# Solar Eruption

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- Observations
- Theoretical Implications

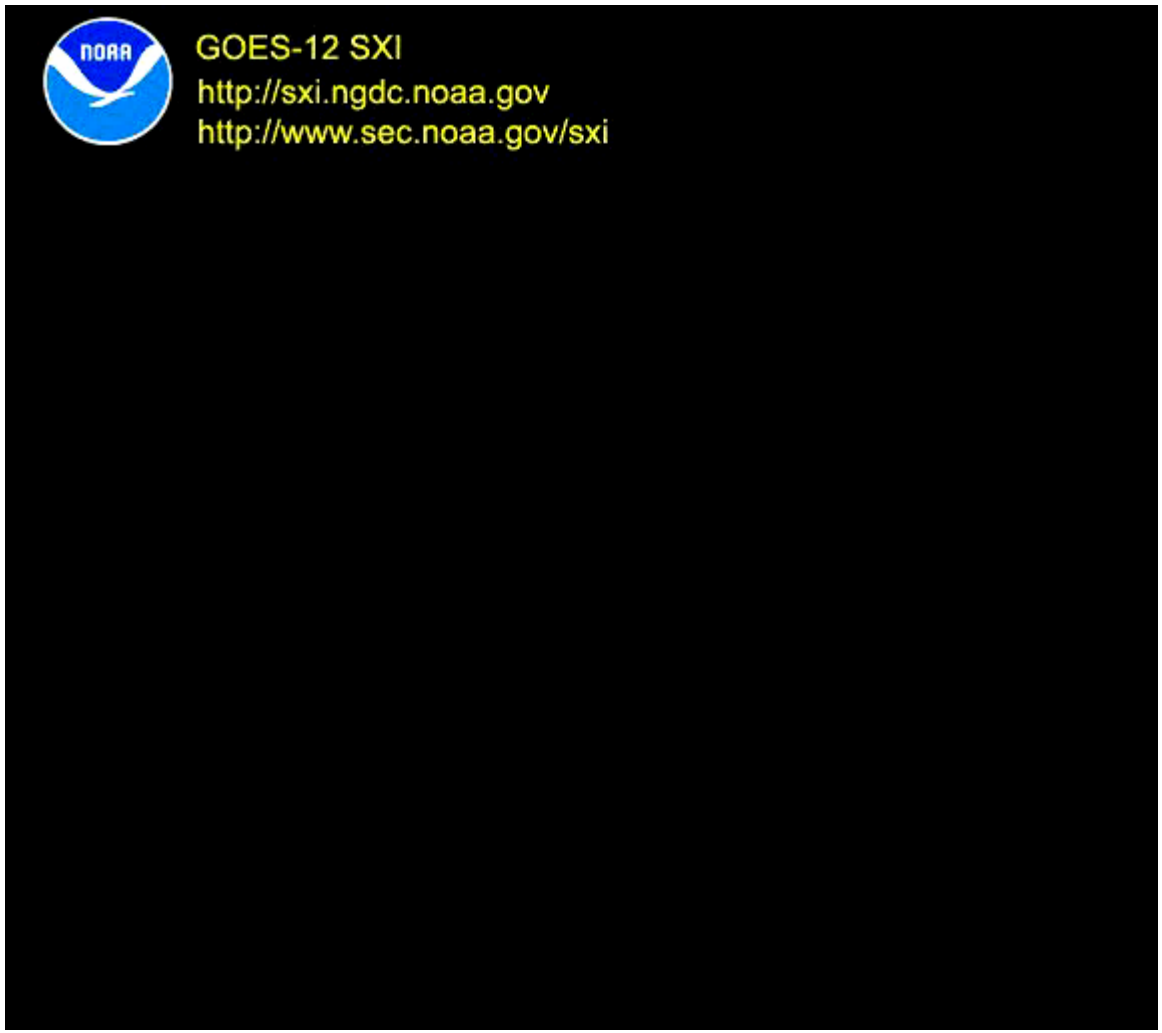
# An overview

- Two main Solar Eruptions
  - CMEs
  - Flares

- Related phenomena
  - Filaments/Prominences
  - Post-eruption loop arcades, Ribbons
  - Dimmings/Waves

- Geo-space consequences – Space Weather
  - Energetic Particles
  - Magnetic Disturbances

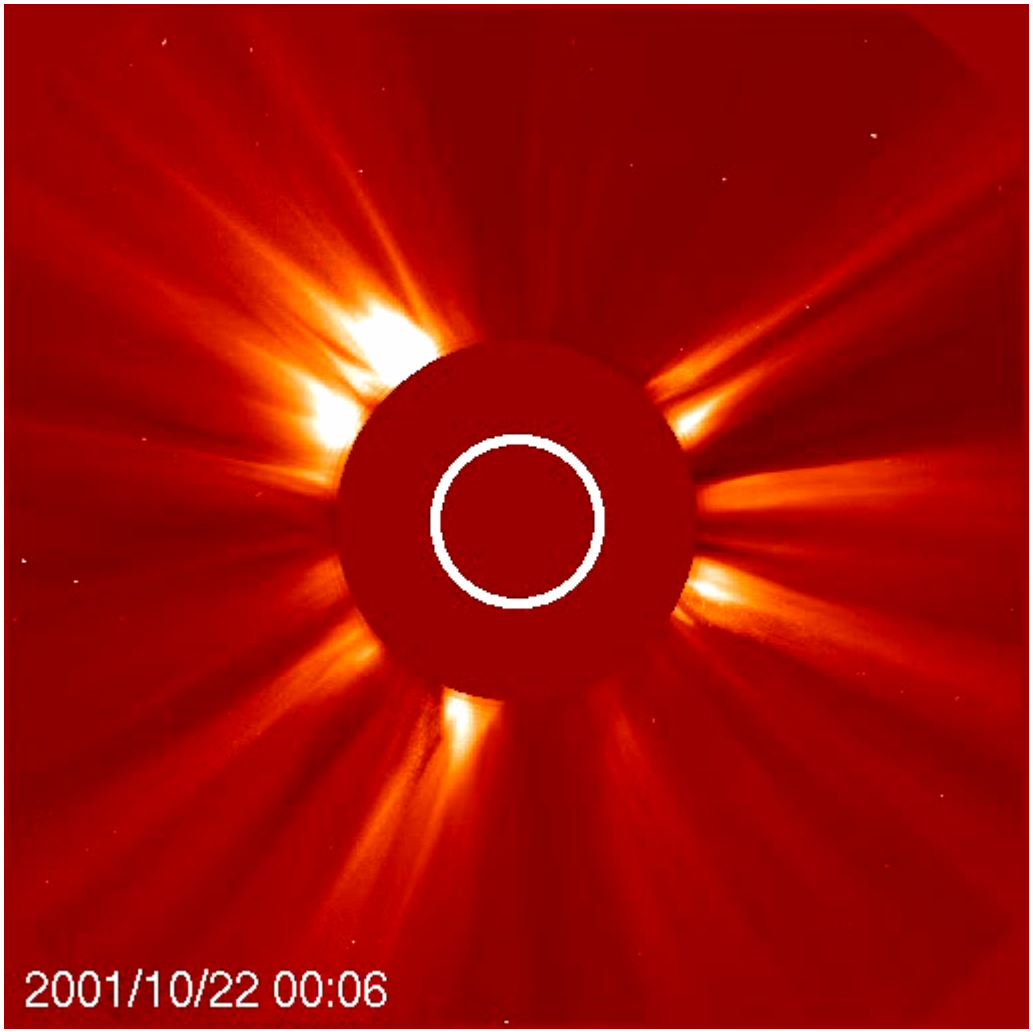
# Examples: Flares




Heating
Particle Acceleration

Small scale
Compact

# Examples: CMEs

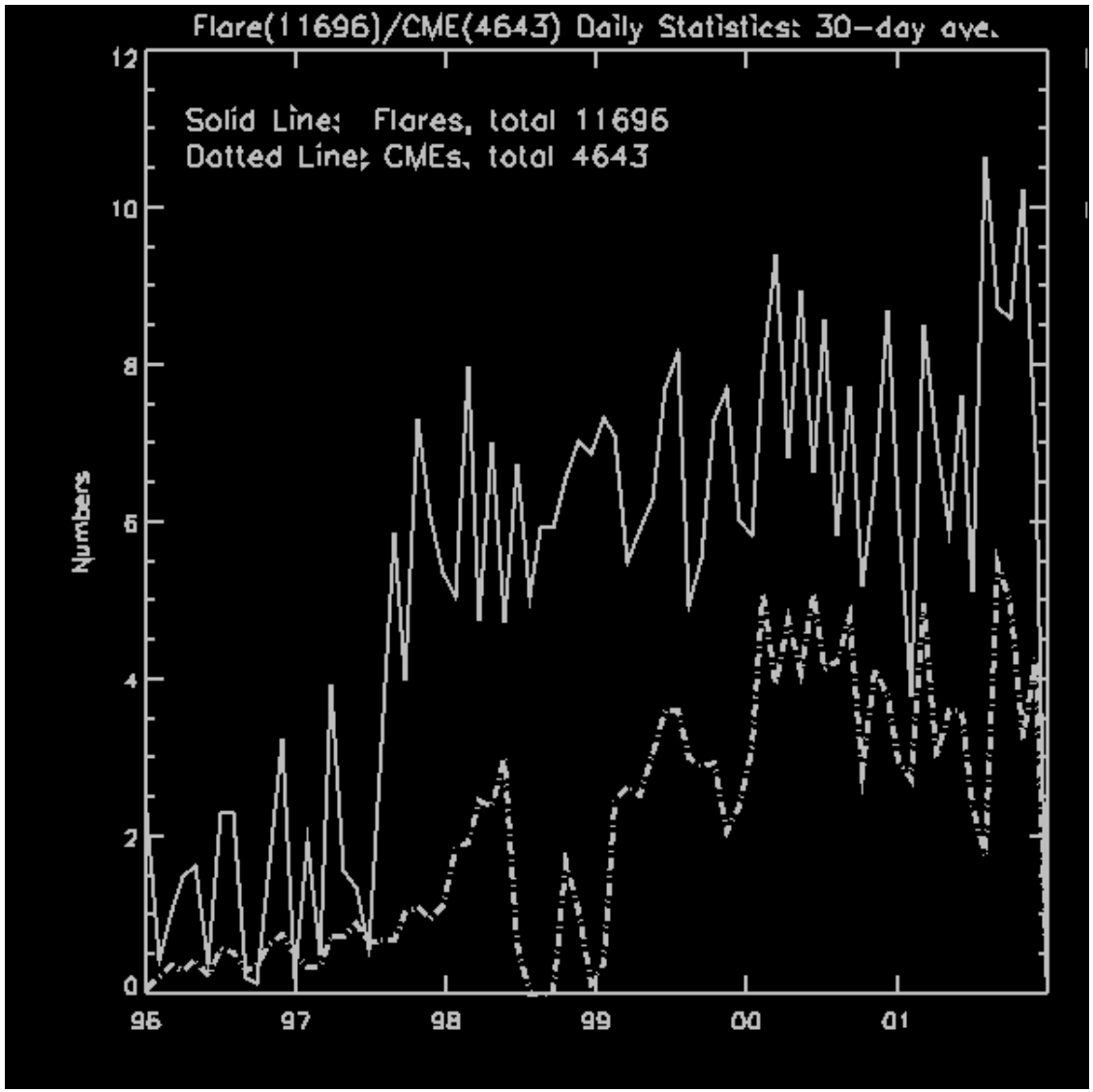



Large Scale
Eruption

Kinetic Evolution

Bulk mass acceleration
Bulk magnetic disruption

# CME/Flare Statistics




**Year 1996 – 2002**

| | |
|---|---|
| **Flare Number** | **11696** |
| **CME Number** | **4643** |

| **Daily** | **Min** | **Max** |
|---|---|---|
| **Flare** | **1.0** | **10** |
| **CME** | **0.4** | **4** |

# The Association

- CMEs are highly associated with flares
(e.g, Monro et al. 1979, Webb and Hundhausen 1987, St. Cyr and Webb 1991)

  - 70% to 90% CMEs are associated with flares
  - 10% to 30% CMEs are not associated with flares
    (e.g., Srivastava et al. 1999, Zhang et al. 2004)

- Flares are less associated with CMEs
  - 10% to 30% flares are associated with CMEs
  - 70% to 90% flare are not associated with CMEs
    (Harrison 1995, Andrews 2004)

- The association trends are (e.g. Sheeley et al. 1975, 1983)
  - The stronger the flare, the higher the association rate
  - The longer the flare, the higher the association rate

# The Question

- **What is the physical relationship between CME and flare, when they occur associated?**

# Four inferred theories

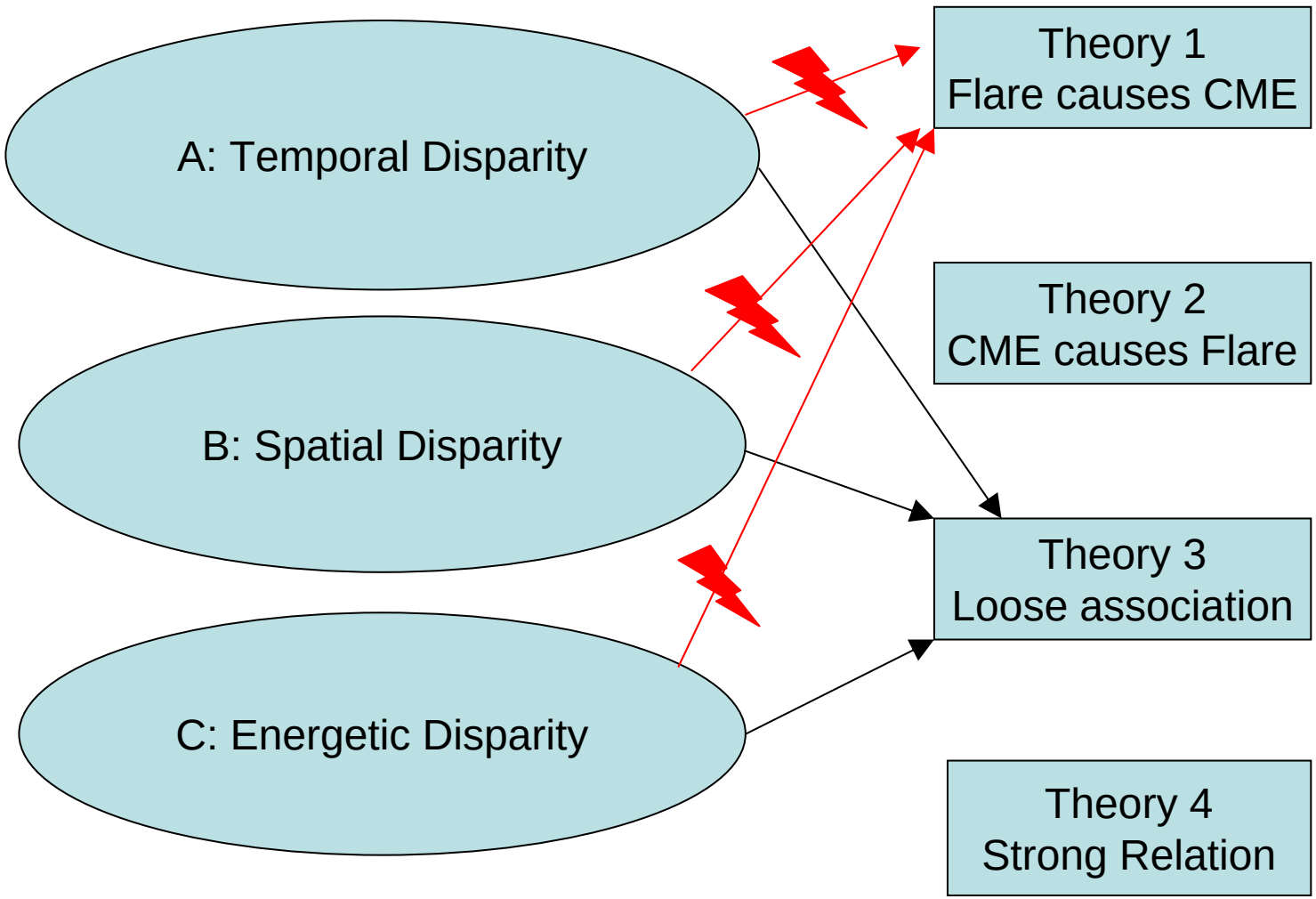
1. Flare causes CME?
e.g., blast-wave model
(Before and in1980s)

2. CME causes flare?
e.g., CME dominant
(In1990s and current)

3. Caused by same coronal process: but loose association
(e.g., Harrison 1995)
(In 1990s and current)

4. Caused by same coronal process: and strong relation
(e.g., Zhang et al., 2001, 2004)
(Current)

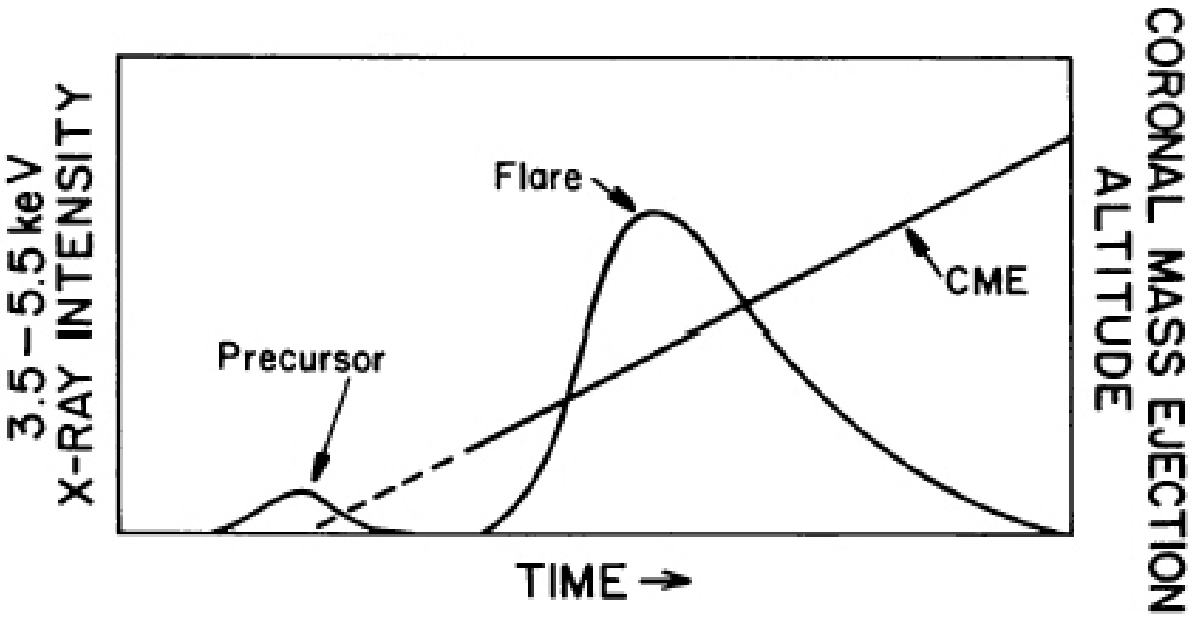
# Three “Established” Observations in 1980s and 1990s



# Temporal Relationship: onset time

- Onset of CME relative to flare
- How to determine CME onset time?
-

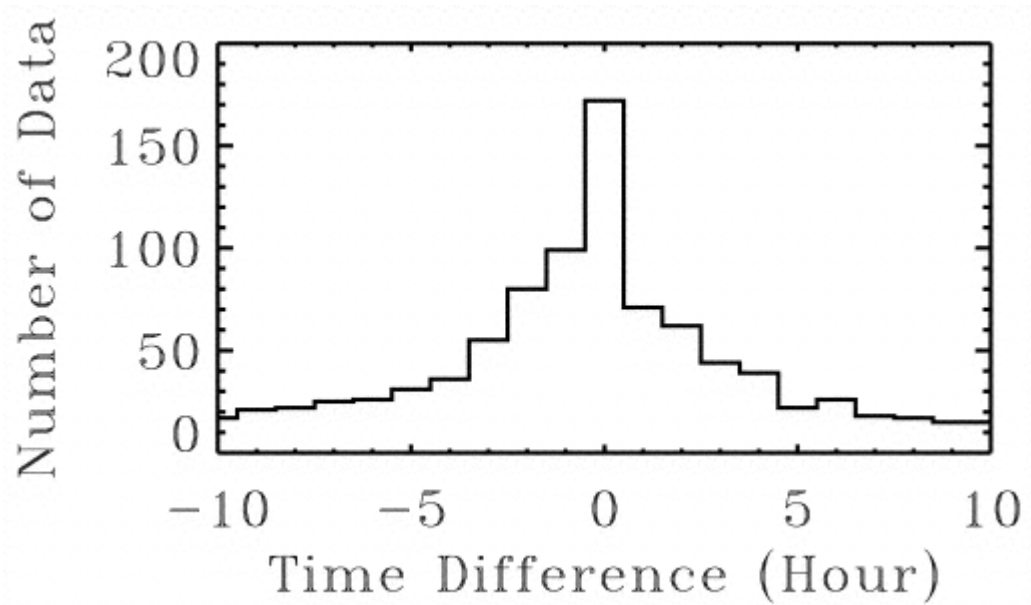
**Linear Extrapolation, is it OK?**




(From Harrison 1986)

# Temporal Relationship: Onset Time (Cont.)

- The extrapolation method always leads to a Gaussian-like distribution of the onset-time difference, centered at zero?

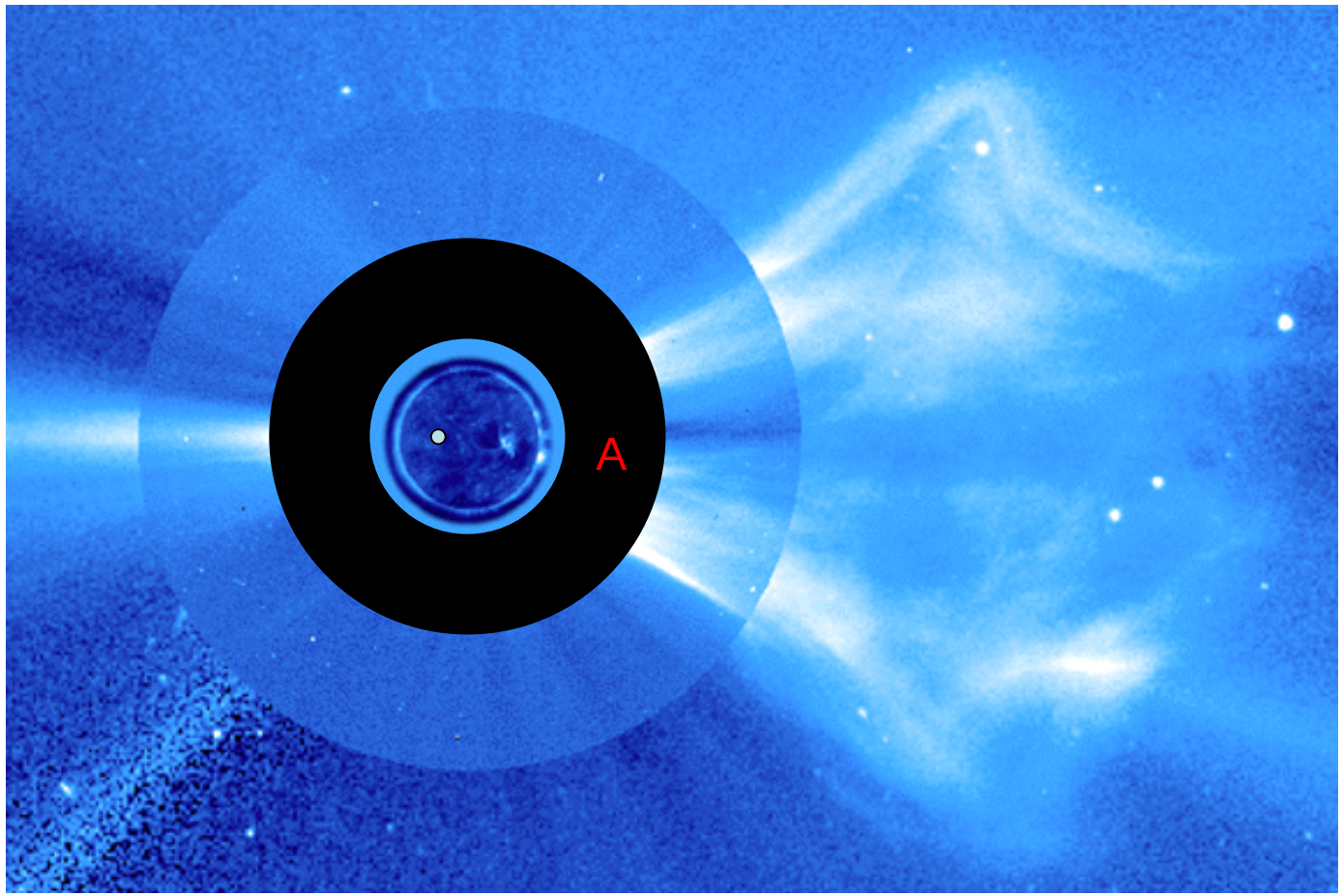



(From Moon et al. 2002, also see Harrison 1995)

- Implication: loose association between CME and Flare (Harrison 1995)
- However, wrong with this method (Zhang et al., 2001, 2004)
  - CME speed is not constant in the inner corona
  - CME is not accelerated instantaneously

# Observations: EIT, LASCO C1/C2/C3

- **CME acceleration starts in the inner corona, and mainly occurs in the inner corona.**



# LASCO/C1 Observations

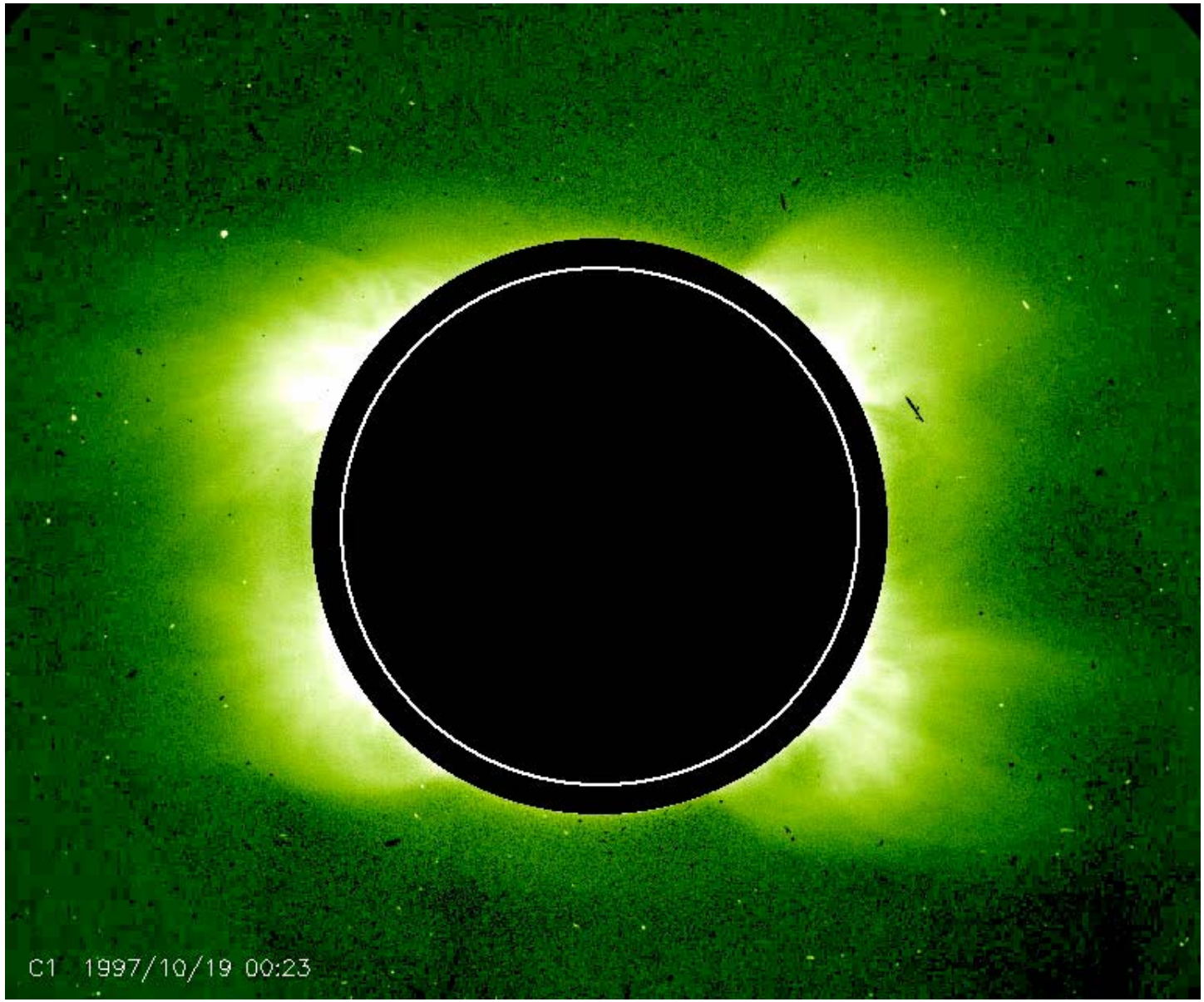
- About C1
  - Field of view: 1.1 to 3.0 Rs
  - Equipped with Fabry-Perot Interferometer
  - Coronal green line at 5302 Å, from Fe XIV
  - Coronal red line at 6376 Å, from FeX

- To study CME acceleration, we have systematically examined all LASCO C1 images, about 100,000 images in total from 1996 January to 1998 June

- Online at http://solar.scs.gmu.edu/research/cme_c1/index.html

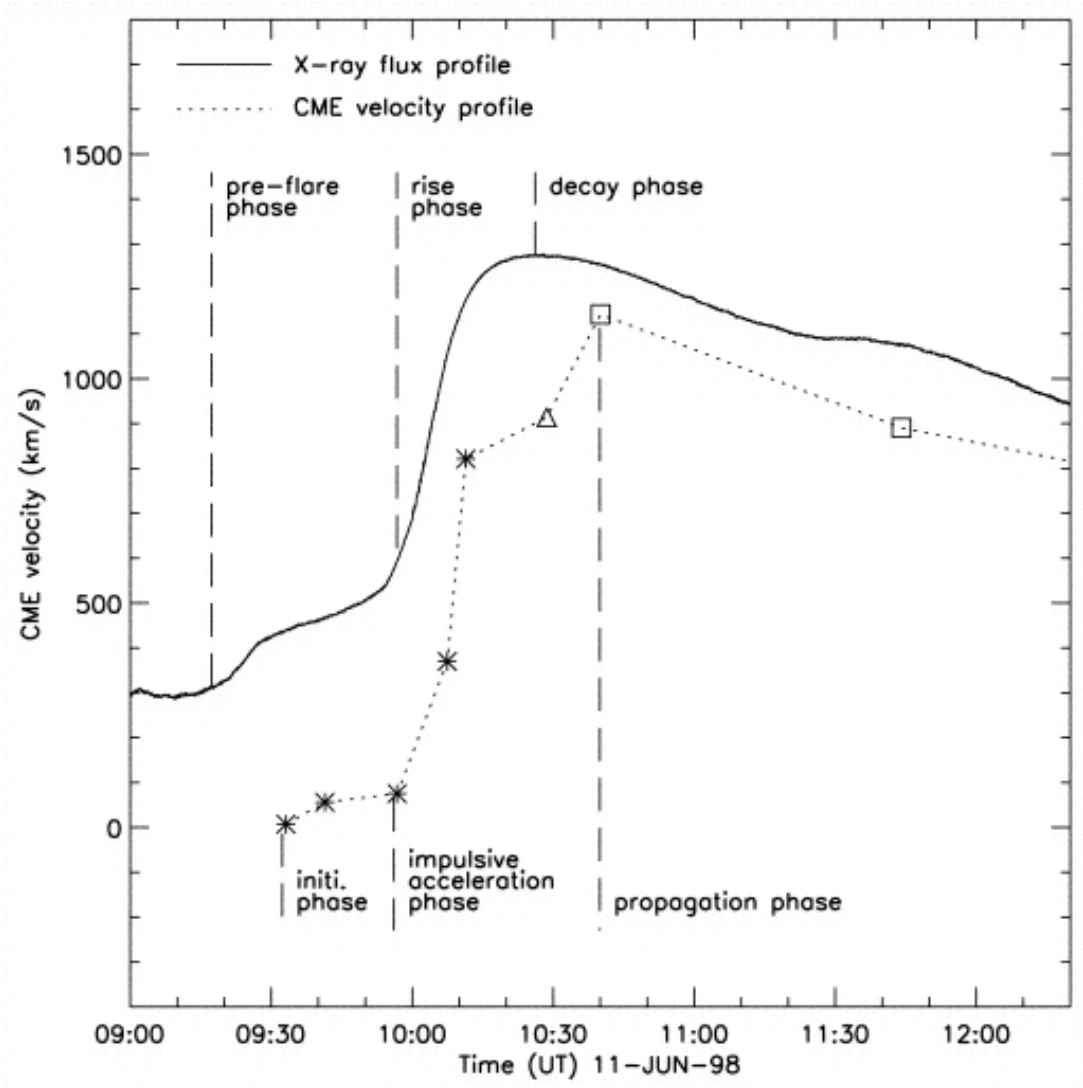
  - A list of all coronal activities, including CMEs, loop arcades, transient brightenings and dimmings et al.
  - A list of 101 CMEs, each with at least 1 LE seen by C1
  - A sub-set of 27 CMEs, each with at least 3 LE seen by C1

# Example: C1 movie



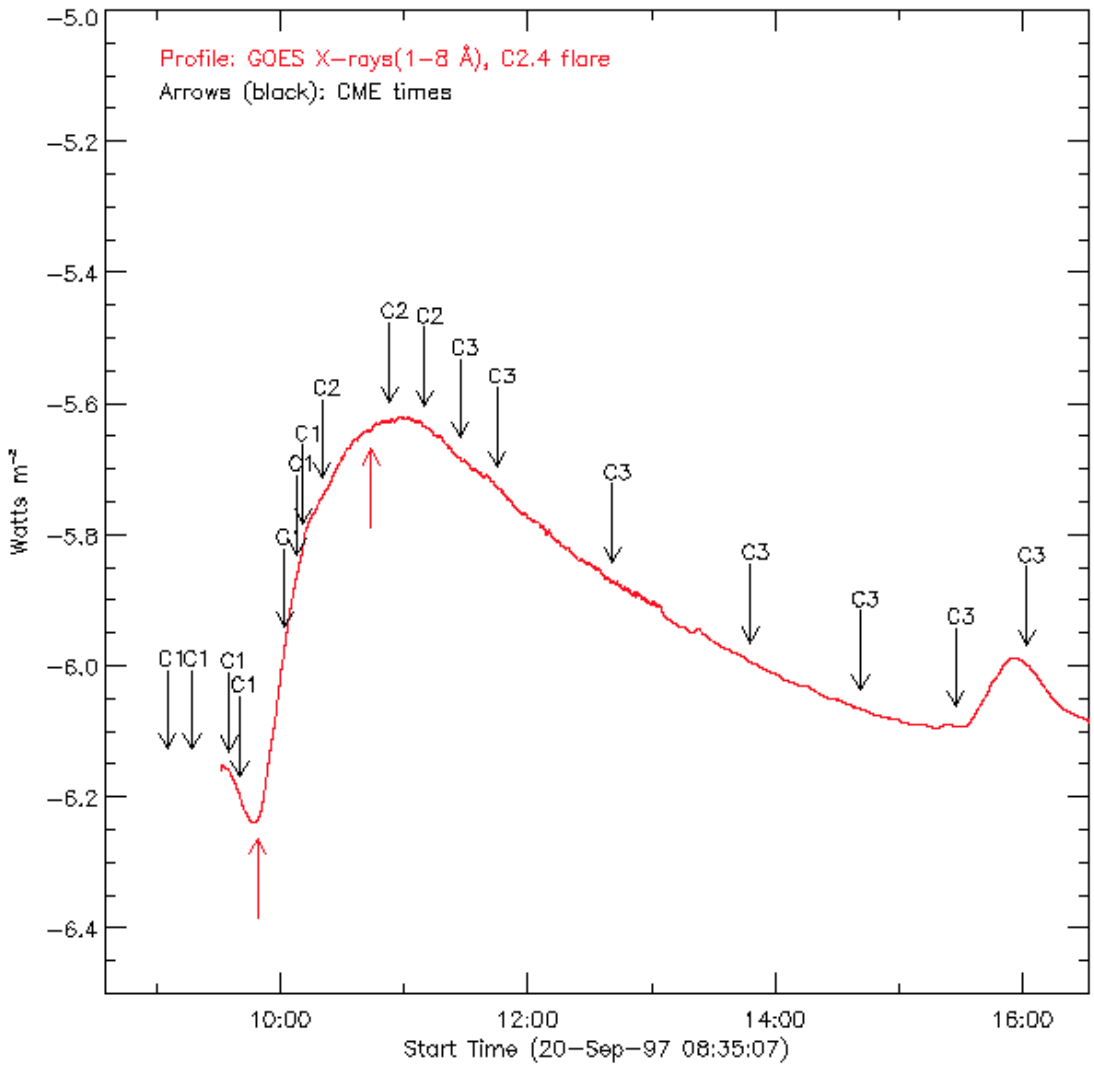
# Temporal Relationship: Three Phases of CME

**No extrapolation, and piece-wise numeric fitting to obtain velocity**




**(From Zhang et al. 2001)**

# Temporal Relationship: 1997 Sep. 20 event

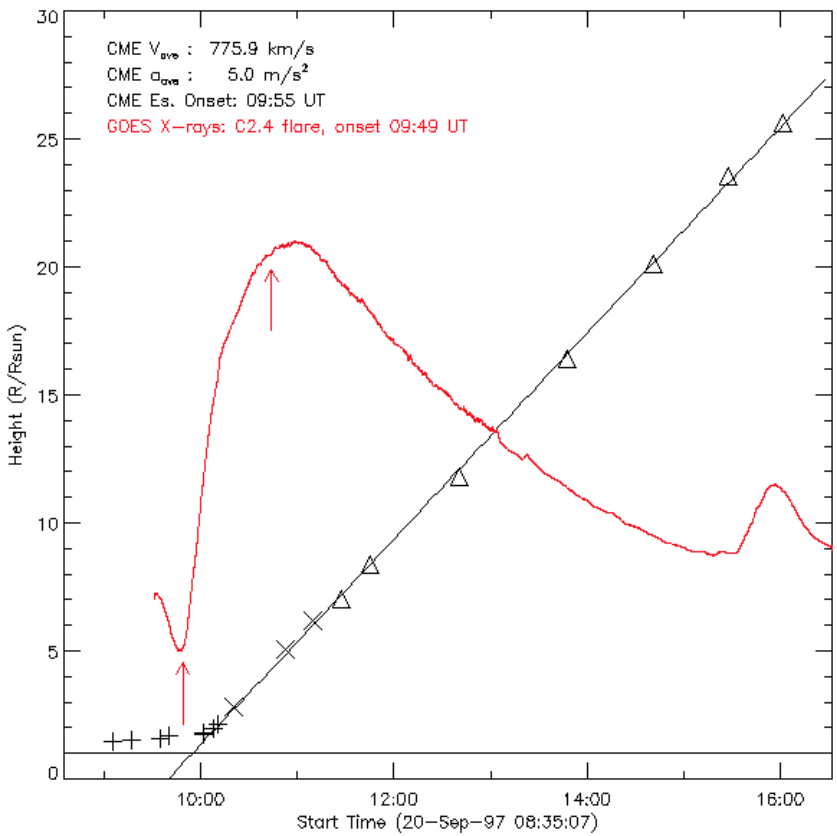



**Time**

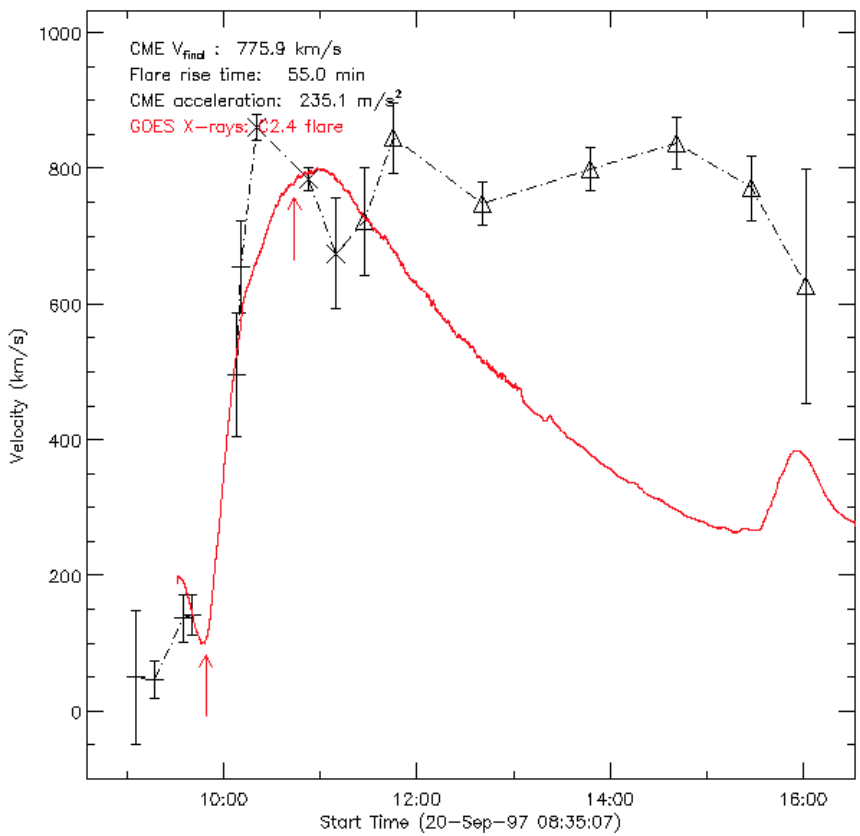
**C1: 8 images**
**C2: 3 images**
**C3: 7 images**

**GOES X-ray Flare: C2.3**

# Temporal Relationship: 1997 Sep. 20 event (Cont.)




**Height --Time Plot**

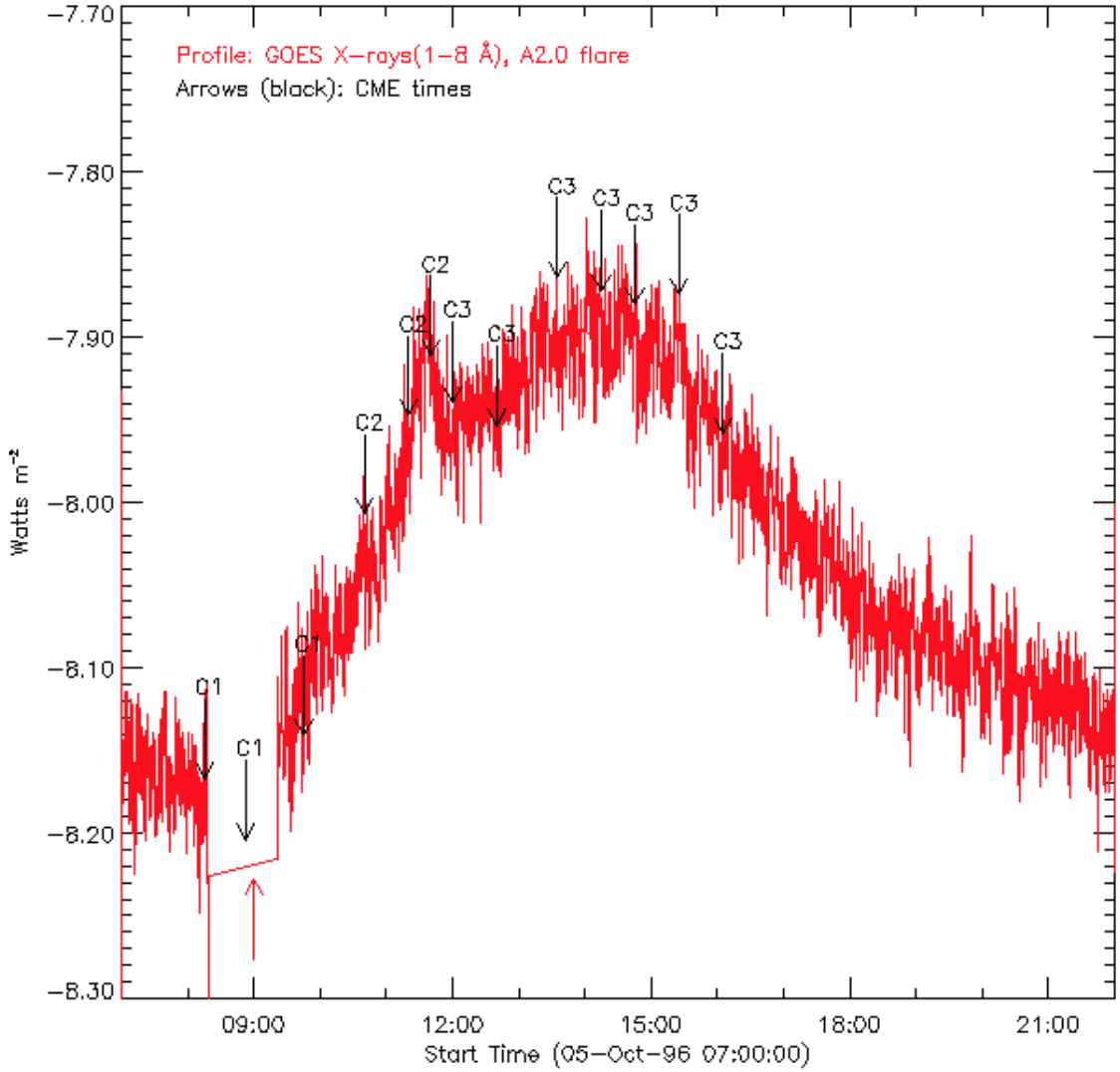



**Velocity -- Time Plot**

**ave. velocity in C2/C3: 775.9 km/s**
**ave. acceleration in C2/C3: 5.0 m/s$^2$**

**acceleration time: 55 min**
**propagation velocity: 775.9 km/s**
**acceleration in acc. phase: 235.1 m/s$^2$**

# Temporal Relationship: 1996 Oct. 05 event

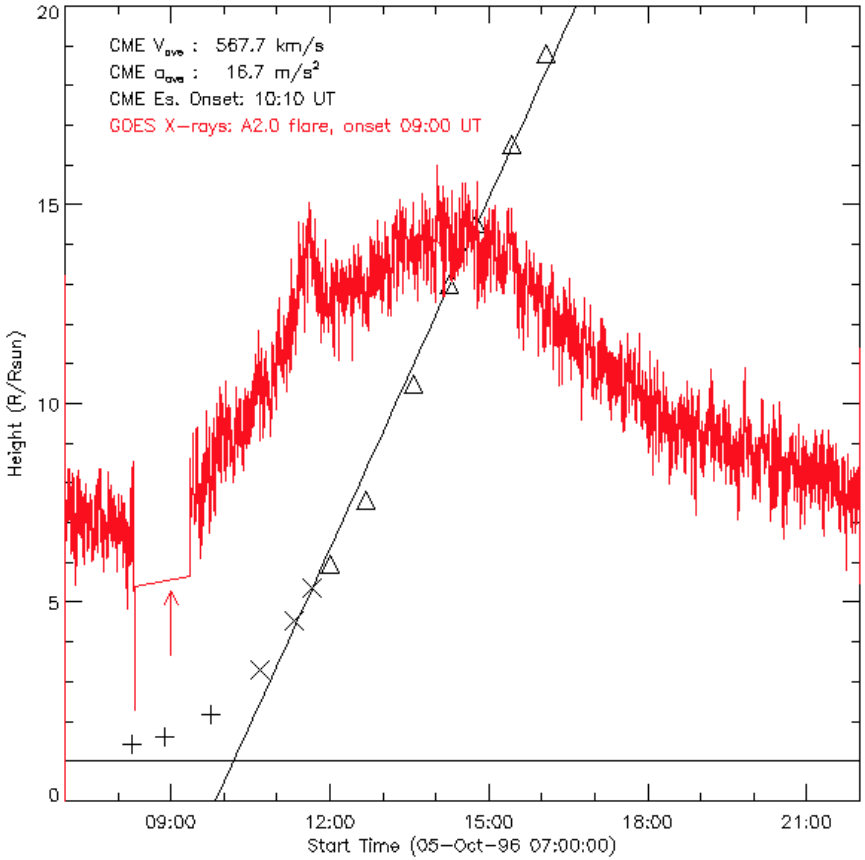



**Time**

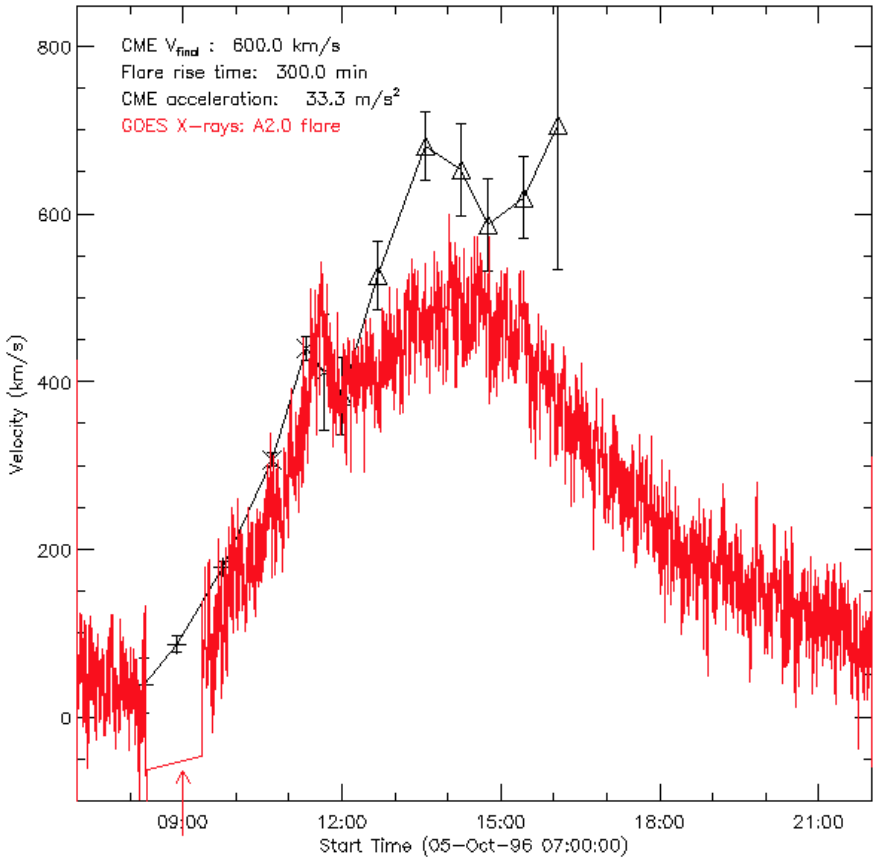
**C1: 3 images**
**C2: 3 images**
**C3: 7 images**

**GOES X-ray Flare: A1.2**
**not in NOAA/SEC catalog**

# Temporal Relationship: 1996 Oct. 5 event (Cont.)




## Height --Time Plot



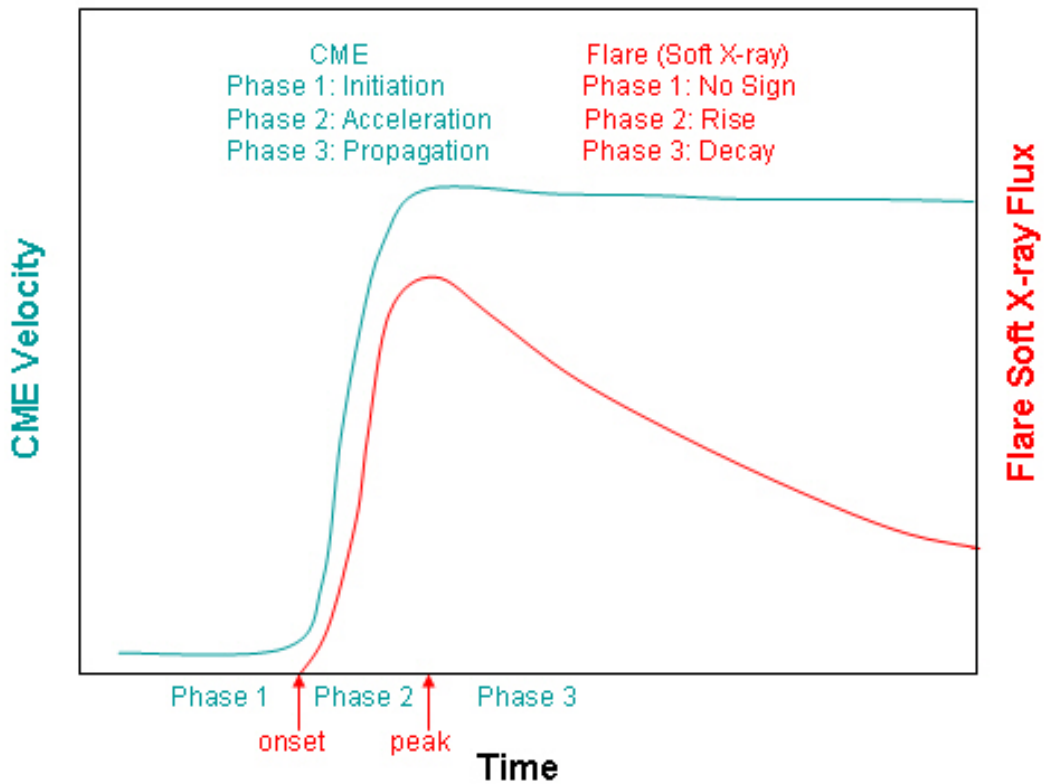

## Velocity -- Time Plot

**ave. velocity in C2/C3: 569.0 km/s**
**ave. acceleration in C2/C3: 16.8 m/s$^2$**

**acceleration time: 300 min**
**propagation velocity: 600.0 km/s**
**acceleration in acc. phase: 33.3 m/s$^2$**

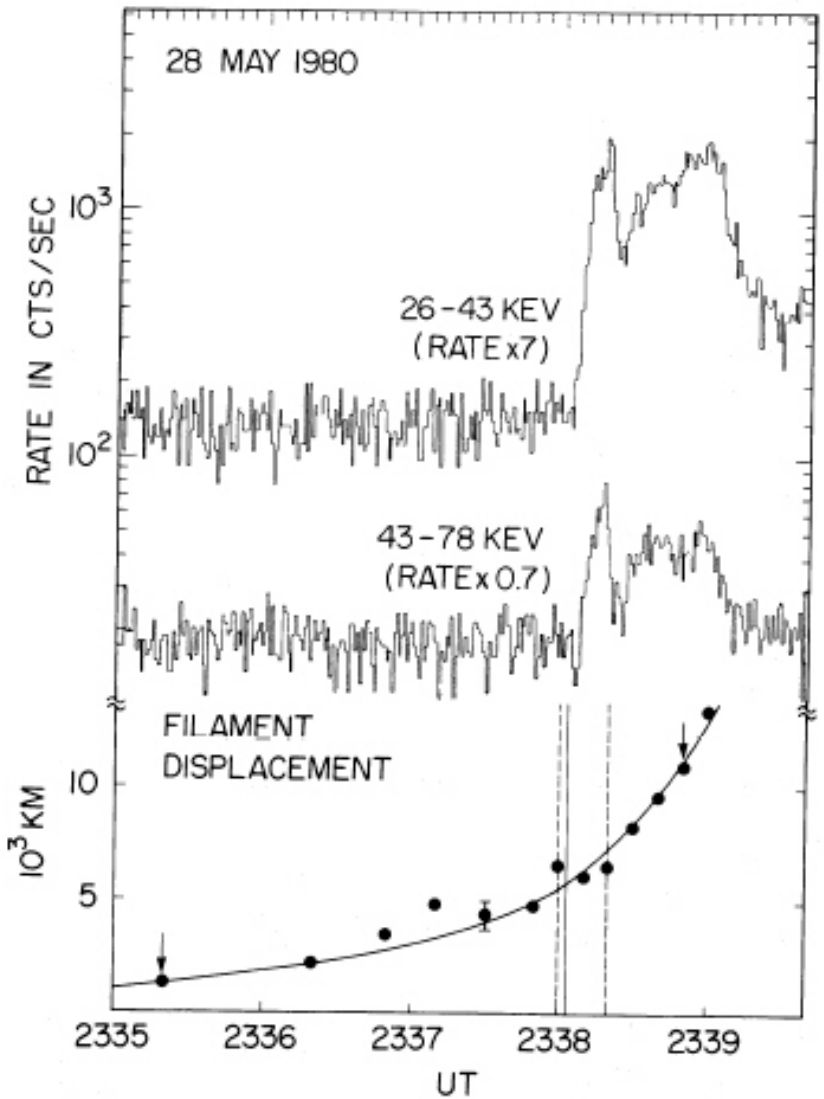
# Temporal Relationship: Time Coincidence

- **Temporal correlation between CME Kinematics and Flare Flux evolution:**
  1. **(slow) initiation phase may start earlier**
  2. **The onset of main (often impulsive) acceleration phase coincides with the onset of the flare**
  3. **The peak of CME velocity coincides with the peak of the flare**
- **Therefore, a strong physical relation instead of loose association**



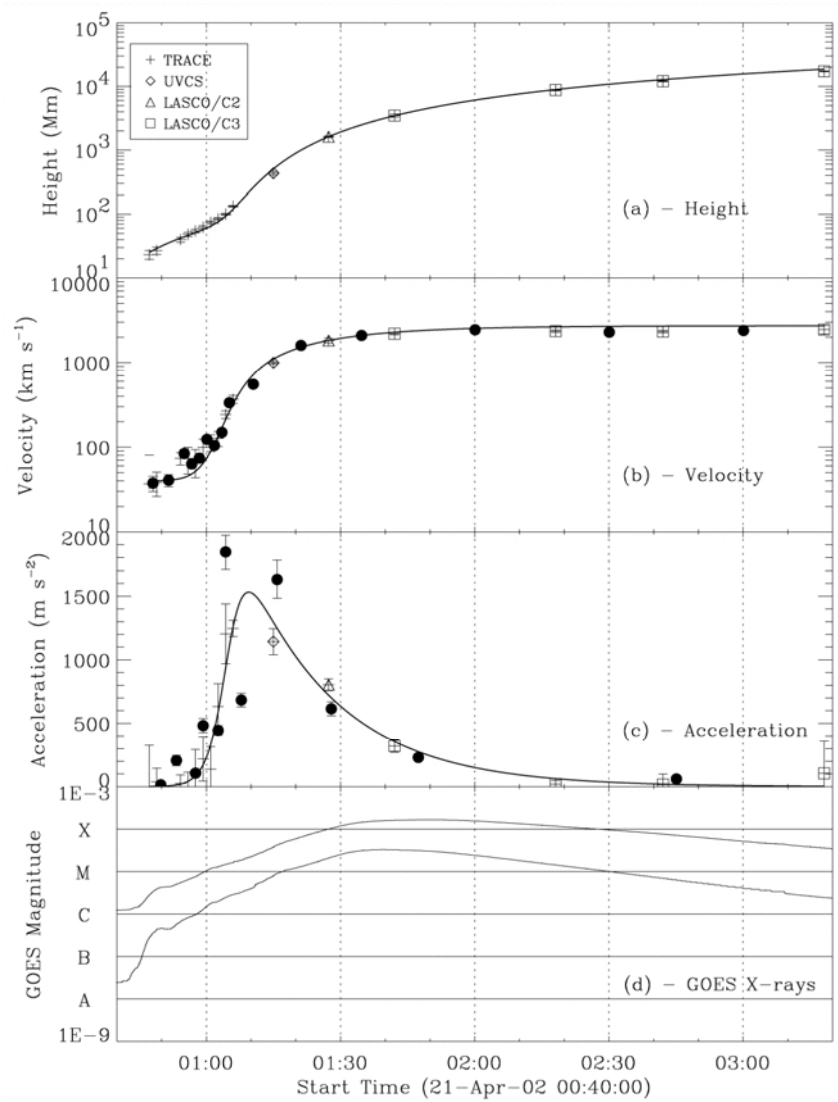
# Time Coincidence: Flare--Filament

## Filament -- Flare



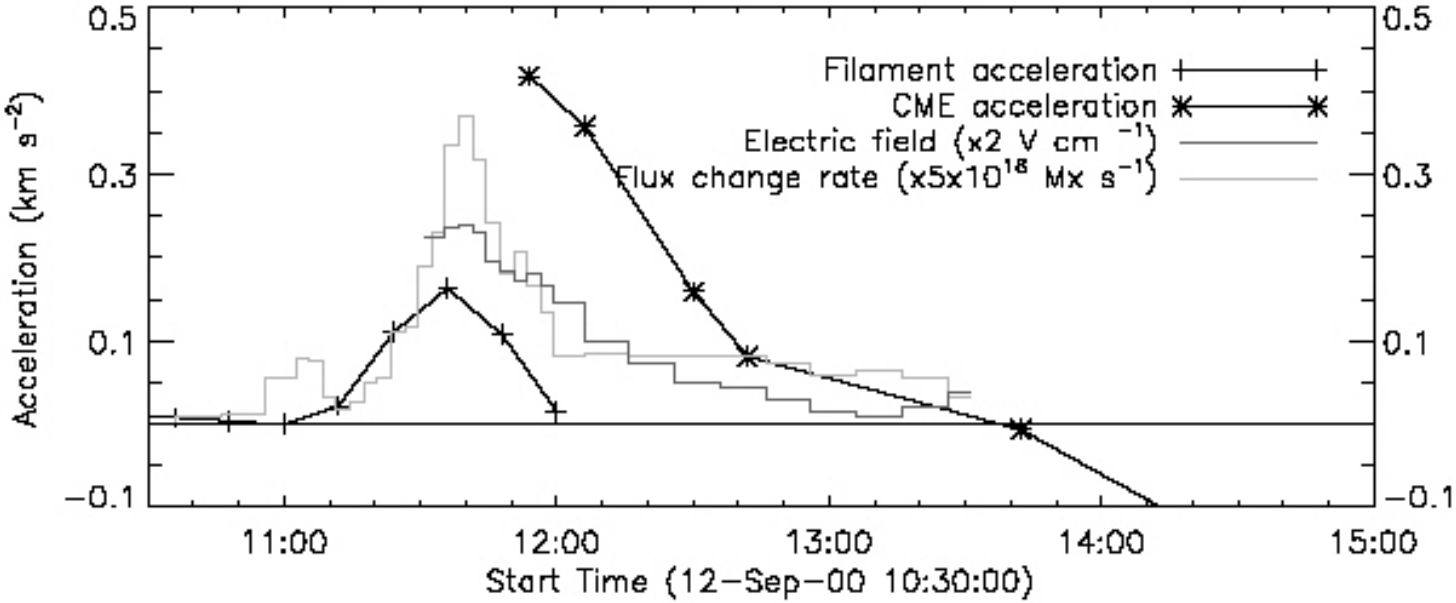

(From Kahler et al. 1988)

# Time Coincidence: Flare– EUV Ejecta/CME




**(From Gallagher et al. 2003)**

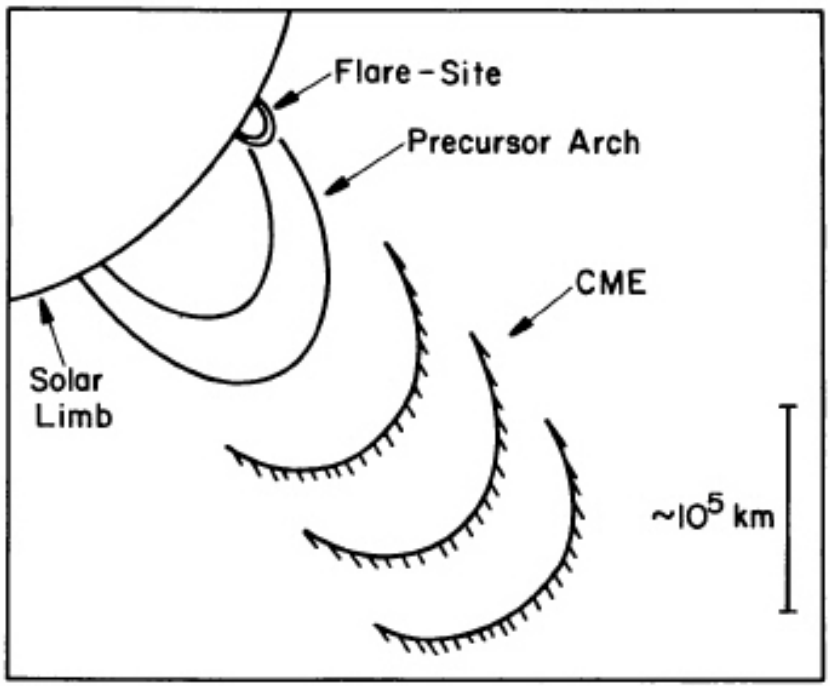
# Time Coincidence: Flare-- Hα Ribbon/Filament



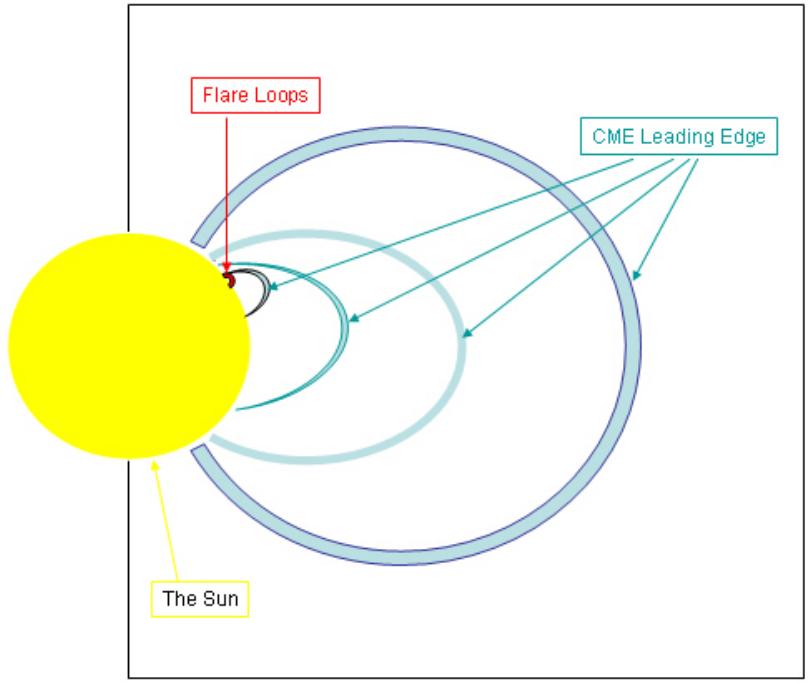

**(From Qiu. 2004)**

# Spatial Relationship

**Size disparity?** **Probably Not**
**Location Disparity?** **Probably Not**



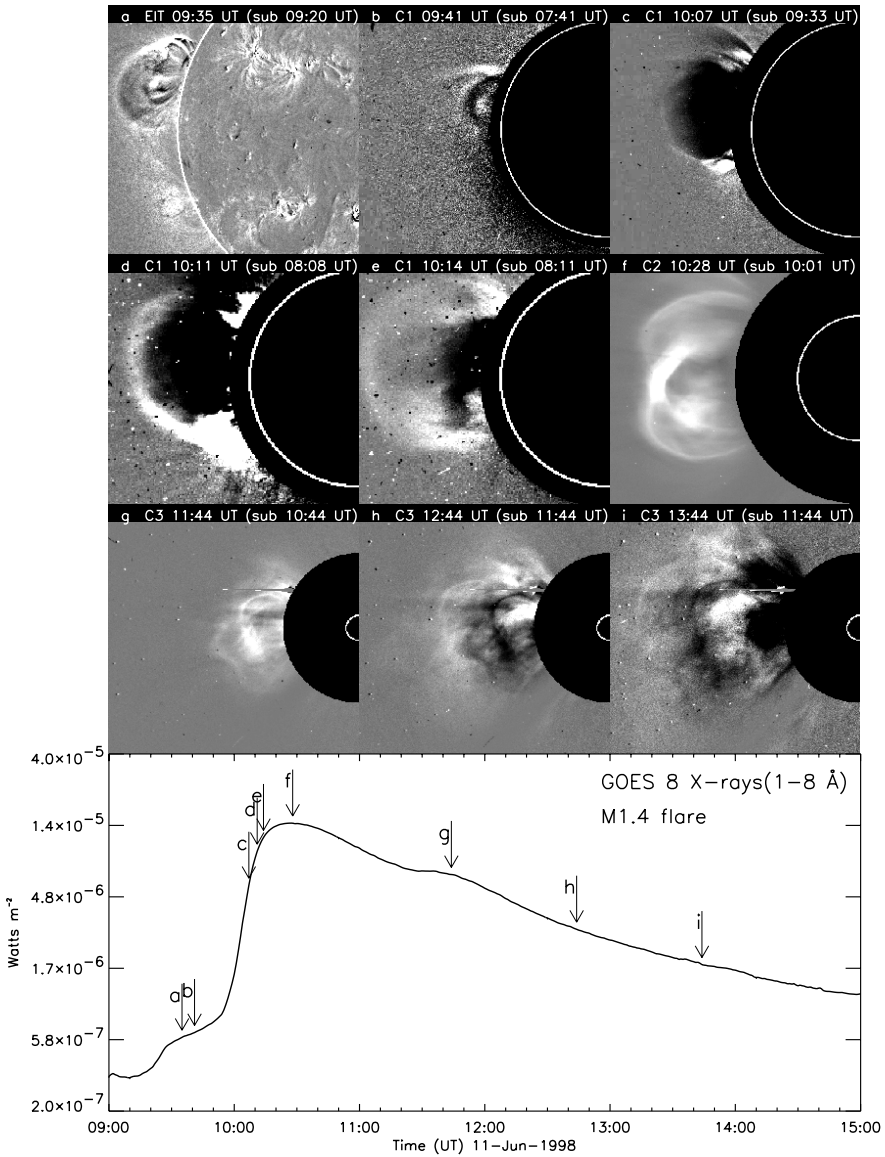

(From Harrison 1986)




(LASCO EIT/C1, present)

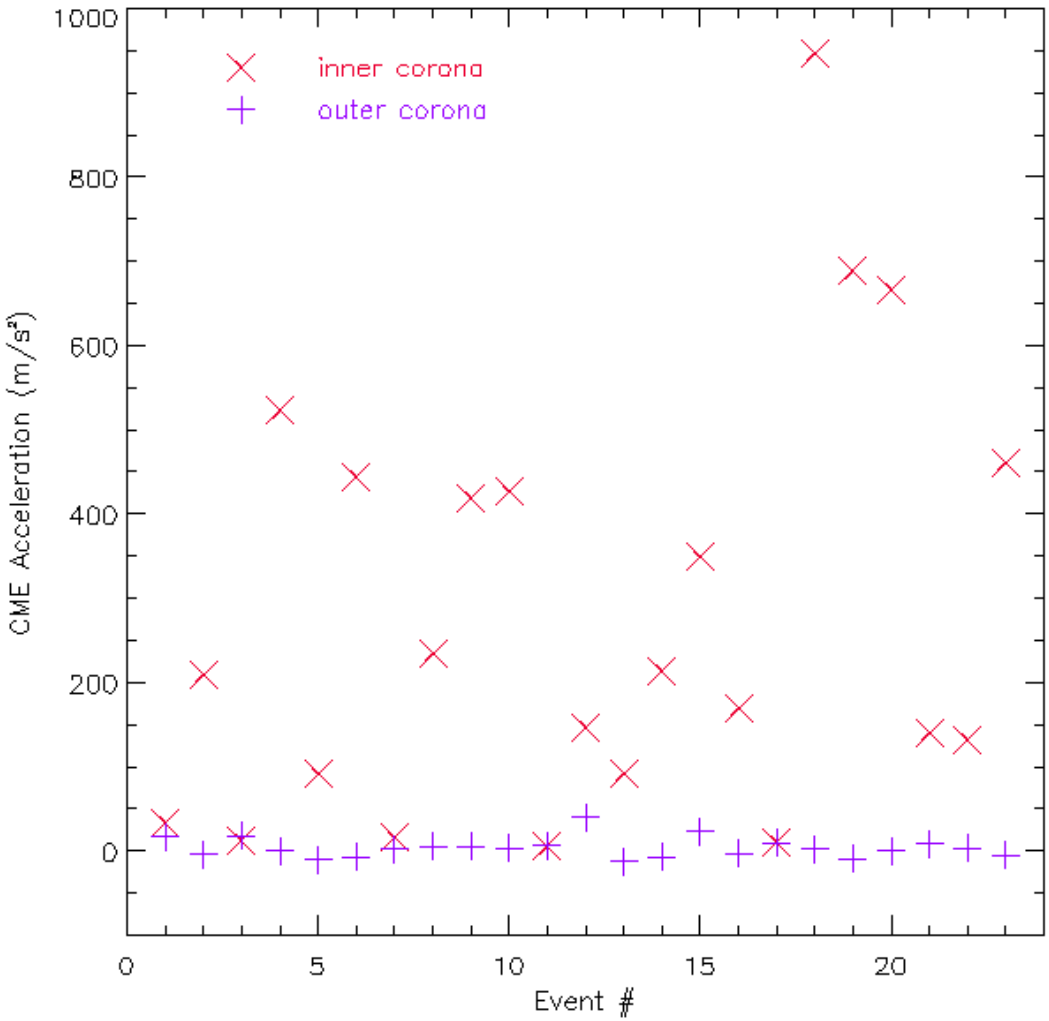
- **(Non-radial) Super-expansion of CME** in the main acceleration phase
- **(Radial) Self-similar expansion** of CME in the propagation phase

# Spatial Relationship




- **Super-expansion**
- **Self-similar expansion**

# CME Acceleration: Magnitude




**23 best observed events with at least 3 LE seen in C1**

**Outer Corona Acc.: averaged in C2/C3**

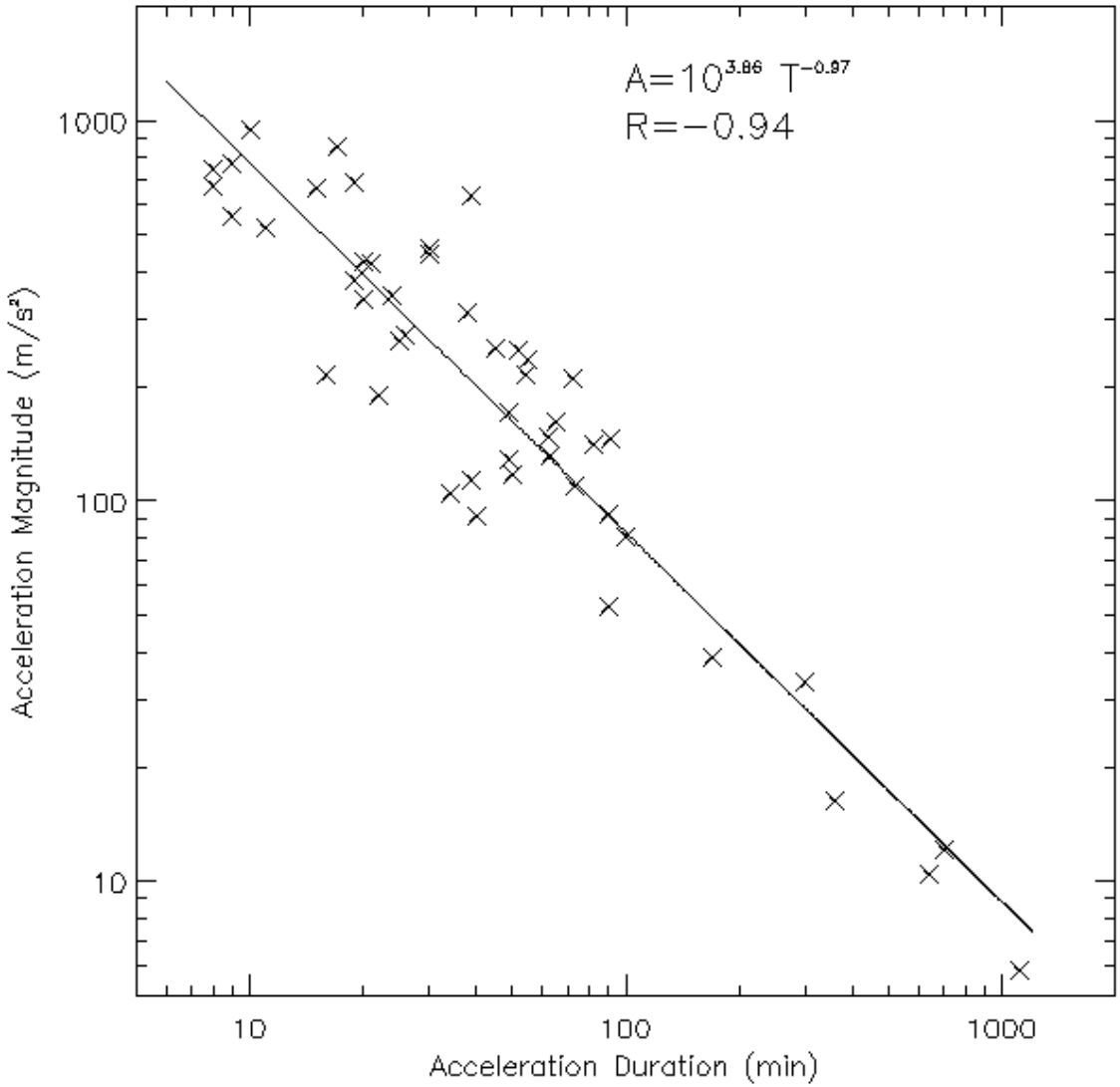
**Inner Corona Acc.: measured in the acc. phase**

| | Inner | Outer |
|---|---|---|
| Lowest | +5.8 | -12.8 |
| Highest | +946.9 | +39.6 |
| Medium | +209.0 | +2.6 |
| Average | +279.0 | +3.5 |

**($m/s^2$)**

**St.Cyr et al (1999)**
**Average +274**
**Medium: +44 (-218--+3270)**

# CME Acceleration: a Scaling Law




**48 events**

**Duration of acc. phase:**
- **Minimum: 6 min**
- **Maximum: 1113 min**
- **Average: 103.6 min**
- **Medium: 40 min**

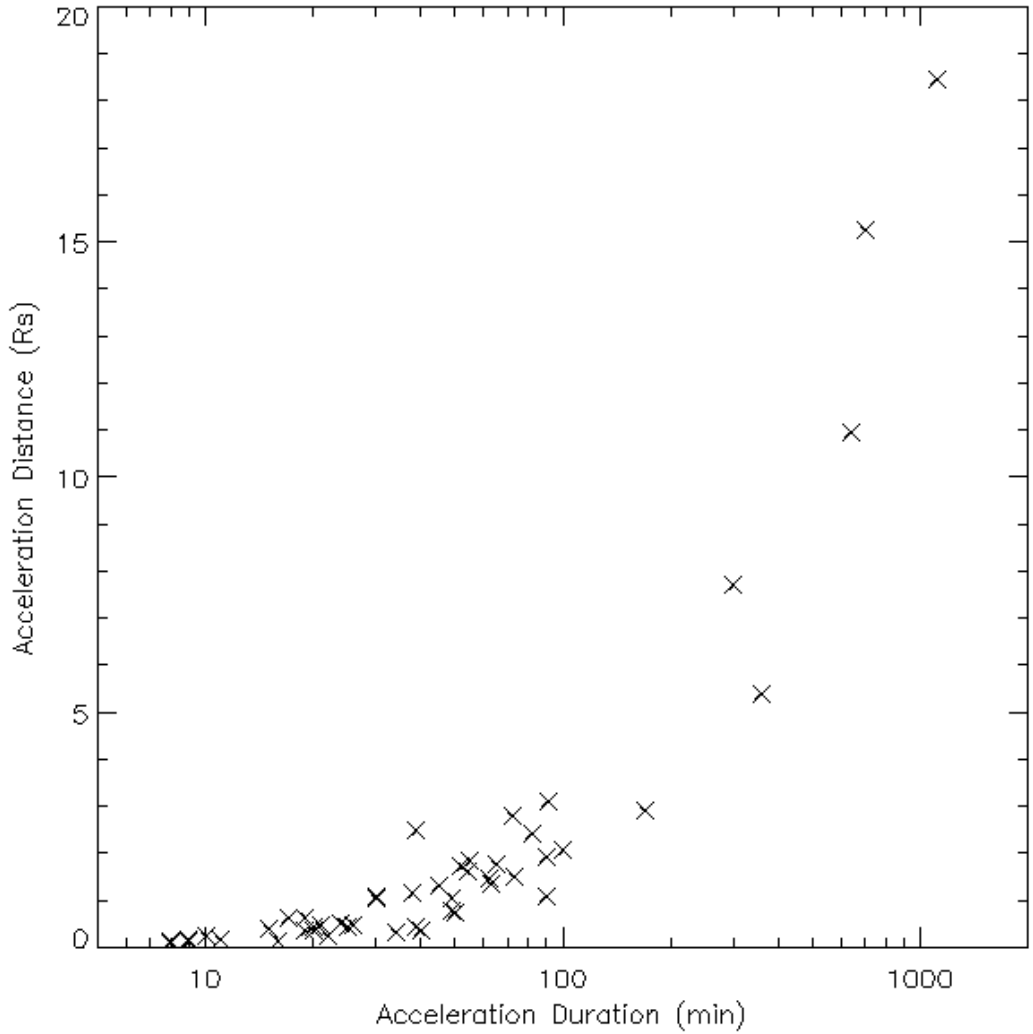
**A Scaling Law:**

$$A = 10^{3.86}\ T^{-0.97}$$

**Or simply**

$$A\ (m/s^2) = 7000\ /\ T\ (min)$$

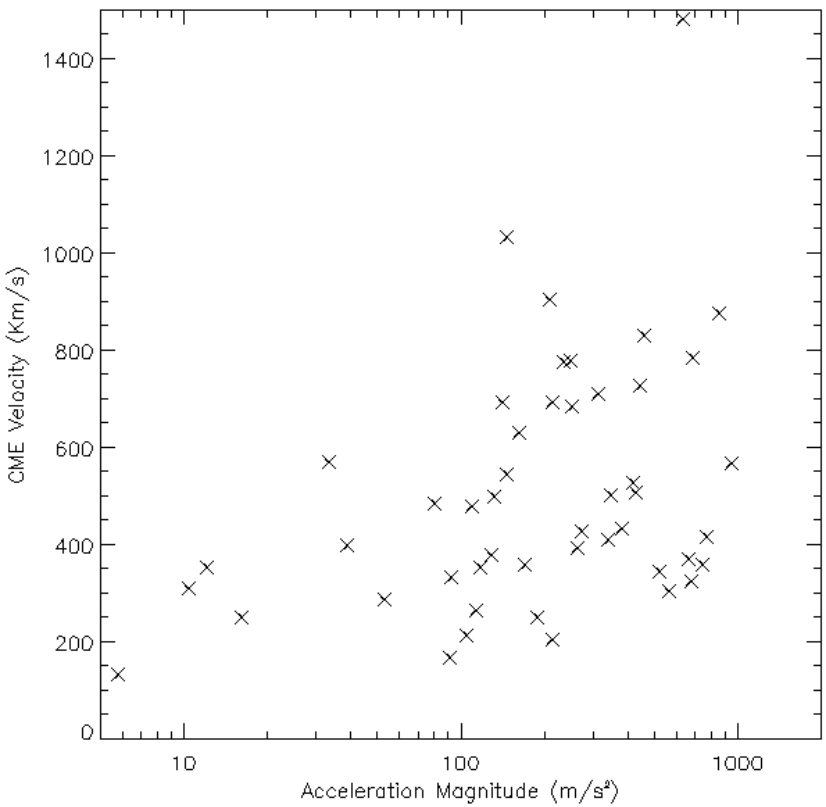
# CME Acceleration: Distance and Duration



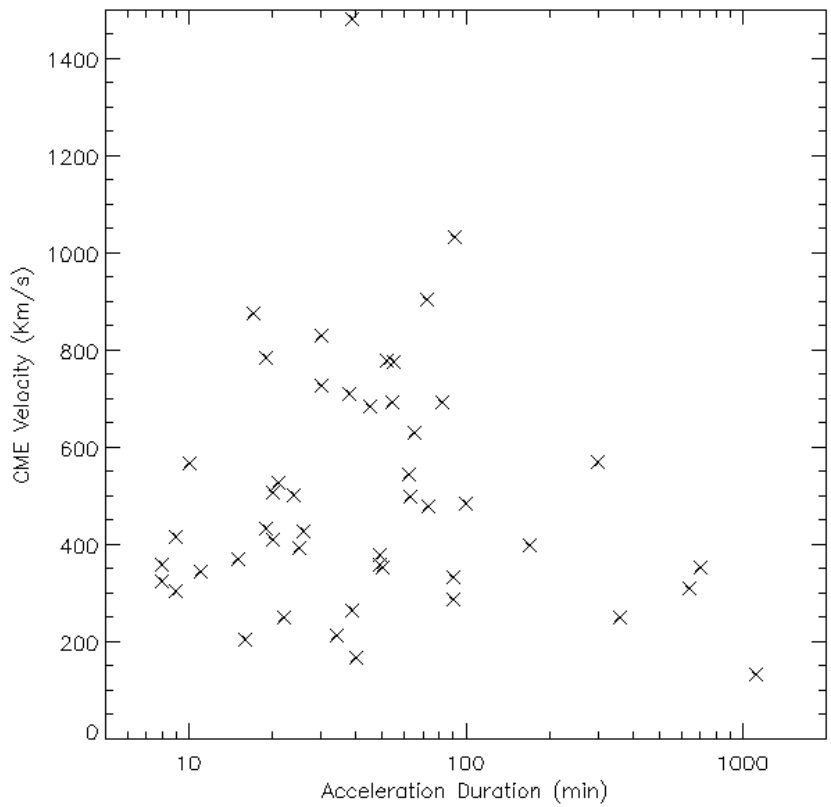

**Distance traveled in the acc. phase:**

- **Minimum: ~ 0.1 Rs**
- **Maximum: ~ 19 Rs**
- **Average: 2.12 Rs**
- **Medium: 1.05 Rs**

# What determine CME final Propagation Speed?




Magnitude

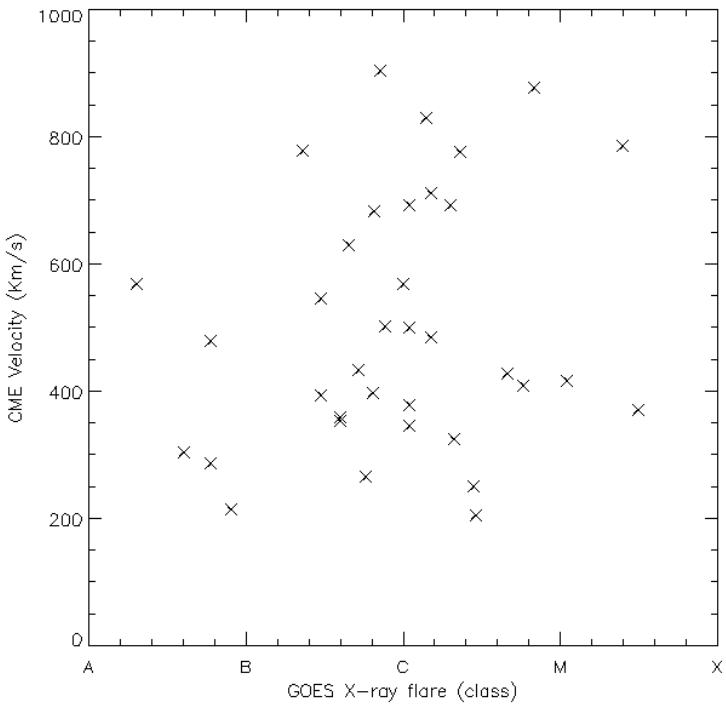


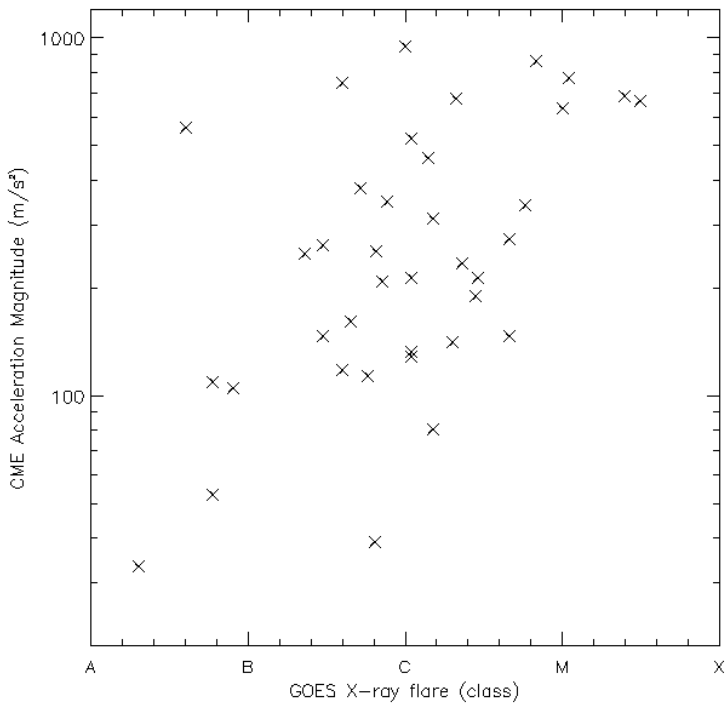

Duration

- **Not dominant by acceleration magnitude**
- **Not dominant by acceleration duration**
- **Equally determined by the two factors**

# Energetic Relationsip: CME/Flare

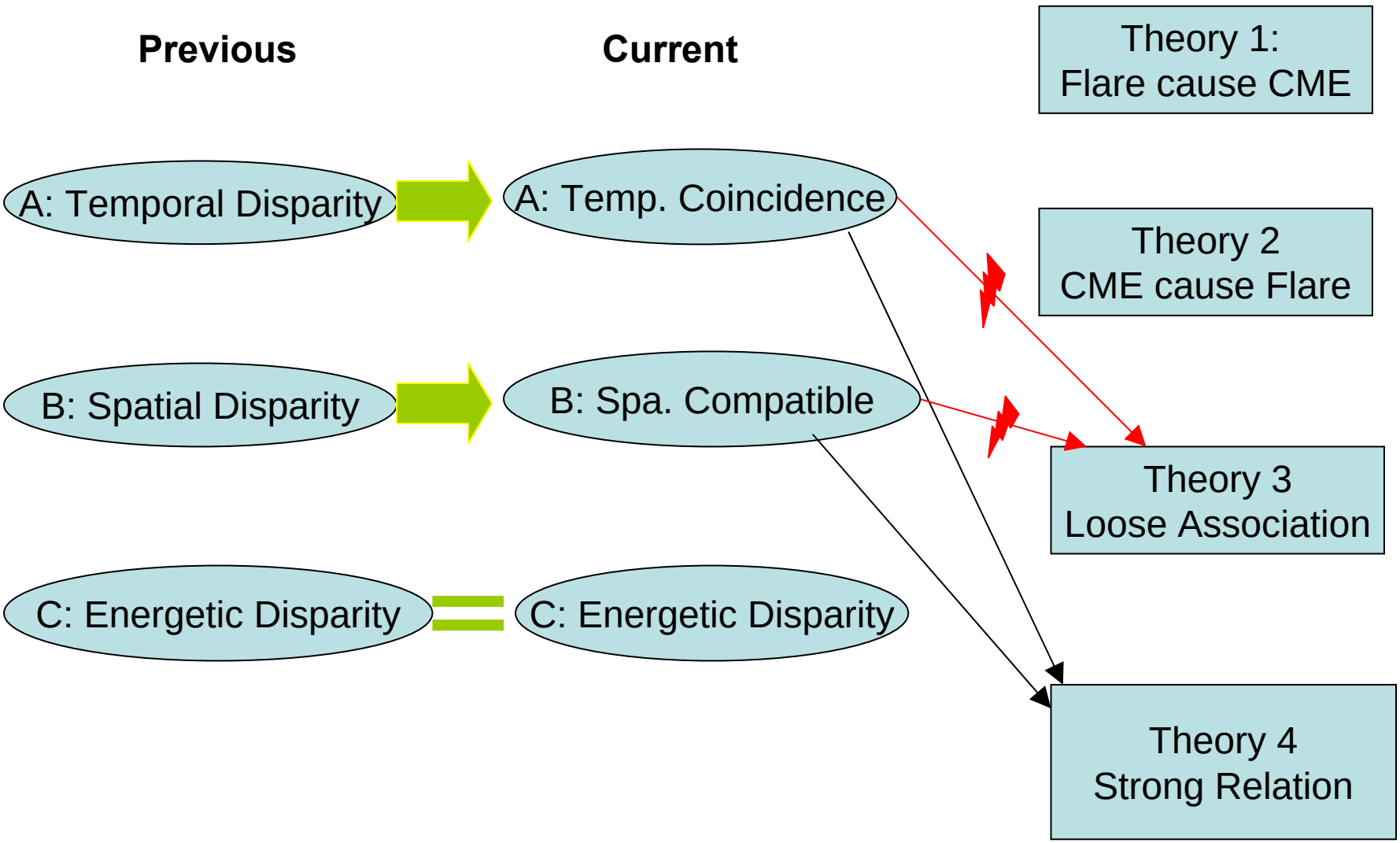
- **Energetic disparity? Probably yes**



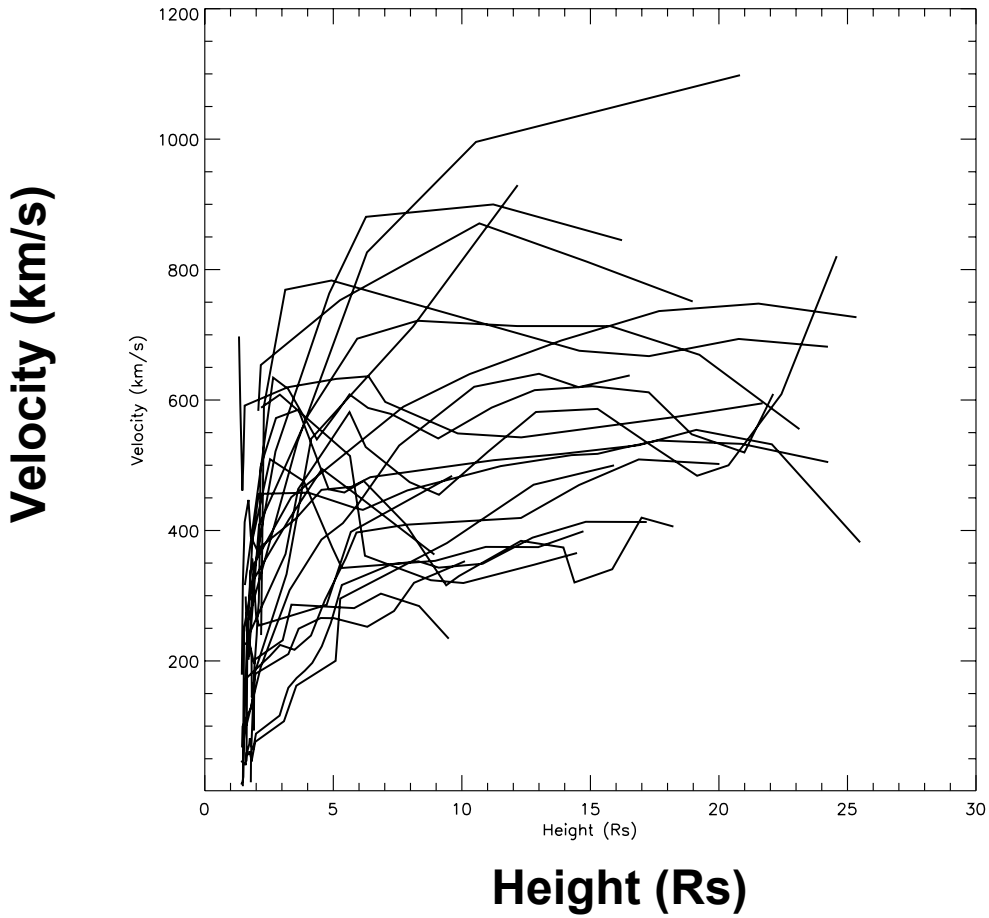

**(also see Hundhausen 1997)**

# Three Established Observations: Theoretical Implications



# CME: Classification or Diversity

- **Two classes: impulsive and gradual** (e.g, MacQueen and Fisher 1994, Sheeley et al. 1999)
- **Probably not. A possible continuous distribution in velocity and acceleration (magnitude, duration and distance)**




**"Intermediate" CMEs:**

**Plunkett et al. 2000**
**Yurchyshyn 2002**
**Zhang et al. 2004**

# Parameters for Three Different CMEs (Zhang et al 2004)

| Event | 1998/06/11 | 2000/10/25 | 1997/10/19 |
|---|---|---|---|
| Characteristics | Impulsive | Intermediate | Gradual |
| Average Velocity (km/s) | 782 | 636 | 147 |
| Average Acceleration ($m/s^2$) | 21 | 26 | 4.3 |
| Acceleration Duration (min) | 30 | 160 | 1440 |
| Acceleration Distance (Rs) | 3.3 | 4.3 | 19 |
| Acceleration in Acc. Phase ($m/s^2$) | 308 | 131 | 4.0 |
| Peak Velocity (km/s) | 1104 | 954 | 347 |
| Peak Acceleration ($m/s^2$) | 402 | 192 | 12 |
| Height at Peak Velocity (Rs) | 4.6 | 7.0 | 19 |
| Height at Peak Acceleration (Rs) | 2.2 | 5.5 | 5.6 |
| Mass (gram) | 5.0e15 | 1.7e16 | 2.0e15 |
| Net Mechanic Force (dyn) | 1.5e20 | 2.2e20 | 8.0e17 |
| Kinetic Energy (erg) | 3.0e31 | 7.7e31 | 1.2e30 |

# Highlights

1. CME and flare, each can occur without the other phenomenon being detected

2. When they occur associated (they often do), their evolution show very good time coincidence.

3. But the energy partition is far from equal.

4. Since CME acceleration phase always coincides with the flare energy release phase, (assuming due to magnetic reconnection), the reconnection may help strengthen the acceleration. It is also possible that the reconnection and the acceleration be mutually feeding each other.

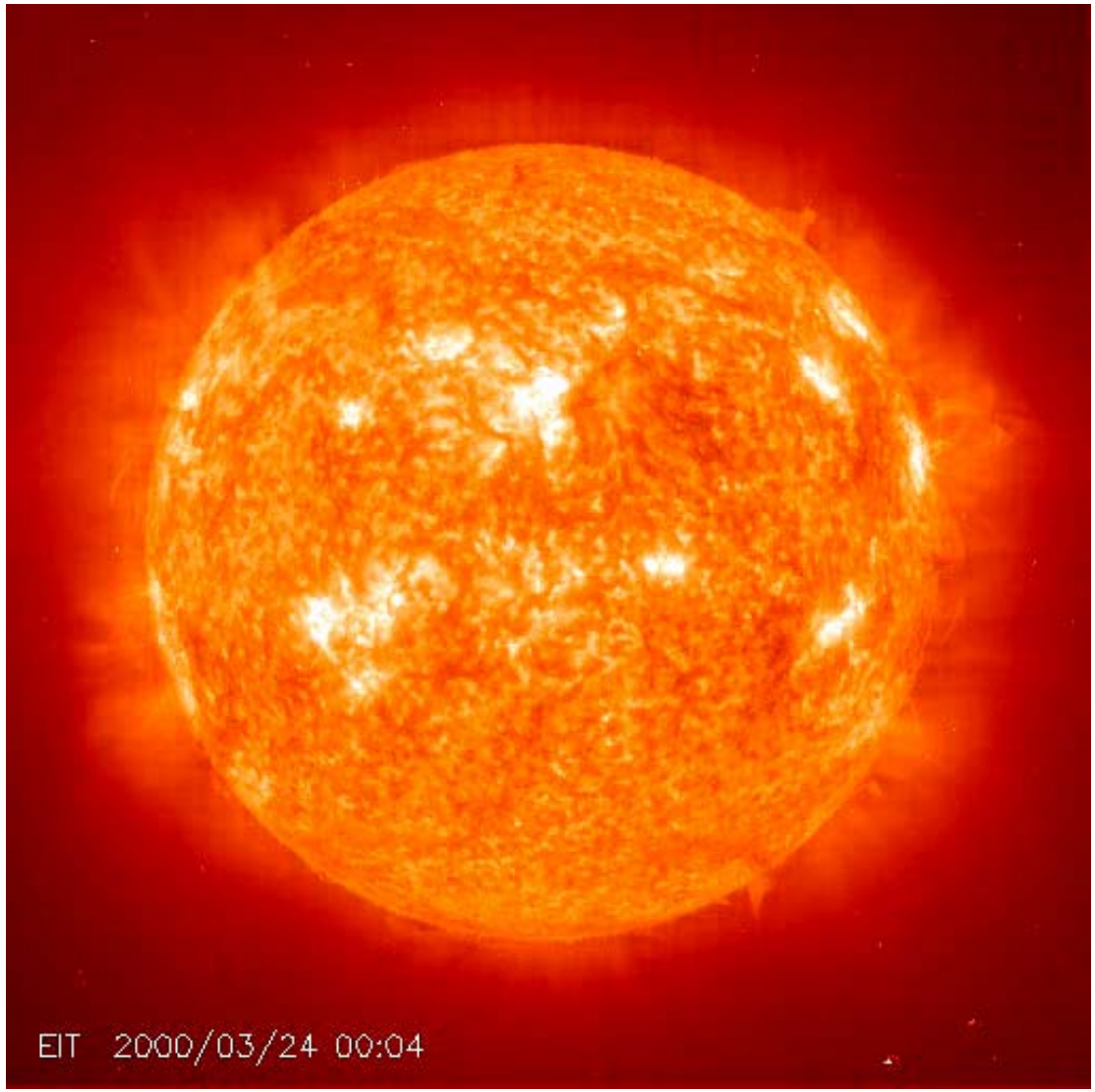
# Theoretical Challenges

1. How to explain the diversity of solar eruption: CME/flare, wide distribution, associated or not

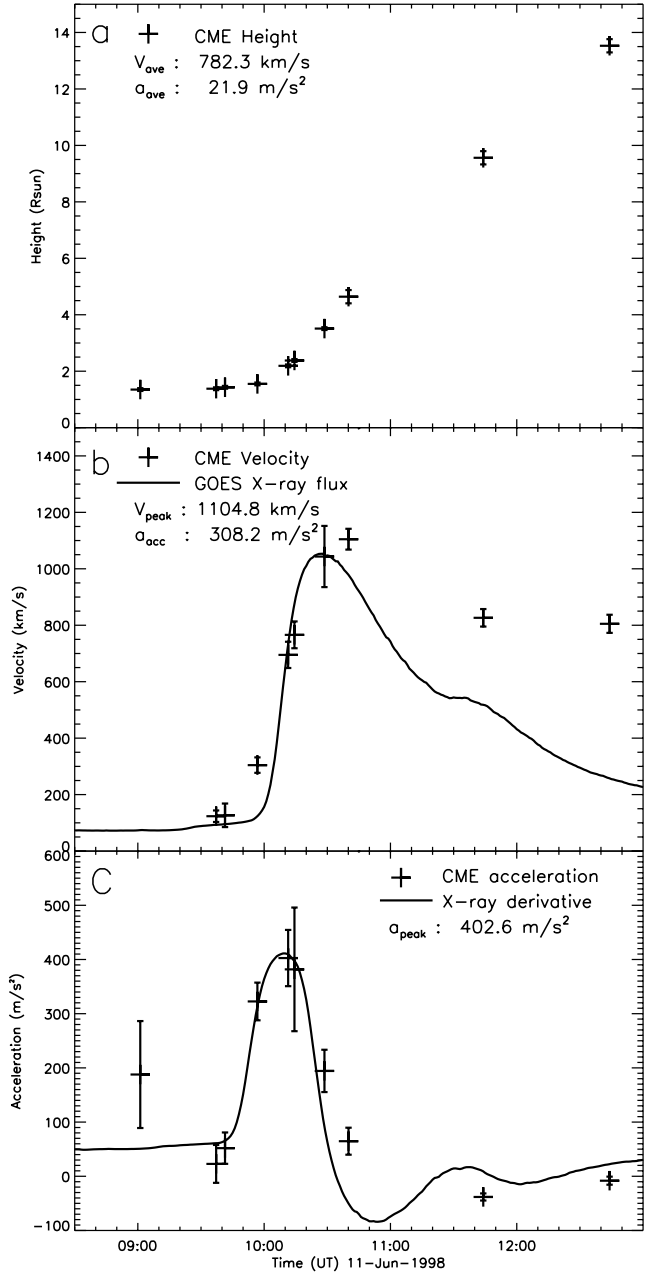
2. How to explain the temporal coupling between large scale CME acceleration and small scale flare heating/particle acceleration, e.g, 2 Rs versus 0.2 Rs? Where is the site of energy release? How does it evolve with time?

3. How to explain the energy disparity between CMEs and flares

# The end



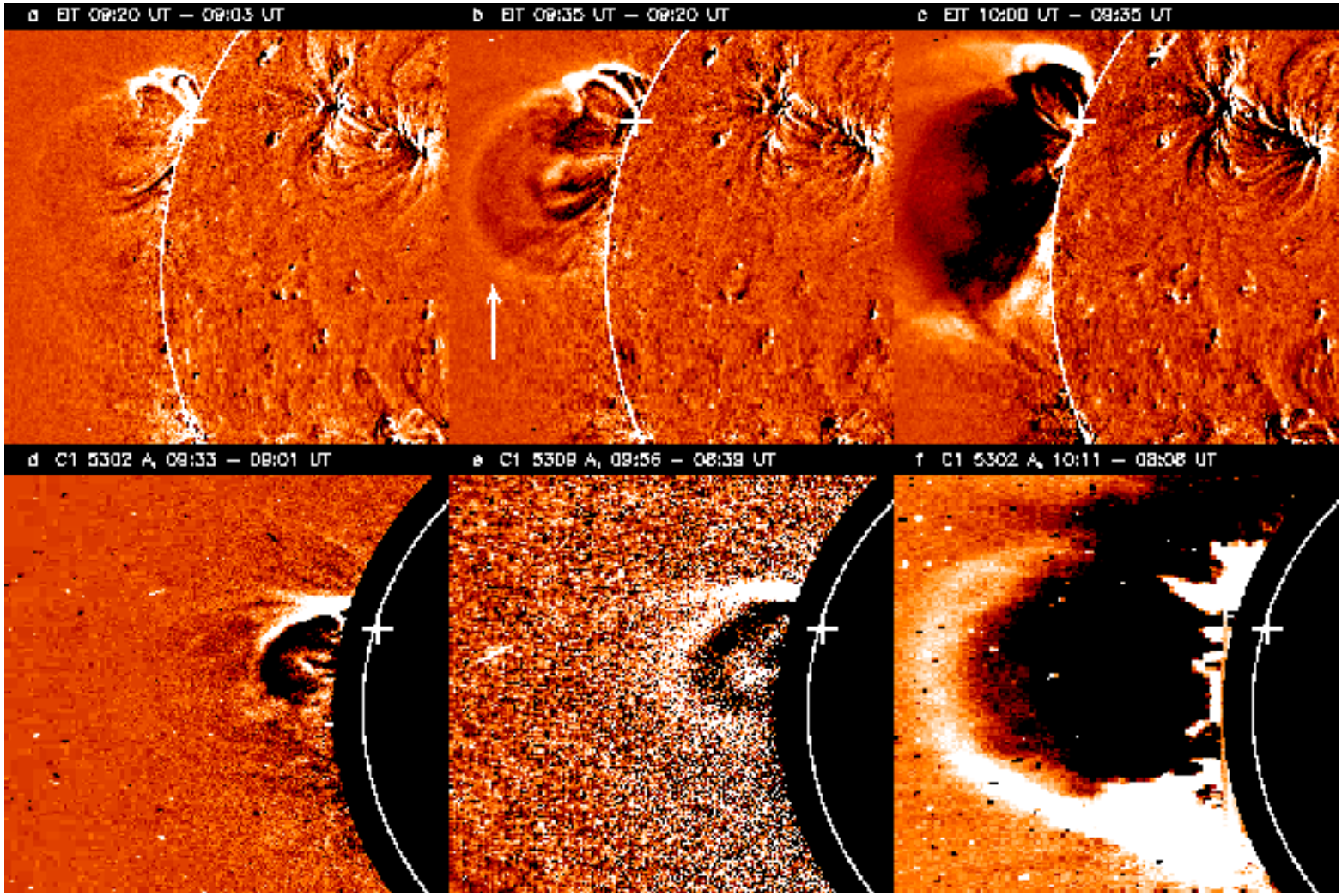

**How to explain and model solar eruptions?**




**(Zhang et al. 2004)**

# Case 1 (continued) : 1998/06/11

09:20 UT 09:35 UT 10:00 UT




09:33 UT 09:56 UT 10:11 UT