Physics of Solar Storms: From Initiation to Heliospheric Propagation

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Introduction

Solar storm = powerful energy release: flare, CME, SEP, shock...
Observations: CME kinematics

- Slow rise: 
  - \( a = 1 - 10 \text{ km s}^{-2} \)
  - \( a = 10 - 100 \text{ m s}^{-2} \)

- Fast: 
  - \( v > 1000 \text{ km s}^{-1} \)
  - \( a < 0 \)

- Overexpansion & shock formation

Self-similar expansion

\[ \text{LE} \]  
\[ \text{EP} \]
1. Acceleration stage: 3-D flux-rope models

"line-tying"

Anzer & Pneuman, 1982, SPh 79, 1
Vrsnak 1990, SPh 129, 295
...
....
Driving force

\[ a = a_L - g - a_d \]

\[ a_L = A \left( \frac{l}{h} + \frac{l}{R} - 2lRX^2 \right) \pm kl/lr \]

\[ A = \frac{\mu I^2}{4\pi M} = \frac{B_\phi^2}{\mu \rho l} = \frac{X^2 B_\parallel^2}{\mu \rho l} \approx \frac{v_A^2}{l} = \frac{l}{\tau_A^2} = l\omega^2 \]

in the absence of reconnection:

\[ \Phi_e = \text{const.} \propto Il \left[ \ln(8R/r) - 2 \right] \]

\[ \Phi_i = \text{const.} \propto Il \]

\[ \Rightarrow I \propto l^{-1}, \quad r \propto R, \quad X \propto r/l \]
Loss of equilibrium

\[ a (\text{m/s}^2) \]

-150
-100
-50
0
50
100
0 1 2 3 4 5

\[ Z \]

\[ a (\text{ms}^{-2}) \]

X=5, A=1300, r=0.1, k1=1300
X=5, A=1350, r=0.1, k1=1300
X=5, A=1400, r=0.1, k1=1300
X=5, A=1426, r=0.1, k1=1300
Eruption **without** reconnection

\[ a (\text{ms}^{-2}) \]

- \( X=5, A=1426, r=0.1, k1=1300 \)
- \( X=4, A=1445, r=0.1, k1=1300 \)
- \( X=5, A=713, r=0.2, k1=1300 \)
- \( X=5, A=4574, r=0.1, k1=4000 \)
Eruption with reconnection

\[ a (\text{m s}^{-2}) \]

\[ \Delta \Phi = 0 \]
\[ \Delta \Phi = 50\%, 1 < Z < 12 \]
\[ \Delta \Phi = 50\%, 1 < Z < 4 \]
\[ \Delta \Phi = 50\%, 1 < Z < 2 \]
\[ \Delta \Phi = 100\%, 1 < Z < 2 \]

\[ \frac{\Delta \phi}{\phi} \times 10 \]

\[ a (\text{ms}^{-2}/10), \frac{\Delta \phi/\phi}{t (\text{min})} \]

\[ I \propto t^{-1} \]
CME acceleration / flare reconnection

Miklenic et al. 2009 AA 499, 893
[idea proposed by Poletto & Kopp, 1986]

2. Coronal propagation: Observations

\[ a = a_L - \gamma (v-w)|v-w| \]

\[ v_0 \ (a_L > 0) > v_0 \ (a_L = 0) \]

\[ a_L = k \Delta v_0 \]
3. IP propagation
• fast CMEs decelerate, slow CMEs accelerate
• deceleration of massive CMEs is weaker than in case of light CMEs
• deceleration is weaker when a CME propagates in high-speed solar wind
• velocities of ICMEs converges to solar-wind speed
• ...

„MHD-aerodynamic” drag

\[ a = a_L - \gamma (v-w)|v-w| \]
MHD drag:

Momentum and energy are transferred by magnetosonic waves

(Collisionless environment: low viscosity, resistivity → dissipative processes are negligible)
Drag-Based Model

\[ a = (a_L - g) - a_d \]  
\[ a_d = -\gamma (v-w)|v-w| \]
\[ \ddot{r} = -\gamma(r) (\dot{r}-w(r))|\dot{r}-w(r)| \]

\[ \gamma = c_d A \rho_w / M \]

\[ A \sim r^2 \]
\[ \rho_w \sim r^{-2} + c r^{-4} + ... \]

\[ w(r) = \text{const.} \]

\[ \gamma (r) = \text{const.} \]  
analytical solution
\[ \Gamma = 0.1 \ ; \ w = 400 \text{ km/s} \]
**Shock Formation & Propagation**

**Formation:**
3D piston („explosion phase”; „overexpansion”)

**Coronal propagation:**
- lateral (piston-driven → freely propagating)
- upward (driven: piston/bow)

**CME-driven propagation**
freely propagating

\[ V_{CME} \sim V_{\text{sw}} \]

\[ v(R) \]

-corona

IP: 1/R
Arrival-time prediction: Can we do it better?

- arrival prediction +/- 10 h = not good enough
- hit/miss prediction = not good enough

why?
- Input parameters (observations): speed, width, direction, mass...
- Input parameters (modelling): background solar wind
- Beyond which distance Lorentz force can be neglected?
- CME-CME & CME-HSS interactions, heliospheric preconditioning
- Deflections
- ....

Recipe?
- Permanent upgrading input parameters [type II, IPS, (L5)]
- ???
The End

Thank You
For Your Attention!