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MANIFESTATION OF PULSATION INSTABILITY IN SOLAR RADIO EMISSION PRECEDING PROTON FLARES

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Abstract. The investigation of solar radio emission fluctuations at the wavelength $\lambda \simeq 3$ cm led to the discovery of a visible increase in pulsations with periods of about 30–120 min prior to proton flares. These pulsations were observed before all (seven) proton flares included in our cycle of observations from 1969 to 1974. The phenomenon was not found to occur before non-proton flares. The assumption is made that the observed pulsations are a manifestation of pre-flare instability in coronal structures. Estimations have been made for fluctuations of the gyro-resonance radiation from the regions above spots associated with the magnetic field variations when a groove instability of a coronal condensation is developed. They are in good agreement with the observational data. The discovered manifestation of the pre-flare instability in fluctuations of the solar radio emission open new ways to study the flare development and to predict geo-effective phenomena on the Sun.

1. Introduction

Studying questions about powerful flares (especially, proton flares) in solar active regions is one of the most urgent problems of solar physics and solar-terrestrial relations. The urgency of this problem is not only of theoretical, but (mostly) of practical, interest from the viewpoint of forecasting the geo-effective phenomena on the Sun. Numerous investigations devoted to this problem have been made based on observations of solar radio emission over different wavelength ranges. A brief review of the problem is given in the paper by Tanaka and Enome (1975) where the microwave structure of coronal condensations and their relations to proton flares are studied.

Until recently, however, investigations have been concerned with a state of the active region before a flare by using morphological data having little information on the dynamics of pre-flare processes. Studying the fluctuations of radio emission from active regions and, first of all, their quasi-periodic changes have opened new possibilities for investigating these processes. The observation of quasi-periodic pulsations (QPP) is described in a paper by Kobrin *et al.* (1976b).

The productivity of QPP observations for forecast purposes may be significant because the flares do not occur suddenly, but are preceded by a restructuring of the active region or development of a different kind of instability caused by a flare-trigger mechanism or pumping processes and energy accumulation in the active region. Reflecting the oscillations in the solar atmosphere with these pro-

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cesses, QPP may be somehow an indicator of pre-flare instability. It may be assumed that the occurrence of the latter in an active region will be distinctly revealed in fluctuations of the frequency spectrum of the gyro-resonance radiation and in the polarized radiation, since the changes in these characteristics are mostly associated with the magnetic field variations in the active region.

The appearance of pulsation instabilities for 1–2 hr before flares was pointed out (Yurovsky, 1969; Covington, 1973) in observations of the emission flux intensity at centimeter wavelengths.

To study the relation between quasi-periodic changes in the radio emission fluctuations of the Sun and its activity, we made a series of observations during the period from 1969 to 1974 and discovered seven events on the Sun accompanied by strong proton fluxes. They were the proton events on March 7, 1970; September 1, 1971; August 2, 4, 7, 1972; July 3, 4, 1974. Some of them (September 1, 1971, and August 2, 4, 7, 1972) were described by Castelli *et al.* (1973a), Kuznetsov *et al.* (1975). For other events we used the criteria by Castelli *et al.* (1973b) and Akinjan *et al.* (1976) for determination of flares originating them.

According to these criteria, the proton events on July 4, 1974 may be due to solar flares that occurred at 06:48 UT or 13:54 UT. However, the flare at 13:54 UT and the accompanying bursts were more powerful, and a deca meter IV type burst was observed. It is our opinion that this flare was responsible for the proton event on July 4, 1974. As for the proton event on March 7, 1970, it is difficult to define the time of flares on March 6 and 7 accompanied by protons. Most probably, the main source of protons was associated with powerful flares at 01:53 UT on March 7.

TABLE I

The main parameters of the radio telescopes

Observation intervals	Antenna diameter (m)	Parameters measured	Freq. (MHz)	Receivers characteristics	Observation spot
July-August, 1972	2	F, ΔF	$f_1 = 9870$	superheterodyne	Tchukotka
			$f_2 = 9670$	$F\,\delta T = 1$ K ($\tau = 1$ s)	
				$\Delta F\,\delta T = 1.6$ K ($\tau = 1$ s)	
June–July, 1974	22	ΔF	$f_1 = 9670$	superheterodyne	Crimea
			$f_2 = 9480$	$\Delta F\,\delta T = 1$ K ($\tau = 1$ s)	
February–March, 1970	2	F, ΔF, F_{R-L}	$f_1 = 9870$	$F\,\delta T = 3$ K ($\tau = 1$ s) ΔF, $F_{R-L}\,\delta T =$ 0.8 K ($\tau = 1$ s)	
			$f_2 = 9670$	superheterodyne	Cuba
August–September, 1971	2	F	$f_1 = 9600$	$F\,\delta T = 0.3$ K ($\tau = 16$ s)	
			$f_2 = 8600$	superheterodyne	Kislovodsk

F = flux, $\Delta F = F_{f1} - F_{f2}$ spectral slope, F_{R-L} = polarization, δT = sensitivity, τ = integration time.

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Measurements have been done with radio telescopes, the main parameters of which are given in Table I. To increase the observation time and thus the possibility of recording the long-period (several hours) variations of the observed parameters of solar radio emission, the investigations were carried out once at latitudes above the Arctic circle.

2. Observations

We give the results of observations carried out in the period when the above-mentioned proton flares occurred on the Sun.

It is necessary to note that the data obtained within the periods before the flares on March 7, 1970 and September 1, 1971 are not complete due to retrospective treatment. We have given them as supplementary illustrative material testifying, to a certain extent, to the observation results carried out in the period of July–August, 1972 and June–July, 1974. Preliminary observation data are reported in the paper by Kobrin *et al.* (1976a).

2.1. Flares on August 2, 4 and 7, 1972 in the active region McMath 11976

Observations were made above the Arctic circle, enabling us to increase the observation period up to 15 hr. Measurements were made every day from July 15 to August 16, 1972. The difference and the sum of fluxes of the radio emission from the Sun at the frequencies of 9870 and 9670 MHz were measured by a radio telescope with a 2-m diam. paraboloid and a superheterodyne receiver (Kobrin *et al.*, 1973b; Korshunov and Prokof'eva, 1976).

The powerful flares occurring early in August 1972 were responsible for unusually strong radio bursts covering a wide range of wavelengths, strong ejection of energetic particles, and enhanced geomagnetic activity. All three flares were classical proton ones. They occurred in the active centre (with complex magnetic fields) of McMath 11976, the appearance of which on the solar disc gave rise to an increase in the S-component up to 25% of the quiet-Sun emission. The flares were preceded by the occurrence of large gradients of the magnetic field near the neutral line. This active region first appeared on the east limb on July 27, 1972.

Figures 1a, b, c, d, e, f illustrate the typical records of the flux F and the slope of the spectrum ΔF averaged over 20 min intervals. These were made on July 28–31 and August 1–3, 6–7, 1972. One can see a pronounced periodic character in the change of the slope of the spectrum during the pre-flare period. As seen in Figure 1, the observed periods of the fluctuations are not constant and vary during the observation time. It is most likely determined by the change in the structure of the active region (in particular, in its size and the continuous emergence and disappearance of separate elements of the group) that produces the appropriate changes in the magnetic field configuration. Such changes in the group were well observed

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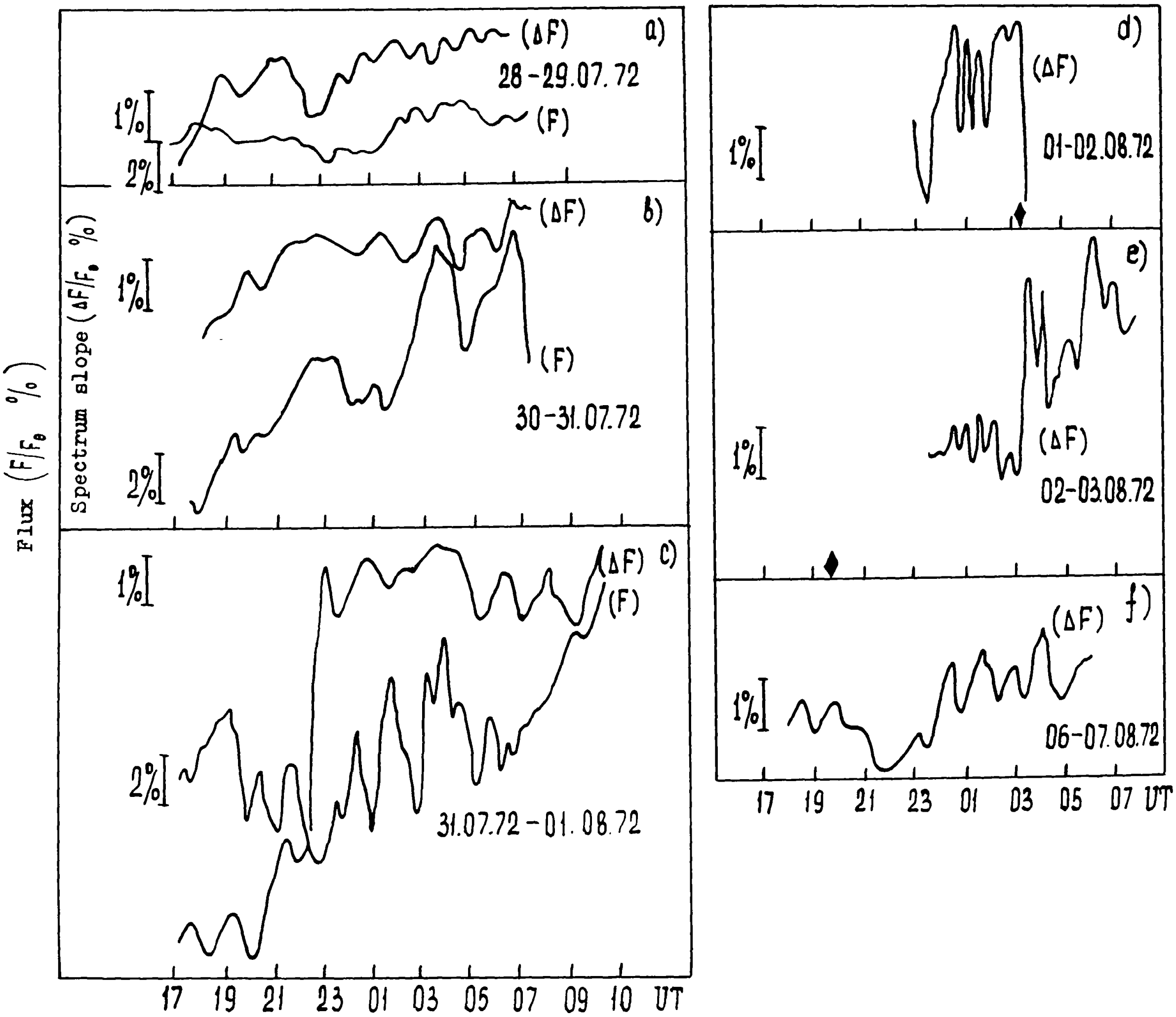

Fig. 1. Records averaged per 20 min of the flux (F) and the spectral slope (ΔF) of the solar radio emission made on July 28–29 (a), 30–31 (b), July 31–August 1 (c), August 1–2 (d), 2–3 (e), 6–7 (f), 1972; $F_\odot$ is the mean flux of emission from the Sun. The moments of occurrence of proton flares are marked on the time axis.

during its passage over the solar disc. We point out an increase in the oscillation amplitude of the spectral slope and the flux fluctuations during the pre-flare period of developing the active centre. Sufficiently long continuous observations allow us to investigate the presence and behaviour of QPP with periods much longer than 30 min. The fact that the change in the fluctuation amplitude is different for QPP with different periods is most essential. Figure 2 shows the change in the daily average values of fluctuations of the flux (δF) and the spectral slope ($\delta \Delta F$) of solar radio emission during the period from July 29 to August 10, 1972. For pulsations with the periods longer than 30 min the changes of their intensity are related to flares. The fluctuation value is given in percent of the emission of the quiet Sun at the middle frequency ($\delta F/F_\odot$ and $\delta\Delta F/F_\odot$). As seen from Figure 2 the value of fluctuations with the periods longer than 30 min increases for some days before proton flares and falls right after them. Most clearly it is expressed in the spectral

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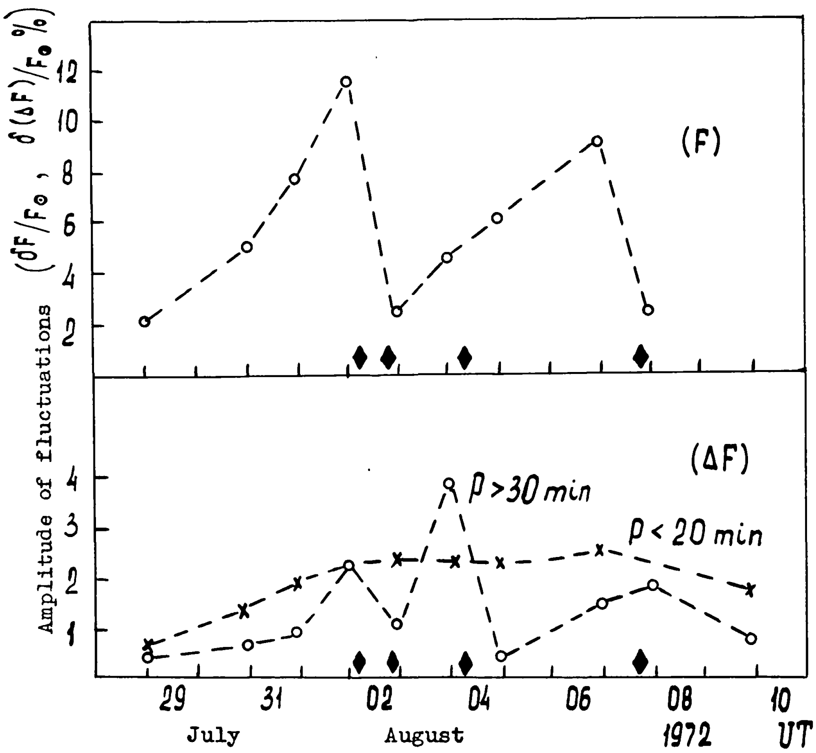

Fig. 2. Change in the averaged per day amplitude of quasi-periodic components of fluctuations in the flux (F) and the spectral slope (ΔF).

slope of radio emission. The changes of fluctuations with shorter periods are connected only with the growth and decrease of the common activity of the Sun.*)

2.2. Flares on July 3, 4, 1974 in the Active Region McMath 13043

In the events considered above the radio emission fluctuations of the Sun were observed using low-angular resolution antennas and therefore, generally speaking, it might not be possible to directly associate QPP of radio emission with the periods longer than 20–30 min with definite active regions. To specify such structural relation and to exclude a possible overlapping of radio emission fluctuations from different formations of the solar atmosphere, we have made observations of the spectral slope of solar radio emission using the 22 m radio telescope of the Crimea Astrophysical Observatory on June–July 1974 (Arbuzov *et al.*, 1976). During the same period of time and using the same radio telescope, the Crimea radio-astronomers carried out their own measurements of the solar radio emission intensity and polarization at the wavelengths of 1.9, 2.5, and 3.5 cm (Bachurin *et al.*, 1976). The 5–6 arc-min beam-width at $\lambda \simeq 3$ cm allowed us to investigate the radio emission from separate active regions.

* The increase in QPP with periods less than 20 min with the growth of the common activity of the Sun was already pointed out in the first papers on the study of radio emission fluctuations (Durasova *et al.*, 1971).

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Our radiometer registered the flux difference at the frequencies of $f_1 = 9480$ MHz and $f_2 = 9670$ MHz (the spectral slope ΔF). In the period of June 27 to July 27, 1974 we successively followed two active regions on the Sun (McMath 13043 and McMath 13057). The quiet regions were observed, as well. The active region McMath 13043 appeared on the east limb of the Sun on June 29 as a well-developed complex group. During passage of this active region across the solar disc, a number of powerful flares were recorded, two of which were proton flares (July 3 and 4, 1974).

On July 9, 1974 active region McMath 13057 appeared on the limb and was accompanied by low flare activity.

Figure 3a, b, c, d, e, f, g shows the records of the spectral slope averaged over 20 min interval for active region McMath 13043 during the period from June 27 to July 5, 1974. It is difficult to single out some quasi-periodic oscillations in the record taken on June 27, 1974. On June 30, 1974 marked fluctuations appeared. On July 1 and 2, namely, for 2–3 days before proton flares, a considerable increase in the amplitude fluctuations was pointed out, the change in the slope of the spectrum being of pronounced quasi-periodic character with the pulsation period ~ 60 min. The fluctuation amplitude reaches the value 10% of the antenna temperature of the quiet Sun.

After the flare (on July 3, 1974) we observed a sharp decrease in the amplitude of fluctuations. The amplitude increased again up to the time of the second powerful flare (on July 4, 1974). By averaging the fluctuations obtained for different periods of time (0 to 30 min) QPP with the periods up to 120 min were singled out.

There was an essential difference in the behaviour of QPP amplitudes of the spectral slope of radio emission with the periods $p > 30$ min and $p < 20$ min during the prior- and after-flare periods. Analogous to the events on August 1972 the QPP (averaged per day) amplitude of the spectral slope with $p > 30$ min increases some times before the proton flares and after them it sharply decreases.

The changes in the pulsation amplitude with the periods $p < 20$ min has a smooth character with gradual rise and fall as the active region moves along the solar disc. As one can judge, these changes are not related to proton flares. The described pattern is distinctly seen in Figure 4a.

Great values of the radio emission intensity fluctuations with the averaged period of about 100 min were observed by Bachurin *et al.* (1976) in the same active region at the wavelengths of 1.9, 2.5, and 3.5 cm (Figure 4b). Fluctuations with relatively short periods were observed practically continuously. Their amplitude can be compared with that of small bursts.

Figure 3h illustrates a characteristic form of the spectral slope of radio emission from McMath 13057, where strong flares have not been observed. During observations of this region, none of the cases of the considerable increase in the fluctuation amplitude of the spectral slope was pointed out. For a 'quiet' region of the solar surface the fluctuations of the spectral slope were much less intensive.

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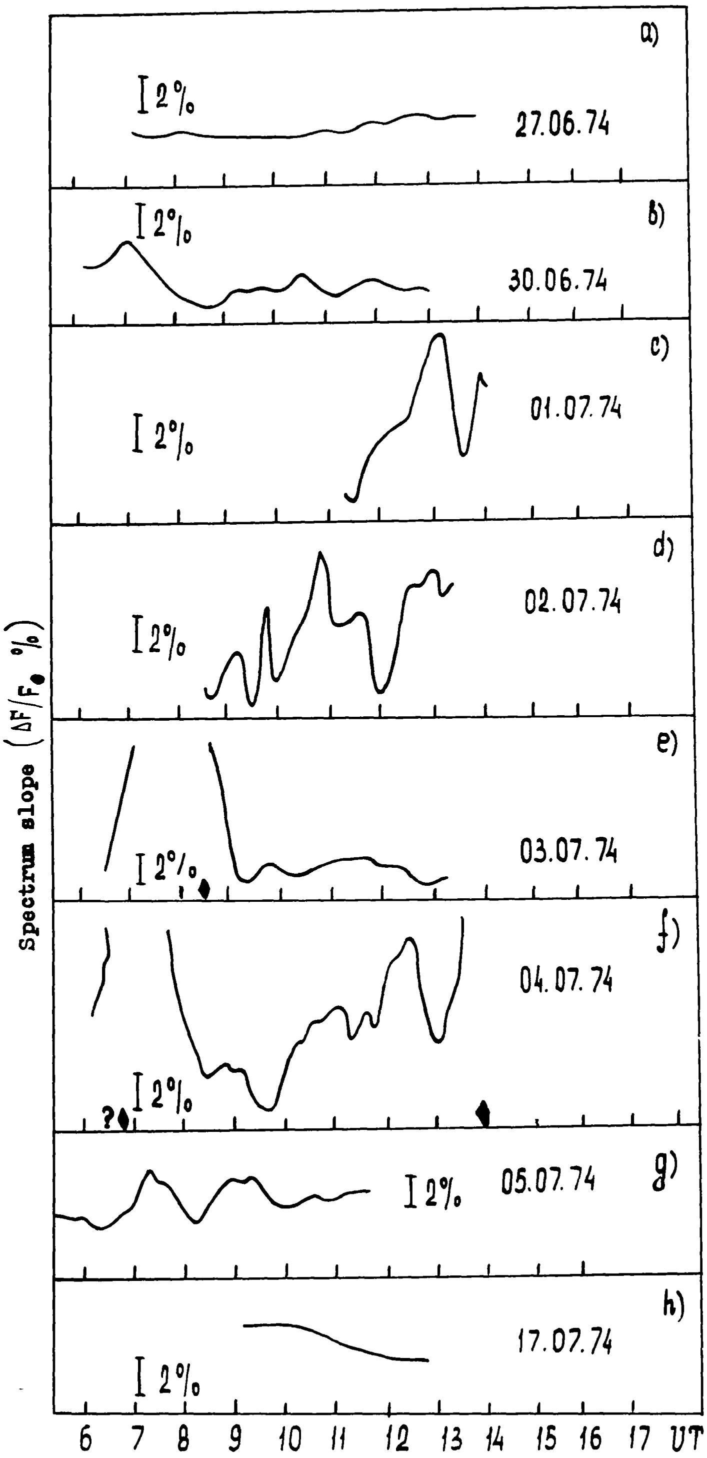

Fig. 3. Records averaged per 20 min of the spectral slope of the solar radio emission from active region McMath 13043 made with the 22 m radio telescope on June 27 (a), 30 (b), July 1 (c), 3 (e), 4 (f), 5 (g), 1974 and active region McMath 13057 on July 17 (h), 1974. $F_{\odot}$ is the radio emission flux from the quiet region.

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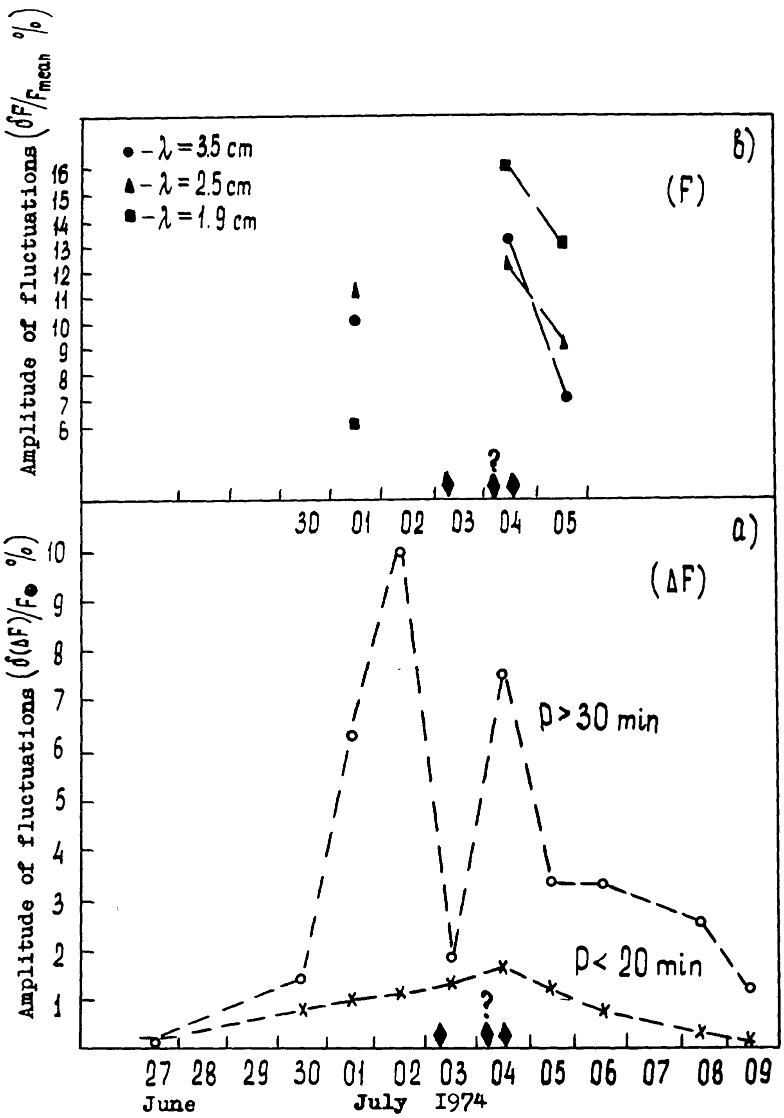

Fig. 4(a). Change in the averaged per day amplitude of quasi-periodic components of fluctuations with periods $p > 30$ and $p < 20$ in the spectral slope (ΔF) of the radio emission from active region McMath 13043. (b) The values of the amplitudes of quasi-periodic fluctuations of the radio emission intensity (F) at the wavelengths of 1.9; 2.5; 3.5 cm obtained by Bachurin *et al.*. (1976).

2.3. Flares in the Active Region McMath 10618 on March 7, 1970 and McMath 11482 on September 1, 1971

The observations on March 1970 were carried out using a radio telescope with a 2-m paraboloid antenna. The flux (F), polarization (F_{R-L}), and the slope of the spectrum (ΔF) of the solar radio emission were measured at $\lambda = 3$ cm (Belov *et al.*, 1974).

Analysing the averaged per 5 min records taken on March 5 and 6, 1970 (Figure 5a, b), one can see that as far as approaching the day of occurrence of the proton flare on March 7, the amplitude of fluctuations of the spectral slope and polarized radiation of the Sun increases. Their values reach 1.5–2% of the emission level of the quiet Sun. (On March 1, 1970 the value of the amplitude did not exceed 0.5%.)

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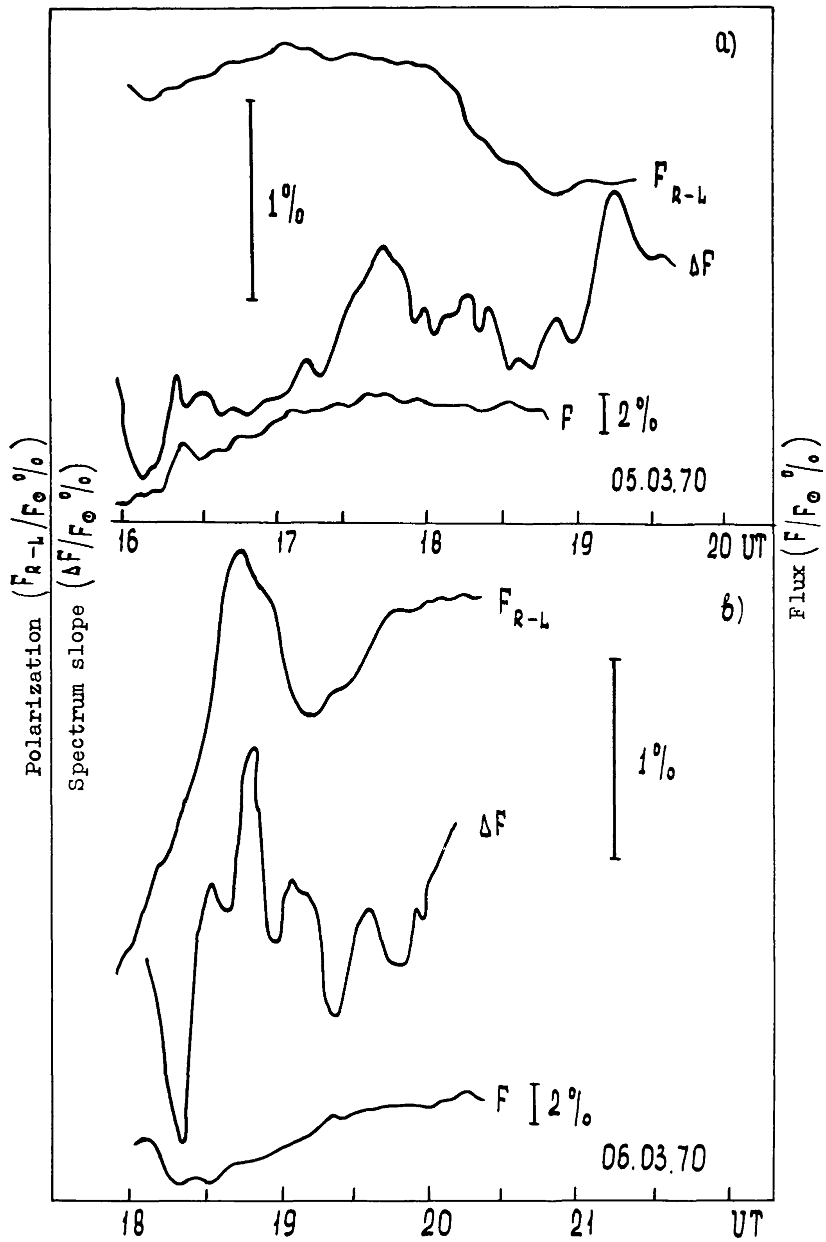

Fig. 5. Recordings averaged per 5 min of the flux (F), the spectral slope (ΔF), and polarization (F_{R-L}) of the solar radio emission made on March 5 (a) and 6 (b), 1970. $F_{\odot}$ is the mean flux of emission from the Sun.

The fluctuations of the slope of the spectrum become periodic with the period of about 30 min. Such a pronounced periodicity was not observed in the records of fluctuations of the radio emission flux.

Observations, including the moment of the onset of the proton flare on Sepgember 1, 1971 were made using a 2-m radio telescope (Kobrin *et al.*, 1973a). The integral flux of the solar radio emission was measured at the frequencies of 9600 and 8600 MHz.

The proton flare occurred on September 1, 1971 in the group McMath 11482 which went behind the limb on August 31, 1971.

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On days before the flare, in addition to McMath 11482, there were some more active regions on the solar disc. But the contribution to the S-component of the solar radio emission from the local source McMath 11482 at $\lambda = 6$ cm and $\lambda = 9$ cm was the greatest (*Soln. Dann.*, 1971). At the same time the flux received from this local source moving over the disc towards the west limb decreases more slowly than according to the cosine law that testifies to the growth of the source activity.

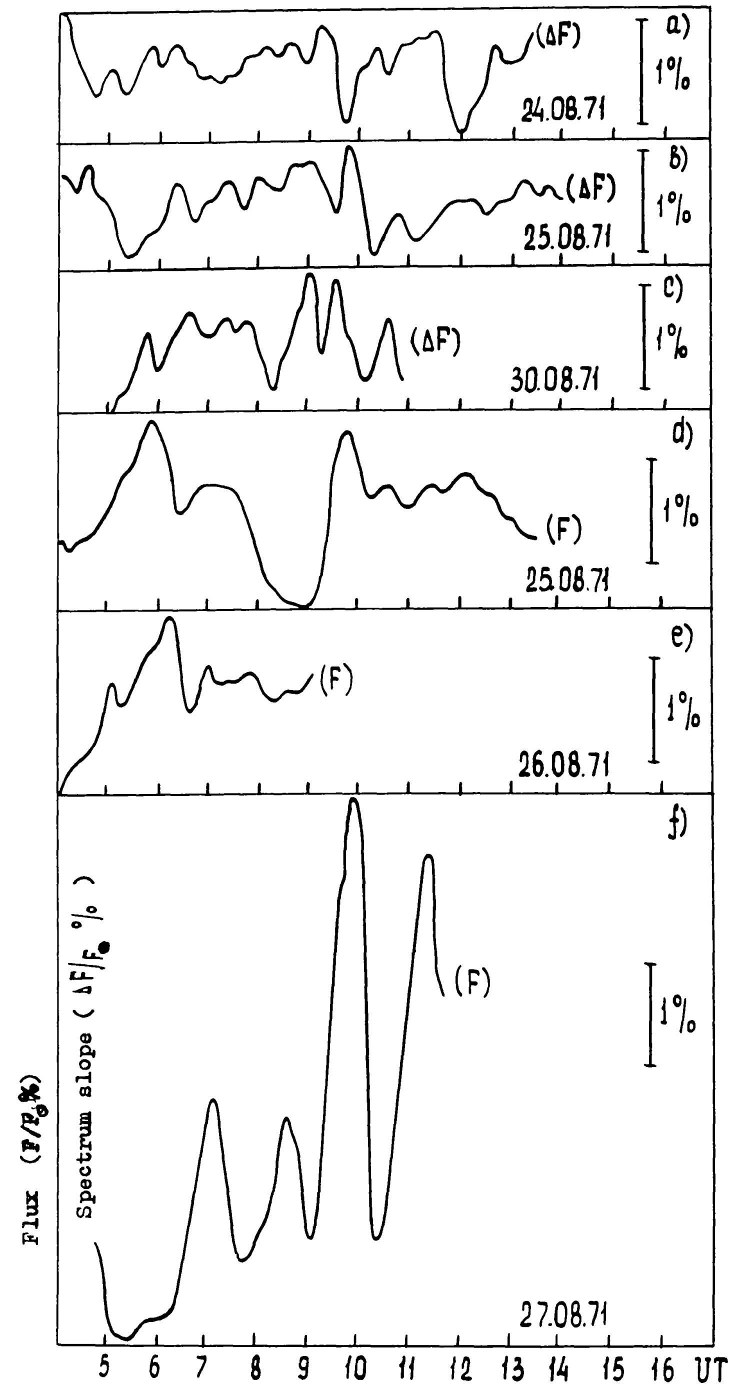

Fig. 6. Recordings averaged per 20 min of the flux (F) and the spectral slope (ΔF) of the solar radio emission made on August 24 (a), 25 (b, d), 26 (e), 27 (f), and 30 (c), 1971. $F_\odot$ is the mean flux of emission from the Sun.

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For 6–7 days before the proton flare (during this period the active region came through the disc centre and the emission flux did not decrease due to its directivity) the fluctuations in the slope of the spectrum amounted to 1% (Figure 6a, b). All flux observed fluctuations and the spectral slope were averaged over 20 min. On August 30, 1971 despite the decrease in the radio emission received because the local source was at the disc limb, the fluctuations in the slope of the spectrum even increased and became more regular (see Figure 6c).

Unfortunately there were no observations on August 28, 29, 1971 and on August 26, 27, and 31, 1971 we had only a single-channel (9600 MHz) reception.

We observed quasi-periodic fluctuations with the period of about 80 min (Figure 6f) in the flux received on August 27, 1971, i.e., for three days prior to the proton flare. The observed fluctuations reached 2–3% of radio emission from the quiet Sun. This type of pattern was not observed until August 27, 1971 (see Figure 6d, e).

Thus, based upon the given observational data, it may be concluded that long-period pulsations in the observed radio emission from the Sun are closely related to strong manifestations of the solar activity. The amplitudes of the flux pulsations and, especially, of the spectral slope of the active region are sharply increased. For some days before the proton flare, the QPP of the spectral slope with the periods longer than 20–30 min begin to be distinctly manifested. The amplitude may reach several percent of emission from the quiet Sun. It should be noted that the oscillations with the same periods were also pointed out in emission bursts generated during the proton flares (Kobrin *et al.*, 1973b). The pulsation intensity decreases immediately after the flares.

A general cycle of our observations consists of about 120 days. During this time, in addition to the described proton flares, there were recorded more than 20 chromospheric flares of 2B magnitude and two flares of 3N and 3B. According to the data available, these flares were classified as nonproton flares. Before the given nonproton flares, we did not record the behaviour of the emission spectrum fluctuations typical of proton flares. The fluctuations during nonproton flares either did not exceed some mean level typical of the given active region or we observed their increase in the form of 1–3 pulsations for 1–2 hr before the powerful flare.

As an example, Figure 7a shows the record of the emission spectral slope of active region McMath 13043 obtained before the 3N flare (July 7, 1974) and Figure 7b exhibits the record of the spectral slope of the radio emission from the Sun before the 3B flare (August 20, 1971).

3. Discussion and Conclusion

All these facts permit one to assume that the instability processes before proton flares are explainable by a general mechanism or are connected with a definite class of structures the parameters of which do not differ significantly. The presence of characteristic periods of radio emission fluctuations before flares can be explained by swaying of coronal structures by some subphotospheric oscillation processes (for

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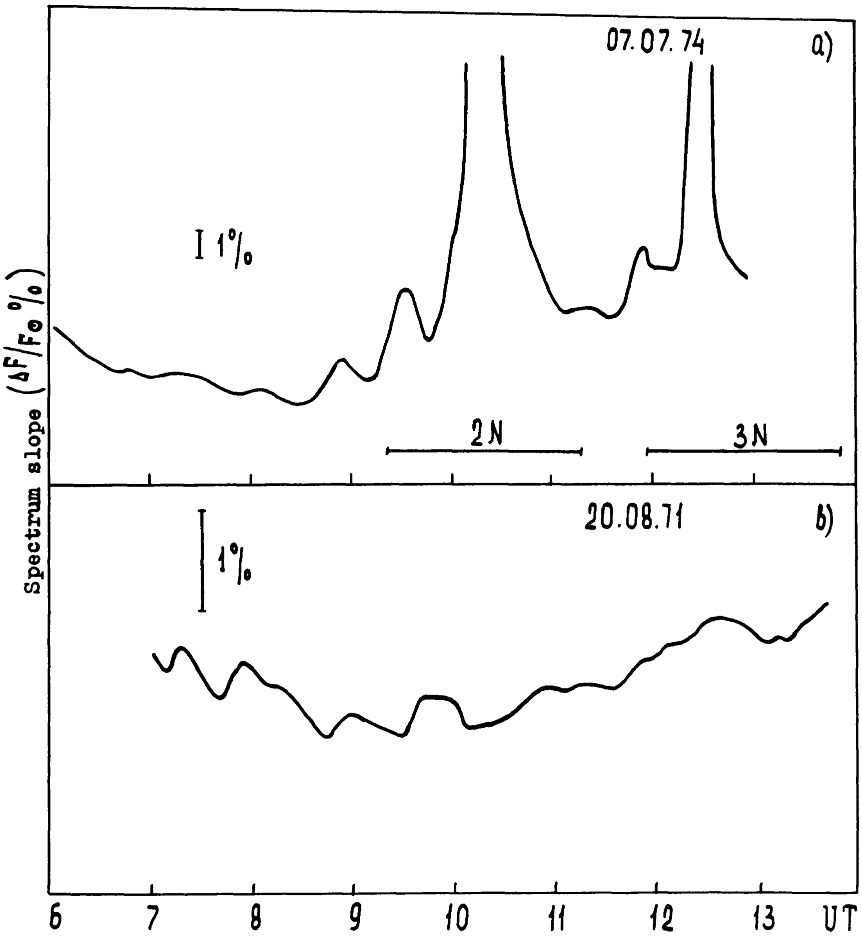

Fig. 7. Recordings (averaged over 20 min) of the spectral slope of (a) the radio emission from active region McMath 13043 made on a day before the 3N magnitude flare of July 7, 1974, (b) the radio emission from the Sun before the 3B magnitude flare of August 20, 1971.

example, self-oscillations of the whole Sun (Aleshin *et al.*, 1973; Wolf, 1974; Hill and Stabbins, 1975) or by self-oscillation excitation of coronal structures under definite conditions.

The plasma instability, for example, groove instability (Pustyl'nuk, 1975, 1976) may become the triggering mechanism of the flare, which produces destruction or essential changes in the coronal structures resulting in a sharp decrease or change of the corresponding components of fluctuations.

The fluctuations of gyromagnetic radiation calculated for the coronal condensation with the development of the groove instability are in good agreement not only with the observed amplitude of fluctuations of the radio emission flux, but also with the observed relation between the amplitudes of fluctuations of the flux and the spectral slope*.

* The analysis of fluctuations for thermal bremsstralung and synchrotron radiation of relativistic electrons out of the coronal condensation showed that these types of radiation could not provide observed relations.

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It is necessary to note that the observed values of fluctuations at $\lambda = 3$ cm are explainable by the consequence of the change in the coronal condensation magnetic field, but not in the source area as it was assumed by Pustyl'nik (1975). Indeed, in case of the groove instability of the coronal condensation a relative change in the source area may reach ~0.1. For the events on August 1972 (active region 11976) when the source emission of the S-component at $\lambda = 3$ cm amounted to 25% of emission from the quiet Sun the change in the source area gave the fluctuation amplitude of the flux of emission 2.5% of emission from the quiet Sun whereas the observed value of fluctuations of the flux amounted to 5–10% (see Figure 2). In addition it may be shown that for realistic values of the temperature gradients and the magnetic field in the solar atmosphere, the observed relation between the amplitudes of fluctuations of the flux and the spectral slope of emission received cannot be provided only by the change in the source area.

On the other hand, the change in the magnetic field of less than 10% with the kinetic temperature gradient of $\sim 10^3$ K per km in the transition region between the chromosphere and the corona is sufficient to explain the observed amplitudes of fluctuations of flux and the spectral slope of radio emission.

It should be noted that the amplitudes of fluctuations of the emission parameters and the relation between them are sensitive to choice of the height dependence of the kinetic temperature. The radio emission fluctuations at $\lambda = 3$ cm increase with the growth of the chromosphere heating and the temperature gradient in the transient region from the chromosphere to the corona. It is possible that the increase in fluctuations at $\lambda = 3$ cm before proton flares is connected with the chromosphere heating above the spots. Note that this agrees with the criteria suggested to predict the proton events, in particular, by Tanaka and Kakinuma (1964) and the criterion on the maximum shift of the S-component spectrum (Krüger, 1969) before proton flares. On the other hand, an insufficient heating of the chromosphere above the spots may be responsible for the absence of the marked fluctuations before nonproton flares. In the model of the triggering mechanism for nonproton flares (Pustyl'nik, 1975) this may be due to the fact that a hot coronal gas flowing into the prominence takes the heat from the dissipation region of MHD waves.

The study of the dynamics of the solar radio emission fluctuations at the wavelength 3 cm during the period from 1970 through 1974 indicated that:

(1) For some days before all proton flares in our observational cycle there was a marked increase in fluctuations of the solar radio emission flux and the spectral slope. In the latter, QPP with periods longer than 30 min begin to be distinctly revealed. Immediately before the flares, the quasi-periodic changes in the slope of the spectrum are revealed especially strongly and reach several percent of the emission of the quiet Sun.

(2) There is an essential difference in the behaviour of quasi-periodic components of fluctuations of the slope of the spectrum with periods longer than 30 min and less than 20 min before and after the proton flares. In the first case the

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amplitude value averaged over a day increases before the proton flares and sharply decreases after them. In the second case, no direct relation between the mean daily values of the amplitudes and proton flares was observed. There existed only a relation between the mean values of fluctuations and the general activity of the Sun.

(3) The behaviour of fluctuations of the spectral slope before proton flares differs greatly from that before non-proton flares (even of the 3B importance). Before non-proton flares, we observed only a brief (1–2 hr) increase in fluctuations which was frequently related to the emission bursts.

(4) A general character of fluctuations before proton flares and their time dependences (30–120 min periodicity) remained during the whole observation period covering almost half of the 11-year cycle.

Our observations of the long-period components of fluctuations have been carried out for a limited period of time. Nevertheless, the available data allow us to believe that the discovered manifestation of the pre-flare instability in fluctuations of the solar emission opens new ways for studying these processes and for forecasting geo-effective phenomena on the Sun.

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