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QUASI-PERIODICAL VARIATIONS OF SUN'S RADIOEMISSION IN THE 3.3 CM WAVELENGTH

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SUMMARY

The results are presented of experimental study of fluctuations of Sun's radioemission flux. The correlation functions and registration spectra related to "quiet" and "active Sun are investigated. Quasi-periodical variations of the flux with periods of about ~250 and ~700 sec are discovered. The intensity variations in the spectrum maximum correlate with the variations of solar activity. A possible relation is discussed between the observed and other manifestations of periodicity in Sun's atmosphere motions.

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Investigations of various dynamic processes in solar atmosphere and of phenomena (solar flares, radiobursts, etc) conditioned by them, offer great astrophysical and geophysical interest [1,2]. One of the sources of information on solar chromosphere is the microwave radioemission. Lately, alongside with the study of greater intensive and large-scale processes, a great interest has been centered on the study of weak perturbations [3,5].

A work was conducted since 1963 at the radioastronomical station NIRFI in Zimenkakh, of which the goal was the study of a possibility in applying the methods of statistical radiophysics to the analysis of temporal variations of Sun's radioemission flux. The observations were conducted in the 3.3 cm wavelength. Basic attention was centered on working-off a method of detection and analysis of weak fluctuations of the flux [6,8]. An attempt was undertaken to reveal the differences in autocorrelation functions and fluctuation spectra of the "quiet" and "active Sun's flux [9]. The main difficulty in this work was connected with the low intensity of the investigated phenomena. This hindered their reliable separation against the background of signal level variation due to such factors as apparatus' instability, influence of propagation conditions [10,14], etc.,

Analysis of obtained registrations of Sun's radioemission variations presents no less a complicated problem. It was natural to consider these registrations as the realization of a random process, and to apply for their analysis spectro-correlational methods. The principal difficulty in the application of these methods is connected with the nonstationary state of processes on the Sun.

I. METHOD OF OBSERVATIONS AND PROCESSING

The registration of radioemission was performed in conditions of continuous Sun tracking, simultaneously on two radiotelescopes, located 500 m apart [6,8]. The amplification on both radiometers was regulated in such a way that the fluctuation amplitude be sufficient for reading of values from the tape of the self-recorder with an average precision of no less than 10%, and variations of automatic recorder readings on both radiotelescopes be identical at same temperature variations at the antenna input. The subsequent realization analysis was performed on a BESM-2 computer.

As a result of various factors' influence, say, a systematic error of the tracking system, intensity variations of radiometer, instability of parameters determining the propagation conditions of radiowaves in the atmosphere, and the nonstationary state of the very processes on the Sun, as a rule, the readings were also found to be nonstationary.

Therefore, the program included the processing of the curves by the method of sliding averaging [15], and the finding of primary curve deviation at each measured point from the averaged one. As a result a new realization was obtained

$$y(t) = x(t) - \overline{x_{\Delta t}(t)},$$

where $x(t)$ is the initial registration, $x_{\Delta t}(t)$ is the curve, obtained by means of sliding averaging in the Δt interval. Then the autocorrelation and mutual correlation functions were computed for the simultaneous registration from two radiotelescopes, i.e.,

$$B_{yy}(T, \tau) = \frac{1}{T-\tau} \int_0^{T-\tau} y(t)\, y(t+\tau)\, dt,$$

$$B_{yy'}(T, \tau) = \frac{1}{T-\tau} \int_0^{T-\tau} y(t)\, y'(t+\tau)\, dt,$$

where T is the realization length, $y(t)$ and $y'(t)$ is the realization from various telescopes, $\tau < T$. According to computed autocorrelational and mutually correlational functions the instant energy spectrum was found [16]

$$f_y(\omega) = \int_0^{\tau_1} B_{yy}(T, \tau)\left(1 + \cos\frac{\pi\tau}{\tau_1}\right)\cos(\omega\tau)\, d\tau.$$

The correlation functions and spectra thus obtained are related to the transformed process $y(t)$.

Let us examine how these correlation functions and the spectrum are connected with those of the process at radiometer input. For simplicity, we shall consider that $x(t)$ is the stationary process and $\overline{x(t)} = 0$. We shall denote the autocorrelation function and the spectrum of this process according to $B_x(\tau)$ and $f_x(\omega)$. Taking into account that at radiometer output, the process' spectrum up to the RC-filter remains uniform (which is correct for $\Delta\Omega_1 >> \Delta\Omega$ [17]), we shall have the process $x_1(t)$. The correlation function and the spectrum corresponding to this process will be written in the form $B_{x_1}(\tau)$ and $f_{x_1}(\omega) = f_x(\omega)g(\omega)$, where $g(\omega)$ is the spectral characteristic of integrating RC-cell. The spectrum of the averaged process may be written as

$$f_{\overline{x_{1\Delta t}}}(\omega) = f_{x_1}(\omega)\,\Phi(\omega),$$

where $\Phi(\omega) = \left(\sin\frac{k\omega\Delta t}{2} \Big/ \frac{k\omega\Delta t}{2}\right)^2$ is the filter's spectral characteristic, equivalent to the process of sliding averaging [16].

The autocorrelation function and the spectrum of $y(t) = x_1(t) - \overline{x_{1\Delta t}(t)}$ process, may then be written in the form

$$B_y(t) = B_{x_1}(\tau) + B_{\overline{x_{1\Delta t}}}(\tau) - 2B_{x_1,\overline{x_{1\Delta t}}} \simeq B_{x_1}(\tau) - B_{\overline{x_{1\Delta t}}}(\tau) \qquad (1)$$

and

$$f_y(\omega) = f_{x_1}(\omega) - f_{\overline{x_{1\Delta t}}}(\omega) = f_x(\omega)\,g(\omega) - f_x(\omega)\,g(\omega)\,\Phi(\omega).$$

Hence, the fluctuation spectrum of radioemission flux at radiometer input, of interest to us, is obtained from the relation (1)

$$f_x(\omega) = \frac{f_y(\omega)}{g(\omega)\,[1-\Phi(\omega)]}, \qquad (2)$$

where function $\alpha(\omega)$ is

$$\alpha(\omega) = g(\omega)\,[1-\Phi(\omega)] = \frac{1}{1+(RC\omega)^2}\left[1-\left(\frac{\sin\frac{k\omega\Delta t}{2}}{\frac{k\omega\Delta t}{2}}\right)^2\right]$$

This function may also be determined experimentally from the measurement of noise generator's power fluctuation of spectral density at radiometer output.

For the determination of precision of spectral density estimate, an 80% reliable interval was found by the method used in [18].

2. RESULTS OF OBSERVATION

Preliminary results of observations are presented in [9]. Our observations performed at Sun's altitude of 15° above horizon, have shown that at least part of the observed signal variations are of solar origin. The obtained registrations were brought to a stationary form by the method indicated above, after which estimates were computed of the autocorrelational and mutually-correlational functions and energy spectra for each pair of realizations, obtained on the two scattered radiotelescopes.

The autocorrelation functions of the realizations obtained at the registration of generator noise fluctuation at "active" and "quiet" Sun are presented in Fig.1. It may be seen from the diagram that the autocorrelation functions for Sun's noises are essentially different in intensity from the correlation functions of fluctuations of noise generator emission and, mainly, that a reliable discovery was made of a periodical component in the Sun's signal.

For the verification of correlativeness of signal registration obtained on spaced radiotelescopes, mutual correlation functions were computed (Fig.2). Both in these and in the autocorrelation functions quasi-periodical components are found with same periods. This is evidence of their origin due to variations of radioemission flux.

For the determination of quasi-periodical components, spectral analysis was performed. The maxima in fluctuation spectra, which are evidence of quasi-periodical signal variations, are present only in the fluctuation spectrum of Sun's radioemission.(Fig.3). For different realizations the number of maxima in the spectrum varies from one to three. Two maxima are most frequently observed. Altogether 45 realizations were processed. The average value of oscillations was determined by the propagation histogram of oscillation periods (Fig.4). According to the refined data, the average values of the corresponding periods constitute ~ 250 and ~700 sec.

Observations on spaced radiotelescopes were conducted from March to May 1967. During this period increased solar activity was noted from 22 Feb. to 10 March (group No.65, 85) and from 20 March to 1 April (group No.101) [19]. In the registrations relative to time intervals corresponding to periods of activity, correlated low frequency fluctuations were detected visually. Analysis of the results of observations has shown that there exists a statistical link between the appearance in simultaneous pairs of registrations of correlated fluctuations and the passage of the active regions through the Sun's disk. The presence of such a relation is demonstrated by the average dispersion increase of signal fluctuations from $\sigma_q \simeq 3°K$ at "quiet" Sun and $\sigma_a \simeq 4 - 6°K$ at "active" Sun. The magnitude of the mean value of the mutual coreelation factor of registration from two antennas also accrues respectively from $B_q(0) \simeq 0.1$ to $B_a(0) \simeq 0.5$ (Fig.5).

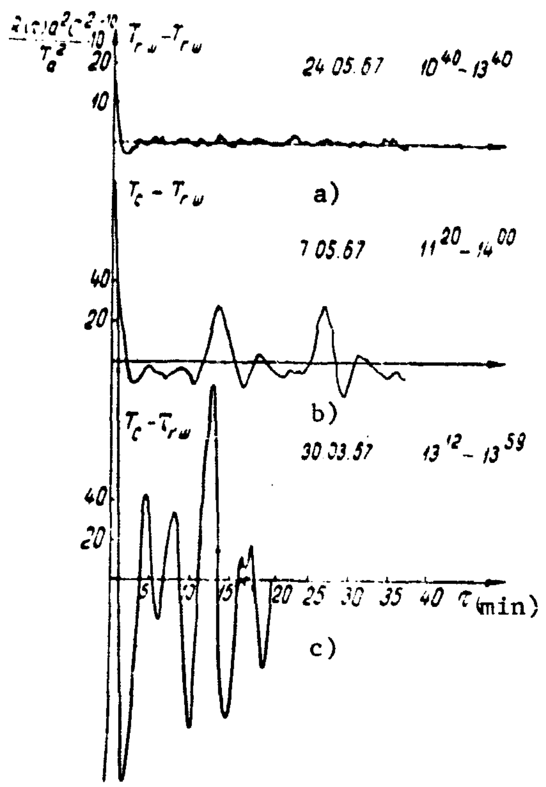

Fig. I.

Estimates of autocorrelation functions of flux fluctuations

a) radiation of noise generator, b) "quiet" Sun, c) "active" Sun

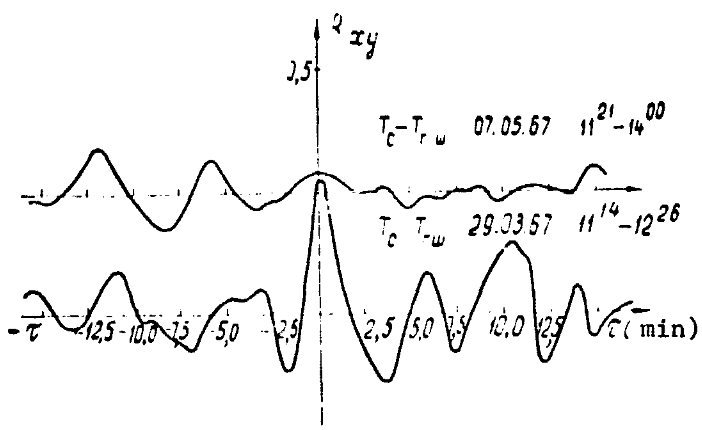

Fig. 2.

Estimates of mutual correlation functions

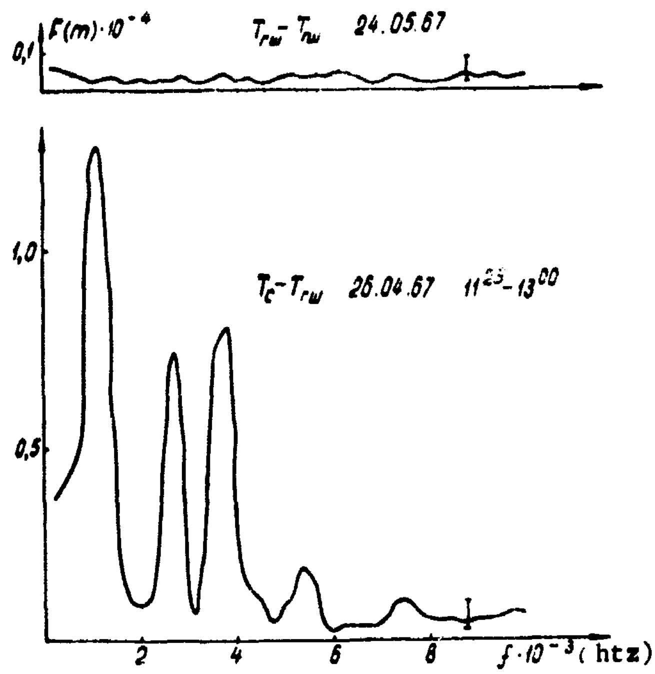

Fig. 3.

Estimates of spectral density fluctuations of the noise generator (above) and of the Sun.

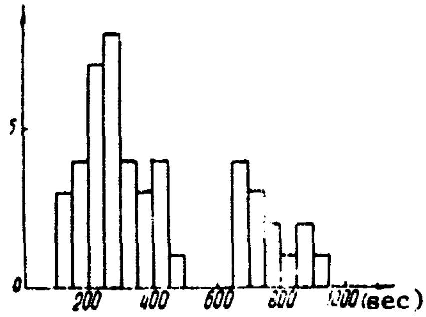

Fig. 4.

Histogram of oscillation periods of Sun's radioemission intensity Shown in ordinates is the number of spectrum maxima in the corresponding period interval.

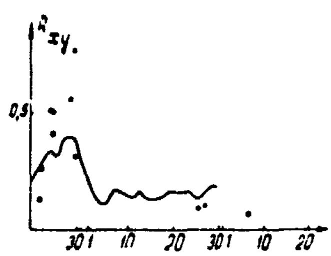

Fig. 5.

Relation of mutual-correlation factors of signal fluctuations from the Sun, registered on spaced radiotelescopes (dots), with the index of solar activity in the radioband (the solid line indicates the Sun's radioemission flux in 10.7 cm).

3. DISCUSSION OF THE RESULTS

In view of the fact that the question of nature of the discovered quasi-periodical variations of Sun's radioemission flux appears to be most important at the present stage of investigations, it was necessary to analyse the results of observations from this point of view more carefully than in [9].

First of all it is necessary to point out that the investigated fluctuations represent not the sporadic and rarely observed phenomenon, but that they actually exist practically continuously, their intensity rising with the increase of solar activity. The general pattern of development of this phenomenon looks as follows. At "quiet" Sun, these fluctuations are manifest in the fact that the noise intensity at radiometer output noticeably exceeds the intensity of fluctuations of thermal radiation; with the appearance of active regions on the Sun's disk, the fluctuation amplitude increases, and there appear nonstationary variations of signal's mean level; further development of activity is accompanied by the appearance of weak microbursts with a fluctuating profile (these are bursts generally registered also at other radioastronomical stations); the bursts' intensity and the fluctuations of signal's level between the bursts continue to accrue; the frequency of bursts' appearance rises also; after disintegration of the active region or its withdrawal behind the western limb of the solar disk, the activity starts to decrease, the bursts gradually disappear, the fluctuations of the flux decrease and pass into the noises of the "active" Sun.

The systematic repetition of such a pattern of solar activity development in the centimeter band actually led us to assume that the investigated fluctuations are of solar origin.

To explain such a pattern by the influence of Earth's atmosphere is cumbersome. To do that, it is necessary to assume that: a) there is a correlation between the appearance of active regions on the Sun's disk and the increase of the number and intensity of inhomogeneities in the troposhere (it is then impossible to explain the close connection between the fluctuations and the microbursts of solar origin) or b) the increase of the amplitude of fluctuations is linked with a more intensive "scintillation" of the source with small angular dimensions (the active region in comparison with the entire solar disk) in the Earth's atmosphere.

Estimates have shown that in our case, this effect could induce an increase of fluctuations' intensity by no more than 5-10%. Experimental data show that fluctuations increase by several factors.

It is well known [20] that the spatial correlation radius of field fluctuation amplitude of a signal propagating in a turbulent medium depends on the ratio of the first Fresnel zone dimension $\sqrt{\lambda L}$ to the outer and inner turbulation scale (L_0 and l_0). In our case $L_0 > \sqrt{\lambda L} > l_0$ (10 m < $\sqrt{\lambda L}$ < 35 m). The conditions of our experiment corresponded to the case, when the fundamental influnce is exerted by inhomogeneities with dimension $l \sim \sqrt{\lambda L}$, related to the experimentally studied interval of spectral density variations of the refraction index $\Phi_n(x)$'s structural function. In this interval $\Phi_n(x) \sim x^{-11/3}$ and the correlation function of amplitude fluctuations has a characteristic scale (correlation radius) of the order of $\sqrt{\lambda L}$.

The influence of large-scale inhomogeneities is to a significant degree weakened. The correlation of fluctuations at antenna spacing by a distance $d \gg \sqrt{\lambda L}$ (d = 500 m) may be explained by a tropospheric mechanism, since, according to data of Kazes and Steinberg investigations [10-12], the correlation of fluctuations, definitely conditioned by the atmosphere, is no longer observed as early as at distances $d \simeq 200$ m.

Besides, the fluctuation of 2-3 maxima, observed in the spectra investigated by us, cannot be explained on the basis of known experimental data on the monotonic form of the dependence $\Phi_n(x)$. Although in the region of great x ($x > 2\pi/L_0$) the form is not universal, and since data are lacking for a theoretical generalization, there exist data on the character of the spectrum of $\Phi_n(x)$ within the section of interest to us [20], confirming the monotonic form of the dependence $\Phi_n(x)$. This means that in the spectrum of flux fluctuations only one maximum may exist in the frequency $f \approx V_\perp/\sqrt{2\pi\lambda L}$, where $V_\perp$ is the displacement velocity of inhomogeneities across the propagation direction of the wave. Comparison of maximum frequencies in spectra with values $V_\perp$, has shown that there is no correlation between them.

Comparison of temporal spectra of various meteorological characteristics with those obtained as a result of our experiments also attests to the fact that the latter could not be explained by the influence of the troposphere. Plotted in Fig.6 are: a) the frequency spectra of temperature fluctuations; b) the index of refraction and c) the Sun's radioemission flux, according to our data [21]. The maxima of our spectra fall into the region of the broad and stable "mesometeorological minimum".

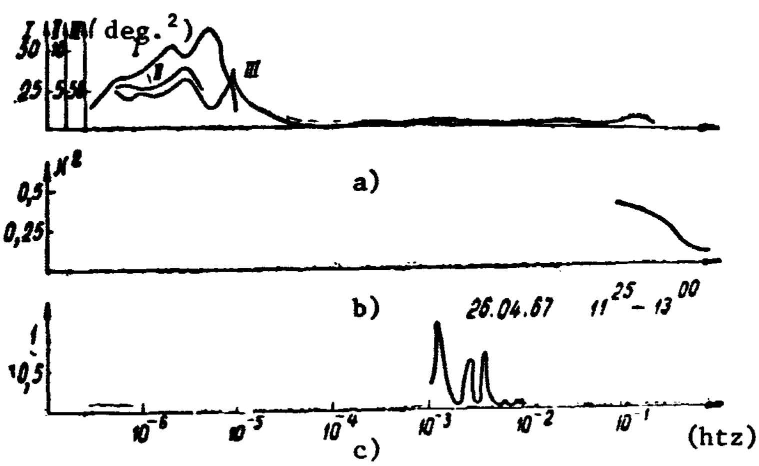

Fig. 6.

Comparison of various meteorological characteristics' temporal spectra with the spectrum of flux fluctuations of Sun's radioemission:

a) temperature pulsation spectrum;

b) pulsation spectrum of the index of refraction;

c) spectrum of flux fluctuations of Sun's radioemission.

Thus, analysis of the basic characteristics of the investigated phenomenon, has shown that for its explanation by the influence of tropospheric inhomogeneities, it is necessary to attribute to the fluctuation field of the index of refraction in the troposphere such specific properties that are in contradiction with all the known experimental and theoretical data on the troposphere's influence on the propagation of radiowaves. All this compels us to reject the possibility of explaining the quasi-periodical variations of the flux by means of the atmosphere, and allows us to confirm that these variations are conditioned by the motions in the Sun's atmosphere.

During field investigations of vertical frequencies and temporal variations of the magnetic fields on the Sun, periodical oscillations were detected with periods of the order of several minutes [1, 22]. The study of these phenomena allowed us to substantially refine the representation on the processes in the photosphere and in the Sun's chromosphere [23]. The periods of the discovered flux variations coincide with those of vertical oscillations of photosphere and lower chromosphere layers discovered by Leighton, Noyes and Simon [24] and Michard and Ewans [25], which point to a possible relationship between these phenomena.

Possible mechanisms of appearance in the spectrum of flux fluctuations of Sun's radioemission of "quasilines" were discussed in [26,27]. On the basis of obtained preliminary experimental data, it is possible to make some estimates of the scale of those processes on the Sun, which may lead to the observed effects.

Compiled in table I (below), are the values of fluctuations of brightness temperatures on elements of Sun's surface which are required so as to make the quasiperiodical flux fluctuations coincide with the experimental data; here N is the number of elements on the solar disk, Ω_e is the angular dimension of the element in seconds of arc.

The upper left-hand part of Table I, separated by a solid line, corresponds to such ΔT_b(°K) values, which could not be realized in the 3.3 cm wavelength at equilibrium radiation. Analogously, the lower right part is limited by the maximum possible number of elements on Sun's disk at their corresponding dimensions, The vertical line corresponds to maximum number of spicules in the upper chromosphere ($N_{cn} < 5.6 \cdot 10^4$). Thus, the most probable element characteristics, leading to perturbations in the fluctuation spectrum of the "quiet" Sun, are limited to the following points:

$10^3\ °K < \Delta T_b < 2.5 \cdot 10^4\ °K;\ 10^2 < N < 10^5;\ 10'' \times 10'' < \Omega_e < 2'' \times 2''$.

TABLE I

Ω_e \ N	10^2	10^3	10^4	10^5	10^6
1" x 1"	10^6	$3 \cdot 10^5$	10^5	$3 \cdot 10^4$	10^4
2" x 2"	$2.5 \cdot 10^5$	$8 \cdot 10^4$	$2.5 \cdot 10^4$	$8 \cdot 10^3$	$2.5 \cdot 10^3$
5" x 5"	$4 \cdot 10^4$	$1.2 \cdot 10^4$	$4 \cdot 10^3$	$1.2 \cdot 10^3$	$4 \cdot 10^2$
10" x 10"	10^4	$3 \cdot 10^3$	10^3	$3 \cdot 10^2$	10^2

In the first approximation these estimates do not contradict the contemporary representations on the structure of solar chromosphere. Therefore, the obtained results permit us to conclude that the peculiarities of the spectrum fluctuations discovered in the Sun's radioemission flux, are conditioned by processes in the upper chromosphere. The latter is confirmed by a high coincidence of maximum frequencies in the pulsation spectra of the field frequencies and the radioline intensity in solar chromosphere, obtained from optical observations [29]. This result turned out to be unexpected, as the currently known data on the structure and dynamics of solar chromosphere [1] did not provide a basis to expect the preservation of the form of spectral motions at transition from the lower to the upper chromosphere.

In conclusion the authors consider it their duty to thank M.I. Korbin, for the problem presentation and continuous attention to this work, and V.V. Zheleznyakov for the participation in the discussion of obtained results and valuable remarks.

**** THE END ****

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