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RADIO EMISSION FROM THE SOLAR CORONA DUE TO SHOCK WAVES

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Abstract

The slowly drifting solar type II radio bursts are believed to be due to the flare associated shock waves propagating radially outward in the corona The main observational characteristics of these bursts show that the shocks responsible are supercritical and quasiperpendicular The electrons accelerated through reflected ion beam excited low frequency waves form gap distributions by getting scattered on whistlers and they fill a large volume just in front and behind the shock front giving rise to the backbone emission The electrons accelerated by fast Fermi process form electron beam escaping from the shock front and give rise to herringbone emission The brightness temperatures, polarization and frequency splitting are self consistently explained

1 Introduction

Our knowledge of the structure of collisionless, quasi perpendicular shocks has increased rapidly in recent years through direct in situ observations of the Earth's bow shock, other planetary bow shocks and interplanetary shock waves accompanied by a detailed computer simulations (Leroy et al, 1982) Collisionless shocks may be responsible for much of the particle acceleration that occurs in the interplanetary medium Increase in energetic ion and electron fluxes are observed in association with solar flare shocks, corotating interaction region shocks and bow shocks in front of planetary magnetospheres The coronal shocks are only indirectly observed by white light and radiowaves (type II bursts and type I chains) The particle acceleration in shock waves and radio emission in them are not understood completely Even though all the above shocks have completely different physical parameters, the basic physics of these collisionless shocks should be the same

Coronal type II burst have been studied observationally and theoretically for last thirty years Excellent reviews of the subject can be found in Kundu (1965), Zheleznyakov (1970) and Nelson and Melrose (1985)

The main spectral properties of the metrewave type II bursts are the following (1) Slow drift of the emission from high to low frequencies at less than 1 MHz sec $^{-1}$ (2) Typical instantaneous bandwidths for the drifting bands vary from a few MHz to 100 MHz (3) Approximately 60% of the bursts appear in harmonic bands (4) Many of the bursts show a secondary doubling of the bands; the splitting $\Delta f/f \sim 10\%$ in each of the fundamental and harmonic bands (5) In some bursts there are several drifting bands or 'lanes which are neither harmonically related not consistent with simple band splitting These are thought to be generated by separate disturbances propagating through the corona or by the interaction of a single extended disturbance with several different coronal structures (7) Approximately 20% of the type II events consist of two components (a) backbone which is a spiky, narrowband emission drifting slowly to lower frequencies and (b) herringbones, which are fast drifting broad band short duration elements shooting out of the backbone to lower and higher frequencies (8) "Herringbones' have a slightly but consistently higher degree of circular polarization than the "backbone" Herringbones resemble type II bursts and are generally interpreted as signatures of a beam of energetic particles accelerated near the source of the backbone (9) Kai and McLean (1968) and Wild (1969) showed that the type II sources at 80 MHz are large (~ 0 5 R_0) whereas Nelson and Robinson (1975) reported that the source size at 43 MHz is still larger (~ 1 R_0)

Collisionless shocks are defined as being either subcritical or supercritical In a subcritical shock enough dissipation can (in principle) be provided by anomalous resistivity to satisfy the Rankine Hugoniot conditions of mass, momentum and energy conservation across the shock without having to invoke ion kinetic effects In supercritical shocks, resistivity cannot provide adequate dissipation so an ion kinetic treatment of the shock is necessary (The ion dynamics arising in this case gives rise to an effective viscosity) The transition from sub to supercritical shocks depends on the physical parameters of the system such as the plasma beta and the angle between the magnetic field and the shock normal Edmiston and Kennel (1982) have shown that the critical Mach numbers for the shock waves lie between 1 and 2, for the typical solar wind parameters The fact is also supported by the ISEE 3 observations of the interplanetary shocks (Bavassano Cattaneo et al 1986), where it has been observed that a majority of the interplanetary shocks possess an overshoot foot and ramp in the magnetic field structure indicating that most of them are supercritical Krasnoselkikh et al (1985) Thejappa (1986, 1987), Benz and Tejappa (1987), Zlobec and Thejappa (1987), and Thejappa et al (1987) use some of the properties of the supercritical shocks in explaining one or the other property of type II bursts In this paper we briefly review the appropriate electron acceleration mechanisms operating in the shock front and apply them to explain the backbone, herring bones, band splitting, blobby structure and polarization of type II bursts

2 Electron Acceleration in the Shock Front

It is now well established experimentally that energetic electrons in the energy range 50 eV 50 KeV originate rather steadily at the Earth's bow shock and propagate upstream in the sunward direction along the interplanetary magnetic field lines The most energetic electrons (energies as high as 50 KeV) are detected at the edge of the foreshock region (i e the upstream region magnetically connected to the earth's bow shock) and come primarily from a small region near the curve of tangency of the interplanetary magnetic field to the bow shock surface, where the shock is nearly perpendicular, lower energy electrons (down to 10 eV) are detected deeper in the foreshock and are released from a much broader region of the bow shock (Anderson et al, 1979, Feldman et al 1983) The energetic electrons have also been shown to be closely associated with the presence of predominantly electrostatic electron plasma waves in the foreshock region (Scarf et al, 1971 Filbert and Kellog, 1979, Anderson et al 1981, Etcheto and Faucheux, 1984, Lacombe et al, 1984), and to act as a source of electromagnetic waves at twice the electron plasma frequency (Hoang et al, 1981) Energetic (~ 2 KeV) electrons have also recently been detected upstream of interplanetary shocks (Potter 1981)

While the observations have reached a rather mature state, the issue of the physical understanding of the acceleration of solar wind electrons by shock waves is still unsettled However, among the various acceleration mechanisms proposed, it appears that there are two mechanisms operating in the shock front, namely, acceleration through the waveparticle interactions (Papadopoulos, 1981, Vaisberg et al 1981) and fast Fermi acceleration (Leroy and Mangeney, 1984 Wu, 1984) Here we propose that both the mechanisms are operating in the shock front, and the electrons accelerated by the reflected ion excited low frequency waves get separated from the ambient population by getting scattered on whistlers filling the volume just in front and behind the shock front giving rise to the continuum type backbone and also to the frequency splitting whereas the electrons accelerated through the fast Fermi mechanism gain very high velocities when the θ_{Bn} is close to $\frac{\pi}{2}$ and runaway from the ambient medium forming the beams consequently giving rise to herringbone structures

2a Electron Acceleration through Wave Particle Interaction

As we have mentioned earlier we propose that the shocks responsible for type II bursts are supercritical and quasiperpendicular The quasiperpendicular ($\theta_{Bn} > 7?^{o}$), super critical configuration has been extensively studied, both theoretically and observationally Theory and extensive simulations [See Leroy et al (1981, 1982)] have shown that the magnetic profile of such shocks is dominated by the temporary reflection of a fraction of the incident solar wind ions, which are mostly transmitted on their second approach to the magnetic ramp In particular the magnetic "pedestal (or foot) and 'overshoot (illustrated in Figure 1) were shown to be caused by the reflected ions The magnetic profile of the simulated supercritical structure was argued to be nearly time stationary in the shock frame of reference provided a specific range of anomalous bulk resistivities was postulated (Leroy et al, 1981, 1982) Paschmann et al (1982) 'have reported the existence of the reflected gyrating' ions which are highly nonthermal ion distributions with large effective thermal spreads in the upstream as well as in the downstream The reflected ions behave like a beam in the foot and ramp and like a ring just behing the overshoot, exciting in both the cases lower hybrid waves There exist two types of instabilities (1) Modified two stream instability (2) Rosenbluth post Loss cone instability for $[\partial f_i/\partial V_\perp > 0]$ The lower hybrid waves have very large phase velocities along the magnetic field line , ranging from a cut off at the electron thermal velocity $V_{Te} > 2 \times 10^{8}$ cm/s to greater than the velocity of light The cut off at low phase velocity is due to Landau damping, which allows only those waves with phase velocity $V_{ph} > V_{Te}$ to exist In laboratory plasmas lower hybrid waves have been shown to be extremely effective in accelerating electrons along magnetic field lines and in producing high energy tails in electron distribution functions (Boyd et al, 1976)

The general dispersion relation including the electromagnetic effects is

$$1 - \frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{\Omega_e^2}\left(1 + \frac{\omega_{pe}^2}{k^2c^2}\right) - \frac{\omega_{pe}^2}{\omega^2}\frac{k_z}{k^2}\left(1 + \frac{\omega_{pe}^2}{k^2c^2}\right)^{-1} = 0 \tag{1}$$

where $\omega_{pi,e}$ are ion, electron plasma frequency and, $\Omega_{i,e}$ are ion, electron cyclotron frequency respectively $\vec{k}$ is the wave vector and k_z is its component along the magnetic field and c is the velocity of light

For $k_z^2 << k^2$, solutions to (1) are

$$\omega^2 = \frac{\omega_{pi}^2 + \omega_{pe}^2 \frac{k_z^2}{k^2} \frac{1}{(1 + \omega^2_{pe}/k^2c^2)} - \frac{\Omega_e^2}{(1 + \omega^2_{pe}/k^2c^2)}}{\omega_{pe}^2} \tag{2}$$

For $[k_z^2/k^2 << 1$ and $[\omega_{pe}^2/k^2c^2 << 1$, the above equation takes the form

$$\omega^2 = \omega_{LH}^2\left[1 + \left(\frac{k_z}{k}\right)^2 \frac{m_i}{m_e}\right] \tag{3}$$

where $\omega_{LH}^2 = [\omega_{pi}^2/(1 + \omega_{pe}^2/\omega_{ce}^2)]$ is called the lower hybrid resonance frequency These waves have $\vec{k}$ nearly perpendicular to $\vec{B}_o$ There is however an electric field component, and wavenumber $k_z << (m_e/m_i)^{1/2}$ k parallel to $\vec{B}_o$ The group velocities parallel and perpendicular to the magnetic field can be obtained from (3) as

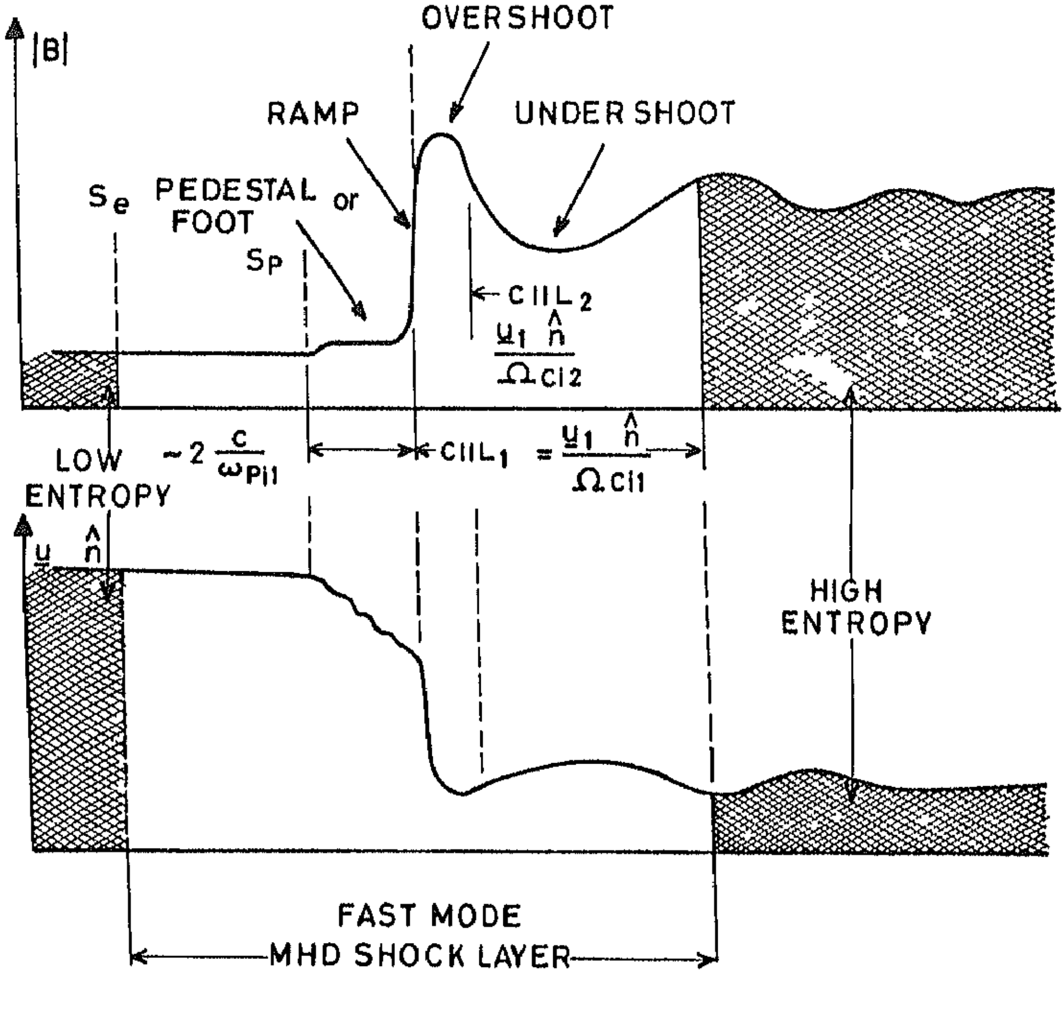

Fig. 1 Substructure terminology of supercritical, fast mode, collisionless shock layer S_e and S_p are electron and ion foreshocks respectively C IIL₂ ion inertial lengths, $\omega_{pi1,2}$ $\Omega_{ci1,2}$ ion plasma and cyclotron frequencies in upstream and downstream respectively, c is the velocity of light

$$\vec{V}_{g_{11}} = \omega_{LH} \frac{k^{11}}{k^2} \frac{m_i}{m_e} (1 \quad \frac{k_{11}^2}{k^2} (1 + \frac{k_{11}^2}{k^2} \frac{m_i}{m_e})^{\frac{1}{2}} \vec{z}$$

$$\vec{V}_{g_{x,y}} = \frac{k_z k_{x,y}}{k^2} \omega_{LH} \frac{k_{11}}{k^2} \frac{m_i}{m_e} (1 + \frac{k_{11}^2}{k^2} \frac{m_i}{m_e})^{\frac{1}{2}} \vec{x} \vec{y} \tag{4}$$

Here we have a umed that $\vec{B}$ i in the z direction From equation (4) and the condition $k_{11}^2 < k^2$ we obtain the ratio $[V_{g_{11}} / V_{g_{x,y}} = (k^2/k_2 k)$ showing that $V_{g_{11}} > |V_{g_{x\,y}}|$
Therefore mo t of the energy flows parallel to the magnetic field The pha e velocity along the field is given by $V_{ph_{11}} = \omega / _{11}$ Using the relation $_{11} \leq (m_e/m_i)^{1/2} k$ and k $\approx \omega/c$, where

$$c_s = [\frac{(KT_e + KT_i)}{m_i}]$$

is the ion acoustic velocity, K i Boltzmann's constant $T_{e,i}$ are the electron ion temperatures respectively, we find that

$$V_{ph_{11}} \geq c (\frac{m_i}{m_e})^{\frac{1}{2}}$$

i e , $V_{ph} \geq V_{Te}$ Thu the phase velocity along the field line is greater than the electron thermal speed

As tated earlier the ions reflected from the hock front flow across the magnetic field lines producing large electro tatic field ($\rho_i >> \rho_e$) and they can be considered as unmagnetized The distribution functions of the reflected ions in the upstream and downstream can be approximated respectively as

$$f_b^u \quad n_b [\frac{m_i}{2\pi T_b}]^{\frac{3}{2}} \exp [\frac{m_i(\vec{V} \quad \vec{V}_b)^2}{2T_b}] \tag{5}$$

and

$$f_b^d \quad \frac{(\pi V_{Tb}^2)^{\frac{1}{2}}}{V_b} \exp [\frac{m_i(V^2 \quad V_b^2)}{2T_b}] \tag{6}$$

The contribution of uch an ion beam to the dielectric permittivity is given by

$$\epsilon_{ion\ beam} = \frac{4\pi^2 e^2}{m_i k^2} i \int \vec{k} \frac{\partial f_i}{\partial \vec{V}} \delta(\omega \quad \vec{k} \vec{V}) d\vec{V} \tag{7}$$

For the ion distribution functions of the form (5) and (6), the growth rates can be calculated using the formula

$$\gamma = [I_m \epsilon / \partial R_e \epsilon / \partial \omega] \tag{8}$$

and are given by :

$$\frac{\gamma}{\omega} = \frac{n_b}{n_o} \sqrt{\pi} \left(\frac{\omega}{k}\right)^2 \frac{1}{V_{T_b}^2} e^{1} \tag{9}$$

$$\frac{\gamma_b^d}{\omega} = \frac{n_b}{n_o} \left(\frac{\omega}{k}\right) \frac{1}{V_b^2} \left(\frac{V_b}{\Delta V}\right)^{\frac{3}{2}} \tag{10}$$

Growth of the lower hybrid waves is insensitive to the electron ion temperature ratio, $[T_e/T_i]$ and can take place even if $T_i >> T_e$

McBride et al (1972) have shown that then lower hybrid wave growth saturates at an energy density given by

$$\frac{W_{LH}}{n_o K T_e} \approx \frac{0\ 05}{(1 + \omega_{pe}^2/\Omega_e^2)} \tag{11}$$

where $W_{LH} = |E_o|^2 / 8\pi$ is the energy density of the lower hybrid wave with an electric field E_o and n is the plasma density Particle acceleration is the process which limits the growth and leads to the saturation

The statistical acceleration of electrons in the tail of the distribution due to interaction with lower hybrid turbulence can be described by the quasi linear diffusion equation (Davidson, 1972)

$$\frac{\partial f_e}{\partial t} = \frac{\partial}{\partial V_{11}} D_{11} \frac{\partial f_e}{\partial V_{11}} \tag{12}$$

where f_e is the electron distribution function and D_{11} is the quasi linear velocity diffusion coefficient, where ΔV is the change in velocity of the particle due to wave particle intraction in time τ Bhadra et al (1982) have shown that

$$D_{11} = \frac{16\pi^2 e^2}{m_e^2} \frac{k_{11}}{\omega} \varepsilon_{k_{11}} \tag{13}$$

where $\varepsilon_{k_{11}}$ is the wave energy density per unit wavenumber For an acceleration region of length L the effective range of k_{11} is

$$k_m \leq k_{11} \leq k_o \tag{14}$$

where k_m is determined by L, and k_o is determined by the strong Landau damping that takes place for $k_{11} = \omega_{LH}/2V_{T_e}$

The total wave energy density is thus

$$W_{LH} = (k_o \quad k_m) \varepsilon_k \simeq k_o \varepsilon_k \tag{15}$$

The time for electrons to be accelerated from V_1 to V_2 by lower hybrid waves is given by

$$\tau_{acc} = \frac{(V_2 - V_1)^2}{D_{11}} \tag{16}$$

A characteristic acceleration length $L_{acc} = \langle V \rangle \tau_{acc}$ where $\langle V \rangle$ is the average electron velocity is given by (13), (14) and (15) as

$$L_{acc} = \frac{\omega_{LH} n_o K T_e \Delta V^2 k_o}{4\pi \omega_{pi}^2 W_{LH} V_{Te}^2 K_{11}} \langle V \rangle \tag{17}$$

$$\Delta V = V_2 - V_1$$

For typical coronal parameter this length is of the order of 1 $R_\odot$

(b) Electron Acceleration by Fast Fermi Processes

The jump in intensity of the macroscopic magnetic mirror and combines with a hump of the electric potential to reflect adiabatically part of the incident solar wind electron distribution (Feldman et al, 1983) The energy of an electron is being conserved before and after reflection only in a particular reference frame where the motional electric field is zero This frame moves at a very large relative velocity with respect to the observer's reference frame for nearly perpendicular shock geometries, thus important energization results when coming back to the observer's frame In the case of adiabatic reflection, i e , gyroradius << shock thickness, the average energy per reflected electron scales as $\approx (\frac{1}{2} mV_0^2)^4 / \cos^2\theta_{Bn}$ for large θ_{Bn} Here θ_{Bn} is the angle between upstream magnetic field and shock normal and V_0 is the upstream flow velocity (or shock speed) The energization is appreciable as θ_{Bn} approaches $\pi/2$

In the plasma frame upstream of a quasi perpendicular shock wave, the shock wave may be conceived as a fast moving 'magnetic mirror which moves with a very high effective velocity V_s along the upstream ambient magnetic field $\vec{B}_1$, where $V_s = V_{HT} \cos\theta + V$ θ denotes the angle between the shock normal $\vec{n}$ and $\vec{B}_1$, $\vec{V}_{HT}$ is the so called de Hoffman Teller velocity, i e

$$\vec{V}_{HT} = \frac{\vec{n} \times (\vec{V}_1 \times \vec{B}_1)}{\vec{B}_1 \cdot \vec{n}}$$

V_{11} is the component of the upstream bulk velocity V_1 parallel to the magnetic field $\vec{B}_1$ For a nearly perpendicular shock (i e , the shock normal $\vec{n}$ is almost perpendicular to $\vec{B}_1$) V_{HT} becomes much higher than V_{11} and therefore can lead to very effective energization (Wu, 1984, Leroy and Mangeney, 1984)

Since the acceleration process relies on the mirror reflection associated with the shock wave, the energized electrons inherently possess a combined "beam loss cone distribution If one assumes that the upstream electrons (before reflection) possess a nearly isotropic distribution to the plasma frame, i e , if one models it by assuming that the distribution consists of two basic parts A "core' distribution, which is characterized by a thermal Maxwellian distribution with a temperature of 200 eV and a Halo" distribution of suprathermal electrons which might have a characteristic energy of a few keV, the electrons energized by the shock may possess a distribution function which is characterized by a combined beam and loss cone feature Wu et al (1986) modelled these electrons by a hallow beam distribution

$$F(\vec{u}) = A \exp\left[-\frac{(u_{\parallel} - u_{0\parallel})^2}{\alpha_{\parallel}^2} - \frac{(u_{\perp} - u_{0})^2}{\alpha^2} \right] \tag{19}$$

where A is a normalized coefficient and

$$A \equiv \left[\left[\pi^{\frac{3}{2}} \alpha^2 \alpha_{\parallel} \left\{ \exp\left(-\frac{u_0^2}{\alpha^2}\right) + \pi^{\frac{1}{2}} \left(\frac{u_0}{\alpha}\right) \left[1 + \mathrm{erf}\left(\frac{u_0}{\alpha}\right)\right] \right\} \right]\right]^{-1}$$

3 Radio Emission

The radio emission from coronal shocks consist of two parts (1) slowly drifting (backbone) (2) fast drifting (herringbone)

3a. Backbone

It is proposed that the electrons accelerated through the low frequency lower hybrid waves excited by the reflected ions get separated from the ambient electrons by getting scattered by the ion excited whistlers They fill a large space just in front and behind the shock front forming gap distributions

These gap distributions radiate both at fundamental and second harmonic frequencies in the upstream as well as in the downstream which is in accordance with the observed band splitting The high energy electrons filling a large volume surrounding the shock front gives rise to the radiation in the form of a narrow banded continuum (backbone)

The brightness temperature for such a gap distributions as suggested by Melrose (1975) is

$$T_1^t = 1.5 \times 10^{12} \frac{n_b}{n_o} f_p \left(\frac{V_o}{c}\right)^{-1} \tag{21}$$

$$T_2^t = 1.8 \times 10^{22} \left(\frac{n_b}{n_o}\right)^2 \frac{V_o}{c} \tag{22}$$

For typical values like $[n_b/n_o \approx 10^{-6}$, $f_p = 100$ MHz $V_o/c \approx \frac{1}{3}$, we obtain $T_1^t \approx 10^{11}$K and $T_2^t = 10^{10}$K which agree well with observed value

3b Herringbone Structures

As it is shown earlier, the electrons by fast Fermi acceleration process may attain very large velocities for nearly perpendicular shock waves And also it was mentioned that the electrons possess a hallow beam distributions

For $(\Omega_e^2/\omega_{pe}^2 << 1$, a hallow beam can excite two types of instabilities those acting mainly on the positive gradient in $u_{\parallel}$ reducing the shift $u_{\parallel 0}$ and others that are mainly driven by the perpendicular gradient eroding the ring Among the electrostatic ring or loss cone instabilities the upper hybrid modes grows fastest Benz (1980) derived the saturated energy level by assuming that nonlinear shift of the cyclotron frequency is the main mechanism of saturation a

$$\frac{W_{uh}}{n_o K T_e} \approx 10^{\,2}\, \frac{n_b}{n_o} \left(\frac{\alpha}{V_e}\right)^2 \tag{23}$$

For typical parameters $\frac{W_{uh}}{n_o K T_e} \approx 6\ 5 \times 10^{\ 5}$

As mentioned earlier, the reflected ions excite lower hybrid waves whose energy saturation i given by equation (11)

We propose that the upper hybrid waves excited by the electron beams accelerated by fast Fermi process interact among themselves and with the lower hybrid waves excited by the reflected ion beams giving rise to the herringbone structures at harmonic and fundamental frequencies The conditions for coupling of three waves are

$$\omega_{em} = \omega_{L1} + \omega_{L2}$$

$$\vec{k}_{em} = \vec{k}_{L1} + \vec{k}_{L2} \tag{24}$$

For the electrostatic (pump) waves propagating in a cold magnetized plasma, the wave numbers $k_{L1,2}$ must satisfy the electrostatic approximation (Stix, 1962):

$$k_D >> k_{L1,2} > k_{min} \tag{25}$$

where

$$k^2_{min} = \frac{\omega_L^2}{c^2} \mid \varepsilon_{ij} \mid_{max} \tag{26}$$

It is the minimum wave number; $|\varepsilon_{ij}|_{max}$ is the largest of the dielectric elements of the plasma computed by using the electrostatic wave frequencies, λ_D is the Debye wave number The first inequality in (25) is inherently satisfied by all plasma waves and is consistent with cold appoximation We have thus the following condition for the cold plasma

$$\frac{\Omega_e}{c k_{L1,2}} \left(\frac{\omega_{pe}}{\Omega_e}\right) >> \frac{V_e}{c} \tag{27}$$

The Eigen mode should also satisfy the respective dispersion relations

$$D(\omega_i, \vec{k}_i) = 0 \tag{28}$$

The eigenmode frequencies of the electrostatic waves can be easily obtained from the electrostatic dispersion relation $D_{es} = 0$, so that

$$W_L^2 = \tfrac{1}{2} \{ \omega_{uh}^2 \pm [\omega_{uh}^4 \quad 4\, \omega_{pe}^2\ \ \Omega_e^2\ \ \cos^2\theta\ ]^{\frac{1}{2}} \} \tag{29}$$

where $\omega_{uh} = (\omega_{pe}^2 + \Omega_e^2)^{1/2}$ is the upper hybrid resonance frequency The plus or minus sign above corresponds to the upper or lower hybrid branch of magnetized electron plasma waves, respectively

For freely propagating R X ( ) and L O (+) electromagnetic waves their frequencies must be above the respective mode cut off frequencies ($\omega_{L\,O}$ and $\omega_{R\,X}$) i e

$$\omega_{em} > \omega_{L\,O \atop R\,X} \tag{30}$$

depending on the mode of propagation (L O or R X) Waves with frequencies higher than the cut off frequencies will propagate freely in the medium Waves with frequencies below the cut off frequencies will be trapped and reflected at the cutoff ($n \pm = 0$) The cutoff frequencie for the L O and R X modes can be obtained by setting $n = 0$, which gives

$$\omega_{L\,O} = \omega_{Pe} \tag{31}$$

and

$$\omega_{R\,X} = \tfrac{1}{2}\,[\,\Omega_e + (4\,\omega_{pe}^2 + \Omega_e^2\,]^{\frac{1}{2}}] \tag{32}$$

In the present case, there are two possible cases (a) $\omega_1 \approx \omega_2 \approx \omega_{uh}$ (b) $\omega_1 \approx \omega_{uh}$ and $\omega_2 - \omega_{Lh}$ resulting in frequencies of the electromagnetic waves $\omega_3 = 2\ \omega_{uh}$ and ω_3 ω_{uh} respectively The radiation at fundamental will be mainly in the ordinary mode since X mode at ω_{uh} can not escape from the source region The O mode wave propagating perpendicular to the magnetic field are linearly polarized parallel to $\vec{B}_0$ As soon a they leave the quasi transverse region, however the waves Faraday rotate to nearly vanishing circular polarization as observed

Since the energy density of the lower hybrid waves excited by the reflected ion beams far exceeds that of the high frequency electron beam excited upper hybrid waves the opacity, μ, is due to the lower hybrid wave

For $\Omega = 4\pi(m_e/m_i) \approx 0.3$ Steradian and $\theta_{Bn} \approx 85^{\circ}$, the radio brightness temperature at the fundamental is (Benz and Thejappa, 1987)

$$T_{rf} = T_{uh} \approx 7 \times 10^{12}\ K \tag{33}$$

compatible with observations

Radiation at about 2 ω_{uh} can be emitted from the region of upper hybrid instability in the electron foreshock The coalesence process is very effective since the waves fill only a small angle near the perpendicular plane For coronal conditions the absorption coefficient of this mechanism is

$$\mu_{uh} \approx 2 \times 10^{-4}\,\frac{W_{uh}}{n_o K T_e} \tag{34}$$

With the estimated values of W_{uh} and the source dimensions derived from observations it is clear that the harmonic radiation is marginally optically thick The maximum brightness temperature of the harmonic is again T_{uh} and

$$T_{LH} \leq T_{uh} \tag{35}$$

Again the tansverse waves are preferentially emitted perpendicular to $\vec{B}_0$ Their initial linear polarization is smeared out by Faraday rotation Thus the observed net circular polarization nearly vanishes

Conclusions

1 The shocks respon ible for solar type II bursts are super critical

2 The reflected ions from the shock front excite low frequency waves both in upstre im and downstream

3 There are two electron acceleration mechanisms operating in the shock front

4 The low frequency waves excited by the ion beams accelerate electrons along the magnetic field, and in most of the case the accelerated electrons get scattered by the whistler and fill a small gap in the downstream and upstream of the shock The distribution of such elections is a gap distribution The resultant radio emission give rise to backbone

5 The electrons accelerated by the first Fermi proce s, gain vlery high energies when θ_{Bn} is nearly $\pi/2$ and escape both in the upstream and downstream The upper hybiid waves excited by these electron beams interact with themselves and lower hybrid waves giving rise to fast drifting herringbones at the harmonic and funda mental respectively

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