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A Scattering Hypothesis for Type V Solar Radio Bursts

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The purpose of this paper is to advance an alternative hypothesis for the underlying distinction between solar radio bursts of spectral type V and 'inverted U' bursts, and to explore its implications.

It is widely accepted that type V bursts and U-bursts, like type III bursts, involve plasma radiation from the Langmuir waves generated by a stream of electrons. However, unlike the streams which generate type III bursts, the streams associated with type V bursts and U-bursts propagate into closed magnetic loop structures (Weiss and Stewart 1965). Weiss and Stewart advanced the following hypothesis for the distinction between type V burst and U-bursts, and their suggestion was explored further by Zheleznyakov and Zaitsev (1968). The distinction involves the injection conditions: injection which occurs over a large area and a long time, leading to electrons trapped in the loop, results in type V emission, while injection over a small area and a short time leading to a bunch of electrons which propagates just once around the loop encountering no mirror point results in a U-burst. This hypothesis has; several unsatisfactory features, the most notable of which is an apparent inconsistency concerning the supposed existence of a mirror point near the injection point for type V bursts. This difficulty was avoided by Zheleznyakov and Zaitsev only through the artificial assumption that injection occurs at the top of the loop structure! It is desirable to explore alternatives to the suggestion that type V bursts result from bunches of electrons trapped in a magnetic loop structure and bouncing back and forth between two mirror points.

The alternative hypothesis explored here is that ***the streams which generate type V bursts experience efficient scattering*** (the 'scattering hypothesis'). The relevant scattering is resonant scattering by whistlers. With the scattering hypothesis one would hope to account for the distinction between type V bursts and U-bursts in terms of whether or not the conditions for such scattering to be effective are satisfied. Also one might account for the observed life times of type V bursts in terms of the time for the energetic electrons to diffuse out of the region where the whistlers are excited.

Scattering by Whistlers

Resonant scattering of energetic electrons by whistlers is known to be important in the Van Allen belts of the Earth (Dungey 1963; Cornwall 1964; Kennel and Petschek 1966). However, some care is required in applying the ideas developed in that connection to the solar corona.

The resonant interaction has the following properties. Firstly, ***a sufficiently anisotropic distribution of electrons can be unstable to the generation of whistlers.*** The relevant anisotropy either must be a 'positive' one in the sense that the distribution function is an increasing function of sin α (α = pitch angle), or it must involve a streaming motion, with speed $\beta_s c$ say, which satisfies

$$\beta_s > \Omega_e/\omega_p \tag{1}$$

(Ω_e = electron gyrofrequency, ω_p = plasma frequency). Secondly, whistlers which either are generated by the electrons themselves or are present from some other source, can scatter the electrons in pitch angle thereby reducing their anisotropy but having little effect on their energy.

In the magnetosphere the distribution of trapped electrons is anisotropic due to the presence of a 'loss cone'. (This corresponds to a positive anisotropy). In this case the predominant build-up in the whistlers occurs near the magnetic equator, and the trapped electrons experience enhanced scattering every time they cross the magnetic equator. It is thought that a quasi-equilibrium results with the loss of electrons due to their diffusion into the 'loss cone' being balanced by some external source of energetic electrons (Kennel and Petschek 1966).

Scattering and Type V Bursts

At first sight the following picture of the scattering of the electron streams involved in type V bursts might seem reasonable. The streaming speed satisfies (1) so that the stream generates whistlers. It can be shown, e.g. by applying the approach used by Melrose (1973) to whistlers, that the maximum e-folding growth rate of the whistlers is

$$\gamma \approx \frac{n_s}{n_e}\,\Omega_e\ , \tag{2}$$

where n_s and n_e are the number densities of electrons in the stream and in the ambient plasma respectively. Granted that around thirty e-folding growth times is required for the whistlers to build up to a level where the scattering becomes effective in randomizing the streaming motion, it follows that scattering would be effective for

$$\frac{\gamma L_s}{\beta_s c} \gtrsim 30, \tag{3}$$

where L_s is the length of the stream. Thus one might conclude that the stream produces a type V burst if inequality (3) becomes satisfied anywhere along its path, and produces a U-burst otherwise.

However, there are two major objections to this picture. First, in order for the type V burst to form at a height well above that where the electrons are injected into the magnetic loop, the left hand side of (3) should be an increasing function of height. Now because the stream is guided by the magnetic field one expects $n_s L_s$, which is inversely proportional to the cross-sectional area of the stream, to vary with height such that it remains proportional to the ambient magnetic field strength. Hence the lefthand side of (3) should vary with height as $(\Omega_e/\omega_p)^2$ which is proportional to the square of the Alfvén speed. It is implausible that $(\Omega_e/\omega_p)^2$ should increase with increasing height in the neighbourhood of a closed magnetic loop structure. Consequently the lefthand side of (3) would be expected to decrease with increasing height.

The second objection is that the growth rate for Langmuir waves should exceed that for whistlers. The growth rate for Langmuir waves is

$$\gamma \approx \frac{n_s}{n_e}\,\omega_p \left(\frac{\beta_s}{\Delta\beta_s}\right)^2 , \qquad (4)$$

where $\Delta\beta_s$ c is the velocity spread of the stream. Even for $\Delta\beta_s \approx \beta_s$ the growth rate (4) exceeds the growth rate (3) (except for $\Omega_e > \omega_p$ which, besides being unacceptable on observational grounds, is incompatible with (1)). Unlike the generation of whistlers, the generation of the Langmuir waves results in a substantial energy loss by the electrons (Shapiro 1963). Thus the stream would be destroyed as a result of the growth of Langmuir waves on a shorter time scale than that associated with the growth of the whistlers.

It would be reasonable to conclude that whistlers cannot be generated effectively by the streams of electrons. If the scattering hypothesis is to be maintained, then the whistlers must be pre-excited in the magnetic loop structure.

Implications of the Scattering Hypothesis

The only plausible source for pre-excited whistlers is a pre-existing anisotropic distribution of energetic electrons. (Under extreme circumstances, specifically for $\Omega_e/\omega_p <$ 4/43, the resonant waves can be hydromagnetic waves which could be generated by an anisotropic distribution of energetic ions). Consequently, the distinction between type V bursts and U-bursts is to be attributed to the pre-existing conditions along the path of the stream. The implications of this include the following.

(a) Type V bursts should be preceded by some activity which involves energetic particles. (The required distribution of trapped electrons could arise only from preceding activity). No such requirement applies for U-bursts.

(b) Either type V bursts and U-bursts should not be seen in association, or, if any association is found, then the U-burst should precede the type V bursts. (In the latter case the U-bursts could be part of the 'preceding activity' referred to under (a)).

(c) The brightness temperatures of type V bursts, assuming second harmonic plasma emission, should be consistent with there being no coherent emission of the Langmuir waves by the fast electrons. For example, for an isotropic distribution of electrons with speeds less than $\beta_0 c$ with $\beta_0 = 1/3$ this would restrict the brightness temperature to 10^9 K, but higher brightness temperatures could be obtained when streaming motions (at less than the thermal speed of electrons) and/or a gap in the energy distribution are taken into account, see e.g. the discussion in section 3(ii) of Tidman and Dupree (1965) and section II(c) of Melrose (1970).

(d) If the lifetime of type V bursts is determined by diffusion of the energetic electrons out of the region where whistlers are excited, then the scattering rate ν derived from the inferred spatial diffusion coefficient D should be compatible with the scattering rate required to maintain the pre-existing distribution of electrons in an equilibrium state. Unfortunately, the latter scattering rate depends on the assumed details and so cannot be inferred in a simple way. On the other hand, for example, if a type V burst lasts 10^2s and the electrons with speed $\beta c = 10^{10}$ cm s^{-1} diffuse over 3 x 10^{10} cm in this time, then one infers D $\approx$ (3 x $10^{10})^2/$ 10^2 cm^2 s^{-1} and $\nu \approx (\beta c)^2/D \approx 10\ s^{-1}$. This value seems reasonable.

Discussion and Conclusions

The conclusions of this paper can be summarized as follows. The existing suggestion for the distinction between type V bursts and U-bursts is unsatisfactory and, as formulated, seems to be internally inconsistent. An alternative suggestion is that electron streams injected into a magnetic loop give rise to type V bursts if the streaming electrons are effectively scattered whilst U-bursts result otherwise. This alternative appears to require that for scattering to be effective whistlers be generated by a pre-existing distribution of trapped electrons.

The only published systematic study of type V bursts is that by Weiss and Stewart (1965). As yet incomplete analysis of unpublished data (Labrum, private communication) suggests that there is an exclusive anti-correlation between the observation of type V bursts and of U-bursts, and that the maximum brightness temperature of type V bursts is several times 10^{10} K. These tentative conclusions offer some support for the scattering hypothesis, although the observed maximum brightness temperatures could be regarded as uncomfortably high.

Type V bursts remain poorly understood.

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