N87-21805

MICROWAVE MILLISECOND SPIKE EMISSION AND ITS ASSOCIATED PHENOMENA DURING THE IMPULSIVE PHASE OF LARGE FLARES

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ABSTRACT

A tentative model is proposed to account for some features of the microwave millisecond spike emission and its links with the physical processes of associated phenomena during the impulsive phase of large flares by comparing the optical, radio and X-ray observations on May 16, 1981 to those on October 12, 1981.

I. INTRODUCTION

The emission of short duration (1-100 ms), high brightness temperature ($\gtrsim 10^{15}$ K) spikes at microwave frequencies during the impulsive phase of some solar flares is now well established [1,2]. The occurrences of these spikes may give us a clue to the physical process of microwave millisecond spike emission(MMSE) linked with its associated phenomena.

On the basis of the observations described in [1], Melrose and Dulk (1982) discussed the relation between the physical processes generating MMSE and hard X-ray bursts. They suggested that MMSE was caused by the loss-cone driven electron-cyclotron maser in a flaring loop [3]. In this paper, we go further to find the physical processes of the MMSE and its links with associated phenomena druing the impulsive phase of some solar flares, but the MMSE is considered to be excited by the electron-cyclorton instability associated with a hollow beam of electrons [4].

We have analysed two major flare-burst events of May 16 and October 12, 1981. The following observational data during the impulsive phase of these two flares were used for comparison.

(1) Radio observations made at 2.84 GHz with the time resolutions of 1 second and 1 ms at the Beijing Observatory,

(2) H_α and photospheric magnetic field observations made at the Yunnan Observatory,

(3)Hard X-ray burst observations made on Hinotori (by courtesy of Dr.K.Tanaka)

(4) Radio spectra for type III and type IV_{DCIM} bursts published in Solar-Geophysical Data.

All the data staed above are summarized in Table 1.

II. A GENERAL DESCRIPTION OF THE TWO FLARE-BURST EVENTS

As shown by Table 1, there existed some similar features between these two events, such as the coincidence with H_α flares of importance 3B, two-ribbon flares, magnetic configurations of type δ and photospheric magnetic intensities $\gtrsim$2500G. However, we can see in the following their significant characteristics different from each other.

1. There appeared strong MMSE's ($T_b \gtrsim 10^{15}$ K) during the first event (1981 May 19) but appear during the second (1981 October 12).

2. A lot of intense decimetric bursts of type III_B , type III_G and type IV_{DCIM} occurred during the first event, but no decimetric burst and only weak metric bursts occurred during the second.

3. Although only the decay phase of hard X-ray bursts was recorded on Hinotori for the first event, the peak values (counts per second) of hard X-ray bursts for the first event still far exceeded those of the second in the same energy range.

4. However, the peak flux density of radio burst at 10.6 cm in the second

event is about six times larger than that in the first.

III. THE MODEL AND KEY PROCESSES

It has been pointed out in [2,6] that after the main phase of the microwave burst there still appeared MMSE's. This means that the fast electrons generating the microwave bursts and those exciting MMSE's do not come from the same source. Furthermore, the simultaneous observations of hard X-ray bursts by SMM and high resolution microwave observations by VLA indicate that the sources of these two bursts are mot coincident with each other in space.

On the basis of these observations and a comparison between the two flare-burst events stated above, we propose a tentative model to account for the links of the physical processes of MMSE's with their associated phenomena as follows (Fig.1.).

1. During the impulsive phase of large solar flares, there probably appear two acceleration regions, One (region A) of them formed in the current sheet by a tearing mode instability is located over the top of the flaring loop, the other (region B) is established just at the top of the flaring loop by turbulence acceleration. Regions A and B are also the energy release regions.

2. A stream of fast electrons escaping outward from region A along open field lines is able to excite type III bursts with a negative frequency drift under certain conditions, while the other stream injected downward with a certain incident angle into the flaring loop is capable of establishing an anisotropic pitch angle distribution of "hollow beam" and stimulate an electron-cyclotron maser to radiate MMSE's or generate type IV_{DCIM} bursts with positive frequency drift. As soon as the fast electrons radiate away energy in the direction perpendicular to the magnetic field, they immediately precipitate into the transition region or the chromosphere, collide with the surrounding plasma and emit hard X-ray bursts (thick target model).

3. The background radiation, i.e. microwave radio bursts superimposed by MMSE's, is generally accepted as a gyrosynchrotron radiation emitted by nonthermal electrons, gyrating about field lines, with an isotopic pitch angle distribution and power law energy spectrum. The microwave burst source is located in region B at the top of the flaring loop.

Table 1. Observed Characteristics for the Events of May 16, 1981 and October 12, 1981

Date	Characteristic parameters	Hα Flare	Magnetic configuration	Radio Burst =10.6 cm	MMSE =10.6 cm	Hard X-ray Burst	Dynamic Spectrum 10cm----1 m	Dynamic Spectrum 1m — 10m
May 16, 1981	Start Time(UT) Maximum(UT) End (UT) Peak Flux Density Importance Type Flare location	0806 0846 0916 3B Two Ribbons $N_{14}E_{14}$	Type δ	0806 0839 1002 1916 (sfu) 47GB	0806 0839 0920 5x10 (sfu)	$9^h00^m13^s$ 9 17 355 counts/sec ($\varepsilon \gtrsim 40$KeV) 2016 counts/sec ($40.7 > \varepsilon > 17$ KeV)	0750.7 08105 0812 0812.5 0816.2 1000 1105 Insensity 2 3 3 3 III_B, III_G, IV_{DCIM}, IV_F	0810.5 0810.5 0816.2 1105 Intensity 3 3 III_G, IV_F
Oct. 12, 1981	Start Time(UT) Max. Time(UT) End (UT) Peak Flux Density Importance Type Flare Location	0626 0633 0830 3B Two Ribbons $S_{17}E_{08}$	Type δ	0614 0650.4 0720 10800 (sfu)	None	$6^h12^m53^s$ $6^h21^m17^s$ 6^h25^m 118 counts/sec ($\varepsilon \gtrsim 40$ KeV) 158 counts/sec ($40 > \varepsilon \gtrsim 17$KeV)	None	0616 0616.4 — — 1544 0617.8 Intensity 2 1 III_S III_G

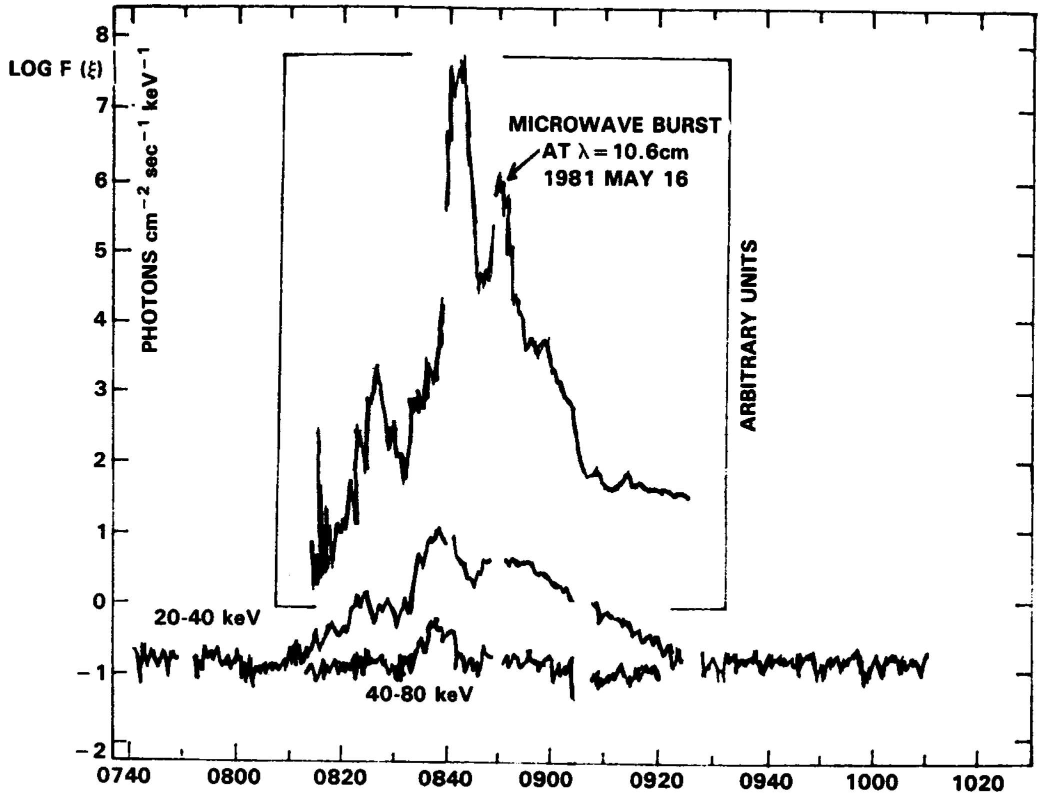

Fig. 1. The large microwave burst at λ = 10.6 cm and hard X-ray bursts recorded by Prognoz 8 satellite during the large flare-burst event of 1981 May 16 [5].

IV. EXPLANATION AND DISCUSSION

1. According to a quasilinear theory, the general formula for the growth rate at s-th harmonic for wave in the magneto-ionic mode is [3, Appendix B]

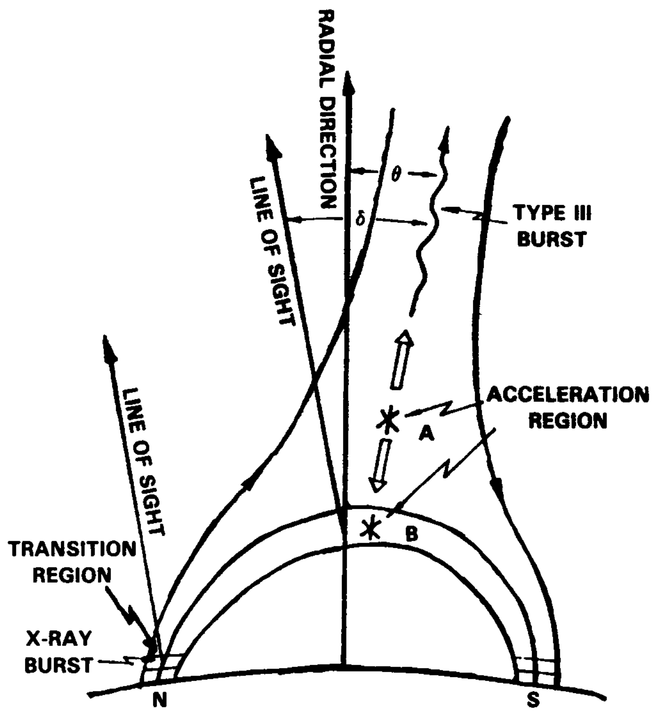

Fig. 2 A model of MMSE and associated phenomena

$$\Gamma_s^{(\sigma)}(k) = \int dp\, A_s^{(\sigma)}(p,k)\,\delta(\omega - s\omega_B/\gamma - k_\parallel v_\parallel)\left(\frac{s\omega_B}{\gamma v_\perp}\frac{\partial}{\partial p_\perp} + k_\parallel \frac{\partial}{\partial p_\parallel}\right) f(p_\perp, p_\parallel) \quad (1)$$

where $p = (p_\perp^2 + p_\parallel^2)^{1/2} = rmv$ is the electron's momentum, $\omega_B = \frac{eB}{mc}$ is the electron-cyclotron frequency, and $\perp$ and $\parallel$ denote components of wave number and velovity to the direction of the magnetic field B, $p_\parallel = p\cos\varphi$, $p_\perp = p\sin\varphi$, and φ is the pitch angle, r is the Lorentz factor.

It can be shown [8] that the sign of the integrand is determined by the sign of

$$\bar{D}f = \left(\frac{m s\omega_B}{p_\perp}\frac{\partial}{\partial p_\perp} + k_\parallel\frac{\partial}{\partial p_\parallel}\right) f(p_\perp, p_\parallel) \quad (2)$$

Positive contributions to $\bar{D}f$ favour the growth and negative contributions favour the damping of the waves.

Suppose that the distriolution function of nonthermal electrons with an isotropic pitch angle and power law energy spectrum for gyro-synchrotron radiation can be written as in [9, 10]

$$f(p)=\frac{G}{4\pi}\left(\frac{p}{mc}\right)^{-1}\left[1+\left(\frac{p}{mc}\right)^{2}\right]^{-1/2}\left[\sqrt{1+\left(\frac{p}{mc}\right)^{2}}-1\right]^{-g} \qquad (3)$$

here G is a constant and g is the spectral index, $g > 0$. one obtains $\frac{\partial f}{\partial p} < 0$, so that $\Gamma_s^{(\sigma)} < 0$. Therefore, the distribution function of fast electrons in expression (3) is capable of producing gyrosynchrotron radiation of microwave bursts [9, 10] but it can not amplify the s-th harmonic waves and generate MMSE's.

Just on the contrary, the "hollow beam' distribution of fast electrons favours the growth of waves and leads to the generation of MMSE's [4].

2. The distribution of the pitch angles of the electrons injected from Region A to Region B on top of the magnetic arch is determined by the distance D between A and B. If D is sufficiently large, then the distribution is isotropic; otherwise, it will be anisotropic. This is because, the large the D, the greater will be the diffusion of the electrons; the smaller the D, the more restricted will be the angle of injection of the electron beams.

Table 1 shows that, for the event of May 16, the Type III bursts began in the decimetric wave range (aroung 60 cm, corresponding to a plasma frequency of 500 MHz, and a height of 23 $\times 10^4$ km above the photosphere, see below). For the Oct. 12 event, they began in the meter wave bands (e.g., 2 m, corresponding plasma frequency 150 MHz and height 2.3×10^5 km above photosphere). Since both events have the same type photospheric magnetic field with strengths $\gtrsim 2500$ G, for both then, we may regard the microwave (10.6 cm) burst source in Region B at the top of the magnetic arch during the impulsive phase of the flare to have about the same size (or $10''$). It then follows that the angle of the cone subtended by the electron beams issuing from Region A (the height corresponding to the starting frequency of the Type III burst) must greater than $24^\circ 20'$ for the earlier event in order to achieve isotropic distribution, and need only $1^\circ 58'$ for the later event. Clearly it is easy to a beam ejected at A to be diffused through the collision with the background particls into a cone as small as $1^\circ 58'$ when reaching B. Thus, for the later event, of October 12, the electron beams injected from A into B had an isotropic distribution of pitch angle and so could not generate any spike emission or intense x-ray bursts. But such isotropic beams would add to the isotropic electrons in Region B and greatly increase the gyro-synchrotron radiation, hence the more intense at 10.6 cm.

For the earlier event of May 16, the Type III burst was strong, its starting frequency was high, the generating electrons had high energies, the downward injected beam was energetic and difficult to disperse, making the incident cone far below the value of $20^\circ 20'$ required for isotropization. The beam, then, was a "hollow-beam" and so generated intense spike emission and also led to strong bursts in hard X-ray. According to the radio dynamic spectrum measured at Dwingloo 5, during the impulsive phase, this event (May 16), at about 0814.5 UT, a Type III burst with a negative frequency drift appeared in 300-380 MHz, and at same time, one with a positive drift appeared in 509-666 MHz. This observed fact shows certainly that Region A in the neutral current sheet can simultaneously eject both one upward (towards the outer corona) and an inward (toward the coronal base) electron beams. It was estimated that the electron density in this acceleration region was about 3×10^4 km above the photospere.

3. Type III_G bursts are the type III bursts (< 10) appearing in groups. In the event of 1981 May 16, the MMSE's recorded at wavelength 10.6 cm often happended in a group-like type III_G burst. Since the radiating electrons of type III_G bursts and MMSE's escape from the same acceleration process. Probably, the duration of each group of MMSE's corresponds to that of each subburst in type III burst. The switch-off structure of MMSE's in [2] corresponds to the interval between two subbursts and the switch-on structure manifests the start of a group of MMSE's due to the injected electrons with a "hollow beam" distribution.

As can be seen in Table 1, an intense type-III burst appears from 0810 to 0816.2UT. It might be in correspondence with the significant switch-off and switch-on structures of MMSE's at about 0815UT during the rising phase in micro-wave burst (at 10.6 cm) of May 16, 1981.

About 0814.5UT in the band 300-480 MHz, type III bursts with negative frequency drifts of about 100MHz/sec were observed with Dwingloo radio-spectrograph, while at the higher frequencies 509-666 MHz positive drifting bursts about + 50 MHz/sec occurred [5]. This is a strong evidence indicating the simultaneous acceleration of electrons upwards and downwards. The electron density in the acceleration region was estimated to be 3×10^9 cm^{-3} and the corresponding height about 2.3 x 10^4 Km.

5. Because the radiating electrons of hard X-ray bursts and type III bursts come from the same acceleration region A, the key problem is whether these electrons possess enough energy to radiate MMSE's and hard X-ray bursts. We should answer this question by evaluating the energy of these nonthermal electrons which may produce type III bursts.

Type III bursts present a rapid drift from high to low frequencies at a rate described in [11].

$$\frac{df}{dt} = (-0.01) f^{1.84} \quad (f \text{ in MHz}) \tag{4}$$

Generally speaking, Type III emission is ascribed to the scattering of Cerenkov plasma waves produced by fast electron streams. It is believed that most type III bursts are observed at the second harmonic of the local plasma frequency

$$f = 2f_p = 2 \times 8.98 \times 10^{-3} \sqrt{N(R)} \tag{5}$$

where R(t) represents the position of type III burst source at instant t. N(R) is the local electron density in cm^{-3}.

From equation (7), the drift rate in frequency can be expressed as

$$\frac{df}{dt} = \left(\frac{f}{2N}\right) \frac{dN}{dR} \cdot \frac{dR}{dt} \tag{6}$$

where $\frac{dN}{dR}$ is the gradient of coronal electron density and $\frac{dR}{dt} = v$ is the velocity vector of the fast electron stream. If θ is the angle between $\frac{dN}{dR}$ and v, and δ the angle between the line of sight and the direction of the electron stream, then for a relativistic electron stream and because of Doppler effect and $\beta^2 \ll 1$, we can obtain approximately $fv = \frac{c\beta f}{1-\beta\cos\delta}$. From Equation (6), the ratio $\frac{v}{c} = \beta$ can be given by

$$\beta(\theta, \varphi) = \frac{a}{\cos\theta + a\cos\delta} \tag{7}$$

and

$$a=\frac{2N}{cf}\cdot\frac{df}{dt}\cdot\frac{1}{\frac{dN}{dR}} \tag{8}$$

For simplicity, we assume that the electron density of the corona is in spherically symmetric distribution and the fast electron streams move outward along the radial direction.

When $\theta = \delta = 0$, we have

$$\beta=\frac{a}{1+a}. \tag{9}$$

The energy of the fast electrons producing type III bursts is given by

$$\mathcal{E}=\left(\frac{1}{\sqrt{1-\beta^2}}-1\right)\times 511\ \mathrm{Kev} \tag{10}$$

Moreover, we use the model of N(R) for solar maximum activity fiven by Table 2 of reference [12]. Finally, the kinetic energy of fast electrons producing type III bursts for different frequencies is shown in Table 2.

If θ and δ are not equal to zero, the value of $\beta(\theta,\varphi)$ evaluated from equation(7) must be larger than that from equation (9) with the same frequency. Hence the energy of fast electrons increases. Therefore, as long as the fast electrons injected downward from acceleratiom region A possess the same energy as those exciting type III bursts, they are still able to produce hard X-ray bursts as those recorded on "Hinotori" or on Prognoz 8 satellite even after losing some energy about tens of kev due to MMSE's.

Table 2. Energy of fast electrons producing type III bursts at different frequencies

f(MHz)	600	300	200
$\mathcal{E}$ (KeV)	11.24	69	34

V. CONCLUDING WORDS

Based on our model and the mechanism of electron-cyclotron instability associated with a hollow beam of electrons, we have explained why there occurred strong MMSE's during the event of 1981 May 16 and why there appeared no MMSE but more intene microwave bursts at 10.6 cm during the event of 1981 October 12. Furthermore, we have shown that there exist some intimate links of MMSE's with their associated phenomena in the physical processes of generation and evolution during the impulsive phase of large flares. Obviously, the discovery of these links with one another is important for clarifying the mechanism of large flares.

ACKNOWLEDGEMENTS

The authors are indebted to Dr. K. Tanaka for sending us the data of hard X-ray bursts recorded on "Hinotori" satellite and to the Yunnan Observatory for the data of photospheric magnetic fields.

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