CME DYNAMICS AND PHYSICAL CONNECTION BETWEEN CMEs AND FLAREs

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Modern Challenges of Nonlinear Plasma Physics
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• **Solar eruptions**: Coronal mass ejections (CMEs), flares, prominence eruptions

• Canonical parameters of solar eruptions:
  – KE, photons, particles \( \sim 10^{32-33} \text{ erg} \)
  – Mass \( \sim 10^{14-16} \text{ g} \)
  – Speed \( \sim 100 - 2000 \text{ km/s} \)

• **Space Weather**: CMEs are the solar drivers of large geomagnetic storms
Observational challenges:
• All remote sensing
• Different techniques observe different aspects/parts of an erupting structure
• 3-D geometry not directly observed

Theoretical challenges:
• An important unsolved question of theoretical physics
• Energy source
  Driving force (“magnetic forces”)
  – Underlying magnetic structure
  Physical relationship between CMEs, flares, and eruptive prominences (EPs)
MAGNETIC GEOMETRY UNDERLYING CMEs

Pre-SOHO

Illing and Hundhausen (1986)

Post-SOHO

Chen et al. (1997)

Hundhausen (1999)

NRL Plasma Physics Division
• Good *quantitative* agreement with a flux rope viewed end-on (Chen et al. 1997)
  – No evidence of structural changes attributable to disconnection

• Other examples of flux-rope CMEs (Wood et al. 1999; Dere et al., 1999; Wu et al. 1999; Plunkett et al. 2000; Yurchyshyn 2000; Chen et al. 2000; Krall et al. 2001; Thernisien et al. 2006)
• A flux-rope viewed from the side

• Halo CMEs are flux ropes viewed head on [Krall et al. 2005]
Magnetic Arcades

Magnetic arcade-to-flux rope
- Energy release and formation of flux rope during eruption
  (e.g., Antiochos et al. 1999; Chen and Shibata 2000; Linker et al. 2001; Lynch et al. 2004, 2009)

Poynting flux $S = 0$ through the surface

Not yet quantitative agreement with CMEs

Magnetic Flux Ropes

Pre-eruption structure: flux rope with fixed footpoints ($S_f$) (Chen 1989; Wu et al. 1997; Gibson and Low 1998; Roussev et al. 2003)

$S \neq 0$ through the surface (Chen 1989)
PHYSICS OF CMEs: Forces

• “Toroidal” magnetic flux rope with fixed footpoints separated by $S_f$

• Major Radial Forces: integrate $f = \rho \frac{dv}{dt} = c^{-1} \mathbf{J} \times \mathbf{B} - \nabla p + \rho \nabla \phi_g$

\[
M \frac{d^2 Z}{dt^2} = \frac{\Phi_p^2}{c^4 L^2 R} \left[ \ln \left( \frac{8R}{a} \right) + \frac{1}{2} \beta_p - \frac{1}{2} \frac{B_t^2}{B_p^2} + 2 \left( \frac{R}{a} \frac{B_c}{B_p} - 1 + \frac{\xi_i}{2} \right) \right] + F_g + F_d
\]

\[
[\text{Shafranov 1966; Chen 1989; Garren and Chen 1994}]
\]

\[
\Phi_p = c L I_t, \quad L = 4\pi \Theta R \left[ \ln \left( \frac{8R}{a_f} \right) - 2 \right]
\]

• Initiation of eruption:

\[
\frac{d\Phi_p(t)}{dt} = \text{poloidal flux "injection"}
\]
MINOR RADIAL DYNAMICS

• Minor Radial Forces: (integrated over $a$)

$$M \frac{d^2a}{dt^2} = \frac{a}{4} \left( B_t^2 - B_p^2 + \beta_p B_p^2 \right) \nabla \beta$$

• $d^2a / dt^2 \approx 0$ is a good approximation [Chen 1989]

• Key property of flux-rope Geometry:
  Constant $S_f$ is an essential scale length

$$R = \frac{Z^2 + S_f^2}{2Z}$$
• Shafranov’s original work:
  – Forces in major and minor radial directions
  – Axisymmetric toroidal equilibrium

• CMEs: An Extension and New Application
  – Local curvature approximation [Chen 1989; Garren and Chen 1994]
  – Stationary photospheric footpoints: nonaxisymmetric ➔ additional lengths scales $S_f, a_f$
  – Dynamical expansion ➔ time scales
  – Momentum coupling to the ambient plasma
  – $S_f$ and $a_f$ are directly manifested in observed CME acceleration data [Chen et al. 2006]

• Comparison with other recent models invoking Shafranov
  – Wu et al. [1997] – 2D axisymmetric MHD simulation with stationary footpoints
  – Lin et al. [1998], Titov and Demoulin [1999], Kliem and Torok [2005] – axisymmetric with no footpoints, no minor radial force equation, no coupling to the ambient plasma
  – Isenberg and Forbes [2007] – major radial force only, no dynamics
  – Roussev et al. [2003], Torok and Kliem [2008] -- MHD simulations with fixed footpoints (invoking Titov and Demoulin and Kliem and Torok but scales are different)
DIRECT COMPARISON OF THEORY AND DATA

• Previous comparison of theoretical predictions and directly observable quantities
  – Good agreement with observed height and acceleration data
  – Agreement of predicted $S_f$-scaling law and observed CME acceleration profiles (17 events)

• A new theoretical prediction: the temporal form of $d\Phi_p(t)/dt$ for a CME should be correlated with that of the X-ray emission profile of the associated flare
  – Physics: $-(1/c)d\Phi_p(t)/dt = \text{electromotive force (EMF)} \propto \text{electric field}$

\[
M \frac{d^2 Z}{dt^2} = \frac{\Phi_p^2(t)}{c^4L^2R} \left[ \ln \left( \frac{8R}{a} \right) + \frac{1}{2} \beta_p - \frac{1}{2} \frac{B_i^2}{B_p^2} + 2 \left( \frac{R}{a} \right) \frac{B_c}{B_p} - 1 + \frac{\xi_i}{2} \right] + F_g + F_d
\]

\[
\text{EMF}(t) = -\frac{1}{c} \frac{d\Phi_p}{dt}
\]
• Define goodness of fit with respect to height-time data: \( G \)

\[
G \equiv \frac{1}{T} \sum_{i=1}^{N} \left| \frac{Z_{\text{data}}(t_i) - Z_{\text{th}}(t_i)}{\Delta Z(t_i)} \right| \delta t_i
\]

• Adjust \( d\Phi_p(t) / dt \) to find theoretical solutions that best fit the observed CME height-time data and compare the calculated \( d\Phi_p(t) / dt \) with observed GOES X-ray data

• Results:
  – The form of \( d\Phi_p(t) / dt \) is strongly constrained by the height data with little freedom
  – Agreement is good for both short- and long-duration flare events

• \textit{Goodness of fit is determined with no regard to speed, acceleration, and X-ray emissions.}
• Set up initial equilibrium flux rope according to available observational proxies: e.g., $S_f$, footpoint separation distance, $B_c(Z_0)$. Adjust $\frac{d\Phi_p(t)}{dt}$

$G = 0.85 \quad S_f = 4.5 \times 10^5 \text{ km} \quad E \sim 1 \text{ V/cm}$

$G = 0.42 \quad S_f = 2.0 \times 10^5 \text{ km} \quad E \sim 15 \text{ V/cm}$

Chen and Kunkel (2009)

Error: 2% of height
Goodness of fit: $G \sim 0.5 – 1.0$
PARAMETER STUDY

- For each set of parameters, adjust $d\Phi_p(t) / dt$ to obtain the best-fit solution
  - All “best-fit” solutions ($G \sim 0.85–1.2$ for this case) have similar FWHM durations
  - For LASCO heights, the fit is sensitive to the duration but not to $V_{sw}$

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• Consistent with observational studies of temporal relationship between acceleration and derivative of soft X-ray: Zhang et al. (2001), Maricic et al. (2007), Temmer et al. (2008)
PHYSICAL INTERPRETATION OF $d\Phi_p(t)/dt$

- In the toroidal flux rope model, $d\Phi_p(t)/dt$ is a prescribed mathematical function
  - A direct proxy for electric field (super Dreicer) for DC acceleration: $E \sim 0.4–15$ V cm$^{-1}$
  - Agreement with form of observed X-ray emission profiles is evidence of physical connection linking $d\Phi_p(t)/dt$, CME acceleration, and flare soft X-rays

- Physical interpretation of $d\Phi_p(t)/dt$:
  - (1) Subphotospheric origin via poloidal flux transport from deep source
  - (2) Coronal origin via macroscopic reconnection [Antiochos et al. 1999; Amari et al. 2000]
  - Neither has been theoretically or observationally verified

- Comparison with arcade-based coronal storage scenario:
  - 2-D MHD simulation with $J$-dependent resistivity [Cheng et al. 2003]: temporal relation between flux-rope acceleration and inferred energy release with $E \sim 10$ V cm$^{-1}$
  - Estimates of reconnected flux based on photospheric magnetograms:
    - 90 V cm$^{-1}$ [Qiu et al., 2002]
    - 0.2–5 V cm$^{-1}$ with reconnected flux of $\sim 0.5 – 10 \times 10^{18}$ Mx s$^{-1}$ [Jing et al. 2005; Qiu et al. 2007]

• Two situations:
  – Source region can be observed—obtain proxies for $S_r$, $Z_0$, etc.
  – Source region not observed—adjust $S_r$, $Z_0$, and fit model solutions to HI1/HI2 height-time data → predict $B$ field at 1 AU
  – For both situations, $d\Phi_p(t) / dt$ is an adjustable parameter that can be validated using GOES X-ray data
Separation angle Stereo A and B is 44 degree
Inclusion of drag in the force equation is essential for the long-time propagation.
Calculated magnetic field at 1 AU

- Comparison with IMPACT/PLASTIC data

Flux Rope Magnetic Field

Dec 30

TIME [UT]

B(1 AU) [nT]

B_p

B_t

Magnetic Cloud [Burlaga et al. 1981]
THEORY SUCCESSES

• CME dynamics are described by a set of two ODEs
  – Calculated dynamics have been compared with LASCO and STEREO data
  – Both major radial and minor radial expansion is correctly described by the theory
  – The main acceleration and the subsequent propagation to 1 AU are correctly captured
    – *Drag coupling between CMEs and the ambient SW is essential*
  – The calculated $B$ field at 1 AU is in agreement with *in situ* measurement at 1 AU (1 event)
  – The best-fit solution yields a temporal profile of $d\Phi_p(t)/dt$ in agreement with the *observed* profile of GOES soft X-ray emissions (five CME-flare events)

• Suggests a new theoretical framework of understanding CME dynamics and flare energy release
  – An initial flux rope is set into motion by injection of *poloidal* flux, which generates an EMF and attendant electric field to accelerate particles to X-ray energies
• Currently, \( \frac{d\Phi_p(t)}{dt} \) is a specified function of time

• Two physical interpretations are possible:
  
  – Coronal origin: macroscopic reconnection is required. All models use numerical and/or artificial dissipation. Not yet simulated acceleration in agreement with data.
  
  – Subphotospheric origin: Not yet observed. Observable photospheric signatures not yet modeled. Favorable if coronal reconnection is not fast enough

• \( \frac{d\Phi_p(t)}{dt} \) is a point of overlap between the two basic paradigms (arcade v. flux rope) [Chen 1996; Chen and Krall 2003]
• Both arcade models and erupting flux-rope model with poloidal flux injection require further work

• **Major Physics Issues**

  • Arcade models:
    – Physical reconnection on macroscopic scales
    – Demonstration of specific realistic photospheric motion for observed eruptions
    – Calculation of acceleration and speed in agreement with observed CMEs

  • Poloidal flux injection model:
    – Demonstration of photospheric signatures in agreement with *well-resolved* observation
    – Simulation of subphotospheric plasma dynamics
• “Coronal transients” (1970’s: OSO-7, Skylab)

• “Thin” flux tubes
  (Mouschovias and Poland 1978; Anzer 1978)

• Halo CMEs (Solwind) (Howard et al. 1982)
  – Fully 3-D in extent

• CME morphology (SMM):
  (Illing and Hundhausen 1986)
  – A CME consists of 3-parts: a bright frontal rim, cavity, and a core
  – Conceptual structure: rotational symmetry (e.g., ice cream cone, light bulb) (Hundhausen 1999)

• SOHO data: 3-D flux ropes (Chen et al. 1997)
  – 3-part morphology is only part of a CME
SOLAR ERUPTIONS: PHENOMENOLOGY

- Sporadic eruptions
  - Solar flares seen in X-rays, EUV, H\(_\alpha\), etc.
  - Filament/prominence eruptions seen in H\(_\alpha\) or white light
  - CMEs in white light
  - All can be accompanied by solar energetic particles (SEPs)

- Solar flares are usually identified by the disk-integrated X-ray emissions detected by GOES satellites

- Stellar flares are recognized by similar X-ray light curves