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 (240-350 MHz) which occurred on March 6, 1972. It is shown that in a stationary situation and for weak magnetic fields a loss cone instability develops which generates Langmuir waves preferably perpendicular to the magnetic field. Efficient conversion into electromagnetic waves will take place through induced scattering, if the number density of the weak relativistic (< 1 MeV) electrons exceeds 6 \times 10^5 cm^{-3}. This requirement is less stringent than for an explanation in terms of synchrotron radiation.

1. Introduction

This contribution concerns the explanation of those type IV dm continua which are characterized by fine structure like sudden reductions, fiber bursts and eventually also zebra patterns as have been observed with the 60-channel spectrograph at NRAO in the range 200-320 MHz. Typical examples of this fine structure can be found in Slottje (1972a,b) and Kuijpers (1973). In our explanation of the continuum radiation we will use values for the source parameters as have been derived from the burst on March 6, 1972, which occurred between 1150 - 1300 UT and consisted of at least three sub-bursts of 10 to 15 min duration. The observations will be published in full detail by Slottje.

2. Source Properties

According to the observations a model should meet the following boundary conditions:
1. The source is quasistationary as indicated by the interferometric observations by Lantos-Jarry (1972).
2. Since the radio burst is associated with a proton event, the responsible particles presumably have weak relativistic velocities, that is their energies range from 300 keV to 1 MeV (Lin, 1970).
3. From the intensity reductions, which occur simultaneously within 1 s over a bandwidth of 80 - 100 MHz and during which the flux is reduced by a factor of two or more (Dröge, 1972), an upper limit of the size of the responsible source is derived of 3 \times 10^4 km. According to Krüger (1972) the missing flux is at least 6.5 \times 10^{-10} erg cm^{-2} Hz^{-1} s^{-1}. Consequently the effective temperature of the burst exceeds 10^{10} K.
4. Large numbers of fiber bursts occur during this event. The instantaneous frequency separation between the ridges is 1-3 MHz. Adopting the explanation of this phenomenon in terms of upconverted whistlers (Kuijpers, 1973), the measured frequency separation corresponds to about one third of the electron gyrofrequency.

Then the magnetic field in the source region has a strength of 1-3 G. Taking into account that zebra patterns in related continua gave values of the magnetic field strength of 3-8 G (Rosenberg 1972), we will use values of 1-8 G.
3. Radiation Mechanism

Two possible candidates for the continuum emission are obvious:
1. The radiation is generated by longitudinal plasma waves. Then using the observed high effective temperature, a coherent excitation of the plasma waves is desired, that is an instability is required. Moreover, an efficient conversion mechanism of the plasma waves into the electromagnetic waves should exist.
2. Alternatively the gyro/synchrotron mechanism is operating, either incoherently or coherently, that is as a single particle mechanism or with some kind of amplification.

3.1. Plasma Waves
Concentrating on the generation by plasma waves we have to consider the weak magnetic field case, \( \omega_H / \omega_p \ll 1 \), as follows from the deduced magnetic field strength in relation to the observing frequencies. Here \( \omega_H \) is the angular electron gyrofrequency and \( \omega_p \) the angular electron plasmafrequency.

The single particle, or incoherent, generation of plasma waves is insufficient, because in this case the effective temperature of the excited waves can never exceed the value given \( E/\kappa \approx 4.10^9 \) K for 300 keV electrons (Melrose, 1970). Here \( \kappa \) is the Boltzmann Constant and \( E \) the kinetic energy of the fastest particles.

On the other hand in a stationary magnetic arch loss cone distribution of the fast particles will be set up. Because the beam of fast particles is depleted below some height by collisions. Starting from these loss cone distributions further influence of the magnetic field on the generation of plasma waves of frequency \( \omega \) can be neglected if \( \omega / \omega_H \ll 1 \) and \( kr \gg 1 \), where \( \omega \) is the wave number and \( r_H \) the Larmor radius of the resonating particle. In the case of Čerenkov excitation \( \omega = k \cdot v \) for a particle with velocity \( v \) of Langmuir waves around the plasma- and upper hybrid frequency the two conditions coincide and reduce to \( \omega / \omega_H \ll 1 \), which is satisfied in the source region. Therefore, an instability will appear whenever the instability criterion for the nonmagnetic case is fulfilled, that is when the reduced (integrated over the velocity directions perpendicular to the wave vector) distribution function has a positive derivative in velocity space (Krauss and Trivelpiece, 1973). Let us take the simple example of a sphere in velocity space with radius \( 10^2 \) cm s\(^{-1} \) (30 keV electrons) and with a uniform distribution outside the loss cone superposed on a thermal background of \( 10^6 \) K. Then an instability will develop for wave vectors perpendicular to the magnetic field and phase velocities ranging from about \( 3V_{te}(10^8 \text{ cm s}^{-1}) \) to \( 5 \cdot 10^9 \) cm s\(^{-1} \) if the loss cone has a half-aperture between \( 70^\circ-80^\circ \). Here \( V_{te} \) is the temperature of the electrons and \( m_e \) their mass. The lower bound of \( 3V_{te} \) is determined by strong Landau damping of the plasma waves on the thermal background. Consequently it is expected that the injection of fast particles into a closed magnetic structure will lead to an unstable situation and to a coherent excitation of the plasma waves, preferably perpendicular to the magnetic field.

Efficient conversion of plasma waves into transverse waves can proceed through induced scattering on particles. In this case amplification or maser action of the generated electromagnetic waves takes place. In principle this scattering could take place on the thermal particles as well as on the fast particles of the beam. Since in our simple example the derivative of the nonintegrated distribution function is zero, induced scattering on the fast particles will not occur (Tsytochich, 1970). On the other hand induced scattering on the thermal particles, here on the polarization clouds of the ions and towards lower frequencies, will occur if the nonlinear transfer time of this process, \( \tau_{NL} \), satisfies the following inequalities.
\[ \tau_{NL} \ll \frac{v_+}{\nu_{gr}} \ll 3 \times 10^9 \text{ cm} , \]

\[ \tau_{NL} \ll \tau_{coll} \approx \frac{n_e}{5.5 n_e \ln(1 + \frac{7}{3})} , \]

where \( v_+ \) is the group velocity of the escaping electromagnetic waves and \( \nu_{gr} \) the background number density. Here the effective collision time, \( \tau_{coll} \), is a measure of the damping of the transverse waves (Zheleznyakov, 1970). The nonlinear growth time is defined by

\[ \frac{dW^t(\omega_p)}{dt} = \frac{W^t(\omega_p)}{\tau_{NL}} , \]

where \( W^t \) is the energy density of the transverse waves. For \( \nu_{ph} / \nu_{te} < 3 (m_i/m_e)^{3/2} \), the dependence of the growth time on the energy density of the longitudinal waves, \( W^l \), can be written as (Tsytovich, 1970)

\[ \tau_{NL} \approx \frac{n_e m_e v^2}{W^l} \left( \frac{m_i}{m_e} \right)^{1/2} \left( \frac{v_{te}}{v_{ph}} \right)^{3/2} . \]

Here \( v_{ph} \) is the phase velocity of the longitudinal waves and \( m_i \) the ion mass. Taking the vacuum value for the group velocity of the transverse waves, \( 7.1 \times 10^9 \text{ cm s}^{-1} \) for the phase velocity of the longitudinal waves, \( 10^6 \text{ K} \) for the temperature of the background plasma and \( 1.1 \times 10^9 \text{ cm}^{-3} \) for its density (\( \omega_p / 2\pi \approx 300 \text{ MHz} \)), the first inequality is satisfied if the longitudinal wave energy density exceeds \( 10^{-25} \text{ erg cm}^{-3} \). Assuming that the fast particles lose about one third of their energy into plasma waves within \( 10^4 \text{ s} \) (the maximum duration of a sub-burst) a density of \( 6.10^4 \text{ cm}^{-3} \) of 300 keV electrons is required. However, the second inequality imposes a higher limit on the fast particle number density at a plasma level of 30 MHz, namely \( 6.10^5 \text{ cm}^{-3} \).

The amplification will be optimum if the escaping electromagnetic waves propagate perpendicular to the magnetic field, since in that case the local plasma density and therefore the frequencies of the excited plasma waves will not vary substantially along the path of propagation. Consequently induced scattering (amplification) will prevail over induced absorption (Tsytovich, 1970).

To investigate a possible appearance of harmonic radiation at twice the plasma frequency, we use the relevant expression for the nonlinear energy transfer from the plasma waves into that mode, which for an isotropic spectrum of longitudinal waves can be written as (Tsytovich, 1970)

\[ \frac{dW^t(2\omega_p)}{dt} \approx \frac{10 (W^l)^2 \omega_p (\omega_p / k^2 c)}{n_e m_e c^2} , \]

where \( W^t(2\omega_p) \) is the transverse wave energy density at twice the plasma frequency, \( k^2 \) the characteristic wave number of the longitudinal waves and \( c \) the velocity of light. Comparing this expression with the above mentioned rate equation for \( W^t(\omega_p) \), we find that generation of the harmonic will be negligible if the transverse wave energy density at the plasma frequency exceeds 2% of the energy density of the longitudinal waves. Indeed the latter will be the case if the conditions for induced scattering are fulfilled.

3.2 Gyro/Synchrotron Radiation

Concerning the synchrotron mechanism for the weak field case \( (\omega_p / \omega_p < 1) \) considered here, the amount of energy fed by a single particle into plasma waves exceeds the synchrotron losses by several orders of magnitude as is shown by Zheleznyakov (1970). Therefore, if the conversion efficiency is better than 1%, the synchrotron emission is far less important, even more so when the plasma waves are generated coherently.
Also an explanation of the observations in terms of possible coherent synchrotron mechanisms requires densities and energies of the fast particles exceeding the corresponding quantities for the case of induced scattering. A detailed discussion of this matter can be found in Kuijpers (1974).

4. Conclusion

From the spectral fine structure of the type IV dm outburst on March 6, 1972 values of the magnetic field strength in the source region could be derived. In this situation (w_H/m_p<<1) quite naturally a loss cone instability develops which generates plasma waves (the upper hybrid). Finally conditions for induced scattering of these plasma waves are less stringent than in case of generation by the synchrotron mechanism. Therefore Čerenkov plasma wave excitation and consecutive induced scattering is proposed as the origin of type IV dm bursts with fine structure like the one on March 6, 1972.

The suggested explanation could account for an eventually observed double source. In this case the trapping magnetic arch would be very extended with loss cones in the highest parts too small for an instability to develop.

References

Lin, R.P. :1970, Solar Physics, 12, 266
Slottje, C. :1972b, Solar Physics, 25, 210