CORONAL EXPLOSIONS AS A SIGNATURE OF CURRENT LOOP COALESCENCE IN SOLAR FLARES

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Abstract

The coronal explosion, discovered by De Jager and Boelee (1984), and interpreted by them as manifestations of plasma streaming out of the flare kernels, can also be interpreted as signatures of current loop coalesscence in the flaring region.

1. Characteristics of coronal explosions

The phenomenon called 'coronal explosion' was discovered by De Jager and Boelee (1984) and was explained by them as manifestations of plasma streaming out of the flare kernel(s) (Lemmens and De Jager, 1986: De Jager, 1987). They are aspects of the impulsive phase explosions in solar flares. The main characteristics of the coronal explosions are summarized as follows:

1. These explosive processes occur during and immediately after the onset of the impulsive phese of flares. They occur only concurrent with the 'chromospheric explosions' and together they form the 'impulsive phase explosion'.
2. They are observable in soft X-ray images of flares: these show that during and immediately after the impulsive phase of solar flares soft X-ray emitting plasma streams out of one or both of the flare footpoints.
3. The projected average velocity of the outstreaming plasma is about 100 kms^{-1}. This outstreaming motion continues for a few minutes after the start of the flare until soon after the end of the impulsive phase.
4. The velocity generally decreases with time as the hot plasma gradually spreads over a large area around the flare footpoints.
5. There is evidence that streaming occurs into and in a number of fluxtubes which extend over a large area. This supports the 'spaghetti-bundle model' for the flaring region.

The first interpretation of the coronal explosions was that they result from chromospheric evaporation of plasma (Brown, 1973, Fisher et al. 1984, 1985, De Jager, 1986), heated impulsively by the sudden impact of beams of energetic electrons. The impulsive hard X-ray bursts result from these impacts.

In the present paper we forward a new interpretation of the coronal explosions, which appears to be able to quantitatively explain the various characteristics, mentioned above. It is particularly also based on the 5th of these characteristics: that the flaring region contains many current loops.

The current loop coalesscence model (see for a review: Sakai and Ohsawa, 1987) provides keys to the understanding of many of the charteristics of solar flares, such as their impulsive nature, simultaneous heating and high-energy particle acceleration. Recently it was show (Sakai, 1989, 1990: Sakai and De Jager, 1989) that the current loop coalescence processes may have different signatures, depending on the geometry of the region containing the two interacting current loops. When the magnetic field B_t (potential field) produced by a sunspot is strong as compared with the magnetic field B_p due to the current loop, the process of coalescence will lead to plasma rotation around the point of reconnection. After the coalescence of the two current loops, the resulting single current loop can still continue to rotate. This motion can drive plasma jets out of the current loop coalescence region (Sakai, 1990).

In section 2 we present some results from the above current loop coalescence model, applied to one particular well-observed flare (21 May 1980: De Jager and Svestka, 1985), and we compare them with the charracteristics (1) to (5) of the coronal explosions. In section 3 we discuss the origin of shocks during the current loop coalescence and we compare these results with the type II radio burst observed during the onset of the flare. We summerize our conclusions in section 4.

2. Plasma jet formaion during current loop coalescence

As shown by Sakai (1989) two plasma jets can explosively be driven out of the region of coalescence. They thereupon move into two opposite directions (Figure 1). Most likely, in the footpoint regions the potential magnetic field B_t is stronger than the current-associated magnetic field B_p. We assume, for the case of Figure 1, that a primary electron beam, accelerated somewhere in the flux-tube,

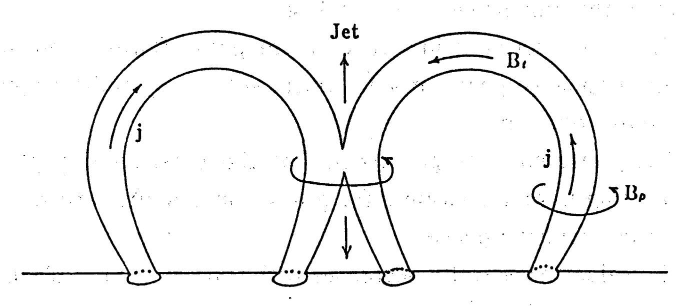

Fig. 1 A schematic picture of current loop coalescence. The plasma current (j) which produces a magnetic field (B_p) flows along the potential magnetic friend (B_t) when $B_t > B_p$ plasma jets flow explosively out of the region of coalescence. The upward directed jet may flow along the current loops.

streams downward along the tube. This has two effects: the electron current increases, and by electron bombardment of lower regions hard X-ray bursts are emitted from the footpoints. As a consequence current loop coalescence may be triggered near the flaring footpoints, where $B_t > B_p$.

The velocity of the plasma jet produced by the rotational motion of the plasma during the coalescence process depends strongly on the β ratio: $\beta = (c_s/v_A)^2$ where c_s is the velocity of sound and v_A the Alfven velocity. A typical example of the time evolution of the jet-velocity is show in Figure 2, for the case $\beta = 0.01$.

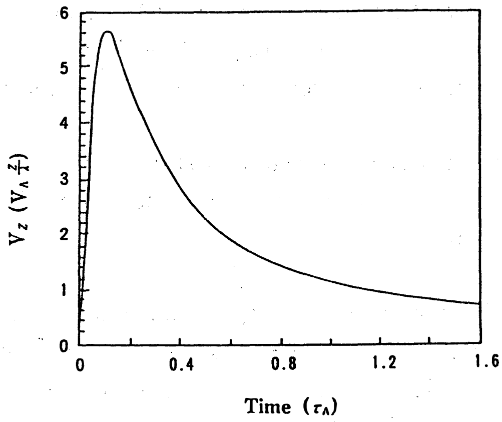

Fig. 2 Time evolution of a plasma jet flow along the loop (z-direction). The time is normalized with respect to the Alfven transit time $\tau_A = \lambda / v_A$.

Table 1 Maximum jet flow velocity and acceleration time for various plasma β ratios.

β	$V_{z,max}(V_A \frac{z}{\lambda})$	Acceleration Time (τ_A)
10^{-4}	0.68	0.97
10^{-3}	1.77	0.38
10^{-2}	5.64	0.11

When β decreases to values much below 0.01 the maximum jet velocity becomes less that the Alfven velocity as shown in Table 1, and the acceleration time to maximum velocity increases. In the β-region between 0.01 to 0.001 the time during which the velocity exceeds the Alfven velocity is a few Alfven transit times (τ_A) where $\tau_A = \lambda / v_A$. Here λ is the characteristjc length of the loop.

From the results described above we derive the physical parameters applicable to the coronal explosion. Assuming the observtional avarage values (De Jager 1987) we take $n_e = 8 \times 10^{10} cm^{-3}$ and $\lambda = A^{-0.5} = 2 \times 10^9 cm$, where A is the flare area, $4 \times 10^{18} cm^2$

If we take for the potential magnetic field the conventional value $B_t = 100G$ (Loran and Brown, 1985) we find $v_A = 700 km\ s^{-1}$ and $\tau_A = \lambda / v_A = 28s$. Taking $T = 10^6 K$ for the plasma temperature near the coalescence region, we obtain for the sound velocity $c_s = 10^7 cm\ s^{-1}$. From these v_A and c_s values we find $\beta = 0.02$. Had we chosen $T = 10^4$K (in case the region of interaction is chromospheric) we would have found $\beta = 2 \times 10^{-4}$. Therefore the β ratio near the flare footpoint kernel region is of order 0.01 to 0.0001.

If we define the characteristic life time of the jets as the time during which the jet velocity exceeds v_A a typical life time of the jets would be a few Alfven transit times, corresponding to a few minutes.

The maximum jet velocity appears to be in the range 500 km s^{-1} (for $\beta = 10^{-4}$) to 4000 km s^{-1} ($\beta = 10^{-2}$). This value is larger than the communicated coronal explosion velocities, because the latter do not correspond to the front of the outstreaming plasma. This front may be invisible anyway, because the smallness of the number of particles involved. For that reason the isochrones of the coronal explosions have been defined as the locations where the maximum X-ray intensity was observed. This reflects an average velocity, not the maximum value. Therefore, the actual outstreaming velocity will be higher than the observed isochronic velocity. We conclude that the physical quantities like the jet velocity and the life time of the jet are in fair agreement with the observational values, as described in characteristics (3) and (4) of the coronal explosion.

In the 21 May 1980 flare (De Jager and Svestka, 1985) the coronal explosions originated in two footpoints, one corresponding with the location of the strong hard X-ray source and the other with a weaker hard X-ray footpoint. This observation may reflect aspect (5) of the coronal explosions.

We therefore conclude that the coronal explosion of the flare of 21 May 1980 can be interpreted as a manifastation of current loop coalescence near the flare footpoint region.

3. Shock formation and type II burst

As noted in their review (De Jager and Svestka, 1985) a type II radio burst was observed at Culgoora starting at a time close to the onset of the coronal explosion of the 21 May 1980 flare. This type II burst can be due to the shock that originated from the super-Alfenic plasma jet flow as well as from the rebound plasma flow near the coalescence region (Sakai, 1989). When the plasma B value descreases to values below about 10^{-3} the jet velocity decreases to below the Alfven velocity. Therefore shock generation during current loop coalescence may not be violent enough to produce type II bursts.

4. Conclusions

We studied the coronal explosions, discovered by De Jager and Boelee (1984) and interpreted by them as manifestion of plasma streaming out of the flare kernels. From a study of one of them (the flare of May 21, 1980) we found that the explosion can be interpreted as well as a signature of current loop coalescence in the flaring region. The new interpretation can quantitatively explain the various characteristics of the observed coronal explosions. The forthcoming Solar-A mission which will contain a soft X-ray imaging instrument and which will be launched during the next solar maximum, may prove to be an exellent instrument to check the above model.

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