Some Considerations for Predicting Solar Eruptions Leading to Flares, Earth-Effecting CMEs, and gradual SEPs

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Three Topics for Prediction:

We will consider potential predictors for three aspects of solar eruptions that could be addressed under PRESTO:

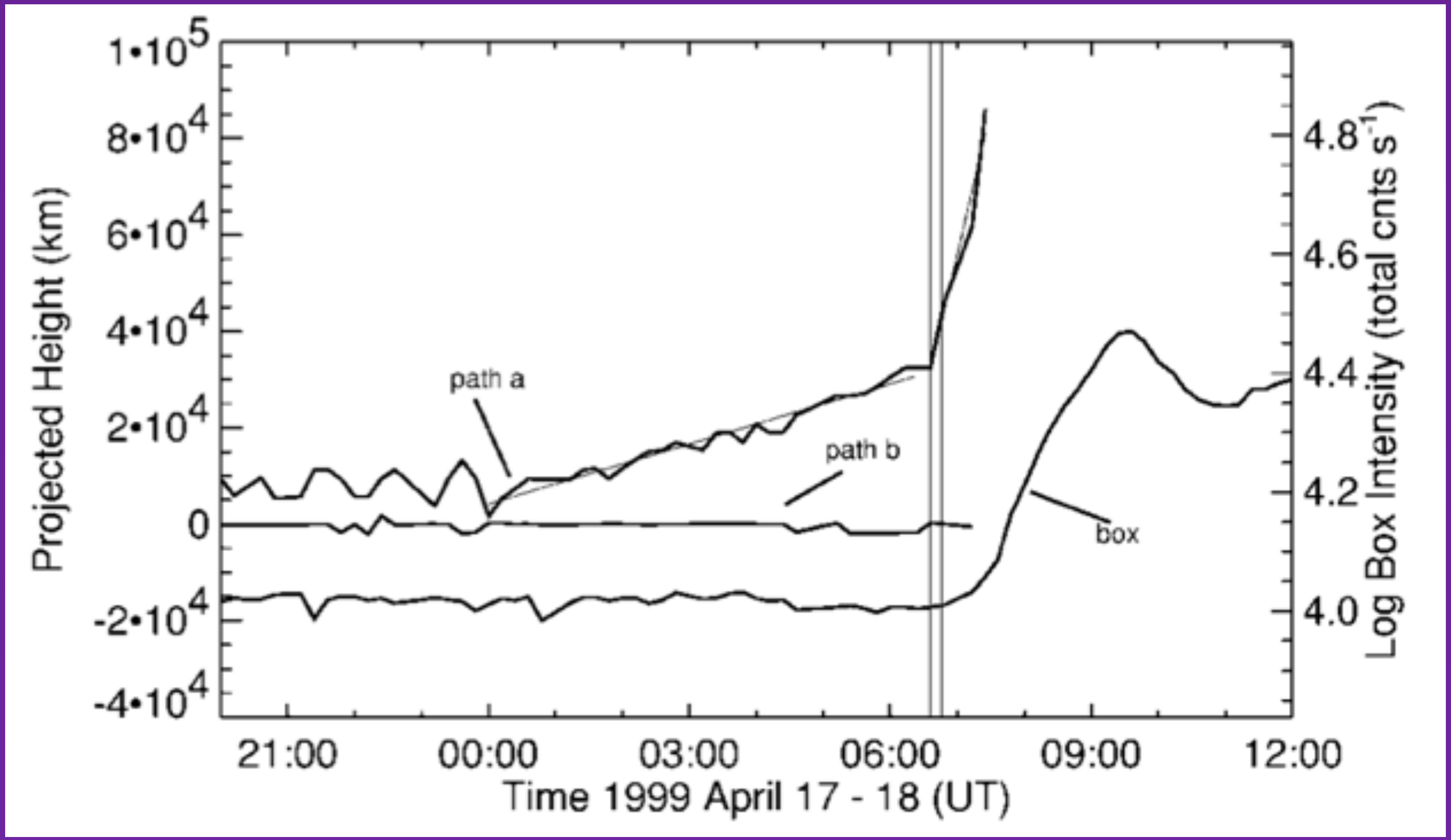
(I) What are early indicators of impending eruption?

(II) Will the solar explosion hit the Earth?

(III) Will the eruption produce a SEP event?

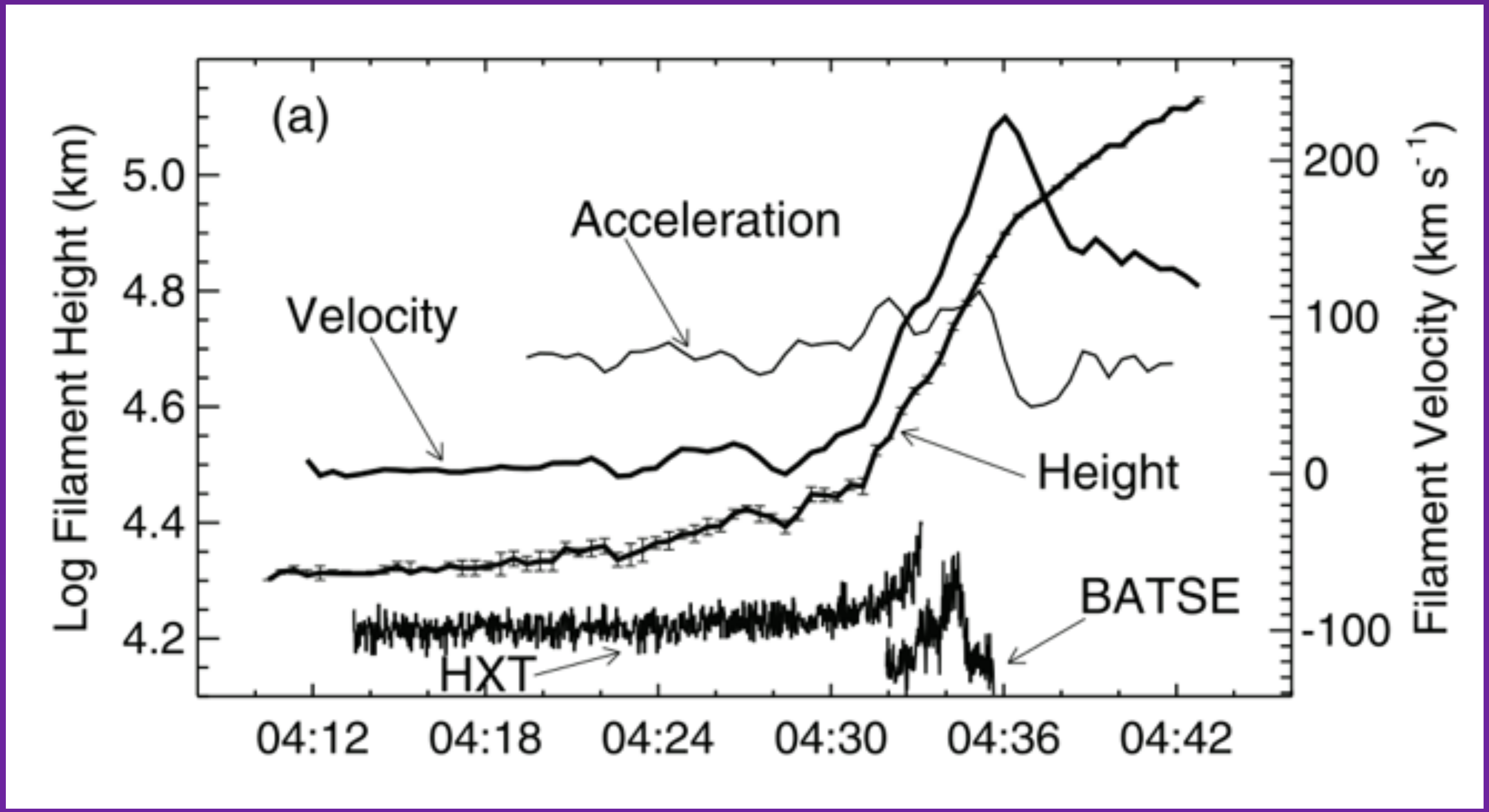
(I) Early eruption indicators

- Many CME-producing eruptions accompanied by erupting filaments.
- Often filaments display a slow rise prior to a rapid eruption.
- This “slow-rise” phase has been observed to last as long as several (~10) hours in quiet-Sun eruptions, but it is often short (tens of minutes) in AR eruptions.



Sterling et al. (2001)

This shows the lead up to a solar quiet-region filament eruption. “Path a” shows the measured projected filament height above the Sun’s surface as a function of time, with the vertical bars showing where the trajectory’s rise-velocity increased suddenly, signifying transition from a slow-rise to a fast-rise phase. For this quite-region eruption the slow-rise phase lasted about six hours. The curve labeled “box” shows the 195 Å EUV flux; it shows an increase due to flare emission about coinciding with the start of the fast rise. (“Path b” measures the trajectory of a different part of the filament; Sterling et al. 2001.) See Sterling et al. (2001,2004) for further details.



Sterling et al. (2005)

This shows the lead up to a solar active region (AR) filament eruption. The curve labeled "Height" shows the measured projected filament height above the Sun's surface as a function of time, measured from the TRACE satellite. For this AR eruption the slow-rise phase lasted only about 10 min (~4:22–4:32 UT). The HXT and BATSE curves show the hard X-ray flux, with increases accompanying flare onset again roughly coinciding with fast-rise onset. See Sterling et al. (2005) for information on other curves and additional details.

Other studies of pre-eruption filament dynamics include Smith & Ramsey (1964); Tandberg-Hanssen (1980); Kahler et al. (1981); and Seki et al. (2017, 2019), Since many filaments show such slow rises prior to eruption, it may be possible to use the rise trajectory as a signature of an impending eruption. Additional potential signatures are also possible (e.g., Seki et al. 2017, 2019) Studies are required to confirm and refine these methods, however.

Although not detailed in this presentation, longer-term predictors of eruption may result from studies of the magnetic evolution of ARs (and other eruptive regions) in the hours and days prior to eruption (e.g., Amari et al. 2011, Panesar et al. 2016, Sterling et al. 2018, Chintzoglou et al. 2019).

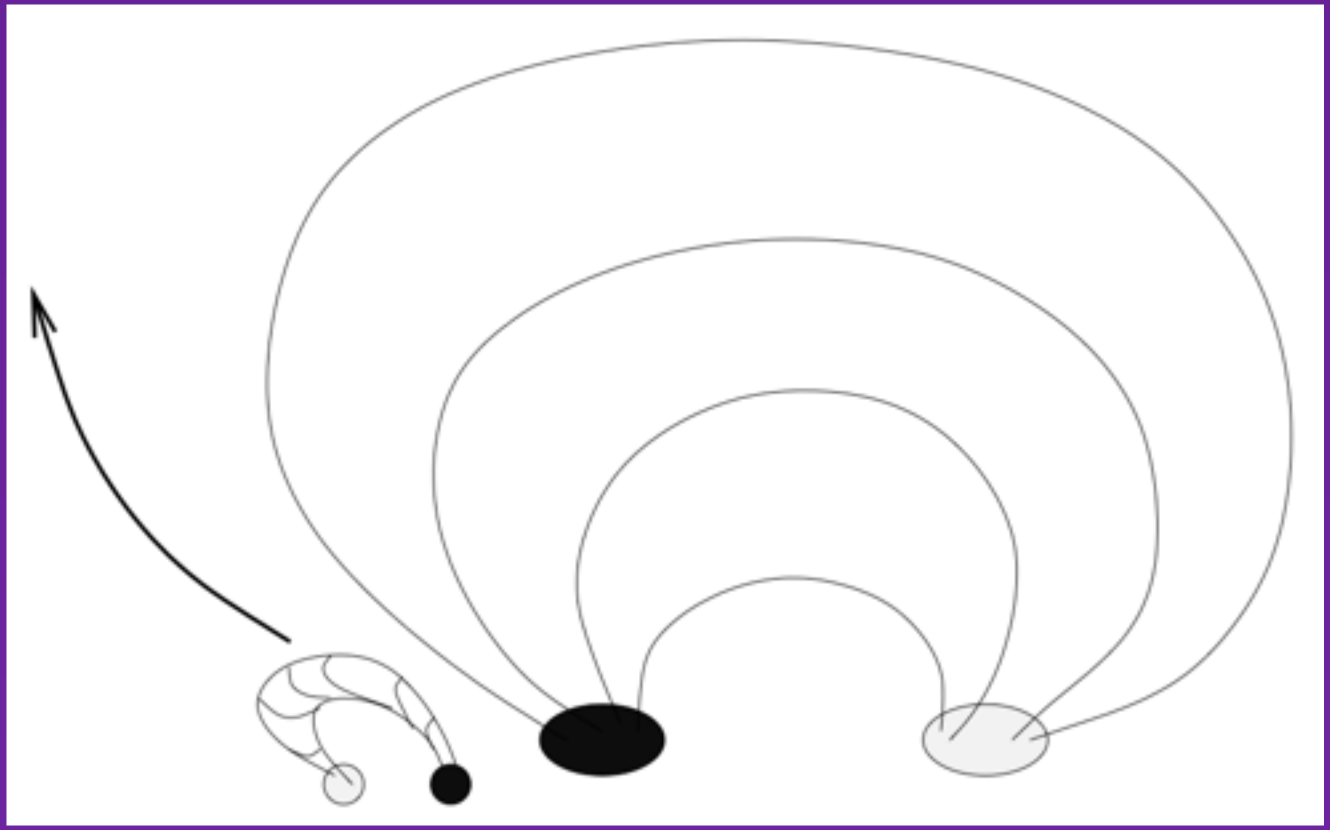
(2) Will the solar explosion hit the Earth (i.e., will the launched CME be directed toward us)?

These two factors are important for this question when the CME is still near the Sun:

(2a) Deflection of the CME.

(2b) Width of the CME.

2(a) Deflection

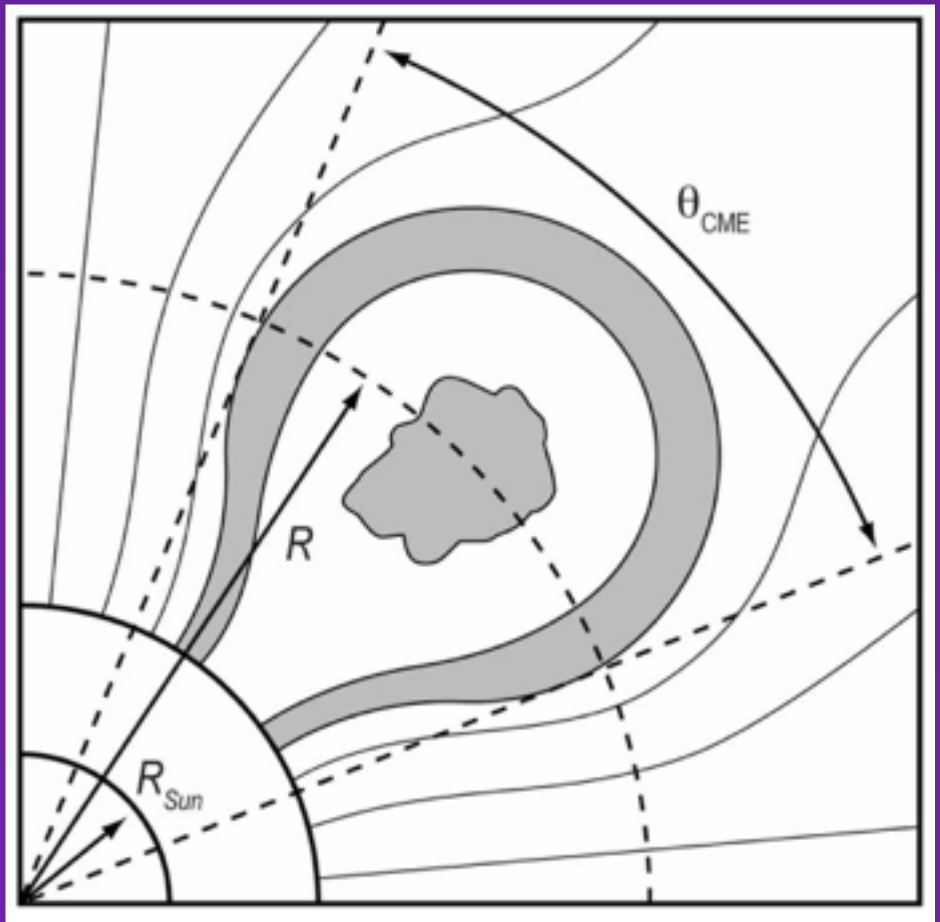


Sterling et al. (2011)

Schematic representation of a CME-producing erupting bipole. The erupting bipole is on the left side of a stronger bipole. The trajectory of the eruption was substantially deflected by that adjacent stronger bipolar region. This demonstrates that direction of the CME resulting from the eruption can in some cases be substantially offset from the photospheric/low-coronal site of the solar flare that accompanies the eruption. For details see Sterling et al. (2011).

Other studies of CME deflection from coronal structures include Gopalswamy et al. (2009, 2014); Xie et al. (2013); Mäkelä et al. (2013); Imada et al. (2014); and Yang et al. (2018).

2(b) CME Width



Moore et al. (2007)

Geometry of a CME extending beyond the LASCO/C2 coronagraph. According to Moore et al. (2007), the CME will expand in width until its internal magnetic pressure equals that of the surrounding ambient interplanetary field. The CME's magnetic pressure is determined by the amount of the flux that erupts and escapes as a flux rope forming the CME core. Based on this concept, and on measurements of three eruptions, Moore et al. (2007) found that the average flux at the photosphere swept out by the ribbons of the flare accompanying the eruption was $\langle B_{flare} \rangle = 1.4\ (\theta_{cme}/\theta_{flare})^2$, where θ_{cme} and θ_{flare} are respectively the maximum angle from Sun center subtended by the CME (pictured) and the maximum angle from Sun center subtended by the photospheric flare ribbons. Details are in Moore et al. (2007).

(3) Are there special characteristics of eruptions that produce gradual SEPs?

- Observations indicate that gradual SEP events result when a CME passes through a cloud of "pre-headed" particles. (Kalher, etc(?))
- At least in some cases, observations support that SEP events result from a series of two close-in-time (<~24 hrs) CMEs passes through a cloud of "pre-headed" particles. (e.g., Kahler 2001, Kahler & Reames 2003). This is consistent with the above point whereby the first CME primes the particles, and the second further accelerates them (e.g., Gopalswamy et al. 2001, 2003, 2004; Li et al. 2012).
- A "double eruption" event, consisting of two eruptions within ~2 hrs produced two close-in-time CMEs, and a strong SEP event (Cheng et al. 2013, Joshi et al. 2013). The double eruption occurred when a first eruption removed/reorganized magnetic field above an already sheared filament-carrying flux structure, which subsequently erupted. Sterling et al. (2014) argue that the second eruption occurred when the first eruption removed a magnetic "lid" over the second structure.
- Systematic studies of the solar source of many SEP events will reveal whether such "lid-removal" eruptions are a common precursor of (and hence, potential predictor for) SEP events.

Discussion

- The described studies were - for the most part - motivated by science goals, e.g., trying to understand the energy-release mechanism for solar eruptions.
- Statistical studies can confirm which of the foregoing can be used as predictors, and refine the predictive capabilities.
- It is also important to calibrate the predictors with non-eruptive events, to avoid “false positive” indicators. Also, further study is needed of so-called “stealth CMEs,” which are eruptive events lacking (or with weak) traditional signatures.

Summary

We introduced three solar processes that could potentially be developed into effective predictors:

(1) Pre-eruption filament motions, and pre-eruption magnetic buildup of eruptive regions.
(2) Effect of coronal magnetic structure on CME near-Sun trajectory (deflection and width).
(3) Types of events that produce SEP events.

So far studies of these items has concentrated on questions such as what triggers solar eruptions. These show promise for potential predictors, but statistical studies are required to determine which specific approaches are most reliable for prediction, and to assure that "false positive" flags can be avoided.

References

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