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THE GENERATION OF PROTON BEAMS IN TWO-RIBBON FLARES

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ABSTRACT

It is shown that in the current sheet at the top of the arcade of postflare loops in a two-ribbon flare, particle beams are generated by direct electric field acceleration. The acceleration process is *completely collisionless* and is limited only by the gyromotion along the component of the magnetic field *perpendicular* to the sheet. This mechanism is similar to the particle acceleration in the geomagnetic tail.

Neutral beams emanate from the sheet with almost zero pitch angle, making *protons* the main carriers of the beam energy. Approximately 10^{35} protons s^{-1} are generated with a typical energy of 200 keV. Their energy distribution is a single power law, with an upper and lower energy cut-off. Such a population is capable of simultaneously generating the observed impulsive phase hard X-rays and the γ-rays.

Subject headings: particle acceleration — Sun: flares

I. INTRODUCTION

Models for two-ribbon flares have frequently emphasized the intimate connection between the filament eruption and the flare itself (Van Tend and Kuperus 1978; Pneumann 1980; Kaastra 1985; Kuin and Martens 1986; Moore 1988). This is underscored by the observations that the kinetic energy of the erupted filament is roughly equal to the radiative flare energy (10^{32-33} ergs). The ultimate energy source for both is generally believed to be the magnetic field existent prior to the flare onset. The conversion of free magnetic energy into particle kinetic energy probably takes place in current sheets. The energetic particles then generate the radiative flare products upon impact on the chromosphere (see Canfield 1986 for a recent review). Open questions in this scenario are the location of, and the exact energy conversion mechanism in, the current sheet, and the mechanism of the generation of the hard X-rays (see Dennis 1985).

The magnetic configuration of two-ribbon flares is described in Kaastra (1985) and Martens and Kuin (1987) and can be retraced to Carmichael (1964). Observational evidence and basic models for the field configuration have been presented by Dennis (1985, Fig. 17) and Cliver *et al.* (1986, Fig. 10).

Kaastra (1985) has shown that a filament current embedded in a potential background field leads to the origin of an *X*-type neutral line below the filament, where a current sheet may be formed (Syrovatskii 1971). The evolution calculations of Martens and Kuin (1987) demonstrate that as a result of the filament eruption a large current is generated in the sheet.

This current sheet is subject of the present *Letter*. Here the bulk of the magnetic energy conversion and particle acceleration take place. Particle acceleration in a current sheet at about 10,000 km has recently been demonstrated by Takakura *et al.* (1986) from *Hinotori* observations of a limb flare. The main questions addressed in this *Letter* are how many particles, and of what energy are produced, and what is their spatial distribution?

II. THE PHYSICAL PARAMETERS OF THE CURRENT SHEET

For the 1981 May 16 flare, modeled in Martens and Kuin (1987), the length of the current sheet is roughly equal to that of the filament, $L = 1.2 \times 10^{10}$ cm. In the simulations the width (vertical extent) of the sheet during the impulsive phase of the flare is found to be $2b = 8 \times 10^8$ cm and the sheet electric field peaks at 2 V cm^{-1}. Observational indications for these electric fields come from Kopp and Poletto (1986) and Foukal, Little, and Gilliam (1987). Kopp and Poletto calculate an electric field of 1–10 V cm^{-1} from the observed lateral velocity of the Hα-ribbons and the photospheric line-of-sight magnetic field. Their result is basically the motional field of a rising coronal current sheet: with a magnetic field of 100 G and a velocity of 20 km s^{-1} one finds indeed an electrical field of 2 V cm^{-1}. Foukal *et al.* find an upper limit to the electric field of 5–10 V cm^{-1} for two erupting prominences by analyzing the Stark broadening of the Paschen emission lines. (However, it is not *a priori* clear whether this restricts the sheet electric field.) Note that 2 V cm^{-1} is four orders of magnitude larger than the Dreicer field, so the entire electron and proton population will be accelerated. It has been known for over 20 years from *in situ* spacecraft observations that in the current sheet of the geomagnetic tail the electric field strength is eight orders of magnitude larger than the Dreicer field (see Lyons and Williams 1984 for the relevant parameters). This shows that the usual theoretical arguments for supposing that the electric field in a plasma cannot exceed the Dreicer field do not hold in nearly collisionless space plasmas. It will be shown in the rest of this *Letter* that there is a strong similarity in this respect between the geomagnetic tail and the current sheet in solar flares.

The typical energy of the particles responsible for the hard X-rays in the case of thick target emission is about 30 keV (U_e) for electrons (Lin and Schwartz 1987), and $U_p = 200$ keV for protons (Simnett 1986). This leads directly to an estimate for the acceleration length (l) in the electric field,

$$l_{e,p} = \frac{U_{e,p}}{eE} = \begin{cases} 1.5 \times 10^4 \text{ cm for electrons} \\ 10^5 \text{ cm for protons} \end{cases} . \qquad (1)$$

These lengths are many orders of magnitude smaller than the mean free paths for both electrons and protons (λ_e and λ_p):

$$\lambda_{p,e} = [n_p \pi e^4 (\ln \Lambda)^2 / U_{p,e}{}^2]^{-1} \approx 10^{10-11} \text{ cm} , \qquad (2)$$

where n_p ($\sim 10^{10}$ cm^{-3}) is the proton density, and $\ln \Lambda$ (~ 20) the Coulomb logarithm. The consequence is that the acceleration mechanism in the sheet must be *completely collisionless*, even when the mean free paths are shorter by several orders of magnitude due to collective (anomalous) interactions. Therefore, one has to consider *individual* particle orbits in the sheet in order to find the acceleration lengths.

About 10^{35-36} s^{-1} electrons at 30 keV ($\dot{N}_{\rm out}$) are needed for the generation of the hard X-rays (Dennis 1985). Heristchi (1986) finds that with equal velocities protons generate about 1000 times ($\sim m_p/m_e$) more X-rays than electrons, so I assume equal conversion rates from beam to X-ray energy. Hence the number of beam protons is just $U_p/U_e \approx 7$ times smaller than that of electrons. There has to be a continuous particle inflow ($\dot{N}_{\rm in}$) to compensate the loss of accelerated particles. $\dot{N}_{\rm in}$ is calculated in equation (3), where v_d represents the plasma drift ($E \times B$) into the sheet ($v_d = 2 \times 10^6$ cm s^{-1} for a 100 G field):

$$\dot{N}_{\rm in} = 2 \times 2b \times L \times v_d \times n_{e,p} \approx 4 \times 10^{35}\ {\rm s}^{-1}\ . \qquad (3)$$

This number is just sufficient to cover the needed supply of electrons, and clearly sufficient for the protons.

Given the number of accelerated particles one can calculate the total current through the sheet:

$$I_{e,p} = \dot{N}_{\rm in} \times e \times (l_{e,p}/L) \approx 10^{20-21}\ {\rm statamp}\ . \qquad (4)$$

The factor $l_{e,p}/L$ represents the fact that at any cross section only the particles that entered the sheet within one acceleration length in front of the cross section contribute to the current; the other particles either already have left the sheet or enter behind the cross section.

Given the current, the component of the magnetic field that changes sign across the sheet follows from the integration of Ampere's law: $B_s = (\pi I)/(cb) \approx 20$ G for electrons, and 130 G for protons. This result resolves an important objection against the beam models raised by Hoyng (1977) and Spicer (1983). These authors calculate the electric current generated by the beam in a loop geometry and find the result of equation (4), without the factor l_e/L. Hence their current and magnetic field are five orders of magnitude larger than those in the present *Letter*, which is totally unacceptable for the solar corona. In the geometry of the present model, the particles are distributed over an arcade of loops. Hence the hard X-rays are expected to coincide with the flare ribbons. This has been confirmed by HXIS observations in many—but not all—cases (see Machado *et al.* 1988): the hard X-ray footpoints tend to form a patchy structure within the ribbons, coincident with the Hα preflare brightenings. This indicates that the sheet is not uniform along its length, but "torn up," as one would expect from stability considerations.

The final aspect of the sheet physics that I will discuss in this section is the net resistivity in the sheet. From the momentum equation for the electrons and protons the Spitzer collisional resistivity is easily derived:

$$\eta_e = \frac{m_e v_e}{n_p e^2 \lambda_e} \approx 1.2 \times 10^{-18}\ {\rm s}\ , \qquad (5)$$

where λ_e is the mean free path, given by equation (2). When the acceleration of a particle in the sheet is limited by other processes than collisions, the *effective* resistivity is found by replacing the mean free path by the acceleration length. The physical reason is that as a particle leaves the sheet, the momentum imparted on it during its acceleration is lost. Hence the effective *collisionless* resistivity for 200 keV protons is

$$\eta_{{\rm eff},p} = \frac{(2U_p m_p)^{1/2}}{n_p e^2 l_p} \approx 4.5 \times 10^{-12}\ {\rm s}\ , \qquad (6)$$

which is over six orders of magnitude larger than the standard Spitzer resistivity! For electrons of 30 keV the analogous result is $\eta_{{\rm eff},e} \approx 2.7 \times 10^{-13}$ s, five orders of magnitude larger than the classical value. This resolves the inconsistency between the macro physical sheet resistance (Kaastra 1985; Martens and Kuin 1987) and the microphysical resistivity in the sheet. With an energy conversion rate $P \approx 10^{29}$ ergs s^{-1}, required for the hard X-ray emission in the impulsive phase, and a current strength of 10^{21-22} statamp, leading to acceptable values of B_s, the sheet resistance is defined as $R_s = P/I^2 \approx 10^{-13}$ s cm^{-1}. The same result is obtained with Ohm's law, $R_s = V/I$, and $V = EL$.

Integration of the microphysical resistivity gives

$$R_s = \frac{\eta_{\rm eff} L}{4b\delta}\ , \qquad (7)$$

with δ the thickness of the sheet. With $\eta_{\rm eff}$ derived above, and the b and L known, one finds the value of δ that makes the microscopic and the macroscopic descriptions consistent. In the case of electron acceleration, a sheet thickness of about 17 cm is needed, and for protons the result is 340 cm. For comparison, the gyroradius for electrons before acceleration is 0.32 cm (with $T_e \approx 200$ eV), and for protons 13 cm. Note that with classical resistivity the sheet thickness would be orders of magnitude smaller than the gyroradii.

III. THE PARTICLE ACCELERATION MECHANISM

Completely collisionless current sheets of a thickness of several tens of proton gyroradii have been studied for 20 years as models for the geomagnetic tail. The initial calculations were done by Speiser (1965). The thickness of the geotail, derived from *in situ* spacecraft observations, is 0.1 Earth radii, equivalent to about 10 proton gyroradii. This is comparable to the thickness of 26 gyroradii for the solar current sheet of this *Letter*. Since the magnetic field changes significantly over one gyroradius, the guiding center theory is inadequate in the sheet, and the individual particle orbits have to be calculated.

Speiser (1965) assumes a very small perpendicular magnetic field component (B_p), which restricts the particle trajectories in the sheet to roughly one gyroradius of B_p (the relevant velocity being the average particle velocity in the sheet). Initially, as it is convected into the sheet, the particle undergoes its normal gyromotion. After entering the sheet the particle is accelerated by the electric field and starts oscillating around the midplane of the sheet, where the sense of rotation of the gyromotion changes sign. It further undergoes a gyration with large radius in the sheet plane, because of the small perpendicular magnetic field component. At the end of one such gyration the particle is ejected from the sheet. This complication motion is summarized by Lyons and Williams (1984, chap. 4).

When the initial energy of the particles is much less than their final energy, simple analytical expressions for the energy and acceleration length exist. In the solar case the initial energy depends on the coronal temperature, about 200 eV, much less indeed than the particle energies in the beams. Hence

$$U_{p,e}({\rm final}) \approx 2m_{p,e}c^2(E/B_p)^2\ , \qquad (8)$$

and

$$l_{p,e} \approx \frac{(2m_{p,e} U_{p,e})^{1/2} c}{eB_p}\ . \qquad (9)$$

From equation (8) it is clear that whatever the values of E and B_p, the proton energies are *always* a factor m_p/m_e larger than the electron energies! Hence for this type of acceleration process the protons *must* be the carriers of the bulk of the beam energy. Also, the protons and electrons have the same *final velocity* and therefore the beams leaving the sheet will be neutral. Finally the pitch angle of the beams from the sheet is very small according to Speiser [$\sim$arctan (B_p/B_s)].

A B_p of 0.5 G is sufficient to produce the proton energies around 200 keV and acceleration length of 10^5 cm required by observations. This is indeed only a very small fraction of the sheet magnetic field of 130 G. It is clear that any sheet model requires a perpendicular field component as a result of the reconnection in the sheet. A classical sheet structure (e.g., Petscheck 1964) would give a B_p that is maximal at the sheet edges and changes sign at the sheet axis. It is easily checked that such a field structure produces a power-law spectrum of protons with the power depending on the variation of B_p along the width of the sheet. There is an upper cut-off at the total voltage drop along the sheet (20 GeV) and a lower-cut off at the energy given by the maximum of B_p at the edges of the sheet (of the order of 100 keV).

At this point it is important to note the similarities between the geotail and the solar current sheet of this *Letter* with respect to particle acceleration. First, there is the aforementioned large ratio between the proton gyroradius and the sheet thickness from the onset of the acceleration in both models. After their acceleration to 200 keV in the solar current sheet, the gyroradius of the protons is about equal to the thickness of the sheet. The same is true for the 3–100 keV protons accelerated in the geotail.

Second, although for the solar current sheet the width is 10^6 times the thickness, and for the geotail this number is only about 10^2, in both cases the acceleration path of the protons is orders of magnitude smaller than the extension of the sheet, and thus for the purpose of calculating particle orbits the extension of the sheet is infinite in *both* cases, as was indeed assumed in Speiser's (1965) original calculations.

IV. DISCUSSION AND CONCLUSIONS

A current sheet with the gigantic dimensions proposed above, and with proton and electron velocities of the order of 6×10^8 cm s^{-1} (about equal to thermal electron speed), must be violently unstable. However, since the reconnection in the sheet is continuously driven by the eruption of the filament, the sheet will reform every time after disruption. The duration of the acceleration process is about $l_p/v_p \approx 10^{-4}$ s. One would expect strong variability in the hard X-rays down to that time scale.

The high-energy protons responsible for the formation of γ-line radiation can be accelerated directly in the electric field around the sheet axis, where B_p vanishes. The acceleration of a 100 MeV proton takes about 4×10^{-3} s, so the whole proton spectrum is produced instantaneously. In fact, one would expect the γ-line radiation peak *before* the corresponding hard X-ray peak, because it takes 100 MeV protons only about 0.1 s to travel toward the footpoints of the postflare loops, while 200 keV protons need about 1.5 s. Observations by Forrest *et al.* (1981) and Chupp *et al.* (1982) indeed show the necessity of instantaneous acceleration of high-energy protons in γ-ray flares.

Recent calculations by Heristchi (1986) have shown that a single power-law proton spectrum can produce the observed ratio between γ-ray and hard X-ray emission, alleviating a longstanding drawback of the proton beam model. The relative advantage of proton beams is that one does not have to invoke two separate mechanisms for producing the hard X-rays and the γ-rays. Further evidence for proton beams has been discussed by Simnett (1986).

In summary, then, the scenario of proton beams, generated by direct electric field acceleration in a collisionless current sheet above an arcade of postflare loops has the following very attractive properties:

1. The convection of plasma into the sheet continuously supplies the needed 4×10^{35} protons s^{-1}.
2. The sheet magnetic field (130 G) is acceptable despite the large number of accelerated protons.
3. Neutral particle beams are injected into the postflare loops with almost zero pitch angle.
4. The generation, timing, and spatial distribution of γ-rays, hard X-rays, can be explained from a single power-law proton spectrum, with a cut-off at 100 keV and 20 GeV.
5. The *effective* resistivity in the current sheet is over six orders of magnitude larger than the classical Spitzer resistivity. This makes the total sheet resistance derived from a macroscopic analysis consistent with the microscopic physics.

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