ON PECULIAR QUASI-PERIODIC COMPONENTS AND THE POSSIBLE STRUCTURE OF THE GENERATING REGION OF THE TYPE IV EVENT OF AUGUST 4, 1972

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Abstract: Based on a detailed study of H-alpha filtergrams, photospheric magnetic field measurements, and radio flux and polarization measurements, a discussion of the physical conditions of the proton flare on 1972, August 04 has been made. A possible model for the occurrence of a low frequency (periods ~ 100 ... 300 s) modulation of the radio emission especially on decameter waves has been proposed. As a condition for the generation of low-frequency modulation there appears the equality of the wavelength of a disturbance of the magnetic field with characteristic dimensions of the source region of the radio emission in the considered frequency range.

Introduction

Associated with the transit of the active region, associated with the McMath plage region No. 11976 (spot group No. 223 (331) of the Solnechnye Dannye numeration) a series of big solar flare events occurred, which have evoked considerable interest with solar physicists. Especially the event of August 4, 1972 which was not only the strongest one of this series, but perhaps also of the whole present solar cycle, revealed some remarkable features. In the present report a preliminary comprehensive discussion of this event is given, based on extended optical and radio observations made at IZMIRAN and HHI.

One outstanding feature of the event considered here was a strong and long lasting quasi-periodic low-frequency ($f_m \sim 10^{-2}\ \mathrm{s}^{-1}$) modulation of the intensity and (circular) polarization of the radio emission in the meter and decameter parts of the spectrum, commencing in the second stage of the event after the maximum of the H-alpha emission. Such a well developed low-frequency modulation with high amplitudes ($\sim 5 \,.\, 10^4$ s. u.) has never been reported yet. In the following, this feature, together with the development of the whole event, will be considered and possible physical processes involved will be discussed.

The Observations

Preliminary representations of the observational background are contained in [1, 2], additional treatment of related observations will be discussed in [3—5]. The optical observations have been made mainly with the tower telescope at IZMIRAN, comprising photographic measurements of magnetic fields and detailed chromospheric observations with a narrowband ($\Delta\lambda = 0.2$ Å) H-alpha interference polarization filter (Opton). The filtergrams have been obtained cinematographically with a time sequence of 30 s during the whole life time of the flare with discrete displacements of the passband over the line contour thus giving the opportunity to study the evolution and dynamics of the structural details of the H-alpha flare and derive a map of Doppler velocities of the flare region.

A temporal and spectral analysis of radio fluxes is based on a set of single frequency observations of the HHI covering the 10 MHz to 10 GHz region and measurements of other stations. The spectral distribution of the sense of circular polarization could also be included as a new quality. Additional information has been derived from radiospectrographic records obtained at IZMIRAN in the 45—90 MHz region.

Analysis of the Main Radio Burst Components

As an outline, a spectral diagram and a polarization diagram of the radio event are shown in Figures 1 and 2, respectively. The numerical data are plotted in Tables 1 and 2. It can be seen that the event exhibits a multi-component structure, typical for large solar events.

The *type IV μ component* is clearly expressed in the range from 1 to (extrapolated) 100 GHz. Its spectrum exhibits a typical broad-band structure suggesting magnetic fields of the order of 1000 Gauss and electron energies of $\beta \sim 0.9$, if synchrotron radiation is adopted. Assuming extraordinary mode emission, the sense of the circular polarization reveals a predominance of northern magnetic polarity opposite to the leading spot

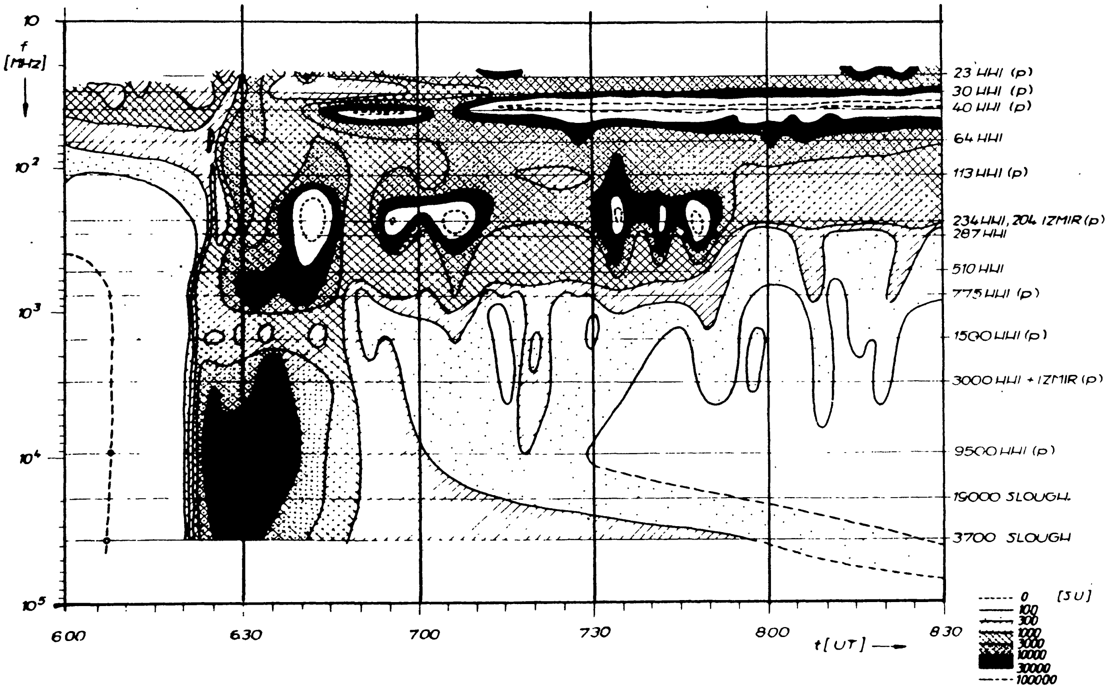

Fig. 1. Spectral diagram of the radio event of August 4, 1972.

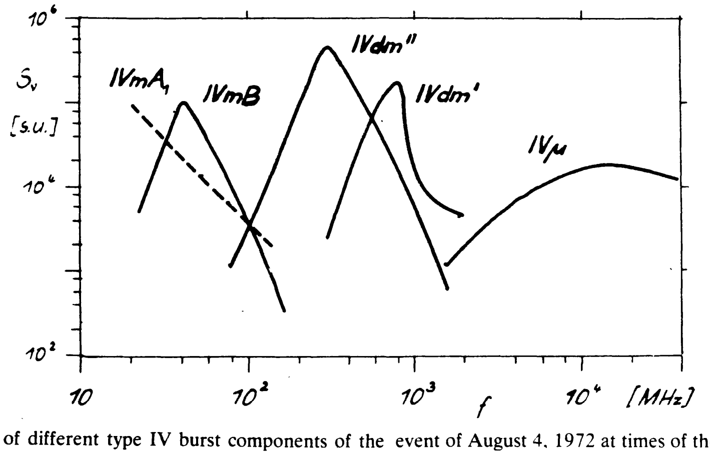

Fig. 3. Spectra of different type IV burst components of the event of August 4, 1972 at times of their maxima.

Table 1

Component	Commencement [UT]	Maximum [min]	Duration [min]	Maximum	Maximum flux density [s.u.]	Sense of polarization
IVμ	06 20	06 35	180	19000	2×10^4	R—L—R
IVdm$'$	06 26	06 30	9	775	10^5	L
IVdm$''$	06 35	06 42	420	234	5×10^5	L
IVmB	06 36	–	480	40	10^5	L
II	06 30	06 32	3	40—23	10^5	O

Table 2

	Type IVdm components				AFFS (LPS)		
No.		Commencement [UT]	Maximum	Duration [min]	Commencement [UT]	Maximum	Remarks
1	IVdm$'$	06 26	06 30	9	06 24	06 29	AFFS in region of a single spot duration 32 min
2	IVdm$'_1$	06 35	06 42	13	06 35	06 45	
3	IVdm$'_2$	06 52	06 56	10	06 50	06 55	
4	IVdm$'_3$	07 02	07 08	10	07 01	07 10	Successive brightening and weakening of a group of AFFS in several locations between the two ribbons, duration 100 min
5	IVdm$'_4$	07 30	07 35	8	07 27	07 34	
6	IVdm$'_5$	07 38	07 42	7	07 35		
7	IVdm$'_6$	07 45	07 49	9	07 43	07 49	

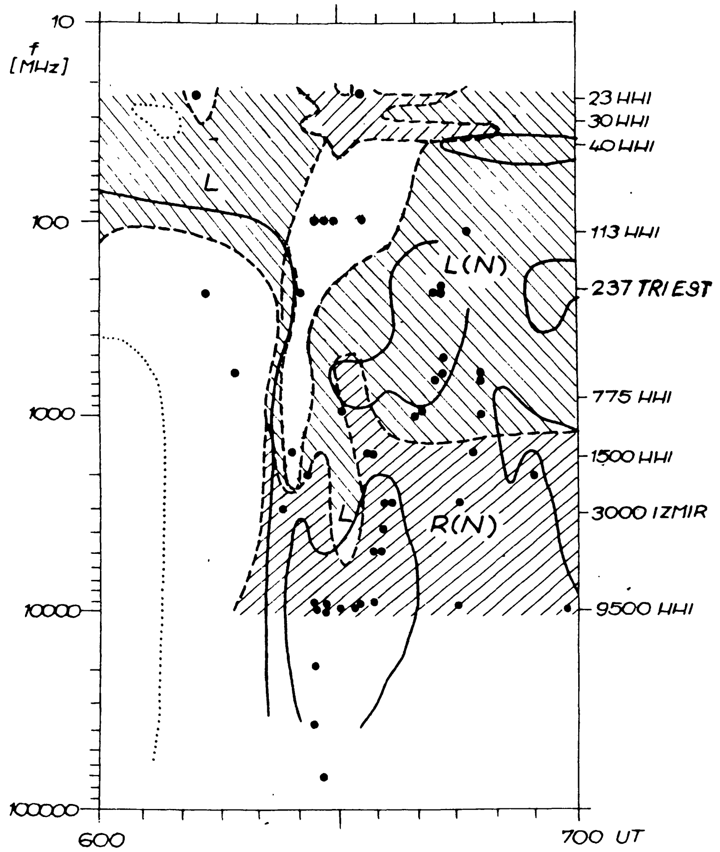

Fig. 2. Polarization diagram of the radio event of August 4, 1972 (R — right handed, L — left handed circular polarization).

polarity with the exception of a short period during the explosive phase where left-handed polarization was dominating. Apart from this temporary reversal, a spectral reversal of the sense of circular polarization occurred nearly constantly between 775 and 1000 MHz throughout the whole event.

In contrast to that which is typical of proton flares [6, 7], the *type IVmA component* — if at all present — was only weakly developed in the observed spectral region. Possibly the magnetic field was too distorted for a stable IVmA-source region to form, or the region was shifted greater heights, corresponding to frequencies outside the ground-based detectable range of the radio spectrum. Owing to this uncertainty, no distinction between mowing and quasi-stationary type IVmA components could be made.

Another, as yet unclear, question touches a possible superposition of *type II emissions.* Inspite of a possible frequency drift and the low degree of polarization at about 06.31 UT, a first inspection of the spectrographic records of IZMIRAN and other stations [8] yields no clear evidence of a type II burst. The question of the existence of type II bursts is of interest in estimating the magnetic field intensities in the corona, because an absence of shock waves, indicated by the type II burst, should satisfy the condition [9]

$$v\left[\frac{H}{4\pi m_i N}\right]^{-(1/2)} < M_c = 1 + \frac{3}{8}\left[\frac{8\pi NkT}{H^2}\right]^{1/3} < 2 \qquad (1)$$

(v — (shock) velocity, H — magnetic field intensity, m_i — ion mass, N — particle density, M_c — critical Mach number, k — Boltzmann constant, T — temperature).

The *type IVdm component* consists of several patches, located at two different peak frequencies (cf. Table 2). The spectrum, sense and degree of polarization indicate the existence of two different source regions which may be related to the development of an expanding arch flare filament system (AFFS) [10, 11].

Finally, the stationary *type IVmB component* commenced after the explosive phase at about 06.40 UT. The peculiar modulation of this relatively strong emission ($S \sim 10^5$ s. u.) was accompanied by an activation of a 'quiet' absorption filament which was located along the zero line of the photospheric field $H_{\parallel}$. The peak frequency, frequency extent and average intensity of the IVmB component did not change essentially during more than 6 hours. Subsequently, the burst developed a noise storm.

Comparison with Optical Observations

In the visible part of the spectrum the event of August 4, 1972 also exhibited some pecularities which are characteristic of a great proton flare. About 50 minutes before the onset of the main flare, there was a smaller pre-flare (at 05.30 UT) which was repeated in the main structural details by the proton flare, including microwave and X-ray emissions [8] (cf. Fig. 4). The proton flare itself started at about 06.20 UT with steep increases of brightness and an emitting area of two flare ribbons, reaching the maximum at 06.28 UT. Each ribbon was related to one magnetic polarity without crossing the neutral line of $H_{\parallel}$. The temporary inversion of the sense of circular polarization of the microwave emission coincided with the appearance of a bright broadening light bridge (Fig. 5) between the ribbon corresponding to a rise of chromospheric matter and magnetic fields in line with the development of the AFFS or loop prominence system (LPS).

The dynamics of 'quiet' filament could be observed by cinematographic small-band scanning of the H-alpha line profile. From the beginning of the emissive phase until 06.40 UT the filament exhibited very remarkable fluctuations (Fig. 6) which possibly originated from a shock wave. The perturbations of the filament then developed into quasi-periodic motions, reminding of standing waves. It cannot be excluded that this phenomenon may be linked with the modulation effect of the type IVmB radio emission as discussed below.

Figure 7 shows a map of the magnetic field, derived from photographic observations of polarization spectrograms of the Fe-line 6302 Å from IZMIRAN, magnetograms of the Kitt Peak Observatory (USA), and an analysis of chromospheric

▲ Fig. 5. H-alpha filtergram of the flare near the maximum (06.40 UT) exhibiting bridges between the two ribbons.

◀ Fig. 4. H-alpha filtergram of the active region obtained with an interference polarization filter H_α — 0.25 Å at the point $\Delta\lambda + 0.4$ Å: a) before the commencement of the main flare (06.05 UT), b) immediately after the commencement of the main flare (06.24 UT).

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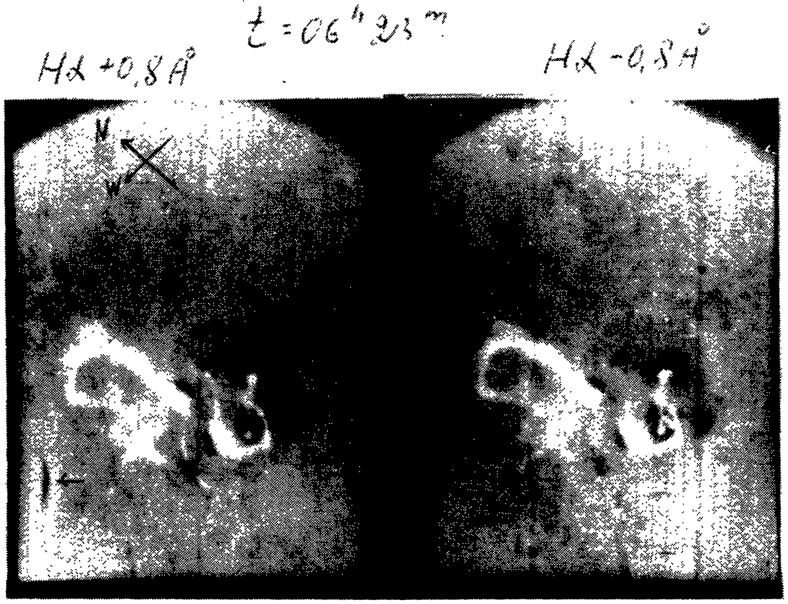

Fig. 6. H-alpha filtergrams obtained at the wings of the line (± 0.8 Å), revealing oscillatory disturbances of the 'quiescent' filament.

Fig. 7. Map of the magnetic field (H_{II}-component) of the active region (spot group No. 223 H (331)) on August 4, 1972.

fine structures, according to the H-alpha filtergrams.

The total magnetic flux of the northern spot polarities was about 4.5×10^{22} M, dominating over the flux of the southern spot polarities which only amounted to 1.8×10^{22} M in accordance with the observed polarization characteristics of the radio emission. There are some reasons for the complicated photospheric field structure to simplify with increasing height. Applying the method described in [12] by taking the photospheric field as a total of vertical dipoles and assuming current-free coronal fields, a qualitative picture of the field structure can be obtained. Figure 8 shows this structure schematically along the profile AB of Figure 7. There appear two quite different field configurations: a closed structure above the 'quiescent' filament in the NE-direction and an open structure in the SW-direction, situated above the bright flare ribbons where the AFFS appeared during the explosive phase. The following features are in favour of this structure:

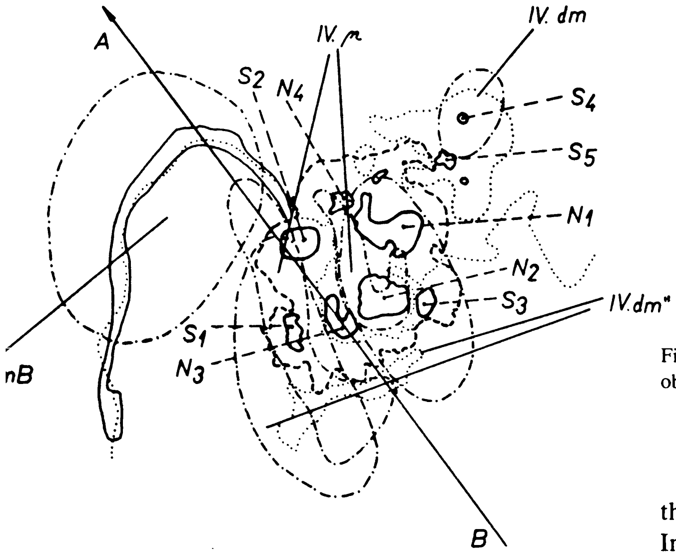

Fig. 8. Schematical structure of the magnetic field.

— A system of two long-living AFFS observed on 2nd August 1972 [4, 13] which is in accordance with the structure proposed above (Fig. 9).

— The distribution of filaments and chromospheric structures during August 2—10, 1972 (Fig. 10) which becomes especially impressive in the limb observations of August 11, 1972 (Fig. 11). Extended cinematographic records show that the eastern system remained quasi-stationary, whereas in the western part phenomena like loop prominences and surges always appeared. Coronal observations in the Fe X 6374 Å line also indicate a closed system above active filaments and an arc system above loop prominences.

— We consider the tentative localization of the sources of different components of the radio emission, sketched in Figure 12, to be an indirect hint to the existence of two different magnetic structures. In this picture the source region of the type IVmB component, which exhibited the modulation effect, should be linked with fluctuations of the filament joined to the eastern closed structure. The source of the type IVmA component, which is related to the generation and release of solar cosmic ray particles, should be located near the Y-like zero point of the opened western magnetic structure. The source of the microwave emission, which is closely associated with the X-ray emission, should be located immediately above the bright ribbons of the H-alpha emission.

Fig. 9. Arc flare filament system (AFFS) in the active region observed on August 2, 1972. The H-alpha filtergram was obtained in the far red wing of the line ($\Delta\lambda + 1.6$ Å).

— Concerning the type IVdm component, several authors suggest an origin in the expanding magnetic arcs which are closely related to arc-like ejections of chromospheric matter [15, 16]. The present filtergrams do not contradict this sugges-

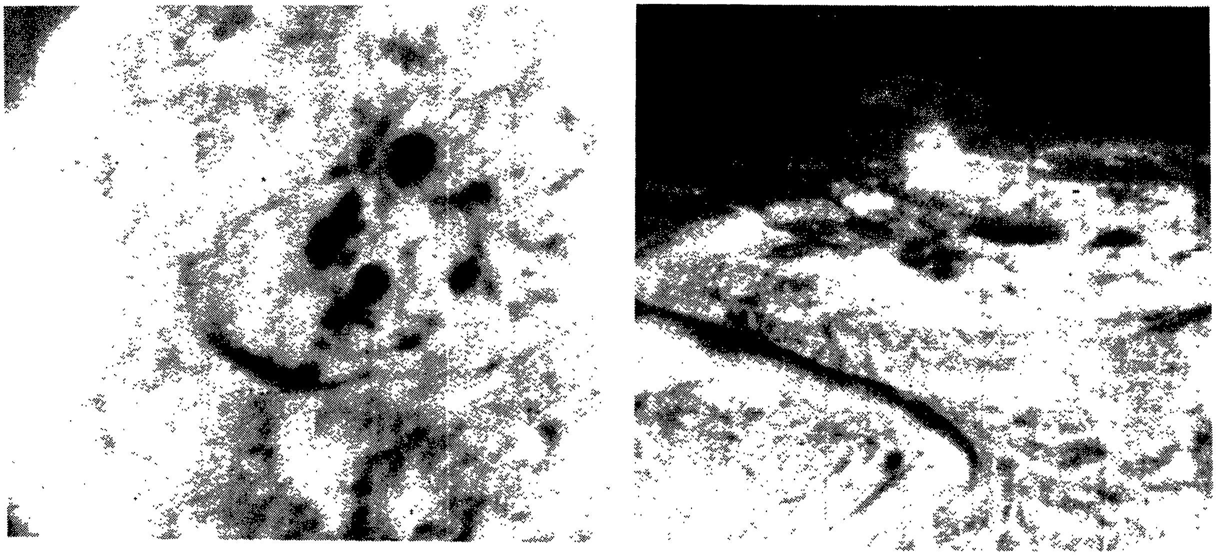

Fig. 10. H-alpha filtergrams according to observations on August 2 and 10, 1972. Note the AFFS and distorted structure of the 'quiescent' filament. 10a — on August 2; 10b — on August 10.

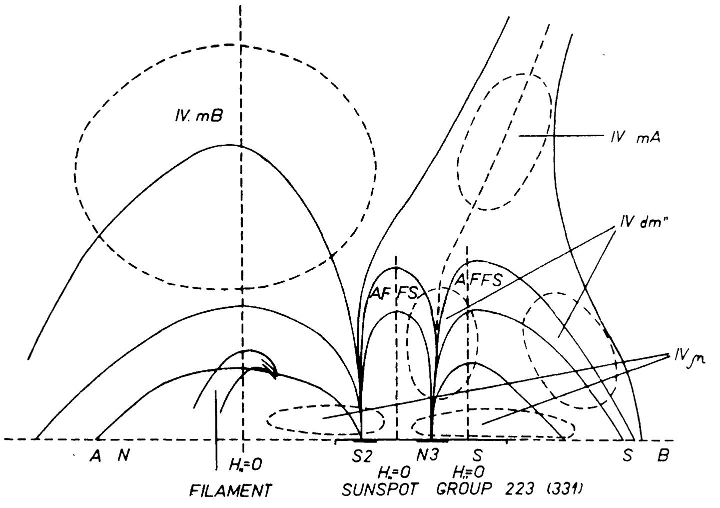

Fig. 12. Proposed location of the sources of different type IV burst components on August 4, 1972 along section AB of Fig. 8.

tion. Table 2 indicates that each type IVdm component may probably be related to a characteristic AFFS (cf. Fig. 13). According to the dynamics of the magnetic field, there is a rise of matter in the central upper part of the loop prominences during the explosive phase [4, 17]. This behaviour is demonstrated in Figure 14 which shows a representation of the field of Doppler velocities in the flare, derived after Leighton's method for H-alpha ± 0.6 Å, revealing expanding velocities up to more than 150...200 km/s. A 'magnetic piston' of this kind necessarily causes an expanding magnetic arch, thought to be connected with the type IVdm component. Moreover, arch-like ejections may stimulate open magnetic structures in the corona.

Fig. 13. H-alpha filtergram during the explosive phase of the flare on August 4, 1972. In the blue wing $\Delta\lambda - 0.6$ Å an ascending AFFS is visible which cannot be seen in the red wing $\Delta\lambda + 0.6$ Å.

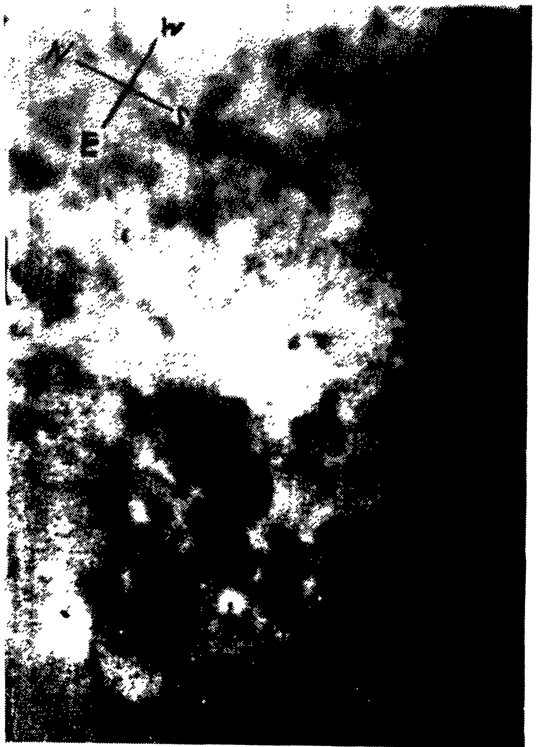

Fig. 14. Example of a superposition of two filtergrams after Leighton's method, showing a characteristic velocity distribution of chromospheric matter including ejections.

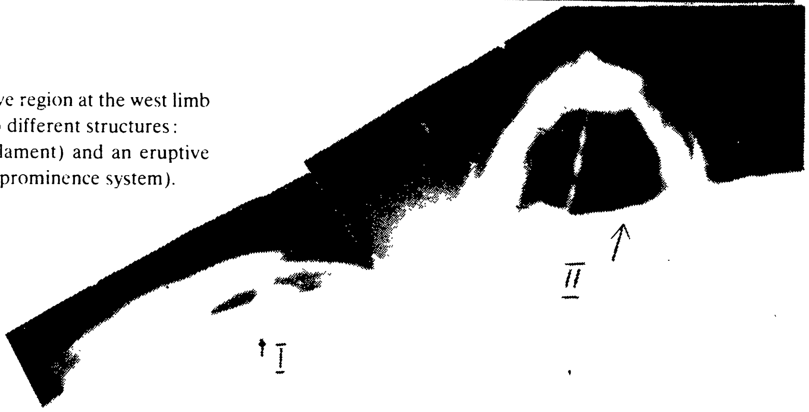

Fig. 11. H-alpha filtergram of the active region at the west limb on August 11, 1972. Note the two different structures: An active prominence ('quiescent' filament) and an eruptive arc-like ejection (expanding loop prominence system).

Low-frequency Modulation of the Type IVmB Radio Emission

An inspection of the single frequency records shows that the modulation effect was maximally expressed in the type IVmB burst at high flux densities ($\sim 10^5$ s. u.) in the 23—113 MHz range (Fig. 15). The basic period is of the order of 5 minutes, but shorter periods are also indicated. The spectral maximum lies at about 40 MHz, the relative modulation amplitude amounted to about 100 per cent, diminishing at both sides of the spectrum to about 80 per cent at 23 MHz and 20 per cent at the high frequency edge of the IVmB emission. The degree of (left-handed circular) polarization ($\sim$ 80 per cent) was in phase modulated with the intensity. Sometimes a frequency drift corresponding in order of magnitude to 10^8 cm/s was indicated.

Similar modulation effects, but showing smaller amplitudes, have hitherto been known to exist for the S-component (amplitude 1...2 per cent) [18], the noise storm continuum (5...10 per cent) [19], as well as the quasiperiodic fluctuations of the photospheric and chromospheric Doppler velocities and of magnetic fields. It can be assumed that the modulation is due to the propagation of wave-like disturbances of the magnetic field through the plasma [20—22]. However, modulations as strong as in the August 4, 1972 event have not been described before. The correspondence between optical and radio data indicates a connection between the modulation effect of the type IVmB radio emission and the perturbation of the 'quiescent' filament.

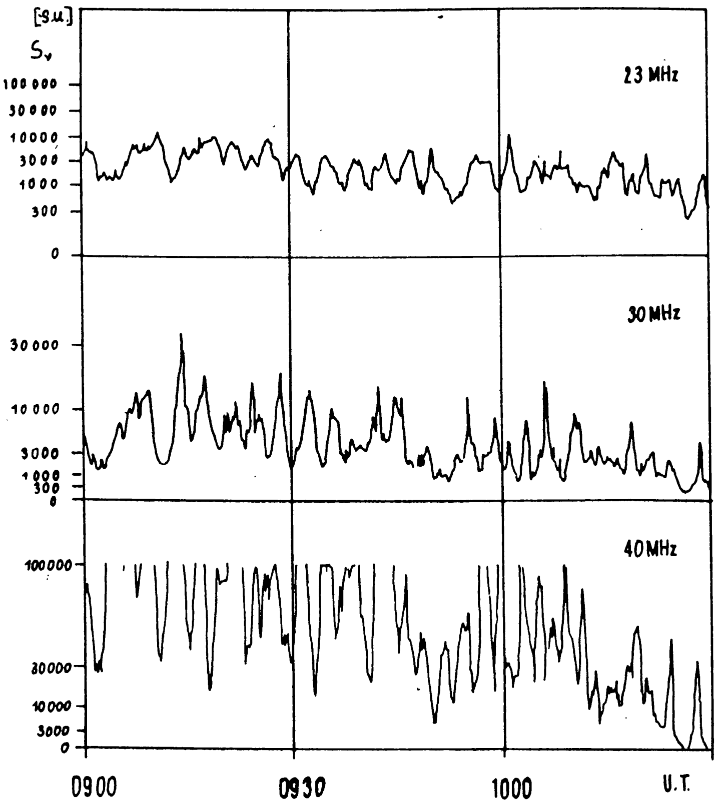

Fig. 15. Examples of radio records, showing the modulation effect of the type IVmB component.

Discussion

For a physical discussion of the modulation effect, described above, it would be desirable to know the contributing radio emission processes. However, this question has not been satisfactorily solved yet and different mechanisms, based on cyclotron emission or plasma waves [23—25] with several alternatives (e. g., [26, 27]) have been suggested.

Some doubts still exist as to the plasma wave hypothesis of the type IVmB bursts: With respect to the measured heliographic source dimensions [28—30], it is not clear, how the required energy density of the order of 10^{-4} erg cm^{-3} could be generated in the source region. On the other hand, a direct incoherent cyclotron emission would hardly fit the observations, e. g., high intensities and polarization characteristics. Nevertheless, as indicated by the detection of gamma emissions at 0.5 and 2.2 MeV [31] and other measurements in our case, the existence of accelerated particles upto mildly relativistic and relativistic energies can be postulated which principally could account for a coherent synchrotron emission. Therefore, in the following some properties of such a model are discussed in more detail as far possible.

It was shown, e. g., in [32, 33], that mildly relativistic electrons ($E/mc^2 > 1$) can emit coherent synchrotron radiation which is more effective by some orders of magnitude than the incoherent emission process. The condition for the appearance of the coherent synchrotron emission

$$-\mu L \gg 1 \qquad (2)$$

(μ — synchrotron reabsorption coefficient, L — characteristic dimension of the source region)
is satisfied, if [33]

$$N_c \geqslant \frac{N_c^{5/2}}{30 H_\perp^4 L} \tag{3}$$

(N_c — density of non-thermal electrons)

$$\frac{E}{mc^2} \gtrsim 5.3 \,.\, 10^{-3} \frac{N_e^{1/2}}{H_\perp}, \tag{4}$$

corresponding to a high value ($\gtrsim 10^3$) of the optical depth

$$\tau_\gamma = \frac{4.6 \,.\, 10^4 L H_\perp^4 N_c}{N_e^{5/2}}. \tag{5}$$

Taking $N_e \sim 5 \,.\, 10^7$ cm^{-3}, according to the Newkirk model, corresponding to a proposed emission height of $h \lesssim 0.7 \ldots 1.0$ R$_\odot$, the magnetic field $H_\perp$ can be estimated from the position of the spectral maximum of the type IVmB component, resulting in $H \gtrsim 14$ G/$H \gtrsim 18$ $N_e\, \nu_m^{-1}$ [33]. A similar result is obtained by extrapolating the magnetic field in the filament region ($h \sim 0.08 \ldots 0.01$ R$_\odot$, $H \sim 300$ G), derived by damping the oscillatory motion of the filament [34], having adopted the semi-empirical formula

$$\frac{H_i}{H_v} \approx \left(\frac{h_v}{h_i}\right)^{2.1} \tag{6}$$

which leads to $H_i \approx 8$ G. A corresponding extrapolation, applying data on the type IVdm component ($h \sim 0.18$ R$_\odot$, $H \sim 280$ G), yields $H_i \approx 14$ G.

With the aid of Eqs (2) — (5) we find

$$N_c \geqslant 10^2 \text{ cm}^{-3}, \quad \frac{E}{mc^2} \gtrsim 2, \quad \tau_v \gtrsim 1500,$$

which should cause an amplification of the synchrotron emission by a factor of $k \sim 500$ [cf. 32, 33, 36]:

$$I_M = 6.7 \,.\, 10^{-20} a(\gamma)\, L k H^{(\gamma+1)/2} \left(\frac{6.26 \,.\, 10^{18}}{\nu}\right)^{(\gamma-1)/2} [\text{erg cm}^{-2}\ \text{H}_z^{-1}] \tag{7}$$

i. e.

$$I_M = A H^{(\gamma+1)/2} \tag{8}$$

(γ — exponent of the energy spectrum $N_c \approx N_0 E^{-\gamma}$).

Putting $\gamma = 3$, in accordance with space observations, we have

$$I_M = A H^2, \tag{9}$$

which could principally account for the modulation effects of the radio emission (including polarization effects) by pulsations of the magnetic field.

Concerning the magnetic field, the following model may be proposed: A stationary magnetic loop containing the source of the type IVmB component is considered above the filament. Inside this bottle, disturbances of the magnetic field, arriving with a period ω_M from the fluctuating filament, propagate at the Alfvén speed. Estimating ω_M by means of a spherical model [37] of a pulsating plasma blob, the energy of the 'deformation' of the magnetic field ($\Delta H \lesssim 0.1$ H)

$$W_M = \frac{\alpha\, (\Delta H)^2\, r^3}{4} \tag{10}$$

(r — radius of the plasma blob, α — deformation ratio $= \Delta r(r)$ is transformed into kinetic energy

$$W_K = \frac{1}{5}\, \pi N \alpha^2 r^5 \omega_M^2. \tag{11}$$

Hence

$$\omega_M = \frac{\sqrt{5}\, \Delta H}{r\, (4\pi N)^{1/2}} = 2\pi\nu_M \tag{12}$$

in our case leads to

$$\nu_M \lesssim 3 \,.\, 10^{-2}\ [\text{s}^{-1}]$$

which fits the modulation frequency of the type IVmB component well. The energy of the pulsation of the magnetic field of the source region becomes $W_M \approx 1.9 \,.\, 10^{18}$ erg which is approximately $\lesssim 15$ per cent of the energy content of the fluctuations of the filament [4].

The condition for the appearance of the slow modulation effect appears to be that the dimension of the magnetic flux tube should be of the order of the wavelength of the travelling disturbance. In our case this means that, if we compare the mean local Alfvén velocity of $v_A \sim 3 \,.\, 10^8$ cm s^{-1} with the modulation frequency $\nu_M \sim 3 \,.\, 10^{-2}$ s^{-1}, we obtain $\lambda_M \sim 10^{10}$ cm, which is indeed of the order of $L \sim 5 \,.\, 10^{10}$ cm, as suggested before.

To avoid confusion it should be noted that this condition cannot, of course, be applied to the shorter period fluctuations of period of tens of seconds which also occurred during this event, but which have not been discussed in this paper.

The condition, given above together with the high directivity of the type IVmB burst emission may be the reason, why slow modulations of the radio emission are rare events.

The present considerations have been conducted, proposing a coherent synchrotron emission mechanism which seems capable, under reasonable conditions, to account for observations of the spectral distribution, long duration (because of great radiation damping times $T_s \sim 100$ h), periodic oscillations of the frequency of the spectral maximum interpreted as frequency drifts and, perhaps even, polarization characteristics. A quantitative study of these topics, based on a detailed Fourier spectral analysis, is forthcoming.

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