One might suppose that the rise in temperature over a wide range in optical depth is caused by a nearly complete absorption of the emergent flux by TiO molecules. To test this hypothesis we have calculated models with a truncated spectrum. In this case the rise in temperature is far more pronounced.

We find from this comparison that absorption by TiO molecules, which is produced in the surface layers of the atmosphere and is very effective there, amounts to a nearly complete cutoff of the flux in the visible range, causing all the layers of the atmosphere to be heated. However, another molecule absorbing very efficiently, CO, extends over a much larger range in optical depth, and therefore is responsible not only for heating the deep layers but for strongly cooling the surface layers. To illustrate this behavior we include in Fig. 1 curves for the TiO and CO abundance distribution with respect to the total number of hydrogen atoms.

[1]B. M. Krupp, J. G. Collins, and H. R. Johnson, "The effects of TiO opacity on the atmospheric structure of cool stars," Astrophys. J. 219, 963-969 (1978).

[2]T. A. Kipper, "More about molecular absorption bands in the spectra of late-type stars," Publ. Tartu, Astrofiz. Obs. 44, 91-105 (1976).

[3]T. Tsuji, in: Colloquium on Late-Type Stars, ed. M. Hack, Trieste (1966).

[4]S. A. Golden, "Approximate spectral absorption coefficients of electronic transitions in diatomic molecules," J. Quant. Spectrosc. Rad. Transf. 7, 225-250 (1967).

[5]J. G. Collins and T. D. Fay, "Radiative opacities for the α, γ, and φ systems of TiO," J. Quant. Spectrosc. Rad. Trans. 14, 1259-72 (1974).

[6]M. L. Price, K. G. Sulzmann, and S. S. Penner, "Electronic-band oscillator strengths for the α and γ bands of TiO," J. Quant. Spectrosc. Rad. Transf. 14, 1273-75 (1974).

Development of fluctuations in local solar radio sources, and the growth of sunspot groups

G. B. Gel'freikh, V. G. Zandanov, and A. N. Korzhavin

Central Astronomical Observatory, Academy of Sciences of the USSR, Pulkovo,
Institute of Terrestrial Magnetism, the Ionosphere, and Radio-Wave Propagation, Siberian Branch, Academy of Sciences of the USSR, Irkutsk,
and Leningrad Branch, Special Astrophysical Observatory, Academy of Sciences of the USSR

(Submitted December 26, 1977; revised May 26, 1978)

Pis'ma Astron. Zh. 5, 42–46 (January 1979)

The time characteristics of the radio fluctuations of local solar sources at $\lambda = 3.5$ and 3.9 cm are investigated. Fluctuation components of period longer than 20 min are observed to strengthen when the leading sunspot in a group is growing larger. The oscillations tend to appear episodically. Peaks in the power spectrum often recur at the same value of the period.

PACS numbers: 96.60.Tf, 96.60.Qc, 96.60.Rd

A program of observations of solar radio emission with nearly continuous 24^h coverage was organized in April-May 1971 under the auspices of the Pulkovo Observatory and the Siberian Institute of Terrestrial Magnetism. These observations were carried out in Irkutsk at wavelength $\lambda = 3.5$ cm and at the Tonantzintla Observatory in Mexico at $\lambda = 3.9$ cm, using short-baseline radio interferometers. The instruments have a sensitivity adequate to reveal flux variations amounting to only 0.05% of the level of radiation from the entire sun.

The data have been reduced by techniques described elsewhere.[1,2] Figure 1 shows a sample power spectrum for the radio fluctuations. Distinct peaks occur at periods ranging from 5^m to $2^h.5$. Several authors, beginning with Yudin[3] in 1968, have remarked on the discrete character of the spectrum. The properties of the fluctuations have been reviewed in detail by Kobrin et al.[4,5] Nevertheless, the dependence of the fluctuation power spectrum on the evolution of groups of sunspots has not yet been adequately studied. To cope with this problem we need accurate estimates for the amplitude and the confidence of the individual peaks in the spectrum. In carrying out such an analysis we have assumed that each realization comprises an ensemble of both quasiperiodic and random components. Since the power spectrum falls off toward higher frequencies, the random part cannot be described as white Gaussian noise. We have therefore estimated the amplitudes and confidence levels in two steps.

First we suppose that the random component is white noise, and we determine the peaks in the spectra that differ from the estimated noise component at the 0.95 significance level. These peaks are subtracted from the realization. Then we assume that the autocorrelation function of the random component may be approximated by an exponential for the form $\exp(\alpha|\tau|)$. This assumption is equivalent to regarding the radio emission of local sources as modulated not only by a quasiperiodic component but by noise with a spectral density of the form $S(\omega) \sim \alpha/(\alpha^2 + \omega^2)$ ("red" noise). The amplitudes of the peaks are measured from the corresponding curve for the spectrum

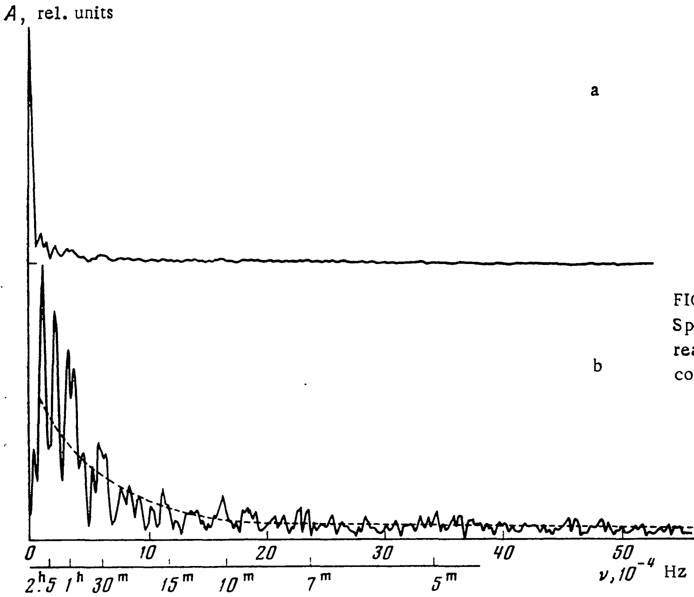

FIG. 1. Power spectrum for fluctuations observed on May 27, 1971. a) Spectrum for the original series of measurements; b) spectrum of the same realization after removal of the trend; dashed curve, spectrum of the noise component.

of the random component, and are compared with the values of that component in the interval where a given peak is located.

We have applied the results obtained in this way to examine how the fluctuations depend on the evolution of spot groups. To this end we have studied the changes in the fluctuation power spectrum from May 20 to 31, 1971. Figure 2 illustrates the amplitudes of the spectrum components having periods $T \approx 1^h.5$, 30^m, 10^m, and 7^m. Notice that the amplitudes of the components with $T > 20^m$ were substantially larger on May 25-27 than on the other dates. The lower part of Fig. 2 shows the areas of the leading spots of the various groups as published in the USSR solar bulletin, Solnechnye Dannye.[6] Within the time interval considered here we can discriminate three different phases in the development of the spot groups:

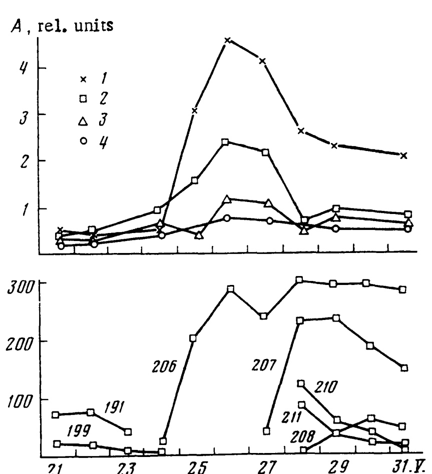

FIG. 2. Correlation between the fluctuation power spectrum and the evolution of the spot groups. Top, amplitude of spectrum components with periods T of approximately: 1) $1^h.2$-$1^h.5$; 2) 25-30^m; 3) 10-12^m; 4) 7^m. Bottom, area of leading spots in groups numbered according to the bulletin Solnechnye Dannye.

a) May 21-24. Two groups of relatively low activity were present on the sun, and on these dates the fluctuations maintained a low level.

b) May 25-27. The fluctuations with $T > 20^m$ had significantly larger amplitudes. Meanwhile groups 206 and 207 (as numbered in Solnechnye Dannye) were developing intensively.

c) May 28-31. The groups reached their maximum area, showing no further growth, but the amplitudes of the fluctuation components mentioned above held at about the same level as on May 21-24.

Since we are comparing amplitudes of the spectrum components averaged over the length of the realization and values of the areas at particular times, the conclusions may seem of doubtful reliability. For example, the leading spot in group 206 grew considerably larger between May 24 and May 25, and the growth may have occurred on either date. A comparison of the sunspot magnetic-field charts given in Solnechnye Dannye (at $\approx 5^h$ UT) with the Hα photographs and photospheric charts (at $\approx 14^h$ UT) published in Solar–Geophysical Data[7] indicates that the principal changes in the group took place on May 25; the amplitudes of the fluctuations with $T > 20^m$ were much larger on that day than on the preceding one. A similar comparison for group 207, whose leading spot enlarged greatly between May 27 and May 28, shows that the development of this group ceased beginning May 28 (at $\approx 5^h$ UT). Hence the enhanced level of the fluctuations with $T > 20^m$ might be associated with the development of group 207. The components with $T < 20^m$ did not exhibit any appreciable rise in amplitude on May 25-27; slight rises by practically the same amount also occurred during the other phases in the evolution of the groups.

We have made a further analysis of the character of the relatively short-period fluctuations ($T \leq 30^m$). Realizations covering many hours were divided for this purpose into $1^h.5$ series with extensive overlap; the start of each subsequent interval was shifted by 20^m. The resulting realizations were then analyzed in the manner de-

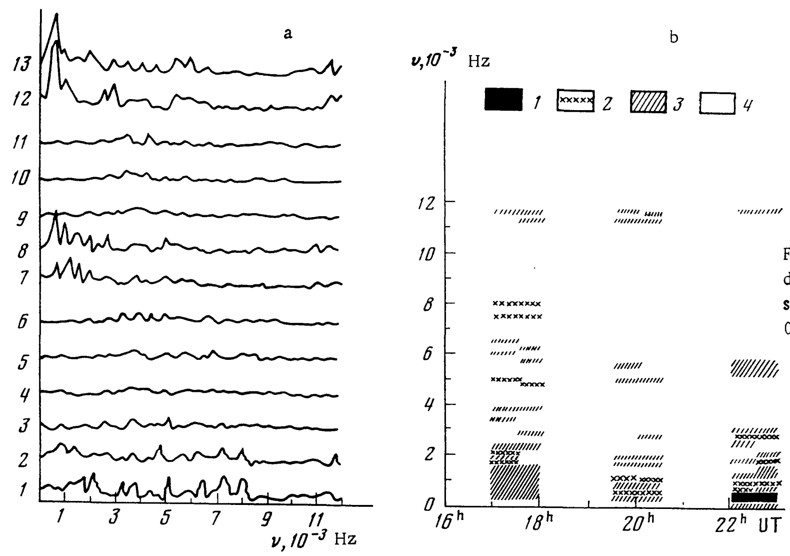

FIG. 3. Evolution of the fluctuation power spectrum on a typical date, May 21, 1971. a) Sliding power-spectrum curves; b) dynamic spectrum of fluctuations. Hatching: 1) $A > 0.5A_{max}$; 2) $A = (0.25\text{-}0.5)A_{max}$; 3) $A = (0.1\text{-}0.25)A_{max}$; 4) $A < 0.1A_{max}$.

scribed above. Figure 3a displays an example of one of these sliding power spectra. The corresponding dynamic spectrum of the fluctuation is shown in Fig. 3b. From our analysis of the dynamic spectra for 20 days, we can recognize several important properties: a) The fluctuations develop episodically, usually appearing in one or two successive realizations but sometimes in a larger number; intervals of a rise in the level of the fluctuations alternate with intervals of sharp decline. b) Peaks in the power spectrum generally occur in clusters, covering a fairly broad frequency range. c) When oscillations recur, there is a tendency for repeated formation of peaks in the same portions of the spectrum.

Previously we have attributed[8] the quasiperiodic oscillations in the radio flux of local sources to an excitation of structures present in the corona by a flux of magnetohydrodynamic waves, which would travel up from the photospheric layers along the field rubes of the spots. In this event, intensive damping of the waves at particular resonance (with respect to the MHD oscillations) frequencies of the coronal condensations could serve to produce quasiperiodic modulation of the radio emission of the local sources.

Our present results show, however, that these structures are not excited continuously, but rather in a pulsed manner. And when fluctuations arise we observe oscillations of various periods. The fluctuations could then be regarded as a consequence of local releases of energy in the corona above active regions, such as through the formation and turbulization of current sheets. Unlike chromospheric flares, which are generally associated with current sheets, the process we are discussing here is far weaker in terms of energy, and thus probably occurs more often. The relative stability of the magnetic field configuration above spot groups is responsible for the repetition of periods, and the broad frequency bands observed in the power spectrum could result either from the development of overtones of the fundamental frequency characteristic of a magnetic structure in the corona or from the diversified sizes of active regions.

The emergence of new magnetic field tubes at the surface (the growth in the area of spots) serves either to produce a current sheet or to excite internal gravitational waves, followed by their capture in the transition zone between chromosphere and corona.[9] Long gravitational waves will naturally have oscillations with lower natural frequencies. This point of view accords with the fact that the fluctuations in solar radio emission become stronger during periods when flare activity is enhanced.[10-12]

[1]A. B. Berlin, G. B. Gel'freikh, V. G. Zandanov, A. N. Korzhavin, and L. E. Treskova, "Preliminary results of a power-spectrum analysis of solar radio fluctuations," Radiofizika 16, 1366-68 (1973) [Radiophys. Quantum Electron. 16, 1050-52 (1975)].

[2]V. G. Zandanov and T. A. Treskov, "An interferometer for measuring fluctuations in solar radio emission" [in Russian], Issled. Geomag. Aeron. Fiz. Solntsa No. 26, 187-196 (1973).

[3]O. I. Yudin, "Quasiperiodic low-frequency solar radio-wave fluctuations," Dokl. Akad. Nauk SSSR 180, 821-823 (1968) [Sov. Phys. Dokl. 13, 503-505 (1968)].

[4]M. M. Kobrin, A. I. Korshunov, and V. V. Pakhomov, "Quasiperiodic components in the fluctuations of solar radio emission," Usp. Fiz. Nauk 109, 773 (1973) [Sov. Phys. Usp. 16, 287-288 (1974)].

[5]M. M. Kobrin, "An analysis of solar radio fluctuations, and an opportunity for obtaining information on certain physical processes on the sun," Phys. Solariterr. (Potsdam) No. 2, 3-21 (1976).

[6]Solnechnye Dannye (1971), No. 5.

[7]Solar–Geophys. Data No. 323, Part 1, 67 (1971).

[8]G. B. Gel'freikh, O. G. Derevyanko, A. N. Korzhavin, and N. P. Stasyuk, "Periodic fluctuations in the flux of local solar radio sources" [in Russian], Solnech. Dannye (1969), No. 9, 88-94.

[9]V. V. Kasinskii and V. A. Krat, "On the solar tsunami," Solar Phys. 31, 219-228 (1973).

[10]M. M. Kobrin, A. I. Korshunov, S. D. Snegirev, and B. V. Timofeev, "A sharp enhancement of the quasiperiodic components of the fluctuations in the slope of the 3-cm solar radio spectrum prior to the active events of August 1972" [in Russian], Solnech. Dannye (1973), No. 10, 79-85.

[11]L. A. Pustil'nik and N. P. Stasyuk, "Periodic fluctuations in the flux from local sources of the S-component of solar radio emission" [in Russian], Astrofiz. Issled. – Izv. Spets. Astrofiz. Obs. Akad. Nauk SSSR No. 6, 55-91 (1974).

[12]G. B. Gel'freikh, V. G. Ledenev, and V. P. Nefed'ev, "Fluctuations in the polarized 3.2-cm solar radio emission, and flare activity in sunspot groups" [in Russian], Issled. Geomag. Aeron. Fiz. Solntsa No. 37, 19-23 (1975).