

ACCELERATION THROUGH X-TYPE COALESCENCE IN A SMALL ENERGETIC FLARE

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Abstract

We studied the acceleration conditions in the small but fairly energetic flare of May 21, 1984 at 13 : 26 UT. The most pronounced aspect of this flare was a series of 13 microwave / x-ray spikes, each lasting for about 0.1 s. A previous study has shown that each of these was due to a series of successive sudden formations of small plasma knots of high energy particles. Each of these knots lost its energy in about 50 ms. In the present study we show that these knots can originate by the process of x-type (3-D) flux tube coalescence. The predicted rise time (30 to 50 ms) and energy are in good agreement with the observationally derived parameters.

1. Introduction

On May 21, 1984 at 13 : 25 UT a solar flare was observed in microwave and hard x-rays, which was in many respects remarkable (Kaufmann et al., 1985). An interesting aspect of the flare was its short duration (only one minute in x-and radio-waves) but most remarkable was one of its flare burst which lasted for about three seconds. At millimeter waves (90 GHz) this short burst was the strongest burst of the flare. In x-rays it emitted at higher energies than the other bursts of the flare complex, with a noticeable radiation component above 100 keV. Its most interesting aspect was that at 90 GHz the burst consisted of about 13 short-lived spikes, each with a lifetime of about 0.1 s. The spikes were about symmetrical in their time profiles, having rise-and decay-times of about 60 ms.

Several explanations have been proposed for this high-energy component of the flare (Kaufmann et al., 1985,1986; De Jager et al., 1987) . In the latter paper it was shown that each of the 100 ms spikes could be explained by the following emission model : The individual spikes, both in microwaves and in hard x-rays were produced by the same electron population: the x-rays by their bremsstrahlung, and the microwaves by their gyrosynchrotron emission. The emission sources were small, with a characteristic size of about 350 km. They had an electron density of about 10^{11} cm^{-3} , a 'temperature' of $5 \times 10^8 \text{ K}$ and a magnetic field of about 1400-2000 G. Energy

injection should have occurred in less than about 50 ms (as judged from the rise times of the spikes). It could be shown that plasma knots with the character described above should lose their energy by saturated convective flux (collisionless conduction) in about 30 ms, a time which is in good agreement with the observed decay times of the spikes (60 ms). The fact that 13 spikes were observed in a rapid succession then leads automatically to the conclusion that this was due to the successive formation of 13 plasma knots as described above. These successive energizations could occur by successive interaction between many small flux tubes ('flux threads') which are assumed to occur in the flaring region and which interact, a process that may occur by external forces acting on and deforming the system of flux threads. Since the thermal energy of the flare knots was about 10^{26} erg, this must be the amount of energy released in each of the flux-thread interactions.

Hence, the emission mechanism of the bursts can be understood. The problem remains how the bursts originated. It will be shown in this Letter that this aspect can be explained by the mechanism of x-type (3-D dimensional) flux tube coalescence, a mechanism presently being studied by one of the authors (Sakai and de Jager, 1990.). We note here that the mechanism of flux-tube coalescence has been described and studied earlier (see review by Sakai and Ohsawa, 1987), but so far only for the one- and two-dimensional cases. In the present (x-type) case we are dealing with two crossed flux-tubes, interacting in one point, a fundamentally new process as compared to the 1-D and 2-D cases.

2. Energetics; conditions suitable for coalescence

A spherical region with a diameter of 350 km and a magnetic field B of 1400 to 2000 G would contain a magnetic energy $B^2 V/8\pi$, being about 2 to 4×10^{27} erg. The thermal energy content of that volume, assuming an electron density $n_e = 10^{11}$ and temperature $T = 5 \times 10^8$ K, is 1.5×10^{26} erg. Hence the magnetic energy of the region is sufficient to provide the energy of the flare spikes.

In order to know if the conditions in the flaring area are suitable for explosive coalescence one has to know the value of $\beta = (c_s/v_A)^2$. Here, c_s is the sound velocity and v_A the Alfvén velocity. The value of v_A has to be calculated using the magnetic field produced by the loop current (and not the ambient field.). With again $n_e = 10^{11} \text{ cm}^{-3}$ and taking $B = 1500$ G and $T = 5 \times 10^8$ K we find $v_A = 2000 \text{ km s}^{-1}$ and $c_s = 20000 \text{ km s}^{-1}$. Hence the value of β after coalescence is $\beta = 0.01$, with some uncertainty: v_A is proportional to B^{-2} and to T . It seems safe to assume $\beta \ll 1$ (after the coalescence). This is a condition that would be suitable for explosive coalescence if it would apply to the pre-coalescence situation. For large values of β , close to unity, our numerical calculations show that the coalescence would not be explosive in character.

3. X-type coalescence applied to the 21 May 1984 bursts

The β value given above (0.01) is the value that occurs after the explosion, but for a study

of the coalescence process we are interested in the value before the start of the coalescence. These β values may be larger than 0.01. Detailed numerical calculations are so far only available for the case $\beta=0.5$. To start with, we will work with this value. Below we will find it to be a good approximation. The calculations show that after coalescence the particle density has increased by a factor 10 and the field strength B (produced by the current loop) by a factor 100. The field strength B along the loop would increase by a factor 10. That means that the pre-coalescence value of v_A should in that case have been about 300 km s^{-1} . Assuming a coronal temperature of 10^2 eV before the coalescence, one would have $c_s=100 \text{ km s}^{-1}$. Hence the initial (pre-coalescence) value of β would have been 0.1, which is not too far from our tentative value $\beta=0.5$.

In such conditions the Alfvén transit time over an area of 350 km would be about 1 second. Numerical calculations, given in Figures 1 and 2, show that the duration of the coalescent explosion is of the order of 0.03 to 0.05 Alfvén transit times. Since the latter is about 15, the explosion should have lasted for 30 to 50 ms, as was indeed observed.

The numerical calculations also show that for $\beta=0.5$ the maximum explosion velocity is about $200 v_A$, which is about 60000 km s^{-1} . This corresponds with an electron energy still below 100 keV ; but if the initial β value would have been 0.1 (the more likely case) then the explosion velocity would have been $c/3$, yielding electron energies above 100 keV , as observed. We note that, as stated above, $\beta=0.1$ is indeed the most probable pre-coalescence value.

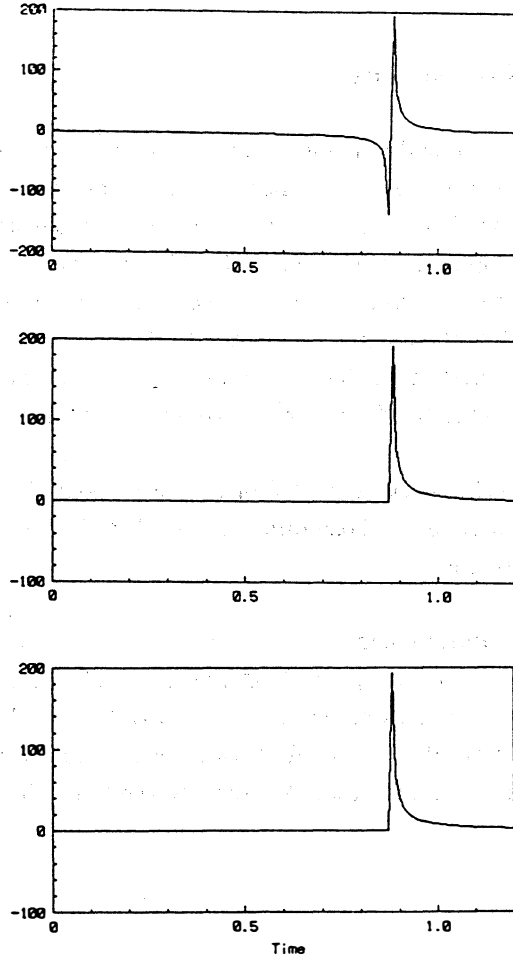


Fig. 1 Velocities in X-type (3-D) coalescence, calculated for the case $\beta=0.5$. The three diagrams show the velocities in the 3 cartesian coordinates. The upper diagram gives the velocity component in the direction of coalescence; the two others in directions perpendicular to it. Horizontal axis: time in units of the Alfvén transit time; Vertical axis: velocities in units of the Alfvén velocity.

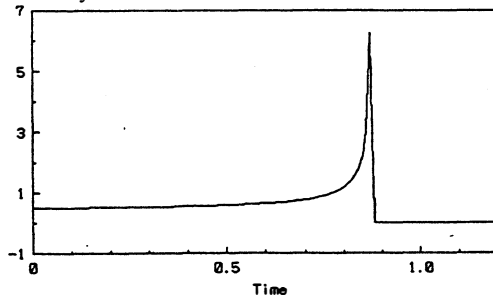


Fig. 2 Density in X-type coalescence. horizontal axis: time in units of the Alfvén transit time; vertical axis: density in arbitrary units. The initial density is 0.5 units.

4. Conclusions

We found that the conditions in the area producing the remarkable flare bursts of 21 May 1984 were indeed such that the many flare spikes could have been due to explosive coalescence. The pre-flare conditions were an electron density of 10^{10} cm^{-3} and a magnetic field produced by the loop current of about 15 G. The magnetic field along the loop must have been 150 G. This is so because in the case $\beta=0.5$ coalescence causes the field along the loop to increase by a factor 10 while the magnetic field due to the loop current increases by a factor 100. It seems furthermore likely that the interacting flux threads must have had diameters of the order of 350 km, other wise the flare kernels would have been larger in size.

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