NUMERICAL SIMULATION OF THE PROPAGATION OF TYPE III RADIO EMISSION

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Abstract

Recently solar Type III bursts with fine time structure have been observed by radio telescope UTR-2 at frequencies $10 - 30$ MHz. For the first time Type III-like bursts with high frequency drift rates were observed at these frequencies too. All this became possible due to both high sensitivity and high time resolution of UTR-2. The properties of decameter Type III bursts can be understood if we take into account the spatial dependence of the electromagnetic wave group velocity as well as the fine spatial structure of the cloud of fast electrons responsible for Type III bursts. These effects are considered numerically in this paper. The fine time structure of Type III bursts is shown to be observed in the days when the associated active region is situated near the central meridian. In other days such structures disappeared. The Type III-like bursts with frequency drift rates of $10 - 20$ MHz/s should also be observed, when the associated active region is near the central meridian. These peculiarities are confirmed by observations.

1 Introduction

Type III bursts have been observed since the middle of the last century by Wild [1950], and they are the most studied component of the sporadic solar radio emission. It is believed that the bursts are generated by clouds of fast electrons accelerated due to solar activity up to a velocity of $0.3c$ (c is the speed of light), which propagate in the plasma of the solar corona along open magnetic field lines. Type III bursts have been observed in a wide range of frequencies from 1 GHz to tens of kilohertz [Suzuki and Dulk, 1985]. Numerical calculations of the parameters of the Type III bursts have been reported previously [Itkina and Levin, 1992; Itkina et al., 1993; Ledenev, 2000; Li et al., 2009]. For example, Itkina and Levin [1992] studied a two-dimensional corona model with thin streamers of fibrous structure which leads to Type III bursts with fine structure. Itkina et al. [1993] studied the group delay of electromagnetic waves numerically studied versus cloud parameters of Type III burst in the decameter frequency range.

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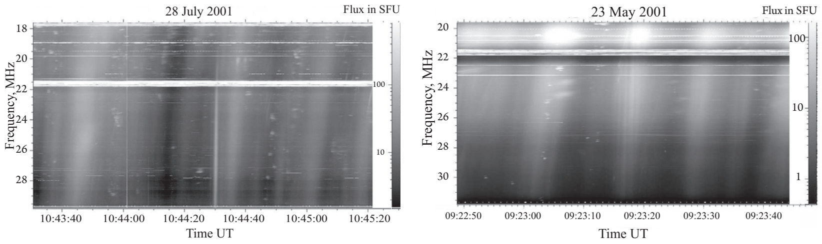

Figure 1: a) Type III-like burst (10:44:30) against background of usual Type III bursts; b) Type III burst with fine structure (09:23:17).

In this paper we study the propagation of Type III electromagnetic waves in the solar corona in the frame of the generally accepted theory of Type III burst generation [Ginzburg and Zhelezniakov, 1958] taking into account the spatial dependence of the group velocity of electromagnetic waves and regarding that the Type III electron clouds had finite sizes.

In this paper we find

- an analytical expression for the frequency drift rate in the case of infinitely small source but having in mind the spatial dependence on of the group velocity,
- a numerical profile of accepted signal generated by an electron cloud of finite size,
- the frequency drift rate of the signal versus the electron cloud size and propagation angle of the cloud.

We analyze cases when the fast electron cloud is homogeneous and when it consists of some layers. On the one hand, this allows to describe usual Type III bursts and Type III-like bursts [Melnik et al., 2008] (also known as fast Type III bursts [Young et al., 1961]) in the same model and, on the other hand, to understand the fine time structure of decameter Type III bursts [Melnik et al., 2005]. The results of the numerical model for special parameters of the electron cloud can explain the Type III bursts observed by UTR-2 radio telescope in the decameter range. Comparing the observed data and numerical results gives us an opportunity to diagnose solar corona and the fast electron clouds.

2 The Model

Recently Type III-like bursts (Fig.1.a) and Type III bursts with fine time structure (Fig.1.b) have been detected by the radio telescope UTR-2 [Mel'nik et al., 2005; Mel'nik et al., 2008]. It is commonly accepted that the usual Type III bursts are generated by fast electrons clouds. In this paper we solve the numerical problem of propagation of an

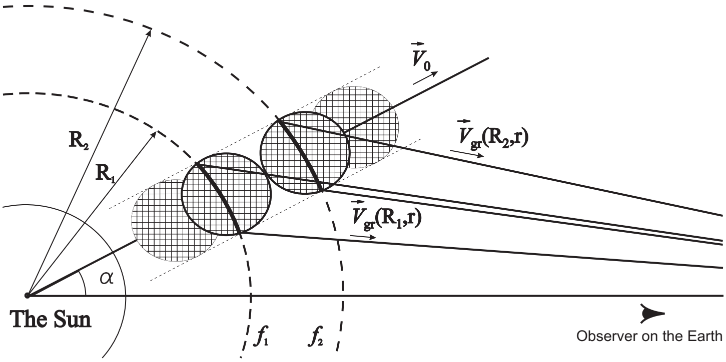

Figure 2: Geometry of the discussed problem.

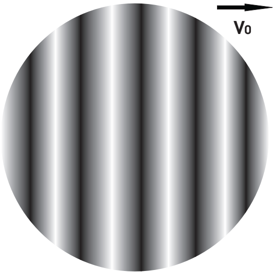

Figure 3: Cloud of fast electrons with variable density.

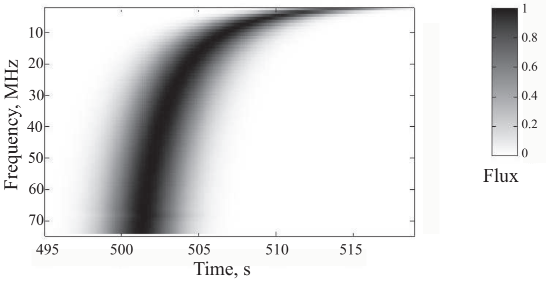

Figure 4: A dynamic spectrum of the radio emission of fast electron cloud with constant size.

electromagnetic signal from the spherical cloud of finite size. Figure 2 shows the scheme of our numerical model. In the numerical simulation we replace the moving electron cloud by an ensemble of elementary cells, where each cell is described by three coordinates and the time of emission. Every cell being at distance R_i (where $i = 1$ or 2) radiates the electromagnetic wave of the same intensity at frequency f_i. For calculation of the frequency drift rate one needs two signals, at two frequencies f_1 and f_2. In Figure 2, R_1

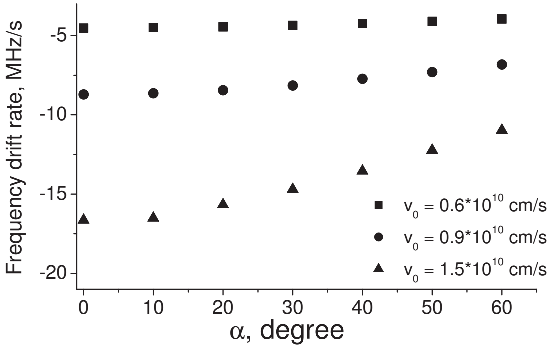

Figure 5: The calculated frequency drift rates as a function of the angle α for different velocities of the electron cloud.

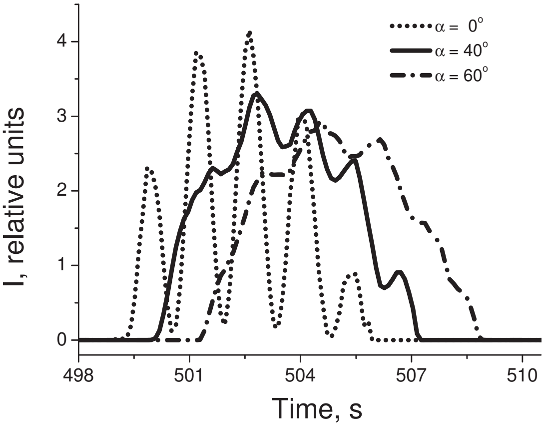

Figure 6: Examples of Type III burst profiles with fine time structure for different angles α.

and R_2 are the heights in the spherically symmetrical corona where the generated signal has the frequencies f_1 and f_2 correspondingly, v_{gr} is the group velocity of electromagnetic waves, and α is the angle between the direction of cloud propagation and the direction to the observer. We calculate the propagation time to the observer of the signal from each elementary cell corresponding to a given frequency f_i, and find the total flux of radio emission from all cells situated at the same R_i. The maximum of this electromagnetic signal at frequency f_i occurs at the moment t_i. Then the frequency drift rate of the Type III burst can be calculated as the ratio $(f_2 - f_1)/(t_2 - t_1)$. We numerically consider the cases when α ranges from 0° to 60°.

The description of the cloud as a set of elementary cells allows us to consider clouds of various shapes, sizes, and densities. To simulate the Type III bursts with fine structure, we assumed that the cloud consists of separate layers of different density perpendicular

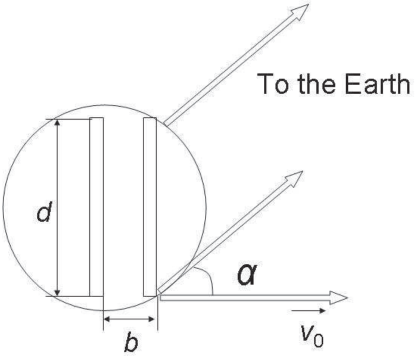

Figure 7: A spherical electron cloud of radius $0.5R_\odot$ *with internal structure in the form of a sequence of lunar layers.*

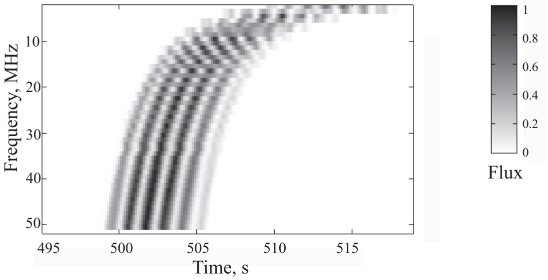

Figure 8: A dynamic spectrum of radio emission of electron cloud with internal structure.

to the velocity of the cloud (Fig.3).

3 Results

In the numerical calculations we take into account that the group velocity is a function of two variables (see also Ledenev [2000] and Li et al. [2008]), the point of generation R and the current coordinate r:

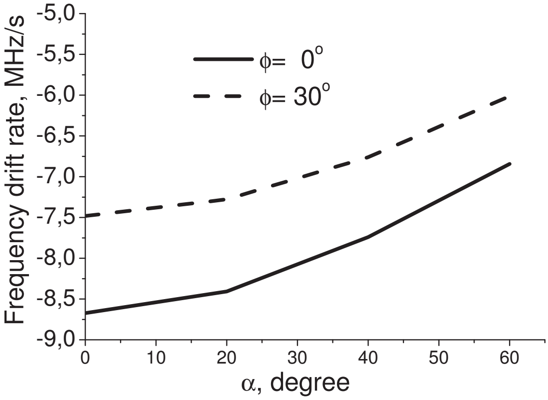

Figure 9: Calculated frequency drift rate for an expanding electron cloud with different widen angle $\phi = 0°$, $30°$.

$$v_{gr}(R,r) = c\sqrt{1 - \frac{\omega_{pe}^2(r)}{\omega_{pe}^2(R)(1 + 3v_{Te}^2/v_0^2)}} \tag{1}$$

where $\omega_{pe}(r)$ is the plasma frequency, which depends on the density of the plasma at point r, v_0 is the cloud velocity, $v_{Te} = 4 \cdot 10^8 cm/s$ is the thermal velocity of the coronal electrons. Having considered the profiles for a set of frequencies, we have calculated the dynamic spectrum of Type III bursts (Fig.4). We found that the duration of the burst depends on the size of the electron cloud responsible for the burst. For example, the calculated durations are $2.8s$ and $8s$ for electron cloud size of $0.2R_\odot$ and $0.5R_\odot$ ($R_\odot$ is the solar radius) correspondingly. In the frame of this model we also calculate the dependence of the frequency drift rate versus the propagation angle α for different velocities of the electron cloud (Fig.5). At decametre wavelengths, the frequency drift rates of Type III-like burst is more than 5 MHz/s [Melnik et al., 2008]. One can see that for the cloud velocity above $0.6 \cdot 10^{10} cm/s$ the calculated drift rate corresponds to that of the fast Type III bursts. Moreover, the drift rate decreases with the angle α that is also in agreement with observations. The numerical results agree well with the analytical equation at $\alpha = 0°$ for the frequency drift rate of the point-size cloud. The frequency drift rate can be calculated analytically as a limit of the ratio:

$$\frac{df}{dt} = \lim_{R_2 \to R_1} \frac{f_2(R_2) - f_1(R_1)}{t_2(R_2) - t_1(R_1)}. \tag{2}$$

Assuming that the beam velocity is a constant and the group velocity of generated radio emission is changing according to Equation (1) the time delay between signals radiated in the points R_1 and R_2 is given by:

$$t_1(R_1) - t_2(R_2) = \int_{R_1}^{Earth} \frac{dr}{v_{gr}(R_1,r)} - \frac{(R_2 - R_1)}{v_0} - \int_{R_2}^{Earth} \frac{dr}{v_{gr}(R_2,r)}. \tag{3}$$

Finally, the frequency drift rate at the frequency f_1 is calculated as the limit of the above ratio (2) at $R_2 \to R_1$, which can be calculated analytically and is equal to:

$$\left.\frac{df(R_1)}{dt}\right._{point} = \frac{\omega_{pe}}{4\pi}\frac{N'}{N}\left(\frac{1}{v_{gr}(R_1,R_1)} - \frac{1}{v_0} + \frac{Q \cdot R_1}{2c}\frac{N'}{N}\right)^{-1} \tag{4}$$

where N is plasma density, $N' = dN(R_1)/dR_1$; for given model of corona the coefficient Q is given by numerical integration of $(1/v_{gr}(R_1, r) - 1/v_{gr}(R_2, r))$ between R_2 and the Earth, and can be derived from Equation (3) in the limit $R_2 \to R_1$. For example, for Baumbach-Allen's corona $Q \approx 4.6$, and for Newkirk's corona $Q \approx 1.5$.

Figure 6 presents the calculated radio flux I of Type III bursts with fine structure generated by a cloud with variable density (Fig.3). One can see that for an angle above 40°, the fine structure disappears. Indeed in order to produce peak of intensity from two subsequent high density layers the dispersion of the signal propagation time from each layer must be less than the time interval between the peaks: $\sin\alpha \leq cb/v_0 d$, where b is the thickness of layers and d is the characteristic width of the high-density layers in the cloud (Fig.7). In our calculations we assumed $b/d = 1/6$, $v_0 = 0.3c$. It should be noted that the fine structure of Type III bursts is usually observed when the active region is located near the central solar meridian. Figure 8 shows the calculated dynamic spectrum of Type III bursts with fine structure, and Figure 9 shows the dependence of the frequency drift rate versus α in the case of a monotonically growing spherical cloud. Such clouds can be parameterized by the angle ϕ describing the increase of the cloud size ($\phi = 0°$ corresponds to a cloud of constant size). One can see that in the case of expanding cloud the dependence of frequency drift rate on the angle α is less pronounced than for a cloud of constant size.

4 Conclusion

Consideration of the propagation effects of electromagnetic waves explains large drift rates of Type III-like bursts. The presented numerical model gives the profile and the dynamic spectrum of Type III bursts. The existence of Type III bursts with fine time structure can be explained by an electron cloud of variable density. Bursts with fine structure can be observed if α is less than certain maximum angle associated with the relative dimensions of the cloud and the inhomogeneities in it. The results presented here allow us to solve an inverse problem of determining the cloud parameters and the solar plasma characteristics from observational data. For example we derive that the usual Type III bursts are initiated by the electron clouds with the velocity $6 \cdot 10^9 cm/s$, while the Type III-like bursts require the velocity $10^{10} cm/s$. We note that the frequency drift rates of Type III bursts decrease with increasing angle α in agreement with observations.

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