SESSION VI

SOLAR BURSTS - DECIMETER AND LOW FREQUENCY OBSERVATIONS

THEORY OF TYPE IV dm BURSTS

Jan Kuijpers
Astronomical Institute, Utrecht, The Netherlands

ABSTRACT

The study of fine structures in continuum radio emission from the sun is important to probe the physics of radio sources and of flares in particular. In this light the existing fine structure theories are reviewed and an application to a radio flare is given.

Type IV dm bursts are characterized as radiocontinua with a rich occurrence of the following fine structures: zebra patterns, fiber - also called intermediate drift - bursts and sudden reductions - also called absorptions - (see Figure 1). In general the emission has a relatively small bandwidth, less than 100 MHz, and the bursts are associated with Hα flares. For an extensive description of the observations I refer to Slottje (1980). The bursts occur mainly but not necessarily in the decimeter wavelength region. Apparently the same underlying processes can operate in the solar corona at the dense levels of the primary flare energy release up to the large altitudes of type I storm continua, occasionally leading to bursts in the centimetric band or at metric wavelengths. What is important however is the appearance of fine structures which indicate the presence of a *variety of plasma waves* in the source region. Therefore these fine structures can serve as a diagnostic probe of the source region. Eventually from these features in the stationary post flare continua one might hope to trace the *flare conditions* from highly variable plasma emission processes at the location of the primary flare energy release.

The *main problems* in the theory of type IV dm bursts at present are the following:

1. Which radiation process is operating to give emission at the *fundamental*? This problem is of importance for all those kinds of radio bursts that are excited at the plasmafrequency. For the case of weak turbulence this problem is reviewed in these proceedings by Melrose (1979). In the case of strong Langmuir turbulence recent calculations of emission at the plasmafrequency have been made by Goldman et al. (1979) and by Wentzel (1979).

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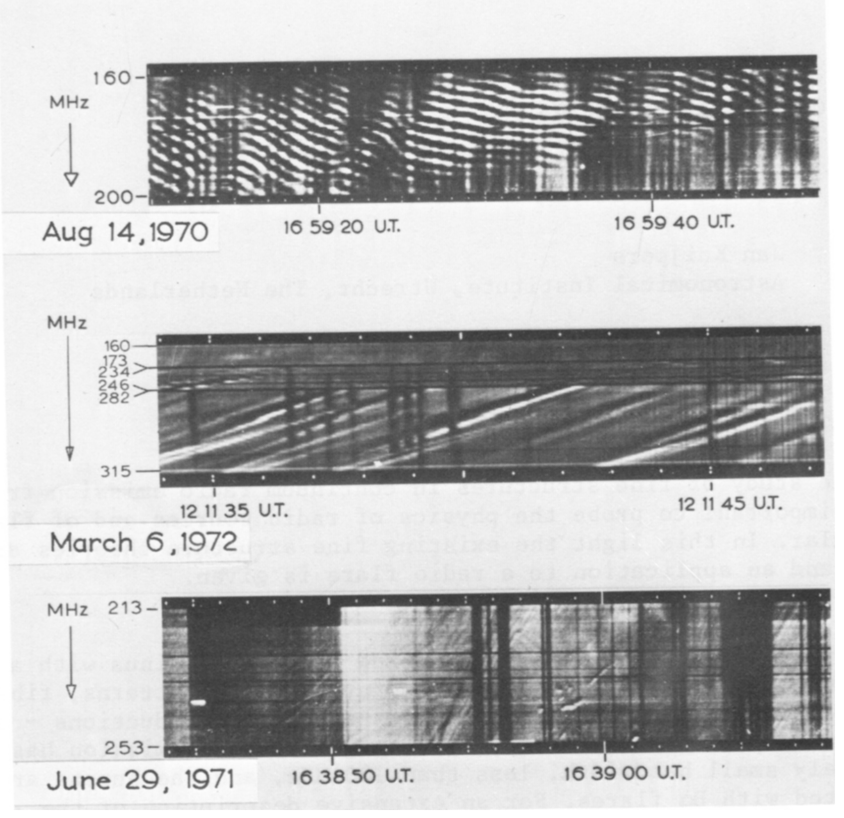

Figure 1. - Examples of fine structures in type IV dm bursts as observed with the 60-channel Utrecht spectrograph. From top to bottom: zebra pattern, fiber bursts and broadband sudden reductions. The time indication is in hours, minutes and seconds.

2. The *nonlinear stage* of the plasma instabilities arising in a stationary magnetic trap. This is very important in describing the actual stationary wave levels, filamentation in space and relaxation phenomena that lead to quasi-periodic or discrete structures in time. So far the work that has been done concentrates mainly on the collapse of Langmuir waves in the presence of a beam (Goldman et al., 1979 and references therein). In the context of a magnetic trap saturation effects have been studied only in a fragmentary way (Zaitsev and Stepanov, 1975; Kuijpers, 1975c; Benz and Kuijpers, 1976; Benz, 1979). But these are not suitable for a review at present. Therefore it will be extremely worthwhile if future efforts are dedicated to this problem.
3. Which instabilities arise in a coronal magnetic trap after the occurrence of a flare and can they explain the observed *fine structures*?

Here I shall review the third topic: the instabilities are discussed with emphasis on the remaining problems in section 1 and the confrontation with the observations is presented in section 2. Finally in section 3 an attempt is made to explain decimetric radiation from what I think is a flaring region in the corona.

1. STATIONARY MAGNETIC TRAPS

Since the observed fine structures cannot be explained by incoherent gyro-synchrotron radiation I shall first discuss the possible instabilities for various kinds of plasma waves when fast electrons with typical energies of tens to one hundred keV are trapped after the occurrence of a flare in a static coronal magnetic flux tube. Fast electrons which have their mirror points at a sufficiently small altitude quickly lose their energy by collisions with the background plasma of which the density increases abruptly more than a millionfold from corona to photosphere. As a result only fast electrons with sufficiently large pitch angles are trapped. A so-called *loss-cone distribution* of fast electrons develops superimposed on an isotropic background plasma with a coronal temperature. If the fast particles are not injected in the part of the flux tube with the smallest magnetic field strength, fast particles with large pitch angles are absent in the smaller field regions and their distribution function also shows a so-called anti-loss-cone (Figure 2). In a stationary magnetic trap various kinds of plasma waves can be generated coherently. The most important instabilities are *Langmuir waves* around the electron plasma and upper hybrid frequency (section 1.1), *high frequency electromagnetic waves* at the first few harmonics of the electron cyclotron frequency (section 1.2) and low frequency electromagnetic waves below the electron cyclotron frequency or "*whistlers*". The latter will not be discussed here since the treatment of their instability offers no problems. (Kuijpers, 1975c; Berney and Benz, 1978).

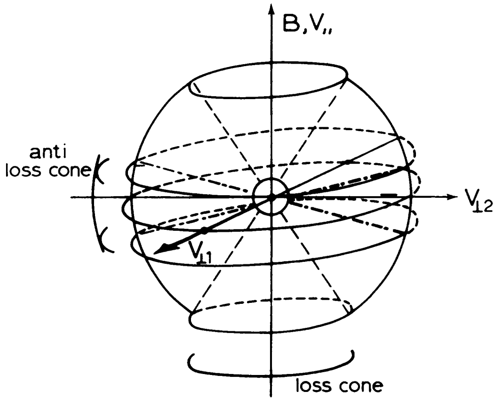

Figure 2. - The drawing shows the electron distribution function in velocity space. The small inner sphere represents the Maxwellian background distribution; from the outer sphere a loss-cone and an anti-loss-cone have been cut away.

1.1. High frequency electrostatic instability

Maximum duration. In a Maxwellian plasma with a small addition of fast electrons Langmuir waves can be excited in three ways: through *Landau-resonance* from a "bump-in-tail" (or anti-loss-cone) distribution, through *normal Doppler resonance* from the loss-cone distribution or through *anomalous Doppler resonance* (cf. Section 3) when the fast particles show a preferential anisotropy parallel (and/or antiparallel) to the magnetic field direction. Let us suppose that the acceleration or the injection of fast particles has come to an end. Then on a time scale $L/\Delta v$ after the main acceleration phase (here L is the length of the trap and Δv is the velocity spread of the fast particles) a stationary situation develops. The distribution function is monotonically decreasing in velocity everywhere in the trap with locally a loss-cone and possibly an anti-loss-cone.

In the case of an *anti-loss-cone* a bump-in-tail instability results in strong quasilinear relaxation and in the destruction of the anti-loss-cone, quenching off the instability on the quasilinear time scale. Subsequently the Langmuir waves decay on the collisional time scale. Further instability might reappear due to the preferential action of collisions on the slowest of the high-energy particles, thus again creating a positive slope (Zheleznijakov and Zaitsev, 1970). In that case the maximum duration of the bump-in-tail instability is given by the collisional energy loss time of the particles with the largest energy $t_E(E_{max})$.

In the case of a *loss-cone distribution* the same collisional mechanism restores instability after the initial quasilinear relaxation has taken place and the loss-cone is filled by quasilinear diffusion (Benz and Kuijpers, 1976). At the same time however particles scattered into the loss-cone escape from the trap and therefore also recreate conditions for instability. Since by this process the fast particles are lost from the region of instability, refillment of the loss-cone distribution is required (Stepanov, 1974); the *maximum duration* of the instability is therefore given by $\min\left(t_D\,(E_{max})\,L/\Delta L\;,\;t_{qls}\,L/\Delta L\right)$. Here L is the length of the trap, ΔL the length of the unstable region, $t_D\,(E_{max})$ is the collisional deflection time of the particles with the largest energy and t_{qls} is the deflection time arising from diffusion by the waves in the stationary state.

For electron energies below 300 keV the energy loss time and the deflection time are of the same magnitude. The characteristic collision time for a 100 keV electron and a background density of $10^9\ \mathrm{cm}^{-3}$ is $t_E \simeq t_D \simeq 2$ min and this duration represents an upper limit for the duration of a characteristic type IV dm burst unless *reacceleration* takes place (Kuijpers, 1975a). However, above we have assumed that fast electrons once inside the loss-cone escape "immediately", viz. within their free streaming transit time (of the order of 1 sec). If on the other hand a sufficiently large wave level is present the fast electrons cannot escape freely from the trap but rather diffuse down the field lines on a longer time scale (Wentzel, 1976) and the burst duration is increased. Concerning the possibility of reacceleration evidence for ongoing injections after the main flare phase is provided by the abundantly occurring sudden reductions (Section 2). Also a different kind of reacceleration could occur when a substantial fraction of the wave energy is being fed into a small fraction of higher energy particles (Todoroki et al., 1974).

Loss-cone instability at the upper hybrid frequency. A distinction is useful between situations with a large and with a small magnetic field strength:

1. $\omega_{pe}/\omega_{ce} \simeq 1$. Here ω_{pe} is the angular electron plasmafrequency and ω_{ce} the (non-relativistic) angular electron cyclotron frequency. In this case the electrostatic loss-cone instability has been treated by Stepanov (1974). This instability was invoked by him to explain moving type IV bursts at metric wavelengths but is relevant also for stationary traps. The instability occurs at the *upper hybrid frequency* ω_{UH} $(\omega_{UH}^2 \equiv \omega_{pe}^2 + \omega_{ce}^2)$ and arises through the normal Doppler resonance at the $s = 1$ cyclotron interaction. (The general resonance condition is $\omega - k_{\|} v_{\|} = s\omega_{ce}$, where ω is the angular wave frequency, k the wave number, v the particle velocity, the suffix $\|$ denotes a vector component along the magnetic field direction and s takes on integer values). Since Stepanov (1974) invoked coalescence of Langmuir waves to produce electromagnetic radiation at the *first harmonic* of the upper hybrid frequency the radiation would be essentially unpolarized if $\omega_{pe}/\omega_{ce} \gg 1$ in contrast with the observations of (moving) type IV emission from the footpoints of the source (Wild, 1969). Only if the field strength were large $(\omega_{pe}/\omega_{ce} \simeq 1)$ preferential gyroresonance absorption of the extraordinary mode on its way through the corona at the third harmonic of the local electron cyclotron frequency would cause the escaping radiation to be correctly polarized. It is clear that the radiation is also strongly circularly polarized if the emission is at the *fundamental* upper hybrid frequency or results from fusion with sufficiently low-frequency waves for any value of ω_{pe}/ω_{ce} (the condition being that the frequency of the produced electromagnetic radiation is below $0.5\,\omega_{ce} + (0.25\,\omega_{ce}^2 + \omega_{pe}^2)^{\frac{1}{2}}$).

2. $\omega_{pe}/\omega_{ce} \gg 1$. Neglecting the role of the magnetic field it has been shown that the loss-cone situation can give rise to an instability for high-frequency electrostatic waves at the *upper-hybrid frequency* (Kuijpers, 1974).

While this work of Stepanov (1974) and Kuijpers (1974) gave a plausible mechanism for the origin of type IV dm continuum radiation with high brightness temperatures arising in stationary traps, a controversy existed concerning the ratio of the electron plasma to the electron cyclotron frequency. As to the type IV dm source region this value is unfortunately not given unambiguously by other observations (Dulk and McLean, 1978). In section 2 I shall come back to this question.

Furthermore initially the role of the magnetic field in the weak field case, apart from the creation of a loss-cone distribution, was not realized properly. The most drastic effect of the field is first the appearance of unstable Bernstein waves near harmonics of the electron cyclotron frequency. Secondly the growth rate is *enhanced* at the upper hybrid frequency in regions within the trap where the upper hybrid frequency is an integer multiple of the electron cyclotron frequency

$$\omega_{UH} = N\omega_{ce} .$$

We shall call such regions within the source *resonant surfaces*. Only the observations of the zebra patterns gave an indication of the proper magnetic field effects to be taken into account (Chiuderi et al., 1973; Zheleznijakov and Zlotnik, 1975a,c; Kuijpers, 1975b). While the principal physical idea to explain the zebra patterns as radiation from the resonant surfaces is contained in both latter papers, a discrepancy existed concerning the precise nature of the instability (hydrodynamic or kinetic).

While the hydrodynamic version of the loss-cone instability from Pearlstein et al. (1966) was used by Kuijpers (1975b), Zheleznijakov and Zlotnik (1975c) proved that a kinetic instability already exists for a much smaller density of fast particles relative to the ambient density. However in subsequent work by Berney and Benz (1978) and by Berney (1979) it was claimed that the hydrodynamic instability would arise for very small fractions of fast particles. It is worthwhile to define the ranges of applicability of these different treatments. There are now two approaches:

The *kinetic* approach takes into account the contributions from the poles in the dispersion relation. These poles arise for particle velocities with

$$\omega - k_{\parallel} v_{\parallel} - s\omega_{ce}(v) = 0 \tag{1}$$

In Eq. (1) $\omega \equiv \omega_r + i\gamma$ is the complex angular wave frequency, ω_r is the real part of the frequency and γ the growth rate and $\omega_{ce}(v) \equiv \omega_{ce}(1 - v^2/c^2)^{\frac{1}{2}}$ is the relativistic electron cyclotron frequency (c is the velocity of light). At this stage the relativistic dependence of the cyclotron frequency cannot be neglected (Zheleznijakov and Zlotnik, 1975a).

In the *hydrodynamic* approach contributions from the poles are neglected. The hydrodynamic treatment is correct provided the resonance as defined from Eq. (1) does not play a role for the wave mode and particle distribution function under consideration. More precisely: in the case of a loss-cone distribution a hydrodynamic calculation is justified provided (see Mikhailovskii, 1974)

$$|\omega - s\omega_{ce}| \gg |k_{\parallel}| v_T + \left| s\left(\omega_{ce}(v_T) - \omega_{ce}\right) \right| . \tag{2}$$

Here v_T is the velocity dispersion of the (fast) electron distribution. For weakly relativistic electrons ans perpendicular waves $(k_{\parallel} = 0)$ this condition can be written as

$$|\omega_r - s\omega_{ce} + i\gamma| \quad >> \quad 0.5 \; |s|\omega_{ce} \; v_T^{\,2}/c^2 \; . \tag{3}$$

For the hydrodynamic instability at double resonance ($\omega_r = \omega_{UH} = N\omega_{ce}$) the left-hand part reduces to the absolute value of the growth rate. Substituting the respective expressions for the growth rates from Pearlstein et al. (1966) and from Berney and Benz (1978) in Eq. (3) we arrive at a lower limit on the fraction ε of fast particles as shown in Table I. Consequently in the case of strictly perpendicular propagation the hydrodynamic treatment is at best allowed when the fraction of the loss-cone distribution is rather high. Further the claim by Berney and Benz (1978) that the hydrodynamic instability would be faster in the domain $5.10^{-4} < \varepsilon \lesssim 4.10^{-2}$ is invalid. As a matter of fact, in coronal conditions the *kinetic instability* as treated by Zheleznijakov and Zlotnik (1975a,c) and by Berney (1979) *prevails*.

Although the question kinetic versus hydrodynamic treatment is answered, one important problem remains, viz. how to define the *precise form of the loss-cone distribution*, since this influences the resulting kinetic relativistic instability quite sensitively. While Zheleznijakov and Zlotnik (1975c) arrive at an instability in the hybrid band at frequencies slightly below the cyclotron harmonic for $k_{||} = 0$, Blanken et al. (1969) also consider small non-zero values of $k_{||}$ and find instability at frequencies above the first cyclotron harmonic frequency which exceeds the upper hybrid frquency. In figures 3a and b the distribution function used by Zheleznijakov and Zlotnik (1975a,c) and by Blanken et al. (1969) respectively is schematically indicated by level curves in momentum space. The resonance condition (1) can be written as

$$m\omega - s\, m_0\, \omega_{ce} - k_{||}\, p_{||} \quad = \quad 0 \; , \tag{4}$$

where m_0 is the electron rest mass, m the relativistic mass and p the particle momentum. For a given value of s Eq. (4) represents an

Table I

Applicability of the hydrodynamic treatment

	γ/ω_{ce}	lower limit for ε
Pearlstein et al. (1966)	$0.5\;\varepsilon N^{*1}$	$v_T^{\,2}/c^2 \;\simeq 0.1$
Berney and Benz (1978)	$0.2\;\varepsilon^{\frac{1}{2}*2}$	$25\; v_T^{\,2}/c^2 \;\simeq 1.8$

$*_1$ valid if $\varepsilon > 2\;(\pi N)^{-1}$

$*_2$ valid for $N = 10$, $v_T = 8.10^9$ cm s^{-1} , $\sigma = 20$

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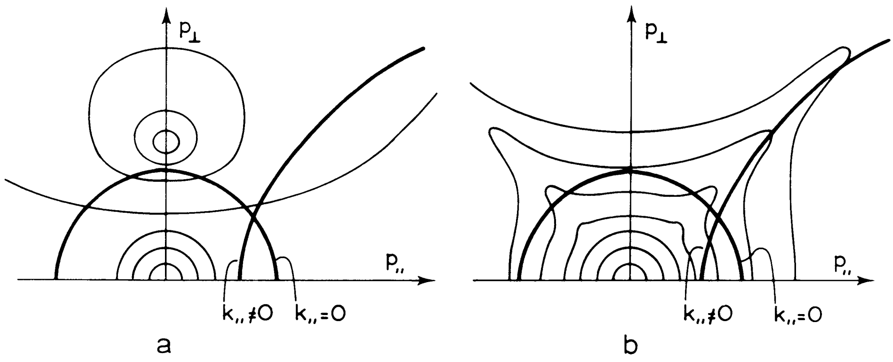

Figure 3. - The level curves of the electron distribution functions are indicated schematically in momentum space ($p_\perp$ is the momentum component perpendicular to the magnetic field direction and $p_{\parallel}$ the parallel component).Also indicated are two resonance curves for typical cases $k_{\parallel} = 0$ and $k_{\parallel} \neq 0$. In a a Maxwellian distribution is indicated with a superimposed fast electron population as used by Zheleznijakov and Zlotnik (1975a,c). In b the loss-cone distribution is the one used by Blanken et al. (1969).

ellipse for $k_{\parallel} c < \omega$ in momentum space as is clear from the following rearrangement (substituting the momentum dependence of m)

$$\left(\frac{p_\perp}{m_0 c}\right)^2 + \left(1 - \frac{k_{\parallel}^2 c^2}{\omega^2}\right)\left(\frac{p_{\parallel}}{m_0 c} - \frac{s\,\omega_{ce}\,k_{\parallel}\,c}{\omega^2 - k_{\parallel}^2 c^2}\right)^2 =$$

$$= \frac{s^2 \omega_{ce}^2 - \omega^2 + k_{\parallel}^2 c^2}{\omega^2 - k_{\parallel}^2 c^2} \tag{5}$$

If $k_{\parallel} = 0$ (the case of Zheleznijakov and Zlotnik (1975a,c)) the resonance curves are circles centered at the origin (see Figure 3a) and interactions only exist for frequencies *below the harmonics* as follows from the right-hand side of Eq. (5). Moreover it is clear that instability can be expected if the radius of the circle is sufficiently large so as to minimize damping by the background (regions where $\partial f/\partial p_\perp < 0$; f is the distribution function),yet sufficiently small so as to have large positive contributions of $\partial f/\partial p_\perp$ from the fast particle population with a secondary maximum.

For the distribution used by Blanken et al. (1969) large positive values of $\partial f/\partial p_\perp$ exist at the edge of the fast particle component (see Figure 3b). From Eq. (5) it can be seen that the resonance curve which traverses this part of velocity space has $k_{\|} \neq 0$, for in this case 1. the ellipse becomes excentric; and 2. the right-hand side of Eq. (5) is minimized. As a consequence the damping contribution from the background disappears and the unstable waves can exist at a frequency slightly *above the harmonic*.

From the above examples it follows that it is important to use distributions that occur in real coronal traps rather than to look for analytically convenient representations as the double humped distribution function in the case of Zheleznijakov and Zlotnik (1975a, c).

1.2. High-frequency electromagnetic instability

This instability is better known as *coherent gyroradiation* (Melrose, 1980 and references therein; Holman et al., 1980). Recently this instability has been studied for a loss-cone distribution superimposed on a colder Maxwellian background for the case of perpendicular propagation ($k_{\|} = 0$) by Stepanov (1978). In this case coherent generation of gyroradiation by slightly relativistic electrons ($\gtrsim$ 30 keV) can overcome the cyclotron damping by the background electrons on its way out of the corona at the first four harmonics of the cyclotron frequency. Consequently this mechanism only works for rather large field strengths with $\omega_{pe}/\omega_{ce} \leqslant 4$.

The growth rate for this instability is less than that for longitudinal plasma waves. However, since only a small fraction of these plasma waves might eventually be converted into escaping radiation, the idea is that the net efficiency of the linear cyclotron instability might well exceed that of the nonlinear plasma radiation process. Unfortunately Stepanov (1978) did not take into account the cyclotron absorption of the radiation arising in those regions of the source on its path outwards where the radiation frequency is outside the local amplification band. Thus it might well be that the net efficiency of this process is bedevilled with a similar difficulty as exists in the case of induced scattering of Langmuir waves into transverse waves. After an initial amplification the transverse waves suffer from absorption in outer regions of the source where their frequency exceeds that of the local Langmuir turbulence (Melrose, 1980). In both cases such absorption can be prevented if the escaping ray remains inside the amplification band throughout the fast particle trap. For the electromagnetic instability this means that one of the source dimensions is less than

$$s\,\beta^2 L_B \simeq 0.5\, L_B \tag{6}$$

Here L_B is the scale length of the magnetic field strength, β is the characteristic velocity of the fast particles relative to the speed of light ($\beta \gtrsim 1/3$) and the harmonic number s has a value $s \leqslant 4$.

As in section 1.1 the stationary level of *longitudinal* waves is determined by the balance between particle influx into the loss-cone from diffusion in the wave field and escape of particles inside the loss-cone from the trap. According to Stepanov (1978) the longitudinal waves do not give rise to a higher level of radiation than the level resulting from the electromagnetic instability only if the length of the trapping region is sufficiently large ($> 10^{10}$ cm). However such a large dimension is unlikely to be compatible with condition (6) for realistic magnetic field scale lengths.

Thus the high-frequency electromagnetic loss-cone instability is probably of less importance than the longitudinal one. It may be possible however that the former instability is greatly enhanced in the upper hybrid region as has been observed in the laboratory (Kuckes and Sudan, 1971).

Finally, since the electromagnetic instability only works if the field strength is large throughout the source ($\omega_{pe}/\omega_{ce} \leqslant 4$) this mechanism could not explain the zebra patterns with a large number of ridges (generally much more than four) which require the simultaneous occurrence of an equally large number of harmonic surfaces.

1.3. Summary

The most important high-frequency instability in stationary magnetic traps in the solar corona is the loss-cone instability of *upper hybrid waves* at *the resonant surfaces*.

The *relativistic dependence of the cyclotron frequency* on the electron mass and a precise knowledge of the *distribution function* are of prime importance in determining the properties of the instability.

A simple criterion [Eq. (2)] exists to judge the validity of *hydrodynamic versus kinetic* treatment.

Finally *continued acceleration* seems to be required for type IV dm bursts some of which have been observed to last longer than typical collision times.

2. FINE STRUCTURES

In Table II I present characteristics of the most important fine structures in type IV dm bursts in the 160-320 MHz band as described mainly by Slottje (1980). The (in)consistency of proposed loss-cone explanations (indicated by abbreviations above the columns) with these observational characteristics is shown by crosses (inconsistent), ticks (in agreement) or required conditions. Non-discriminating observational characteristics have been left out in Table II but are presented together with numerical specifications of the fine structures in Table III

From Table II it can be seen that the observations of zebra patterns are only satisfactorily explained if the frequency difference of the zebra pattern (and continuum) radiation and the plasmafrequency in the region where the radiation is produced is much less than the

Table II

Confrontation of theories with observed fine structures *1

zebra patterns *2 (66% *3)	homogeneous source B + (B or UH) (1)	double resonance UH (+ lfw) (2)	UH + UH (3)
ridges non equidistant *4	×	√	√
up to 67 ridges at 200 MHz	×	$\omega_{ce} << \omega_{pe}$	$\omega_{ce} << \omega_{pe}$
disappearance of single ridge	×	√	√
causal relation to continuum		inhomogeneity	
strongly polarized in ordinary sense *5		√	$\omega_{ce} \gtrsim \omega_{pe}$
fiber bursts (48% *3)	**(B or UH) + w**	**UH + w (4)**	**UH + w**
absorption edge on lf side		√	×
ridge separation ≃ 10^{-2} frequency		$\omega_w \simeq 10^{-2}\ \omega_{pe}$	×
same polarization as cont.		$\omega_w \lesssim 0.5\ \omega_{ce}$	
frequency drift mainly negative		w due to anisotropy	
clusters of discrete fibers		$\Delta L << L$	
frequency drift in between type II and III drift		$v_A < v_w << c$	
avoid zebra patterns			

broadband sudden reductions (80% *3)	wave modulation	beam injection
repetitive but aperiodic	×	√
reduction, no enhancement	×	√

*1 abbreviations: B Bernstein wave, UH upper hybrid wave, lfw low-frequency wave, w travelling wave, L tube length, ΔL length of unstable region, v_A Alfvén speed, v_w speed of travelling wave, c speed of light.
*2 excluding the rare braided and tadpole zebra patterns.
*3 indicating the fraction of type IV events in which the structure occurs.
*4 decreasing or increasing in frequency.
*5 Chernov, 1976.

(1) Chiuderi et al., 1973; Zheleznijakov and Zlotnik, 1975a,b.
(2) Zheleznijakov and Zlotnik, 1975c; Kuijpers, 1975b; Benz, 1979.
(3) Stepanov, 1974; Zheleznijakov and Zlotnik, 1975c.
(4) Kuijpers, 1975c; Chernov, 1976; Kuijpers and Slottje, 1976.
(5) Rosenberg, 1970; Meerson et al., 1978.
(6) Zaitsev and Stepanov, 1975; Benz and Kuijpers, 1976.

local electron cyclotron frequency. This does not specify the conversion mechanism at the fundamental, e.g. whether the transformation of the upper hybrid waves takes place by scattering or by coalescence with low-frequency waves. An example of the latter process can be found in Benz (1979) where the coalescence is with locally generated whistler waves which have frequencies much below the frequencies in those whistler wave packets that arise in lower lying stronger field regions (Kuijpers, 1975c). In any case it can be concluded from Table II that apparently the source conditions are favourable for generation of *radiation at the fundamental* and not at the first harmonic of the electron plasma-frequency (see conflicting conditions in the last column). Also from the second column it follows that an inhomogeneous source region is required to account for the most common type of zebra pattern.

From the observations of fiber bursts the third column of Table II shows that these can be explained from travelling wave packets through the source provided a number of conditions is met which force one to the conclusion that the travelling waves can only be *whistler waves*.

Finally the observations of the broadband sudden reductions which are very common in type IV dm events suggest that the source regions are repeatedly provided with new injections of fast particles (lower part of Table II) and that continued *acceleration in pulses* takes place.

From the interpretation of both the most common type of zebra patterns and the fiber bursts I conclude that mostly the *electron cyclotron frequency is far below the electron plasmafrequency* in type IV dm source regions (cf. sections 1.1 and 3). This is in contrast with the remark by Dulk and McLean (1978) that decimetric bursts take place at a radial distance $1.05 - 1.1\ R_{\odot}$ from the solar centre where the cyclotron frequency appears to be comparable to the plasmafrequency. However, we note that firstly the present results are based on fine structures in bursts down to 160 MHz. In these regions, according to Dulk and McLean (1978), the plasmafrequency much exceeds the cyclotron frequency both for the cases of a coronal density model twice or eight times the Newkirk values. Secondly the derived field strengths are easily compatible with the compilation by Dulk and McLean (1978) if the type IV dm emission originates in relatively dense loops higher up in the corona. In view of its association with flares and the fact that the density in solar flares exceeds by one to two orders of magnitude the density of the quiet atmosphere (Svestka, 1976), there doesn't seem to be any conflict with our conclusion.

Summarizing this section we conclude from a comparison of the observed properties of fine structures with the existing theories that the observations can only be consistently explained within the following scheme:

1. continuum radiation is produced near the *fundamental* of the electron plasmafrequency,
2. the zebra patterns arise from enhanced generation of upper hybrid waves near the resonant surfaces in an inhomogeneous source region,
3. if the fibers result from the interaction with a travelling wave phenomenon only *whistlers* come into consideration,

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Table III

Observed characteristics of type IV dm bursts *1

Continuum:		
frequency extent	:	$\lesssim$ 100 MHz *4
duration	:	$\lesssim$ 300 sec (sometimes up to 1^{hr})
directivity half-aperture	:	50^0
no threshold in importance of associated Hα flares		
Zebra patterns:		
frequency extent	:	$\gtrsim$ 40 MHz
number of consecutive lines	:	5 - 20 (up to 70)
line spacing at 160-200 MHz	:	2 - 3 MHz
at 800-900 MHz	:	20 MHz
Fiber bursts:		
frequency extent	:	30 MHz (up to 120 MHz)
duration	:	5 - 10 sec
single frequency duration	:	0.2 - 0.4 sec
instantaneous bandwidth	:	$\lesssim$ 1 MHz
drift rate, -df/dt	:	10^{-2} f + 6.10^{-5} f^2 *2
number in one group	:	10 - 30 (up to 300)
flux at 160-320 MHz	:	200 su *3
at 500-900 MHz	:	500 su
Broadband sudden reductions:		
frequency extent	:	50 - 100 MHz
duration	:	$\lesssim$ 0.3 sec
interval	:	$\lesssim$ 1 sec
inverse of drift rate	:	0 $\pm$ 3 msec/MHz

*1 compiled from Slottje, 1980, for observations mainly at 160-320 MHz
*2 f is the observed frequency in MHz
*3 1 solar flux unit (su) = 10^{-19} erg cm^{-2} Hz^{-1} sec^{-1}
*4 see also Benz and Tarnstrom, 1978; Tarnstrom and Benz, 1978.

4. in sources that produce the common type of zebra patterns and fiber bursts the electron *cyclotron frequency is far below the plasma-frequency*, and
5. the commonly occurring broadband sudden reductions indicate the occurrence of *continued acceleration* or injection *pulses* in the type IV dm source region.

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3. THE REMARKABLE TYPE IV dm BURST OF JUNE 25, 1978: A RADIOFLARE?

As has been shown above the explanation of the observed fine structures in a typical type IV dm burst is fairly unique. The instabilities which occur in a natural way in a stationary coronal magnetic trap can account for the observed structures. Also the diagnostics of the post-flare type IV dm source region from the observed fine structures is relatively simple (see the references under Table II).

This final section does not have the character of a review. Rather I would like to present a tentative and perhaps a provoking explanation of a remarkable type IV dm burst (see Figure 4) as originating from a flaring region. Thus in contrast with sections 1 and 2 here we do not assume that the main flare phase has ended nor that a loss-cone type distribution has already developed. Furthermore in this case the ratio ω_{ce}/ω_{pe} turns out to be of order unity, in contrast with most type IV dm sources.

The event occurred on June 25, 1978, was observed with the 60-channel radio spectrograph at Dwingeloo between 509 and 666 MHz, where it lasted roughly from 15^h36^m - 15^h38^m UT. The fine structures have been analysed by Van der Post (1979). Essentially the observed radiation (see Figure 4) consists of a background continuum which shows pulsating structure with a period of one second and superimposed spikes with opposite sense of polarization which first occur at random in the frequency-time plane but later on arrange themselves in the form of a so-called braided zebra pattern (see Slottje, 1980). According to NOAA Solar Geophysical Data strong outbursts occurred at 2.8 GHz from 15^h30^m - 16^h00^m UT with a maximum at 15^h40^m UT. Also hard X-rays have been observed (0.5 - 4 A; 1 - 8 A) between 15^h33^m - 16^h31^m with a maximum at 15^h58^m.

We tentatively identify the radio emission of this rarely observed phenomenon as emission from a flaring region at an unusual large altitude in the corona (see Figure 5). We assume that the flaring region consists of a magnetic flux tube in which locally the *tearing mode* reconnects the magnetic field lines at several places (Spicer, 1977). In the tearing regions induced electric fields arise parallel to the magnetic field direction. As a consequence *runaway electrons* are produced.

The nonlinear dynamics of the runaway process has been analysed by Liu et al. (1977) for $\omega_{ce} > \omega_{pe}$. They found a *pulsating production* of energetic particles and of plasma waves and explained this in the following way:

1. First electrons are accelerated with velocities above the runaway velocity

$$v_0 = (E_D/E)^{\frac{1}{2}} v_{te} , \tag{7}$$

where E is the induced electric field strength,

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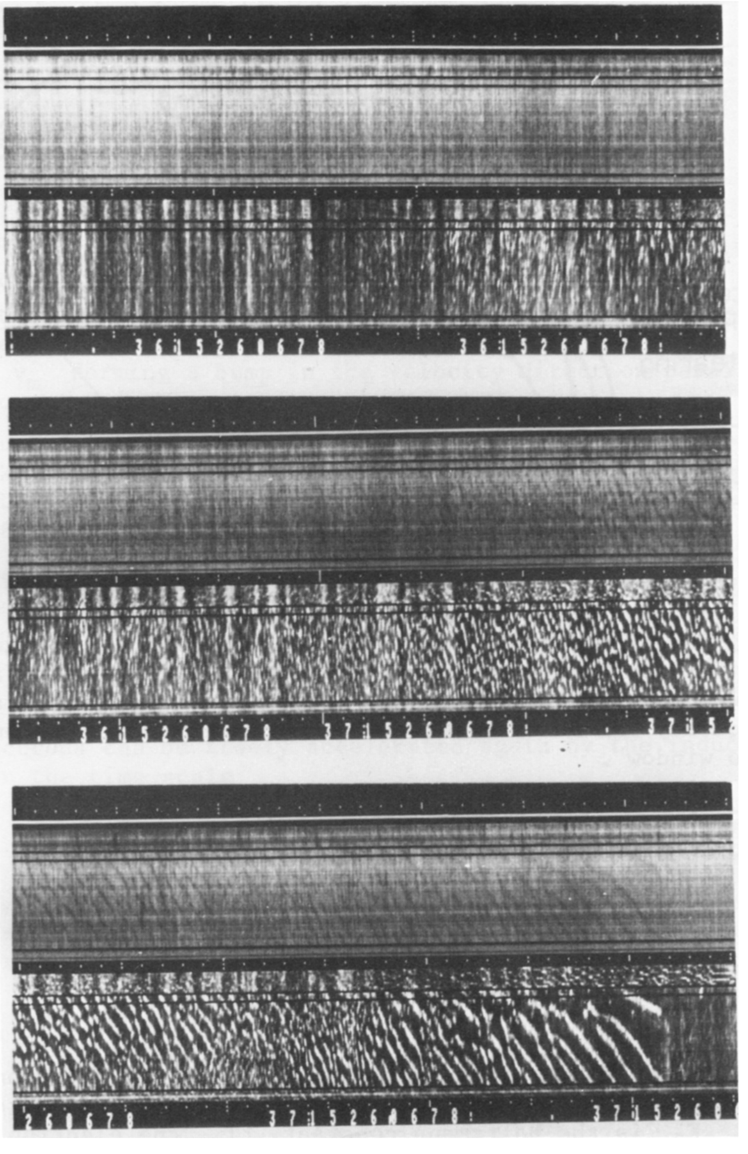

Figure 4. - Event of June 26, 1978 observed with the Utrecht spectrograph. Two ticks are one second apart. Circular polarization is indicated in the upper half of each part by the degree of black or white. The lower half of each part gives the flux (floating zero level with time constant of 3 sec). The 60 channels are spread in three groups, from top to bottom 509 - 533, 574 - 614 and 655 - 666 MHz as indicated once at the left. UT is indicated below each part in the order minute, hour, day, month and year.

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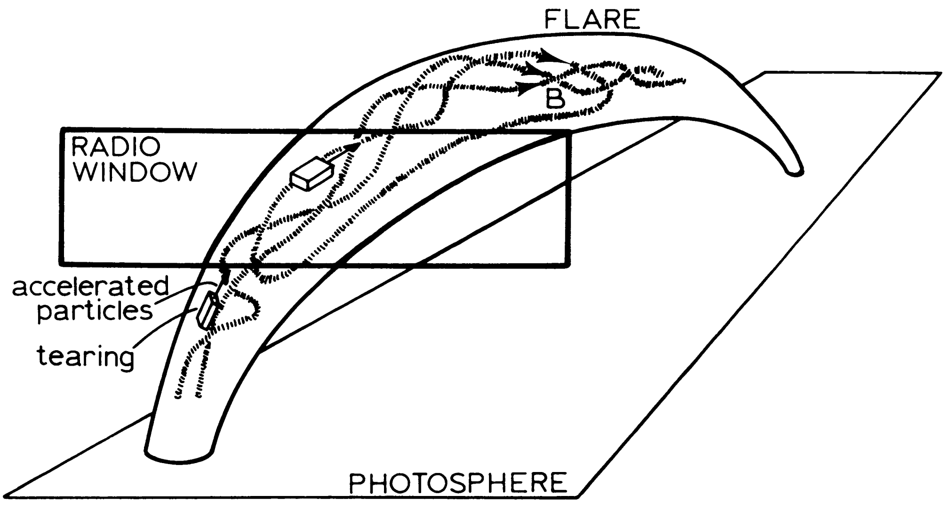

Figure 5. - Sketch of a flaring flux tube in which a few magnetic field lines have been drawn. Presumably tearing occurs in many thin regions two of which are indicated. Radiation from the tube at the plasmafrequency can be observed with the radiospectrograph only within the "radio window".

$$E_D = e \, \ell n \, \Lambda \, / \, \lambda_D{}^2 \tag{8}$$

is the Dreicer field,

$$v_{te} = \left(2 \, K_B \, T_e \, / \, m\right)^{\frac{1}{2}} \tag{9}$$

is the thermal speed of the electrons, e is the electron charge, $\ell n \, \Lambda \simeq 20$ is the Coulomb logarithm, $\lambda_D = 0.7 \, v_{te}/\omega_{pe}$ is the Debye length, K_B is the Boltzmann constant, T_e the electron temperature and m is the electron mass.

2. When sufficient acceleration has taken place "slow" plasma waves with

$$\omega = \omega_{pe} \, |k_{\|}| \, / \, k \tag{10}$$

can be excited through anomalous cyclotron resonance

$$\omega + \omega_{ce} = |k_{\|}| \, . \, |v_{\|}| \tag{11}$$

A necessary condition for their excitation is that the Landau damping

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by the background is negligible, or

$$|k_{||}| < \omega/v_0 . \tag{12}$$

Thus (with Eq. (10)) only particles with

$$v > v_m = \left(1 + \frac{k}{|k_{||}|} \frac{\omega_{ce}}{\omega_{pe}}\right) v_0 \tag{13}$$

excite these slow plasma waves. As a result of quasilinear relaxation these particles are scattered to large pitch angles and pile up around v_m forming a bump in the velocity direction parallel to the field (curve 2 in Figure 6).

3. Now a bump-in-tail instability of "fast" Langmuir waves ($\omega \simeq \omega_{pe}$; $|k_{||}| \simeq k$) sets in and two thirds of the beam energy flows into plasma waves. Due to quasilinear relaxation a plateau is formed (curve 3 in Figure 6) and the generation of Langmuir waves ceases.

4. Subsequently the plasma waves are damped on the collision time scale

$$t_c = T_e^{3/2} (5.5 \text{ n } \ell n \Lambda)^{-1} \text{ sec} \tag{14}$$

and

5. The electrons can be freely accelerated again by the induced electric field on the time scale

$$t_a \simeq t_c E_D/E . \tag{15}$$

Thus since in the runaway process the acceleration time scale is necessarily longer than the collision time scale which itself is longer than the various plasma wave excitation and relaxation time

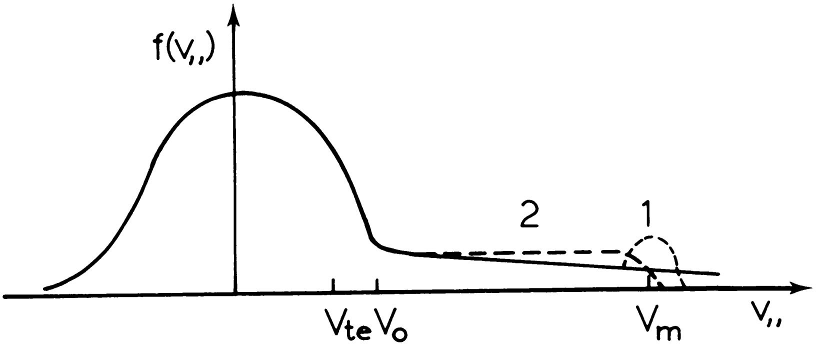

Figure 6. - The figure shows the "reduced" velocity distribution function (after integration over the velocity components perpendicular to the electric field direction).

scales the cycle is repeated and periodic acceleration and production of plasma waves take place.

It is important to realize that the above picture is only applicable if the electrons remain sufficiently long in regions with the induced fields. Since the transit time of an accelerated particle through the flaring tube in the corona is about one second the pulsating regime of the runaway process can only operate if most accelerated particles are trapped inside the tube. Such a trapping could be achieved by the existence of closed magnetic field lines above the dense photosphere which can arise from the tearing process itself (see Figure 5). Here we shall simply assume that trapping is achieved and apply the above picture to the observed fine structures.

If one assumes that the pulsations arise from standing *radial oscillations* of the flaring flux tube (Rosenberg, 1970; Meerson et al., 1978) and adopting a value of 5000 km for its internal radius (probably a lower limit for flaring tubes) the observed period of the pulsations 1 sec gives a value for the Alfvén velocity of $v_A \simeq 5000$ km s^{-1} . Further assuming that the (polarized) spike radiation arises at the fundamental of the plasmafrequency ($\omega/2\pi \simeq 600$ MHz) the characteristic density is $n \simeq 4.4 \,.\, 10^9$ cm^{-3}. Then the magnetic field strength is $B \simeq 152$ G and the electron cyclotron frequency $\omega_{ce}/2\pi \simeq 425$ MHz , of the same order as the plasmafrequency.

Further the observed duration of individual spikes ($\lesssim 0.08$ s) corresponds according to the model to the collision time t_c . The temperature in the flaring loop cannot be smaller than the normal coronal temperature of $2 \,.\, 10^6$ K which at the present density corresponds to a collision time $t_c \simeq 0.005$ sec. We shall adopt a value of $t_c \simeq 0.02$ sec with a corresponding temperature of $T = 5.10^6$ K. Further the spike interval represents the acceleration time in Eq. (15) and has a characteristic value of 0.2 sec so that the electric field has a value $E/E_D \simeq 0.1$ and the local Dreicer field is (see Eq. (8)) $E_D = 2.10^{-7}$ ESU. For the minimum runaway velocity we find (see Eq. (7)) $v_0 \simeq 3\, v_{te}$.

For the *dimensions* of a separate tearing region we derive the following values: An upper limit for the thickness is given by the product of spike duration and Alfvén velocity which is 100 km. Its length can be found from the spike width

Table IV

Physical conditions in the radioflare

tube inner radius	$5 \,.\, 10^3$ km
magnetic field strength	152 G
density	$4.4 \,.\, 10^9$ cm^{-3}
electron temperature	$5 \,.\, 10^6$ K
induced electric field strength	$2 \,.\, 10^{-8}$ ESU
minimum runaway velocity	$3 \,.\, 10^9$ cm s^{-1}
length of a tearing region	$1.5 \,.\, 10^3$ km
thickness of a tearing region	< 100 km

of 3 MHz which reflects the variation in density in a single tearing region and from the scale height (for $T = 5.10^6$ K). We find a length of $L \simeq 1500$ km (see Table IV). Finally from the observed flux ($\simeq$ 200 SU (Slottje, 1979)) and the dimensions we derive a radio brightness temperature for the spikes of $T_b \simeq 5 \,.\, 10^{13}$ K. This radio brightness temperature cannot exceed the effective temperature of the plasma waves which themselves cannot have a larger energy density than the thermal energy density. Thus from the derived density and temperature and adopting a spread in wave number for the Langmuir waves of λ_D^{-1} we derive an absolute upper limit for the effective temperature of the plasma waves of $T_\ell < 4.10^{14}$ K which indeed is substantially larger than the radio brightness temperature T_b. Finally, the fraction of particles which runs away is determined by E/E_D and is of the order $n_R/n \simeq 4.10^{-3}$.

As a consequence of the emission of "slow" plasma waves the accelerated particles acquire large pitch angles. So, an appreciable part of the acceleration energy resides in motion perpendicular to the magnetic field direction. In this way the fast electrons radiate gyro-radiation which would explain the (oppositely) polarized pulsating continuum. Each spike on the other hand would be the result of a short excitation of Langmuir waves in a single tearing region. As the flare goes on the tearing process might gradually take on the systematic pulsating appearance as described above. As a result the spikes occur in slowly drifting bands rather than at random in frequency and time.

If the above explanation is valid it offers the interesting situation that one is directly observing the acceleration region of a flare which occurs at an unusual altitude in the corona. Furthermore in flares one naturally expects a relatively large value of ω_{ce}/ω_{pe}, which seems to be required for the pulsating regime of acceleration by induced electric fields. Perhaps the (small) class of braided zebra patterns represents radio emission originating directly in flares.

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DISCUSSION

Stewart: On the question of the sense of circular polarization, does the observed polarization fit your model prediction for o-mode emission spikes and x-mode continuum?

Kuijpers: Since I have no spatial information I cannot tell. However the observed sense of circular polarization of the spikes is indeed opposite to that of the continuum.

Benz: The non-linear development of loss-cone instabilities is not well known. I have made some calculations on the influence of the unstable waves on the electron orbits. The result is that electrons can easily be perturbed delayed or speeded up in their gyration. This puts them out of resonance with the wave (assuming only one). This limits the growth of the waves to a relatively small energy density.

D. Smith: Did you calculate the number of electrons which can be accelerated by the induced electric fields in tearing modes self-consistently? I find that less than 0.05% of the energy released can go into these electrons and think that your figure of 10% of the electrons running away is far too high.

Hudson: A runaway fraction as large as 10% will probably lead to a bright hard x-ray source. Thus x-ray observations could help to determine the number of runaways; more interestingly the forthcoming imaging observations of hard x-rays (for example from SMM) may fix the geometry more definitively.

Kuijpers: From the model I derived that the induced electric field was at least of the order of 10% of the Dreicer field, from which the fraction of accelerated electrons follows to be about 10%. Whether the tearing mode can actually give rise to such fields I just assumed to be true.