TYPE II SOLAR RADIO EMISSION – A SELF-CONSISTENT APPROACH*

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Abstract. An attempt is made to construct a self-consistent model for type II radio bursts. It is proposed that a majority of the type II shocks are super-critical and the reflected ions from such type II shock fronts are described by the drifted Maxwellian in the upstream and by the Dory–Guest–Harris distribution in the downstream. The low-frequency waves excited by these ions accelerate electrons resonantly along the field lines both in the upstream as well as in the downstream, which are responsible for the lower-frequency and upper-frequency bands in the dynamic spectrum of a type II radio burst. The functional behaviour of the distribution functions of the accelerated electrons is the same in both the cases whereas the number densities of the accelerated electrons in the downstream is smaller than that in the upstream.

1. Introduction

Type II bursts, which are characterized by the slow drift in their spectral features from high to low frequencies are generally accompanied by a large flare. On the plasma hypothesis the frequency drift is found to correspond to a velocity of the order of 10^3 km s^{-1} and the moving source had been identified with a flare-associated collisionless MHD shock wave (Pikel'ner and Gintzburg, 1963). Later, direct evidence for the generation of type II radiation by shock waves was given by the space observations of interplanetary type II bursts and interplanetary shock waves (Malitson *et al.*, 1973; Cane *et al.*, 1982). The estimates of type II shock speeds are subject to considerable error because of the uncertainty in the coronal density models. Velocities derived from heliograph observations of source positions are even more uncertain because of the imperfectly known effects of coronal scattering and refraction and of ionospheric refraction (see Nelson and Melrose, 1985).

In this paper, we propose, contrary to the usually accepted picture that the majority of the type II shocks are supercritical since the estimated Mach numbers of the most of the type II shocks exceed the recently revised critical Mach number M_c by Edmiston and Kennel (1984), which lies between 1 and 2 for typical solar wind parameters. This fact is also supported by the studies of the forward interplanetary shocks observed by ISEE-3 (Bavassano-Cattaneo *et al.*, 1986); where it has been shown that a majority of the interplanetary shocks are supercritical. We also propose that many of the shocks responsible for type II radiation have an overshoot, foot and ramp in the magnetic field structure in consistence with their supercritical character. The reflected ions which behave like a beam in the foot and ramp of the shock front, and like a ring in velocity

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space just behind the overshoot (Leroy *et al.*, 1981, 1982) accelerate electrons to ultra-relativistic energies both in the upstream as well as in the downstream through resonantly excited low-frequency waves.

Regarding the shock propagation angle relative to the magnetic field, Dulk *et al.* (1971) suggested that propagation is likely to be more parallel than perpendicular. These authors, however, could not arrive at any firm conclusions. Later Stewart and Magun (1980) analyzed a case where a transverse shock seemed to be required in order to explain the herringbone structure of a type II burst. Therefore, the observational evidence is not consistent with either strictly perpendicular or parallel shock propagation for all type II events. The range of shock angles over which type II bursts can be produced seems to be quite large. The advantage of the proposed acceleration mechanism over the fast Fermi process or the shock drift acceleration (Wu, 1984; Leroy and Mangeney, 1984; Holman and Pesses, 1983) is that it is applicable for a wide range of shock angles.

It is well known that in some cases the fundamental and harmonic bands of type II bursts are split in two. The present model is consistent with the qualitative model suggested by Smerd *et al.* (1975), who attributed the split-band structure of type II bursts to simultaneous plasma-frequency emission from plasma ahead of and behind a type II shock front. Nelson and Robinson (1975) reported that at a given frequency the U and L sources were circular, essentially the same size and in the same position where U and L represent the upper frequency band and lower frequency band, respectively. At the fixed observing frequency the L band is observed earlier in time than the U band and so it is inferred that at a given time the L source is further from the Sun than the U source confirming the model of Smerd *et al.* (1975) for band splitting.

2. Electron Acceleration

Uchida (1974) proposed that the type II radiation comes both at fundamental and harmonic from the low-V_A regions, where the shock has a relatively high Mach number. Gary *et al.* (1984) reported that the Mach number of type II shock lies in the range 1.3 to 3. Kennel *et al.* (1982) first reported that among 10 interplanetary shock, the fast wave Mach number M_F ranged from 1.3 to 4.7, where the critical Mach number $M_F \approx 2.5$. However, Bavassano-Cattaneo *et al.* (1986) reported that among 34 forward interplanetary shock waves observed by ISEE-3 during 1978 and 1979, 19 were supercritical, seven had a Mach number close to the critical Mach number, four were subcritical and the remaining four shocks were ambiguous. However, the average critical Mach number $\langle M_c \rangle$ was taken as 1.5 due to its strong dependence on shock parameters.

Kennel *et al.* (1982) as well as Bavassano-Cattaneo *et al.* (1986) have detected large-amplitude low-frequency electrostatic noise, whistler turbulence and a high-frequency ($\gtrsim f_p$) continuum near each shock and for up to several hours downstream. In the cases observed by Kennel *et al.* (1982) no type II bursts were observed at 1 AU, although intense impulsive Langmuir waves were observed an hour upstream from one shock. Impulsive Langmuir waves were present for a few minutes on either side for other shocks.

It is well known that the structure of a shock wave propagating perpendicular to the ambient magnetic field in a collisionless plasma undergoes a distinct change of shape when the Alfvén-mach number is increased above a critical value M_c. In addition to the ramp, the spacecraft observations (Russel and Greenstadt, 1979) show that there is a precursor structure of length equal to a few c/ω_{pi} which appears closely associated with the presence of ions reflected off the ramp, and is usually called the 'foot' where c is the velocity of light and ω_{pi} is the ion plasma frequency. Also it is seen (Russel and Greenstadt, 1979) that in the immediate post-ramp region the magnetic field exceeds its downstream value (magnetic field overshoot) and develops further downstream a somewhat oscillatory behaviour with a scale length of an ion gyroradius. Leroy *et al.* (1981, 1982) from numerical computations showed that the reflected ions behave essentially like a beam in the shock front (in the foot and ramp region), whereas they tend to form a gyrating stream in the downstream region behind the overshoot. Krasnosels'kikh *et al.* (1985) approximated the distribution function of the reflected ions in the foot and ramp as:

$$f_b^u = n_b \left(\frac{1}{2\pi \Delta V_b}\right)^{3/2} \exp\left(-\frac{(\mathbf{v}-\mathbf{v}_b)^2}{2\Delta V_b^2}\right), \tag{1}$$

where n_b is the reflected ion beam density, V_b and ΔV_b are the beam velocity and velocity spread, respectively. More realistic representation of the reflected ion distribution function in the downstream, which includes thermal effects, is the Dory–Guest–Harris distribution (Dory *et al.*, 1965):

$$f_b^q(V_\perp, V_\parallel) = \frac{1}{\pi^{3/2}(N+1)!}\,\frac{1}{\Delta V_{b_\parallel}\Delta V_{b_\perp}^2}\left(\frac{V_\perp}{\Delta V_b \perp}\right)^{2N} \times$$

$$\times \exp -\left(\frac{V_\parallel^2}{\Delta V_{b_\parallel}^2} + \frac{V_\perp^2}{\Delta V_{b_\perp}^2}\right), \tag{2}$$

where N is the anisotropy index and $\Delta V_{b_\perp}$ ($\Delta V_{b_\parallel}$) is the thermal speed $\perp$ ($\parallel$) to the ambient magnetic field (Thejappa, 1986; Akimoto *et al.*, 1985). These ion beams whose distribution functions are given by (1) and (2) in upstream and downstream, respectively, excite low-frequency waves described by the following dispersion relation (Galeev, 1984a; Krasnosels'kikh *et al.*, 1985):

$$\omega^2 = \frac{\omega_{LH}^2}{(1+\omega_{pe}^2/k^2c^2)}\left[1 + \frac{m_i}{m_e}\,\frac{k_\parallel^2}{k^2}\,\frac{1}{(1+\omega_{pi}^2/k^2c^2)}\right], \tag{3}$$

where $\omega_{LH} \approx \Omega_e \Omega_i$ is the lower hybrid frequency; Ω_j is the cyclotron frequency of jth kind particles; ω_{pe}, electron plasma frequency; m_j, mass of the jth plasma species; $K_\parallel$, the component of the wave vector parallel to magnetic field. The above dispersion relation is derived under the conditions $\Omega_e \gg \omega \gg \Omega_i$, $\omega_{pe} \gg \Omega_e$, and $K_\parallel \ll K_\perp$. Krasnosels'kikh *et al.* (1985) estimated the growth rate of these waves in the upstream as

$$\gamma_b^u = \frac{\pi}{2}\,\omega\,\frac{m_e}{m_i}\,\frac{\Omega_e^2}{(K\Delta V_b)^2}\,\frac{n_b/n_0}{(1 + \omega_{pe}^2/k^2c^2)}\,. \tag{4}$$

The growth rate of the same waves due to ring ions in the downstream is given by:

$$\frac{\gamma_b^d}{\omega} = -\frac{2}{(N+1)!}\,\frac{n_b}{n_0}\,\frac{m_e}{m_i}\,\frac{\Omega_e^2}{\omega^2}\,\frac{t^3 e^{-t^2}}{(1 + \omega_{pe}^2/k^2c^2)} \times$$

$$\times \int_0^\infty \mathrm{d}x\, e^{-x^2}(t^2 + x^2)\left(1 - \frac{N}{t^2 + x^2}\right), \tag{5}$$

where $t = \omega/K_\perp V_\perp$ (see Barbosa *et al.*, 1985; Thejappa, 1986). The growth rate due to the ion beam at $N = 1$ is given by:

$$\left(\frac{\gamma_b^d}{\omega}\right)_{\max} = \frac{\pi}{2}\,\frac{n_b}{n_0}\,\frac{m_e}{m_i}\,\frac{\Omega_\alpha^2}{(K\Delta V_b)^2}\,\alpha\,. \tag{6}$$

Here the maximum growth occurs when $t = t_0 \approx 0.52$ (Barbosa *et al.*, 1985) and $\alpha = 2/\sqrt{\pi}$ to $e^{-t_0^2}(0.5 - t_0^2) \approx 0.095$.

Papadopoulos (1981) proposed that these waves can accelerate electrons in the ambient plasma to very high energies due to the resonance $\omega = K_\parallel V_\parallel$, since the phase velocities along the magnetic field is much greater than that of perpendicular. Vaisberg *et al.* (1983) and Galeev (1984a) later successfully applied such mechanism for Earth's bow shock and galactic jets, respectively. Krasnosels'kikh *et al.* (1985) and Thejappa (1986) could explain many features of type II radiation adopting the above mechanism. If we assume that the energy taken by the waves from the reflected ions is completely given to the electrons by accelerating them, the solution of the wave balance equation gives us the distribution function of the accelerated electrons, i.e., by solving

$$\gamma_b^{u,d} + \gamma_e = 0\,, \tag{7}$$

where γ_e is the damping of waves due to electron acceleration and is given by:

$$\frac{\gamma_e}{\omega} = \frac{\pi}{2}\,\frac{\Omega_e^2}{k^2}\left(1 + \frac{\omega_{pe}^2}{k^2c^2}\right)^{-3}\frac{1}{n_0}\,\frac{\partial F}{\partial V_\parallel}\bigg|_{V_\parallel = \omega/K_\parallel}\,. \tag{8}$$

By assuming $k^2c^2 \gg \omega_{pe}^2$, i.e., short wave limit, we get for the distribution functions in the upstream F_u as well as in the downstream F_d, after solving Equation (7):

$$F_{u(d)} = n_{s(d)}(V_h - |V_\parallel|)\,, \quad V_\parallel \le V_h\,, \tag{9}$$

where

$$n_{s_u} = n_b \frac{m_e}{m_i} \quad \text{and} \quad n_{s_d} = n_{s_u} \alpha \,.$$

It is clear that $\alpha \ll 1$ for the values of $N > 1$. One should notice that the functional behaviour of the distribution functions remains the same both in the upstream and in the downstream. By substituting these distribution functions again into the quasilinear equation the spectral density of the excited waves can be easily derived and a general analysis shows that the distribution of the energy spectrum of the excited waves in the k-space is of streamer type (see Breizman *et al.*, 1973). The value of V_h calculated by conserving the energy fluxes of reflected ions and electrons (Galeev, 1984b),

$$V_h^2 = \left[\frac{(m_i/m_e)^3}{10 \tan\theta}\right]^{2/5} V_b^2 \,, \tag{10}$$

where θ is the angle between the magnetic filed and the shock front plane, is used in Equation (9) above.

3. Discussion

The frequency splitting, which is one of the main characteristics of the type II bursts is due to the character of the reflected ions, which excite low frequency waves both in the upstream as well as in the downstream. Due to anisotropy in the phase velocities the electrons are accelerated by these waves to very high energies along the field lines. A similar acceleration mechanism was applied by Lampe and Papadopoulos (1977) for type II bursts; these authors considered the same low-frequency waves excited by the modified two-stream instability excited in the shock front, which can accelerate electrons to very large energies in the downstream. The detailed observations of the electron and ion distribution functions in the downstream of the Earth's bow shock as well as interplanetary shocks will be a crucial test to the present model. The energy density of the Langmuir waves excited by these electron beams can be approximately written as

$$W_{L_{u(d)}} \approx 0.1 n_{s_{u(d)}} m_e \frac{V_h^2}{2} \approx 10^{-4} n_0 T_e \,.$$

If one assumes that all the energy is converted into transverse waves and the source size is $\approx 1\, R_\odot$, the brightness temperature can be estimated which lies in the range 10^9 to 10^{11} K. Nelson and Robinson (1975) reported that $T_B^{(L)}/T_B^{(u)} \approx 2.3$. The difference in the number density of the electron beams in the upstream and downstream will account for this difference in the brightness temperature in the two bands. If the anisotropy index N is large, the value of α is decreased which will in turn decrease the electron number density in the beam. This beam density will not be sufficient to excite observable radiation leading to disappearance of the bandsplitting.

4. Conclusions

(1) The majority of the shocks responsible for type II radiation are supercritical, and they are characterized by the ion reflection.

(2) The reflected ions behave like a beam in the foot and the ramp whereas they behave like a ring in the downstream. They resonantly excite low frequency waves whose frequency is near the lower-hybrid frequency both in the upstream as well as in the downstream.

(3) The electrons are accelerated by these low-frequency waves to ultra-relativistic energies due to the anisotropy in the phase velocities.

(4) The present model fully agrees with the suggestion of Smerd *et al.* (1975) regarding the generation of the L and U bands in the upstream and downstream respectively.

(5) The brightness temperature in the L and U bands depends on the number density in the accelerated beams. Since the number density of the electron beam in the downstream is less than that of upstream, the U band is fainter than L band as experimentally observed (Nelson and Robinson, 1975).

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