A COHERENT RADIATION MECHANISM
FOR TYPE IV dm RADIO BURSTS

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Abstract. An interpretation is presented of the decimetric type IV continuum with fine structure on March 6, 1972 and of the corresponding source region, in terms of Čerenkov plasma radiation and alternatively of synchrotron radiation, both in case of coherent and incoherent generation. If the magnetic field strength in the source region is a few gauss, in a stationary situation a loss cone instability develops which generates electron plasma waves coherently. The amount of energetic electrons required for consecutive induced scattering of the plasma waves at the thermal ions into electromagnetic waves is less than in case of synchrotron radiation. It is concluded that the former mechanism provides the explanation of type IV continua with fine structure such as intermediate drift bursts and sudden reductions of the continuum level.

1. Introduction

A type IV continuum which occurred in the dm-band on March 6, 1972 between 1150 UT and 1300 UT has been extensively described by Slottje (1974). Here we repeat briefly the principal observational details and subsequent requirements for a model for dm type IV continua with similar fine structure.

The continuum radiation consisted of at least three sub-bursts of 10 to 15 min duration and ‘decay times’ of about 5 min. In these continua mainly two kinds of fine structures were apparent: intensity reductions and the so called fiber bursts. The intensity reductions are broad band features lasting 0.1–2 s and occurring simultaneously over 80–100 MHz within 0.1 s; the reduction amounted to a factor 2 to 3. Such a structured continuum has been observed on several other occasions with the Utrecht spectrograph. It sometimes shows ‘zebra patterns’ (Slottje, 1972a, b).

The projected source of the March 6 emission, as observed with a one-dimensional interferometer, remained quasistationary (Lantos-Jarry, 1972). We assume that the radiation was caused by fast particles injected into a closed magnetic structure after and during the flare of 1117 UT. The flare was associated with a proton event and it is therefore plausible that the injected electrons had relativistic energies, in excess of 300 keV but mostly less than 1 MeV (Lin, 1970). We use therefore low energy particles in explaining the continuum.

By far the strongest radio component was located near the optical flare region. Magnetograms indicate that the source was probably situated in a magnetic field pointing towards the Sun. Under the assumption that the radiation did not change its sense of polarization on its path through the corona, the sense of polarization in

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the source region was righthanded, i.e. had the same sense of rotation as electrons in a magnetic field.

From the observed abrupt changes in intensity, one finds as the upper limit of the size of the responsible source $3 \times 10^4$ km. The maximum flux at 240 MHz amounted at least to $10^{-16}$ erg cm$^{-2}$ Hz$^{-1}$ s$^{-1}$ around 1223 UT (Dröge, 1972). However during this maximum there were no reduction features of the continuum level by a factor of two or more and we cannot be sure that this emission was produced by the same small region. Strong reductions occurred at 1205 UT around 234 MHz, the 'missing flux' being $6.5 \times 10^{-18}$ erg cm$^{-2}$ Hz$^{-1}$ s$^{-1}$ (HHI, Krüger, 1972). If we take for the effective emitting surface $7 \times 10^8$ km$^2$, the effective temperature of the burst is at least $10^{10}$ K. This strongly suggests a coherent emission mechanism.

The burst was absent at 169 and 530 MHz. The emission was concentrated roughly between 240 and 300–350 MHz and it could be traced up to 410 MHz. From the inferred lower limit on the extent in frequency, 100 MHz, and the upper limit in size it follows that the emission at the different frequencies cannot originate at their corresponding plasma levels in the corona in case of density distributions exceeding 5 times the Newkirk values (Newkirk, 1967); the 200 MHz level corresponds to a height of 0.15 $R_\odot$ in a coronal model with density 5 times the Newkirk values.

As regards the operating mechanism we discuss three possibilities:

(i) induced conversion into electromagnetic waves of coherently generated Čerenkov plasma waves,

(ii) coherent synchrotron radiation in the presence of a background plasma due to a population inversion of the fast particles,

(iii) synchrotron radiation due to phase coherence of bunched particles.

For the magnetic field strength we adopt values of 1–8 G. Values of 3–8 G have been deduced from the observed zebra patterns in related continua (Rosenberg, 1972; Chiuderi et al., 1973), and, perhaps more important in this case, many intermediate drift or fiber bursts are present, each individual burst having a mean frequency extent of 1–3 MHz, which leads to values of the magnetic field in the source region of 1–3 G (Kuijpers, 1973).

2. Radiation from Plasma Waves

For any wave mode an effective temperature, $T_{\text{eff}}$, is defined according to its monochromatic intensity

$$I(\omega, \theta, \phi) \, d\omega = \frac{n^2 \omega^2 \kappa T_{\text{eff}}(k)}{8\pi^3 c^2} \, d\omega$$

in the case where the direction $(\theta, \phi)$ of the ray and the wave vector coincide and $\hbar \omega \ll \kappa T_{\text{eff}}$. Here $n = ck/\omega$, $k$ the wave vector, $\omega$ the corresponding angular frequency of the particular mode, $c$ the velocity of light in vacuo, $\kappa$ and $2\pi\hbar$ the Boltzmann and Planck constants. In thermal equilibrium the effective temperature equals the true temperature.
Furthermore a number density, $N(k)$, of plasmons of any particular mode is defined in wave vector space according to

$$\kappa T_{\text{eff}}(k) = N(k) \hbar \omega(k).$$

Again this relation coincides with the appropriate quantummechanical definition in thermal equilibrium.

2.1. INCOHERENT GENERATION

Considering the case where the transverse waves are generated by electron plasma waves, the effective temperature of the former imposes a lower limit upon the effective temperature of the latter in the following way.

The number density of transverse quanta can never exceed the instantaneous density of the longitudinal quanta in the case of conversion processes for which each ingoing longitudinal plasma wave-quantum corresponds to one outgoing electromagnetic quantum (e.g. scattering at particles or coalescence of waves of different kinds) and situations such that the period of emission of transverse waves from the source equals the time interval during which the longitudinal waves are generated. This is certainly true on time scales as large as the characteristic duration of the continuum outbursts, which is about ten minutes. If moreover the ratio of the frequencies of the outgoing and incoming wave is two or less, the required temperature for the electron plasma waves should exceed half the temperature of the transverse waves, $5 \times 10^9$ K, with the proviso that the occupied volume in wave vector space for both wave modes is about equal. If on the other hand a single particle mechanism is governing the (Čerenkov) emission and absorption of plasma waves, or in other words if the waves are generated incoherently, their effective temperature cannot exceed the kinetic energy of the relevant particles divided by the Boltzmann constant (Melrose, 1970a). Therefore for 300 keV particles the (extreme) upper limit of the observed radiation temperature is $4 \times 10^9$ K, (hardly the observed value), unless the plasma waves are generated coherently.

2.2. COHERENT GENERATION

Will the circumstances lead to an unstable situation in which coherent generation of waves can take place which grow proportionally to the amount of waves present? When a beam of fast particles is injected into a magnetic arch, loss cone distributions will be set up for the fast particles after a few trapping periods, the loss cones being determined by the magnetic structure and the destructive influence of collisions.

It should be mentioned that loss cones can give rise to Harris instabilities at multiples of the cyclotron frequencies (Harris, 1969; Baldwin et al., 1969). This kind of instability is invoked by Mollwo (1971, 1973) in the explanation of a.o. type IV dm bursts. However, essentially he assumes a rather high value of the magnetic field strength ($\omega_H/\omega_p \approx 1$), contrary to the case considered here.

For weak magnetic fields, characterized by $\omega_H/\omega_p \ll 1$, the dispersion relation for
electron plasma waves is

$$\omega^2 = \omega_p^2 + \omega_H^2 \cos^2 \vartheta + 3k^2 v_{te}^2.$$ 

$\vartheta$ is the angle between the wave vector and the field direction, $\omega_p$ is the electron plasma frequency, $\omega_H$ the nonrelativistic gyrofrequency of the electrons and $v_{te} = (kT_e/m_e)^{1/2}$ the thermal velocity of the electrons of the background plasma and $T_e$ and $m_e$ their temperature and mass.

For a particular wave the resonant particles are those having velocity components in the wave vector direction equal to the phase velocity of the wave.

The effect of the magnetic field on the generation of plasma waves with wave number $k$ will be negligible whenever $\omega_H/\omega_p \ll 1$ and $kr_H \gg 1$ where $r_H$ denotes the Larmor radius of the resonant particle. For Čerenkov emission, $\omega = k \cdot v$, the two conditions coincide. Then in the source region, where $\omega_p/\omega_H > 10$, coherent excitation of plasma waves will take place when the instability criterion for the nonmagnetic case

$$\frac{\partial F}{\partial u_{\|}} > 0$$

is fulfilled, where $F(u) = \int f(v) \delta(u - k \cdot v/k) \, d^3v$ and $f(v)$ is the velocity distribution function for the electrons (Krall and Trivelpiece, 1973). Consequently for loss cone distributions an instability may be expected for wave vectors non-parallel to the magnetic field.

For simplicity we proceed from a beam of fast particles with a density in velocity space which is constant within a certain sphere of radius $10^{10}$ cm s$^{-1}$ (corresponding to 30 keV electrons) at the time of injection. In a static magnetic field the resultant equilibrium density distributions will be constant along the flux tube and independent of the velocity in the accessible regions in velocity space, i.e. outside the loss cone (Roederer, 1970). The half-aperture $\alpha$, of the loss cone is given at every point by

$$\frac{\sin^2 \alpha}{H} = \frac{1}{H_c},$$

where $H_c$ is the value of the magnetic field at the 'level' where collisions dominate. Performing the integration of the distribution function over two directions in velocity space, one parallel, the other perpendicular to the magnetic field, and taking the derivative with respect to the third velocity component we find indeed that the distribution is unstable against the excitation of plasma waves. Taking into account that in the instability criterion the total distribution function should be considered including in this case an isotropic distribution of electrons with a temperature of $10^6$ K an instability can occur only for waves that are not too heavily Landau-damped on the thermal background, say with phase velocities larger than $3 v_{te}$, i.e. $1.2 \times 10^9$ cm s$^{-1}$. In our example plasma waves are generated coherently if loss cones have half-apertures larger than $7^\circ$ and up to $80^\circ$, for velocities up to $5 \times 10^9$ cm s$^{-1}$. We conclude therefore that coherent generation of plasma waves in a direction preferably perpendicular to the magnetic field (the upper hybrid wave) will proceed
quite naturally from an injection of fast particles into a closed flux tube with a weak magnetic field up to heights where the field strength has decreased to $10^{-2}$ times the critical field $H_c$.

2.3. SPONTANEOUS CONVERSION

As for the conversion of plasma waves into electromagnetic waves coupling can occur due to the existence of large scale gradients in regions where the approximation of geometrical optics is violated. The efficiency is about $3 \times 10^{-8}$ at 300 MHz for a density scale height of $10^{10}$ cm, a temperature of $10^6$ K and a broad angular spectrum of plasma waves with a solid angle of $2\pi$ steradians and phase velocities of $10^{10}$ cm s$^{-1}$ (Zheezenyakov, 1970).

Coupling (nonlinear) of plasma waves with sound waves is not likely to be important either since there is no reason to assume that ion-acoustic waves are present to an extent larger than the thermal noise level, because the ratio of the electron to the ion temperature is certainly not much larger than unity and therefore their damping rate is high (Fried and Gould, 1961).

In principle in a magnetoplasma other low frequency wave modes, such as Alfvén and magnetoacoustic waves, can be present and may be of importance here. Particularly the observed fine structure can be taken as evidence for their existence, e.g. whistlers for the fiber structure (Kuijpers, 1973) and very low frequency waves for the sudden reductions in a way analogous to the explanation of pulsating structure by Rosenberg (1970). We will not make an ad hoc assumption about their importance in relation to the continuum radiation and exclude them. So, scattering at particles is the only remaining mechanism.

With the scattering process the particle orbits are perturbed by the field of the incoming (plasma) wave and the associated current density acts as the source for the outgoing (electromagnetic) wave. In general one has to include the reaction of the surrounding plasma on the perturbed particle motion, which also generates a current. While in the first case the current is proportional to the electric field of the incoming wave and is known as Thomson or Compton scattering, in the second case the current (for weak fields) is proportional to the product of the shielding field and that of the incoming wave and is known as nonlinear scattering. The latter effect counteracts the former because the shielding gives rise to a polarization cloud with a charge excess of a sign opposite to that of the inner particle while both oscillate not independently in the field of the incoming wave. In general the degree of cancelling depends on the mass of the particle and its velocity.

If no external magnetic field is present, the scattering process is governed by the conservation relation

$$\omega_t - \omega_i = (k_t - k_i) \cdot v.$$ 

Here $\omega_t$ and $\omega_i$ denote the angular frequency of the transverse respectively plasma wave, $k$, and $k_i$ their wave vectors and $v$ the velocity of the scattering particle. In the weak field case, $\omega_H/\omega_p \ll 1$, considered here, this relation is also valid.
If plasma waves are converted into electromagnetic radiation through scattering at particles of the (thermal) background plasma, a predominant role will be played by the ions (Tsytovich, 1970). The reason is that (nonlinear) scattering at the polarization clouds of the ions (far more important than the (linear or Compton) scattering at the ions themselves) dominates the net effect of scattering on the electrons where the two contributions are equal to first order and cancel each other. Because $|k_i \cdot v| \ll |k_i \cdot v|$ the frequency difference between the outgoing and incoming waves satisfies $\Delta \omega \lesssim k_i v_{ti}$ where $v_{ti}$ denotes the thermal velocity of the ions. Further on account of Landau damping the range of possible phase velocities of the plasma waves is restricted to $\omega_l/k_i > v_{te}$, where $\omega_l \sim \omega_p$. Therefore $\Delta \omega < \omega_p v_{ti}/v_{te} \sim 2.3 \times 10^{-2} \omega_p$. Consequently the radiation would originate at the respective plasma levels in the corona, apart from the bandwidth of the original plasma waves due to the finite temperature of the sustaining plasma, e.g. $< 0.2 \omega_p$. The efficiency for the conversion of plasma waves into transverse waves through spontaneous scattering on thermal density fluctuations (the polarization clouds of the ions) is of the order $4 \times 10^{-5}$ for a scattering region with linear dimensions of $3 \times 10^9$ cm, a density of $1.1 \times 10^9$ cm$^{-3}$ and a temperature of $10^6$ K (Zheleznyakov, 1970).

The waves can scatter also on the fast particles of the beam. For relativistic electrons the scattering is essentially Compton scattering (Kaplan and Tsytovich, 1969) and will dominate the non-linear scattering at the polarization cloud, in contrast with scattering at the thermal electrons. Actually these fast electrons have left their polarization cloud trailing behind and consequently they emit (Čerenkov) plasma waves. The frequency difference between the transverse and longitudinal waves will be at most $\omega_l/(\omega_l/k_i v - 1)$ when the transverse wave and the particle are moving in the same direction, four times the plasma frequency for 300 keV electrons. However, due to the small fraction of fast particles, the contribution of this process to spontaneous scattering will be less important compared to that of the thermal ions (Zheleznyakov, 1970).

2.4. Induced Scattering

Apparently the spontaneous conversion efficiency for the different processes is rather low being less than $10^{-4}$. However, the conversion of longitudinal to transverse waves can be stimulated by transverse waves already present. Precisely through such an induced conversion the temperature of the produced waves can eventually reach the temperature of the original waves. The kinetic wave equation for scattering can in the case of homogeneity be written as (Tsytovich, 1970)

$$\frac{\partial N^l(k)}{\partial t} = N^l(k) \sum_a \int w^{\alpha l}_a(p, k, k') \ h(k - k') \ \frac{\partial f^l_a(p)}{\partial p} N^l(k') \frac{d^3p \ d^3k'}{(2\pi)^6} +$$

$$+ \sum_a \int w^{\alpha l}_a(p, k, k') \ f^l_a(p) N^l(k') \frac{d^3p \ d^3k'}{(2\pi)^6} +$$

$$- N^l(k) \sum_a \int w^{\alpha l}_a(p, k, k') \ f^l_a(p) \frac{d^3p \ d^3k'}{(2\pi)^6}. $$
The indices $t$ and $l$ denote the transverse respectively plasma waves, $\alpha$ the particle species, $p$ the momentum and $f_\alpha(p)$ the distribution function in momentum space and $w^{\alpha t}_\alpha(p, k, k')$ the probability per unit time that a particle of species $\alpha$ and momentum $p$ scatters a plasma wave with wave vector $k'$ into an electromagnetic wave with wave vector $k$. The first term on the right hand side describes the induced scattering, the other two the spontaneous contributions.

The formula shows that the conversion rate for induced scattering of plasma waves off the thermal ions will be positive for conversion towards lower frequencies, since for any isotropic distribution the kernel will be proportional to $(\omega_t - \omega_l) \frac{\partial f}{\partial p}$.

At the same time we see that induced Compton scattering at the fast electrons towards higher frequencies can only take place for a population with a positive radial derivative in velocity space. Actually, according to Kaplan and Tsytovitch (1969), the fast particles should also have an anisotropic distribution. However, even in our simple example, the induced scattering off the thermal ions towards lower frequencies is positive while the induced Compton scattering off the fast particles is zero due to the independence of the fast particle distribution on momentum. Consequently we reject Compton scattering off the fast electrons as a possible generating mechanism of the continuum radiation and will proceed to investigate the requirements for induced scattering off the thermal ions.

According to Tsytovitch (1970), the characteristic time for this process is less than or equal to

$$\tau_{NL} \approx \frac{n_e m_e v_{te}^2}{W^l} \left( \frac{m_i}{m_e} \right)^2 \left( \frac{v_{te}}{v_{ph}^l} \right)^3 \frac{1}{\omega_p}$$

for the case of $v_{ph}^l/v_{te} \ll (9 m_i/m_e)^{1/2}$ which is certainly fulfilled here. $W^l$ is the total energy density of the plasma waves, $v_{ph}^l$ their phase velocity. The requirements for induced scattering into transverse waves reduce to

$$\tau_{NL} v_{gr}^l < 3 \times 10^9 \text{ cm}$$

and

$$\tau_{NL} \ll \tau_{coll},$$

where $v_{gr}^l$ is the group velocity of the transverse waves, $\tau_{coll}$ the effective collision time for the electrons and ions of the background plasma, the latter being a measure of the damping of the transverse waves.

The first condition imposes a lower limit of $10^{-5}$ erg cm$^{-3}$ on the energy density of the plasma waves, taking the vacuum value for the group velocity of the transverse waves, $7 \times 10^9$ cm s$^{-1}$ for the phase velocity of the longitudinal waves, $10^6$ K for the temperature of the background plasma and $1.1 \times 10^9$ cm$^{-3}$ for its density corresponding to a plasma frequency of $2\times 300$ MHz. Choosing a value of 300 keV for the energy of the electrons and assuming that they loose about one third of their energy as plasma waves within $10^3$ s (the maximum duration of a sub-burst), then we arrive at a lower limit of $6 \times 10^4$ cm$^{-3}$ on their density.

To satisfy the second condition the derived number density of fast particles should
be as large as $6 \times 10^5$ cm$^{-3}$, the collision time being (Zheleznyakov, 1970)

$$\tau_{\text{coll}} \approx \frac{T^{3/2}}{(5.5 n_e \ln (10^4 T^{2/3} / n_e^{1/3}))} \approx 1.4 \times 10^{-2} \text{ s}$$

for the same environment as before.

Such a density corresponds to a value for the fraction of the background plasma of $5 \times 10^{-4}$. It should be noted that for the mentioned densities and energies the weak turbulence condition, $W \ll nkT$, necessary for the validity of the kinetic wave equation, is easily satisfied. For a sphere of radius $1.5 \times 10^9$ cm the required number of fast electrons amounts to $10^{34}$.

The most plausible geometric configuration in which amplification will take place is one in which the transverse waves move perpendicular to the density gradient, more or less coinciding with a direction perpendicular to the magnetic field. Because in this case they will not enter those regions of the source where most of the plasma waves have frequencies lower than the incoming transverse waves. In these regions induced absorption would prevail and weaken the transverse waves.

### 2.5. Polarization

As regards the polarization of the outgoing radiation, conversion into the extraordinary mode, for which the smallest frequency is $0.5 \omega_H$ above the local plasma frequency, is possible in case that the frequency of the original plasma wave is high enough. This requires a local bandwidth of the plasma waves of 0.05–0.02 $\omega_p$ for a ratio $\omega_p/\omega_H \approx 10–30$.

Although the emission of the extraordinary mode would be easy enough, a predominance of the extraordinary over the ordinary mode is not to be expected because of collisional influence. In a weak magnetic field ($\omega_H/\omega_p \ll 1$) the absorption coefficient for the two modes is

$$K_{eo, o} = \frac{v_{\text{eff}} \omega_p^2}{2 \omega^3 [1 + (\omega_H/\omega)]^2 n_{eo, o}},$$

for parallel propagation (Zheleznyakov, 1970). Here $v_{\text{eff}}$ denotes the effective number of collisions and $n$ the index of refraction. Consequently the influence of collisions on the two different modes is not essentially different.

However, the converting mechanism itself favours the production of waves of the extraordinary mode in the following way. When a particle with velocity $v$ scatters at a plasma wave with wave vector $k_i$, the current produced is proportional to $k_i - (k_i \cdot v/c) v/c \approx k_i$ for the thermal ions (Gaibitis and Tsytovich, 1964). Due to the nature of the loss cone instability the plasma waves will travel preferably perpendicular to the magnetic field. Therefore the generating current will also be perpendicular to the magnetic field. The power radiated into a particular wave mode equals the work done by the electric field $E$ of the outgoing wave on the current and is therefore proportional to $E \cdot k_i$. If the transverse waves are moving perpendicular to the external magnetic field the electric field for the ordinary mode is parallel to the
magnetic field and that for the extraordinary mode perpendicular to it (Krall and Trivelpiece, 1973). Consequently, only waves of the extraordinary mode would be produced. Therefore the suggested mechanism is also consistent with the observed polarization.

2.6. Sudden reductions

If the continuum is indeed generated by the coherent excitation of plasma waves by fast particles and the consecutive induced conversion to electromagnetic waves through scattering off the thermal ions, a natural explanation of the reductions would be provided by sudden absence of the conditions required for induced scattering or coherent excitation. The first will happen when the nonlinear transfer time, $\tau_{NL}$, becomes too large, which happens when the energy density of the plasma waves becomes too small. In its turn the energy density of the plasma waves will drop if the coherent excitation stops. Maybe this could be achieved by low frequency waves travelling through the source region, changing the velocity space distribution of the fast electrons adiabatically.

We conclude that coherent generation of plasma waves is likely to occur in a closed flux tube after an injection of fast particles. Besides efficient conversion into electromagnetic radiation through induced scattering at the thermal ions easily occurs under the constraints from the observed continuum.

3. Gyro-Synchrotron Radiation

The movement of the particles perpendicular to the magnetic field certainly favours the emission of synchrotron radiation.

3.1. Incoherent generation

Firstly we investigate the incoherent emission. In case of weak magnetic fields, when $\omega_H/\omega_p < 1$ and consequently one can neglect the influence of the magnetic field on the Čerenkov emission of electron plasma waves, the amount of energy fed by a single particle into (incoherent) plasma waves exceeds the synchrotron losses by several orders of magnitude (Zheleznyakov, 1970). Therefore if the conversion efficiency for plasma waves is larger than one percent, which means that the conversion should proceed in an induced way, the synchrotron contribution will be far less important than that of the Čerenkov plasma waves; even more so when the plasma waves are generated coherently.

If the continuum is generated by the synchrotron mechanism in an incoherent way, the reductions would have to be caused by sudden changes of the magnetic field. From the amount of flux absent during the intensity reductions we can get an idea of the number of electrons involved, using the results of Ramaty and Lingenfelter, (1968). Again we consider the case of a weak magnetic field, with mildly relativistic electrons. For a magnetic field strength of 3.7 G (a value allowing us to use their calculations),
the observed intensity maximum at 240 MHz (23\(f_H\)) agrees with the spectral maximum of an isotropic velocity distribution of electrons of the form

\[
n(\gamma) \sim \begin{cases} 
\gamma^{-2} & \text{for } \gamma \leq 2.5 \\
0 & \gamma > 2.5
\end{cases}
\text{with } \gamma = [1 - (v^2/c^2)]^{-1/2}.
\]

superposed on the coronal background plasma with \(1.5 F_H/F_P = 0.2\) (\(f\) is the frequency). This implies that the source is situated high in the corona at a plasma level of 80 MHz. The sense of polarization agrees with the observed one, since mildly relativistic electrons radiate predominantly in the extraordinary mode.

Let us take as a characteristic value for the observed flux density of the incoherent radiation, originating in a source of a diameter less than \(3 \times 10^9 \text{ cm}\), a value of \(6.5 \times 10^{-18} \text{ erg cm}^{-2} \text{ Hz}^{-1} \text{ s}^{-1}\). Then \(1.4 \times 10^{34}\) electrons with a Lorentz factor \(\gamma = 2.11\) are required, which corresponds to a density of fast particles in the trapping region of \(10^6 \text{ cm}^{-3}\), more than \(10^{-2}\) times the background number density. This number density is larger than that required for induced conversion and the electrons are of higher energy. It is true that for a magnetic field strength as large as 9 G (the maximum value considered here) the required number density would be much less, as low as a few times \(10^4 \text{ cm}^{-3}\). But one should realize that in the case of a local plasma frequency of 80 MHz the critical density of fast particles required for the induced scattering of plasma waves into electromagnetic waves, reduces to a value of the same order. Therefore we abandon the incoherent synchrotron mechanism as the origin of the observed radiation.

3.2. COHERENT GENERATION

Let us now investigate the conditions for the coherent emission of synchrotron radiation. In this case the observed reductions would arise through sudden violation of the conditions for amplification. The residual radiation would then be due to incoherent radiation originating throughout the whole flux tube. There are two ways in which the coherent excitation can be achieved, either through a population inversion or an anisotropy in velocity space (Wild et al., 1963), followed by stimulated emission, or by bunching of particles (Takakura, 1956).

3.3. POPULATION INVERSION OR ANISOTROPY IN VELOCITY SPACE

For the first way of producing stimulated emission the underlying physical picture is the following. In the presence of a background plasma of sufficiently high density, an electromagnetic wave can cause grouping of the radiating particles through its longitudinal electric component. Such an effect could not occur in vacuo!

For simplicity we consider a monoenergetic and isotropic system of relativistic electrons, situated in a homogeneous background plasma. Then the maser effect is possible if the following conditions are met (Kaplan, 1966):

\[
n_s \geq \frac{n_e^{5/2}}{30 H^4 R}
\]
\[
\gamma \geq \frac{5.3 \times 10^{-3} n_e^{1/2}}{H},
\]

where \(n_s\) is the density of fast particles, \(n_e\) that of the background plasma and \(R\) the radius of the emitting region.

The radiation would be centered around

\[
f_m = \frac{18 n_e}{H}.
\]

For the burst considered \(f_m = 240\) MHz, so \(n_e/H \approx 1.3 \times 10^7\). Given a field strength of 3.7 G the electron density is about \(5 \times 10^7\) cm\(^{-3}\), corresponding to a plasma frequency of 66 MHz. The requirements for the fast electrons are: \(\gamma \geq 10\) and \(n_e \geq 10^6\), and these again are much more stringent than for the discussed Čerenkov mechanism. Therefore this mechanism is ruled out.

### 3.4. Bunched Particles

Coherent generation could also occur in vacuo if the radiating electrons are moving in little lumps (Takakura, 1956). Then effectively the radiating system consists of particles with a mass and charge \(s\) times higher than the corresponding electron quantities, if \(s\) particles are moving together within a volume of wavelength dimension.

However, without a continually working organizing mechanism maintaining the required phase coherence of the electron motion, density fluctuations on the scale of a wavelength will be destroyed very quickly. Already owing to the thermal velocity dispersion this happens within \(10^{-7}\) s for a wavelength of 100 cm. The bunching might be achieved in a plasma by whistler and electromagnetic cyclotron waves with a frequency close to \(\omega_H\), ascending in the solar corona and generated in the form of Alfvén waves at the basis, or by electrostatic cyclotron (Bernstein) waves with frequencies which are a multiple of \(\omega_H\) (Mangeney, 1972; Rosenberg, 1972).

Owing to radiation damping, an electron radiates in a bandwidth

\[
\delta_0 = 2 \left( \frac{2e^2 \omega^2}{3mc^3} \right) = 5 \times 10^{-5} \text{ Hz at 300 MHz.}
\]

Consequently, for a group of \(s\) particles the bandwidth will be

\[
\delta = 2 \left( \frac{2e^2 \omega^2}{3mc^3} \right) s.
\]

If the absorptions are caused by destruction of the phase relation, sudden reduction features would appear in the continuum with a bandwidth of \(5 \times 10^{-5}\) s Hz around 300 MHz. For the observed bandwidth of 100 MHz the number of particles per group would have to be tremendously large, \(2 \times 10^{13}\), corresponding to a monoenergetic and phaserelated density of fast particles of \(2 \times 10^7\) cm\(^{-3}\). So the absorption cannot be explained by this mechanism.
Therefore, synchrotron radiation cannot be considered as an alternative to the Čerenkov mechanism, since the number density required in the case of the former mechanism already implies the existence of the latter.

4. Conclusion

We have looked for an interpretation of the continuum radiation on the assumption that the magnetic field in the source region is weak \((\omega_H/\omega_p \ll 1)\), evidence for which is provided by the work on fine structure in similar continua. From the reduction features an upper limit of the size of the source region was deduced. As a natural consequence of the trapping of the fast particles in a stationary flux tube, a kind of loss cone instability develops generating electron plasma waves in a coherent way. Future interferometric observations of these continua can confirm this suggestion; presumably a double structure refers to the case of a large magnetic arch with loss cones in the highest parts too small for an instability to develop.

The conditions for consecutive induced scattering are less stringent than for an explanation in terms of synchrotron radiation, either coherently or incoherently. Therefore we propose Čerenkov wave generation and consecutive induced scattering off the thermal ions as the generating mechanism of dm type IV continua like the one of March 6, 1972.

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References


