Extreme Ultraviolet Late Phase (ELP) Flares:

Before and during the Solar Dynamics Observatory mission

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Key Results

- EUV Late Phase is defined by having two peaks of warm coronal emissions (e.g. Fe XVI 33.5 nm) during a flare: first peak is associated with the soft X-ray (SXR) peak, and second peak is 1-5 hours later without enhanced SXR emissions. [Woods *et al.*, ***Ap. J.***, 2011].
- Indicators of EUV Late Phase (ELP) flares in the GOES X-ray time series are flares with dual decay periods: first decay period is steep and is associated with the SXR peak, and second decay period is slow and is associated with the EUV second peak [Woods, ***Solar Phys***., 2014].
- Two sets of post-flare coronal loops are required for ELP flares: shorter, lower loops cool faster and are responsible for the SXR peak and the first ELP peak, and longer, higher loops cool slower and are responsible for the second ELP peak [Woods *et al.*, ***Ap. J.***, 2011].
- Examination of GOES SXR data back to 1974 suggest that ELP flares have consistently occurred over 4 solar cycles
  - There are more ELP flares during cycle maximum; however, the frequency of ELP flares (# ELP / # All Flares) is higher near cycle minimum, notably more right after cycle minimum.
  - Solar Cycle 24 (SC-24) has much fewer flares than solar cycles 21-23.

ELP Flares During SDO

Woods *et al.* (Ap J, 2011) defines four conditions for EUV late phase (ELP) flares based on SDO observations:

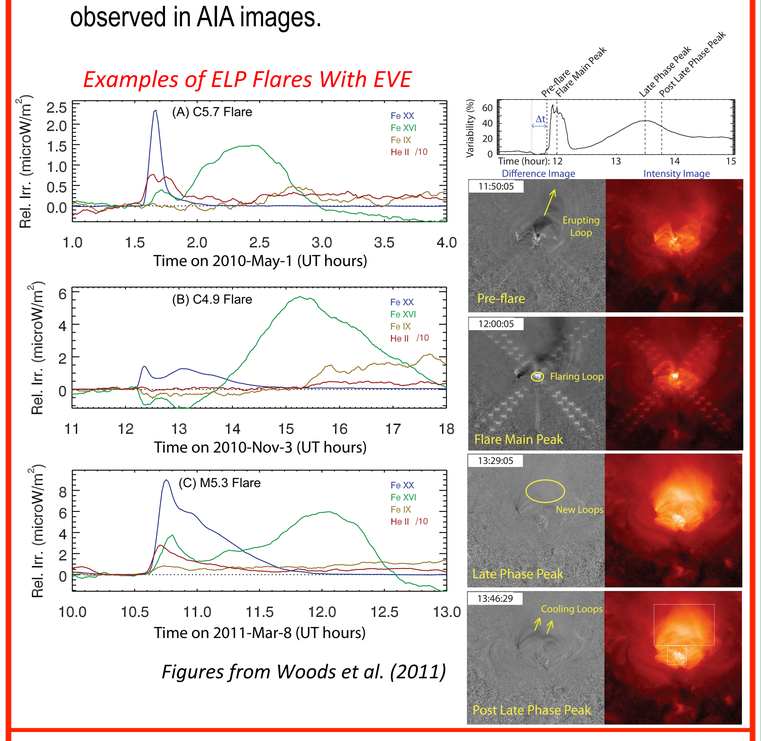
(1) a **second** peak of the warm coronal emissions (Fe XV and Fe XVI) several minutes to a few hours after the GOES X-ray peak,

(2) no significant enhancements of the GOES X-ray or hot coronal emissions (e.g., Fe XX / Fe XXIII 13.3 nm) during this second peak,

(3) eruptive event as seen in the AIA images and is also seen as coronal dimming in the Fe IX 17.1 nm emission,

(4) a second set of longer loops being reconnected higher than the original flaring loops and at a much later time than the first set of post-flare loops formed just minutes after the flare, as observed in AIA images.

Examples of ELP Flares With EVE

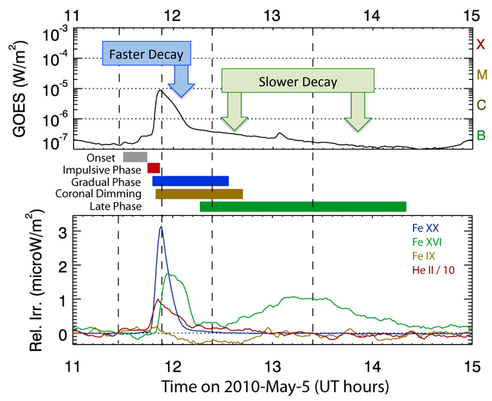


Figures from Woods et al. (2011)

GOES SXR Flares with Dual Decay Periods during SDO Mission

ELP Events	2010/121 -2011/067	2011/068 -2013/120
Validated with EVE Data	41 (57%)	101 (24%)
Small / Marginal ELP	5 (7%)	75 (18%)
False Detection of ELP	26 (36%)	238 (57%)
Total Number Identified	**72** (Woods et al., 2011 time period)	**414**

Indicators of ELP Flares Before SDO



With EUV Late Phase (ELP) flares having two sets of loops, the dual decays seen in the GOES X-ray may be indicator of **two different cooling rates due to different loop lengths**

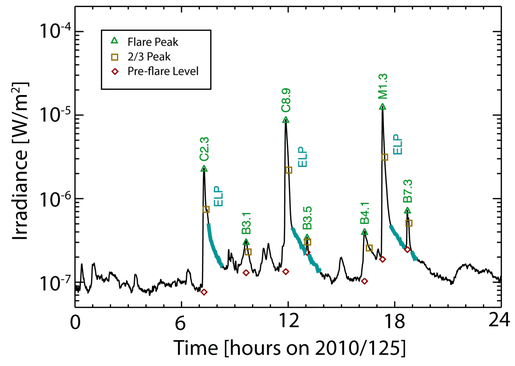
Gradual = faster decay

ELP = slower decay

Algorithms to Detect Two Decay Periods

1) One algorithm finds all the flare peaks: **green Peak**, **red Pre-flare level**, **gold End (1/2 peak)**

2) Second algorithm examines every flare for two decay periods, with the second decay required to be slower than the first decay



Light blue line is the identified second decay.
If rate is ~constant then it is labeled as ELF flare candidate

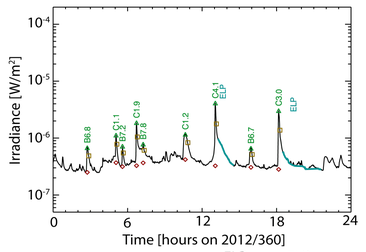
Figure from Woods (2014)

This dual decay algorithm is validated with SDO EVE 2010-2013 observations

5968 ELP candidate flares identified in the GOES X-ray data for flares > C1 using these algorithms from 1974/182 to 2013/234

Validation Results

Example to the right shows two ELP candidates for the C4.1 and C3.0 flares on 2012/360.



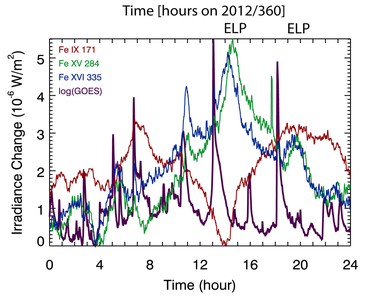
EVE data used to validate GOES ELPs:

- Fe IX 171 dimming for eruption validation
- Fe XV 284 and Fe XVI 335 second peaks for ELP validation

All 3 seen = confirmation of ELP

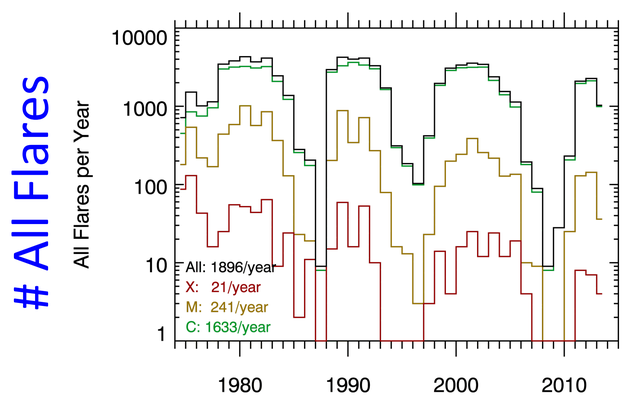
2 seen = small / marginal ELP

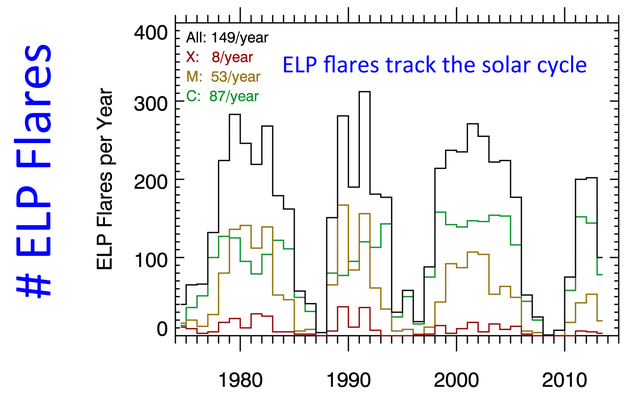
1 or none seen = false detection

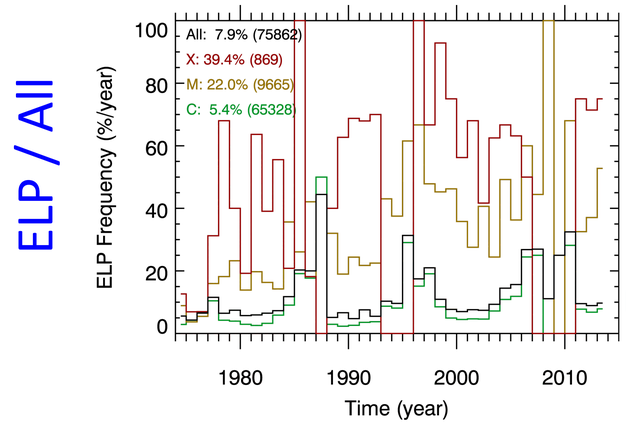


Solar Cycle Variations

- There has been a downward trend in flare frequency at cycle maximum since 1990 maximum.
- SC24 maximum has x 2 fewer flares than previous cycle.







- ELP frequency has out-of-phase relationship with solar cycle and more after cycle minimum.
- This is perhaps related to less complex magnetic fields near cycle minimum (so can have 2 loop sets).

  Note that 100% results are with just 1-2 flares in a year.