Observational Constraints on Flare Energy Release

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SolFER

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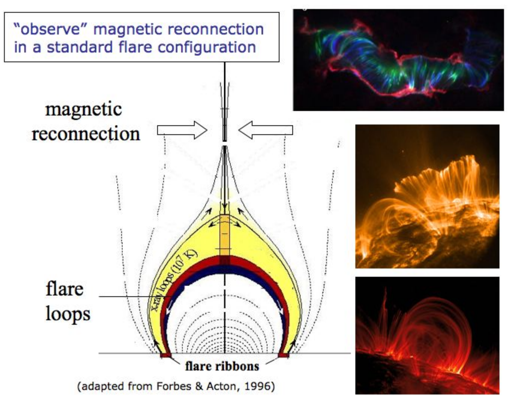
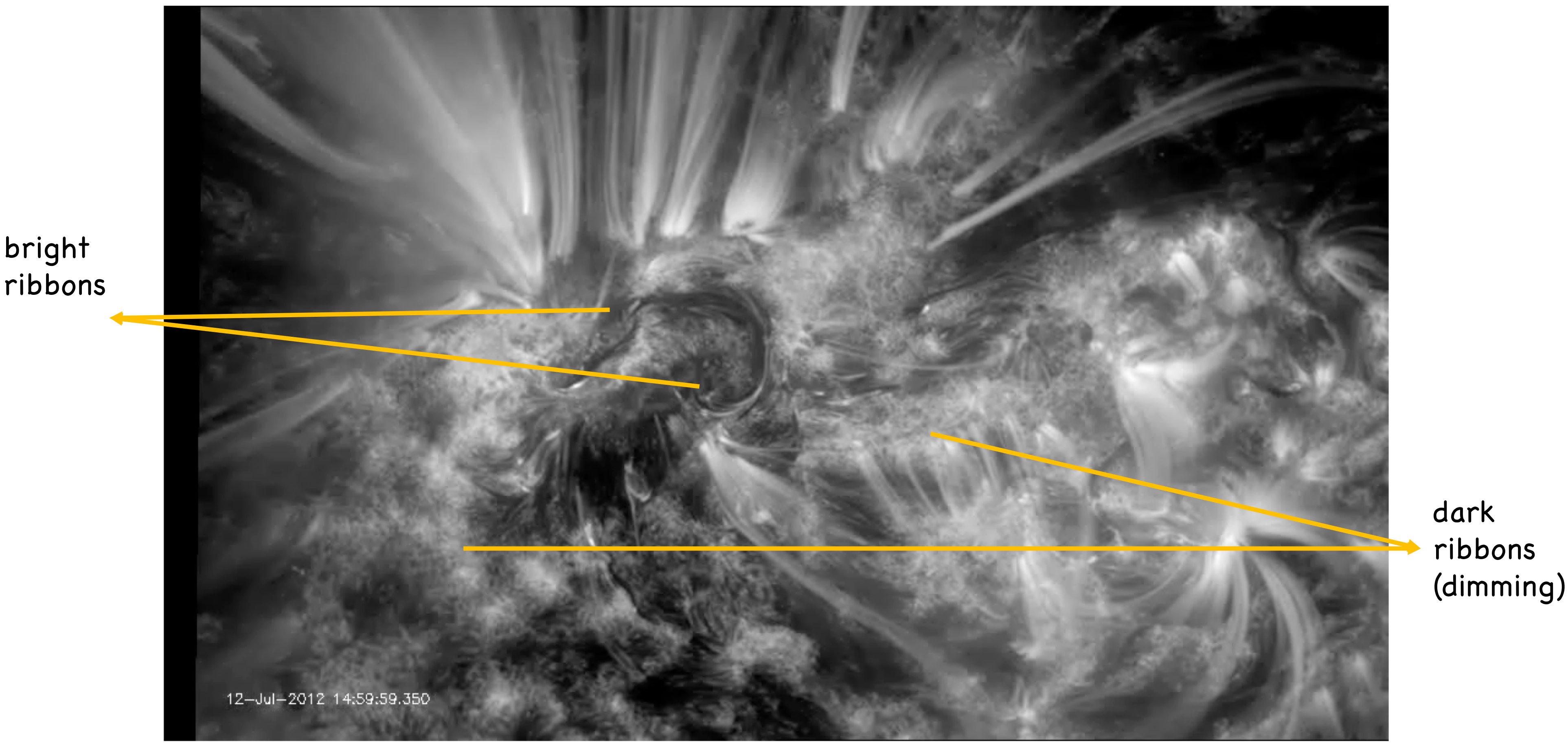


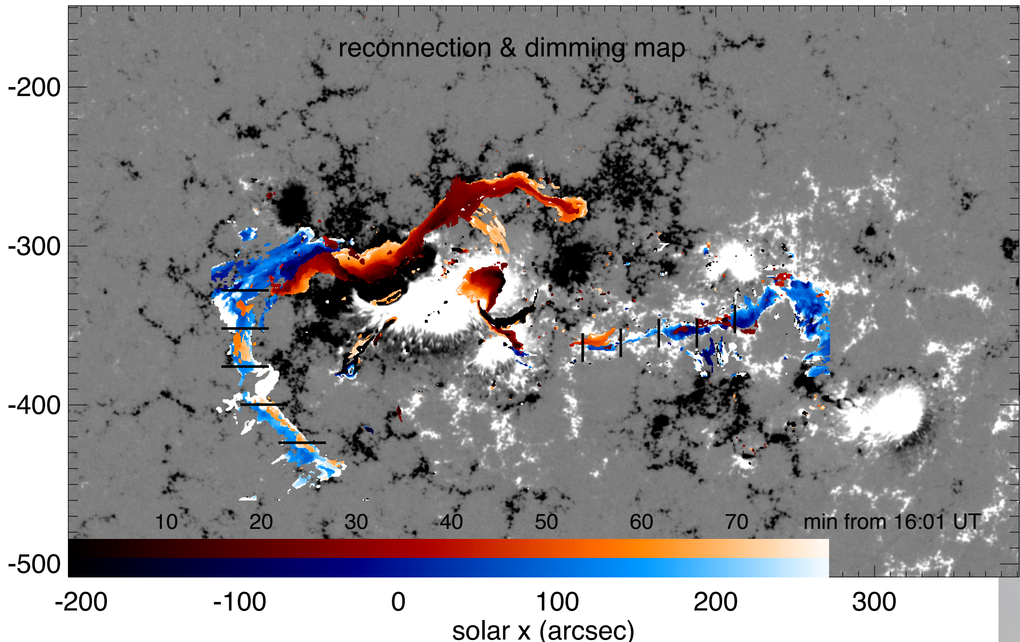
Outline

- Flare ribbons map the topological boundaries in the chromosphere that are dynamically evolving due to reconnection in the corona.
- Temporal and spatial evolution of flare ribbons can be used to infer reconnection properties, such as the reconnection rate, and the dynamics and structure of reconnection in the corona.
- Flare ribbon observations provide diagnostics of flare energetics, which may be governed by reconnection properties, global or local or the interplay between the two.



Chromosphere ribbons outline the feet of magnetic field lines being closed, or opened, by magnetic reconnection in the corona.

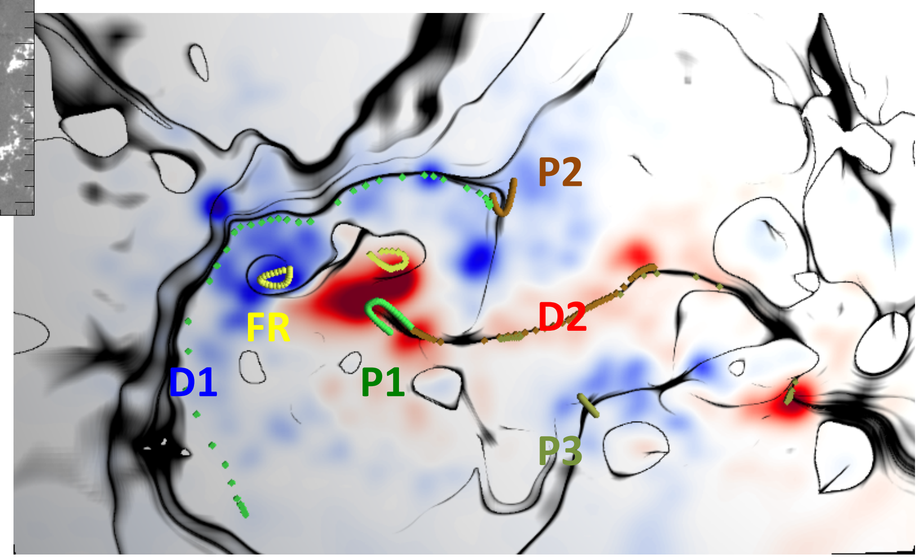
chromosphere ribbons map magnetic reconnection



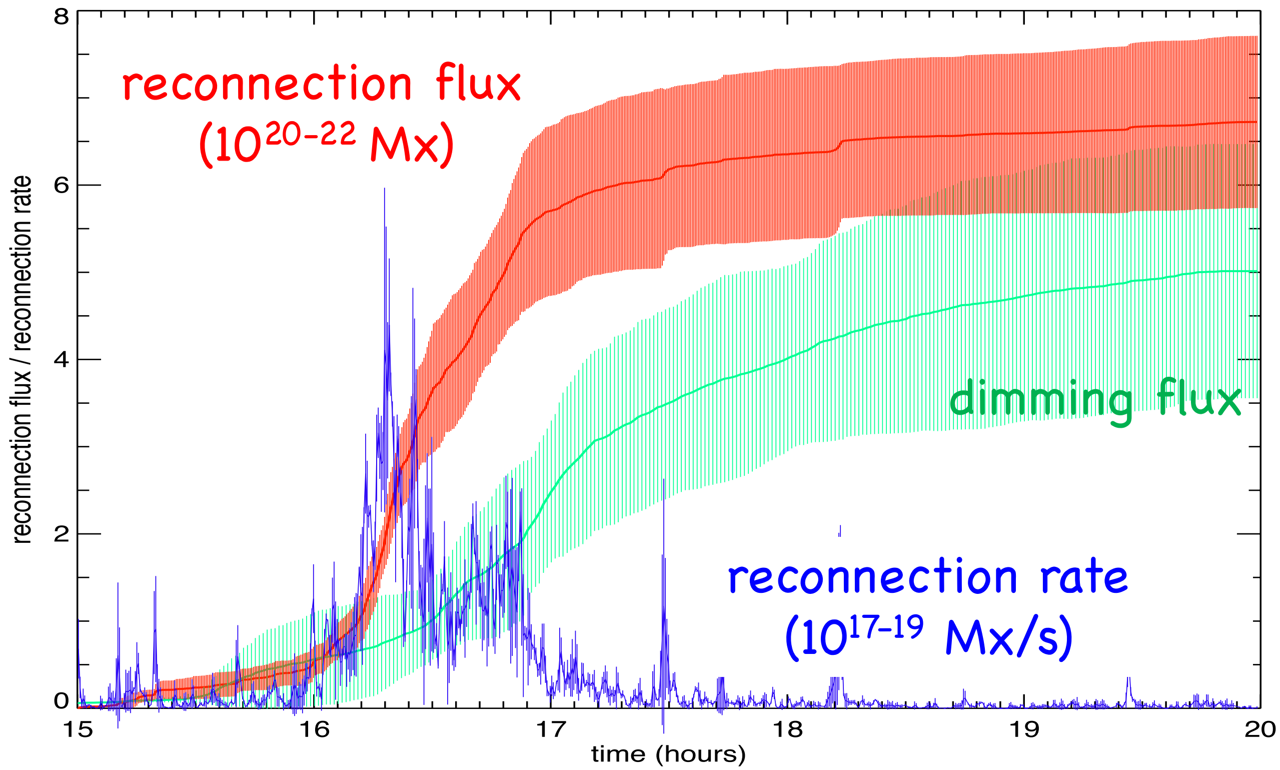
Left: temporal evolution of bright ribbons and dark ribbons (dimming).

Bottom: Q map superimposed on the radial magnetogram (Downs+15, Dudik+14).

Topology analysis shows both flare and dimming ribbons mapping the photospheric interception of the separatrices or QSLs, where magnetic reconnection tends to occur (Demoulin+96, Longcope05).



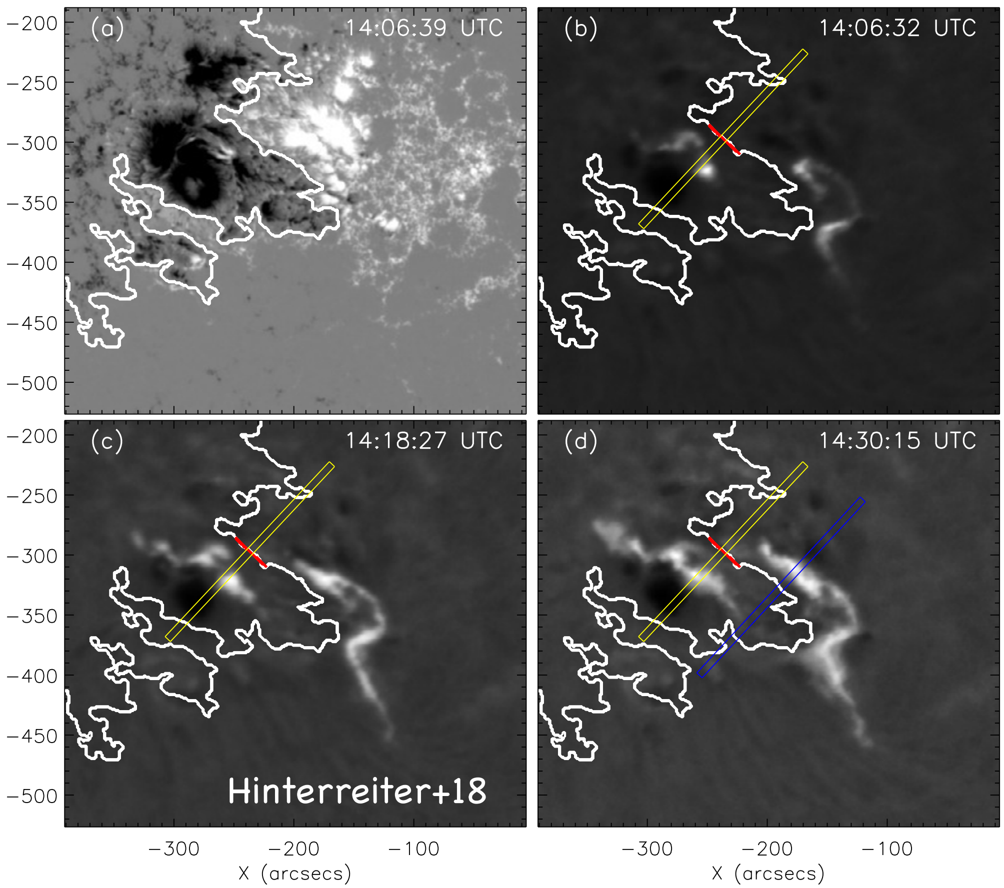
reconnection rate measured from flare ribbons

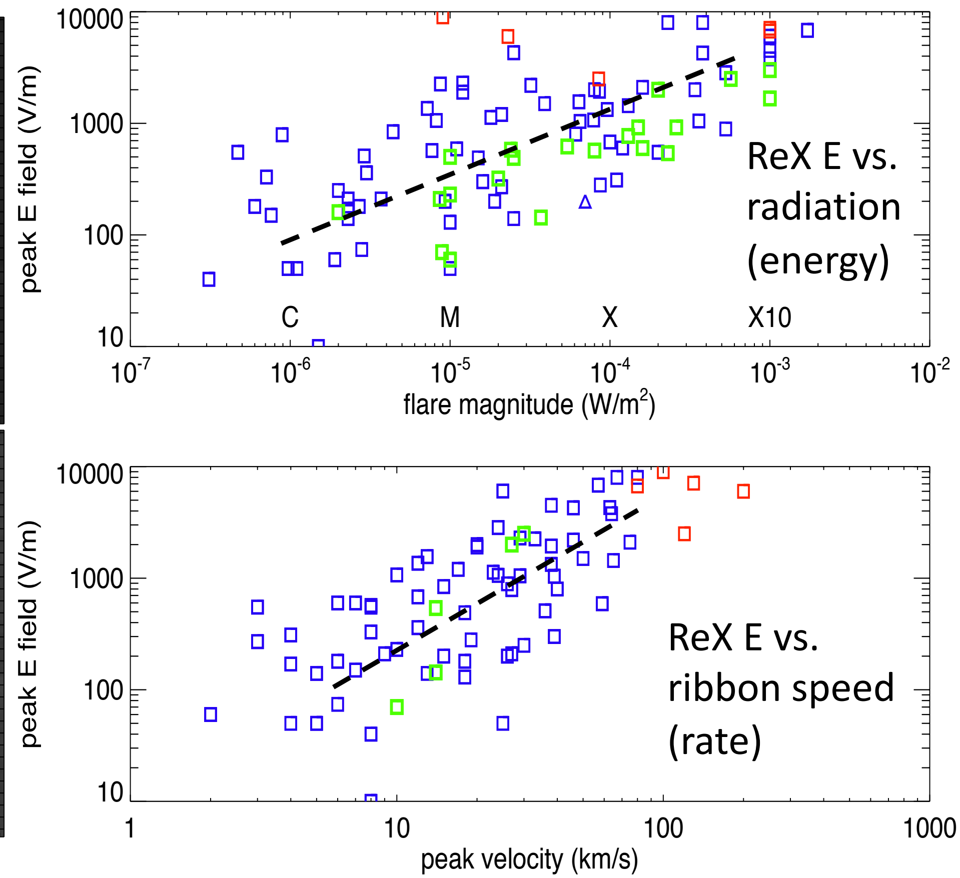


$\langle E \rangle = 500\ V/m$

$$\frac{d\Phi_B}{dt} = \frac{d}{dt}\int B_r dA_r = \frac{d}{dt}\int B_{in} dA_{in} = -\int \vec{E}\cdot\overrightarrow{dl}$$ (Forbes+84, Hesse+05)

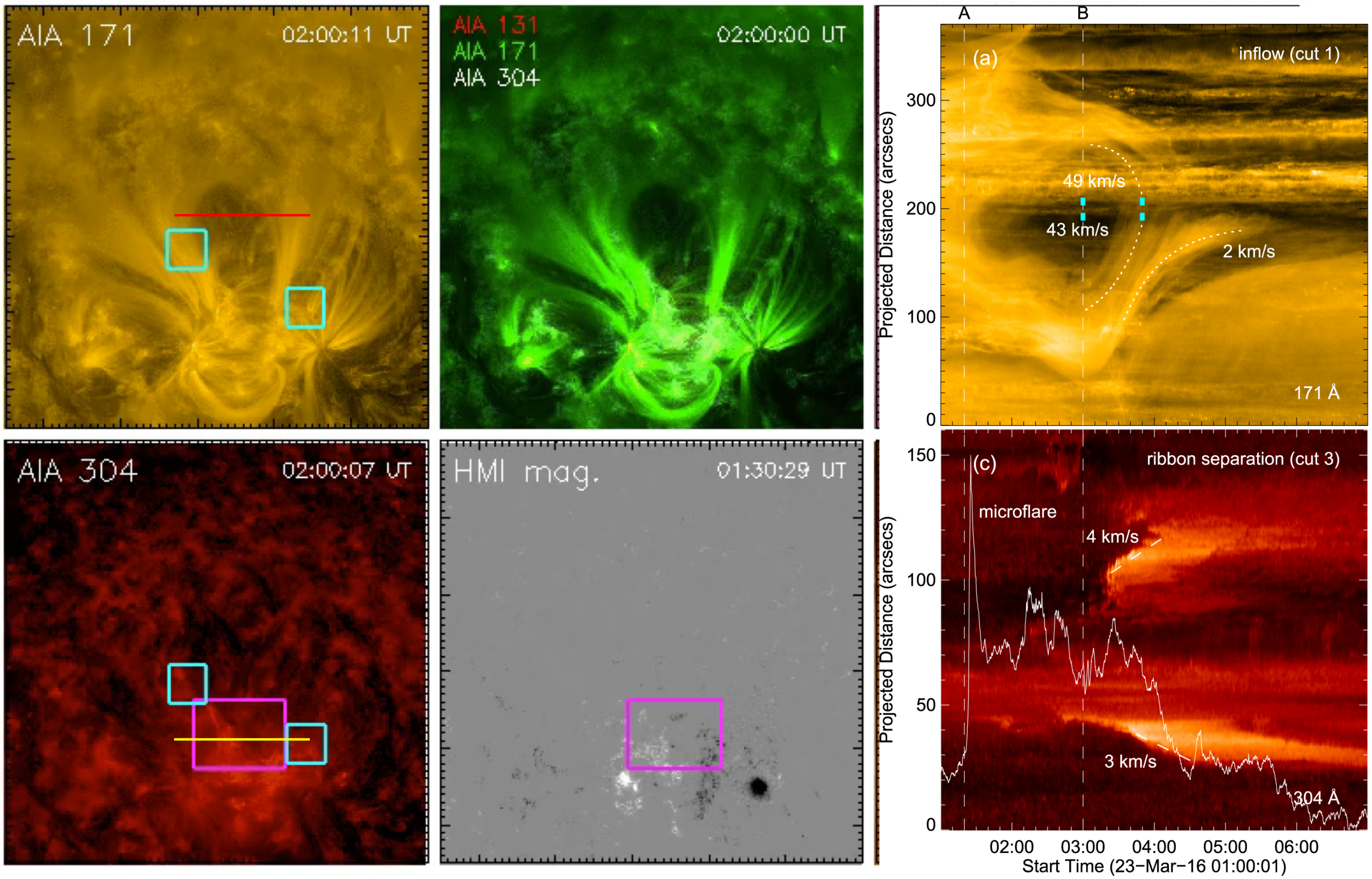
Poletto+86, Fletcher+01, Isobe+02, Asai+02, Qiu+02, Saba+06, Jing+05, Temmer+07, …. Kazachenko+17 ..





$E = v_{in}B_{in} = v_R B_R$ ~ 100 - 5000 V/m; $M_A = \frac{v_{in}}{v_A} = 0.1\ \frac{E(100\ V/m)/B_{in}(10\ G)}{v_A\ (1000\ km/s)} \sim \frac{v_{in}^2\sqrt{n_0}}{E}$

corona chromosphere

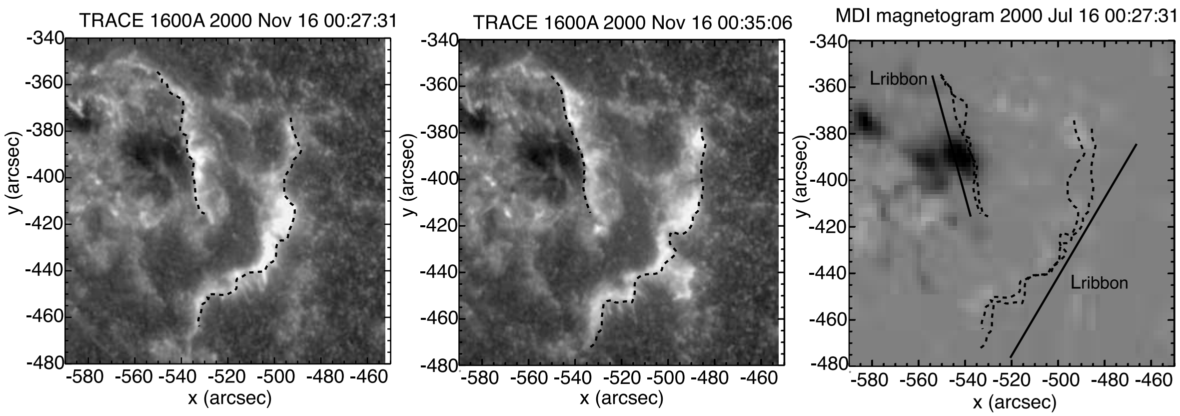


$E \sim 40$ V/m
$v_{in} \sim 40$ km/s,
$B_{in} \sim 10$ G,
$M_a \sim 0.03$
(Wang+17)

consistent with most corona observations (e.g. Yokoyama+01, Chen+20).

Ribbon motion and corona inflow both observed in a microflare (Li+17, Wang+17)

reconnection releases energy



$$\langle M_A \rangle = \frac{\langle v_{in} \rangle}{\langle v_A \rangle} = 0.1 \; \frac{\langle E \rangle^3 \sqrt{n_0}}{\langle H \rangle^2}$$

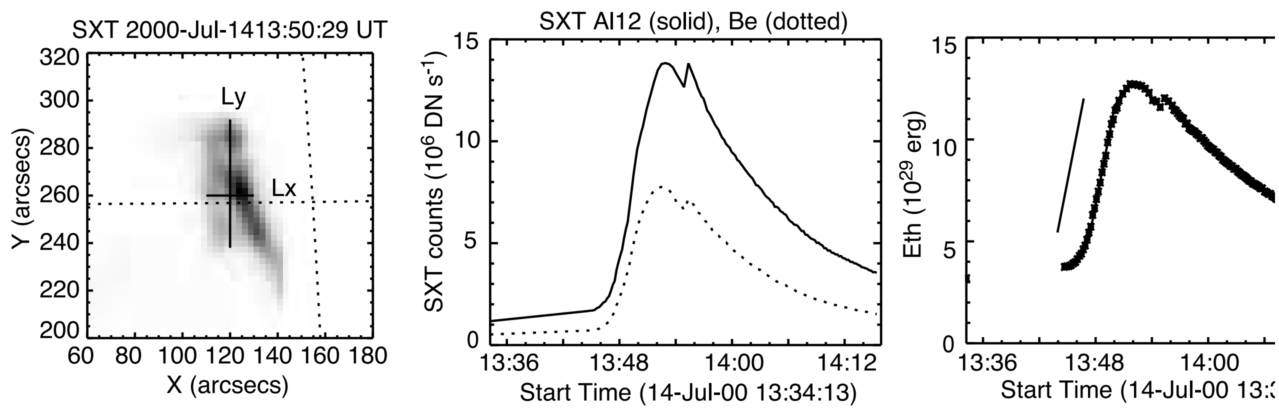
$$\sim 0.01 - 0.07$$

(Isobe+05)

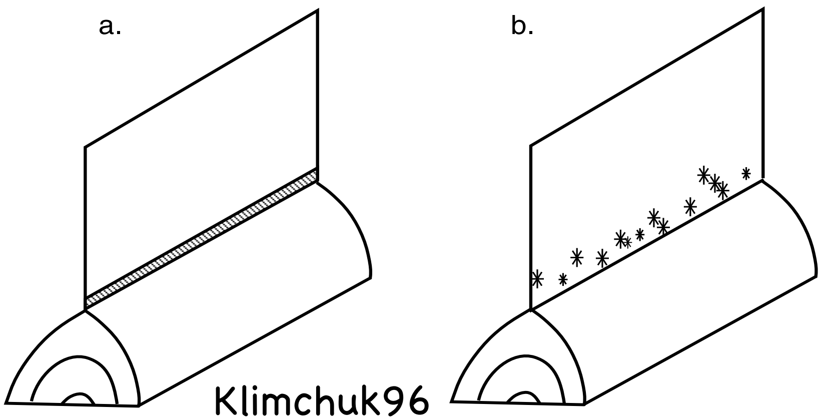
$$\langle E \rangle = \langle v_{in} \rangle \langle B_{in} \rangle = \langle v_R \rangle \langle B_R \rangle$$

$$\sim 100 - 500 \; V/m$$

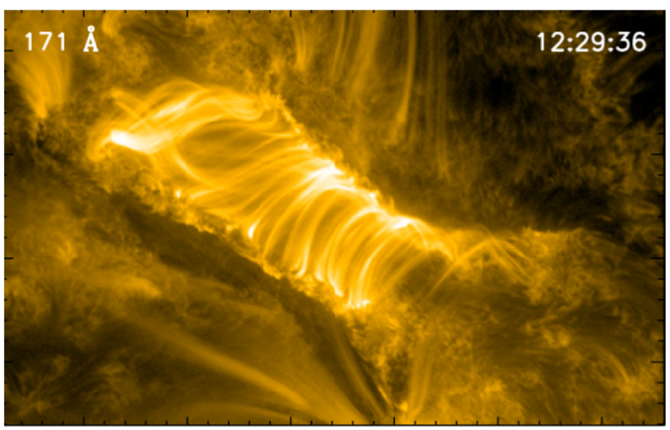
$$\langle H \rangle = \frac{1}{\mu_0} \langle E \rangle \times \langle B_{in} \rangle \sim \frac{1}{A} \frac{dE_{th}}{dt}$$

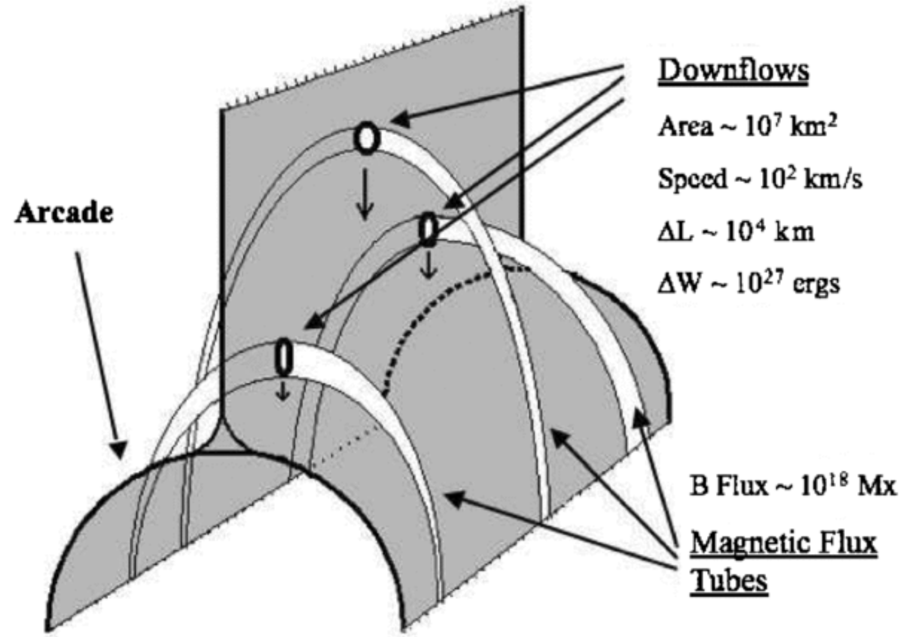


reconnection and energy release are not monolithic



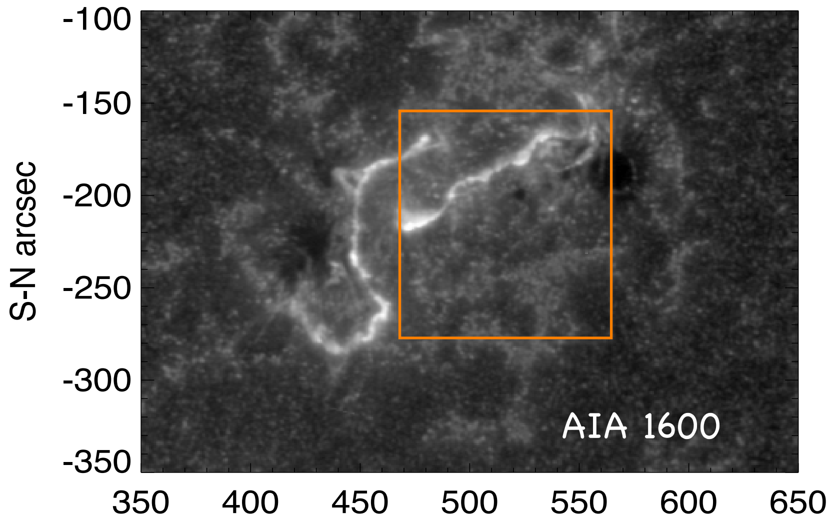
Klimchuk96

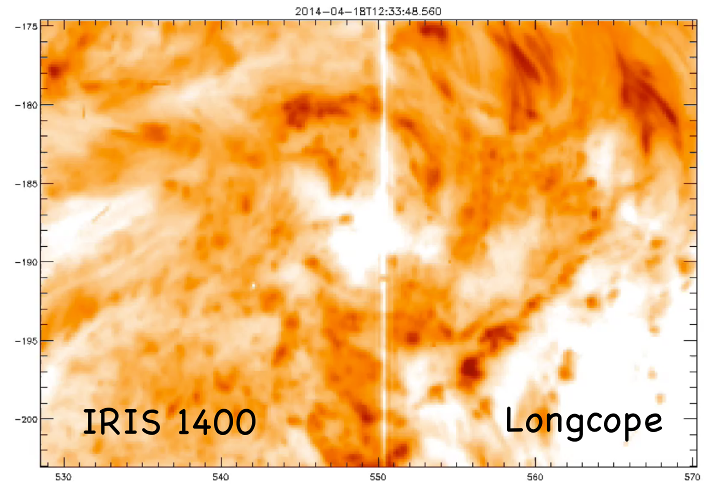




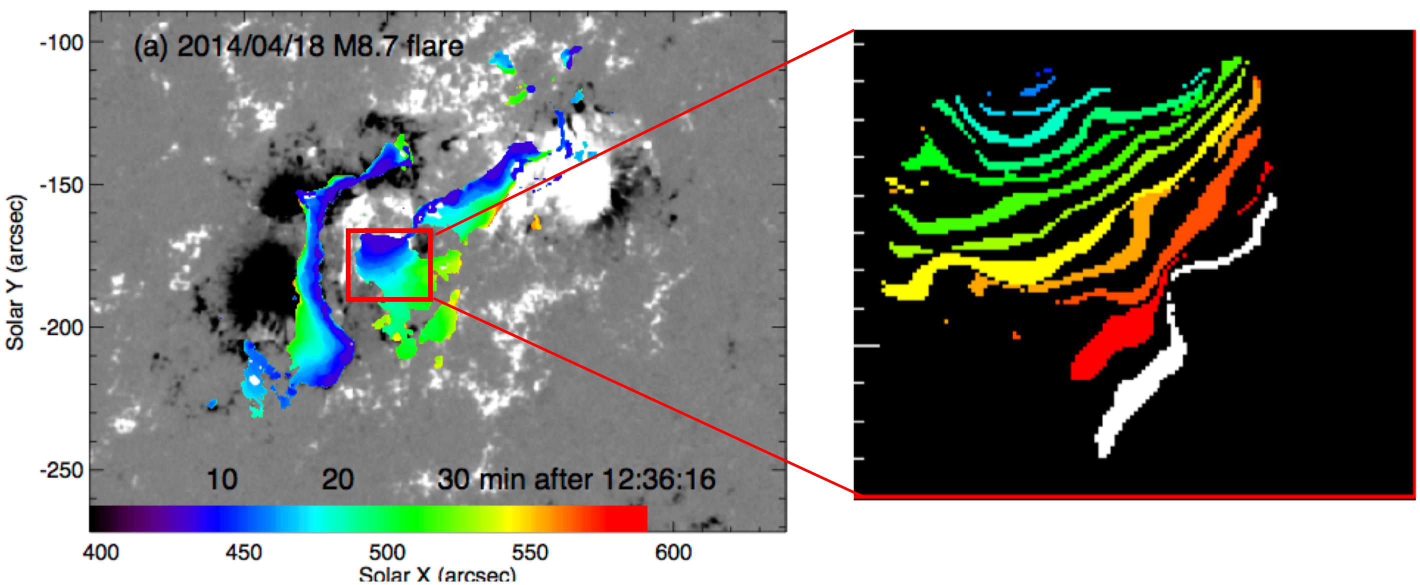
Savage+11

SADs (McKenzie+99)
loops (Aschwanden+01)
kernels (Graham+15)

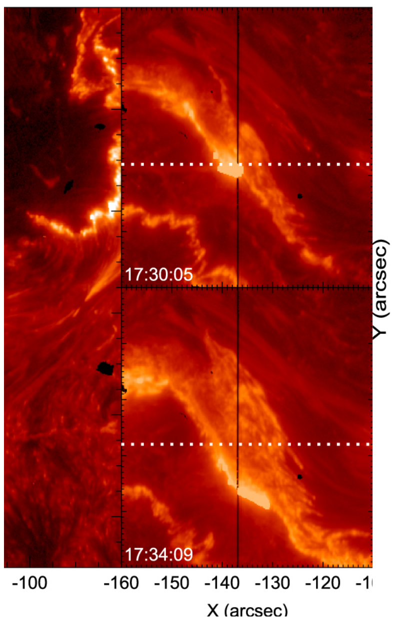


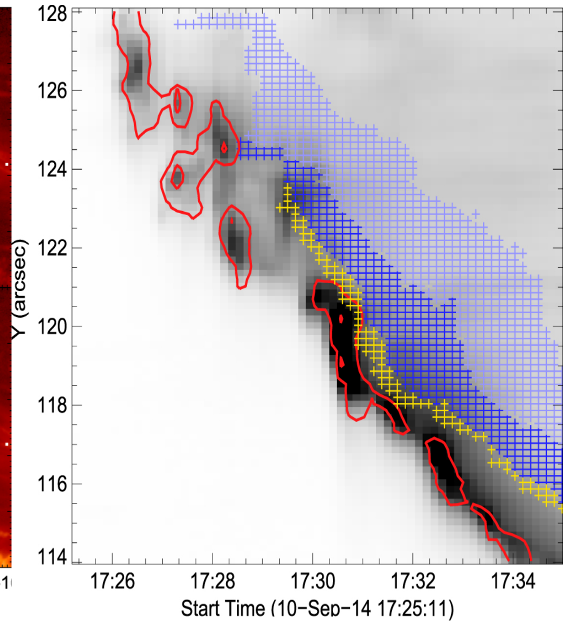


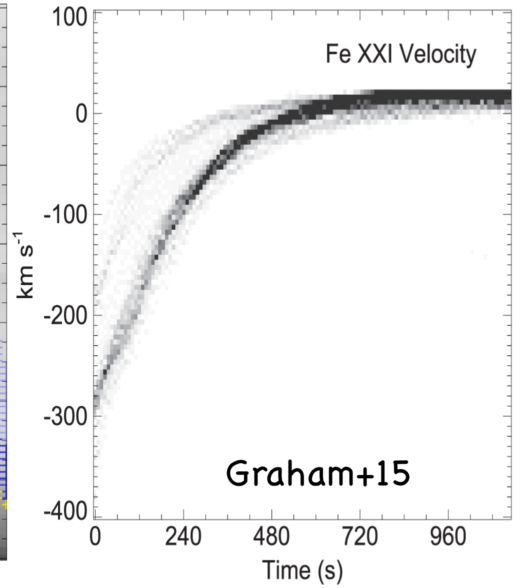
Flare ribbons map energy release events at fine scales ~150–300 km (Graham+15, Jing+16) and dynamics (Brannon+15, Brosius+15)



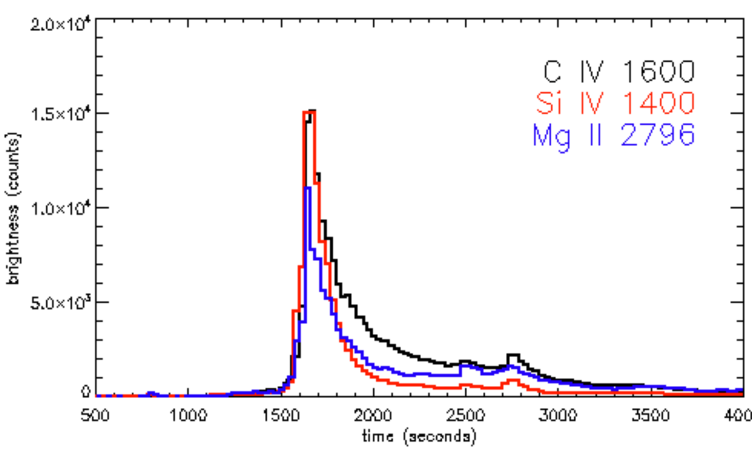
Flare reconnection is highly structured (Naus+21, French+21).

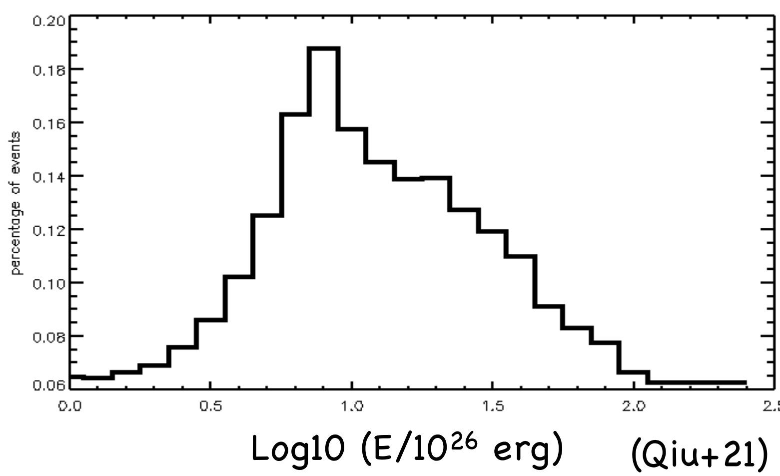






Spectroscopy and photometry observations at the kernels can be used to determine heating rates, where, when, for how long, by how much, and in what form (RubioDaCosta+15, Kowalski+17, Kerr+16-, Reep+16, Graham+20, Ashfield+21).





(Qiu+21)

Energetics in flare ribbons reflect reconnection energetics in the corona.

What we know and what we don't ..

1. Observations of SADs, loops, kernels, illustrate reconnection energy release in temporal/spatial fragments: how do we use & advance these measurements to characterize the structure, dynamics, and nature of reconnection? Scales? Distribution? Evolution?

2. Reconnection energy release is globally organized.
- flare ribbons outline (some) topological boundaries;
- (perpendicular) spreading → fast reconnection w/ $\langle M_A \rangle$ = 0.01 – 0.1;
- (parallel) spreading (Vorpahl76,Kawaguchi+82..) and shear-to-potential evolution (eg., Aulanier+06, Su+07): can we probe the current sheet properties, such as the reconnection guide field, and their implication in reconnection dynamics & energetics (Isobe+02, Shepherd+12, Qiu+10,17, Dahlin+21)?

3. Do properties of reconnection govern energy partition? How?
- where are non-thermal electrons (Fletcher+04, Krucker+05, Lee+06, … Glesner+20, Hudson+21)?
- what is the nature of the slow "cooling" (Qiu+16, Zhu+18, Kerr+20)?