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

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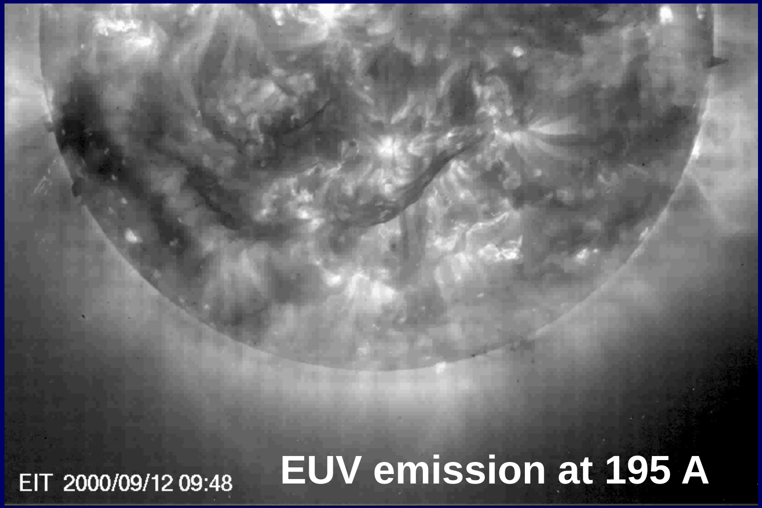
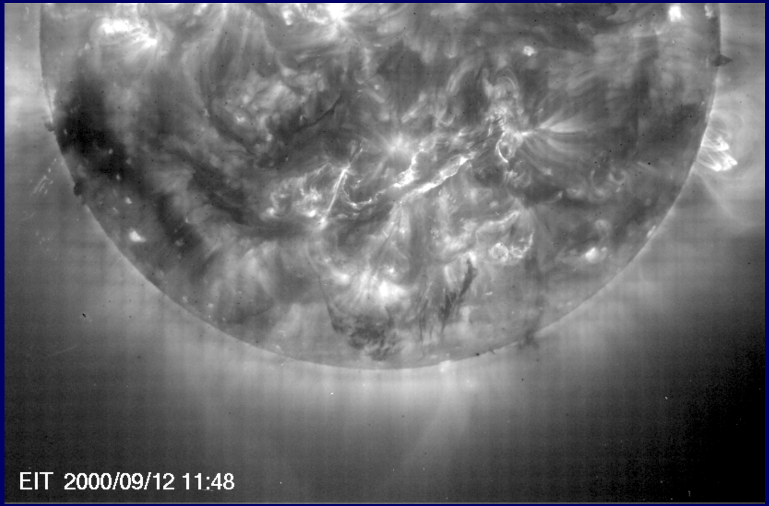
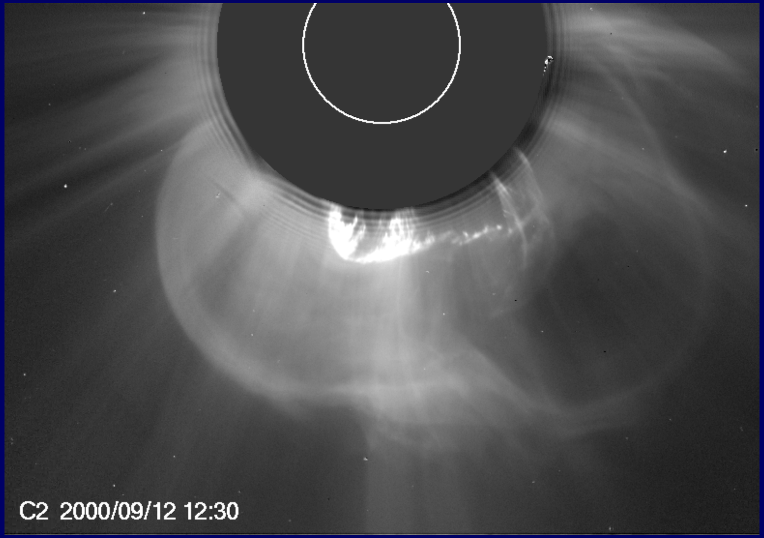


- ***Solar eruptions***: Coronal mass ejections (CMEs), flares, prominence eruptions
- Canonical parameters of solar eruptions:
  - KE, photons, particles ~ 10^{32-33} erg
  - Mass ~ 10^{14-16} g
  - Speed ~100 - 2000 km/s
- *Space Weather*: CMEs are the solar drivers of large *geomagnetic storms*

SCIENTIFIC CHALLENGES





***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

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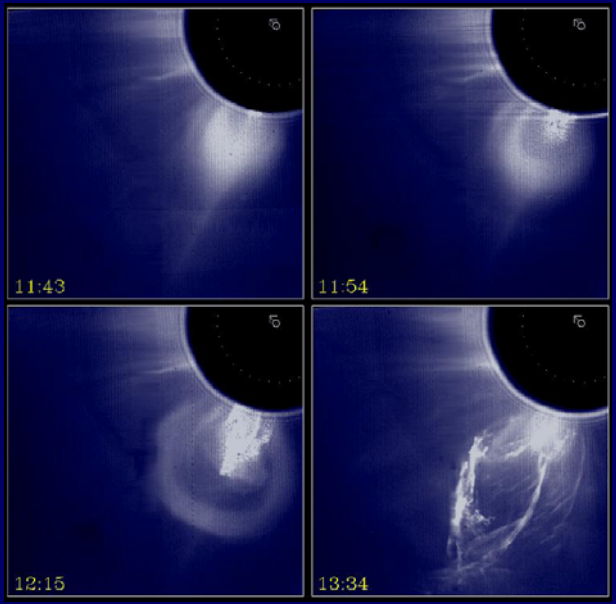
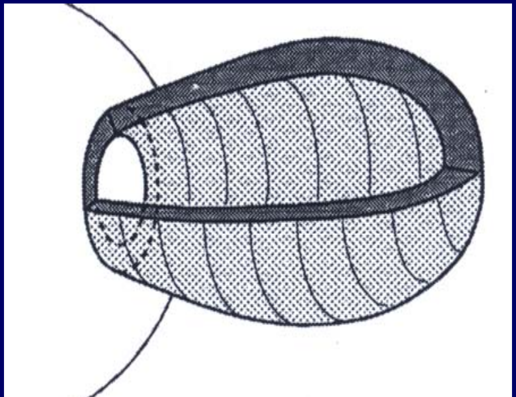
Pre-*SOHO*

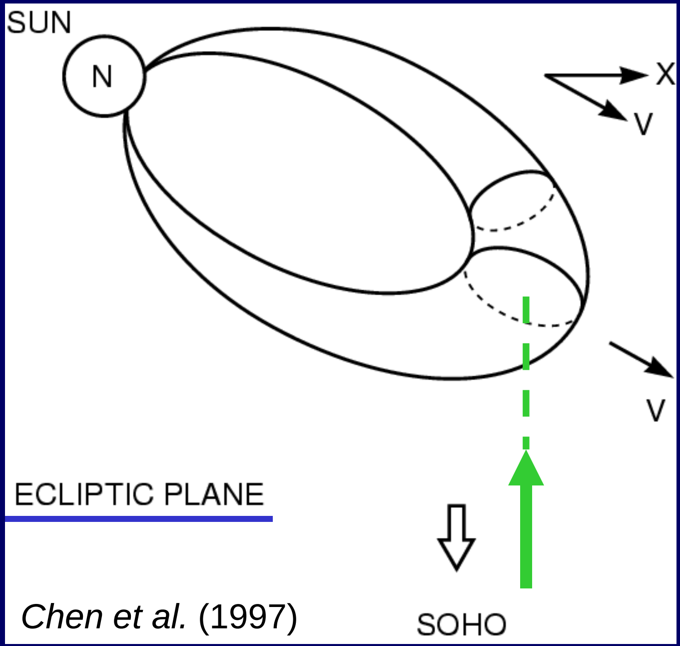


Illing and Hundhausen (1986)



Hundhausen (1999)

Post-*SOHO*



Chen et al. (1997)

OBSERVATIONAL EVIDENCE

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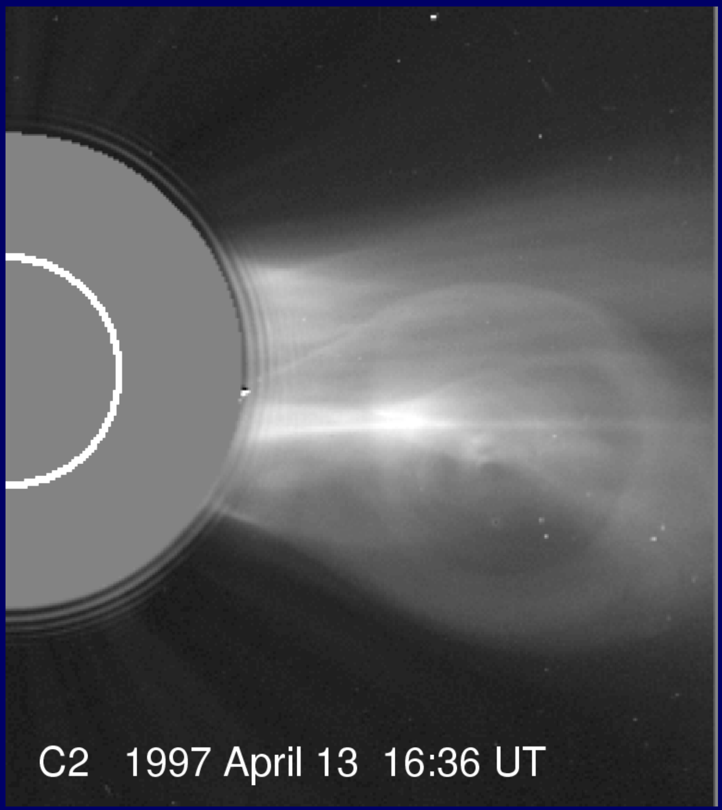

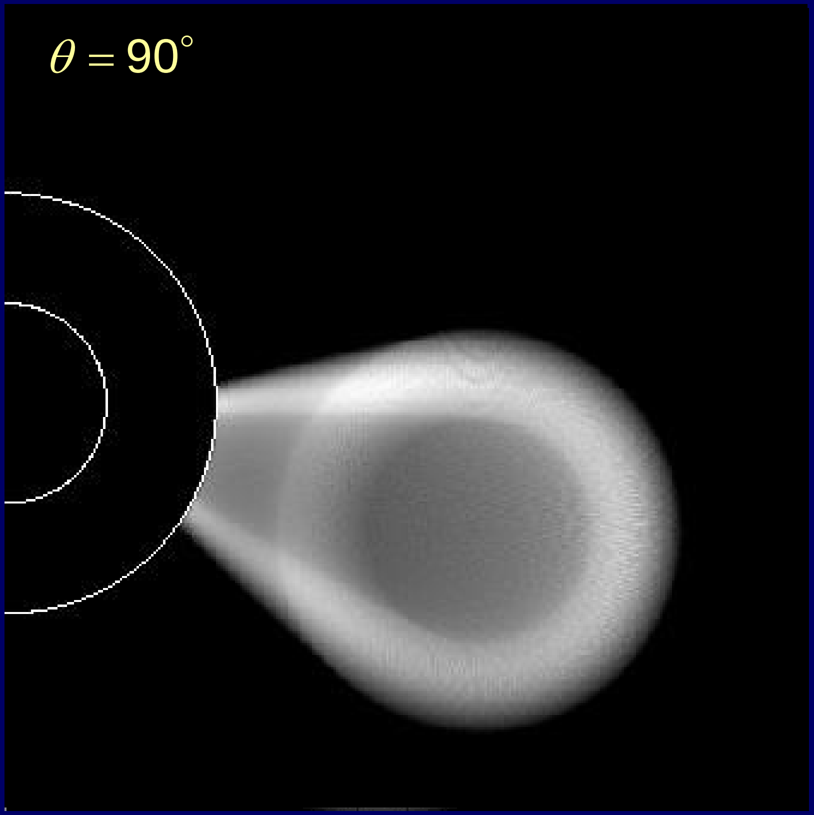

- Good ***quantitative*** agreement with a flux rope viewed end-on (*Chen et al.* 1997)
  - No evidence of structural changes attributable to disconnection
- Other examples of flux-rope CMEs (*Wood et al.* 1999; *Dere et al., 1999; Wu et al.* 1999; *Plunkett et al.* 2000; *Yurchyshyn* 2000; *Chen et al.* 2000; Krall *et al.* 2001; *Thernisien et al*. 2006)

OBSERVATIONAL EVIDENCE (cont'd)

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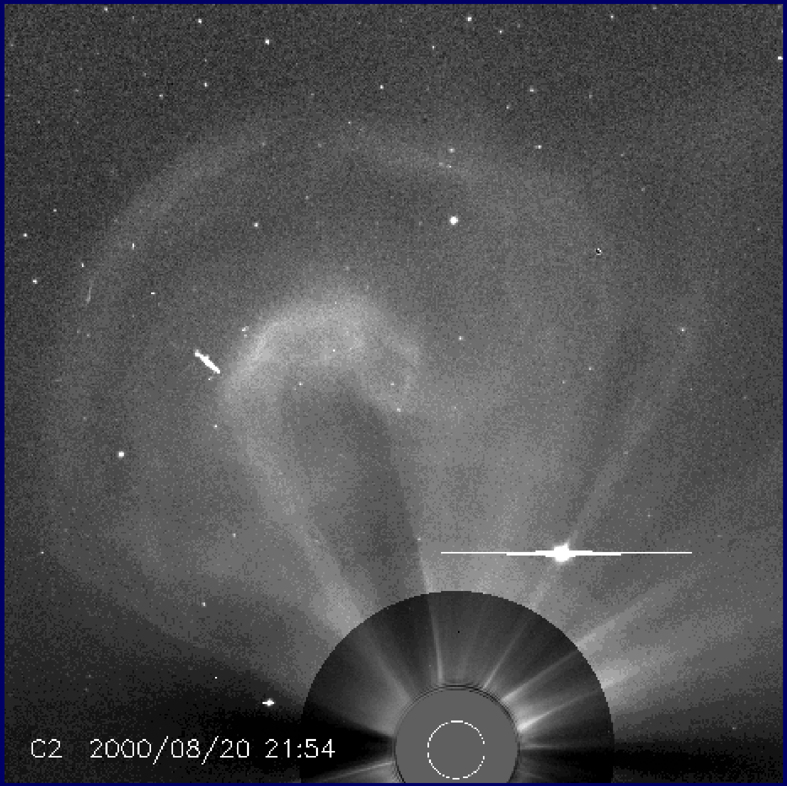

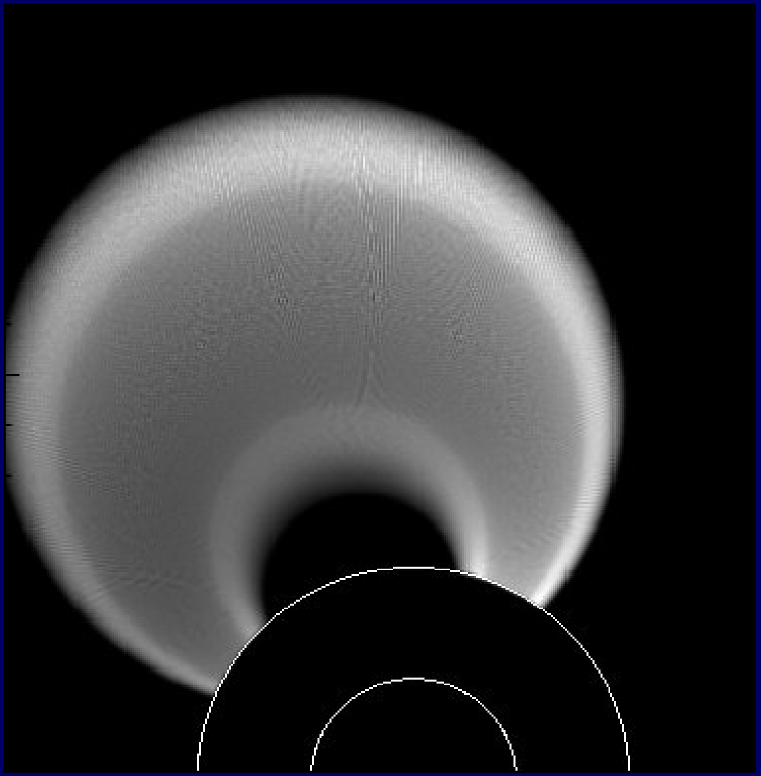

- A flux-rope viewed from the side
- Halo CMEs are flux ropes viewed head on [*Krall et al.* 2005]

THEORETICAL CONCEPTS: TWO MODEL GEOMETRIES

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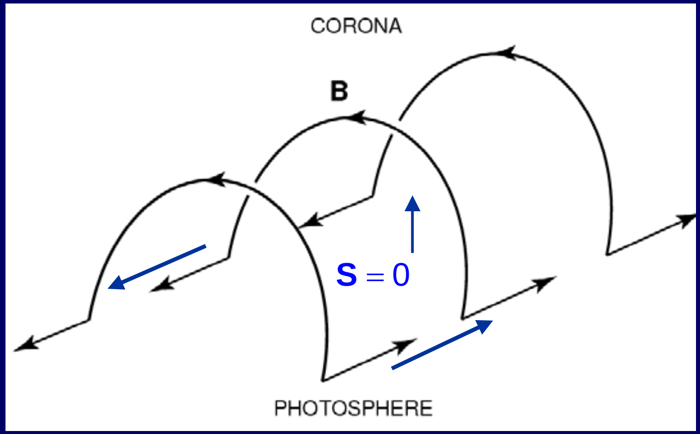
Magnetic Arcades



Magnetic arcade-to-flux rope

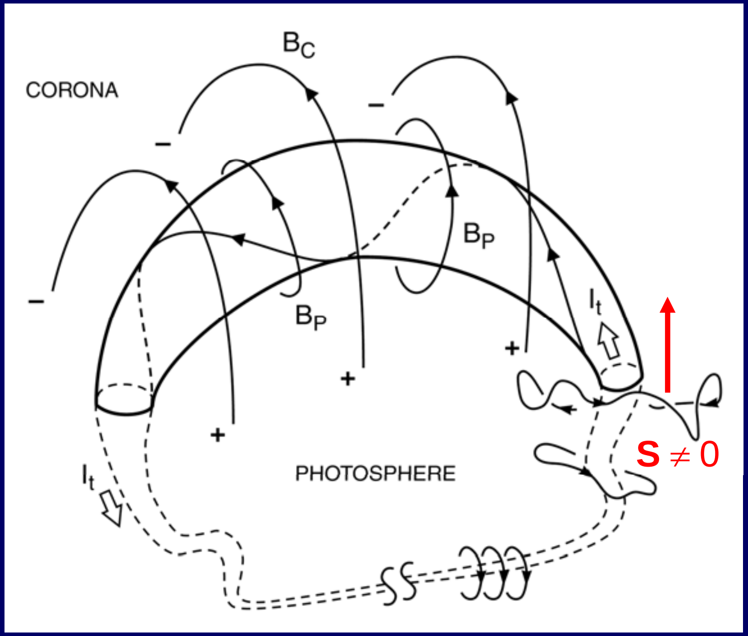
- Energy release and formation of flux rope during eruption

(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 ≠ 0 through the surface (*Chen* 1989)

PHYSICS OF CMEs: Forces

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- "Toroidal" magnetic flux rope *with fixed footpoints* separated by S_f
- Major Radial Forces: integrate $\mathbf{f} = \rho d\mathbf{v}/dt = c^{-1}\mathbf{J}\mathrm{x}\mathbf{B} - \nabla p + \rho \nabla \phi_g$

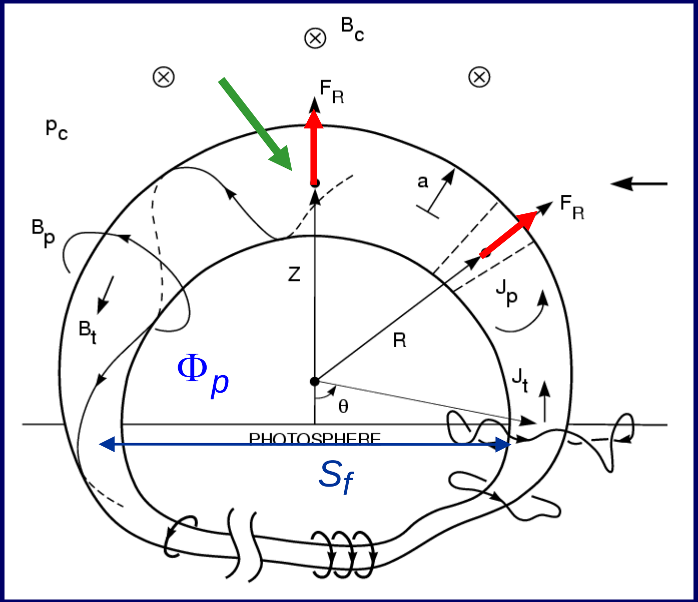
$$M\frac{d^2Z}{dt^2} = \frac{\Phi_p^2}{c^4L^2R}\left[\underbrace{\ln\left(\frac{8R}{a}\right)}_{J_t \times B_p} + \underbrace{\frac{1}{2}\beta_p}_{\nabla p} - \underbrace{\frac{1}{2}\frac{B_t^2}{B_p^2}}_{J_p \times B_t} + \underbrace{2\left(\frac{R}{a}\right)\frac{B_c}{B_p}}_{J \times B_c} - 1 + \frac{\xi_i}{2}\right] + F_g + F_d$$

[*Shafranov* 1966; *Chen* 1989; *Garren and Chen* 1994]

$$\Phi_p = cLI_t, \qquad L = 4\pi\Theta R\left[\ln\left(\frac{8R}{a_f}\right) - 2\right]$$

- Initiation of eruption:

$$\boxed{\frac{d\Phi_p(t)}{dt} = \text{poloidal flux "injection"}}$$



MINOR RADIAL DYNAMICS

- Minor Radial Forces: (integrated over *a*)

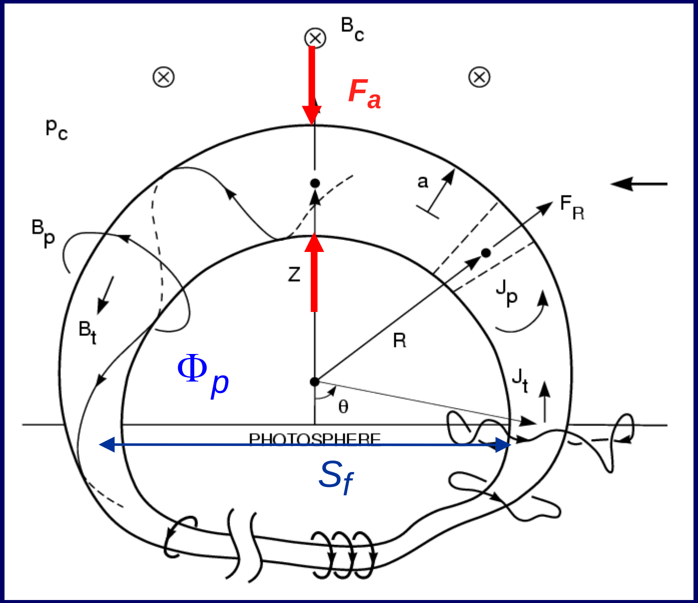
$$M\frac{d^2a}{dt^2} = \frac{a}{4}\left(\overset{J_p \times B_t}{B_t^2} - \underset{J_t \times B_p}{B_p^2} + \overset{\nabla p}{\beta_p B_p^2}\right)$$

- $d^2a/dt^2 \simeq 0$ is a good approximation [*Chen* 1989]

- Key property of flux-rope Geometry**:**

  Constant S_f is an essential scale length

$$R = \frac{Z^2 + S_f^2/4}{2Z}$$



STRUCTURE OF EQUATIONS OF MOTION

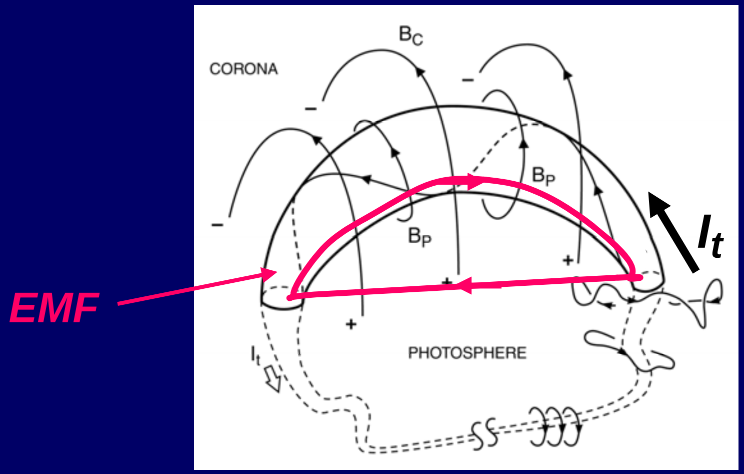
- Shafranov's original work:
  - Forces in major and minor radial directions
  - Axisymmetric toroidal equilibrium
- CMEs: An Extension and New Application
  - Local curvature approximation [*Chen* 1989; *Garren and Chen* 1994]
  - Stationary photospheric footpoints: nonaxisymmetric ⟶ additional lengths scales S_f, a_f
  - Dynamical expansion ⟶ time scales
  - Momentum coupling to the ambient 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 *Sf*-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: $-(1/c)d\Phi_p(t)/dt$ = electromotive force (EMF) $\propto$ electric field

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

$$\boxed{EMF(t) = -\frac{1}{c}\frac{d\Phi_p}{d\,t}}$$



BEST-FIT SOLUTION

- Define goodness of fit with respect to height-time data: *G*

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

- 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

- *Goodness of fit is determined with no regard to speed, acceleration, and X-ray emissions.*

THEORY-DATA COMPARISON

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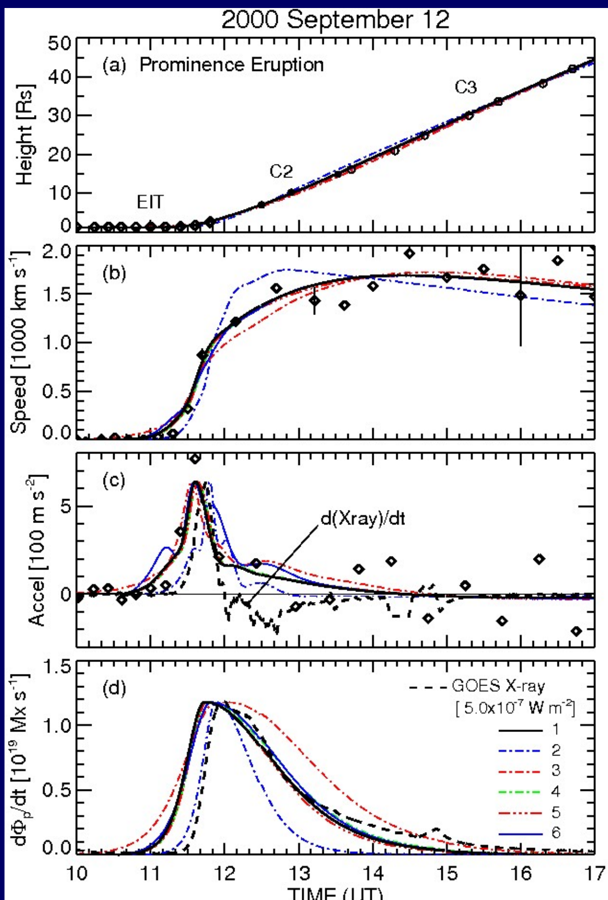
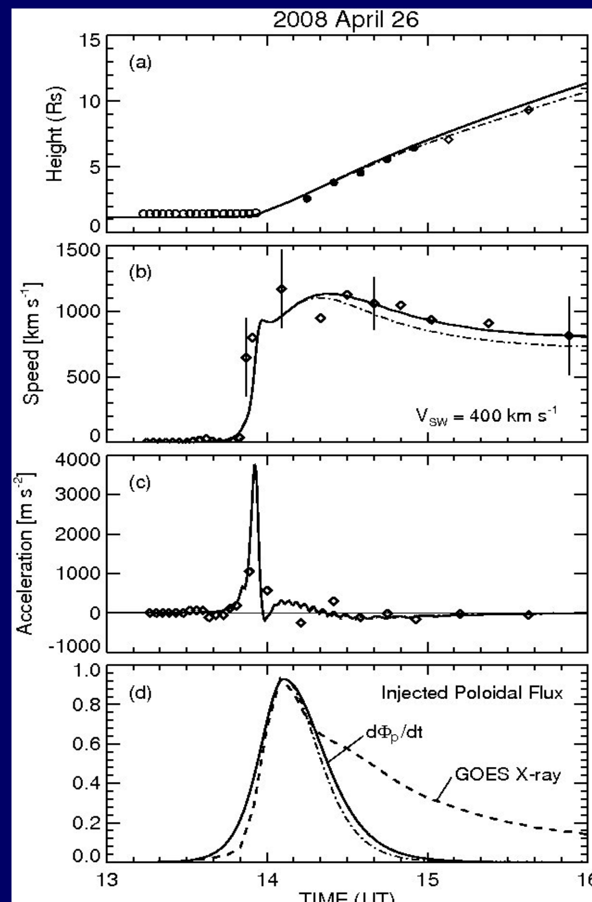
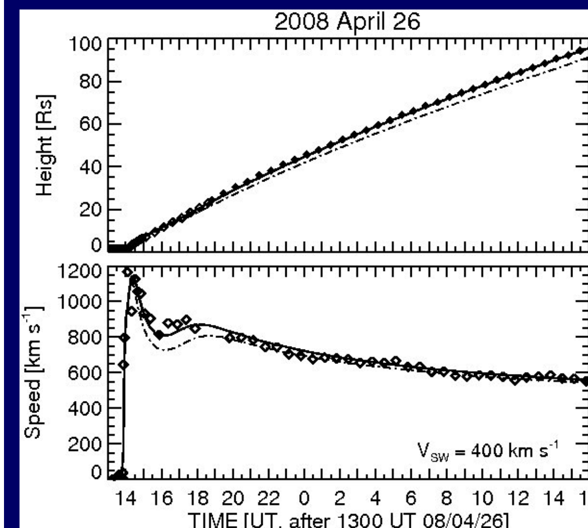
- Set up initial equilibrium flux rope according to available observational proxies: *e.g.*, S_f, footpoint separation distance, $B_c(Z_0)$. Adjust $d\Phi_p(t)/dt$

Chen and Kunkel (2009)







Error: 2% of height

Goodness of fit: $G \sim 0.5 – 1.0$

$G = 0.85$ $Sf = 4.5 \times 10^5$ km $E \sim 1$ V/cm $G = 0.42$ $Sf = 2.0 \times 10^5$ km $E \sim 15$ V/cm

PARAMETER STUDY

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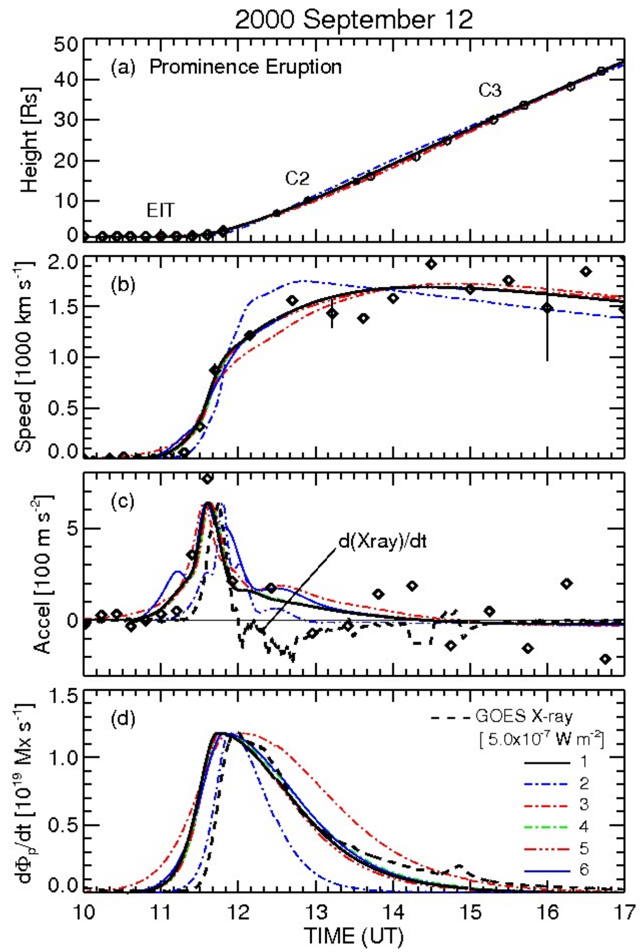
- For each set of parameters, adjust $d\Phi_p(t)/dt$ to obtain the best-fit solution
  - All "best-fit" solutions (G ~ 0.85–1.2 for this case) have similar FWHM durations
  - For LASCO heights, the fit is sensitive to the duration but not to V_{sw}

Form of $d\Phi_p(t)/dt$ (PHIA, DTC, Dtpeal, TSCL1, TSCL2)

	File ID	GFIT	Z0	Sf	ASPCT(	XPP	XNP(	BS0	PHIA	DTC	Dtpeal	TSCL1	TSCL2	Vsw
	240+0	1.03	2.0	4.5	2.5	1.0	1.0	-0.5	9.400	76.0	1.0	25.0	73.0	400
	240+1	0.94	2.0	4.5	2.5	1.0	1.0	-1.5	5.300	76.0	1.0	25.0	75.0	400
	240+2	1.13	2.0	4.5	2.5	1.0	1.0	-1.5	4.500	76.0	2.0	20.0	72.0	400
	250	0.96	1.8	4.5	2.5	1.0	1.0	-1.0	5.850	76.8	0.0	20.0	74.6	400
1	250-1	0.85	2.0	4.5	2.5	1.0	1.0	-1.0	5.600	71.0	0.0	20.0	75.0	400
	250-2	0.97	2.0	4.5	2.0	1.0	1.0	-1.0	6.400	70.0	0.0	20.0	72.5	400
	250-3	0.99	1.8	4.5	2.5	1.0	1.0	-1.0	6.430	70.0	0.0	22.0	73.3	400
	250-4	0.87	2.0	4.5	2.5	1.0	1.0	-1.0	6.150	70.0	0.0	22.0	73.3	400
	252+5	1.18	2.0	4.5	2.0	0.5	2.0	-1.0	6.460	72.0	1.0	20.0	67.9	400
	260+0	0.87	2.0	4.5	2.5	1.0	1.0	-1.0	6.700	71.0	0.0	25.0	76.7	400
	260+1	1.09	2.0	4.5	2.5	1.0	1.0	-1.0	8.000	71.0	0.0	30.0	76.7	400
6	616+2	1.29	2.0	5.5	2.5	1.0	1.0	-1.0	5.600	73.0	0.0	25.0	74.5	400
	0530+0	1.09	2.0	5.0	2.5	1.0	2.0	-1.5	4.500	90.0	0.0	25.0	83.0	400
	0530+1	1.18	2.0	5.0	2.5	1.0	2.0	-1.0	5.530	90.0	0.0	25.0	82.0	400
3	0540+1	1.45	2.0	5.0	2.5	1.0	1.0	-1.0	5.400	130.0	0.0	35.0	89.5	400
	0540+2	2.89	2.0	5.0	2.5	1.0	1.0	-1.5	5.400	110.0	0.0	15.0	30.0	400
2	0540+3	2.19	2.0	5.0	2.5	1.0	1.0	-1.0	5.900	110.0	0.0	15.0	38.0	400
4	0550+1	0.87	2.0	4.5	2.5	1.0	1.0	-1.0	5.590	70.7	0.0	20.0	78.2	300
	0550+2	0.88	2.0	4.5	2.5	1.0	1.0	-1.0	5.590	70.7	0.0	20.0	79.7	250
5	0550+3	0.84	2.0	4.5	2.5	1.0	1.0	-1.0	5.580	71.5	0.0	20.0	70.1	600



THEORY-DATA COMPARISON

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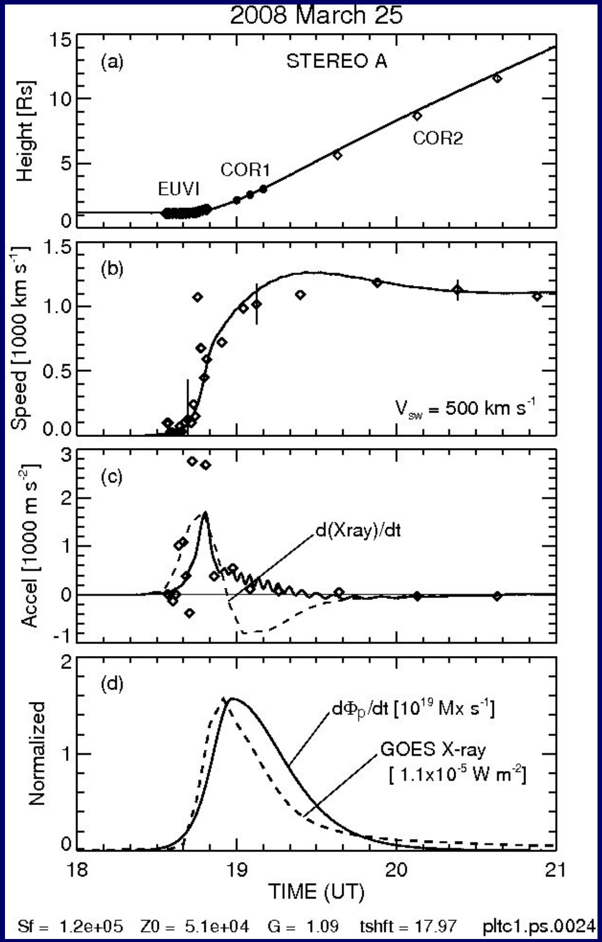
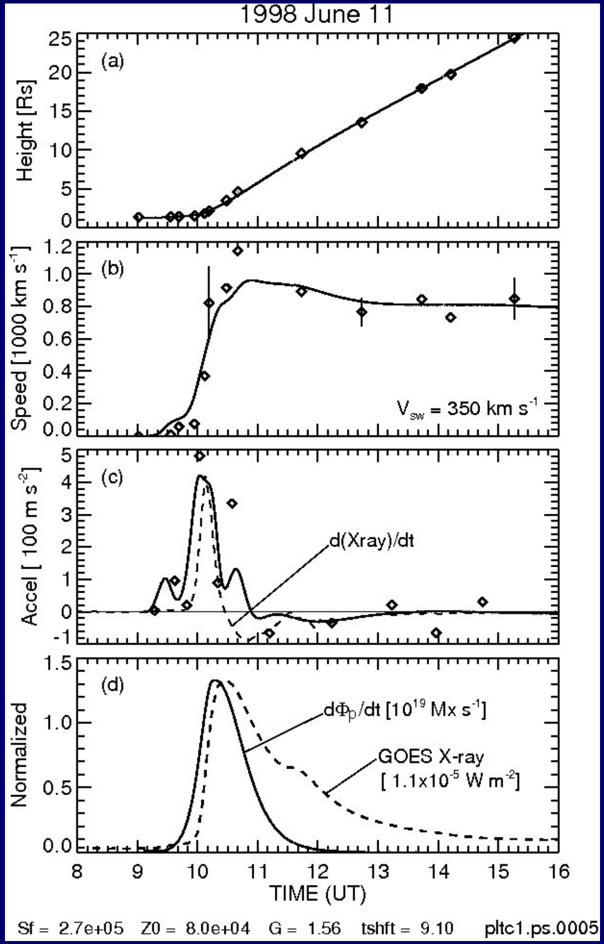
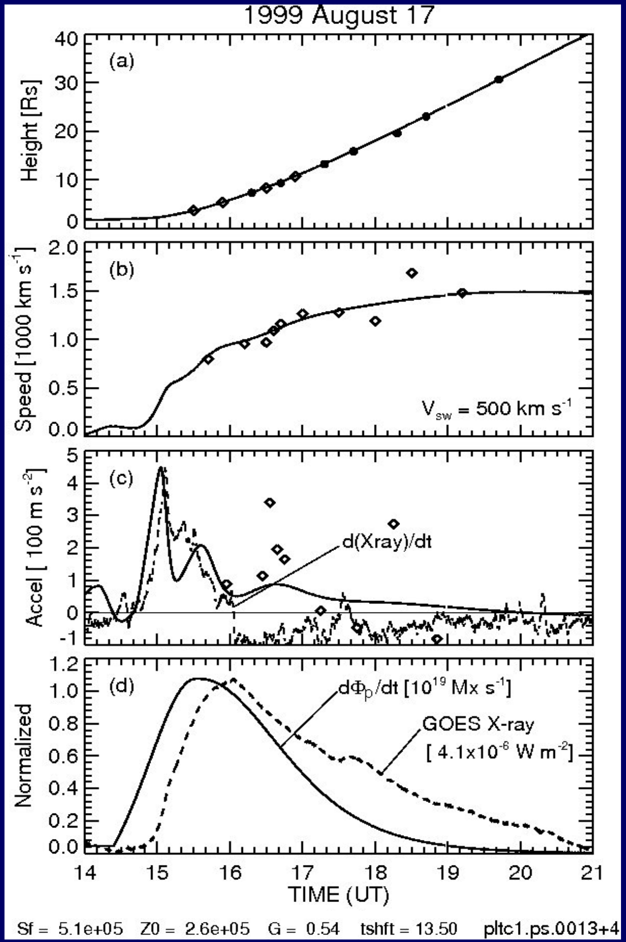


E_{max} **~ 12 V/cm**



***E* ~ 5 V/cm**



***E* ~ 2 V/cm**

- 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 ~ 0.5–10×10^{18} Mx s^{-1} [*Jing et al.* 2005; *Qiu et al.* 2007]

PROPAGATION OF CMEs

- Model the dynamics of a CME (2007 Dec 24) from initiation to 1 AU (STEREO A data). Predict magnetic field at 1 AU and compare with data (STEREO B data). [*Kunkel and Chen*, in preparation, 2009]
- Two situations:
  - Source region can be observed—obtain proxies for S_f, Z_0, *etc.*
  - Source region not observed—adjust S_f, 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

24 DEC 2007 CME

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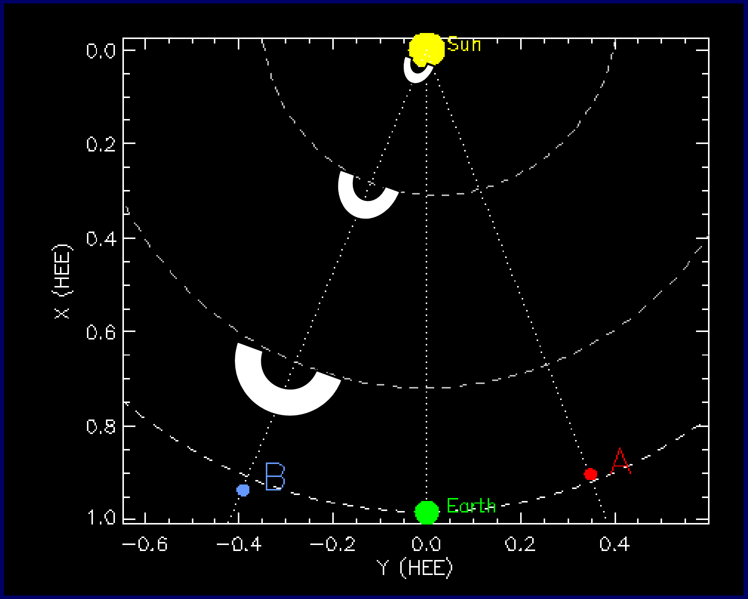
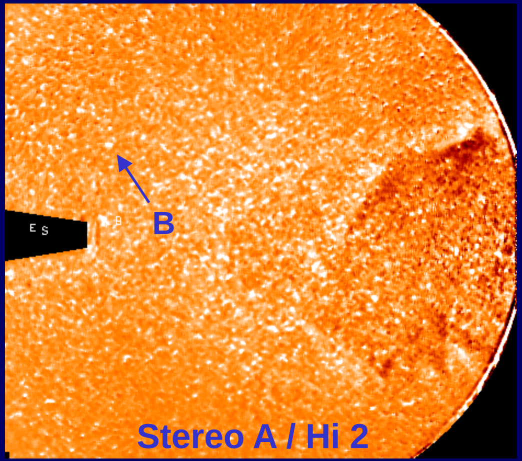
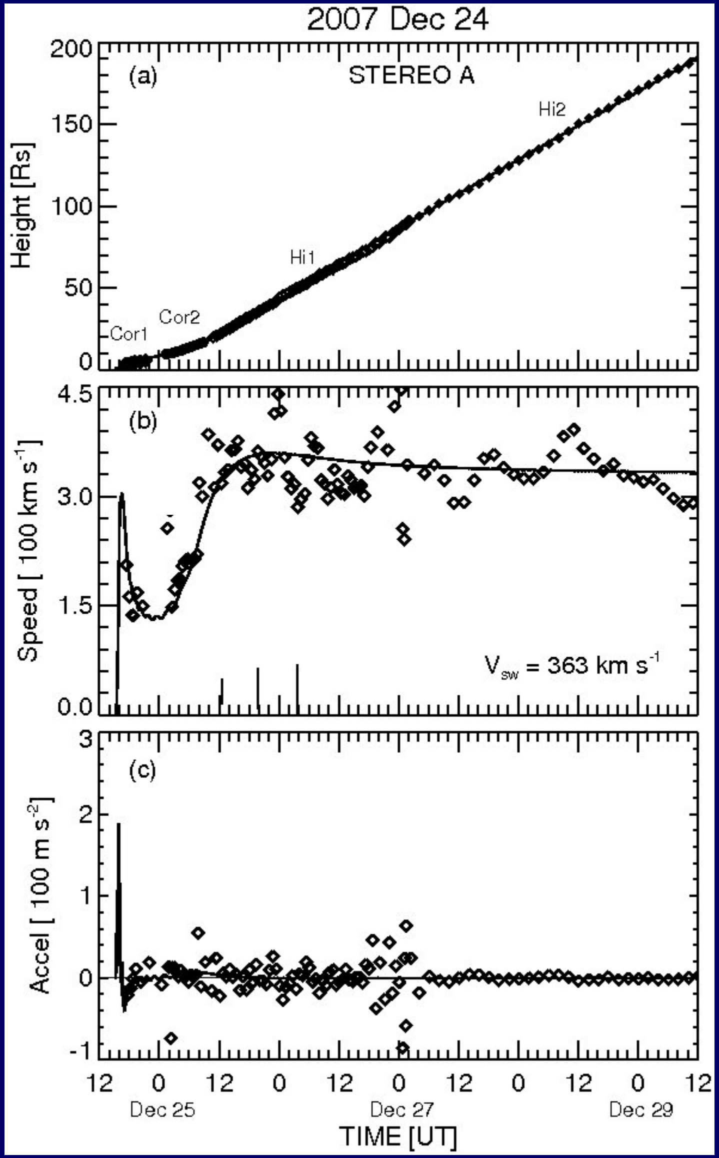


Separation angle Stereo A and B is 44 degree





CME TRAJECTORY: NEAR SUN

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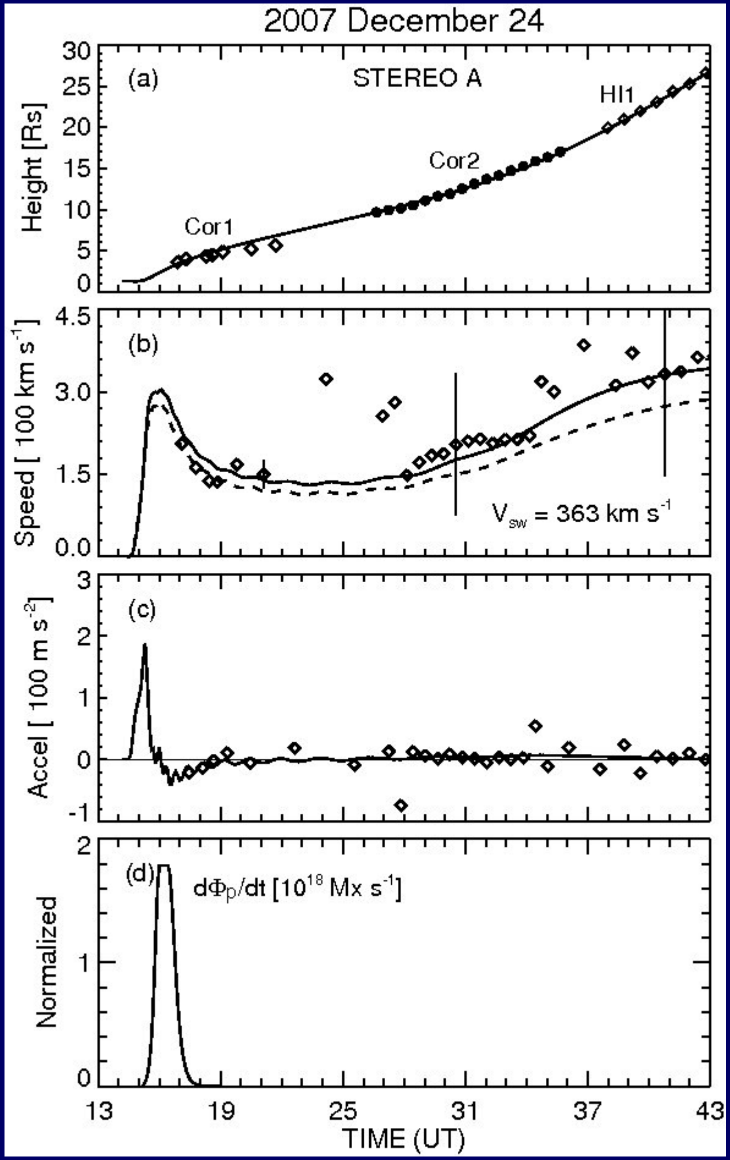

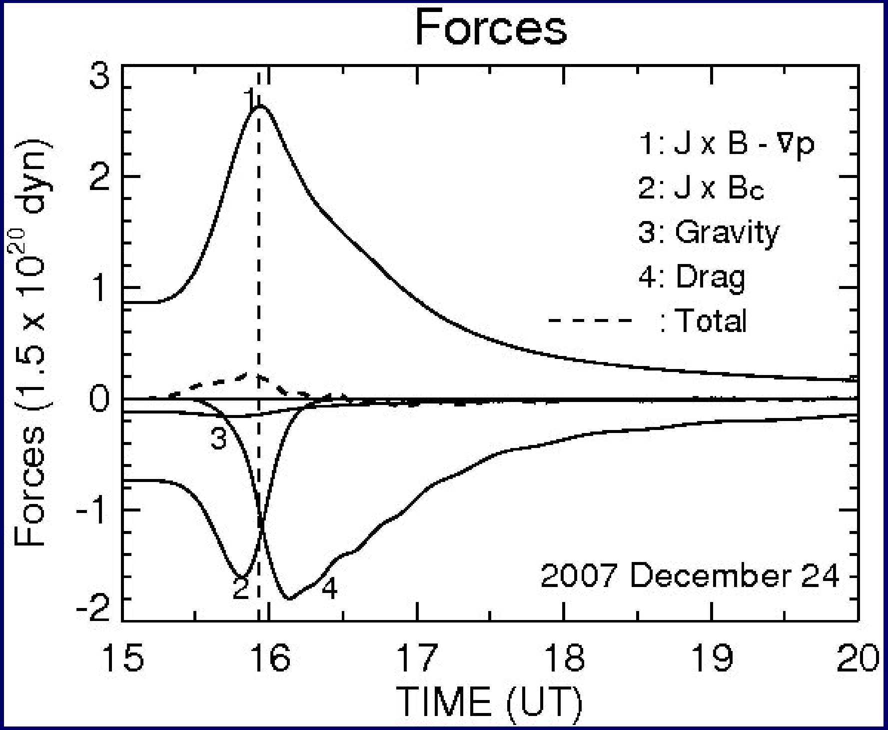

Inclusion of drag in the force equation is essential for the long-time propagation

PREDICTED MAGNETIC FIELD AT 1 AU

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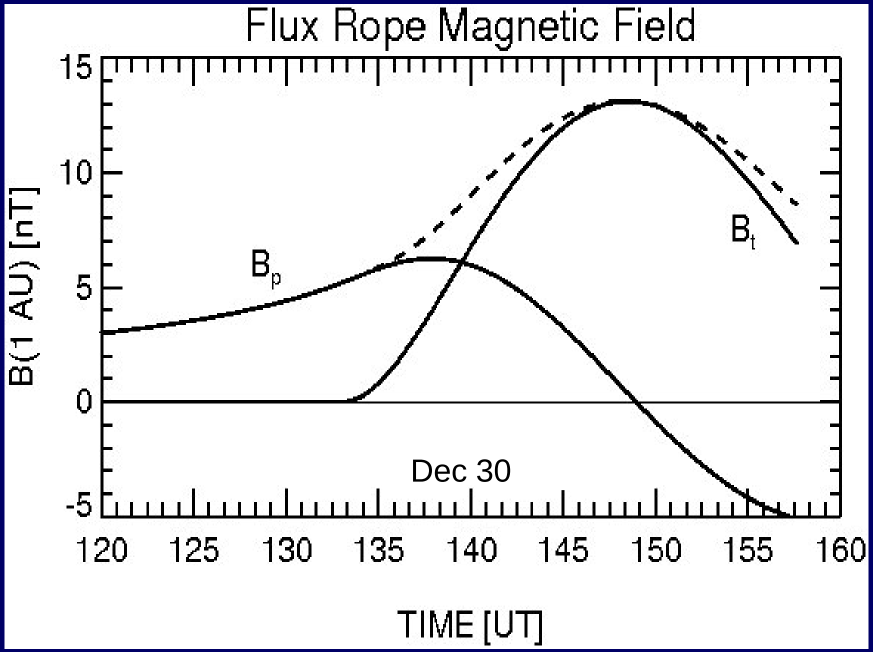
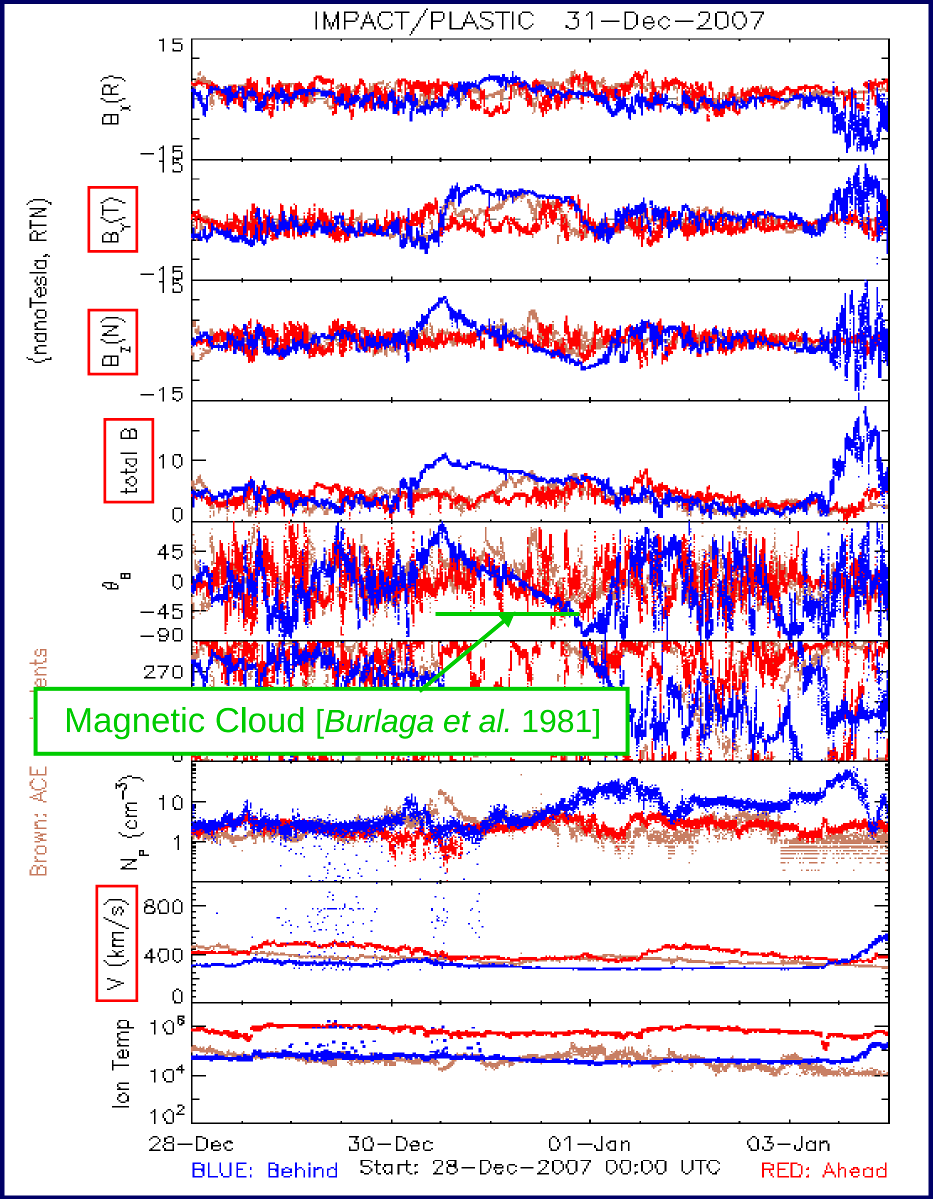
Calculated magnetic field at 1 AU

– Comparison with IMPACT/PLASTIC data





THEORY SUCCESSES

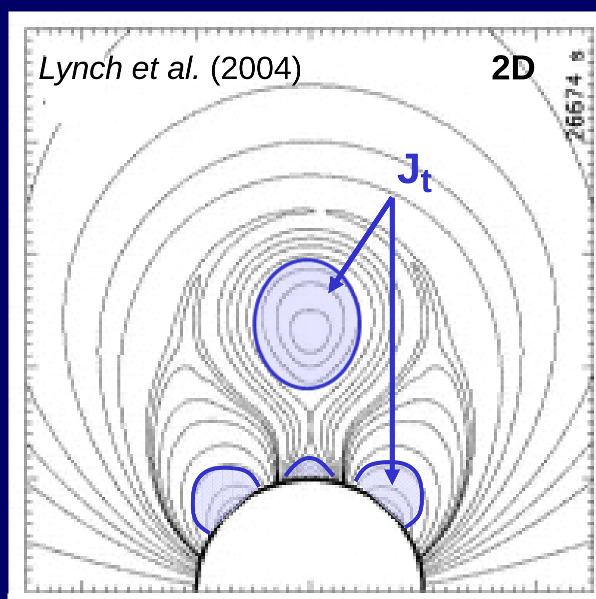
- CME dynamics are described by a set of two ODEs
  - Calculated dynamics have been compared with LASCO and STEREO data
  - Both major radial and minor radial expansion is correctly described by the theory
  - The main acceleration and the subsequent propagation to 1 AU are correctly captured
    - *Drag 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

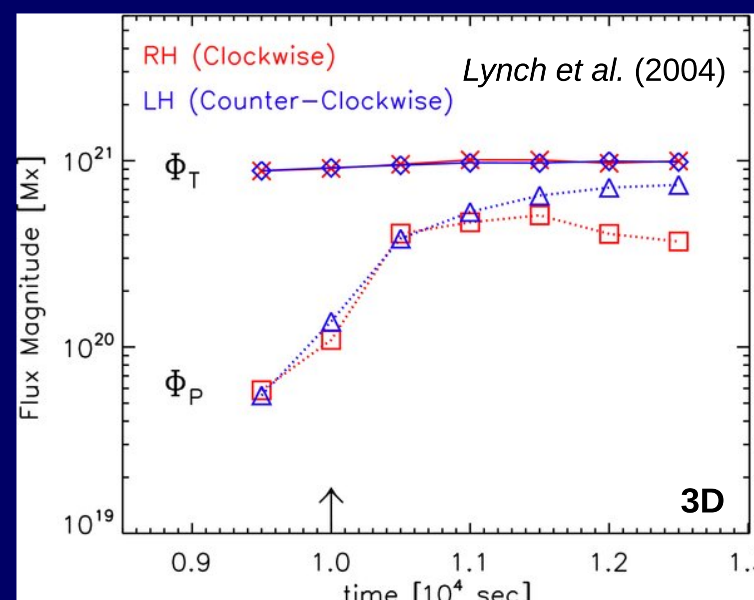
PHYSICS OF POLOIDAL FLUX INJECTION

- Currently, $d\Phi_p(t)/dt$ 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

- $d\Phi_p(t)/dt$ is a point of overlap between the two basic paradigms (arcade *v*. flux rope) [*Chen* 1996; *Chen and Krall* 2003]

Breakout model simulation





OPEN ISSUES

- 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

END

3-D GEOMETRY OF CMEs

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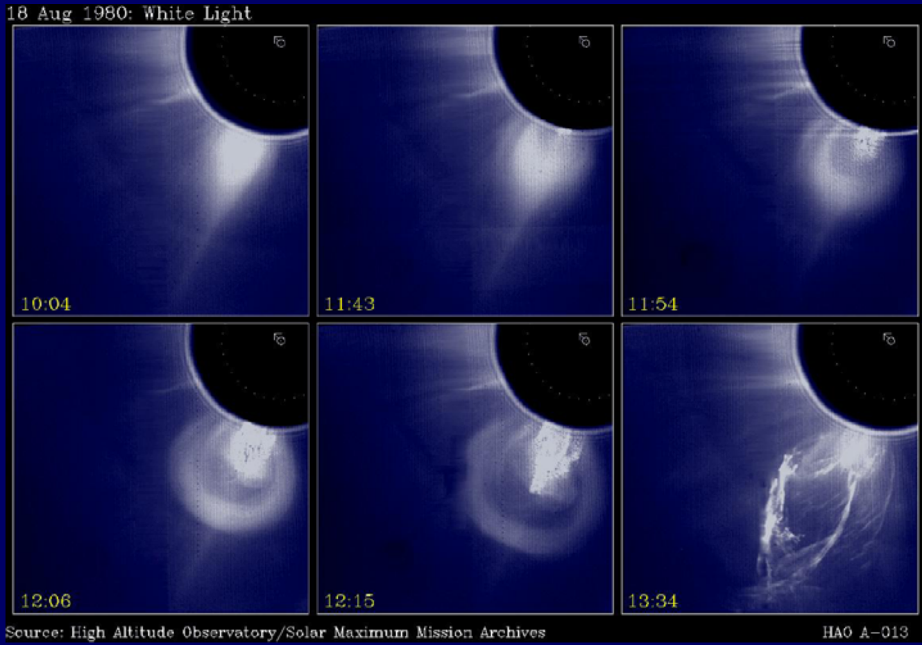
- *"Coronal transients"* (1970's: *OSO*-7, *Skylab*)
- "Thin" flux tubes
  (*Mouschovias and Poland* 1978; *Anzer* 1978)
- Halo CMEs (*Solwind*) (*Howard et al.* 1982)
  - Fully 3-D in extent
- CME morphology (*SMM*):
  (*Illing and Hundhausen* 1986)
  - A CME consists of 3-parts: a bright frontal rim, 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

FOV: 1.7 – 6 R_S

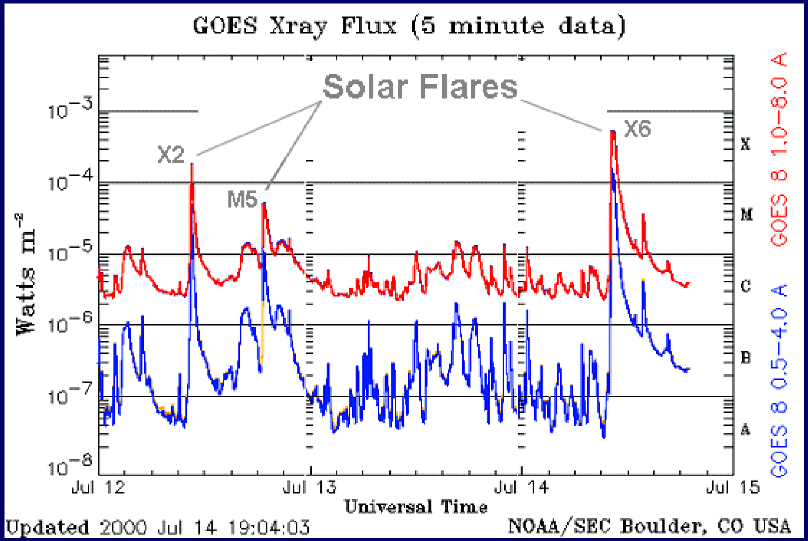


(*Illing and Hundhausen* (1986)

SMM (1980-1981; 1984-1989)

SOLAR ERUPTIONS: PHENOMENOLOGY

- Sporadic eruptions
  - Solar flares seen in X-rays, EUV, Hα, etc.
  - Filament/prominence eruptions seen in Hα 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