

Drift of the Erupting Flux Rope Footpoints: Theory and Observations

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Content

Eruptive flares:

2D - X-type null point, ribbons at PIL; 3D model: Quasi-separatrix layers (QSLs), J-shaped ribbons, slipping reconnection, HFT, latest extension to standard solar flare model in 3D - Drifting of the line-tied footpoints of CME flux ropes:

newly identified 3D reconnection geometries causing drift of flux rope footpoints

Observational evidence for 3D reconnection geometries:

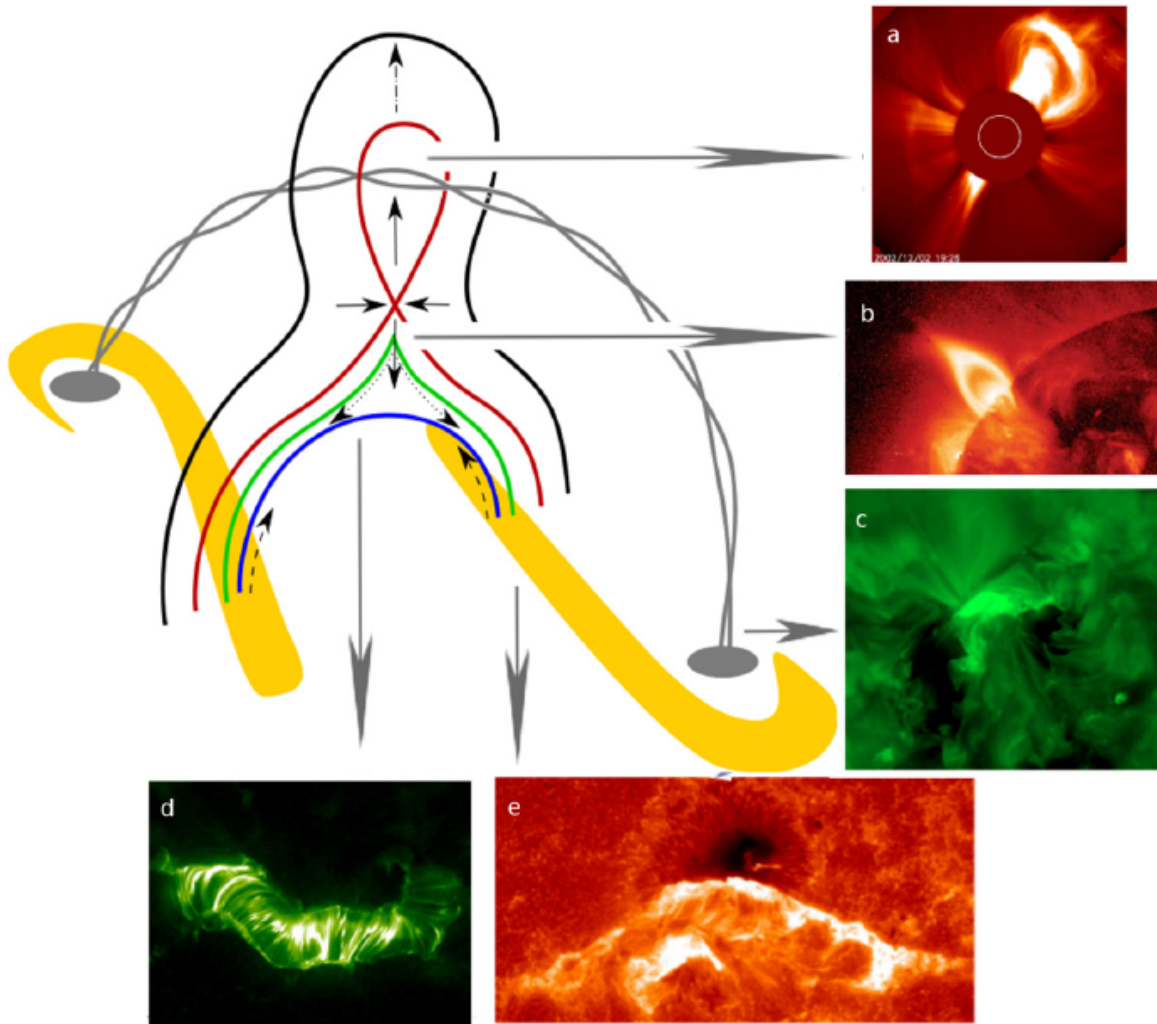
2012-Jul-12: drift and deformation of the ribbon hook

2014-Sep-10: drift and deformation of the ribbon hook

2015-Nov-04: long distance drift of flux rope footpoint, drift and deformation of the ribbon hook

Conclusions

Eruptive flare – Standard flare cartoon

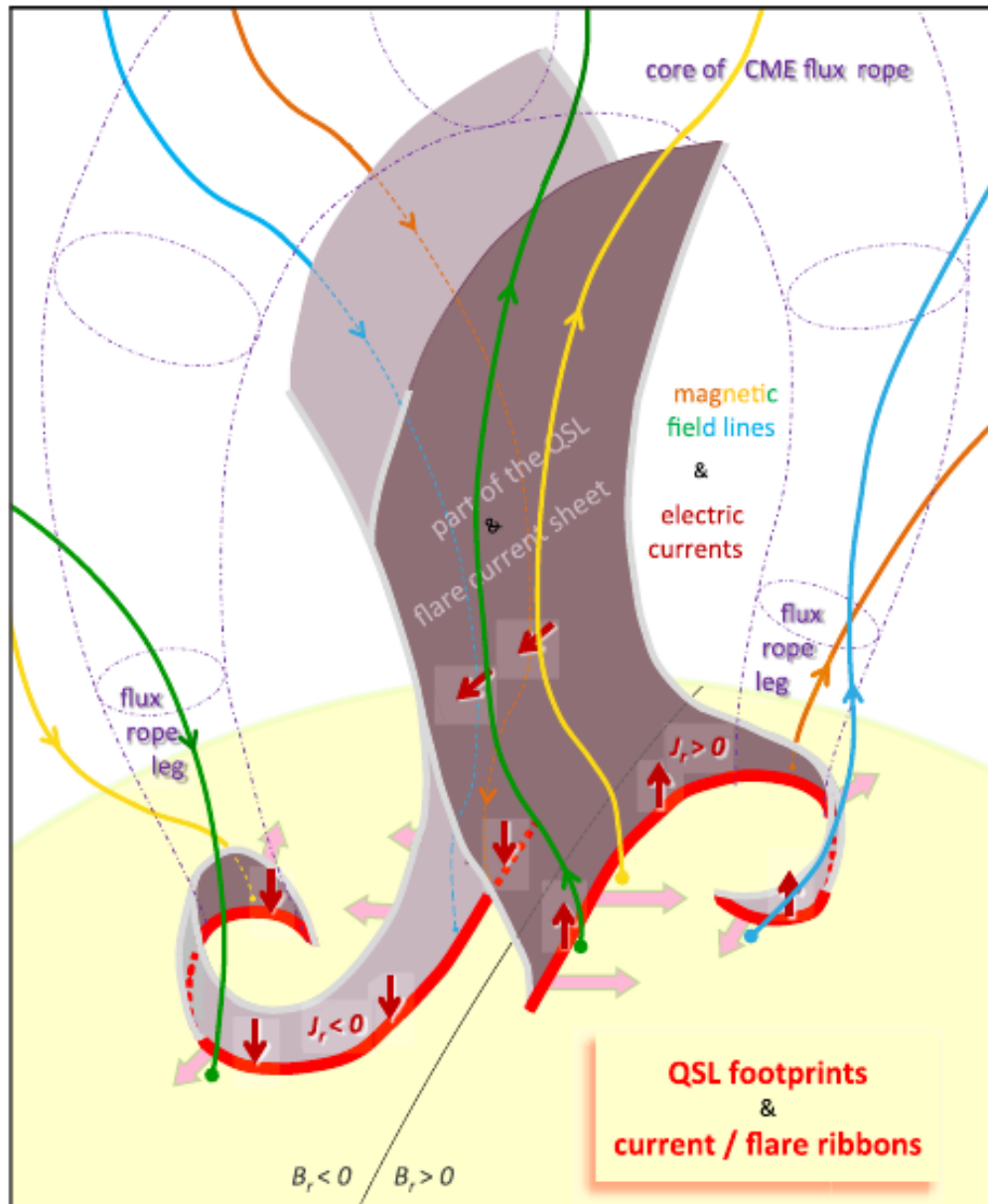


- Rise of a filament/prominence
- Flare ribbons - arcade of flare loops
- SXR – cusp shaped loops
- Rising plasmoid - stretching of overlying loops
- 3 part CME

- 2D – CSHKP model - 2D magnetic reconnection at an X-type null point (Carmichael 1964, Sturrock 1966, Hirayama 1974, Kopp & Pneuman 1976)

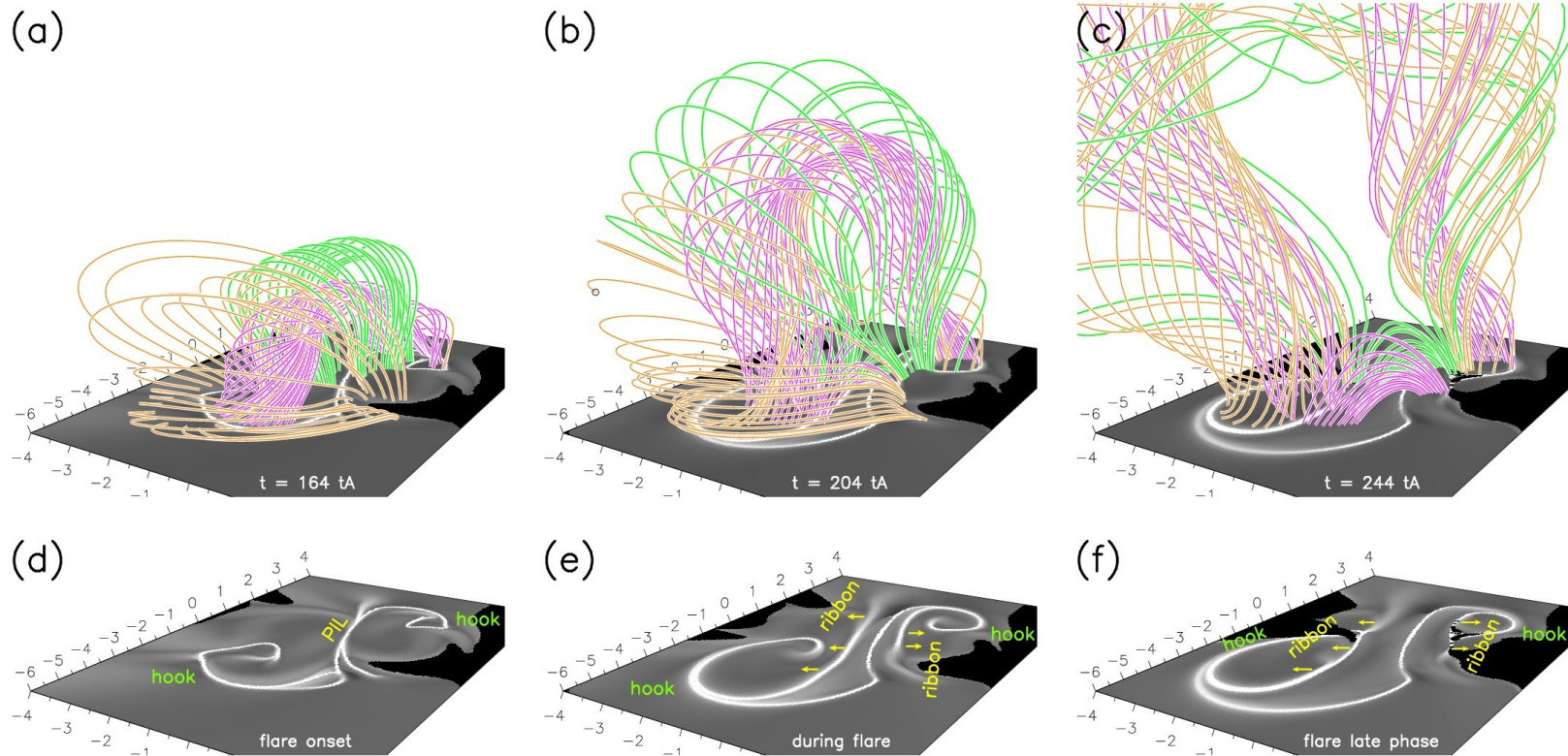
- 3D magnetic reconnection can be crucially different from 2D (Priest, 2016 ASSL427, 101.) – can occur also without null points
- QSLs – regions where the field line linkage changes rapidly (Démoulin, Priest & Lonie, 1996, JGR, 101 A4, 7631; Aulanier, Pariat & Démoulin, 2005, A&A 444, 961.)

The standard flare model in 3D



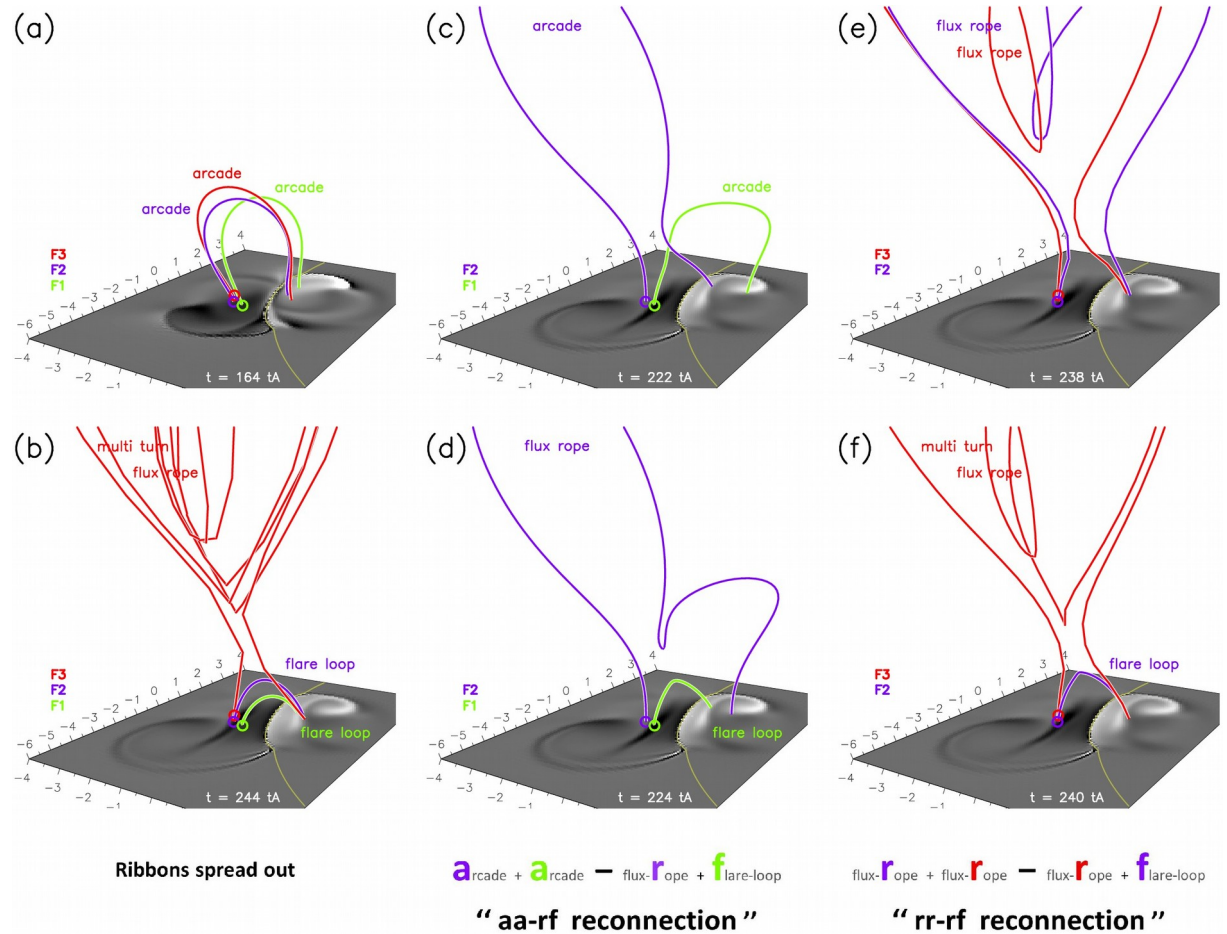
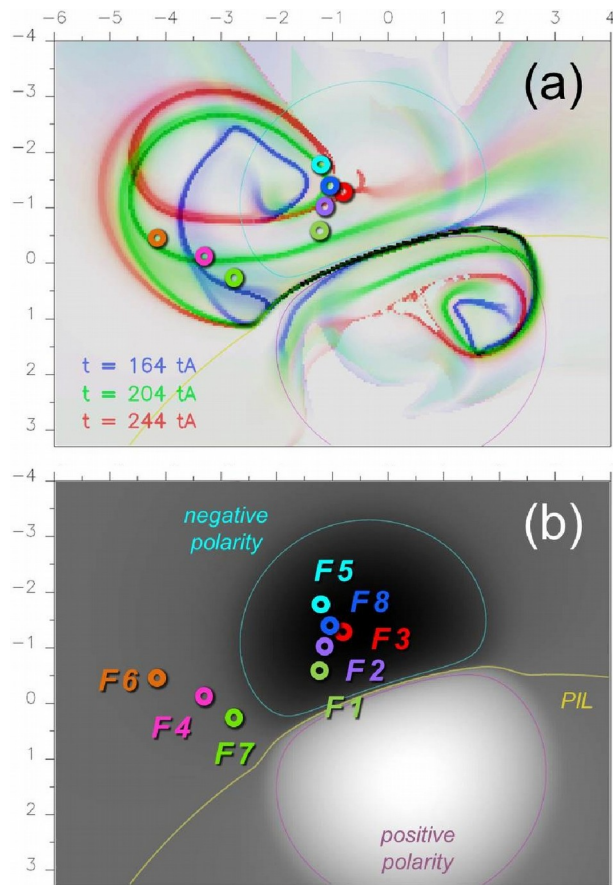
- QSLs – narrow current layers – **J-shaped ribbons** (Janvier et al. 2014, ApJ 788, 60.)
- Magnetic reconnection without null points – slipping of loops (Aulanier, Pariat & Démoulin, 2006, Sol. Phys. 238, 347.)
- **Hyperbolic Flux Tube (HFT)** – generalization of separator – similar topology as in X-point (Titov & Hornig, 2002, JGR 107, A8, 1164.)
- Calculated QSL match the locations and extent of flare ribbons during the flare progress – **QSLs are not static, they evolve** (Savcheva et al. 2016, ApJ 817, 43.)
- Interaction between topologically different loops - new reconnection geometries - drifting of the hooks (Aulanier & Dudík, 2019, A&A 621, 72.)

Drifting of the line-tied footpoints of CME flux ropes



The **pink** (resp. **orange**) field lines correspond to the external edge of the flux rope as it is at the **eruption onset** (resp. **end of the simulation**). The **green field lines** correspond to **overlying arcades** at the eruption onset. The **hooks (QSLs)** evolve in time, ribbons spread away from polarity inversion line (PIL) – there are **new reconnection geometries: aa – rf, rr – rf, ar – rf; where: a – arcade, r – flux rope and f – flare loop**

Drifting of the line-tied footpoints of CME flux ropes

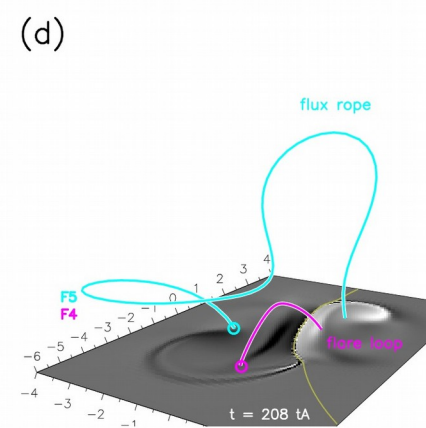
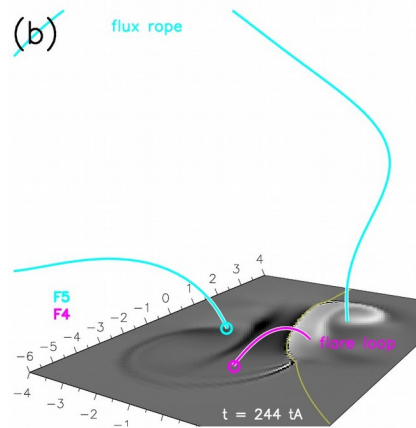
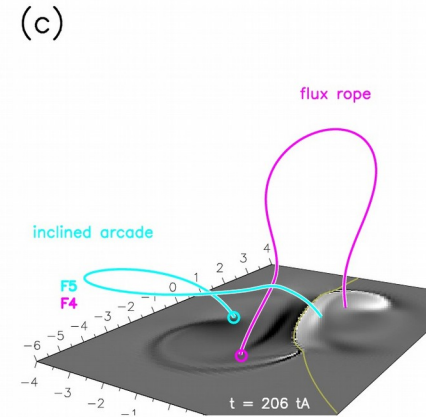
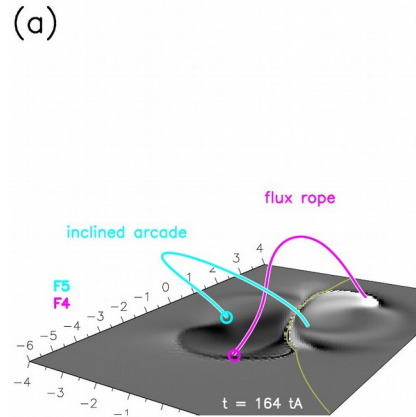
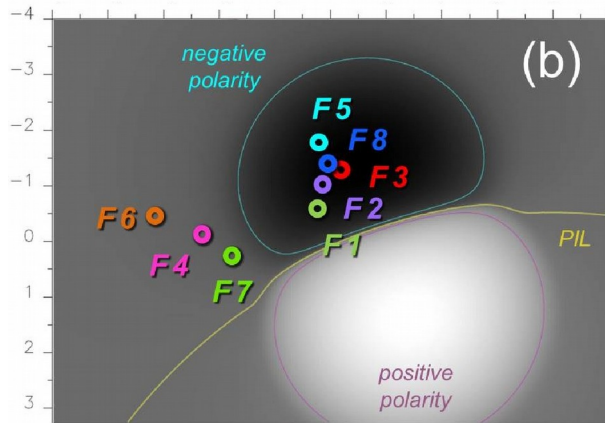
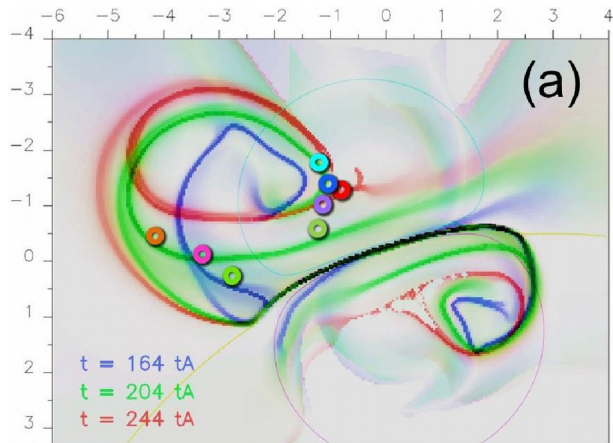


Each field line is labeled according to its topology at the time that it is plotted.

c) – d) reconnection geometry that involves two arcades that turn into a flux rope and flare loop - **aa – rf**

e) – f) reconnection geometry that involves two flux rope field lines that change to another flux rope field line and a flare loop - **rr – rf**

Drifting of the line-tied footpoints of CME flux ropes

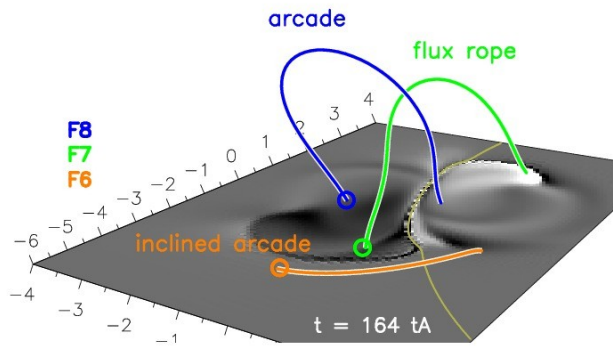


Ribbon swipes hook's surface
while
Hook moves out

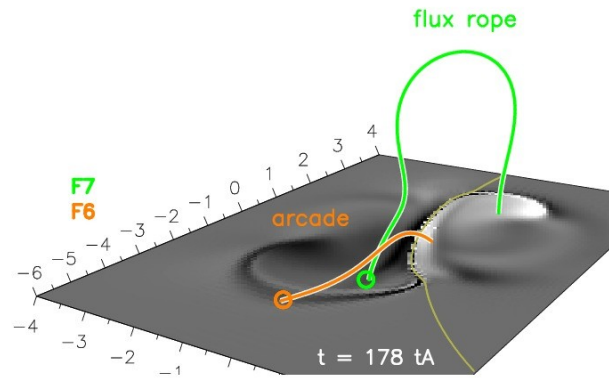
$a_{\text{rcade}} + \text{flux-}r_{\text{ope}} - \text{flux-}r_{\text{ope}} + \text{f}_{\text{lare-loop}}$
"ar-rf reconnection"

! ar – rf – Flux rope erosion from the inner side of PIL –
F4 flux rope at the eruption onset and later becomes a flare loop;
F5 – inclined arcade at the eruption onset and later it turned to flux rope – **drift of the hook**

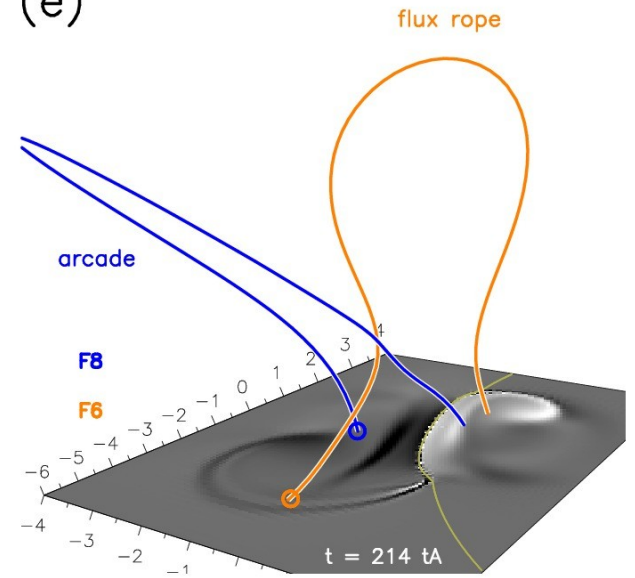
(a)



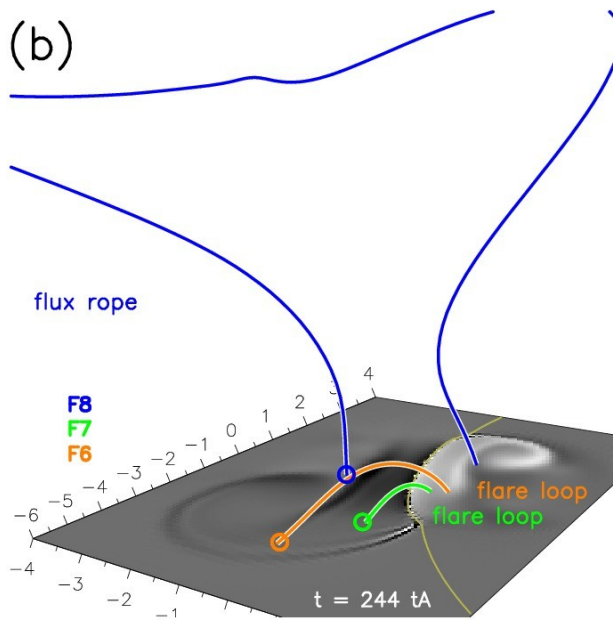
(c)



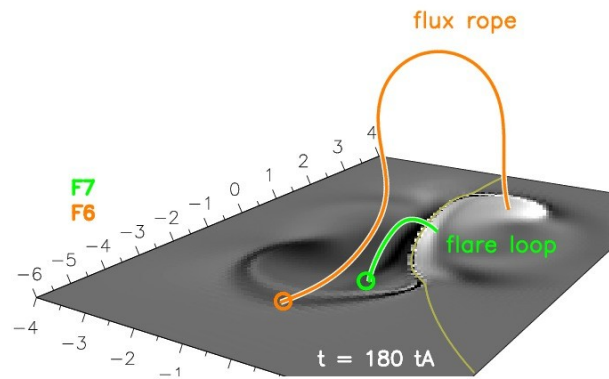
(e)



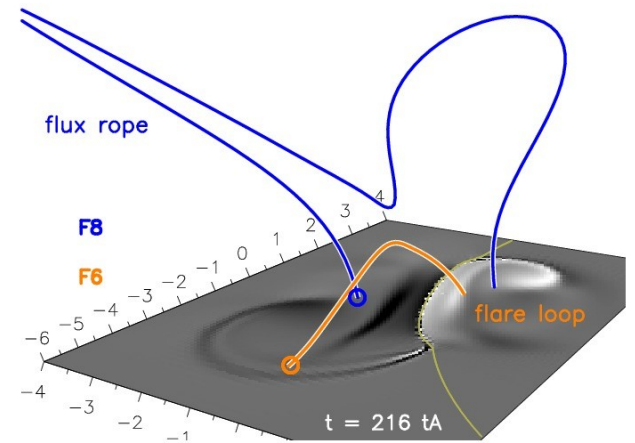
(b)



(d)



(f)



**Hook's surface inflates
and later
shrinks**

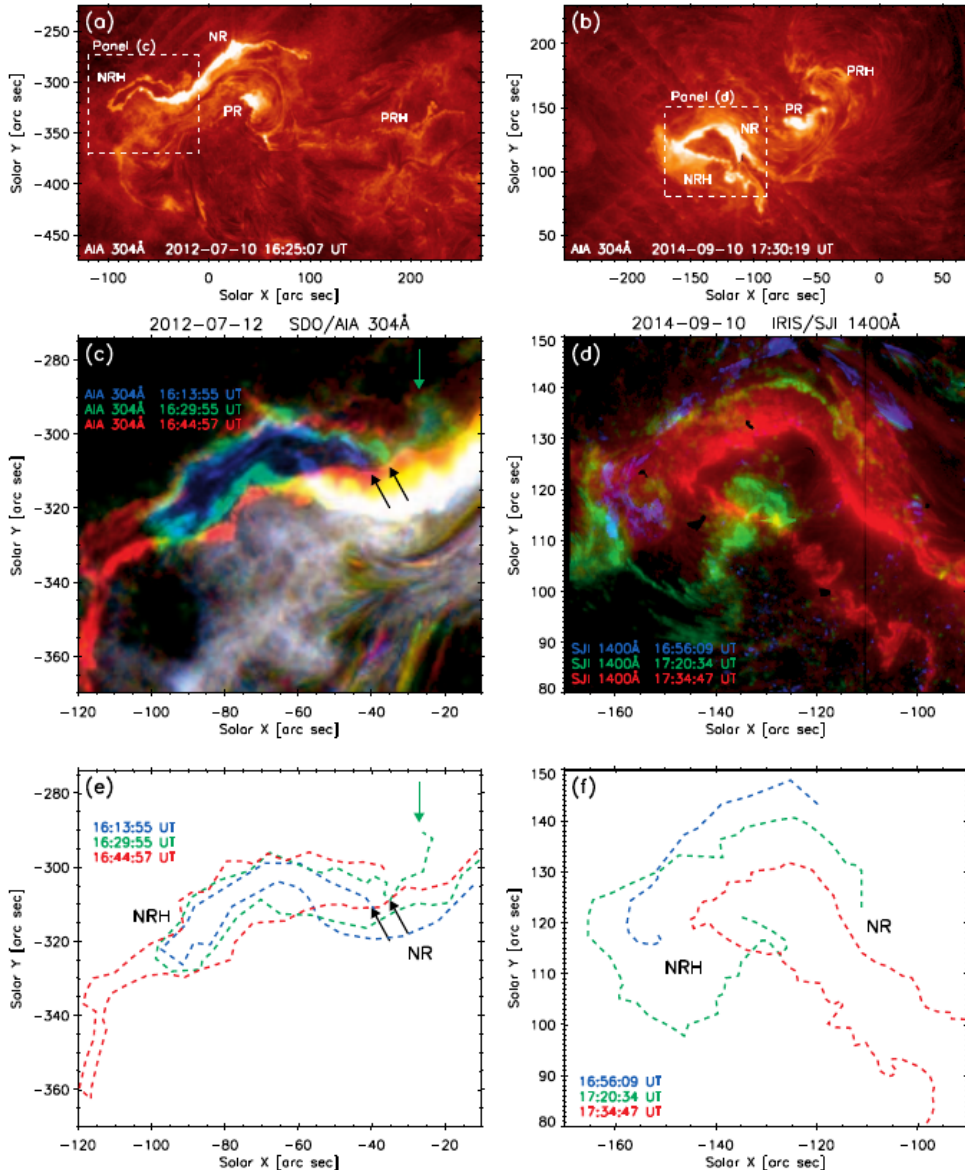
$$a_{\text{arcade}} + \text{flux-}r_{\text{rope}} - \text{flux-}r_{\text{rope}} + f_{\text{flare-loop}}$$

“ ar-rf reconnection ”

$$a_{\text{arcade}} + \text{flux-}r_{\text{rope}} - \text{flux-}r_{\text{rope}} + f_{\text{flare-loop}}$$

“ ar-rf reconnection ”

Deformation and drift of the hooks - Observations



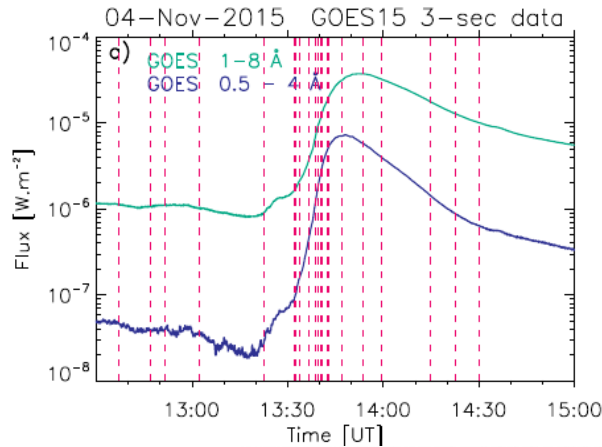
X1.4 2012-Jul-12 – left column (Dudík et al. 2014, ApJ 784, 144)

- **16:14 UT** – start of impulsive phase – eruption of hot flux rope was observed
- **16:30 UT** – NRH expanded laterally and its far end prolonged – green arrow – tip of the hook
- **16:45 UT** – expansion continues – NR moves away PIL sweeping previous locations of the flux rope – black arrows

X1.6 2014-Sep-10 – right column (Dudík et al. 2016, ApJ 823, 41)

- **16:56 UT** – early phase NRH is still evolving
- its tip area coord. $\sim [-150, 112]$
- **17:20 UT** – NRH expanded – undergoes squirming motions which accompany slipping reconnection along it; 17:27 UT – shrinkage
- **17:35 UT** – NRH became very bright and narrow

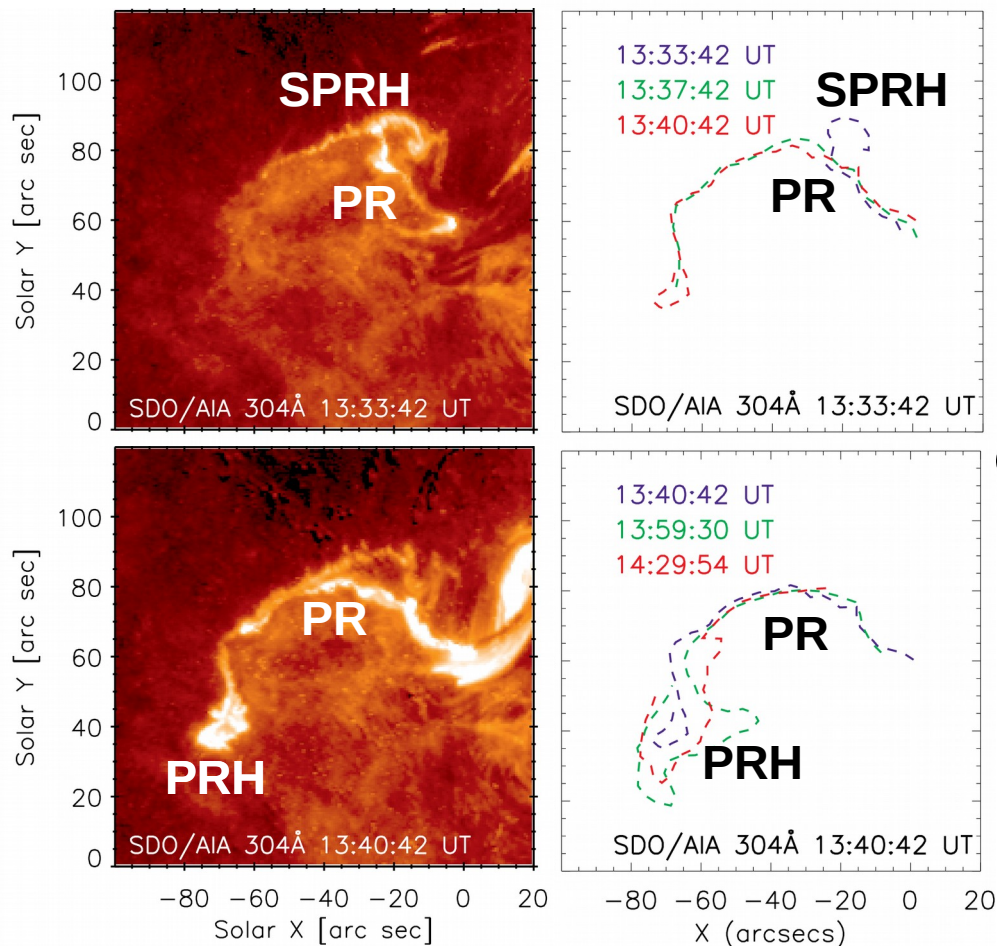
M3.7 flare – 2015-Nov-04



During this flare we observed:

- Long distance drift of the footpoint of erupting flux rope
- Deformation of the curved part of the J-shaped ribbon – expansion and contraction of the ribbon hook

13:31 UT – 13:52 UT – 14:13 UT GOES15
14:48 UT – halo CME detected by SOHO/LASCO C2

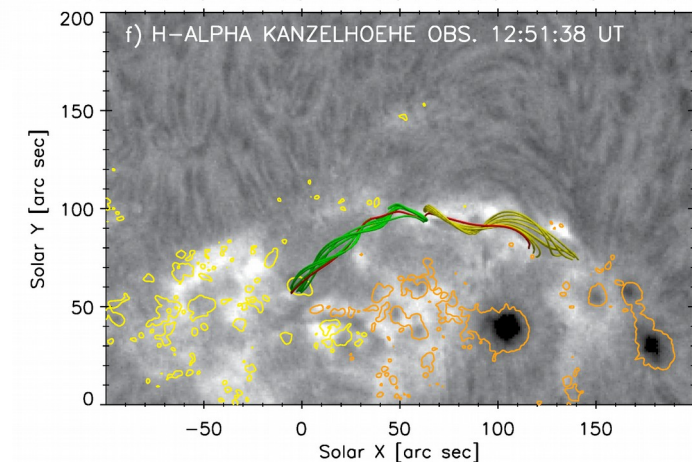
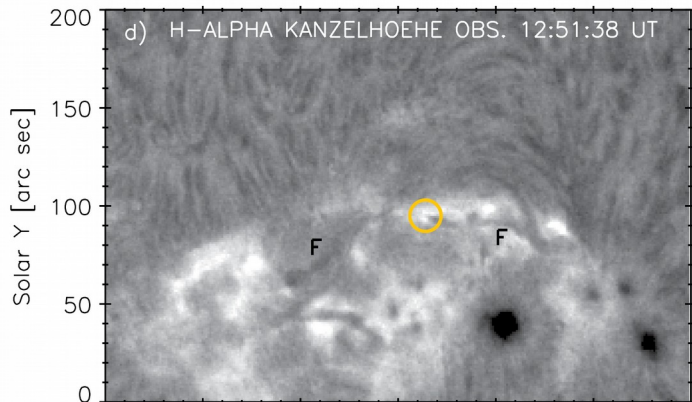
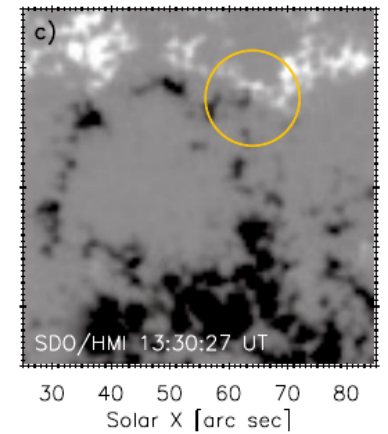
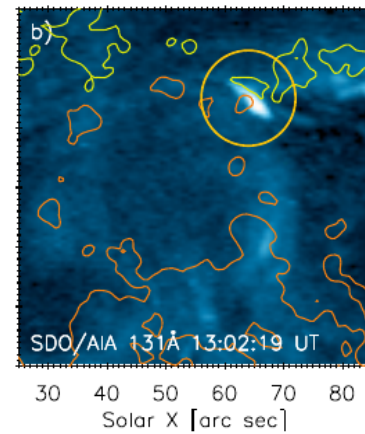
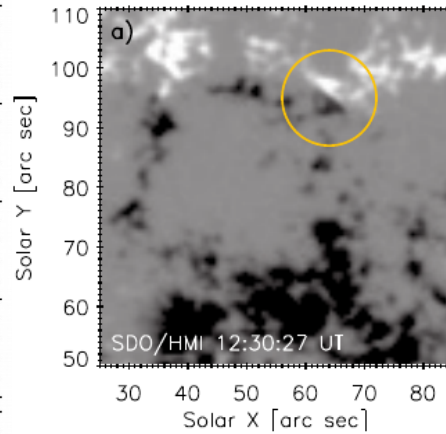
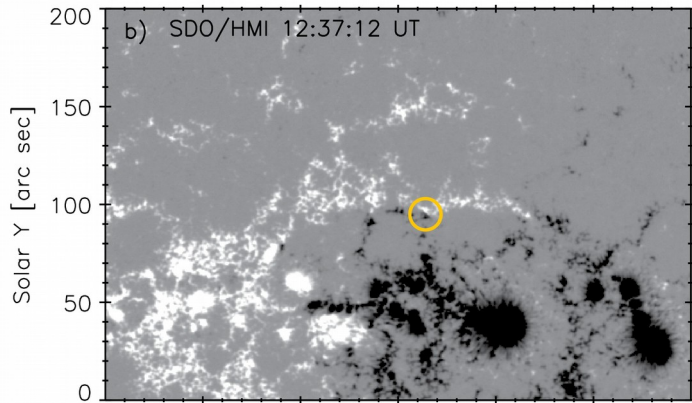


Flare evolution (observations):

- Flux cancellation – filament activation
- Tether-cutting reconnection – a flux rope built-up
- J-shaped ribbons in positive polarity – at first formation of small hook (SPRH)
- Slipping of the hot loops – ribbon elongation – then formation of a new and larger hook (PRH)
- Eruption of the hot flux rope
- Expansion and contraction of the ribbon hook (PRH)

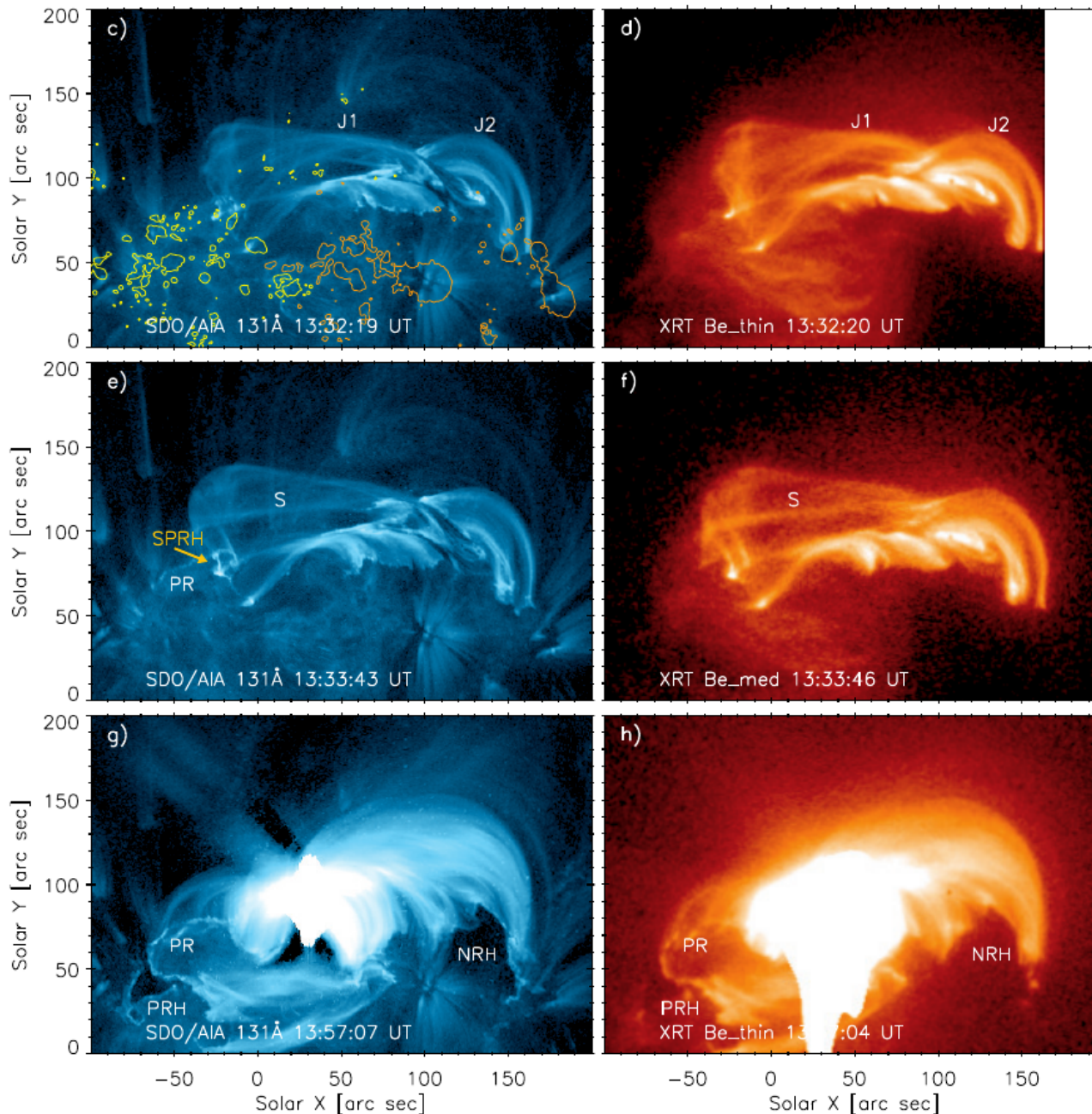
Zemanová, Dudík, Aulanier, Thalmann and Gömöry: paper submitted to ApJ.

M3.7 flare – 2015-Nov-04 – flux cancellation

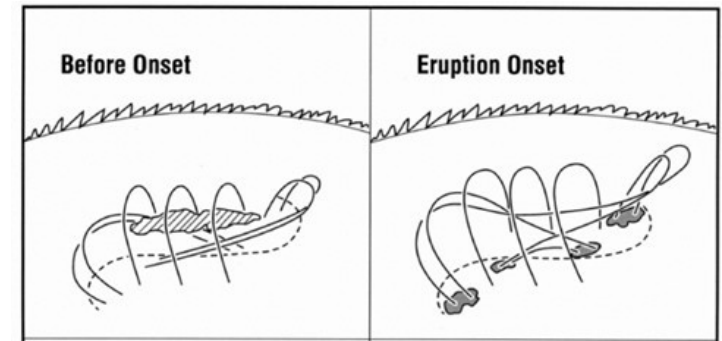


- Flux cancellation – filament activation ~ 13:02 UT
- H-alpha filament F – as observed, consisted of two dark parts
- **NLFFF model of the filament** – two helical systems (green/yellow) – these systems are anchored in small bipolar patch where we observed flux cancellation
- Red field line is threading the body of the filament
- We consider this **filament F – original flux rope**

M3.7 flare – 2015-Nov-04 – flare evolution

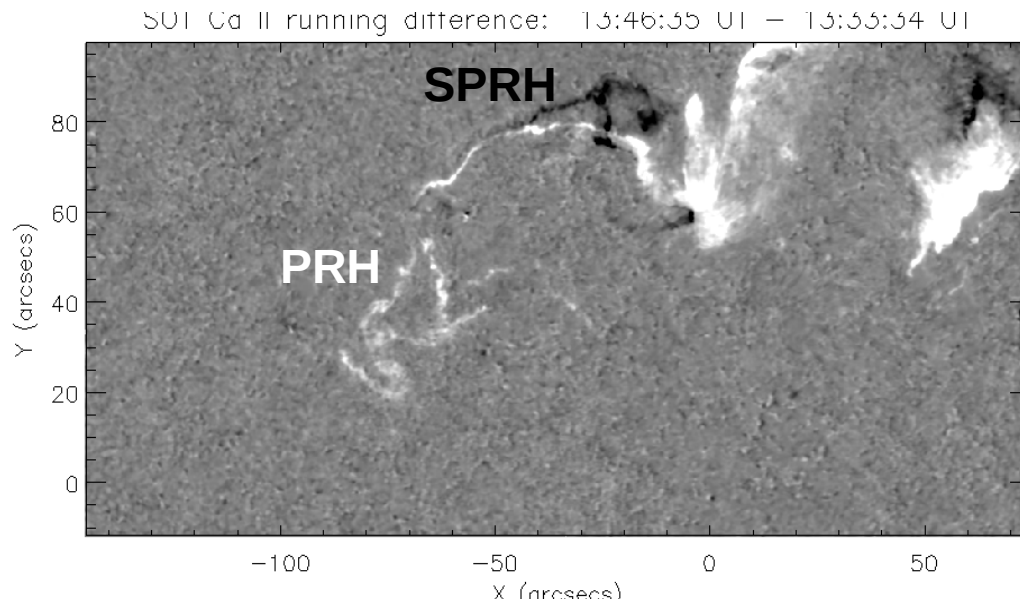
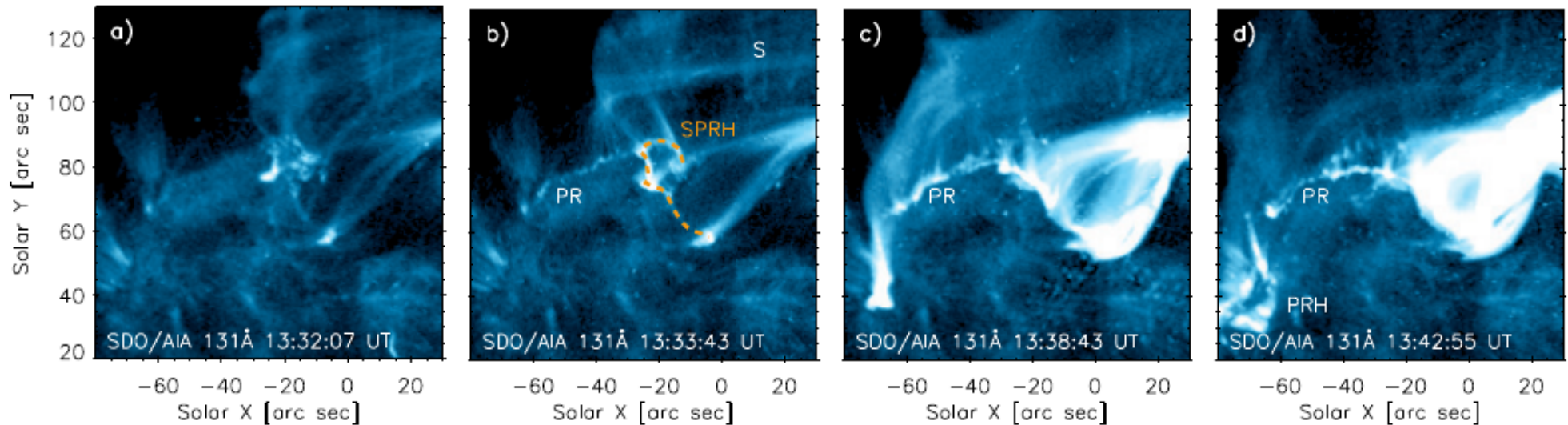


- Tether-cutting reconnection (Moore et al. 2001, ApJ 552, 833) – a flux rope built-up



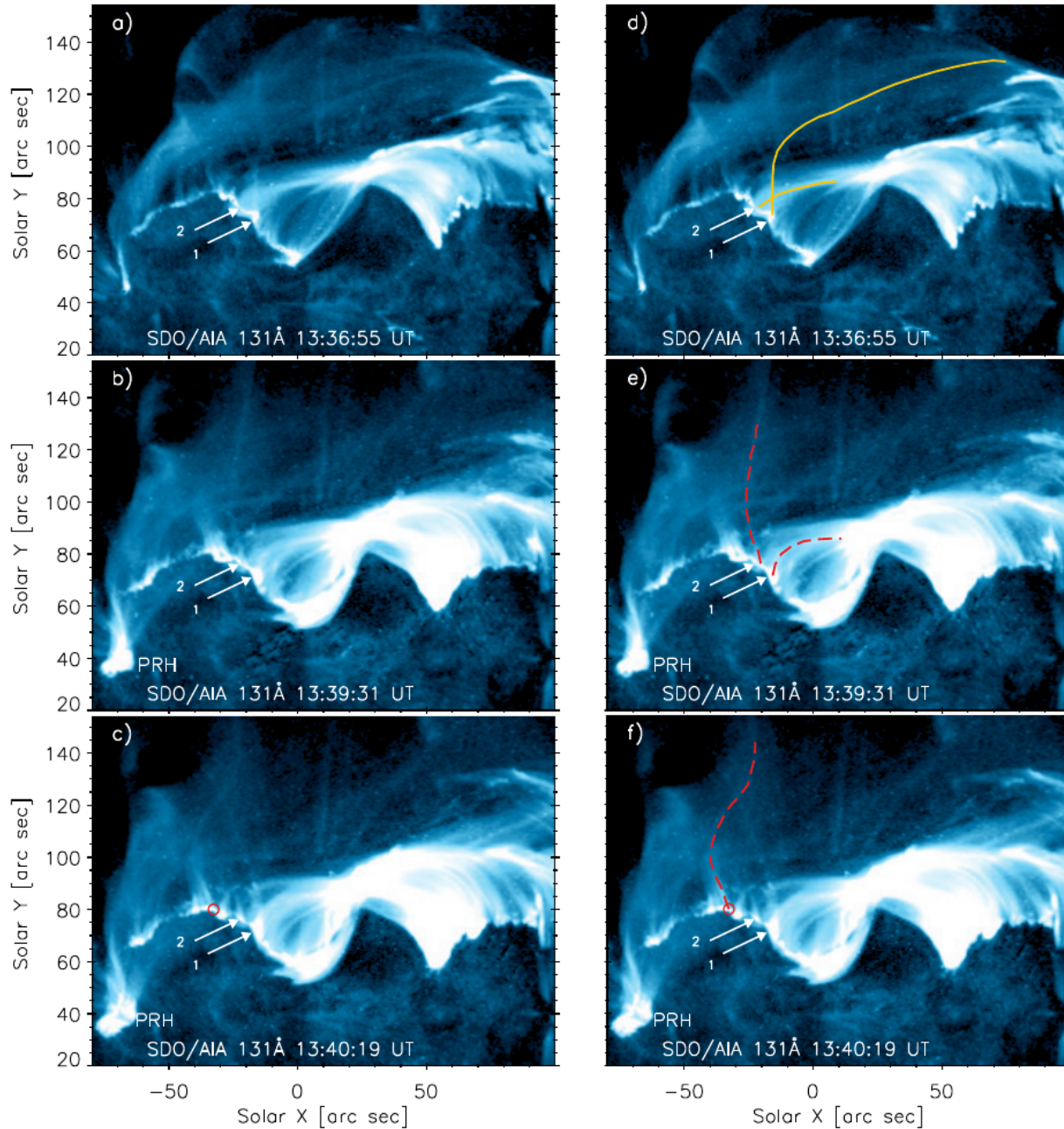
- J-shaped ribbon in positive polarity – with straight part and small hook (SPRH) in which a hot sigmoidal loop structure S was rooted
- After the eruption of the hot flux rope – ribbons with hooks PRH and NRH – dimmed areas
- Arcade of flare loops below the ejected hot flux rope

M3.7 flare – 2015-Nov-04 - drift of the hook



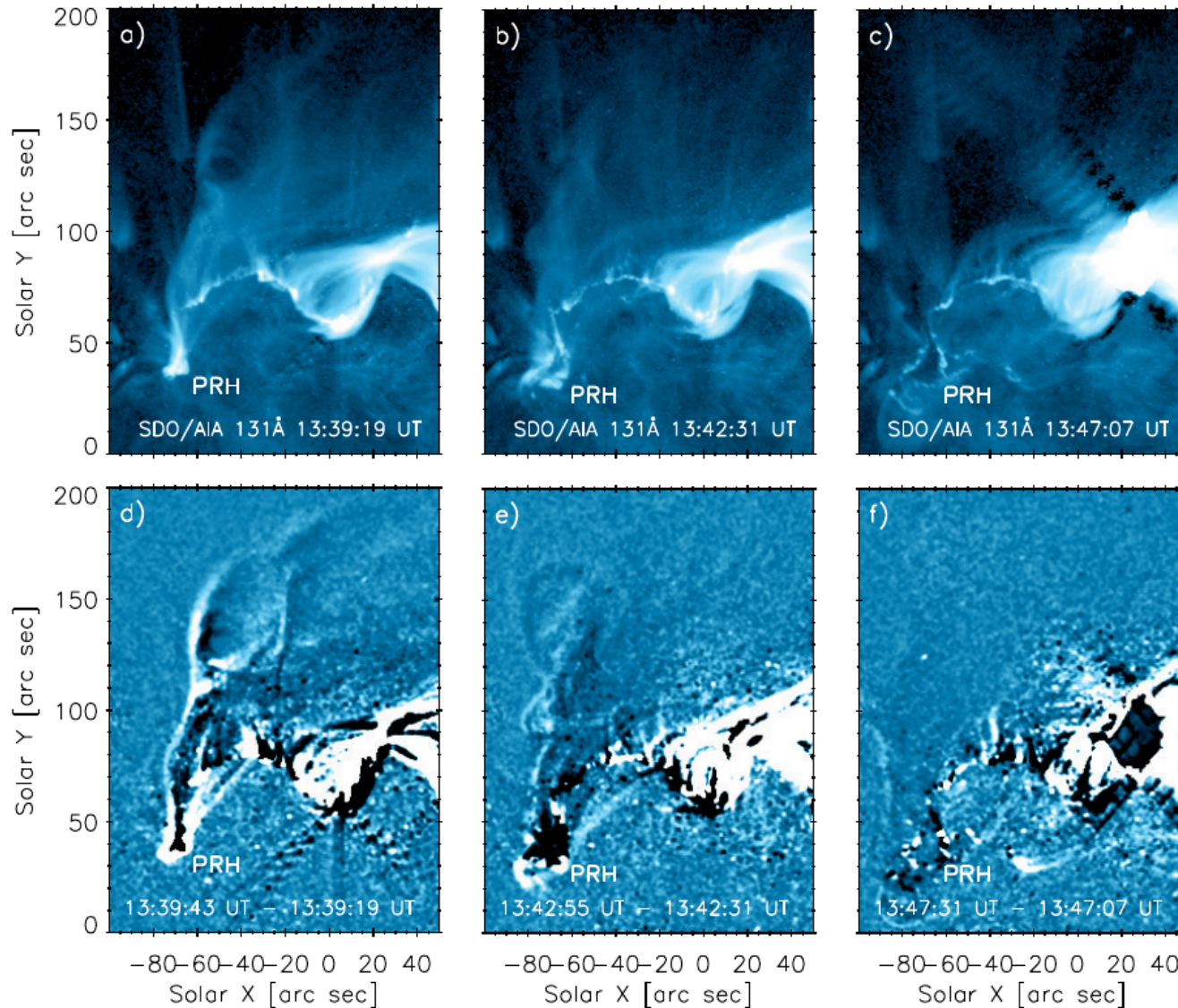
- Tether-cutting reconnection – sigmoidal loop structure S – J-shaped ribbon in positive polarity – at first small hook (SPRH)
- Elongated ribbon – new, larger hook (PRH)
- **Interpretation** – the shift in the position of flux rope footpoint – filament F – flux rope S and finally to the hot erupting flux rope rooted in PRH

M3.7 flare – 2015-Nov-04 – elongation of the ribbon via slipping of the hot loops



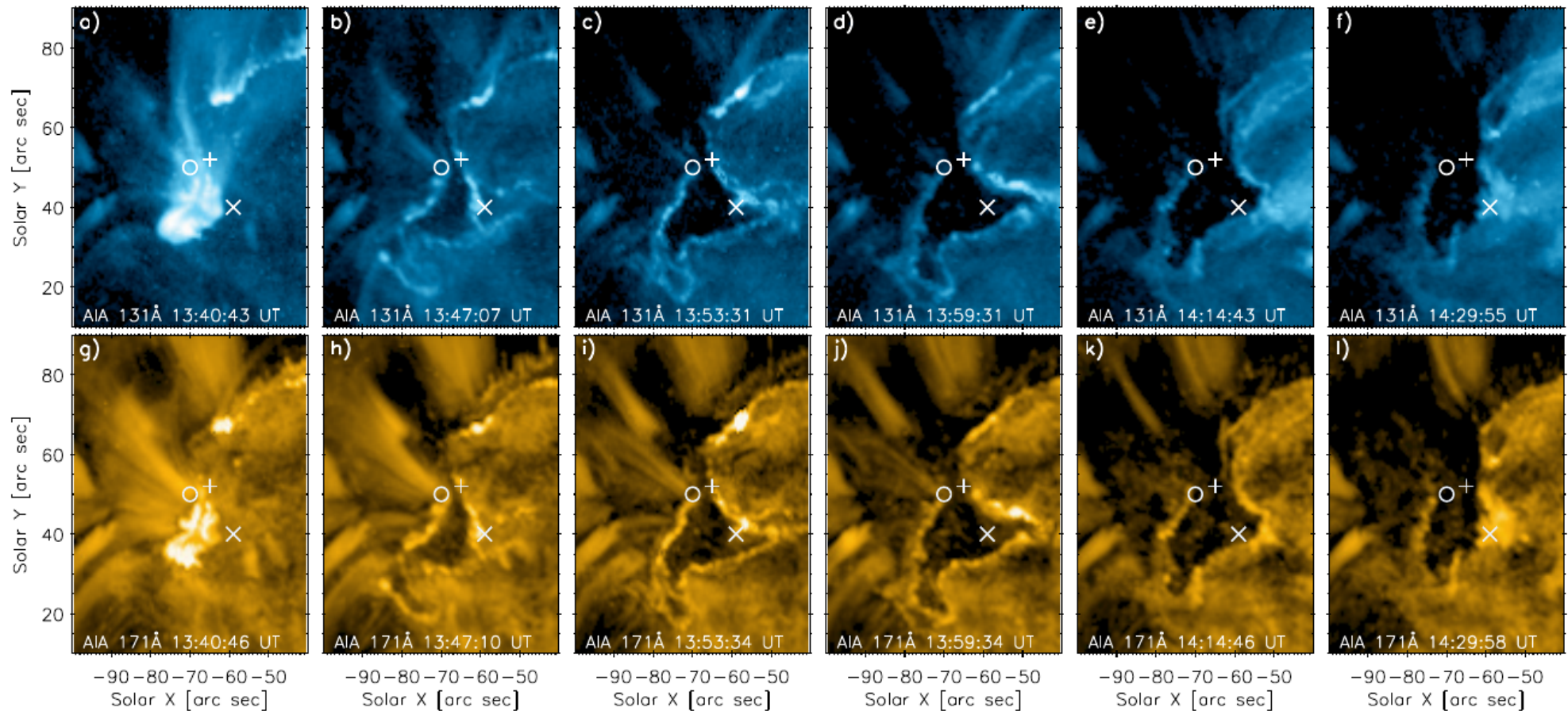
- Positive polarity ribbon was elongated via slipping of the hot loops – then formation of a new and larger hook (PRH)
- The arrows show footpoints at positions 1 and 2 which exchanged their connectivity
- **Pre-reconnection** – loops highlighted by full line
- **Post-reconnection** – loops highlighted by dashed line
- The loops were slipping along the ribbon – through its straight part towards the hooked end building the hot flux rope which erupted

M3.7 flare – 2015-Nov-04 – eruption of elongated flux rope

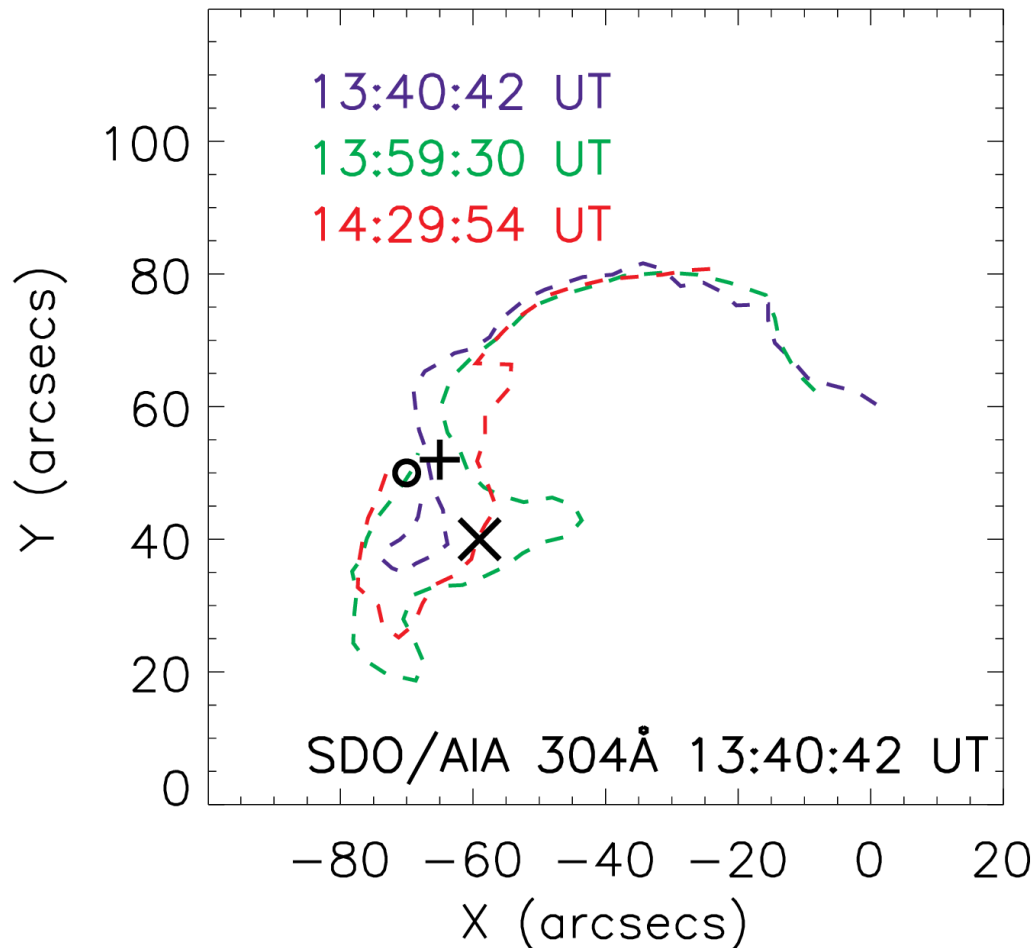


- Slipping of the hot loops – ribbon elongation – formation of a new and larger hook (PRH) – hot flux rope was formed
- It erupted about 13:40 UT
- Since the eruption the expansion of the positive ribbon hook (PRH) was observed
- About 14:05 UT – expansion turned to contraction of the ribbon hook (PRH)

M3.7 flare, 2015-Nov-04 – expansion and contraction of the ribbon hook



M3.7 flare, 2015-Nov-04 – expansion and contraction of the ribbon hook



Fixed footpoint at ,o‘: 13:40 UT – footpoints of a loop system – 13:59 UT hook ribbon – 14:29 UT – dimmed area

Fixed footpoint at ,+‘: 13:40 UT – loop footpoint – 13:53 UT – hook ribbon – 13:59 UT dimmed area

O and **+** – reconnection scheme – arcade loop to flux rope field line
Possible scenarios → **aa – rf** or **ar – rf**

Fixed footpoint at ,x‘: 13:47 – almost at hook ribbon – 13:53 UT – dimmed area – 14:29 UT – flare loops

X – reconnection scheme – inclined arcade to flux rope field line to flare loop – !multiple reconnection!

Possible scenarios (series)→
aa – rf, ar – rf or **aa – rf, rr – rf**
or **ar – rf, ar – rf**

Conclusions

- Older 2D – does not explain all observed features of eruptive flares
- The standard flare model in 3D is able to describe the observed phenomena in EUV/SXR sufficiently
- All of presented events showed J-shaped ribbons associated with QSLs that separate flux rope from its surrounding arcades
- We observed slipping of the hot loops along the ribbons (QSLs) and they continually changed their connection – elongation and build-up of hot erupting flux rope – slipping reconnection
- We observed drift and deformation of the flux rope footpoints – observational evidence of 3D reconnection geometries – aa-rf, rr-rf, ar-rf and their series (3D magnetic reconnection)