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II-3A-11. On the Exciters of Type II and III Solar Radio Bursts

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The exciters of transient solar radio emissions—the type II and type III bursts—are discussed mainly from the view point of velocity with which their sources move in the solar atmospheres.

The propagation velocities of several possible types of disturbances in the physical condition above a typical sunspot are considered in order to account for the observed velocities and their variation with height of each type of bursts, and it is concluded that the exciters of type II bursts are the hydromagnetic shock front, while those of type III bursts are the free streaming group of high velocity charged particles[1].

We wish to look for exciting agencies consistent with the following observed features about each type of solar radio bursts[2] shown in Table I.

First, we notice that, because of the long mean free path of high velocity particles, the motion of particles parallel to the magnetic lines of force in the corona does not make a sharp discontinuity at the front, but a very diffuse one with a thickness of the transition layer of $\sim 10^{10}$ cm, even for the smaller velocity of type II bursts, that is, $\sim 10^8$ cm/s*[3]. For the velocity of type III bursts, the particle, of course, comes out almost freely through the solar corona. In these cases,the phenomena must not be considered as a hydrodynamic waves but an individual particle motion in a plasma. The possibility of excitation of plasma waves by such individual particles is considered later.

Thus the motion perpendicular to the magnetic lines of force is considered as the other extreme case. As the gyro-radius of a particle is rather small in the physical condition above a typical sunspot, the motion in this case always becomes wave-like, so long as the kinetic energy density does not exceed that of the magnetic field. This is the case for most of the disturbances near the sunspot. Since the velocities of both types of bursts, $\sim 10^8$ cm/s and $\sim 10^{10}$ cm/s, exceeds the sound velocity, though the sound velocity perpendicular to the magnetic lines of force rises from $a_0=\sqrt{\gamma RT_0}$ to $c_0=\sqrt{\gamma RT_0+H_0^2/4\pi\rho_0}$, we must consider shock waves, that is, hydromagnetic shock waves.

In the following, the propagation of hydromagnetic shock waves in a model physical condition in the corona above a typical sunspot is treated, by taking into account the dissipation of kinetic energy flux at the shock front. The method of treatment is the step by step application of Brinkley-Kirkwood's method:

$$\frac{dF}{dh}=-\Delta F\,, \tag{1}$$

Table I.

	Type II	Type III
Velocity	$\sim 10^8$ cm/s decreasing outwards** (from dynamic spectra)	$\sim 10^{10}$ cm/s almost constant** (from dynamic spectra)
Duration	$\sim$10 min	$\sim$10 sec
Frequency of occurrence	Rare	Frequent
Frequency region of appearance	$\lesssim$100$\sim$200 Mc/s	$\lesssim$450 Mc/s
Correspondence	Large flare	Rather indefinite

** Large gap exists between the velocities for Type II and Type III.

* As for these outcoming particles along the magnetic lines of force themselves, they may be the corpuscular stream ejected from the sun.

$$F=\int(P-P_0)vdt=(P_1-P_0)v_1\tau\int f(t')dt' , \quad (2)$$

$$\Delta F=c_p\rho_0\left\{\left(\frac{p_1}{p_0}\right)\left(\frac{\rho_1}{\rho_0}\right)^{-\gamma}-1\right\} , \quad (3)$$

where quantities with suffix 1 are derived from the nondisturbed quantities (0) by use of hydromagnetic Rankine-Hugoniot relations;

$$\rho_1 u_1=\rho_0 u_0\equiv m , \quad (4)$$

$$H_1 u_1=H_0 u_0 , \quad (5)$$

$$mu_1+p_1+\frac{H_1^2}{8\pi}=mu_0+p_0+\frac{H_0^2}{8\pi}, \quad (6)$$

$$m\left(U_1+\frac{p_1}{\rho_1}+\frac{u_1^2}{2}+\frac{H_1^2}{4\pi\rho_1}\right)$$

$$=m\left(U_0+\frac{p_0}{\rho_0}+\frac{u_0^2}{2}+\frac{H_0^2}{4\pi\rho_0}\right). \quad (7)$$

Nondisturbed quantities are given by models; $\rho_0(h), p_0(h)$, etc. are given by de Jager's model solar atmosphere, and $H_0(h)$ is assumed to be a magnetic field of dipole nature whose dipole is located 0.05~0.1 $R_\odot$ below the photosphere and having the photospheric intensity of 1000~3000 Γ. Using these models, necessary quantities are computed as the functions of height from the photosphere, h.

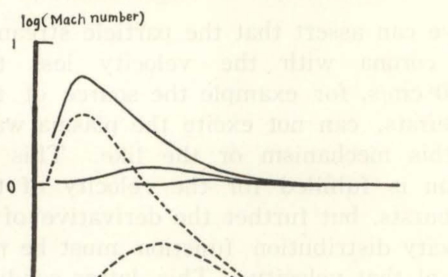

Fig. 1. The runs of Mach numbers of shock front (solid curves) and the material flow behind (dashed curves) versus the height from the photosphere (in cm). Each pair corresponds, from the bottom, to the initial disturbances with the velocities of 10^7 cm/s, 10^8 cm/s, and 5×10^9 cm/s, respectively.

Giving appropriate initial disturbances, we solved the equation of kinetic energy flux transfer in the vertical direction, in an approximate manner. As the result, we obtain the runs of Mach numbers of the shock front $\mathfrak{M}_f(h)$ and of the material stream behind the shock front $\mathfrak{M}_1(h)$ as the functions of height (Fig. 1). This, in turn, is converted into the runs of velocities themselves by use of the computed sound velocity (Fig. 2). In the same figure, the velocity regions of type II and type III bursts reduced from the dynamic spectra (by courtesy of Dr. A. Maxwell of Harvard College Observatory), assuming the plasma frequency level hypothesis, are shown by the hatched regions. These curves show

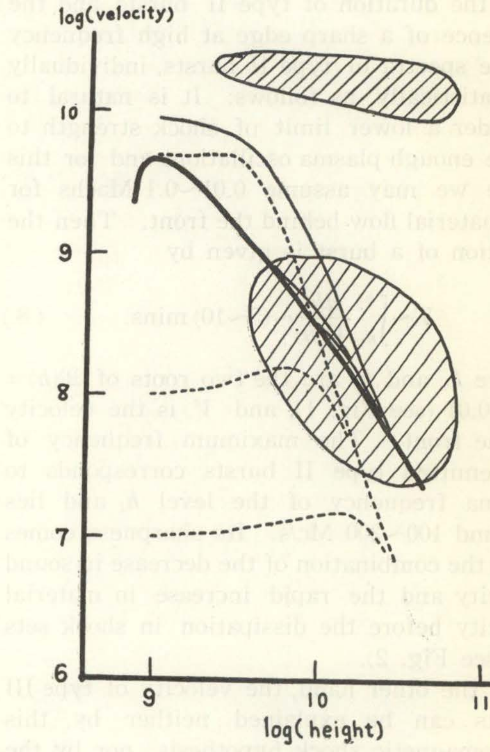

Fig. 2. The runs of velocity of the shock front (thin solid curves) and the material flow behind (dashed curves), converted from Fig 1 by use of $c_0(h)$ (thick solid curve). Shaded regions below and above are the reduced velocity regions of type II and type III bursts, respectively. In both regions, upper parts of right-hand side come from the assumption of 10 times of coronal density.

a fair fit to the velocity of type II bursts in the corona, while the velocity of type III bursts can hardly be explained. A reasonable change in the models does not affect the results essentially. For the case of non-perpendicular disturbances, the motions may be the superposition of a perpendicular propagation and a motion parallel to the lines of force, the latter being a wave-like propagation or a translational streaming, depending on its velocity (the motion becomes a free streaming for the velocity of type II or type III source, as mentioned above, but the motion, of cource, can be a wave-like propagation for the lower velocities).

Consequently, the exciter of type II bursts may be said to be identified as the hydromagnetic shock front in the neighbourhood of sunspot[cf. 4].

If we admit this, we can further explain both the duration of type II bursts and the existence of a sharp edge at high frequency in the spectra of type II bursts, individually or statistically, as follows: It is natural to consider a lower limit of shock strength to cause enough plasma oscillation, and for this value we may assume 0.01~0.1 Machs for the material flow behind the front. Then the duration of a burst is given by

$$T\sim\int_{h_1}^{h_2}\frac{dh}{V(h)}\sim(5\sim10)\text{ mins.} \tag{8}$$

where h_1 and h_2 are the two roots of $\mathfrak{M}(h)=0.1\sim0.01$ (see Fig. 1), and V is the velocity of the front. The maximum frequency of the emitted type II bursts corresponds to plasma frequency of the level h_1 and lies arround 100~200 Mc/s. Its sharpness comes from the combination of the decrease in sound velocity and the rapid increase in material velocity before the dissipation in shock sets in. (see Fig. 2).

On the other hand, the velocity of type III bursts can be explained neither by this hydromagnetic shock hypothesis, nor by the ordinary shock hypothesis as mentioned first. So, the retained possibility of the excitation of plasma wave by individual particles is considered.

In this case, the working mechanism is the electrostatic interaction between suprathermal particles and electronic plasma. As Bohm and Gross have described[5], high velocity charged particles in the trough of potential fluctuation of electronic plasma give their energy surplus to the wave and excite it. This excitation occurs clearly for a wave, at whose phase velocity the velocity distribution function of suprathermal particles has a positive derivative.

The formula for the time rate of excitation given by Bohm and Gross is

$$\lambda=-\frac{1}{2\tau_c}+\frac{\pi}{2}\frac{\omega_p^3}{k^2}f'\left(\frac{\omega_0}{k}\right),\ (\text{amplitude}\propto e^{\lambda t}), \tag{9}$$

where τ_c is the collision interval of electrons with thermal ions, and ω_0 is a frequency fulfilling the dispersion relation

$$\omega_0^2=\omega_p^2+\frac{3\kappa T_e}{m_e}k^2\,. \tag{10}$$

First of all, the velocity of the exciting particles must be larger than the mean thermal velocity of electrons, that is, from (10),

$$v_p\approx\frac{\omega_0}{k}=\sqrt{\left(\frac{\omega_p}{k}\right)^2+\frac{3\kappa T_e}{m_e}}>\sqrt{\frac{3\kappa T_e}{m_e}}$$
$$\sim 7\times10^8\text{ cm/s}\quad\text{in the corona}\ , \tag{11}$$

so we can assert that the particle stream in the corona with the velocity less than 7×10^8 cm/s, for example the source of type II bursts, can not excite the plasma waves in this mechanism or the like. This criterion is fulfilled for the velocity of type III bursts, but further the derivative of the velocity distribution function must be positive at that velocity. This latter condition may be fulfilled by the cutting away of low energy part of suprathermal particle distribution by the Coulomb interaction along the path in the denser lower atmosphere.

It is shown that particles with a velocity less than $v_c\equiv(8G/m_p^2)^{1/4}$ (G is a function proportional to the "passed mass" by particle) cannot come out to the corona. Below this critical value, the distribution function is reformed as $\propto v_p^2$ for most of the initial distribution. This critical value for the velocity is $\sim5\times10^8$ cm/s for protons, if we assume that the acceleration region is in the middle chromosphere. This, however, is smaller than the velocity of type III bursts. Appropriately above this value, the distribution function is shown to remain unchanged. If we assume that the Fermi's acceleration mechanism works fully (without escape of particles) in the acceleration region in lower layers transiently, we may expect that the distribution function of this velocity range is proportional to v_p^2 [6]. So, we assume arbitrarily, $f(v_p) \propto v_p^2$ or v_p, the latter corresponding to the case in which the acceleration works not fully in the acceleration region in lower layers. Then we can compute the value of λ by determining the proportionality constant in $f(v_p)$ from an estimated number of high energy particles generated in a flare. We obtain for (9)

$$\lambda = \begin{cases} -10^0 + 10^{11}\ \mathrm{sec}^{-1} & \text{in both cases in the corona,} \\ -10^6 + 10^{12}\ \mathrm{sec}^{-1} & \text{in both cases in the chromosphere.} \end{cases} \quad (12)$$

So, the rate of growth in the amplitude of plasma waves is

$$e^{\lambda \tau_e} \sim \begin{cases} 10^{4.3} & \text{in the corona,} \\ 10^{0.43} & \text{in the chromoshere,} \end{cases} \quad (13)$$

where $\tau_e \sim D/v_p$ is a time for the high velocity particles to cross the local Debye sphere. This shows that the excitation is enough in the corona but not in the chromosphere. These plasma waves excited will be damped through collisions with thermal ions in 10^0 sec in the corona and 10^{-6} sec in the chromosphere respectively. The rate of excitation λ decreases rapidly for the smaller velocity of exciting particles. This condition and the criterion of possibility of excitation (11), combining with the fact mentioned as to the velocity of type II bursts, may give the reason for existence of wide gap between the velocities of two types of bursts.

In addition, as to the total energy emitted in a type III burst, it is shown that a particle (proton*) stream of rather low density, that is, of the order of $10^{3\sim4}\ \mathrm{cm}^{-3}$ is enough, as long as we assume $10^{-5} \sim 10^{-6}$ for the value of energy conversion efficiency from plasma wave to electromagnetic wave, as is usually adopted. If it is correct, the frequent occurrence of type III bursts can be understood, because such a particle stream of low density could be ejected not only from large flares, but also even from weak flare-like phenomena.

Thus it may be concluded that type II and type III bursts, though having a common radiation mechanism as microscopic plasma oscillation, have distinctly different exciters: For type II bursts, hydromagnetic shocks which give rise to the plasma oscillation perhaps through charge separation at the shock front, while for type III bursts, the free streaming of charged particles with high velocity which causes plasma oscillation through the Bohm-Gross' mechanism.

If we admit these reasonings, the characteristic features and differences of these two types of solar radio bursts are consistently understandable.

References

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Discussion

Thompson, A.R.: I am interested to see that you predict a decrease in the velocity of type II disturbance as it moves through the corona. In a recent paper on type II bursts, Maxwell and I examined the velocity of the disturbance as a function of frequency, from measurements of the rate of frequency drift of the bursts. A model of the solar corona in which the electron density is increased by a factor of 10 above the Baumbach-Allen model was used, and the velocity of the disturbance was found to decrease 1700 km/s at 200 Mc/s to 700 km/s at 50 Mc/s.

* In a private conversation with Dr. Biermann during the Conference, it occurres to me to reconsider the possibility of the exciter of type III bursts to be an electron stream. If the exciter is an electron stream, the critical velocity v_c may become $\sim 2 \times 10^{10}$ cm/sec, and $f'(v_p)$ becomes positive without requiring the initial distibution function to have an actual hump in the high velocity part. Not an actual hump but only a tail in the high velocity part is necessary. The electron stream hypothesis agrees also with the view of Dr. Wild given in his paper (II 3A-P3). However, the density in the stream must be higher by a factor of 10^{2-3} than in the case of proton stream from the energy consideration.