Can Reconnection Directly Produce the Requisite Electron Fluxes needed to Explain the Hard X-ray Bursts that Characterize Flares and CMEs?

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Minimal Constraints on Flare and CME Models

- Typical Constraints
  - Total energy released should be of order 10^{32} ergs
  - Time of energy release must be of order 10-1000s
- Additional Constraints should include
  - The magnetic energy density must be large enough for the instability to grow fast enough to heat the local plasma and keep it hot
  - If the non-thermal hard X-ray hypothesis is correct then the flare mechanism(s) must be able to accelerate $10^{35} - 10^{36}$ electrons/s to an average energy of 10-20keV on very short time scales and accomplish this throughout very large volumes

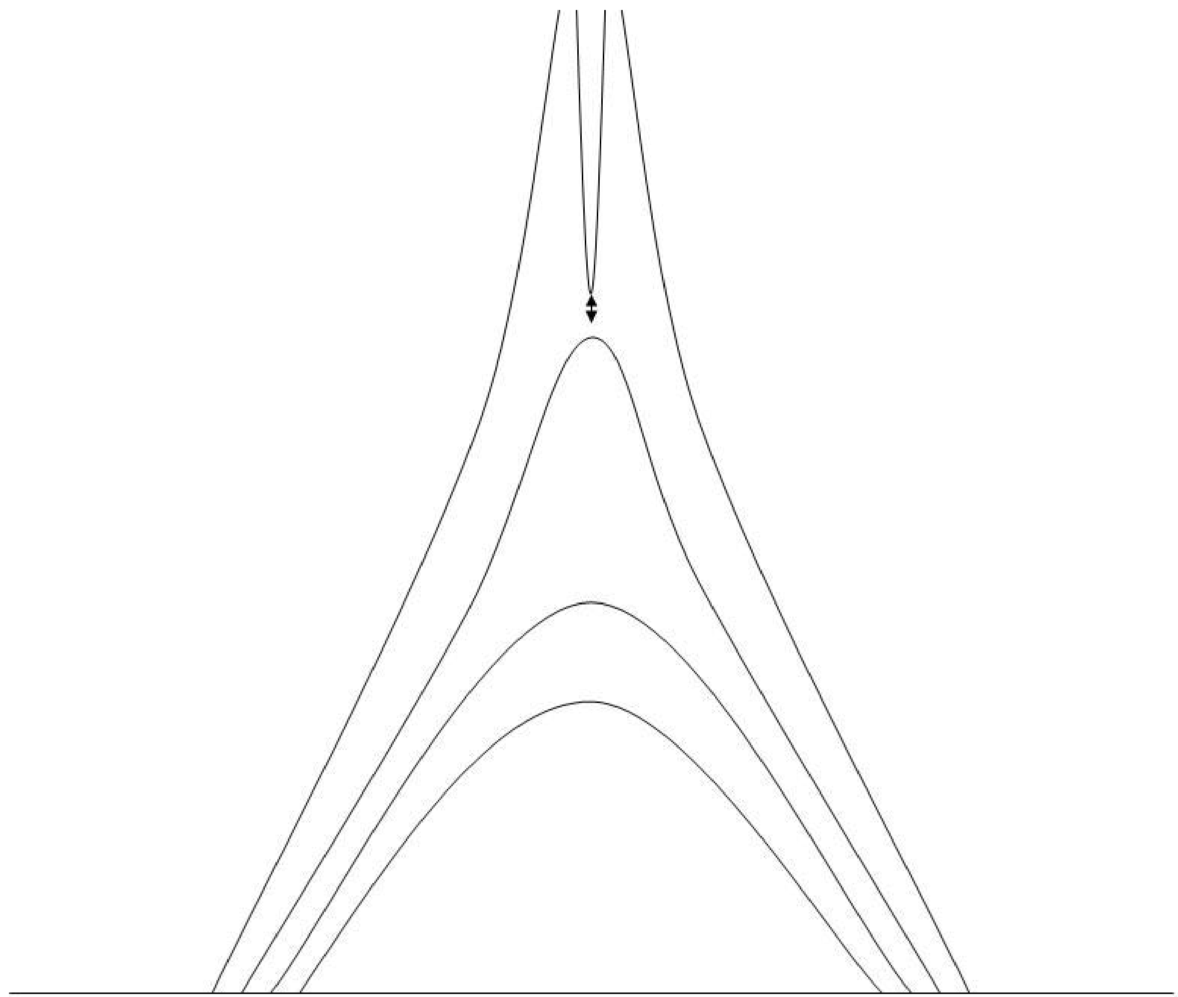
Implications of the Non-Thermal Hard X-Ray Hypothesis

- A large fraction of the total flare energy appears to be needed to generate the non-thermal electrons
- As the efficiency of the acceleration mechanism is unknown the total pre-flare free energy needed might be larger than often assumed

Kopp-Pneuman: Classical Model

- Uses a single current sheet
- “Variations on the KP theme” are widely used to explain CMEs, but not the only model out there.
- Can it satisfy all the constraints without embellishment? The answer is no.

K-P Geometry



Particle Acceleration in the Classical KP Model Occurs in the Current Sheet

- Assumptions of the KP Model
  - Reconnection of a current sheet formed by a simple reversal of the magnetic field
  - Within the sheet particle acceleration occurs due to the reconnecting electric field
  - Inflow speed U_{in} into current sheet
  - Outflow speed U_{out} □ V_{Ain}, where V_{Ain} is the Alfven speed of the magnetic field transported out of the current sheet
  - a/L<<1, where a is the width of the diffusion region and L is the diffusion region length.

Can Such a Current Sheet Accelerate the Needed Electrons?

- The maximum rate at which magnetic energy can be converted directly into heat, or accelerated particles, within the current layer by the reconnecting electric field is

$$\int E \cdot J\, d^3x \approx a \Delta \ell V_{Ain} \frac{B_{in}^2}{4\pi} \quad \text{ergs/s}$$

where we used the well known reconnection relations $a = \frac{\eta c^2}{4\pi U_{in}}$ and $U_{in} = U_{out} \frac{a}{L}$

Acceleration of Electrons will occur only when they become Unmagnetized

- This occurs only within a region $\delta x \approx V_{Te} / \Omega_{ce}$ since the ratio $U_{in} / V_{Te} << 1$
- Typically $\delta x / a << 1$ implying the available direct power input to accelerate electrons, as opposed to $E \times B$ drifts, is much smaller than required (10keVx10^{35} electrons/s)

Conclusions from Back of Envelope Calculation

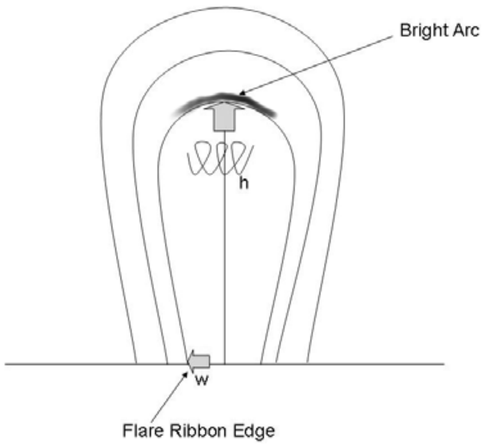
- A single current sheet reconnection model is incapable of accelerating the requisite electrons: Result Not New.
- Reconnection is only important for releasing Maxwell stresses and thereby generating large scale bulk mass motions: Result New

In Such a Model as the KP Model what can Accelerate the Requisite Particles?

- Snow Plow Driven Large Amplitude Current Systems
  - A snow plow acts like a “body” sweeping magnetic fields and plasma ahead of it producing gradients much larger than those found in shocks thereby producing large field aligned current systems
  - Kinetic effects due to snow plow much greater than from shocks
- Betatron Acceleration
  - Magnetic Flux loops “dipolarize” $T = \left(\frac{L_o}{L} \right)^2 T_o$

Snowplowing and Particle Acceleration

- Because a snowplow represents a “body” sweeping up the medium in front of it, the gradients across a snowplowed plasma/magnetic fields can be much greater than those typical of a shock.
- Features in CMEs such as the “bright arc” are a natural consequence of snow plowing and an excellent source region for high energy particles.
- Anticipated effects include inverse mirroring, lower hybrid wave acceleration, and the formation of a large scale counter-streaming current system with a net current that is initial zero.
- Because the snowplow continues to sweep up new undisturbed magnetic fields and plasma, as it moves out, the snowplow will continue setup new current systems and accelerate particles until the “plow” runs out of energy



$$W(t) = \tan(\theta)h(t) \approx \theta h(t)$$

$$\dot{W}(t) \approx \theta \dot{h}(t)$$

Formation of Field Aligned Current Systems

- In the ideal MHD approximation the current density is solenoidal.
- This relation tells us that field aligned currents result from a finite divergence of current perpendicular to the magnetic field.
- If we apply a bulk velocity field perpendicular to B and use Lenz's law we can estimate the number of electrons making up each equal and opposite flux of current

$$\nabla_{\parallel} \cdot \underline{J}_{\parallel} = B\frac{\partial}{\partial s}\left(\frac{J_{\parallel}}{B}\right) = -\nabla \cdot \underline{J}_{\perp}$$

$$\underline{J}_{\perp} = c\frac{\underline{B}\times\left(\nabla P + \rho \underline{g}\right)}{B^2} + c\underline{B}\times\left(\frac{\rho}{B^2}\frac{d\underline{V}}{dt}\right)$$

$$F_{e\parallel} \approx \frac{c\rho}{Be} a\Delta x\Delta z$$ electrons/s

where $$a \approx \frac{1}{\rho}\frac{\partial}{\partial r}\left(\frac{B^2}{8\pi}\right) \approx \frac{V_A^2}{R}$$

R Is the characteristic gradient length of the magnetic field

Or $$F_{e\parallel} \approx \frac{cB}{4\pi|e|}\frac{\Delta x\Delta z}{R}$$

Conclusions

- K-P like models should evolve as follows:
  - Reconnection
  - Generate bulk mass flows
  - Particle acceleration
- Other model types need to demonstrate that the heating/acceleration mechanism utilized must actually work as advertised

Alfvén Waves and Field Aligned Currents

Assume cold plasma

$$\nabla x \underline{B} = \frac{4\pi}{c}\underline{J} \qquad \nabla x \underline{E} = -\frac{1}{c}\frac{\partial \underline{B}}{\partial t} \qquad \rho\frac{\partial \underline{V}}{\partial t} = \frac{\underline{J}x\underline{B}}{c}$$

and

$$\underline{E} = -\frac{\underline{V}x\underline{B}}{c}$$

$$\nabla\left(\nabla\bullet\underline{E}\right) - \nabla^2\underline{E} = -\frac{4\pi}{c^2}\frac{\partial \underline{J}}{\partial t} \qquad \underline{J}_\perp = \frac{c^2}{4\pi V_A^2}\frac{\partial \underline{E}_\perp}{\partial t}$$

Using Eq and noting that the resistivity is zero and thus $\underline{E}_\parallel = 0$ we find

$$\nabla_\parallel\left(\nabla\bullet E_\perp\right) = -\frac{4\pi}{c^2}\frac{\partial J_\parallel}{\partial t}$$

$$\nabla_\parallel^2\left(\nabla_\perp\cdot\underline{E}_\perp\right) - \frac{1}{V_A^2}\frac{\partial^2\left(\nabla_\perp\cdot\underline{E}_\perp\right)}{\partial t^2} = 0 \qquad \nabla_\parallel^2\underline{J}_\parallel - \frac{1}{V_A^2}\frac{\partial^2\underline{J}_\parallel}{\partial t^2} = 0$$

$$Y\left(x_\parallel, t\right) = \Theta\left(x_\parallel - V_A t\right) + \Psi\left(x_\parallel - V_A t\right)$$