Emission Mechanism of a Specific Solar Radio Microwave Burst

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Abstract

Choosing a representative solar radio microwave burst, a typical burst which contains a precursor and an impulsive burst followed by a slowly decaying component, as an example, we have researched its radio emission mechanism and calculated the two important theoretical characteristic parameters, intensity and dimension, of its various sources.

1. Introduction

Although the solar radio microwave bursts are always continuum in nature, their properties, especially the spatial structure, polarization, and brightness temperature change in course of the bursts (Kundu and Vlahos, 1982). In the impulsive phase,the burst sources have a diameter varying from 10" to 1′ arc. The peak brightness temperatures range from $10^8 K$ to $10^9 K$. The bursts are caused by gyro-synchrotron radiation. In the post-burst phase, the burst sources appear to be a diffuse region of relatively large diameter ($> 1'$ arc). Their brightness temperatures usually lie between $10^5 K$ and $10^7 K$. The bursts are generated by bremsstrahlung and / or gyro-resonance radiation.

In the present paper, we have selected a specific and representative solar radio microwave burst, which consists of a precursor and an impulsive burst followed by a slowly decaying component, researched its emission mechanism, and calculated the intensity and dimension of its sources.

2. Example of the Radio Burst

The author observed a microwave burst occurring at the frequency $\nu = 9.395\,GHz$ on March 28, 1981 and lasting from 0523 to 0620 UT. This is a representative radio burst (cf. Figure 1.): first, beginning with a small and slowly varying precursor burst whose peak is marked by P in Figure 1; about 7 minutes later, occurring with an impulsive burst followed by a slowly decaying burst. Obviously, the latter burst component can be resolved into a gradual rise and fall burst whose peak is marked by G in Figure 1 and a superposed impulsive burst whose peak is marked by I in Figure 1.

The maximum flux density of the burst is $F = 249.0\ s.f.u.$ The flux densities of the three peaks mentioned above are tabulated in Table 1. The H_α flare corresponding to the burst started at 0535 UT, maximized at 0539 UT,and ended at 0615 UT.

Table 1. Flux Densities of the Burst Peak Moments

Burst Peaks	P	I	G
Time (UT)	0529	0535.6	0541
Flux Densities (s.f.u.)	8.0	237.4	26.6

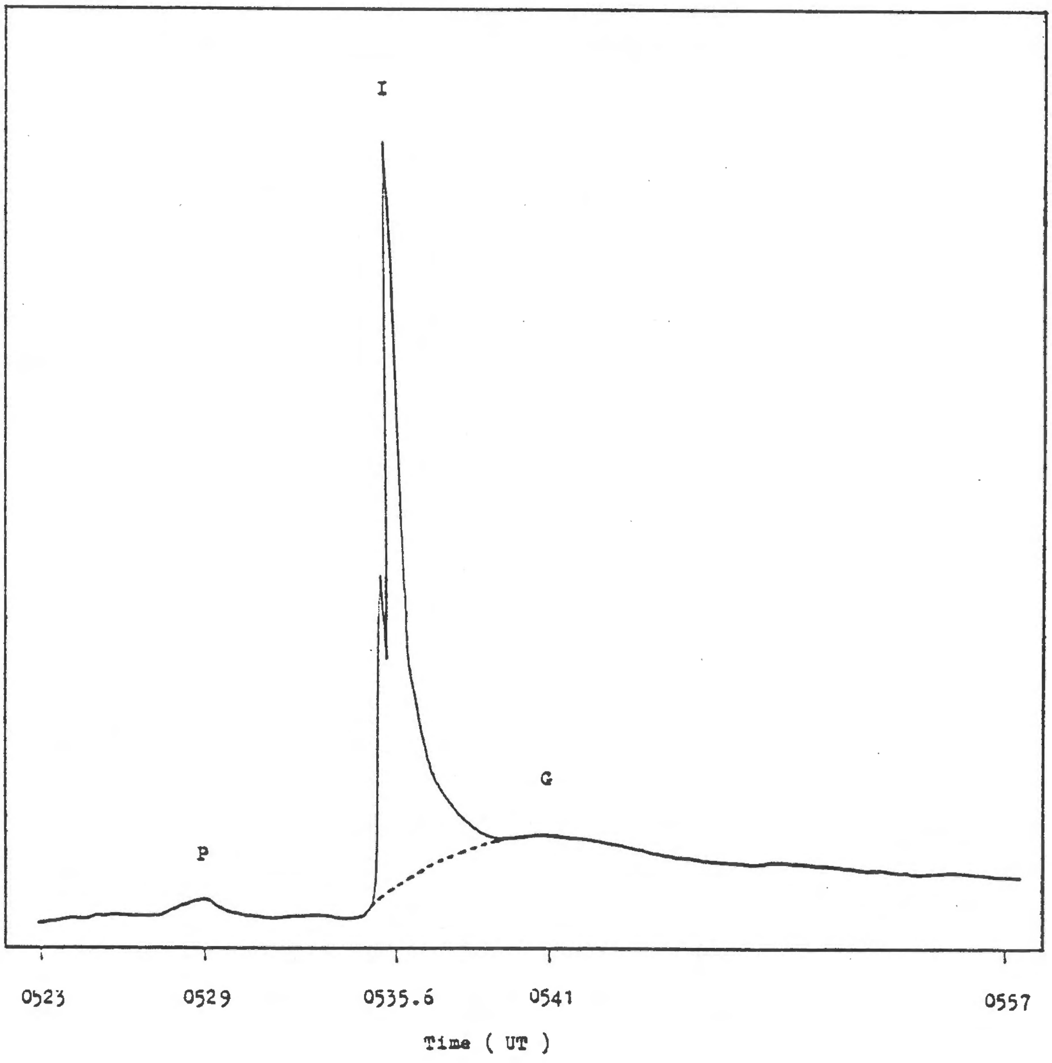

Fig.1 The radio microwave burst occurring at the frequency of 9.395 GHz on March 28, 1981.

3. Emission Mechanisms of the Radio Burst

In the present paper, it is suggested that during the pre-flare phase a small, condensed, and heated plasma volume in an active region appears as a precursor source and generates a weak and slowly varying burst (its peak is shown by P in Figure 1) at the thermal emission mechanism. During the impulsive phase of the flare some energetic particle beams are released from an acceleration region. The high energy electron beams extend throughout a certain region of the magnetic loops and form an impulsive source which produces a strong and steep burst (its peak is shown by I in Figure 1) at the emission mechanism of nonthermal incoherent gyro-synchrotron radiation. Then during the post-flare phase the moderately hot plasma volume having a large dimension becomes a post-burst source and yields a gradual rise and fall burst (its peak is shown by G in Figure 1) through the combined emission mechanism of bremsstrahlung and gyro-resonance radiation.

Because the plasma in the corona has very low density and hence the index of refraction of the medium $n_r \sim 1$, the radiative transfer equation in which the radiative intensity can be expressed by the brightness temperature can be written as

$$\frac{dT_{b,j}}{d\tau_j} = T_{eff,j} - T_{b,j}, \tag{1}$$

where the subscripts $j = x$ and o represent the parameters corresponding to extraordinary wave and ordinary wave, respectively; $T_{eff,j}$ is the effective temperature of the radiating electrons, which replaces the source function S_j, i.e.

$$\frac{k\nu^2}{c^2}T_{eff,j} = S_j = \frac{\eta_j}{\kappa_j}, \tag{2}$$

where c is the speed of light, k the Boltzmann's constant, η_j the emissivity, κ_j the absorption coefficient; and τ_j is the optical depth.

Since we only discuss the radiation of the radio source itself, we do not consider the radiation from the background source under the radio source. The solution of radiative transfer equation (1) , therefore, can be given :

$$T_{b,j} = \int_{\tau_{t,j}}^{\tau_{b,j}} T_{eff,j}\exp(-\tau_j)d\tau_j, \tag{3}$$

where $\tau_{t,j}$ and $\tau_{b,j}$ are the optical depths at the top and the bottom of the radio source, respectively.

We also consider the effects on the source radiation from the $f-f$ absorption and the gyroresonance absorption in the plasma medium above the radio source. The absorption coefficient,κ_j^{f-f} (in $c.g.s.e.$), of the $f-f$ process is (Zhao, 1991a,1993):

$$\kappa_j^{f-f} = 4(\frac{2}{\pi})^{1/2}\frac{e^6}{c^3(mk)^{3/2}}\frac{Q\lambda N^2}{T^{3/2}}F_j(v,u,\theta), \tag{4}$$

where N and T are the number density and the temperature of thermal electrons, respectively; Q is a slowly varying function of N and T; θ is the angle between the magnetic field and the wave vector $\mathbf{k}$; $v = \nu_P^2/\nu^2, u = \nu_B^2/\nu^2$. The optical depth,$\tau_{j,s}^{g-r}$ (in $c.g.s.e.$),corresponding to the absorption coefficient,$\kappa_{j,s}^{g-r}$,of the gyro-resonance process can be expressed as follows (Zhao,1991a,1993):

$$\tau_{2,1}^{g-r} = \frac{2\pi e^2 k}{(mc^2)^2}T_1 N_1 L_{B1}\lambda G(\theta_1) \tag{5}$$

and

$$\tau_{j,s\geq 2}^{g-r} = \frac{s^{2s}}{2^s s!}\frac{\pi e^2 k^{s-1}}{(mc^2)^s}T_s^{s-1}N_s L_{Bs}\lambda G_j(s,\theta_s), \tag{6}$$

where T_s, N_s, L_{Bs} and θ_s are the temperature,the density of the thermal electrons,the characteristic scale and the direction of the magnetic field in s-th gyro-resonance layer. The distributions of the electron density and the electron temperature can be obtained from the chromosphere-corona transition zone model and the corona model (e.g. Zhao, 1991b,1993).

We take the magnetic field in the active region as magnetic dipole field , then the strength B and the direction θ (i.e. $\theta = \angle(\mathbf{B}, \mathbf{k})$ of the magnetic field intensity, in the spherical coordinate (r, ξ, ϕ) can be expressed as (Takakura and Scalise, 1970):

$$B = \frac{B_0 d_0^3}{2r^3}(1 + 3\cos^2\xi)^{1/2}, \tag{7}$$

and

$$\theta = \arccos[\sin\psi \sin(\xi + \alpha)\sin\phi + \cos\psi\cos(\xi + \alpha)], \tag{8}$$

respectively, where d_0 is the depth of the dipole below the photosphere ,B_0 is the strength of the magnetic field at the photosphere and on the axis of the dipole,$\psi = \angle(\mathbf{k}, \mathbf{d})$,and $\alpha = \angle(\mathbf{B}, \mathbf{r}) = \arctan(\tan\xi/2)$. The characteristic scale of the magnetic field is

$$L_B = \mid grad\ \ln B \mid^{-1}. \tag{9}$$

It can be reasonably assumed from the observations that $B_0 = 1500\ Gauss, d_0 = 3 \times 10^9 cm$,and $\psi = 4°$ in the case of the burst.

In the present paper, we only calculate the ray in the direction from the center of the bottom of the radio source to the observer.

3.1. *Thermal Bremsstrahlung and Gyro-resonance Radiation of the Precursor Source and Post-Burst Source*

The radio radiation of a precursor and a post-burst source is generated by the combined emission mechanism of bremsstrahlung and gyro-resonance radiation from thermal electrons having a Maxwellian distribution. Now the effective temperature of radiating electrons in the radiative transfer equation is equal to the thermal electron temperature, i.e. $T_{eff} = T$. Considering the effects of the $f-f$ absorption and gyro-resonance absorption above the source, therefore, the radiation intensity can be derived from equation (3):

$$T_{b,j} = \exp[-\int_{l_t}^{l_\infty}(\kappa_j^{f-f} + \kappa_j^{g-r})dl]\int_0^{l_t} T(\kappa_j^{f-f} + \kappa_j^{g-r})\exp[-\int_l^{l_t}(\kappa_j^{f-f} + \kappa_j^{g-r})dl]dl, \tag{10}$$

where l is the length of the ray measured from the center of the source bottom along the direction of the sight line; $l_t = (h_t - h_b)/\cos\psi$, h_t and h_b are the heights above the photosphere of the source top and bottom , respectively; l_∞ is the ray length at the edge of the corona.

For the sake of simplicity, we take the height of precursor source top $h_t = 3 \times 10^9 cm$, bottom height $h_b = 5 \times 10^8 cm$. We assume the uniform electron density and temperature distributions inside the source and take $N = 10^{10}\ cm^{-3}, T = 3 \times 10^6 K$. Through numerical calculations, we obtain the radiation intensity of the precursor source: $T_b = (T_{b,x} + T_{b,o})/2 = 7.07 \times 10^5 K$.

We take the height of post-burst source top $h_t = 4.4 \times 10^9\ cm$, bottom height $h_b = 5 \times 10^8\ cm$, and the uniform distributions of electron density and temperature, $N = 5 \times 10^9\ cm^{-3}$ and $T = 5 \times 10^6 K$. Integrating the equation (10) along the line of sight, we can compute the radiation intensity of the post-burst source: $T_b = (T_{b,x} + T_{b,o})/2 = 1.32 \times 10^6 K$.

3.2. *Nonthermal Incoherent Gyro-synchrotron Radiation of the Impulsive Source*

The radio radiation of an impulsive source is generated through the emission mechanism of incoherent gyro-synchrotron radiation of nonthermal energetic electrons. We take the top height of the impulsive source $h_t = 4.40 \times 10^9 cm$ ($B = 100\ Gauss$ at the center),bottom height $h_b = 2.13 \times 10^9 cm$ ($B = 300\ Gauss$ at the center). We also assume that the energetic electrons in the source have an isotropic distribution in the pitch angle and a power law distribution in energy (Dulk,1985):

$$n(E) = (\delta - 1)E_0^{\delta-1} N E^{-\delta}, \tag{11}$$

where N is the number of electrons per cubic centimeter with energy $E > E_0 = 10\ keV$. We take $N = 4 \times 10^6 cm^{-3}$,and $\delta = 3$. Thus,when these mildly relativistic electrons gyrate in the magnetic field of $B < 300\ Gauss$,they generate the emission at harmonics $s > 12$ (s is the harmonic number, $s \approx \nu/\nu_B$).

Considering the effects of $f-f$ absorption and gyro-resonance absorption above the source,we can obtain the radiation intensity of the extraordinary wave from Eq.(3):

$$T_{b,x} = \exp[-\int_{l_t}^{l_\infty}(\kappa_x^{f-f} + \kappa_x^{g-r})dl] \int_0^{l_t} \frac{c^2}{k\nu^2}\eta_x^{g-s} \exp[-\int_l^{l_t} \kappa_x^{g-s} dl]dl. \tag{12}$$

Because $s \approx 12$ to 39 along the integral path $l \approx 0$ to l_t, the emissivity of gyro-synchrotron radiation η_x^{g-s} and the absorption coefficient κ_x^{g-s} can be taken approximately as (Dulk,1985):

$$\eta_x^{g-s} \approx 3.3 \times 10^{-24} 10^{-0.52\delta} (\sin\theta)^{-0.43+0.65\delta} (\frac{\nu}{\nu_B})^{1.22-0.90\delta} BN, \tag{13}$$

and

$$\kappa_x^{g-s} \approx 1.4 \times 10^{-9} 10^{-0.22\delta} (\sin\theta)^{-0.09+0.72\delta} (\frac{\nu}{\nu_B})^{-1.30-0.98\delta} \frac{N}{B}, \tag{14}$$

respectively. While for the ordinary wave, the radiation intensity can be found in the form:

$$T_{b,o} = \frac{1 - r_c}{1 + r_c} T_{b,x}, \tag{15}$$

where the degree of circular polarization r_c can be expressed approximately as (Dulk, 1985):

$$r_c \approx 1.26 \times 10^{0.035\delta} 10^{-0.071\cos\theta} (\frac{\nu}{\nu_B})^{-0.782+0.545\cos\theta} \tag{16}$$

For mildly relativistic electrons,the Razin-Tsytovich suppression effect occurs at $\nu \leq \nu_P^2/\nu_B$. While under the present circumstance of $\nu_P^2/\nu_B \leq 9.6 \times 10^8 - 2.9 \times 10^9\ Hz$

(assuming $N_e \leq 10^{10} cm^{-3}$),obviously we have $\nu > \nu_P^2/\nu_B$, therefore we can neglect the Razin-Tsytovich suppression effect.

We have calculated the radiation intensity of the impulsive source from numerical integral: $T_b = (T_{b,x} + T_{b,o})/2 = 1.02 \times 10^8 K$.

3.3. *Horizontal Dimensions of the Radio Sources*

It is well known that the relation between the radiation intensity T_b of the radio source and the flux density F observed on the Earth can be given by

$$F = \int_\Omega \frac{2k\nu^2}{c^2} T_b \cos\psi d\Omega, \qquad (17)$$

where $\cos\psi\Omega$ is the solid angle of the radio source on the Earth. Assuming the uniform distribution of T_b within the solid angle of the radio source,we can calculate the horizontal dimension of the radio source from Eq. (17). From above calculated values of T_b and the values of F given in the Table 1, we can easily obtain the horizontal dimension of the precursor source $D = 4.08 \times 10^9 cm$ (i.e. 56".24 arc),impulsive source $D = 1.85 \times 10^9 cm$ (i.e. 25".51 arc) and the post-burst source $D = 5.45 \times 10^9 cm$ (i.e. 1'.25 arc).

4. Conclusions

For the radio burst observed in 0523 - 0620 UT, on March 28, 1981, at the frequency of 9.395 GHz,according to the combined emission mechanism of thermal bremsstrahlung and gyroresonance radiation, we have calculated the radiation intensity and the horizontal dimension of the precursor source and the post-burst source;while according to the emission mechanism of nonthermal incoherent gyrosynchrotron radiation,we have computed the radiation intensity and the horizontal dimension of the impulsive source. These data are listed in the Table 2.

Table 2. Characteristic Parameters at Different Peak Moments of the Radio Burst Source

Burst Source	Precursor Source	Impulsive Source	Post-burst Source
Burst Peak (time)	P (0529 UT)	I (0535.6 UT)	G (0541 UT)
Intensity T_b	$7.07 \times 10^5 K$	$1.02 \times 10^8 K$	$1.32 \times 10^6 K$
Dimension D	$4.08 \times 10^9 cm$(56".24)	$1.85 \times 10^9 cm$(25".51)	$5.45 \times 10^9 cm$(1'.25)

It can be seen from Table 2 that the various sources of the burst have their respective characteristics: At the first, a small but weaker precursor source arises. A few minutes later, a smaller but strong compact source appears. Then, after that time, a large and weak dispersed source occurs.

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