Observational Properties of Solar Flare Ribbons

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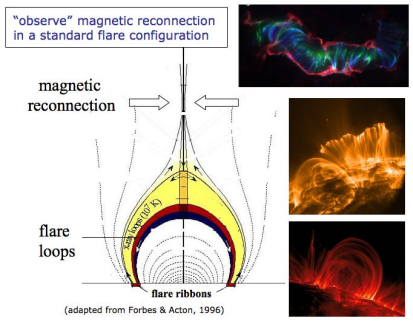


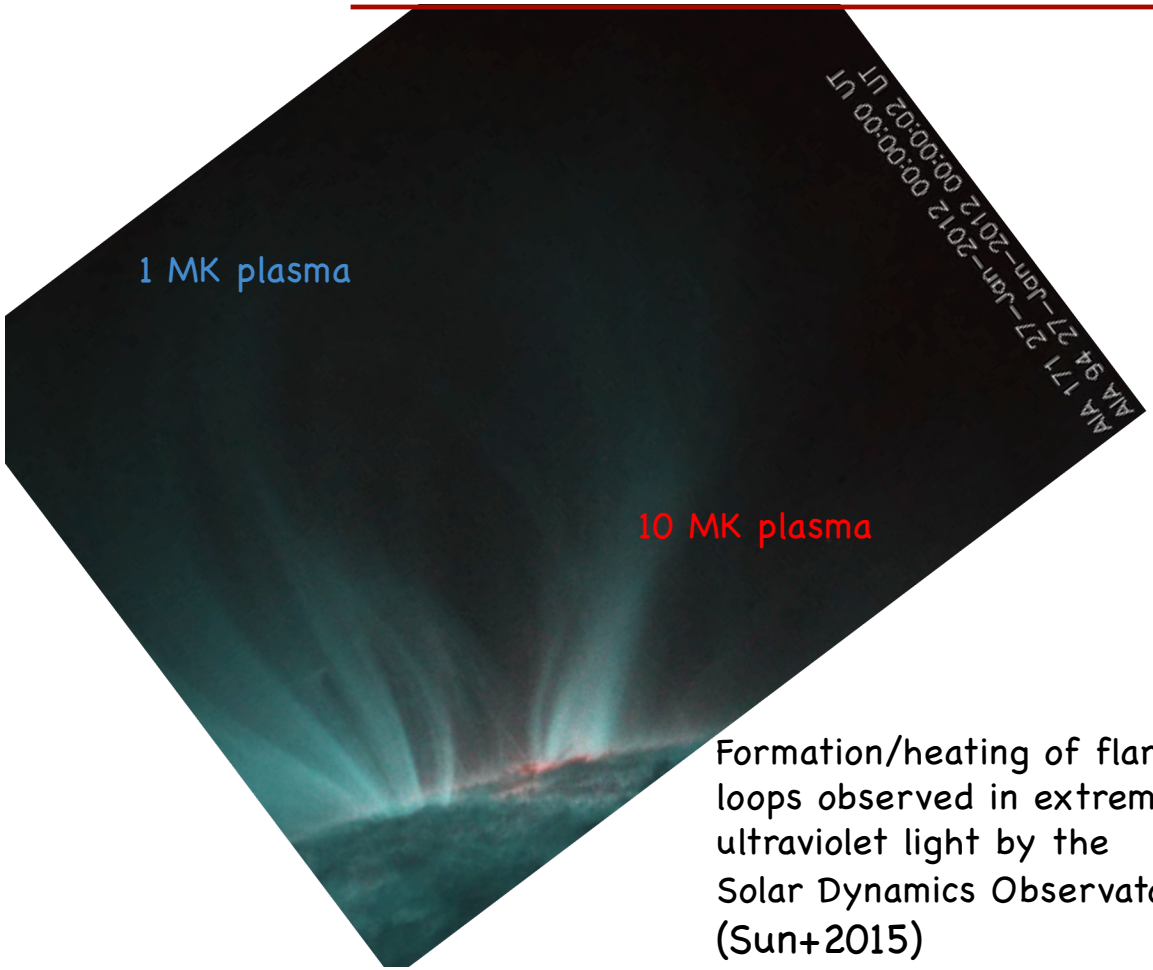
Outline

- During flares, magnetic reconnection takes place in the corona, and the reconnection energy release events can be mapped and therefore measured at flare ribbons.

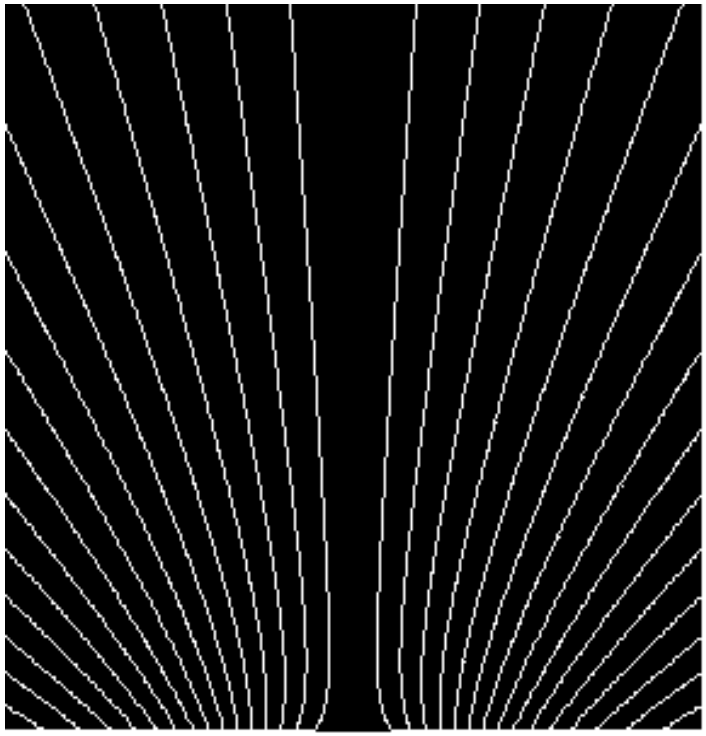
- Flare energetics can be probed with temporal, spatial, and spectral properties of flare ribbons, in connection with coronal observations.

- Joint disk observations of flares and limb observations of the solar corona from multiple vantage points can be used to measure reconnection and CME kinematics.

reconnection in corona forms flare arcade

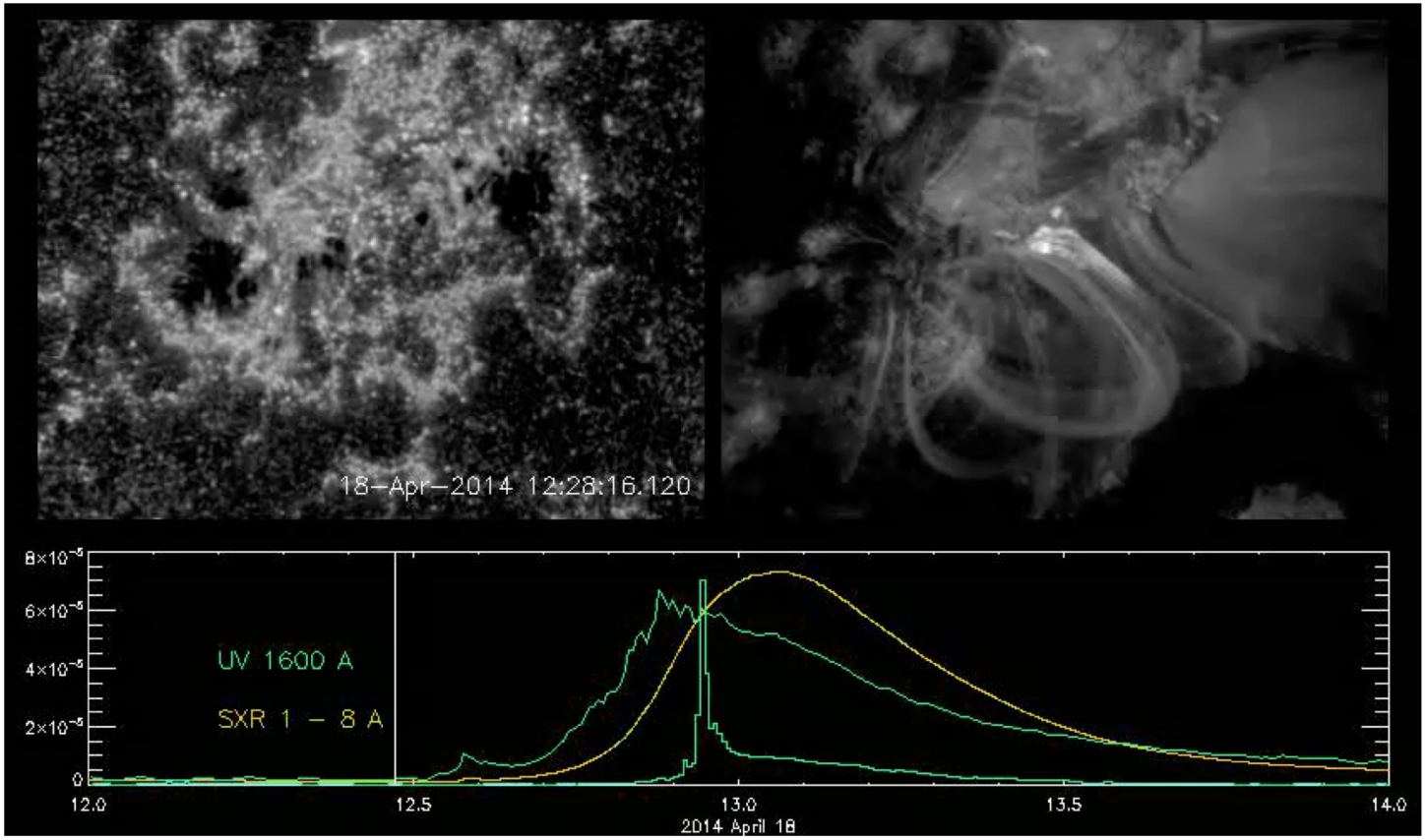


Formation/heating of flare loops observed in extreme ultraviolet light by the Solar Dynamics Observatory (Sun+2015)



from Terry Forbes

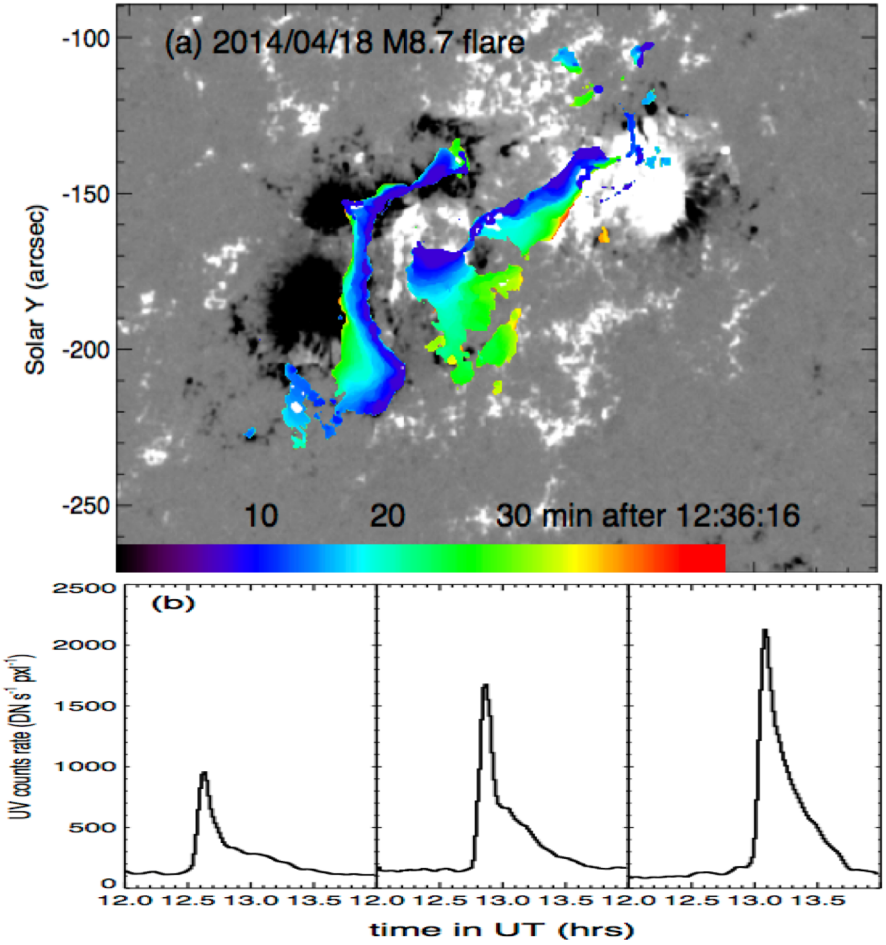
chromosphere / transition region radiation in UV 1600A passband (100,000K)

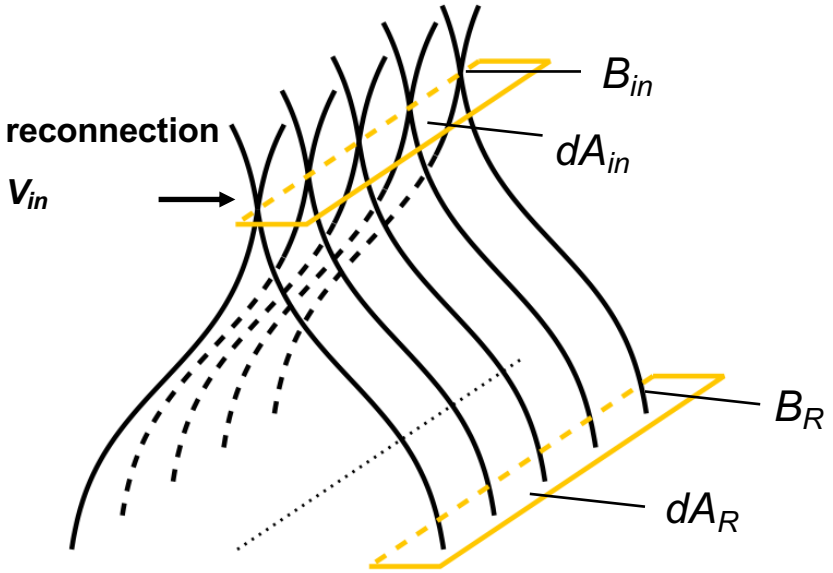


coronal radiation in EUV 171A passband (1MK)

Disk observations also reveal discrete flare loops and their feet as plasmas are heated in post-reconnection flux tubes in the corona and chromosphere.

reconnection measured from flare ribbons

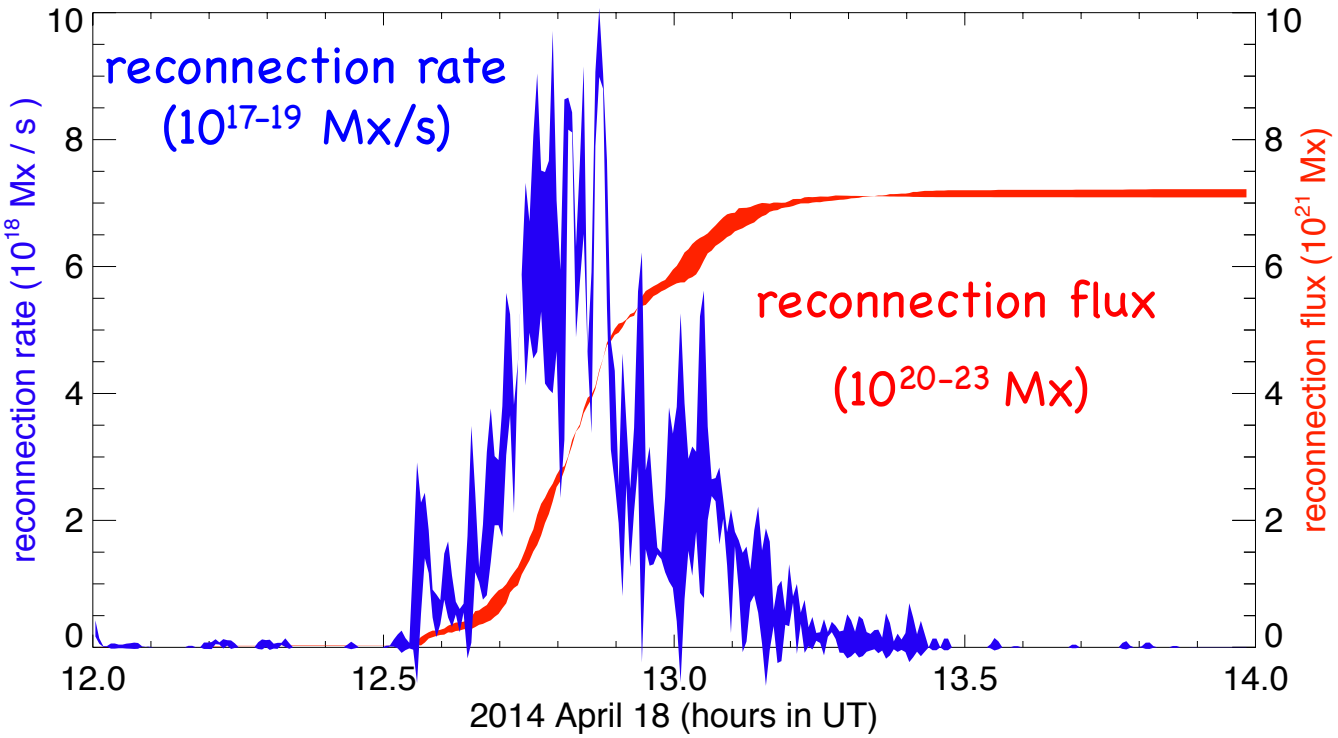




$$\frac{d\Phi_B}{dt} = -\oint \vec{E} \bullet d\vec{l} = \frac{d}{dt}\left(\int B_{in} dA_{in}\right) = \frac{d}{dt}\left(\int B_R dA_R\right)$$

(Forbes & Priest 1984)

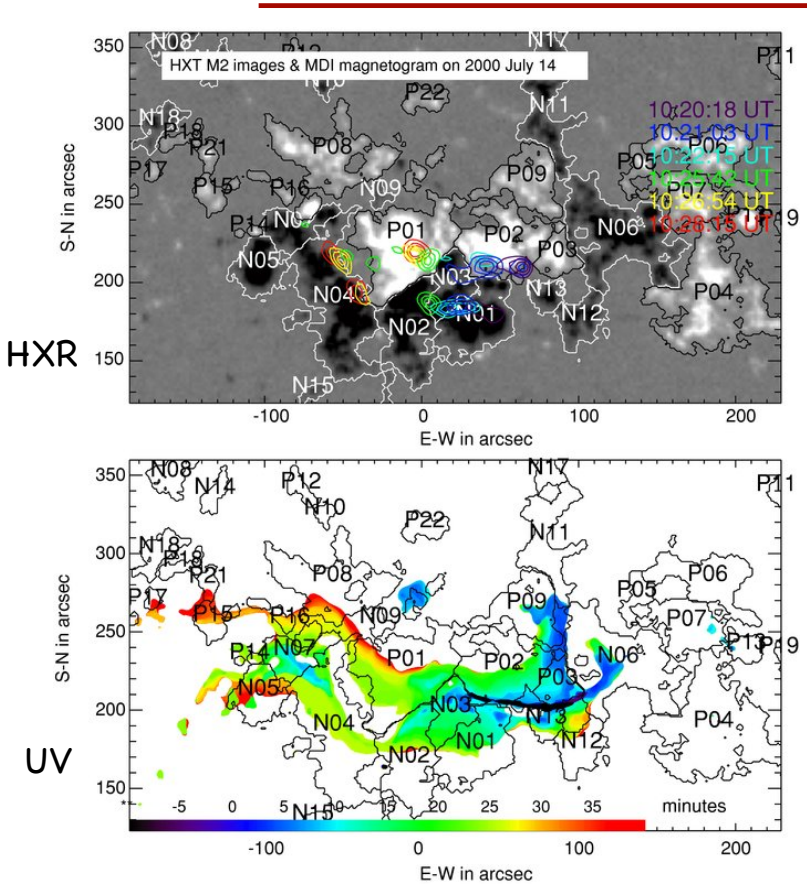
measured total, or global, reconnection rate

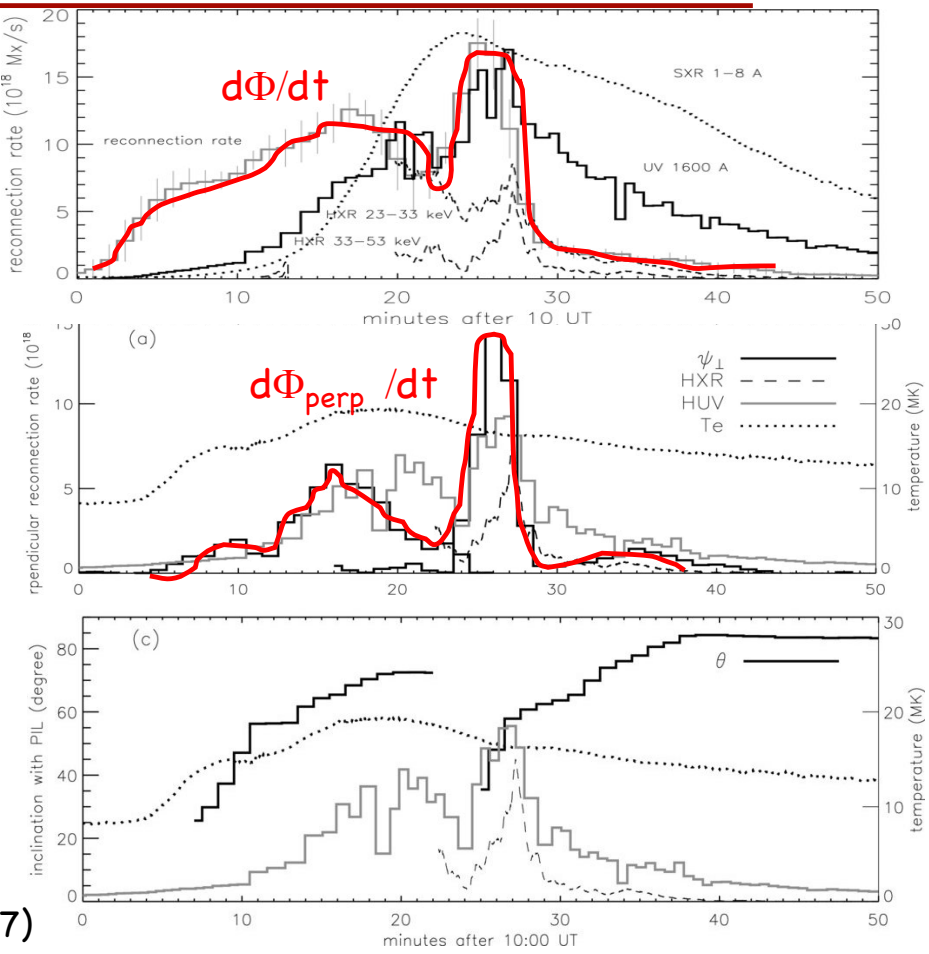


$$\langle E \rangle \approx \frac{d\Phi_B / dt}{L} = 5\ V/cm \qquad \langle M_A \rangle \approx \frac{v_{in}}{v_A} = 0.05$$

(Fletcher+2001, Isobe+2002, Qiu+2002.. see Kazachenko+2017 for measurements of 400 flares)

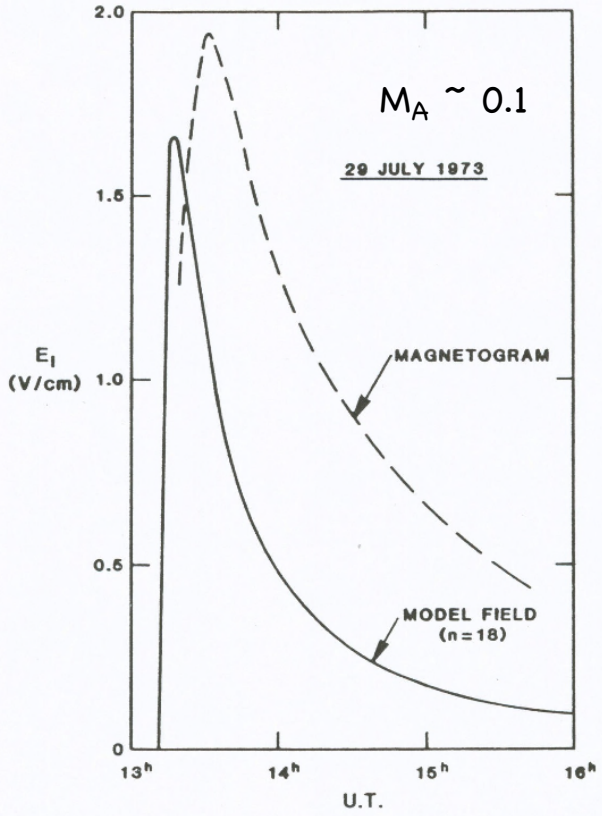
pattern of reconnection, the zipper effect



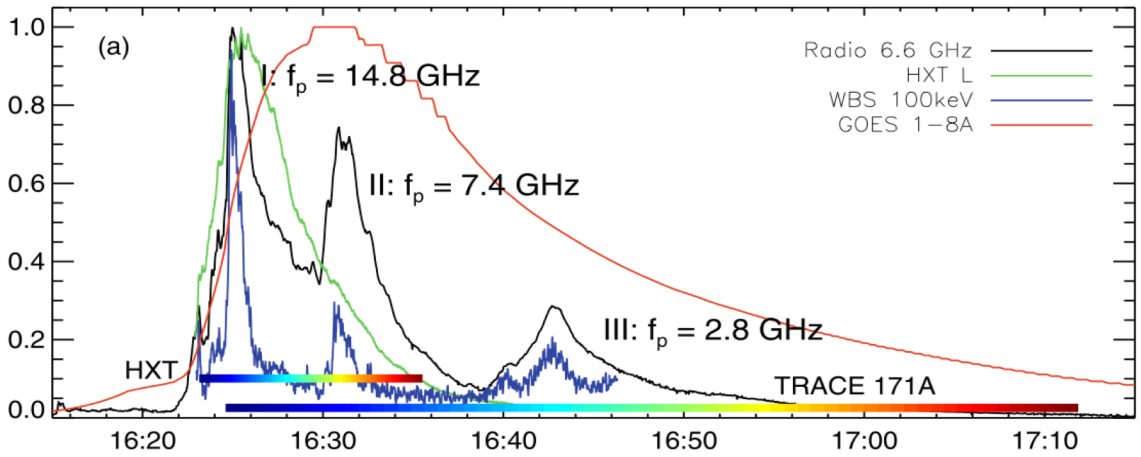


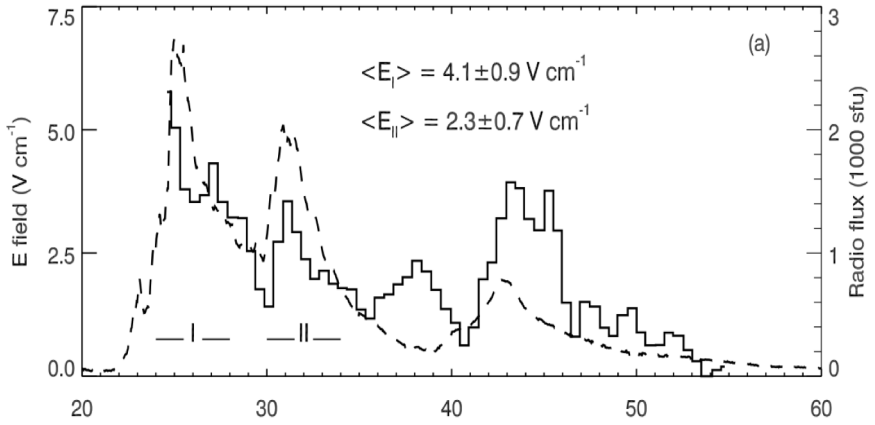
Can we probe the guide field? (Qiu+2010, 2017)

reconnection vs. energetics



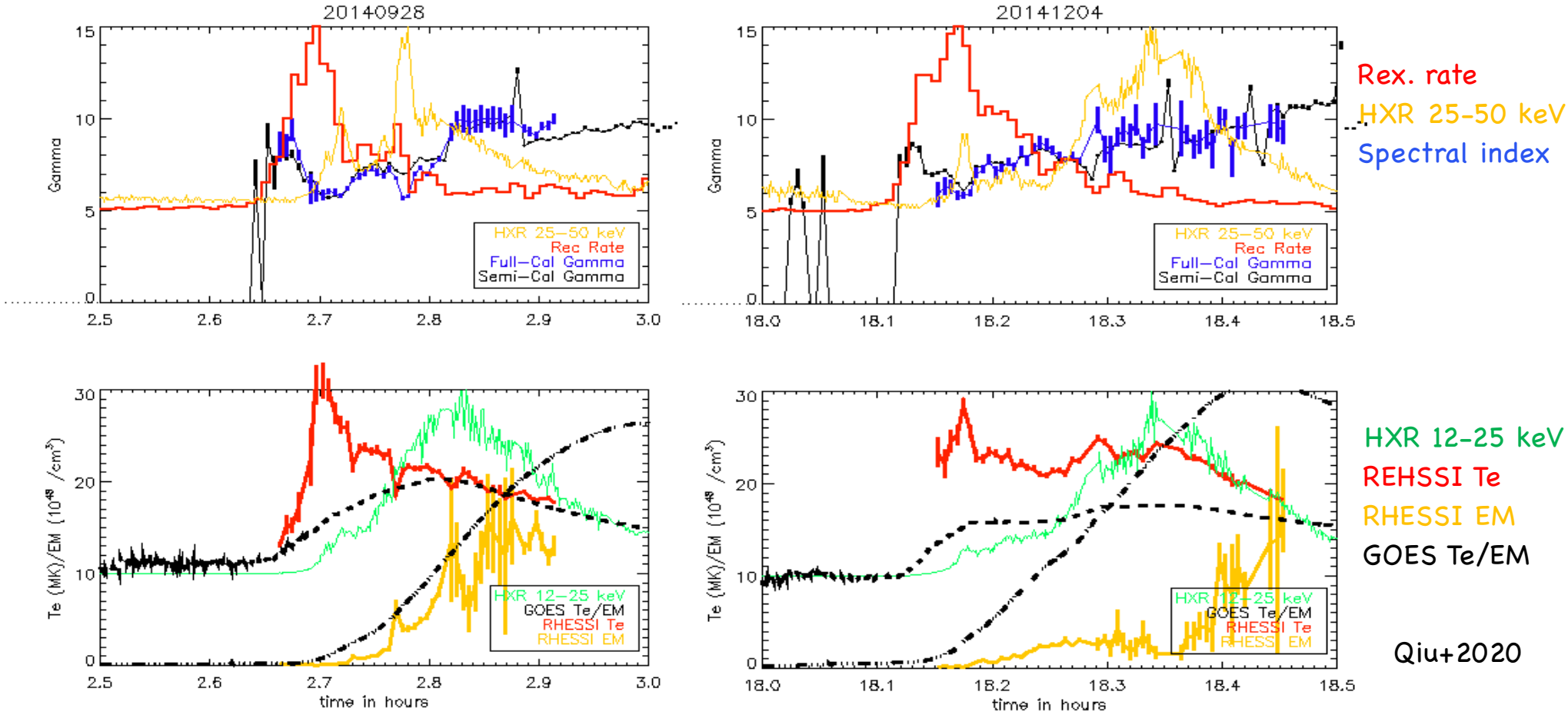
Earliest measurement of reconnection rate by Poletto & Kopp (1986)



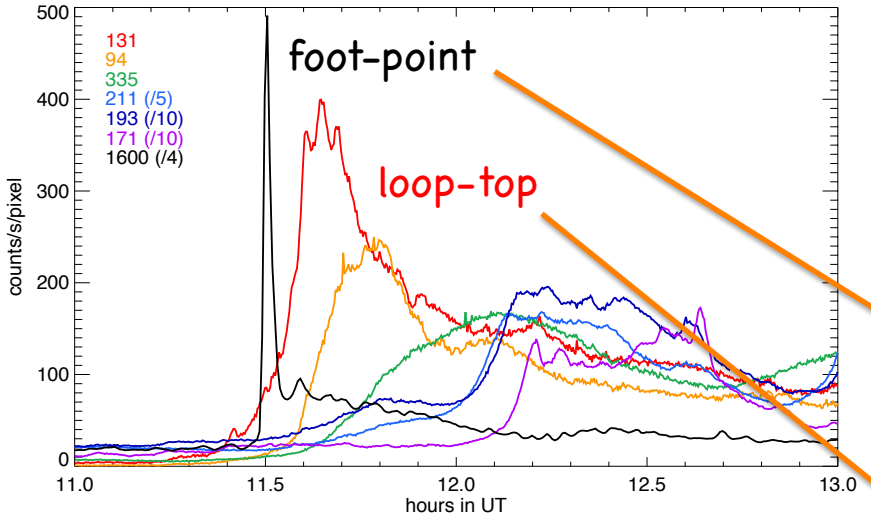


(Qiu+2009)

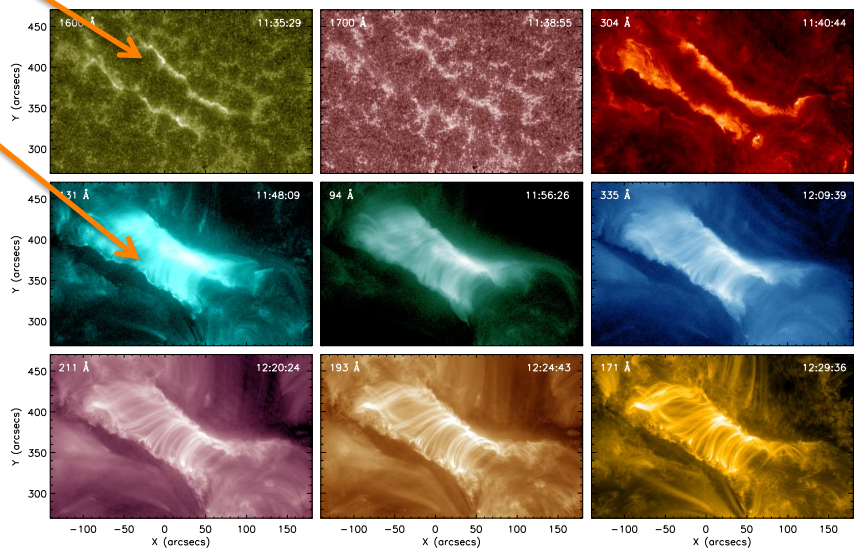
reconnection vs. energetics



energetics inferred from flare ribbons

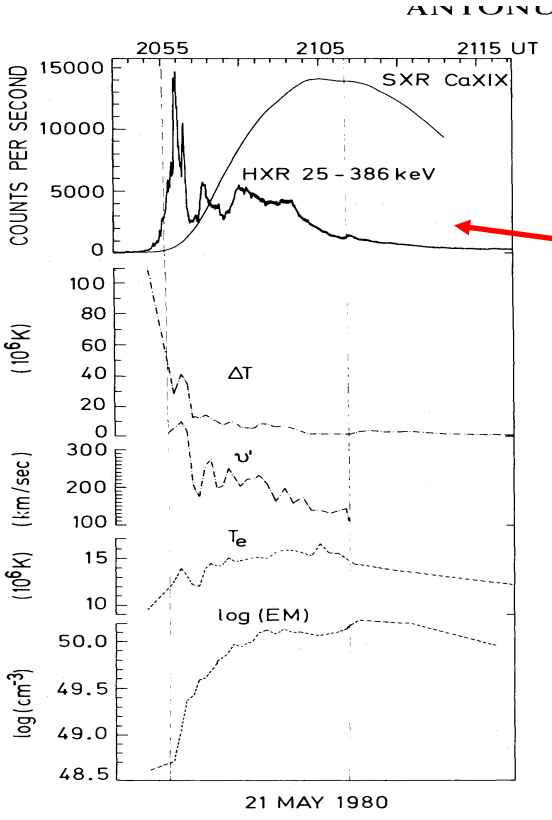


Reconnection forms flare loops, or packets of energy release, which are mapped at their feet, the flare ribbons.

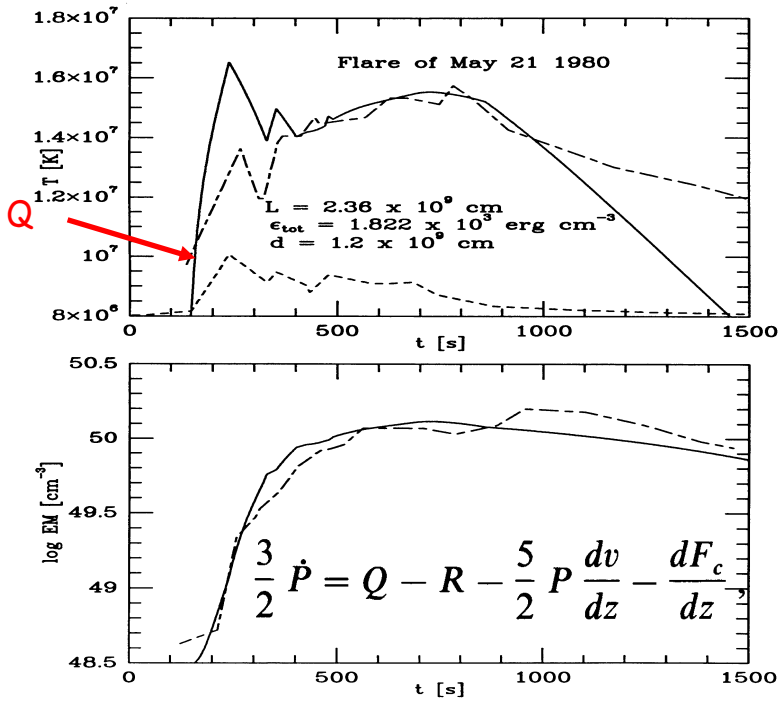


Impulsive emission at the foot-points can be used to infer heating rates (when, for how long, by how much) of instrument resolved flare loops - the UV Neupert effect (Qiu+2012-).

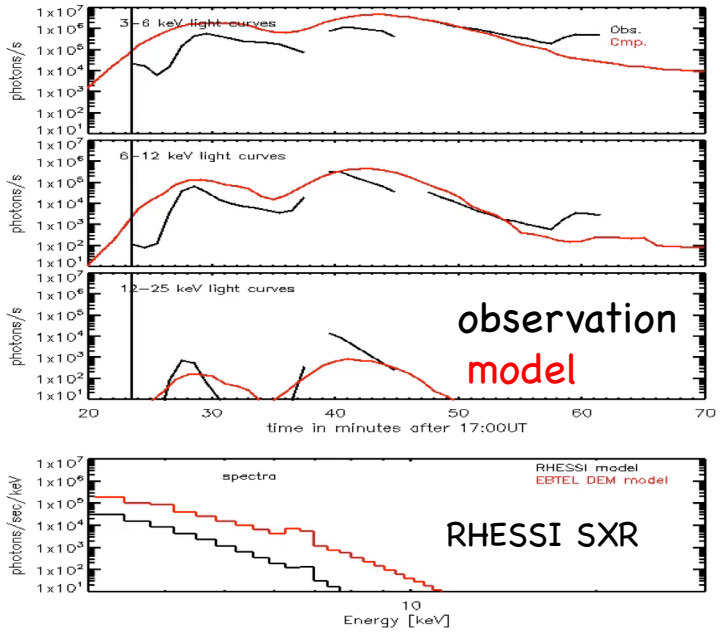
heating of flare loops: the Neupert effect



Antonucci, Gabriel, Dennis 1984

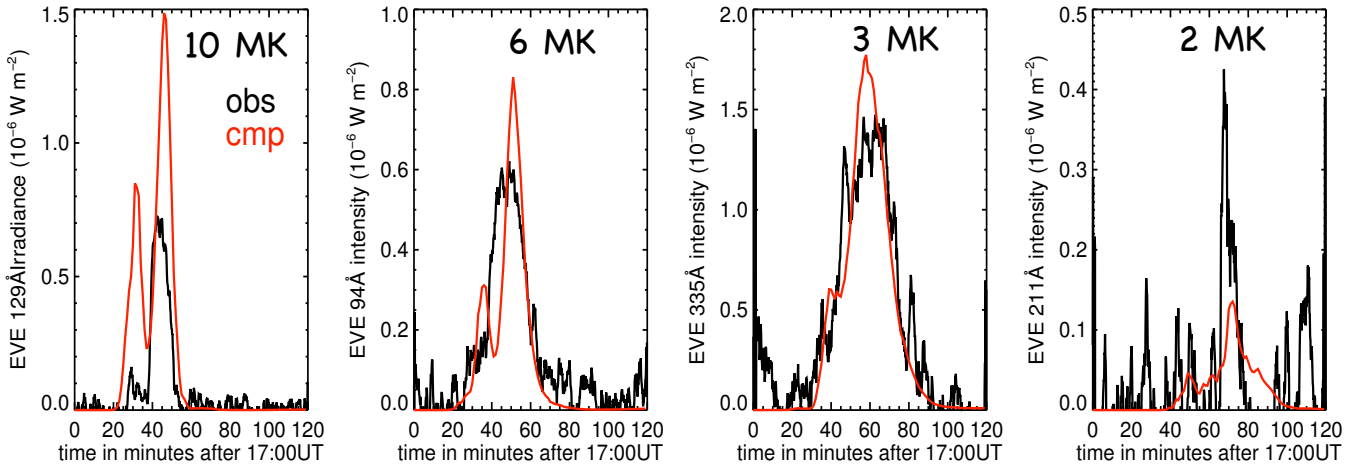


Fisher & Hawley 1990 (also Mariska/Emslie/Li, 1990s; RubioDeCosta+2016, Graham+2020)

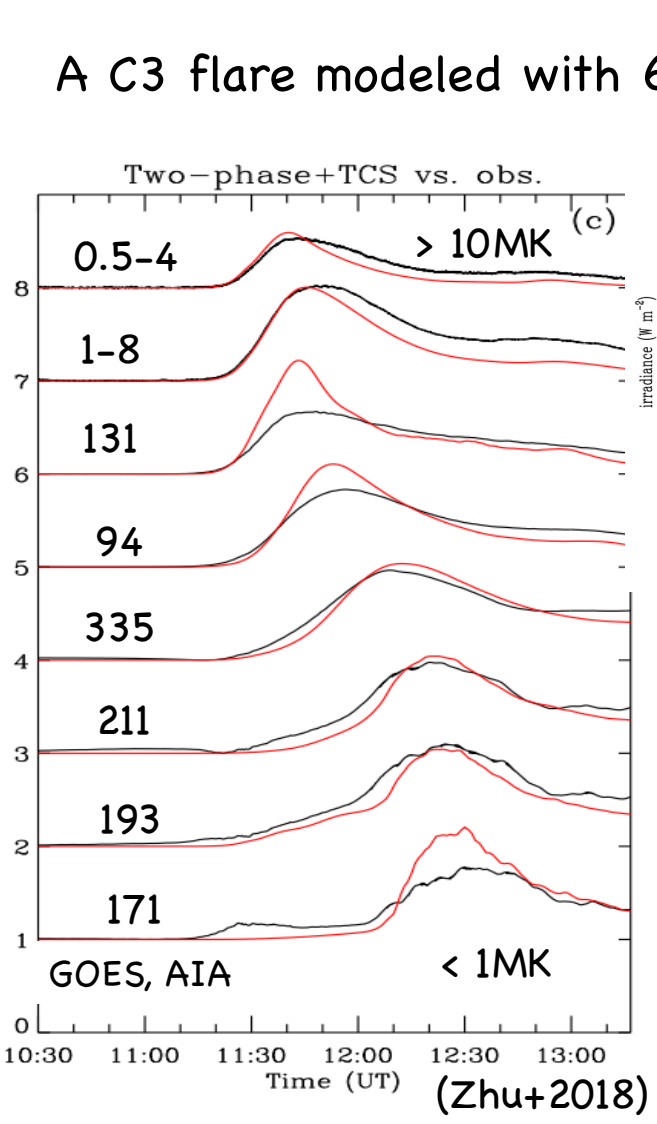


A C-7 flare observed/modeled (Klimchuk+2008) with UV Neupert effect: Φ = 2e19 Mx; E = 8e29 erg.

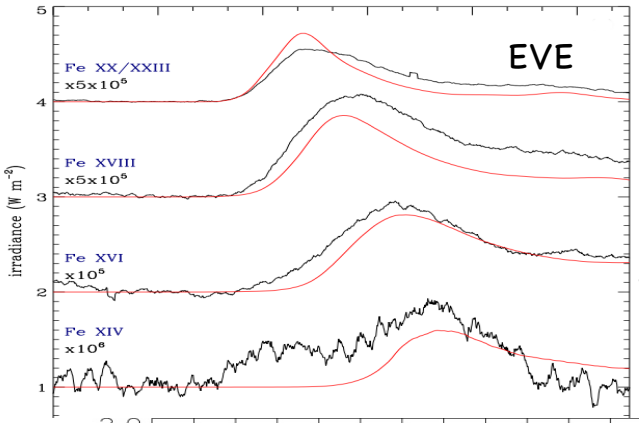
Flare total emission from 1000 heating events, compared with RHESSI, EVE, and AIA (not shown here) observations (Liu+2013; Zeng+2014).

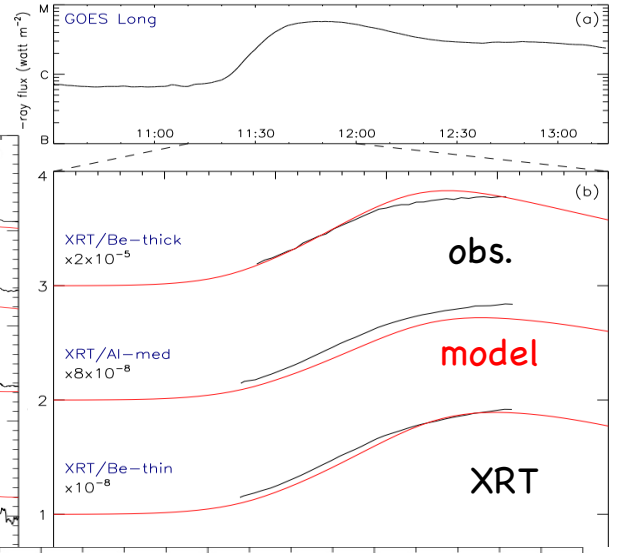


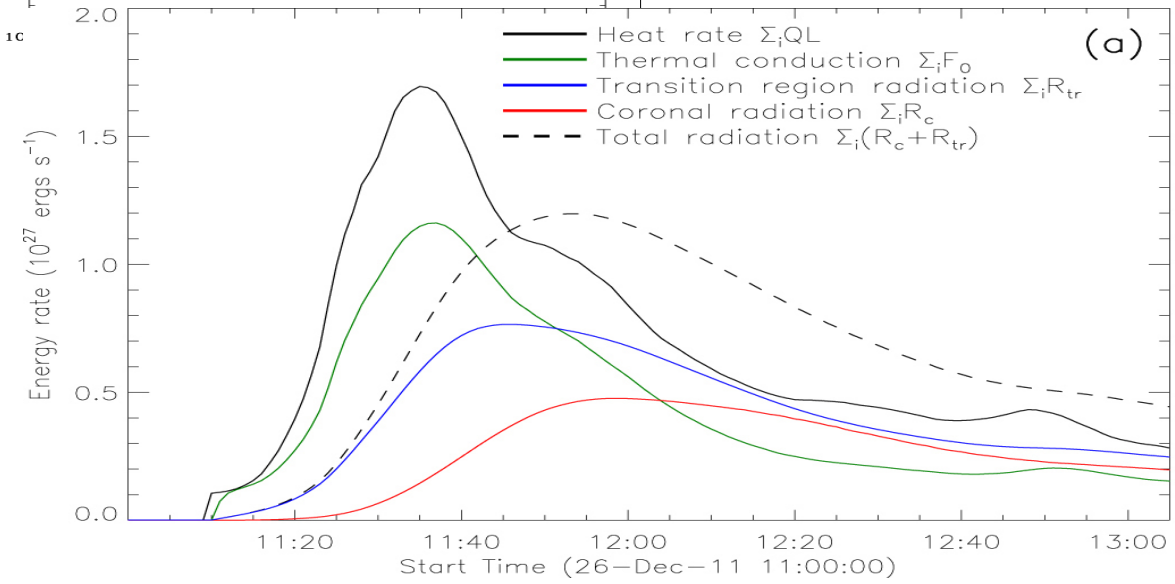
A C3 flare modeled with 6000 heating events

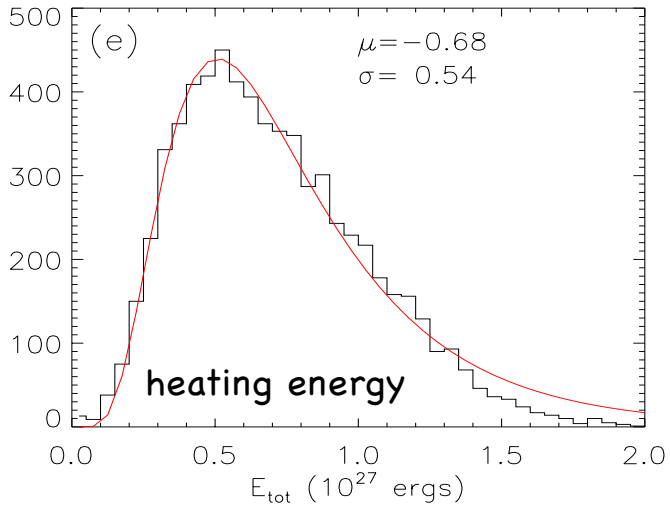


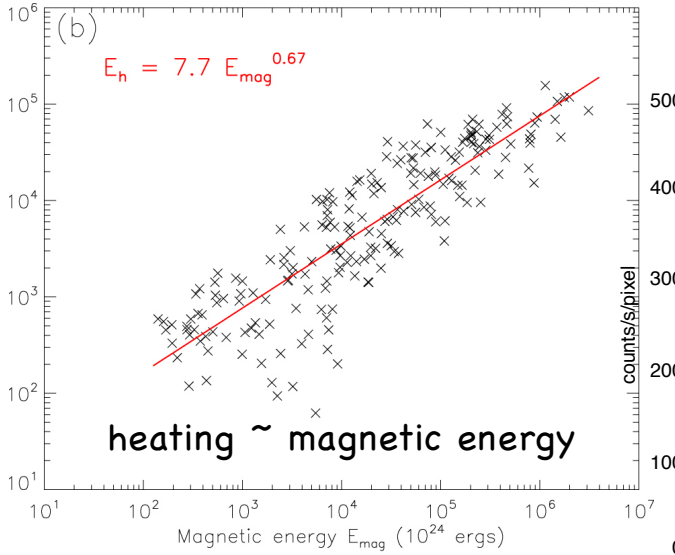
(Zhu+2018)

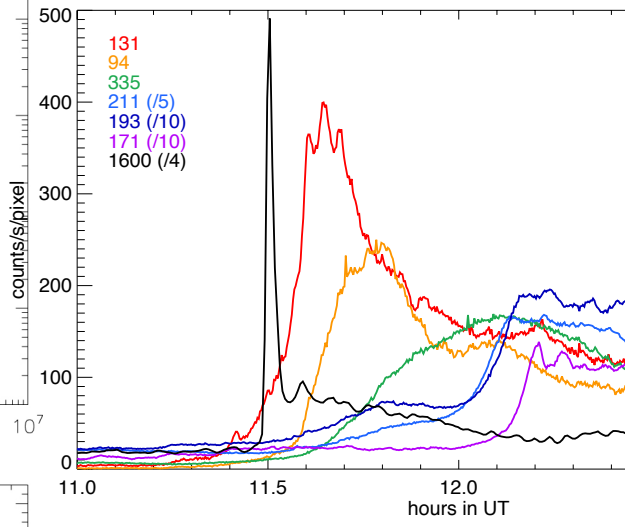


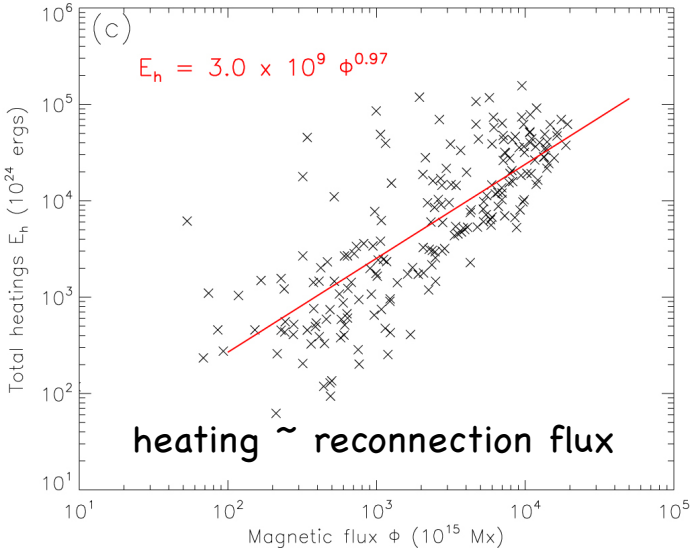


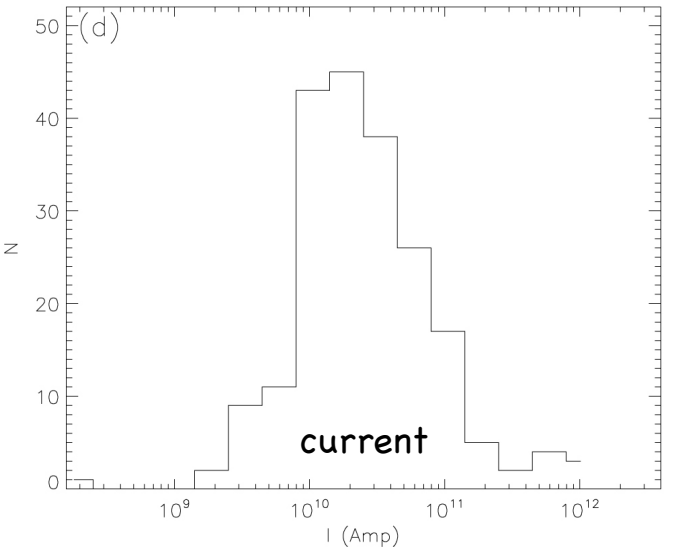






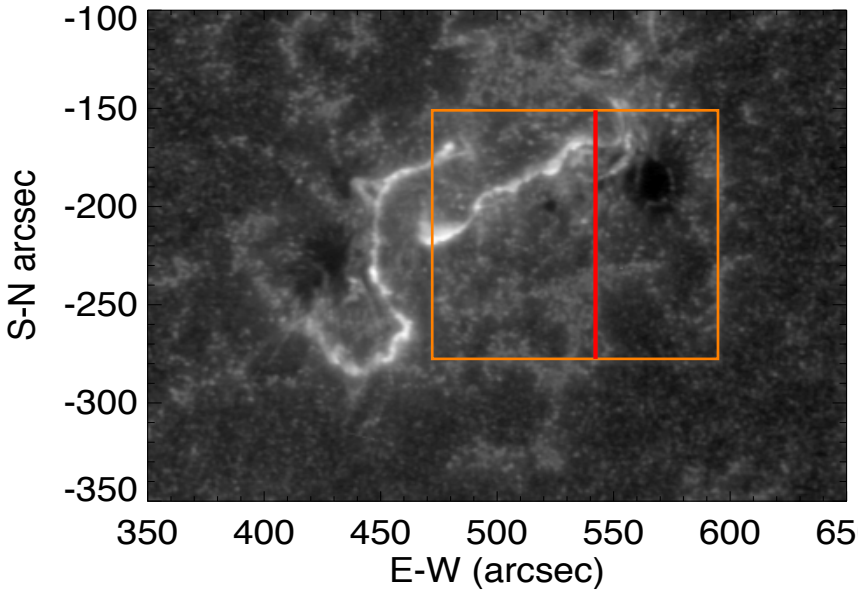




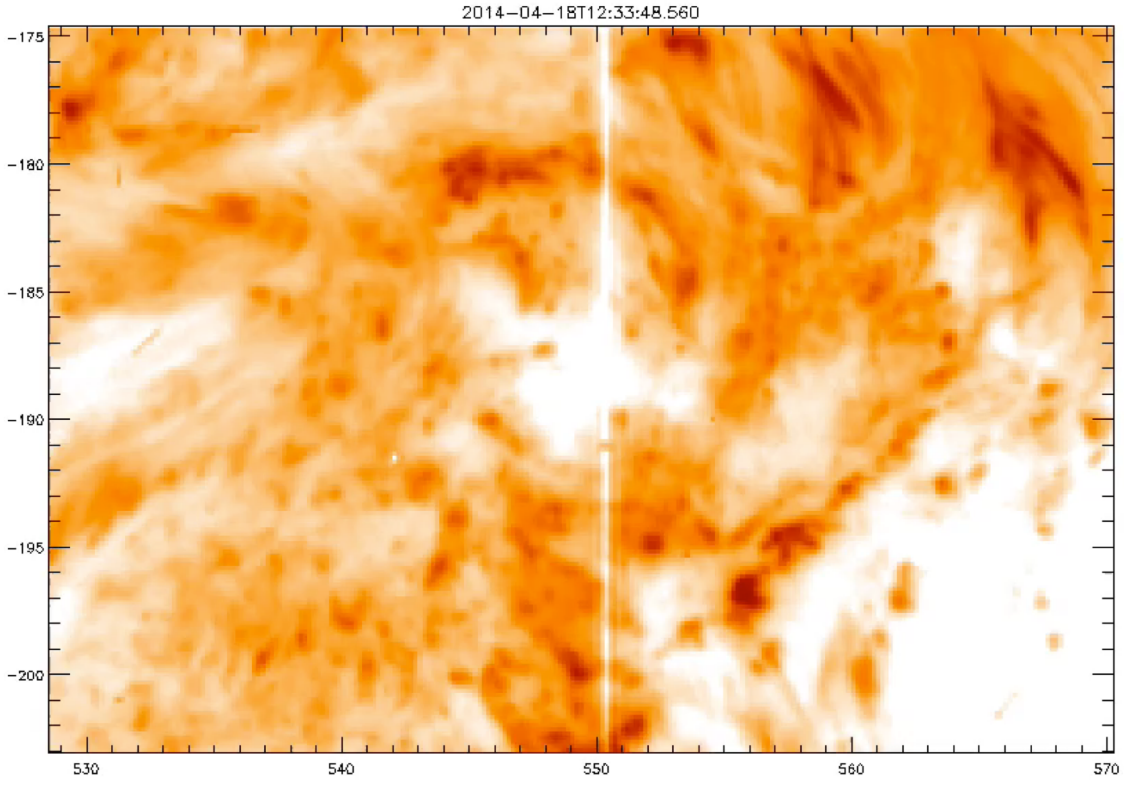


distribution of various properties, in units of AIA pixels (0.6") and timescales (24s).

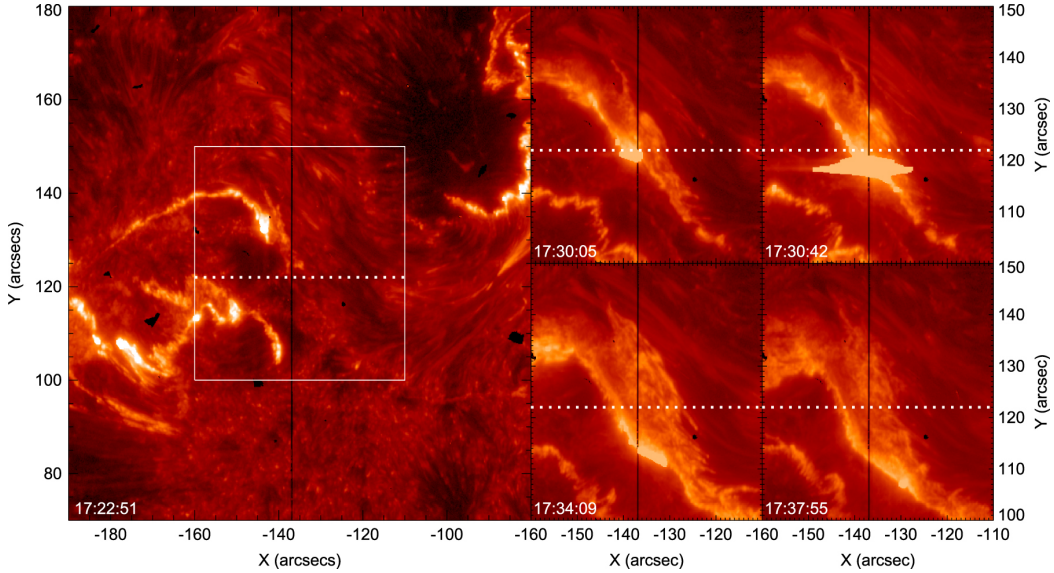
fundamental scales (?) of energy release events

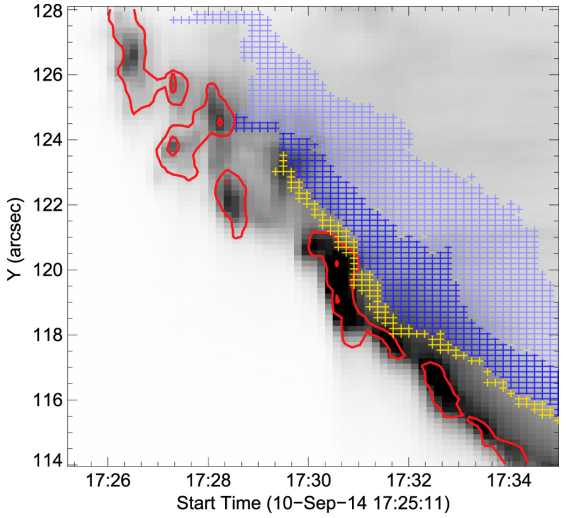


2014-4-18 M7.3 flare observed by imagers on SDO/AIA (0.6", 12-24 s), and spectrographs on IRIS (0.17"-0.33", 9 - 30s), exhibiting QPPSs. Oscillations found in conjugate foot-points, implying the corona origin (Brannon+2015, Brosius+2015).

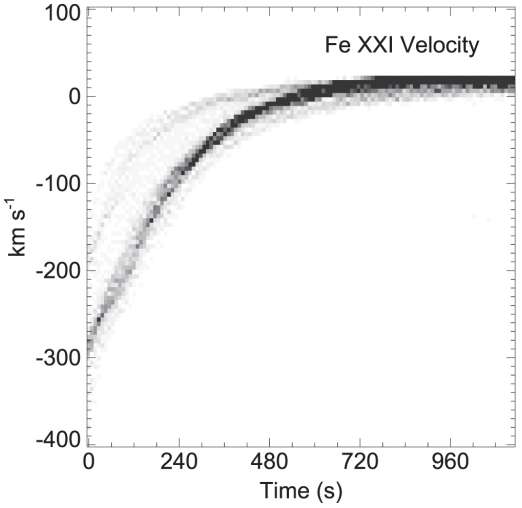


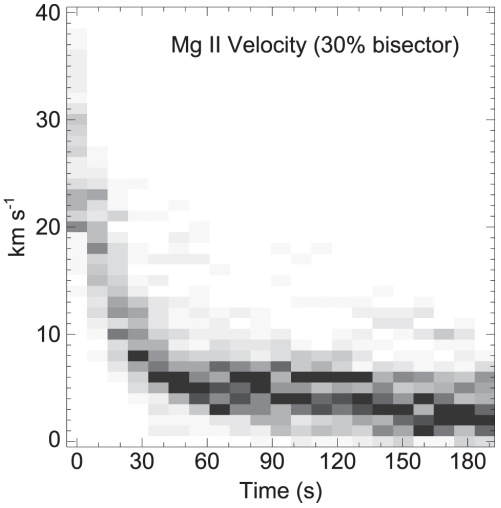
(Courtesy: Dana Longcope)

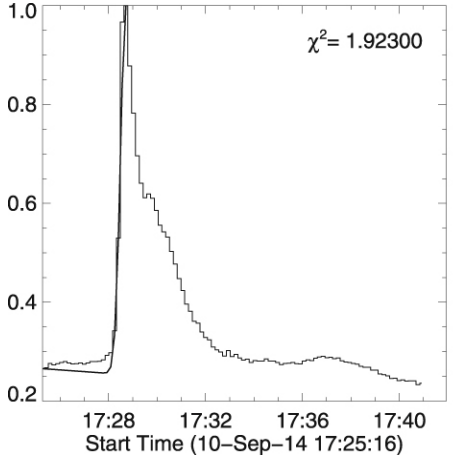


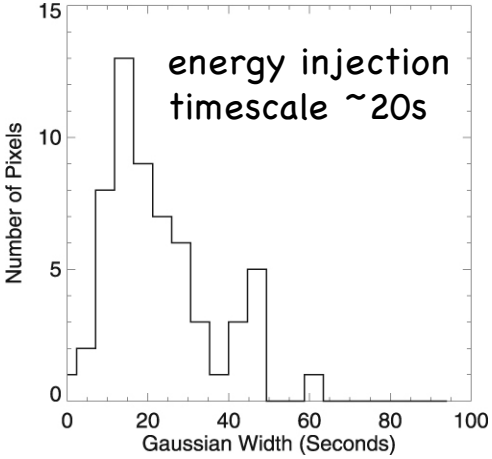


"Fundamental scales" of energy release events probed with IRIS imaging/spectral observations of flare ribbons (Graham+2015, 2020).

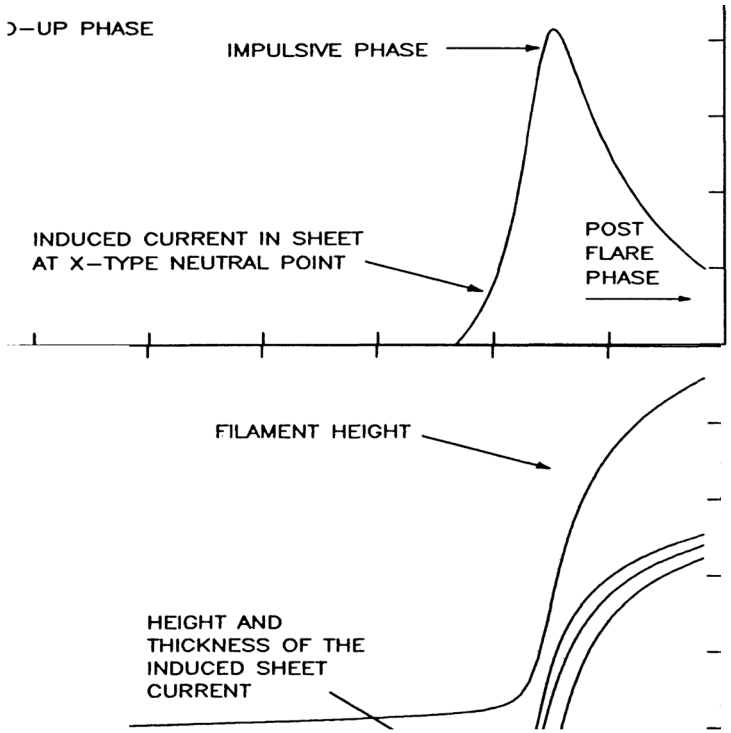




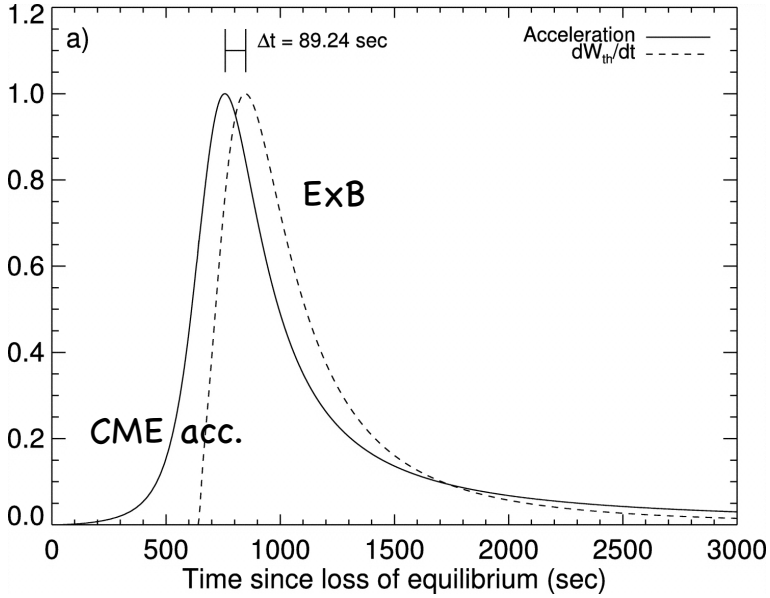




reconnection vs. CME kinematics: models

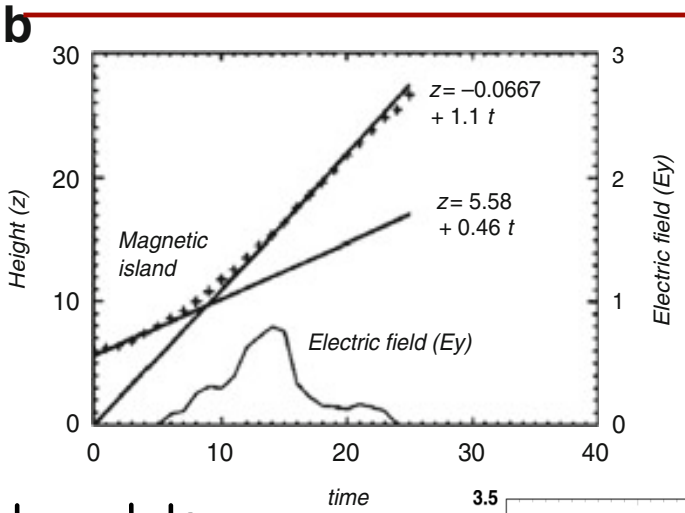


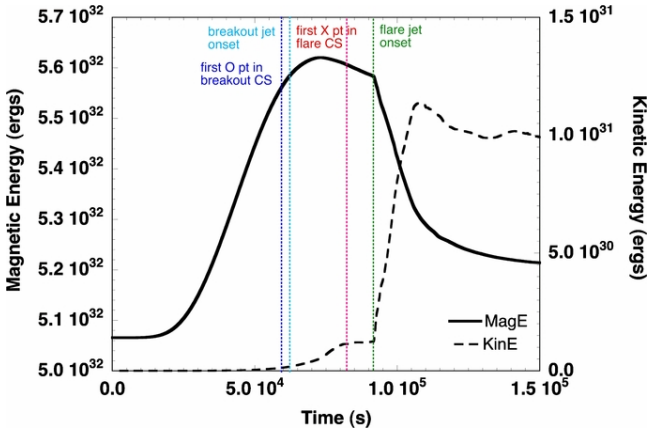
Martens & Kuin 1989



Reeves (2006) (and Forbes-Isenberg-Lin-Reeves)

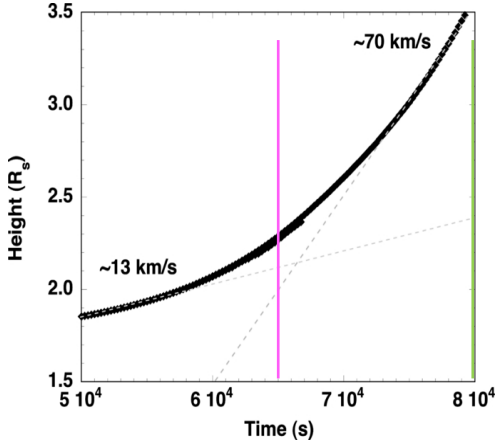
reconnection vs. CME kinematics: models





Numerical models indicating timing of reconnection and CME acceleration.

Magara et al. (1997), Shibata et al (2001), Karpen et al. (2012) ….



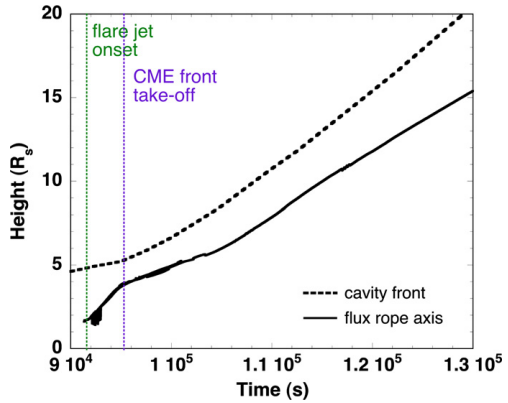
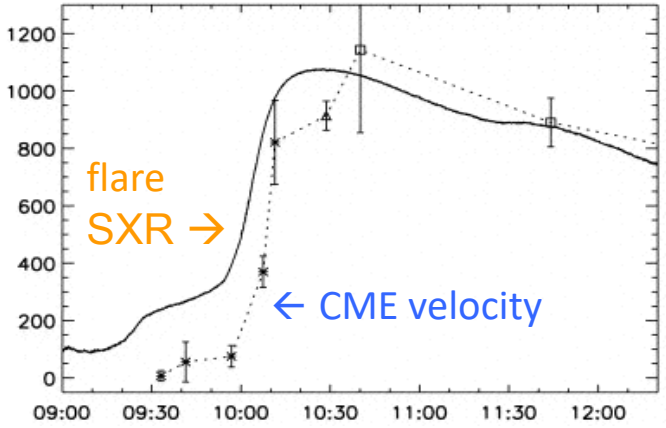
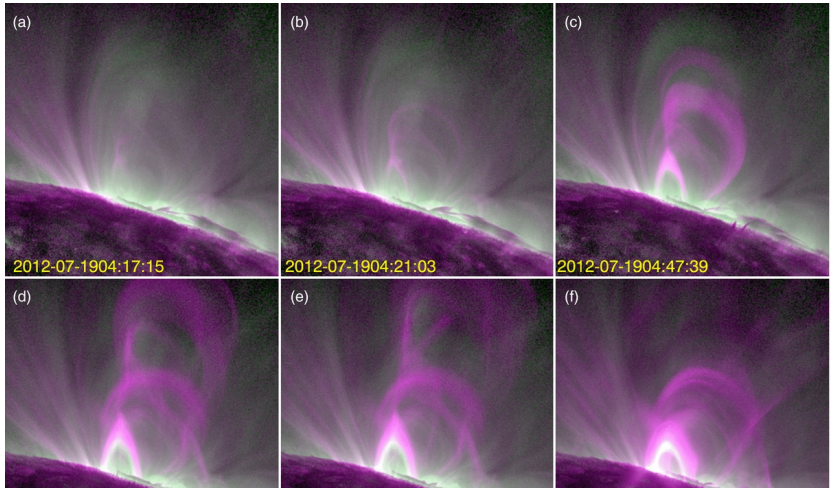


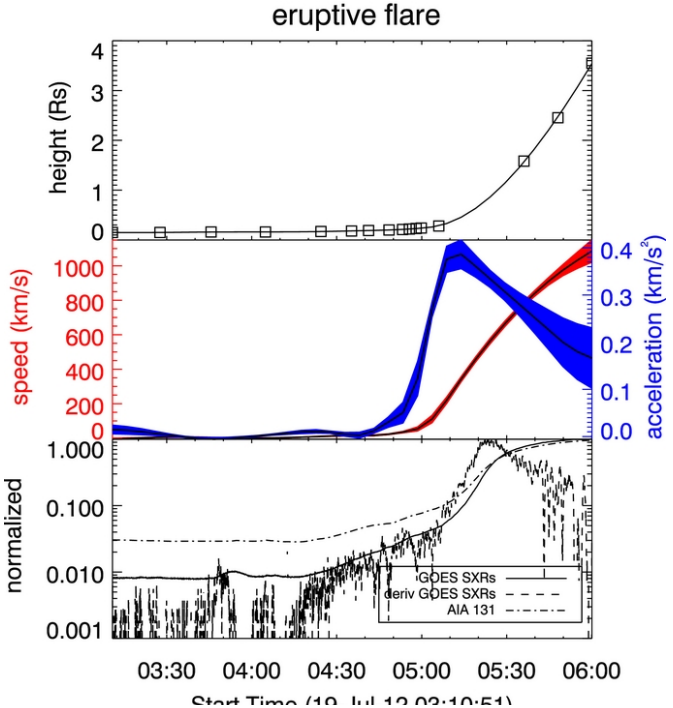
Figure 15. Height of the cavity front and flux-rope axis vs. time. Here the front is defined as the location where the mass density increases sharply behind the breakout current sheet, and the flux-rope axis is an O-type null. A thicker track is shown in certain intervals before ~102,000 s because two O-type nulls exist

CME kinematics and flare emissions

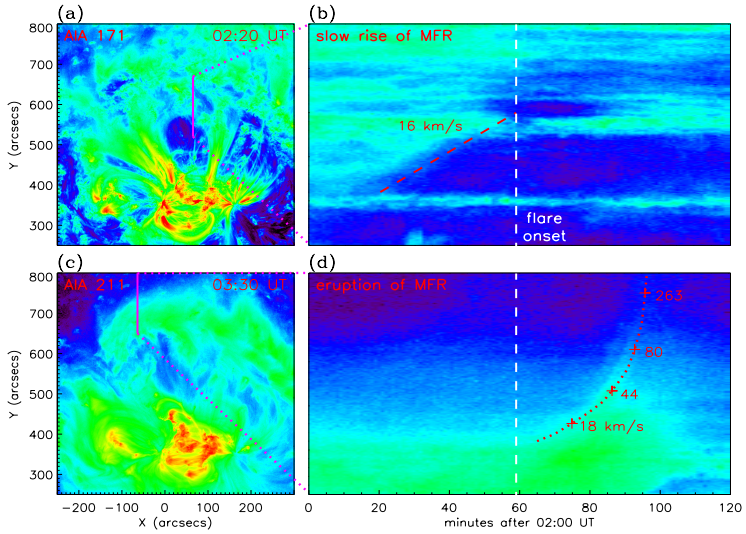


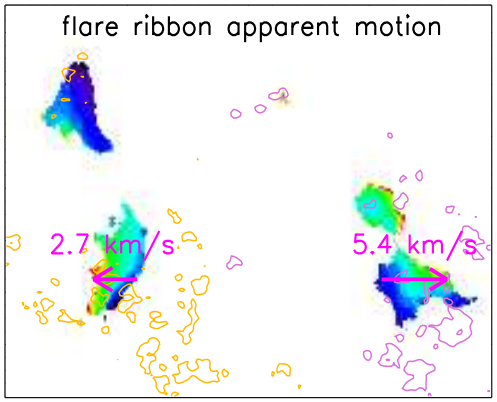
closely related CME motion and flare emission (Zhang et al. 2001; Gallagher et al. 2003 …. Patsourakos et al., 2010 ….)

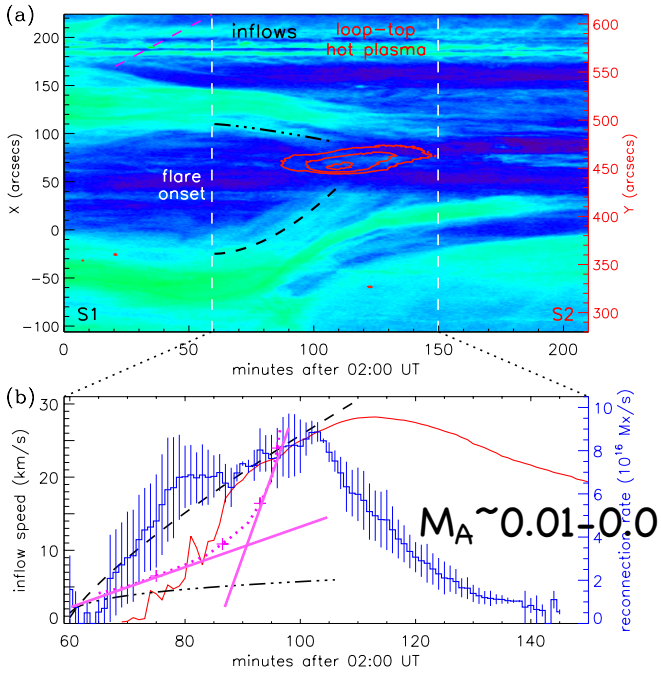




CME kinematics and magnetic reconnection



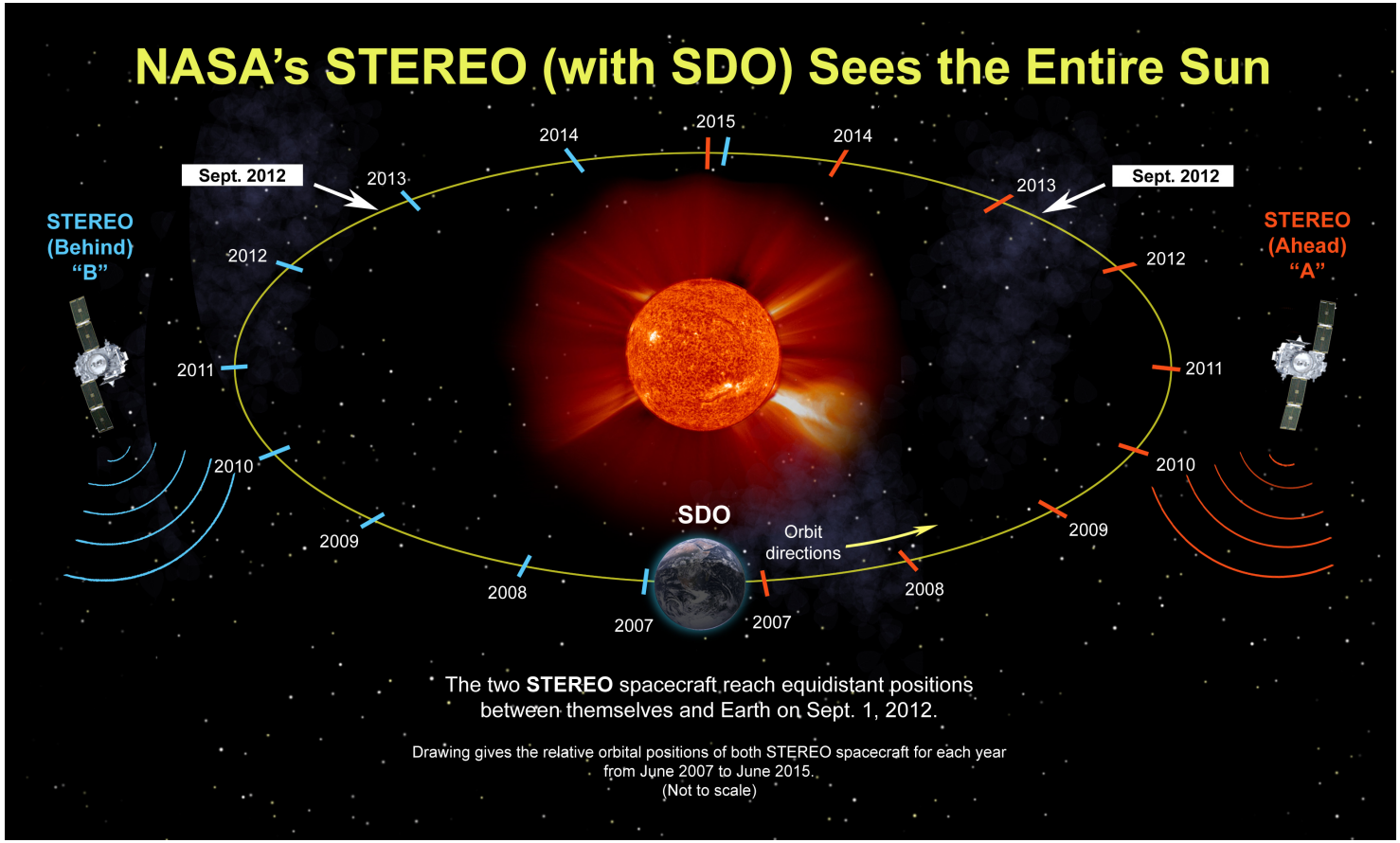




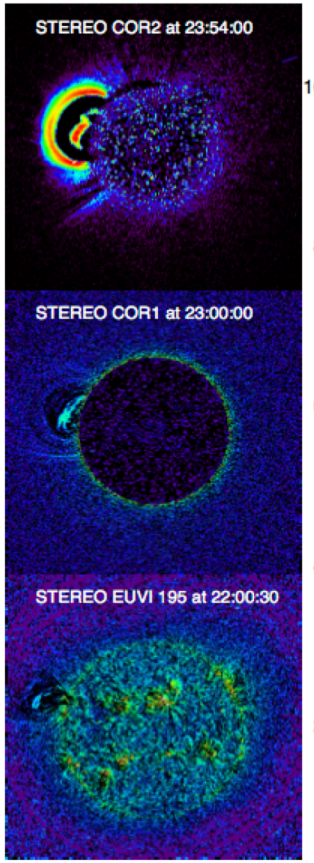
M_A~0.01-0.03

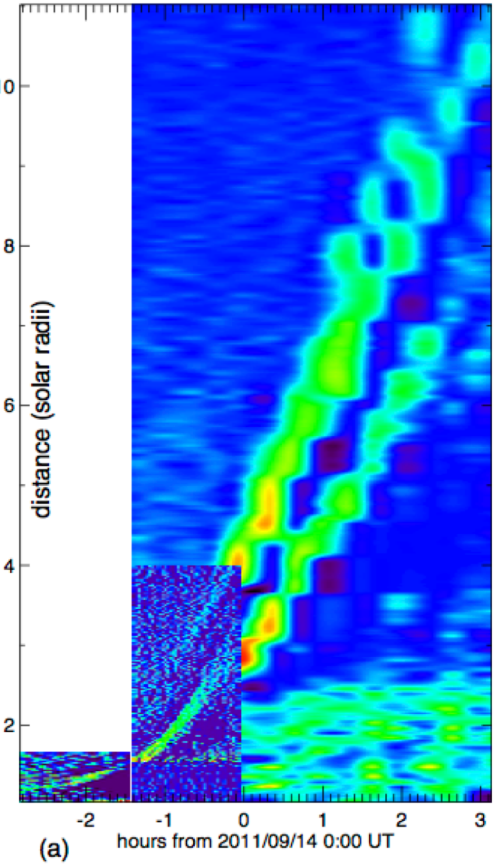
Measure CME and reconnection multiple ways (Li+2017, Wang+2017)

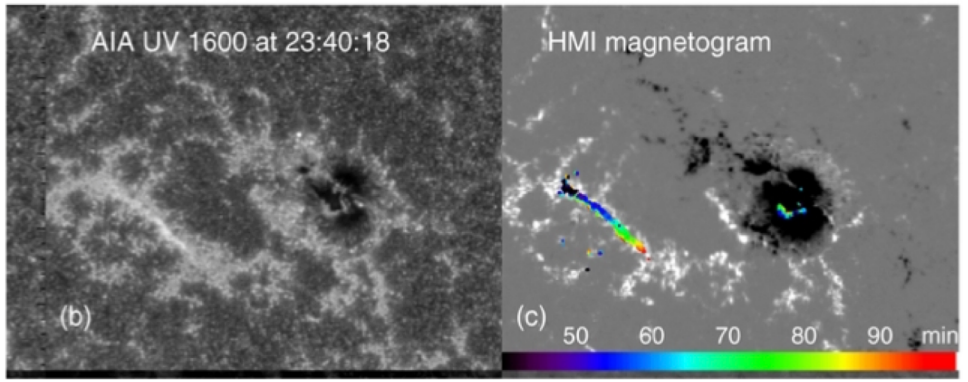
observe flare and CME at the same time

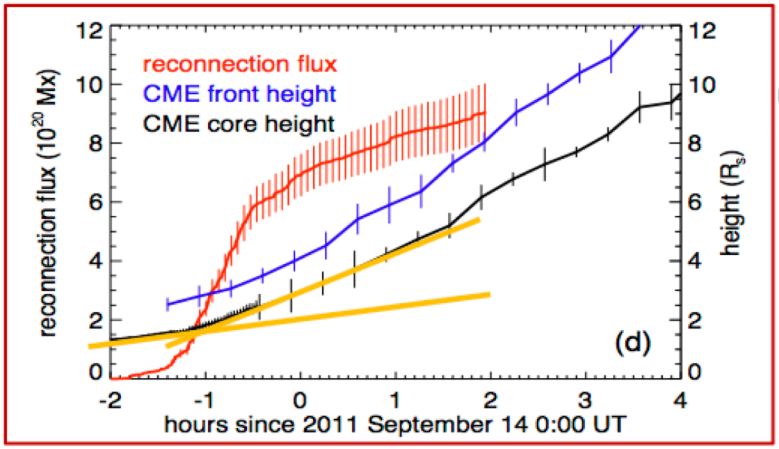


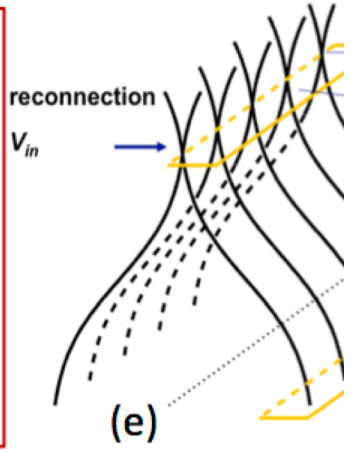
reconnection vs. CME kinematics





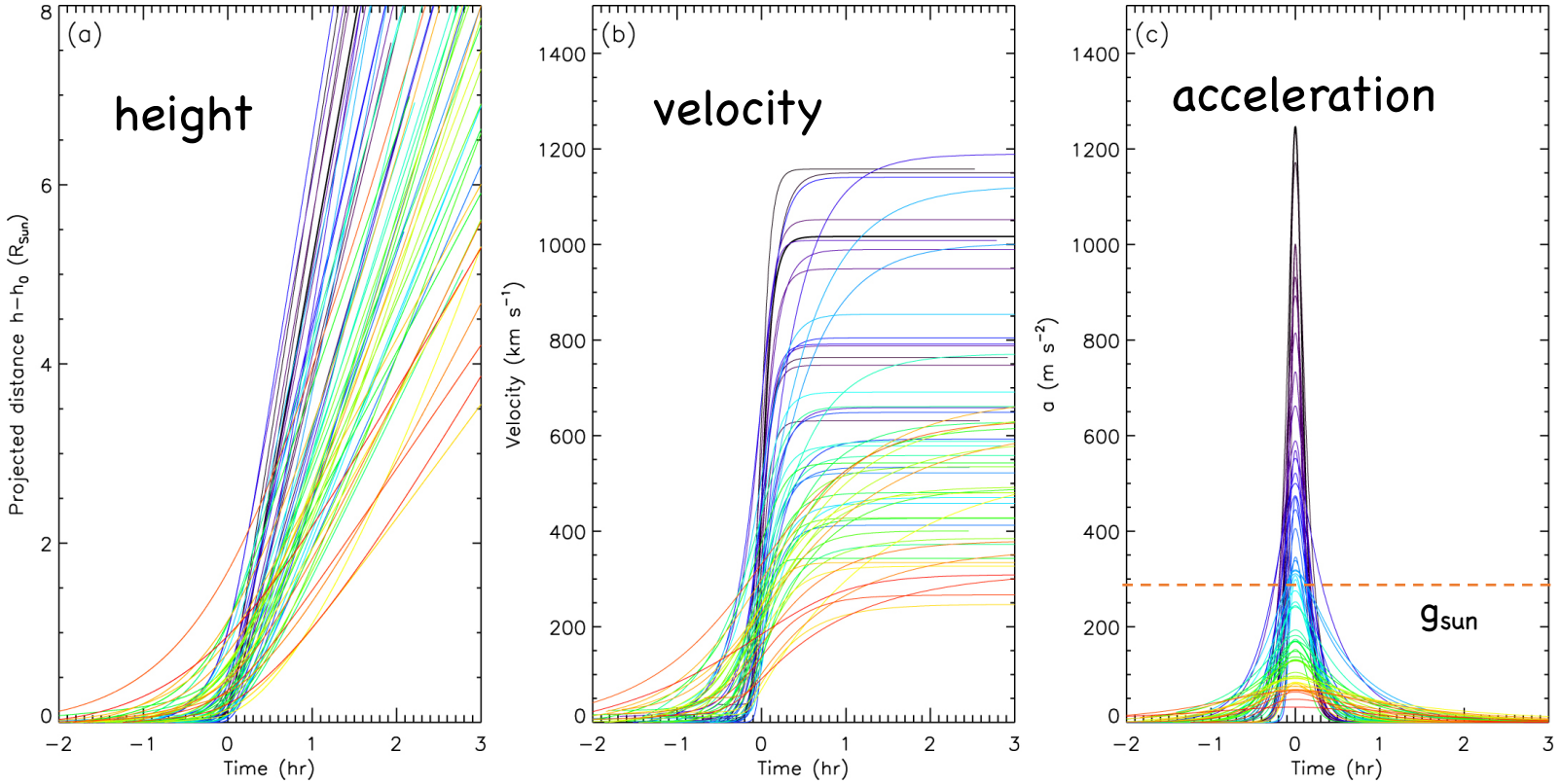






(Hu+2014)

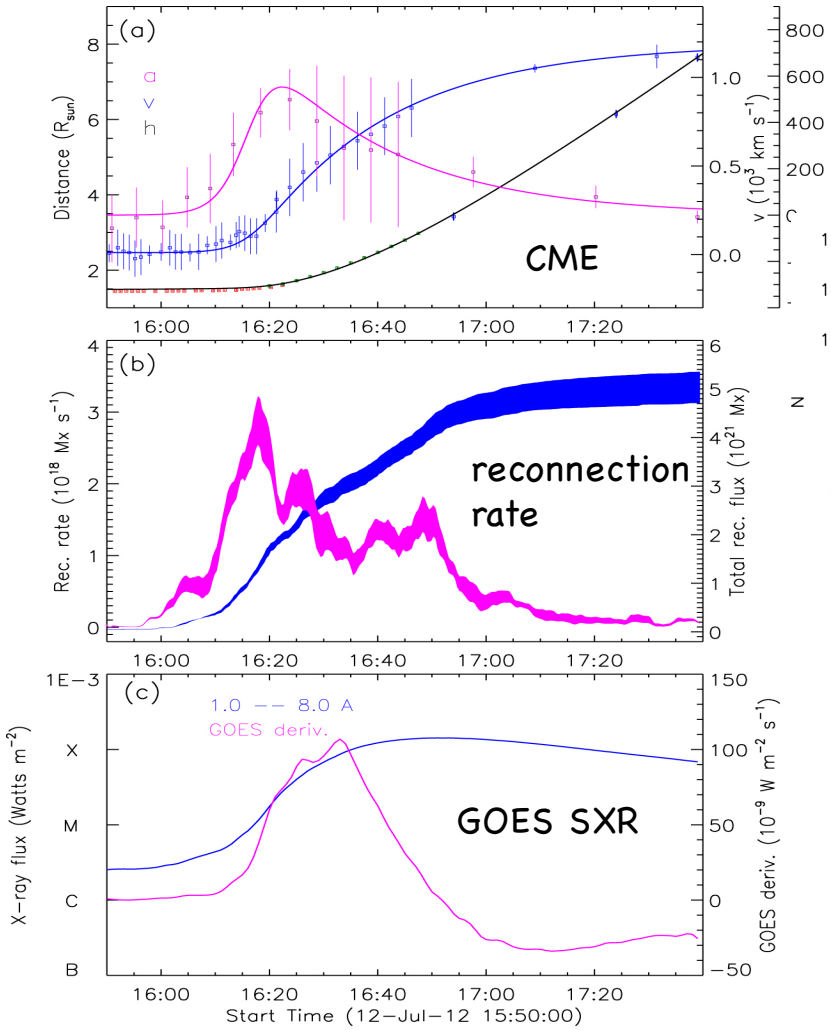
height, velocity, and acceleration of CMEs

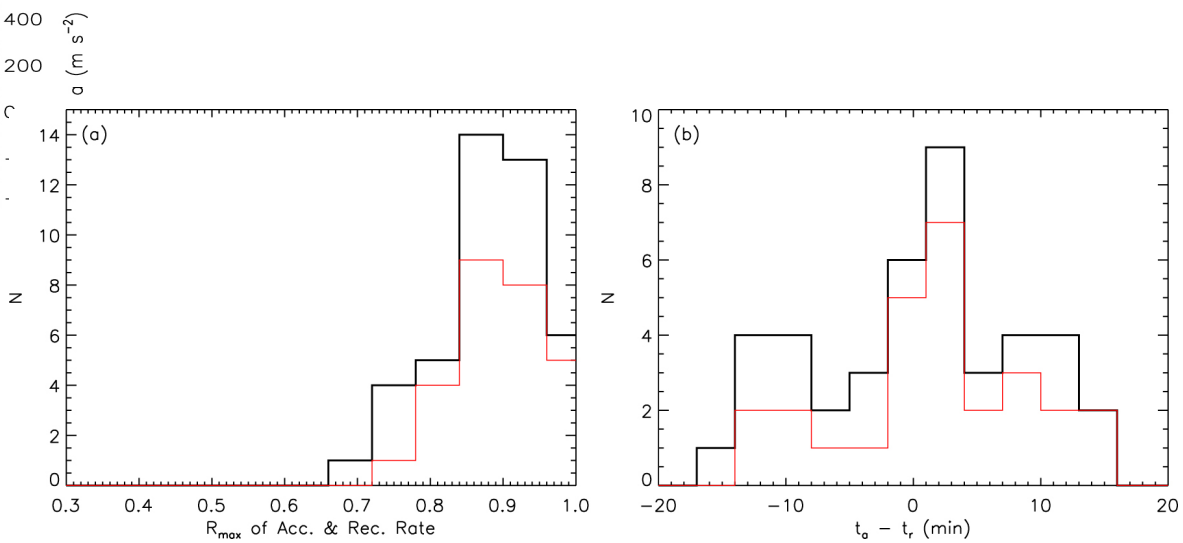


cadence of STA-EUVI: 75s - 5min

Fast CMEs are accelerated within minutes in the low corona (Zhu+2020).

reconnection vs. CME kinematics





Time lagged correlation analysis suggests three populations, and CME-lead events tend to have lower reconnection rate on average (Zhu+2020).

Summary

Magnetic reconnection allows eruptive energy release in flares and CMEs.

State-of-the-art observations and models provide unprecedented opportunities to conduct large-scale and detailed studies of reconnection and energetics in the solar atmosphere, to help answer some outstanding questions in a quantitative manner.