metric disturbances the curvature of the tube will become a periodic function of the longitudinal coordinate. Possibly several linear segments may be formed in the tube, such that for each segment there is no distortion of the entropy gradient in the adjacent nonmagnetized regions. The junction points of the linear segments could be located beneath the convection zone.

It is worth noting that below the zone of field enhancement in this model there will be a transition layer (probably very thin) having a diminished latitudinal gradient of the rotational velocity. This layer might be located, for example, in the transition zone for supergranulation cells to giant convection cells. The angular velocity here would evidently fall off with depth at low and middle latitudes. Such a distribution for the rotational velocity could facilitate the process of change of polarity of the magnetic field with transition from one 11-yr cycle to the next. According to the solar-cycle model that we have discussed in a paper,[10] at the close of the phase of field enhancement a nonaxisymmetric instability will be excited, and part of the nearly toroidal magnetic field will be submerged in layers at a deeper level. If the angular velocity decreases with depth, the submerged field will overtake the surrounding medium. In this event the direction of the meridional field component may undergo a change.[10] The fact that the rotational-velocity distribution may be different at higher latitudes is not so important, because the main processes of field amplification take place at lower latitudes.

---

1)If the field is weak, with $H^2 \ll 8\pi p$, the entropy gradient will be expressed in terms of r-derivatives of the integral in the right-hand member of Eq. (9), even when self-gravitation of the medium is taken into account. We have performed calculations and obtained numerical estimates for the case of a toroidal field.[1,3]

---

[1] Yu. V. Vandakurov, Astron. Zh. 51, 672 (1974) [Sov. Astron. 18, 397 (1974)].

[2] Yu. V. Vandakurov, Solnech. Dannye (1974), No. 5, 72.

[3] Yu. V. Vandakurov, Convection on the Sun and the 11-Year Cycle [in Russian], Nauka, Leningrad (1976).

[4] J. O. Stenflo, Solar Phys. 32, 41 (1973).

[5] S. Chandrasekhar, Astrophys. J. 124, 244 (1956).

[6] J. M. Wilcox, Space Sci. Rev. 8, 258 (1968).

[7] J. O. Stenflo, Solar Phys. 36, 495 (1974).

[8] E. M. Drobyshevskii and V. S. Yuferev, J. Fluid Mech. 65, 33 (1974).

[9] Yu. V. Vandakurov, Astron. Zh. 49, 324 (1972) [Sov. Astron. 16, 265 (1972)].

[10] Yu. V. Vandakurov, Astron. Zh. 52, 351 (1975) [Sov. Astron. 19, 215 (1975)].

Translated by R. B. Rodman

Microstructure in the continuous radiation of type IV meter bursts. Observations and model of the source

G. P. Chernov

Institute of Terrestrial Magnetism, the Ionosphere, and Radio-Wave Propagation, USSR Academy of Sciences

(Submitted October 31, 1975)

Astron. Zh. **53**, 798–811 (July–August 1976)

The results of high-resolution spectral observations for July 3, 1974, during which a unique microstructure of the continuous radiation of a type IV meter burst was recorded on the spectrographs of the Institute of Terrestrial Magnetism, the Ionosphere, and Radio-Wave Propagation, USSR Academy of Sciences, are discussed. The continuum radiation was modulated by one-second pulsations consisting of bands and points in emission and absorption which produced complex chaotic forms in the spectrum. Various radiation microstructures observed in other events are compared and the principal demands on the generation mechanism are worked out. A model is proposed for the radiation source in the form of a magnetic field tube in which the high-frequency emission can be modulated by wave packets of whistlers. The interaction of whistlers with Langmuir oscillations is discussed in detail in the second part of the report.

PACS numbers: 96.20.Sh, 96.20.Qf

I. INTRODUCTION

On July 3, 1974 a unique microstructure of the continuous radiation of a type IV burst was observed in the range of 93-220 MHz on the radio spectrographs of the Institute of Terrestrial Magnetism, the Ionosphere, and Radio-Wave Propagation, Academy of Sciences of the USSR (ITMIRAS). In contrast to events observed earlier with a microstructure of the "zebra" band type having slowly varying parameters, such as that[1] of May 3, 1973, in this event the short-lived emission and absorption bands were distinguished by the complexity of the spectral forms. The microstructure followed short-lived pulsations, in which the flux density reached $2000 \cdot 10^{-22}$ W/m$^2 \cdot$ Hz.

A zebra structure and filaments with an intermediate frequency drift (fiber bursts) had already been recorded by spectral observations in the preceding solar activity cycle. The first event with narrow emission and absorption bands to have startled observers was seen[2] on November 4, 1957. An even more complex band structure was observed on August 18, 1959 by Elgaroy.[3] The individual narrow emission bands, accompanied by absorption with a low-frequency (LF) edge, have received the name of fiber bursts.[4] A whole series of continuous bursts with diverse bands in emission and absorption, which have come to be called the zebra structure[5–9] and other names, have been recorded in recent years.

A unified interpretation of the continuous radiation having a microstructure raises considerable difficulties, in large measure connected with the insufficient systematization of the observational data both in the radio range and on certain optical properties of the active regions. In the present article the principal features of this radiation are analyzed on the examples of several type IV bursts having a microstructure which were observed at ITMIRAS and of all the events described in the literature, and the necessary demands on the generation mechanism are worked out. On the basis of this analysis a model is proposed for the emission source in the form of a magnetic trap filled with wave packets of whistlers which give rise to the modulation of the high-frequency radiation. In the second part of the article we will examine in detail the interaction of whistlers with Langmuir waves with allowance for the conditions of escape of the radio radiation from the corona and we will calculate the frequency profiles of the bands in emission and absorption.

II. GENERAL CHARACTERISTICS OF BURST OF JULY 3, 1974

1. Connection with active region. The radio burst of July 3, 1974 was observed at ITMIRAS on two spectrographs, with an increased recording speed (1 cm/sec) in the range of 180-220 MHz and with a slow speed in the range of 93-186 MHz, and at three fixed frequencies of 74, 207, and 3000 MHz. Only the radiation flux was recorded at the 207 MHz frequency while the circular polarization (parameters I and V) was recorded at 74 and 3000 MHz. The burst began during a large flare of importance 2B in McMath region 13043 according to the data of ref. 10 (or No. 96 in ref. 11). This sunspot group, with an indication of the individual magnetic field strengths at the level of the photosphere in hundreds[11] of oersteds, is shown schematically in Fig. 1 together with a recording of the flux at the 207 MHz frequency. The duration of the flare from the maximum phase is shown by sloping lines in the top part of the figure while its position in the sunspot group is shown by a cross. The group had a large area $S_p \approx 1230$ m.s.n. and numbered ~ 68 spots, extending almost 20° from east to west. The principal spot with northern polarity is smaller in area than the trailing part of the group with a predominantly southern polarity. The radio source was probably located above the trailing part, since its position usually coincides with the position of the concomitant flare. The multipolarity of the region also attracts attention – the penetration into one another of sunspots having opposite magnetic field polarities. Such a structure is connected with the active reorganization of the sunspot group, which becomes noticeable if one compares the magnetograms of Kitt Peak Observatory for July 1 and 4 in ref. 10.

The high flare activity of McMath region 13043, which started on July 1, continued until July 6. High activity of type III bursts was observed on all these days. The flare with which the radio burst under discussion was connected was accompanied by a prolonged burst of protons, recorded on the NOAA-2 and -3 satellites.[10] Several hours after the flare the flux of protons with energies of > 10 MeV reached ~ 130 particle/cm^2 · sec · sr.

2. Spectral classification. The beginning of the radio burst can be traced from the spectrum in the 93-186 MHz range in Fig. 2a. Against the background of a growing continuum at 08^{h}31^m.3 UT there began a series of radiation pulsations which continued to 08^{h}38^{m}UT. According to the data of the spectrograph at Weissenau in ref. 10 pulsations were observed in the 30-960 MHz range and were identified with type III bursts. In contrast to the

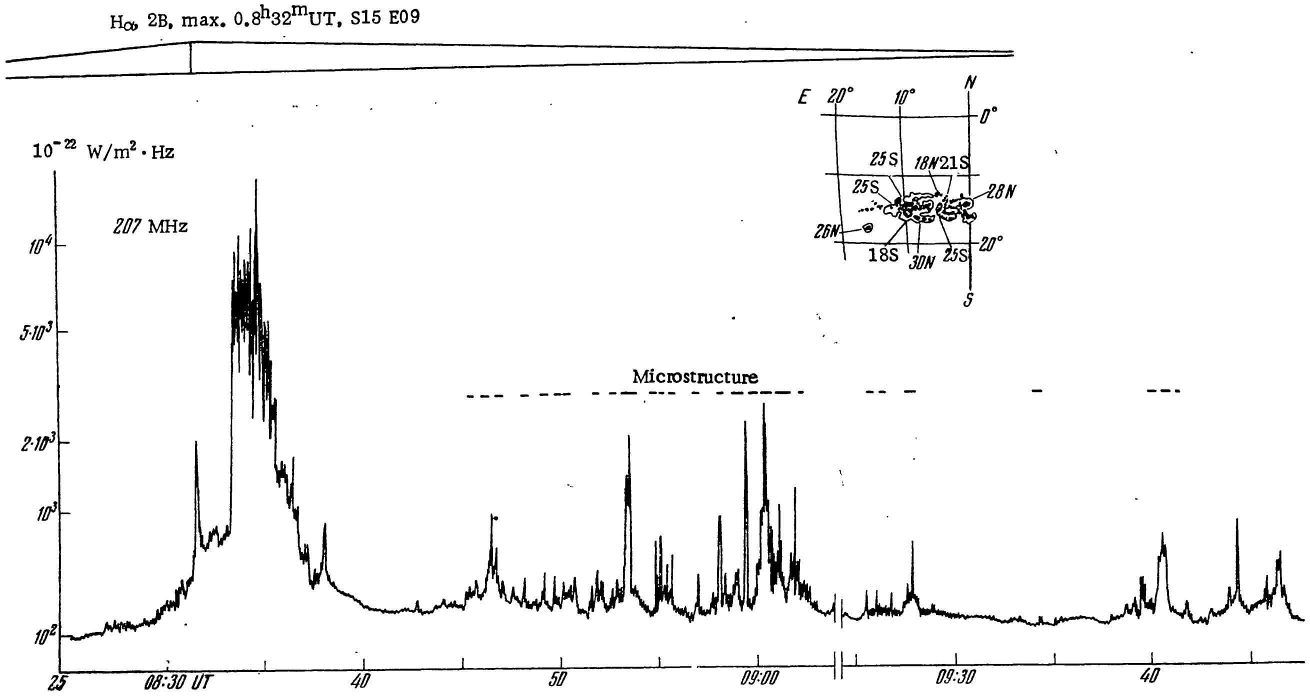

Fig. 1. Flux density at 207 MHz frequency for burst of July 3, 1974 with drawing of active region (Solnechnye Dannye) and parameters of flare.

latter, however, they appear almost instantaneously in a wide frequency range, which is characteristic of radiation pulsations in type IV bursts. The same initial interval of the burst on a high-resolution spectrograph is demonstrated in Fig. 2b-e. The strong pulsations, whose flux density reached $15{,}000 \cdot 10^{-22}$ W/m^2·Hz at maximum, are superimposed on numerous scraps of radiation, characteristic of type II bursts. The weak radiation of a type II burst is probably present in the interval of $08^h32^m.5$–08^h37^m, and the drifting band of bursts in the interval of 08^h35^m–08^h37^m in Fig. 2a may also be a part of it. The large radiation peak at 08^h33^m–08^h37^m must be identified with the strong pulsating phase of a type IV burst (Fig. 1).

At this time the radiation maximum lay in the meter range. At the 3000 MHz frequency the flux density reached only $1100 \cdot 10^{-22}$ W/m^2·Hz. Following the maximum phase the level of the continuum at 207 MHz fell smoothly from 150 to 80 units of 10^{-22} W/m^2·Hz by 10^h00^m UT. Pulsations of the same duration as during the maximum phase (~ 0.5-3 sec) but of an entirely different nature continued to follow during this entire interval. The radiation within the pulsations was strongly modulated and had the character of discrete regions in absorption and emission on the spectrum.

In Fig. 1 the times of appearance of the microstructure in the pulsations are noted by horizontal segments above the recording of the flux at 207 MHz. Groups of type III bursts (III GGRS) occupying the frequency range of 170-700 MHz are given in ref. 10 based on the data of the spectrograph at Weissenau during the time of appearance of the pulsations. On the dynamic spectra of the multichannel spectrograph at Dwingelo (Holland) the pulsations consist of separate bands and points in emission and absorption (Fig. 3b).1) The bands are well seen in the entire range of 200-315 MHz both on the sensitive channels with a smoothing null recording level $[\Delta f(I)/\langle f(I)\rangle]$ and on the coarse logarithmic channels[12] [log f(I)]. The pulsations with a microstructure on the spectra obtained at Dwingelo and ITMIRAS coincide exactly in time, which indicates their solar origin.

The low-frequency boundary of the pulsations with a microstructure is illustrated in Fig. 3a. In contrast to the pulsations during the maximum phase of the burst, which occupied the frequency range from 30 to 960 MHz, the pulsations with a microstructure had a low-frequency boundary of ~ 165 MHz, and in light of the observations at Dwingelo and Weissenau they probably extended to a frequency of 700 MHz. The range of appearance of the pulsations with a microstructure contracted with time and drifted slowly to lower frequencies. After 09^h05^mUT the pulsations with a microstructure became weaker and appeared more rarely. But, starting at the same time, separate bands in emission and absorption began to appear at lower frequencies. In the period from 09^h05^m to 10^h30^mUT the continuous radiation at the fixed frequency of 74 MHz was modulated in the form of surges in emission and absorption having two characteristic durations: 1-3 and 20-40 sec.

3. Polarization. During the burst of July 3, 1974 polarization was recorded at ITMIRAS in the meter range only at the 74 MHz frequency. During the maximum phase of the burst the radiation was weakly polarized with right rotation. Subsequently a smooth rise in the continuum began with a simultaneous growth in polarization. The modulation of the continuum noted above was in the strongly polarized radiation (~ 50%) of the right sign. However, the polarization at higher frequencies, in the range of a 180-220 MHz spectrograph with high frequency-time resolution, is of interest for future analysis. This range is covered by the multichannel spectrograph with simultaneous recording of circular polarization at Dwingelo (Hol-

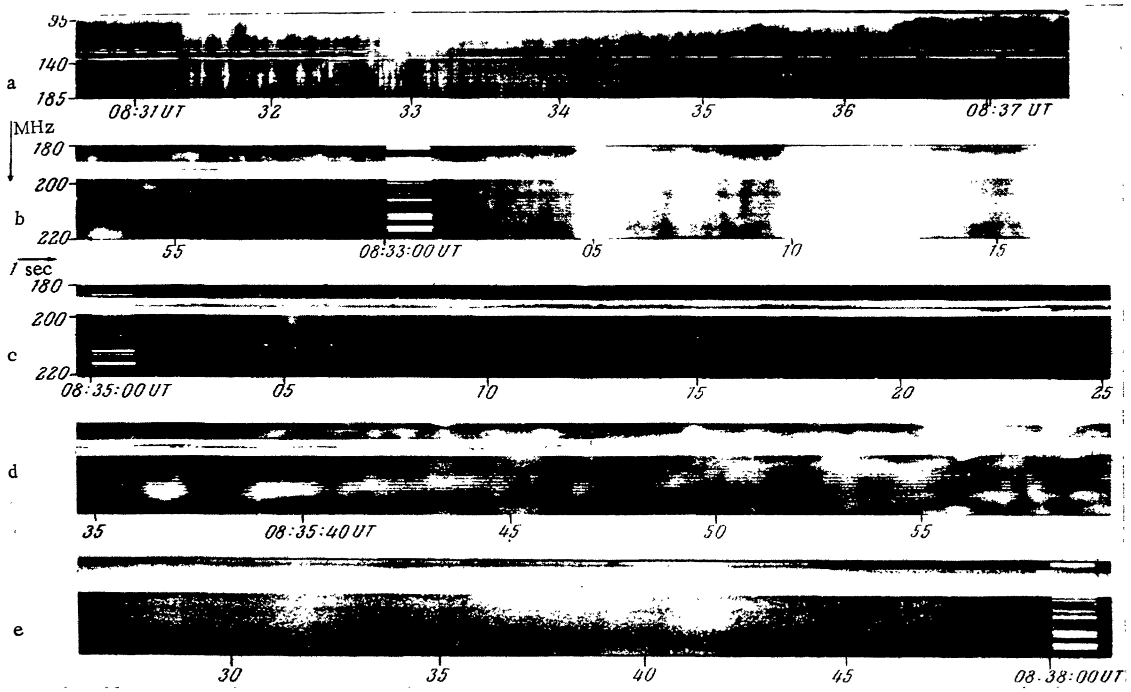

Fig. 2. Start of burst of July 3, 1974 on spectrum in 95-220 MHz range.

land). A typical example of the spectrum of pulsating microstructure during its most developed stage in the range of this spectrograph of 200-315 MHz is illustrated in Fig. 3b. In the polarization part of the spectrum $P = f(I_L) - f(I_R)$ emission is absent, which indicates strong polarization with right rotation.[12] In this case right rotation should correspond to emission of the ordinary wave, since the source lay above a trailing sunspot with a predominantly southern magnetic field polarity.

From all that has been said in Sec. II one can conclude that the source of the type IV burst of July 3, 1974 was probably stationary. The sporadic nature of the radiation, the long duration (the continuum declined smoothly for several hours), and the ordinary type of wave[13] can be brought out in favor of this assertion.

III. MICROSTRUCTURE OF BURST OF JULY 3, 1974

Let us now examine in more detail the dynamic spectra of the microstructure in the range of the high-resolution spectrograph. During the powerful phase of the burst the pulsating radiation revealed almost no microstructure. The pulsations of 1-3 sec duration are themselves the fine structure of the continuous radiation of the type IV burst. Therefore let us clarify what we will consider as the microstructure of the radiation within such pulsations, among which we will include various elements in emission and absorption having a duration of ~ 0.1-0.2 sec at a fixed frequency and an instantaneous band of ~ 1-2 MHz. Of such elements in the initial period one can only note a burst of the "spike" type at $08^h35^m19^s$ in Fig. 2c and the discrete nature of the noise containing elements in absorption at the limit of resolution of the spectrograph at $08^h37^m.5-08^h38^m.0$ in Fig. 2e.

The microstructure developed from scarcely discernible bands, starting at 08^h45^m. Then the pulsations with a microstructure became stronger, reaching a maximum ($\sim 2000 \cdot 10^{-22}$ W/m$^2\cdot$ Hz) at 08^h53^m and $08^h59^m-09^h02^m$ (Fig. 1). Then the pulsations became rarer and weaker, appearing until ~ 09^h43^m. Typical examples of the pulsating microstructure in the order of their appearance are presented in Fig. 4. One can distinguish the following individual elements of the microstructure, denoting them by the serial numbers written above the spectra: 1) bands in emission and absorption with a smoothly varying drift to higher frequencies; 2) bands in emission and absorption drifting to lower frequencies with a constant rate (bands of types 1 and 2 sometimes undergo discontinuities); 3) bands in emission and absorption with an abruptly varying direction of drift (in a saw-tooth form); 4) columns, consisting of bands in emission and absorption, which turn on instantaneously in a wide frequency band in a time of ~ 0.1-0.2 sec; 5) bright points with a band of ~ 1 MHz and a duration of ~ 0.1 sec; 6) points in absorption with a band of ~ 0.3 MHz and a duration of ~ 0.03 sec; 7) chaotic forms of wide-band absorption (gaps in emission); 8) bands in emission of the "spike" type with a duration of ~ 0.04 sec at a fixed frequency and drifting rapidly to higher frequencies; 9) elements of "tadpole" shape with an eye and a tail in emission and a body in absorption; the eye lasts ~ 0.04-0.06 sec while the body and tail last ~ 0.1 sec. Sometimes they can be taken as a superposition of elements of types 3, 5, and 7. The bands and the durations of their component elements are about three times smaller than those of the tadpoles observed[8] on March 2, 1970, and therefore one could call them miniature tadpoles.

The last element (10) can be considered as the very pulsations of the radiation, with a duration of from 1 to 5 sec and sometimes containing several microstructure elements at once, forming a network of different bands.

Elements 1-4 can be considered as a zebra structure

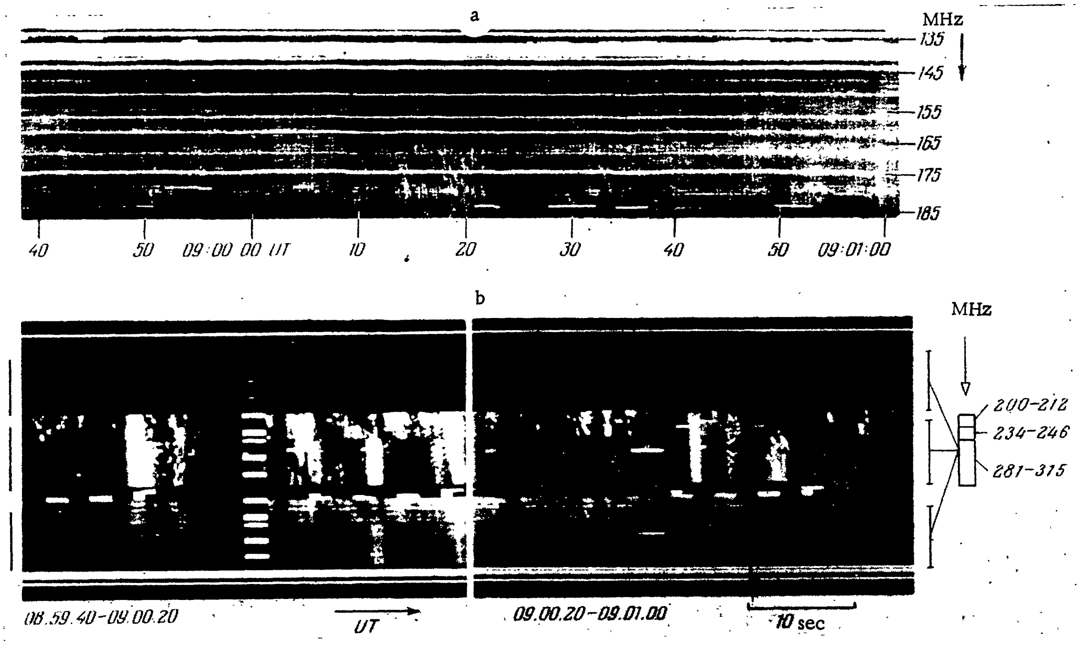

Fig. 3. a) Spectrum of several microstructure pulsations in the burst of July 3, 1974, demonstrating the low-frequency boundary of ~ 165 MHz; b) the same interval of the burst on the spectrum of the multichannel spectrograph at Dwingelo (Holland) (Slottje, private communication). Upper part of spectrum: polarization $P = f(I_L)/-f(I_R)$, middle part: recording with smoothing null level $\Delta f(I)/<f(I)>$, lower part: logarithmic recording[12] log f(I).

Fig. 4. Microstructure pulsations of the event of July 3, 1974 on the high-resolution spectrograph. Numbers above spectra denote the different types of bands in emission and absorption described in the text.

having an unsteady nature. The frequency width of the bands in emission and in absorption varied both with frequency and with time, remaining within the limits of $\sim$1-3 MHz. One or two lines of types 1 and 2 often appeared. The position of the absorption on the LF edge of the line in emission is clearly seen in these cases, and they do not differ from fiber bursts (Fig. 3b and d). The most miniature elements of the microstructure are the points in absorption 6, which were noted in Fig. 2e. They are a frequent element in Fig. 4a, d-f, but are clearest in the enlarged spectrum of Fig. 5c. These absorptions are not always accompanied by emission at the HF edge, in contrast to the bright points of type 5, which, as a rule, are accompanied by absorption at the LF edge.

In order to answer the question of whether the bands in emission stand out as gaps (absorptions) of the continuum or whether strengthening of the continuous emission occurs in them we carried out microphotometry of the spectra. Frequency profiles of the zebra structure at the times marked by arrows above the spectra are illustrated in Fig. 5. The profiles were plotted in relative logarithmic units of intensity with allowance for the nonuniformity of the sensitivity in the range of the spectrograph. It is seen from the figure that the continuum is strengthened by two to five times in the emission lines, while in the absorption lines the radiation level is $\sim$ 0.5-0.7 of the surrounding continuum, the level of which is marked by a dashed line (F_{cp} is the continuum within the pulsations). The average level F_c of the continuous radiation between pulsations remained considerably lower. This result is very important for the interpretation of the zebra structure.

The sporadic nature of the microstructure, expressed in the continuous alternation and superposition of the various elements in emission and absorption, can indicate the common nature of the mechanism of generation of all the microstructure elements. Their variety and superposition are probably a consequence of the unsteady conditions in the source and the simultaneous emission from several sources. The development of a microstructure in a time of $\sim$ 1 h is evidently connected with the reorganization of the active region, which is indicated by the rapid changes in the direction of the magnetic field in McMath region 13043 on July 3 which were noted above.

One can also conclude from an analysis of the observations performed (analogous to the conclusion of ref. 1 concerning the burst of May 3, 1973) that the precise level of the continuous emission beginning with which the radiation reveals a microstructure does not have critical importance, since it was not observed in the strongest radiation pulsations.

IV. FILAMENTARY STRUCTURE OF RADIATION IN OTHER EVENTS

Let us find some common aspects of the structures, consisting of bands (or filaments) in emission and absorption, which have been observed in other events, in order to find the common demands on the generation mechanism. A survey of the spectra of radiation microstructure known from the literature (refs. 2-9 and others) assures one that its shapes are quite varied from event to event. Sometimes a regular zebra structure is observed (June 29, 1971).[8] In other events the microstructure has been very

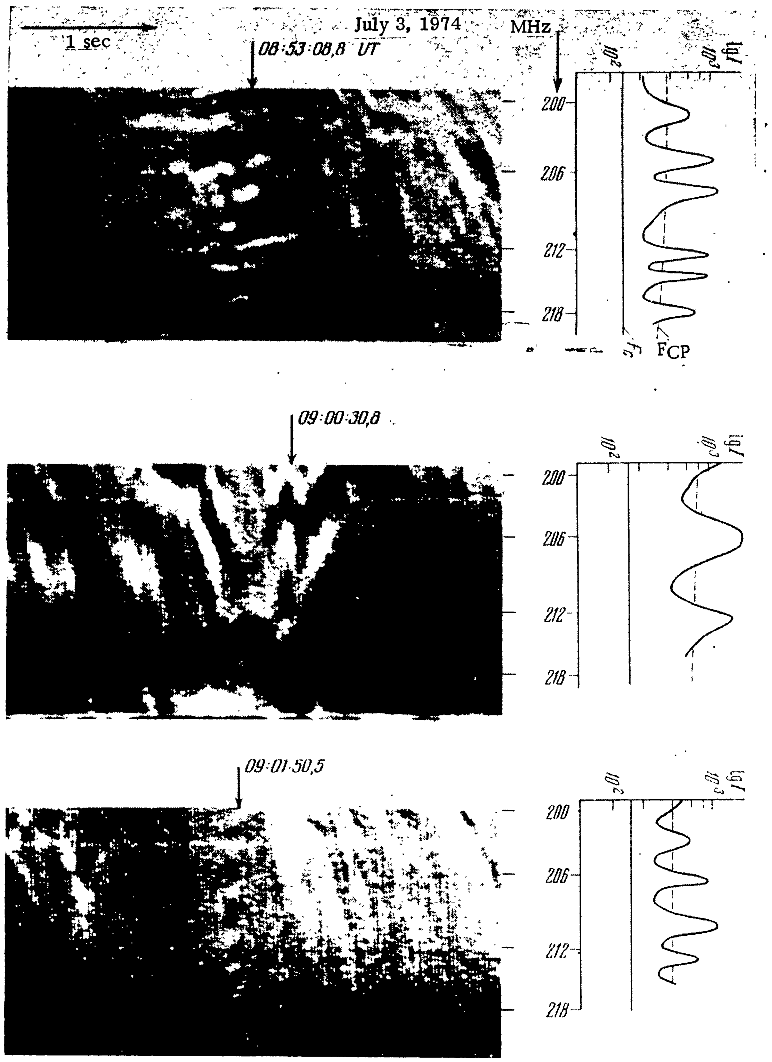

Fig. 5. Enlarged sections of spectra marked in Fig. 4 by the word "profile." Frequency profiles obtained by microphotometry of the spectra in relative logarithmic units at the times marked by arrows above the spectra are presented in the same frequency scale as the spectra.

complex (March 2, 1970,[8] July 3, 1974), and in this case the question of its solar origin comes up. The concordance of spectra obtained in observations from separated sites removes the question of the origin of the microstructure in the earth's magnetosphere or ionosphere. Even for the first event having narrow radiation bands accompanied by absorption at the LF edge on November 4, 1957 it was shown that spectra obtained at sites separated by 2000 km coincided in the smallest details.[2] Similar confirmations of the solar origin of the microstructure were made in ref. 3 for the event of August 18, 1959 and in ref. 8 for the event of March 2, 1970, as well as for the bursts observed at ITMIRAS on May 3, 1973 and July 3, 1974. Let us now examine the principal characteristics of this radio radiation and its connection with active regions.

1. Type of activity in radio range. A microstructure has been observed, as a rule, in the continuous radiation of type IV bursts. Of the 38 cases of the appearance of a microstructure collected from the literature it has been observed without a wide-band type IV burst in only 12. In all 12 of these cases, however, continuous meter bursts were also observed, but they were weak and not prolonged and often accompanied by type III bursts. These include the event of November 4, 1957,[2] bursts having parallel bands with constant frequency drift (PCDB) observed on June 3, 7, and 9, 1968,[6] the event of July 23, 1970,[14] and several bursts noted in ref. 5 (March 17, May 27, and September 4, 1969 and February 8, June 13, September 6, and November 14, 1970). Microfilament bursts characteristic of wide-band type IV bursts were not observed in any of these cases.

It is also important to know whether the source producing the type IV radiation with a microstructure is moving or stationary. Since measurements of the positions of the sources of such bursts have not been conducted, the type of source can only be presumed, knowing the type of wave and the overall spectrum of the event. It is known that the extraordinary wave is emitted by moving sources while the ordinary wave is emitted by stationary sources.[13,15] The ordinary type of wave for stationary type IV sources is confirmed by observations on the Culgoora radio helio-

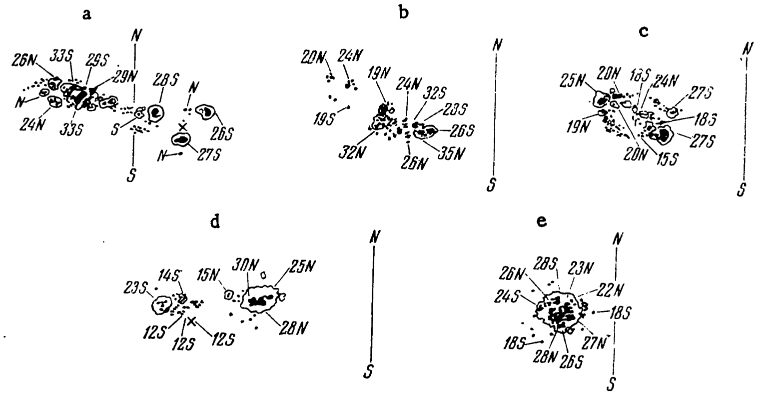

Fig. 6. Drawings of several sunspot groups, demonstrating the multipolarity and large numbers of sunspots in the regions associated with continuous radio bursts with a microstructure: a) May 25, 1967[6]; b) July 23, 1970; c) November 13, 1970[5]; d) March 6, 1972[7]; e) August 4, 1972.[19]

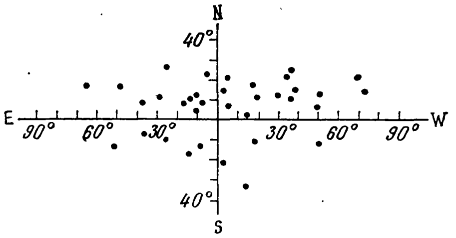

Fig. 7. Heliographic positions of flares connected with 35 type IV bursts with a zebra structure.

graph. It is not hard to confirm this by comparing maps of the magnetic fields of the corresponding sunspot groups with the sign of the polarization for the bursts discussed in ref. 16 (Fig. 20) and ref. 17 (Fig. 4).

Polarization measurements of the zebra structure were not carried out in each event, however, and in many cases the sign of the polarization does not make it possible to determine the type of wave, since the corresponding active regions display multipolarity of the magnetic field (Fig. 6). In all the cases when circular polarization was recorded the degree of polarization was high. A high degree of polarization was noted in the events of November 4, 1975,[2] August 18, 1959 (ref. 3, p. 232), March 2, 1970,[18] June 29, 1971,[8] March 6, 1972,[9] and May 3, 1973.[1] However, the type of wave is determined reliably only in the two events observed at ITMIRAS on May 3, 1973 and July 3, 1974 (the ordinary type of wave and the nature of the development of these two events indicate a stationary source) and in the bursts of March 2, 1970 and March 6, 1972[8] [the strong polarization with right rotation corresponds to an ordinary wave if one considers that the respective flares took place above sunspots of southern polarity (Fig. 6)]. Combined observations on radio heliographs, spectrograph-polarimeters, and optical magnetomers are required for more precise knowledge of such data.

2. Connection with active regions. The identification of events having a microstructure with optical flares is made successfully in the majority of cases. Of the 38 events examined in refs. 1-9, 14, and 19, 35 of them reliably coincide in time with flares in the Hα line according to the data of "Solar-Geophysical Data." Strong type IV bursts with a microstructure always coincide with flares of importance 2B-3B, while the weak unprolonged bursts listed above took place after weak flares of importance 1N or less. But regardless of the type of burst and the importance of the flare the corresponding active regions display a large number of sunspots in the group and multipolarity. This is characteristic of the regions connected with the events of May 3, 1973,[1] July 3, 1974 (Fig. 1), and May 29, 1972 (see Fig. 8, below). Active regions which demonstrate these properties most clearly for five more events are presented in Fig. 6.

The heliographic positions of the 35 identified flares are shown in Fig. 7. Not one of them is a limb flare, although type IV bursts are often connected with limb flares and even flares beyond the limb. This may be a consequence of the higher directionality of the radiation with a microstructure compared with the unmodulated continuum.

Of the 30 bursts with a microstructure which were observed from 1967 to 1974 for which there are complete data on solar protons in ref. 10, 23 are connected with proton flares, with protons not being recorded at all in only five cases, while the data are not complete for two cases. In these seven cases the flares were weak, while in 12 of the cases enumerated above the radio bursts consisted of an unprolonged meter continuum. In some cases protons were not recorded on near-earth satellites of the Explorer type although they were observed on heliocentric satellites of the Pioneer type. The corresponding flares in these cases occurred in far eastern regions, and therefore this fact may be a consequence of the directed motion of the protons in interplanetary space. For example, during the event of March 2, 1970, connected with McMath region 10607, N8° E40°,[8] a large burst of low-energy protons (0.6-13 MeV) of ~ 40 particle/cm$^2\cdot$sr was observed only on the Pioneer-6 satellite, which was 80° to the east of the sun–earth line at the time of the flare (ref. 10, No. 308). A similar fact was noted in ref. 1 for the event of May 3, 1973.

Thus, about 80% of the continuous bursts with a microstructure are connected with proton flares. And if one

1976SvA....20..449C

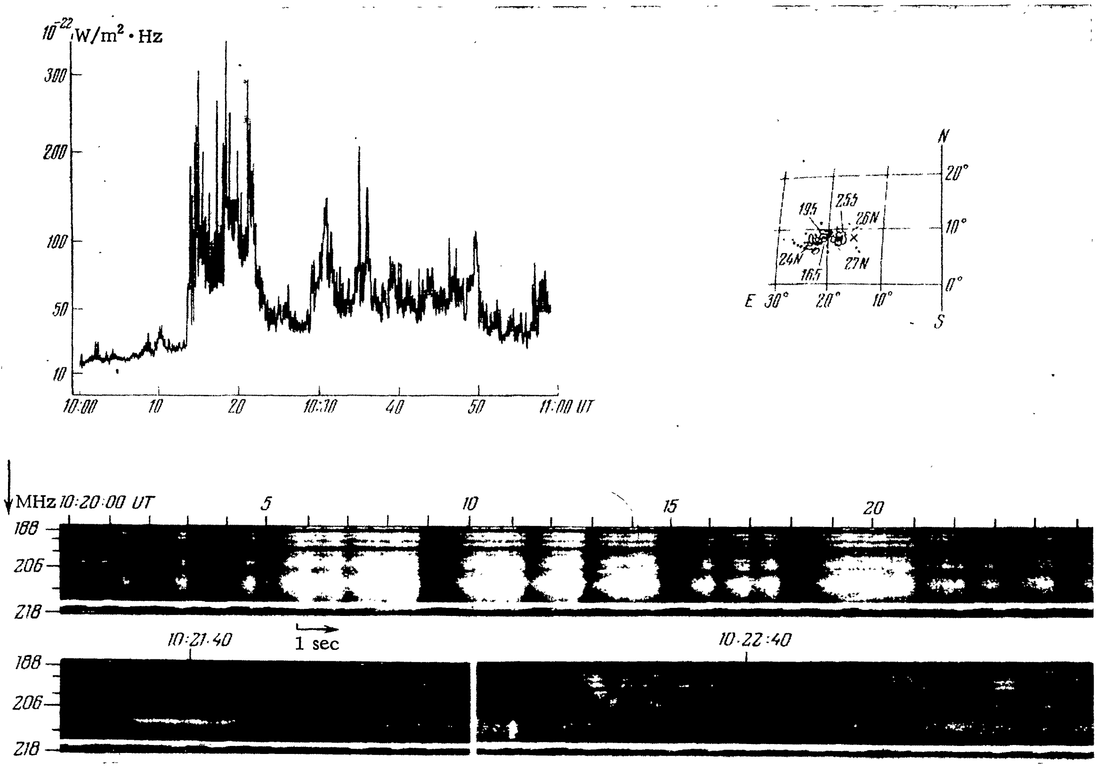

Fig. 8. Type IV burst with microstructure on May 29, 1972. Top: flux density at 207 MHz frequency (ITMIRAS) and drawing of corresponding sunspot group (Solnechnye Dannye); cross: Hα flare, 1B $11^h15^m-11^h55^m$ UT, McMath 11895. Bottom: high-resolution spectra of pulsations with filaments in emission and absorption.

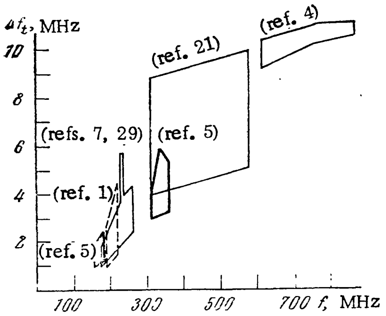

Fig. 9. Dependence of frequency separation between maxima in emission and absorption in bands of zebra structure on the frequency (Δf_t) for several events described in the literature.

selects events with allowance for the scaled nature of the microstructure radiation (for example, in accordance with an occupied frequency range of ~ 50 MHz, a duration of ~ 0.5 h, and a flux density of ~ 200 W/m² · Hz) then the recording of a microstructure in meter radiation can serve as an additional criterion for the determination of the probability of the escape of protons into interplanetary space. It is more reliable to match it with the Castelli criterion,[20] which takes into account the overall spectrum of the event.

3. Spectral characteristics. In many events the microstructure has an unsteady nature and consists of a collection of varied elements in emission and absorption. One can assume that all the elements have the same nature and that their variety is connected with the unsteady conditions in the radiation source. Fiber bursts often do not differ at all from individual bands of zebra structure.[1]

In all the elements the absorption lies on the LF edge from the emission region.[1,4,8] The frequency drift of the filaments can rarely be considered as intermediate (fiber bursts); often it is stationary. The aforementioned is illustrated in Fig. 8 by spectra of the microstructure in a type IV burst observed at ITMIRAS on May 29, 1972. This burst was unprolonged and relatively weak, but the radiation was very unsteady in the form of a picket fence of pulsations with a duration of 0.5-3 sec. Filaments in emission with LF absorption were observed in some of the pulsations. The group of filaments at 10^h20^m15-18°UT resembles a zebra structure. The starting and ending parts of the filament at $10^h21^m35-38^s$ have opposite frequency drifts.

The bands of the zebra structure are also rarely regular. On the basis of an analysis of several events having a zebra structure Slottje[7,8] concludes that its individual bands are independent phenomena whose superposition forms the various groups of bands with varying parameters. The possibility of this explanation is confirmed by the measurements of Elgarøy.[5] In this connection, the zebra structure should be characterized not by the frequency separation between bands but by the instantaneous band of frequencies between neighboring maxima in emission and absorption. If one neglects the differences between the widths of absorption and emission which is sometimes observed then the latter quantity is half as large as the former.

It is known that a microstructure is observed in a wide range of frequencies from[21] ~ 100 MHz to[4] ~ 900 MHz. In order to trace the frequency dependence of the frequency separation between maxima in emission and absorption, in Fig. 9 we show the limits of variation of this quantity for several well-known events. Despite the shortage of observational data in the 350-650 MHz range, a definite growth is seen in the frequency separation Δf_t from 1-1.5 MHz at a frequency of ~ 150 MHz to 10 MHz at 700 MHz. The increase in Δf_t with frequency appears not only in a survey of different events but also within the range of the microstructure in a single event.[1,5]

4. Conclusions. The above examination of bursts with a microstructure consisting of a collection of various elements in emission and absorption in the dynamic spectrum allows one to draw the following conclusions.

1. The microstructure is quite varied from event to event and has an unsteady, sporadic nature in each event. The microstructure can be explained as a collection of independent elements in emission with LF absorption (filaments, tadpoles, etc.).

2. Modulation of the radiation is accomplished in sources located above complex multipolar sunspot groups. These are usually steady type IV sources connected with proton flares.

3. The mechanism of generation of the microstructure must provide strongly polarized radiation, most probably corresponding to an ordinary wave.

4. The microstructure is most often manifested in the form of pulsations with a duration of from 0.5-1 to 3-5 sec. It is formed both at a low and a high level of continuous emission.

5. The emission of the continuum is suppressed only partially in the absorption region. The power of the enhanced emission in the bands can considerably exceed the level of the surrounding continuum.

6. Modulation of the continuous emission appears at frequencies of from ~ 100 to 900 MHz and can even encompass this range in a single event. The frequency separation between neighboring maxima in absorption and emission grows with frequency from ~ 1 MHz at 150 MHz to ~ 10 MHz at 700 MHz.

5. Interpretation. The discovery of a fine structure in almost all types of meter solar radio bursts gave a new impetus to the development of the theory of generation of the radio radiation. The presence of pulsations in the continuous radiation of type IV bursts demanded the application of methods of modulation of synchrotron radiation owing to variations in the magnetic field strength (ref. 22 and others). Subsequently the wide-band pulsations were interpreted through the mechanism of the generation of a conical instability into a system of "cold plasma + hot electrons" as a result of the injection of another group of hot electrons into the magnetic trap.[23,24] The zebra structure was interpreted independently from the pulsations.

Back in 1961 Elgarøy proposed that the frequency of the separation between neighboring bands is equal either to the proton plasma frequency f_{Pi} or the electron gyrofrequency f_{He} in the source. In ref. 25 it was noted that the occurrence of bands cannot be connected with the modulation of radiation at the frequency f_{Pi}, since in this case the value of the frequency separation would sometimes prove to be less than the observed value.

A second hypothesis of Elgarøy was based on the synchrotron nature of the continuous radiation from relativistic electrons in a magnetic field of a few gauss. The formation of bands should be the result of the interaction of relativistic and nonrelativistic electrons. With an increase in the energy of the emitting electrons the harmonics of the gyrofrequency merge into the continuum, while in the intermediate case, as noted in ref. 6, the generation of split harmonics is possible in the gyrosynchrotron radiation. Plasma mechanisms of generation of type IV bursts (beam and cone instabilities) have been developed in recent years, however (refs. 26-28 and others).

In this connection Rosenberg[29] has proposed a theory in which a structure of bands is explained by the electromagnetic radiation resulting from the nonlinear interaction of plasma waves at the upper hybrid frequency $\omega_{UH} = (\omega_{Pe}^2 + \omega_{He}^2)^{1/2}$ and electron cyclotron harmonics (the Bernstein mode) at the total frequency

$$\omega = \omega_{UH} + n\omega_{He} \quad (n = 1, 2, \ldots). \tag{1}$$

Zheleznyakov and Zlotnik made a detailed analysis of this mechanism in three reports.[30a,b,c] The general analysis of the cyclotron instability performed in ref. 30a is applied in ref. 30c for the interpretation of the regular zebra structure under conditions of double plasma resonance ($\omega_{UH} = n\omega_{Hc}$) in an extended source. Different combinations of kinematic and relativistic increments are used in ref. 30b to explain the tadpoles observed simultaneously with the pulsating zebra structure on March 2, 1970.[8] In this case the pulsating mode of the zebra structure is connected with the considerable growth of the magnetic field strength in the point source (~ 3 Oe/sec). However, the fact that the pulsations in this event appeared in a wider frequency range than the zebra structure and tadpoles, as if independently of them, remained unexplained.

Moreover, difficulties arise in the explanation of the strong polarization, which was not considered in ref. 30. Since it can be assumed that the blending (1) proceeds equally efficiently in ordinary and extraordinary waves while the total frequency considerably exceeds the local plasma frequency of the electrons, both waves should escape from the source without hindrance. The difficulties in the explanation of the strong polarization within the framework of this mechanism were also noted in ref. 31.

It should be noted that all the emission schemes mentioned above cannot explain the complex unsteady nature of the zebra structure observed, for example, on July 3, 1974. The interpretation of the complex structure becomes possible within the framework of the mechanism of interaction of Langmuir waves with wave packets of whistlers. This mechanism was proposed by Kuijpers in refs. 32a and analyzed in more detail in ref. 32b to explain fiber bursts. In ref. 32 attention is not drawn to the role of nonlinear effects on the behavior of whistlers in the corona, the allowance for which permits one to extend this mechanism to the explanation of more complex filamentary structures by assuming the elements of the microstructure to be independent phenomena. Before considering a possible model of a source in which such a mechanism is realized let us give the principal parameters of the coronal plasma, which will be used later.

V. PARAMETERS OF CORONA

The characteristics of the coronal plasma are known only approximately. The analytical representations of the electron concentration N_e do not always coincide with the sparse experimental data. The best agreement of the model representations of the N_e distribution for the middle corona above an active region is found in the coronal condensation of Waldmeier and for the double value of N_e in Newkirk's model.[33] The variation with height in the magnetic field strength above an active region is even less well known. But one can definitely say that in the middle and outer corona it falls off more slowly than a dipole dependence, while in the deep layers, close to the transitional layer between the corona and the chromosphere, it falls off faster than a dipole dependence (ref. 9, Fig. 3a).

The presumed dependence of the plasma frequencies f_{Pe} and f_{Pi} and the gyrofrequency on the height, expressed in solar radii, is presented in Fig. 10 with allowance made for individual experimental values. The lower curve shows the dependence of the frequency of the lower hybrid resonance $f_{LHR} \approx f_{He}/43$, which is, as is known, the critical frequency for whistlers. In the deep layers of the corona, where f_{He} approaches f_{Pe}, the frequency f_{LHR} becomes approximately $\sqrt{2}$ times less than the value $f_{He}/43$ [see Eq. (2) in article II].

It is shown in the figure that the ratio f_{Pe}/f_{He} of the plasma frequency to the electron gyrofrequency in a large interval of the outer and middle corona (up to frequencies of ~ 300 MHz) remains close to 20. A rapid rise in the gyrofrequency occurs in the deeper layers and this ratio becomes ~ 1 at a level corresponding to $f_{Pe} \approx 1000$ MHz. The straight lines emerging from the axes mark the range of frequencies and heights at which the microstructure in the continuous radiation is formed according to the observational data.

VI. MODEL OF SOURCE

It is known that the modulation of continuous radiation is observed mainly in steady type IV bursts. The steady sources are usually located above bipolar regions and consist of magnetic traps.[17,27] The electrons captured into the trap generate plasma waves, with a beam instability predominantly developing at the top of the magnetic arc, where the electron velocities are maximal, and a conical instability developing near the mirrors.[27,32b] The conversion of longitudinal plasma waves into electromagnetic waves in processes of spontaneous and induced scattering leads to radio emission at the fundamental harmonic of the plasma frequency ω_{Pe}. Observations indicate that an ordinary wave from the corresponding plasma levels usually emerges from the source.[34,35]

The trapped electrons also generate low-frequency waves: ion-sonic waves and whistlers (see article II for more detail). At a certain stage of development of the plasma turbulence, therefore, the magnetic field tube is filled with wave packets of whistlers. The interaction of whistlers with Langmuir waves provides the modulated electromagnetic radiation: The enhanced radiation at their combined frequencies escapes freely from the source, which leads to absorption of the continuum in the height interval encompassed by the whistlers (LF absorption).

The high-frequency boundary of the appearance of the microstructure (~ 900 MHz) is probably connected with the fact that whistlers cannot propagate in the corona into the deeper layers, being reflected from the level where their frequency becomes equal to the local frequency of the lower hybrid resonance (Fig. 10). Moreover, at heights corresponding to $f_{Pe} \approx 1000$ MHz the formation of whistlers from ion-sonic waves is suppressed because at these heights the frequency f_{LHR} approaches the proton plasma frequency, which is the upper boundary of the existence of ion-sonic waves. The mechanism of beam instability, which gives rise to the Langmuir oscillations, also becomes inefficient at the same levels (where $f_{He} \sim f_{Pe}$). The low-frequency boundary of the microstructure (~ 150 MHz) is explained by the natural minimum value of the magnetic field strength at these heights (several oersteds) which is still able to confine the fast electrons in the trap. Therefore the source of the radiation microstructure must occupy the height interval from 1.03 to 1.3 $R_\odot$ and consist of a curved magnetic field tube completely filled with wave packets of whistlers. The latter can be modulated in amplitude, as a result of which a variety of the microstructure elements is achieved. According to the data on the multipolarity of the active regions the radiation can be received from several sources at once. The continuous radiation without a microstructure escapes from a much larger height interval, encompassing the decameter and microwave ranges.

The frequently observed pulsations may be connected with the stimulation of radio emission by whistlers in the height interval encompassed by the field tube (by the scheme discussed in refs. 36 and 37). Modulation of the wave packets of whistlers, formed as the result of the interaction of the whistlers with plasma particles and with each other, leads to the appearance of a microstructure within the pulsations.

VII. CONCLUSION

The above analysis of several continuous bursts with a microstructure in the meter range observed at ITMIRAS, as well as of events known from the literature, showed that the microstructure, consisting of bands and other elements in emission and absorption, is usually observed in steady type IV bursts connected with proton flares. The most probable type of wave is the ordinary wave. More precise information on this radiation is required, however, which can be obtained by joint observations on a radio heliograph, spectrograph-polarimeter, and optical magnetograph.

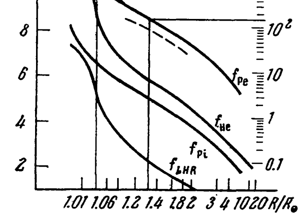

Fig. 10. Principal plasma frequencies of coronal plasma as a function of height expressed in solar radii. f_{Pe} and f_{Pi} are the electron and proton plasma frequencies, f_{He} is the electron gyrofrequency, and f_{LHR} is the frequency of lower hybrid resonance.[9,33]

The great variety of the microstructure parameters can be explained by the interaction of low- and high-frequency emissions in a source of the magnetic field tube type filled with wave packets of whistlers. Thus, the presence of a microstructure in the continuous radiation can indicate a considerable level of turbulence of the plasma in the source, under the conditions of which the escape of protons into interplanetary space is accomplished.

The author is grateful to Dr. C. Slottje, who presented the spectra of the multichannel spectrograph at Dwingelo (Holland) before publication, to O. S. Korolev for help in performing the spectral observations, and to V. V. Fomichev for useful discussions.

---

1) The dynamic spectra of the multichannel spectrograph at Dwingelo in the interval of $08^h59^m40^s$– $09^h02^m20^s$UT were presented by Dr. C. Slottje.

[1] G. P. Chernov, O. S. Korolev, and A. K. Markeev, Solar Phys. 44, 435 (1975), Preprint Inst. Zeml. Magnet., Ionosf., Raspr. Radiovoln. Akad. Nauk SSSR No. 127 (1975).

[2] A. Boischot, F. T. Haddock, and A. Maxwell, Ann. Astrophys. 23, 478 (1960).

[3] Ø. Elgarøy, Astrophys. Norveg. 7, 123 (1961)

[4] C. W. Young, C. L. Spenser, G. E. Moreton, and J. A. Roberts, Astrophys. J. 133, 243 (1961).

[5] Ø. Elgarøy, Proceedings of Second Meeting, Comm. European Solar Radio Astronomers, Bordeaux (1973), pp. 170 and 174.

[6] G. L. Tarnstrom and K. W. Philip, Solar Radio Spike Bursts, Univ. Alaska (1971), p. 138.

[7] C. Slottje, Proceedings of Second Meeting of Comm. European Solar Radio Astronomers, Utrecht (1971), p. 88.

[8] C. Slottje, Plasma Physics and Solar Radio Astronomy, Mangeney, Ed., Meudon (1973), p. 245; Solar Phys. 25, 210 (1972).

[9] H. Rosenberg, Instabilities in the Solar Corona, Thesis, Utrecht (1973).

[10] Solar-Geophys. Data No. 360, I; No. 361, I; No. 365, II (1974).

[11] Solnechnye Dannye No. 7, "The magnetic fields of sunspots" (Appendix) (1974).

[12] J. Van Nieuwkoop, A Multi-Channel Solar Radio Spectrograph, Thesis, Utrecht (1971).

[13] M. R. Kundu, Solar Radio Astronomy, Interscience Publ., New York (1965), p. 418.

[14] O. Elgaroy and E. Lyngstad, Astron. Astrophys. 16, 1 (1972).

[15] V. V. Zheleznyakov, Radio Radiation of the Sun and Planets [in Russian], Nauka, Moscow (1964).

[16] J. P. Wild and S. E. Smerd, "Solar Bursts," Ann. Rev. Astron. Astrophys. 10, 159 (1972); Usp. Fiz. Nauk 113, 503 (1974).

[17] R. T. Stewart and K. V. Sheridan, Proc. Astron. Soc. Austral. 2, 61 (1971).

[18] A. Abrami, Mem. Soc. Astron. Ital. 41, 231 (1970).

[19] S. T. Akin'yin, A. M. Karachun, V. A. Kovalev, A. K. Markeev, V. V. Fomichev, G. P. Chernov, and I. M. Chertok, Solnechnye Dannye No. 7, 108 (1973).

[20] J. P. Castelli, J. Geophys. Res. 72, 549 (1967); Proceedings of Third Meeting of Comm. European Solar Radio Astronomers, Bordeaux (1973), p. 69.

[21] A. R. Thompson and A. Maxwell, Astrophys. J. 136, 546 (1962).

[22] H. Rosenberg, Astron. Astrophys. 9, 159 (1970).

[23] A. K. Markeev, V. V. Fomichev, and I. M. Chertok, Astron. Zh. 52, 338 (1975) [Sov. Astron. 19, 207 (1975)].

[24] V. V. Zaitsev and A. V. Stepanov, Solnechnye Dannye No. 11, 71 (1975).

[25] H. Rosenberg and G. L. Tarnstrom, Solar Phys. 24, 210 (1972).

[26] V. V. Zaitsev, Radiofizika 16, 742 (1973).

[27] A. V. Stepanov, Astron. Zh. 50, 1243 (1973) [Sov. Astron. 17, 781 (1974)].

[28] V. G. Ledenev, Research on Geomagnetism, Aeronomy, and Solar Physics [in Russian], Sib. Otd. Inst. Zem. Magnet., Ionosf., Radiovoln. Raspr. (1974), p. 78.

[29] H. Rosenberg, Solar Phys. 25, 188 (1972); C. Chiuderi, R. Giacheti, and H. Rosenberg, Solar Phys. 33, 225 (1973).

[30] V. V. Zheleznyakov and E. Ya. Zlotnik, Solar Phys. a) 43, 431 (1975); b) 44, 447 (1975); c) 44, 461 (1975).

[31] W. N.-I. SY, Solar Phys. 34, 427 (1974).

[32] J. Kuijpers, a) Proceedings of Third Meeting of Comm. European Solar Radio Astronomers, Bordeaux (1973), p. 170; b) Collective Wave–Particle Interactions in Solar Type IV Radio Sources, Thesis, Utrecht (1975).

[33] T. de Groot, Weak Solar Radio Bursts, Thesis, Utrecht (1966).

[34] J. P. Wild, Proc. Astron. Soc. Austral. 1, 365 (1970).

[35] S. F. Smerd and G. A. Dulk, IAU Symposium No. 43, 616 (1971).

[36] Y. T. Chiu, Solar Phys. 13, 420 (1970).

[37] Y. C. Chin, Planet. Space Sci. 20, 711 (1972).

Translated by Edward U. Oldham