to electrons accelerated in the initial, explosive phase of a flare; though it is known that several stages of acceleration and release of energetic electrons can be distinguished during the flare development [30]; but their energy spectrum can be different for different acceleration conditions. This subject matter requires a special discussion and is not considered here in detail.

We remind that hectometric bursts arise, when energetic electrons propagate along the open field lines of the interplanetary magnetic field associated with the active region on the Sun. Analyzing the data included in the Table, as well as the time profiles of bursts similar to those shown in the figure, one can conclude that a rapidly drifting burst at frequencies of 1500–100 kHz after the expansion phase of a flare propagates to reach the Earth in a time of no longer than approximately an hour, i.e., long before the onset of a geomagnetic storm which gains strength and reaches its maximum development about two days later.

From considerations of the geometry of the propagation trajectory of CME and energetic particles it follows that, in order that the geoeffective solar wind (the magnetic cloud) would arrive at the Earth, the disturbance on the Sun should take place near the central meridian, and the flare that generates energetic particles coming to the Earth, is usually located at western heliolongitudes.

The issues of magnetic field topology, in connection with propagation of CME and energetic particles, are discussed in [31].

Apparently, in order that solar events be geoeffective, it is also important that the active region, in which the flare has been developed, should be a part of the complex of interacting active regions which is extended in longitude. (This aspect was studied in paper [32] when discussing the boundaries of a sectorial structure of the photospheric magnetic field). In such a case, energetic electrons from the western flares rapidly propagate to the Earth along the IMF lines, and the solar plasma flows in the solar wind arrive together with IN and a shock wave, propagating in almost radial direction within a wide solid angle.

CONCLUSIONS

Thus, the analysis of the data of observations on the *INTERBALL-1* satellite has shown that during the chromospheric flares preceding intense geomagnetic storms the hectometric radio bursts were recorded in the range of 100–1500 kHz with a fast drift in frequency, which is typical for the type III bursts. The bursts were characterized by a high amplitude of the flux $S_f = 10^{-17}$ to 10^{-15} W/m^2 Hz and duration longer than 10–20 minutes. These bursts were associated with chromospheric flares of M and X importance, located predominantly to the west of the central meridian in the range of heliolongitudes from 7 E up to 66 W. The flares were accompanied by powerful halo coronal ejections, as well as by magnetic clouds, shock waves, and the fluxes of energetic particles associated with these ejections. The presence of the southward B_z-component in the solar wind was noticed in all events, which is known to be typical for the geoeffective solar wind streams and is taken into account in the forecast [33].

Our results agree with the conclusions of papers [22–24] that one can predict geomagnetic storms based on increasing fluxes of solar energetic protons. But in our case the forecast can be based on observation of hectometric radio bursts in the frequency range of 100–1500 kHz and of the fluxes of energetic electrons coming from a strong flare, combined with observations of properties of halo-type CME and B_z-component with the southern orientation of the interplanetary magnetic field.

So, the observations during solar flares of long-wave radio bursts in the interplanetary medium and of fluxes energetic electrons propagating to the Earth can be considered, along with the other factors, as possible precursors of geomagnetic storms.

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