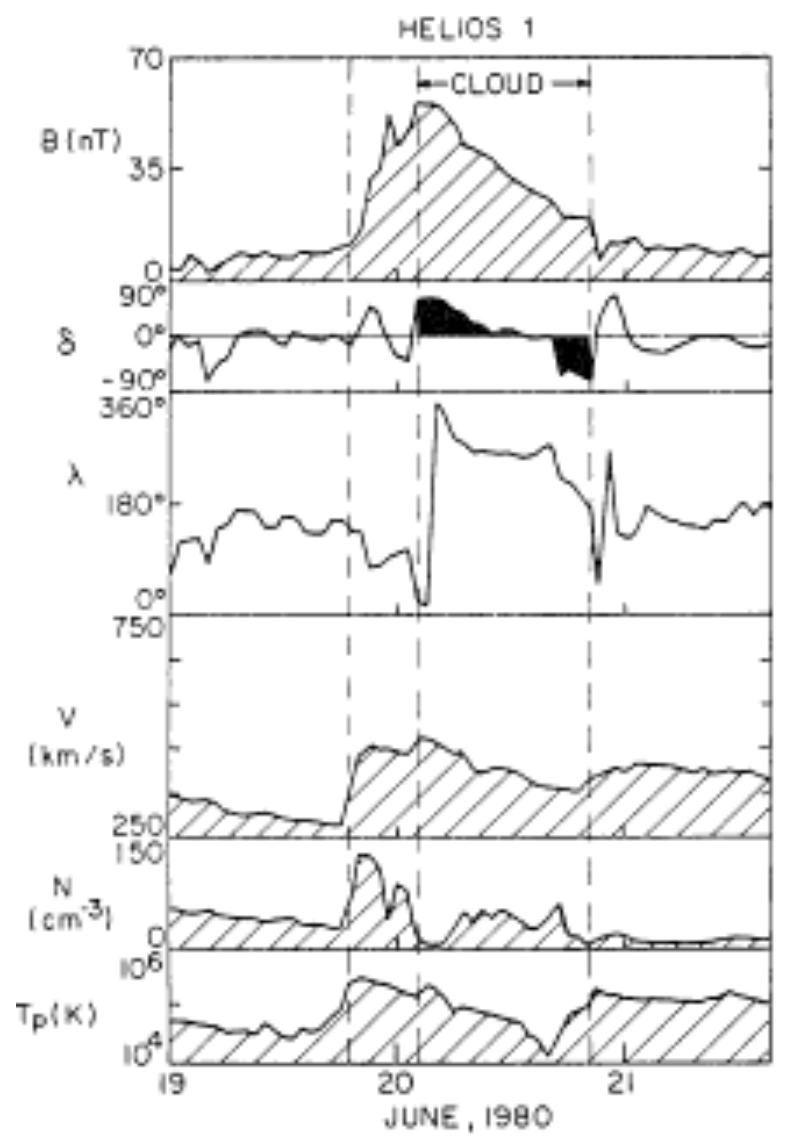
# Observations of magnetic flux ropes in the solar atmosphere: what next?

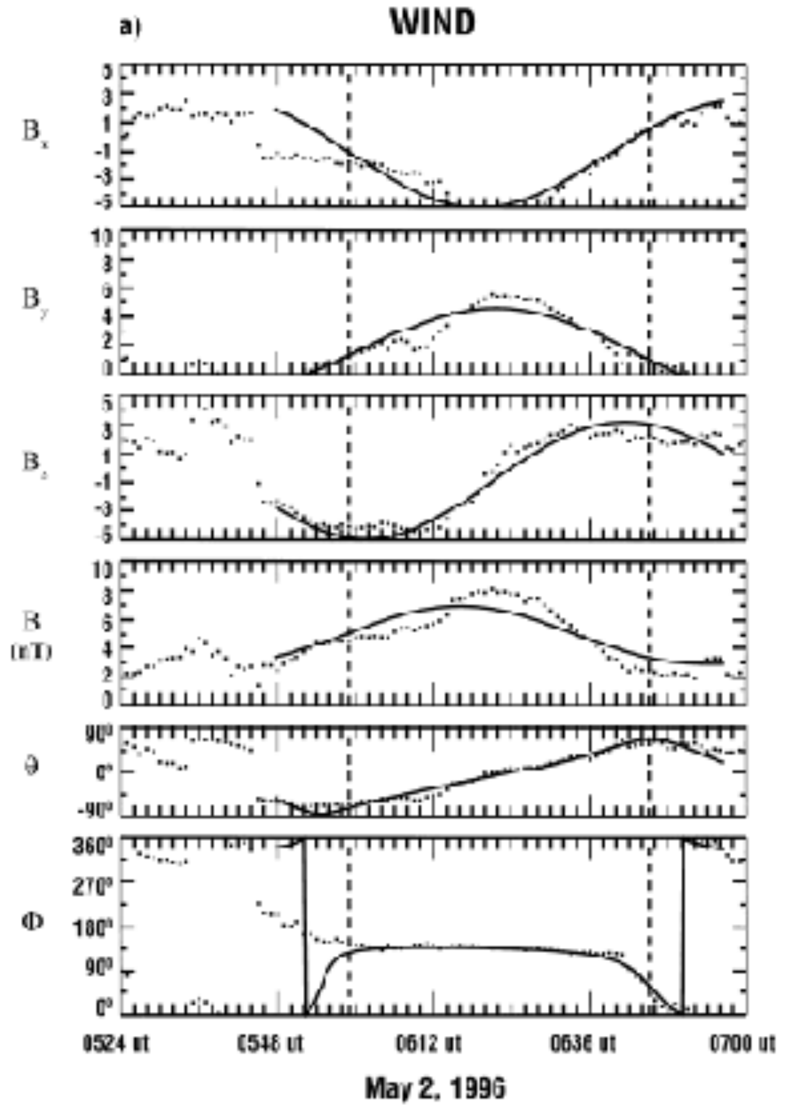
**Lucie Green**

Mullard Space Science Laboratory, UCL



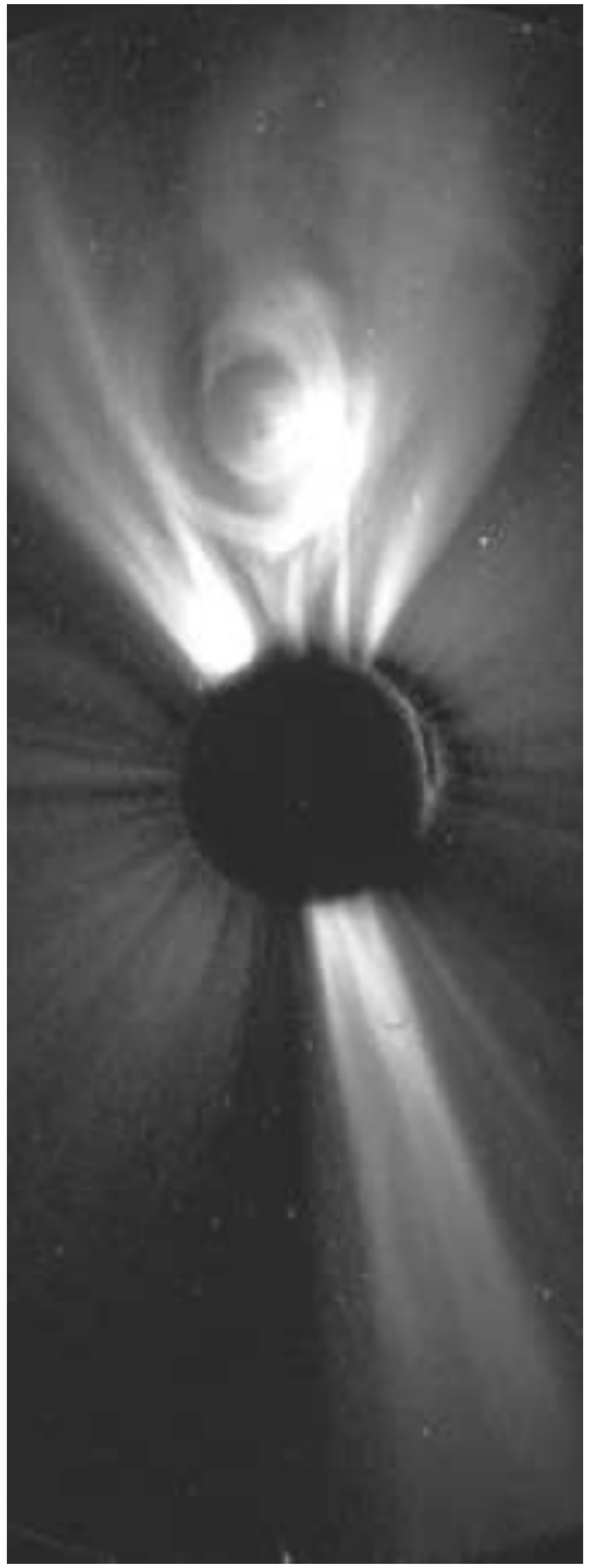

**Magnetic clouds**

Lepping and Burlaga




**Small flux ropes**

(Moldwin et al., 2000)



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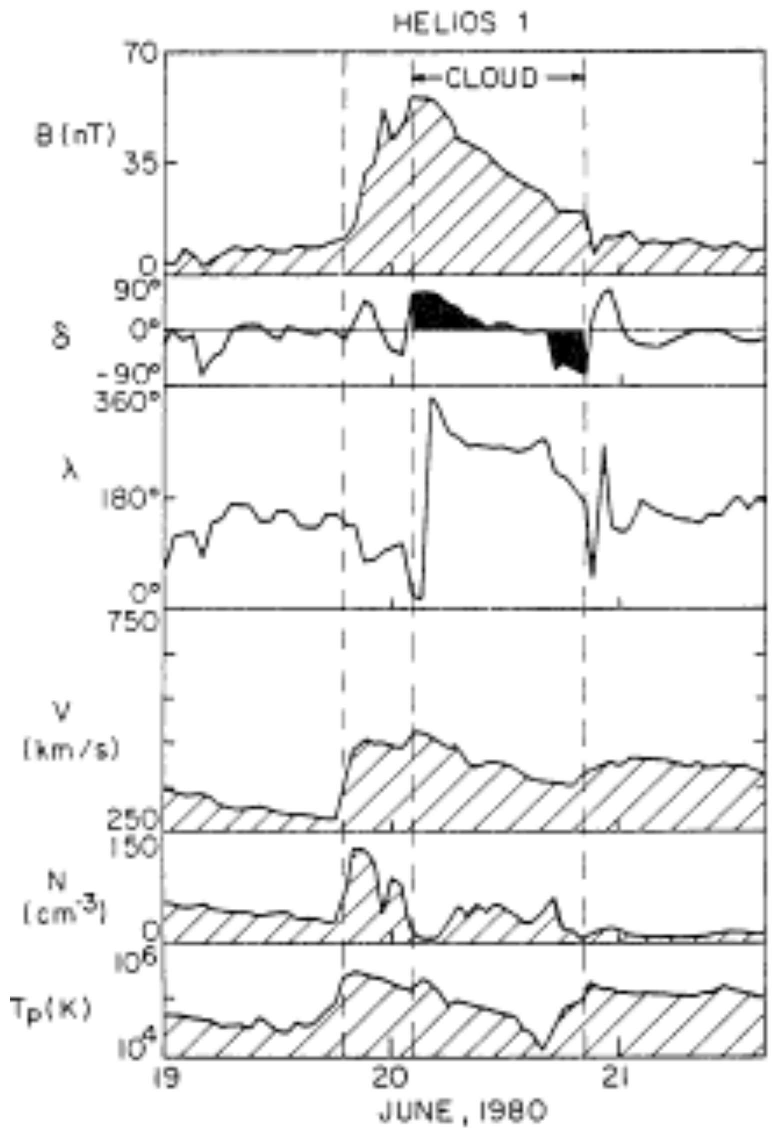


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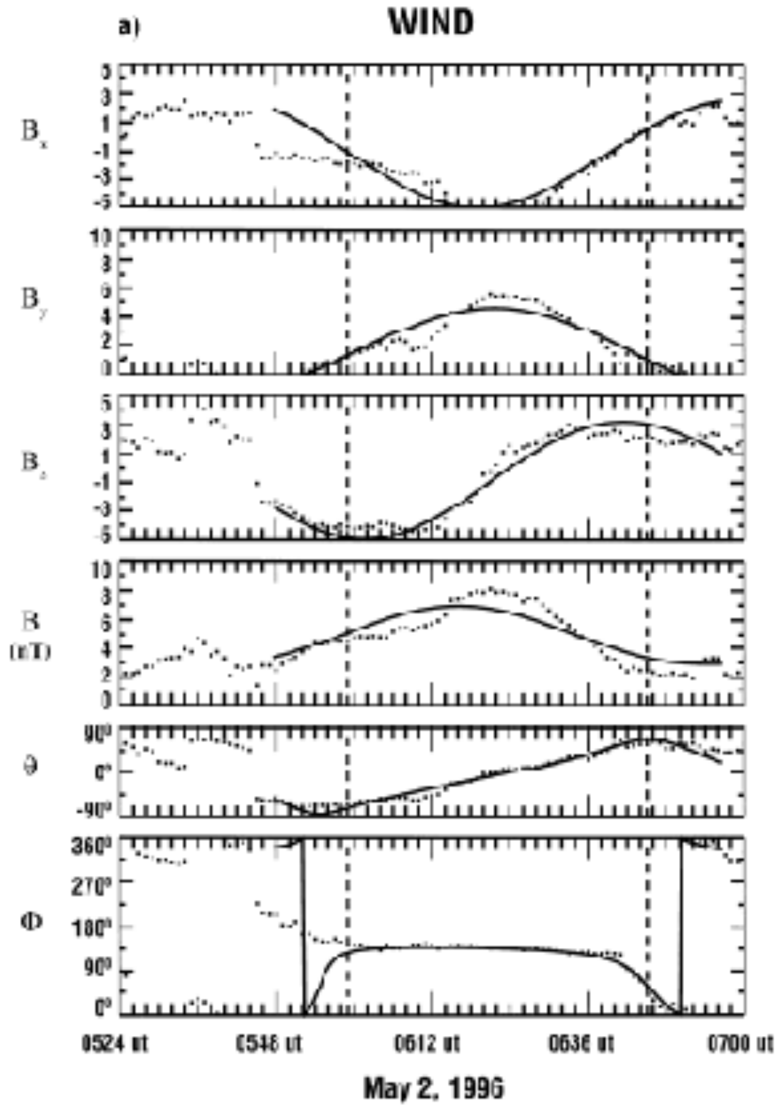


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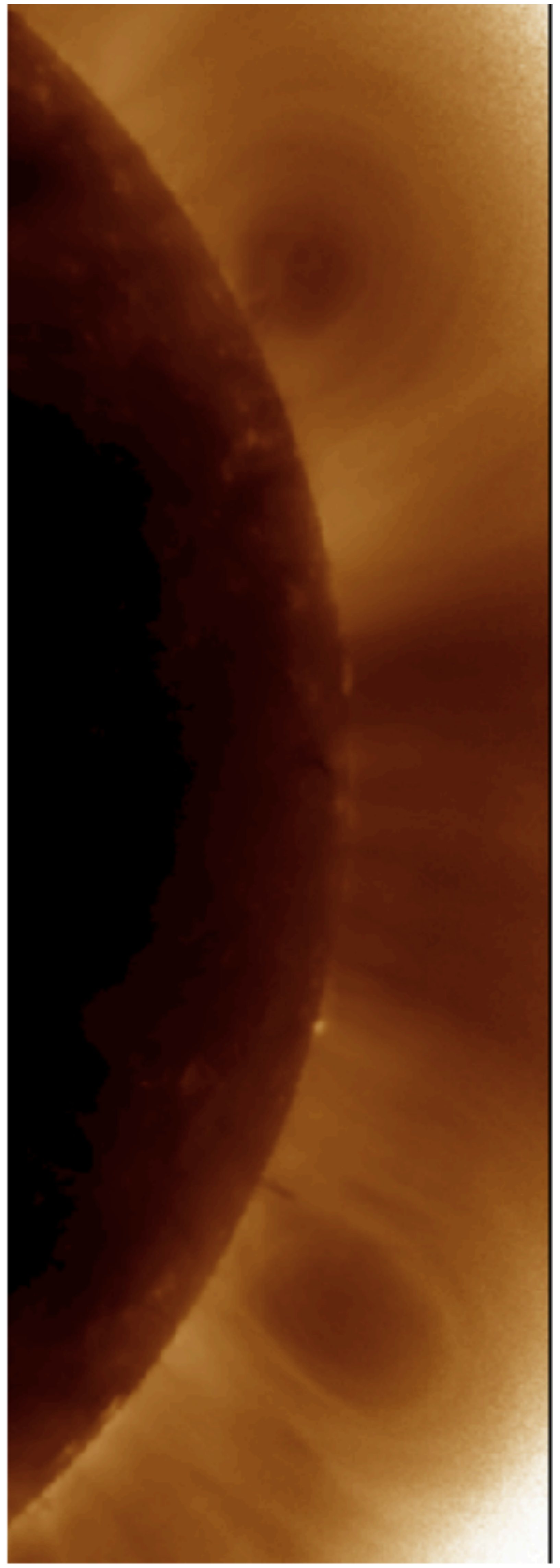

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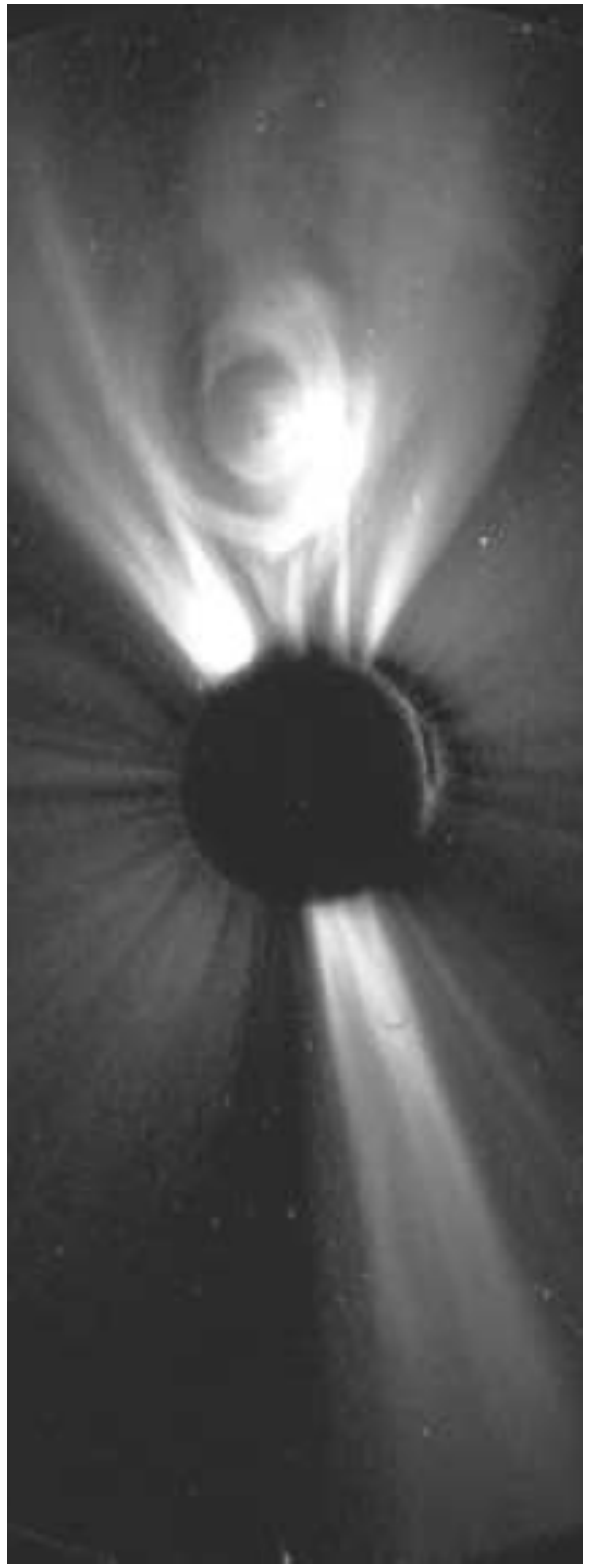

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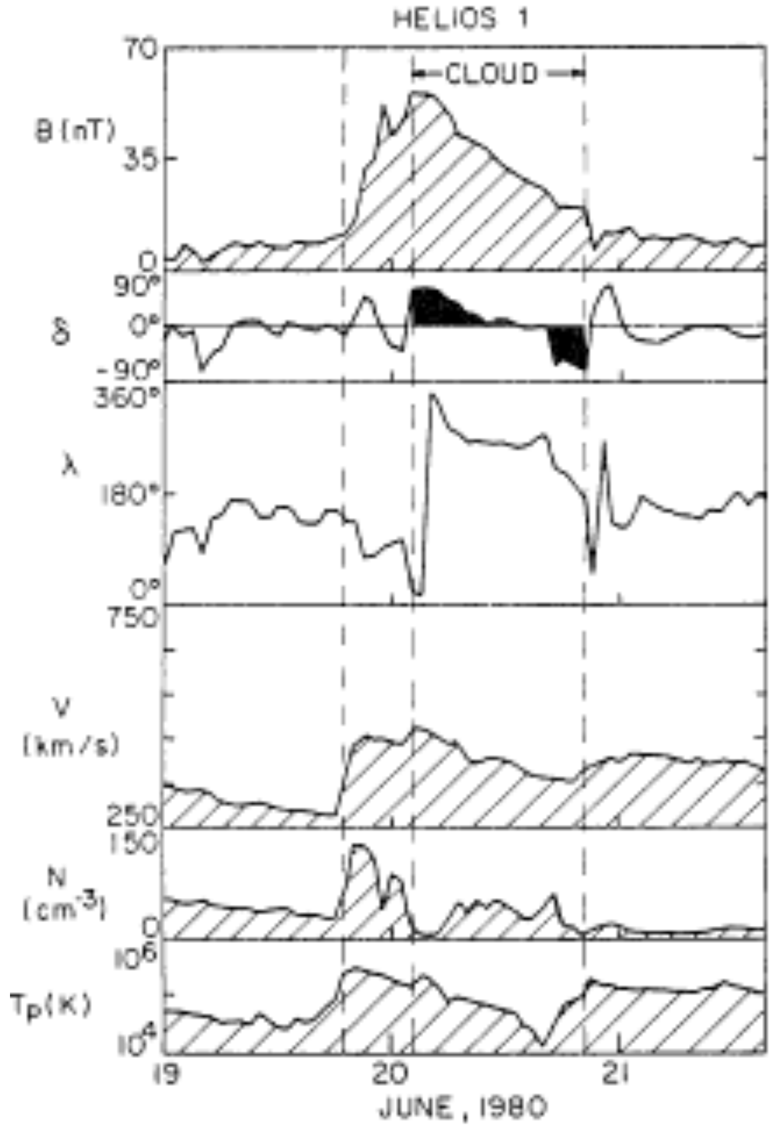


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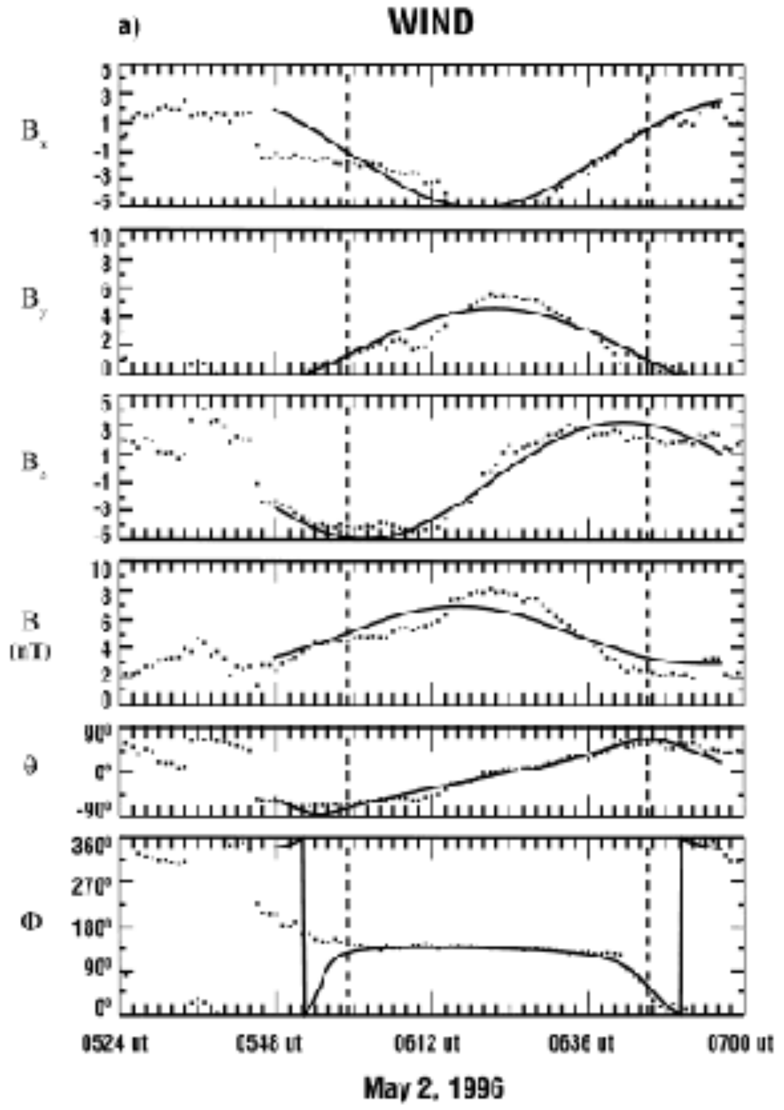


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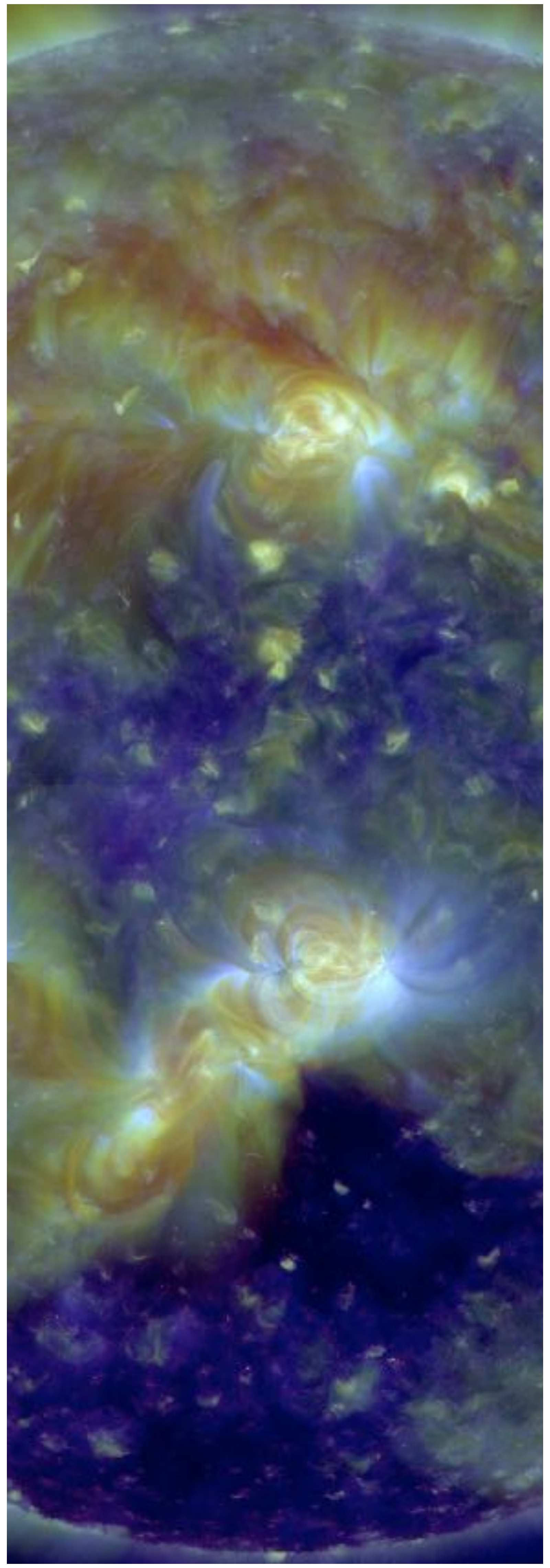

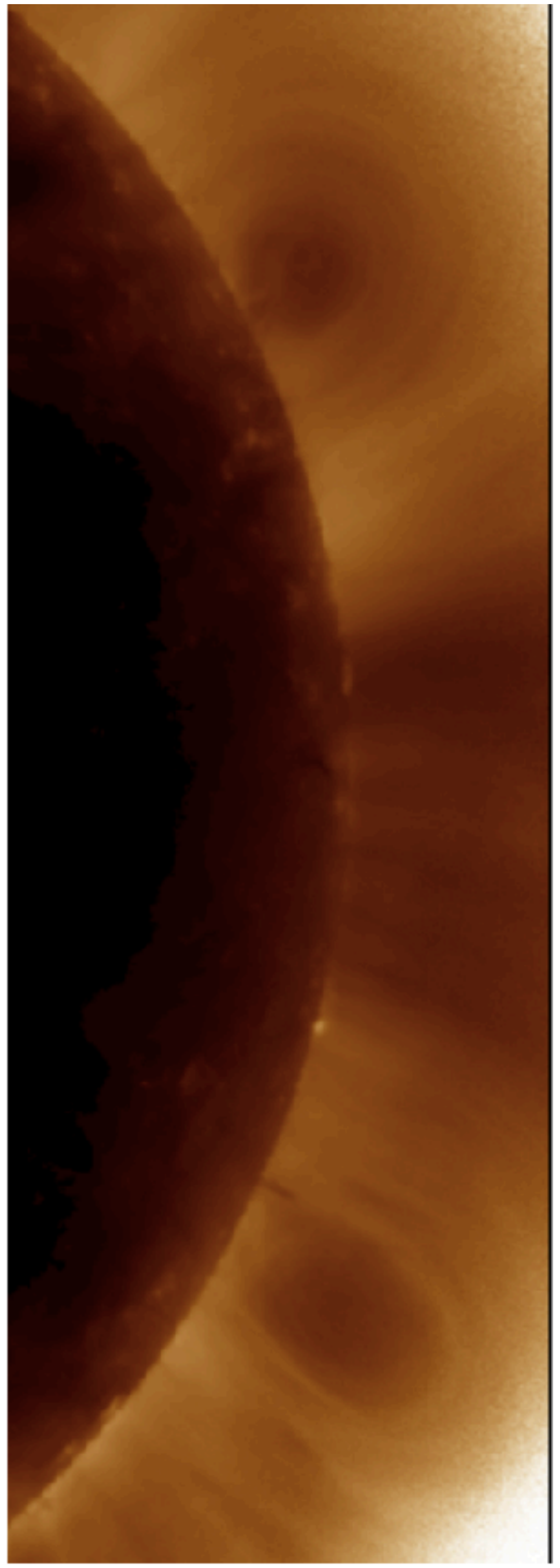

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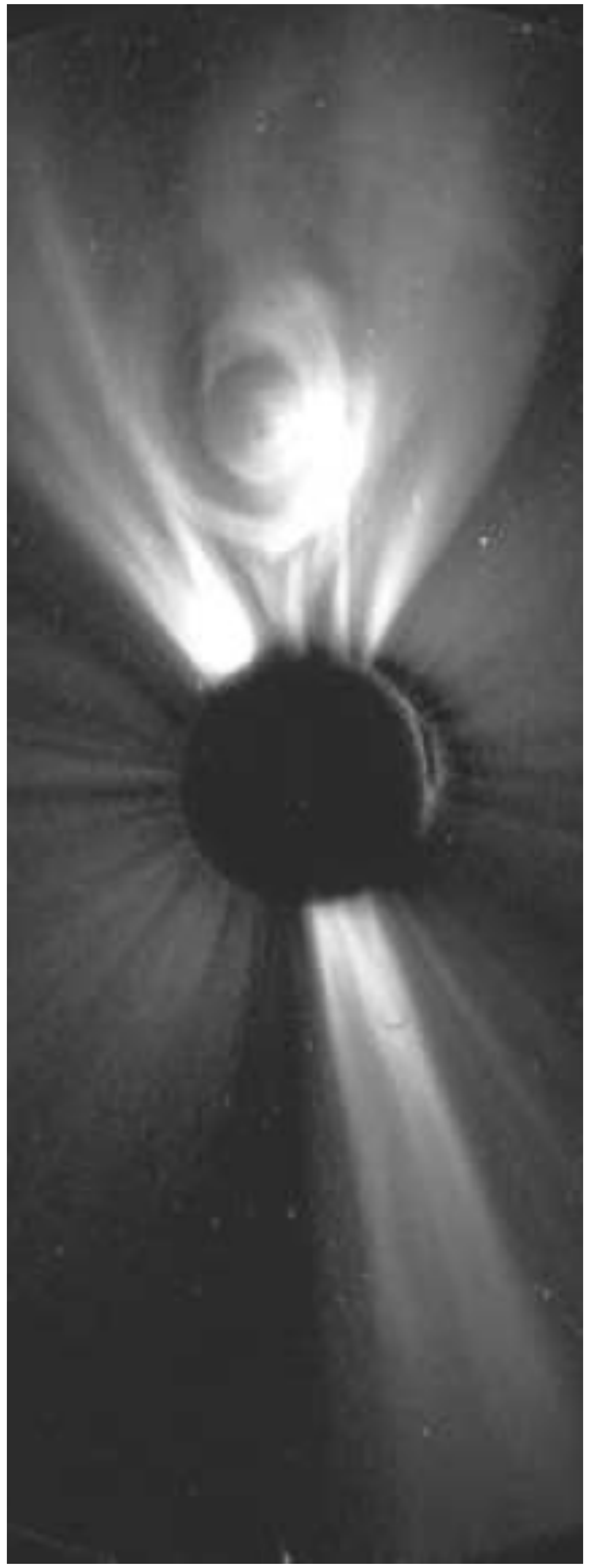

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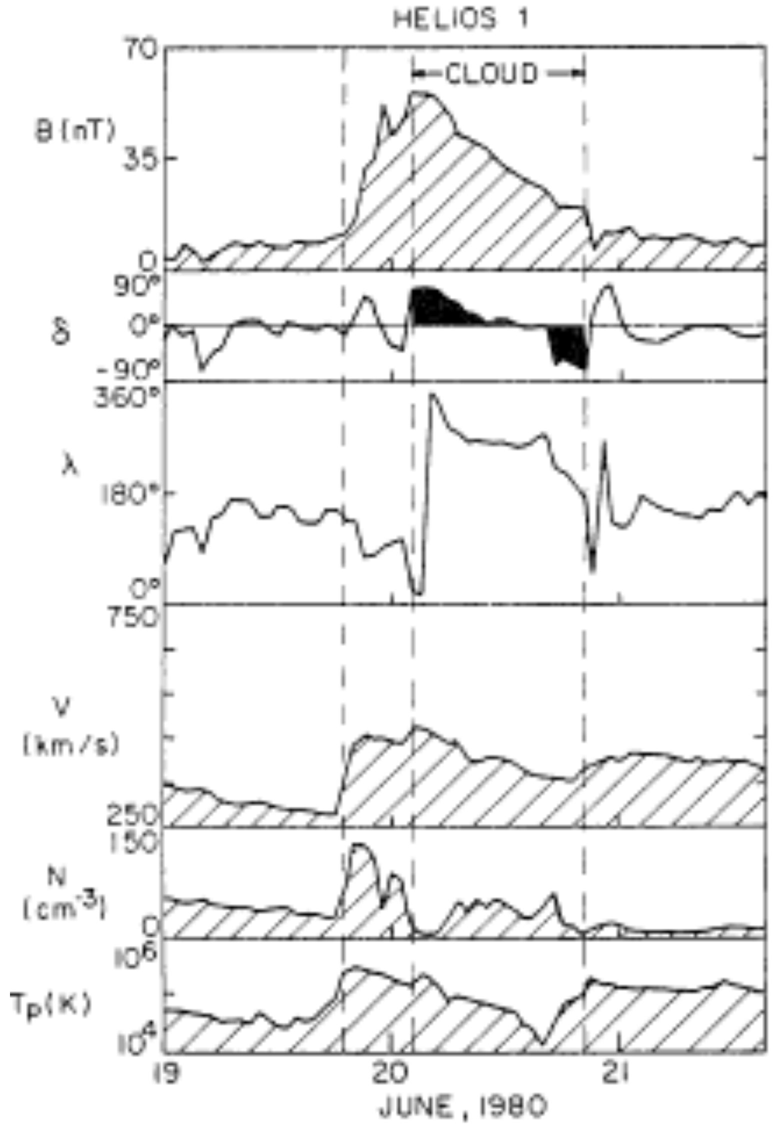


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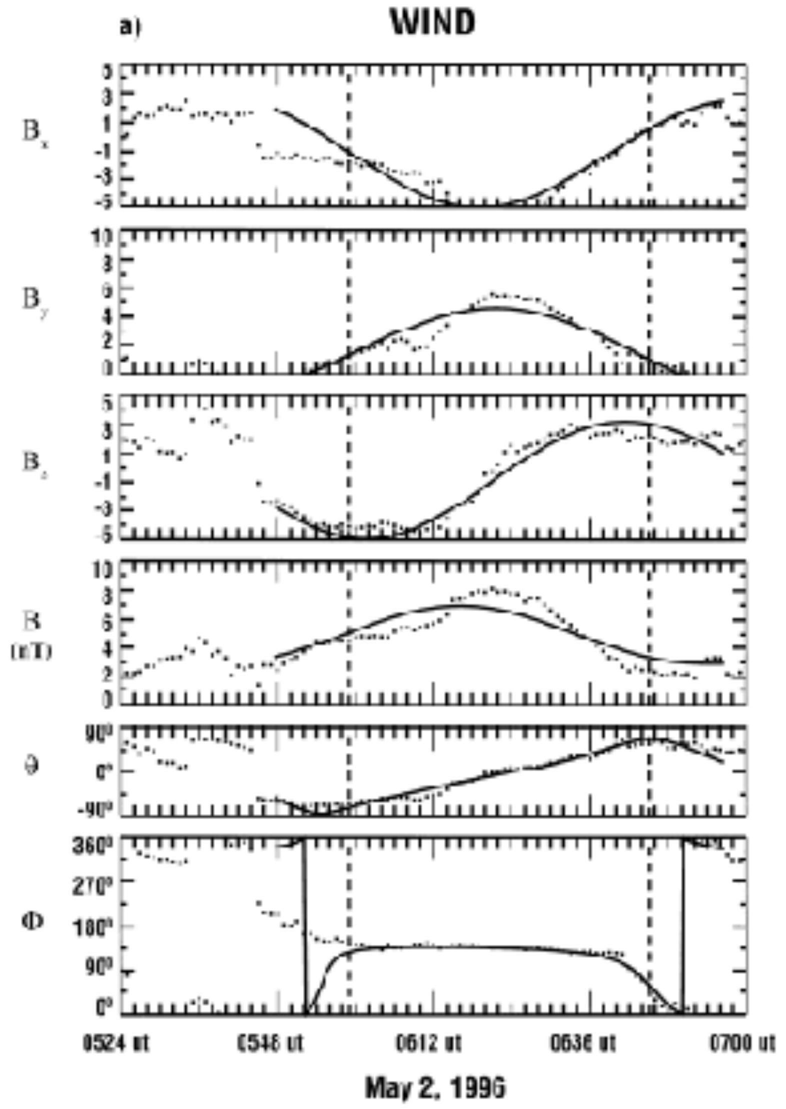


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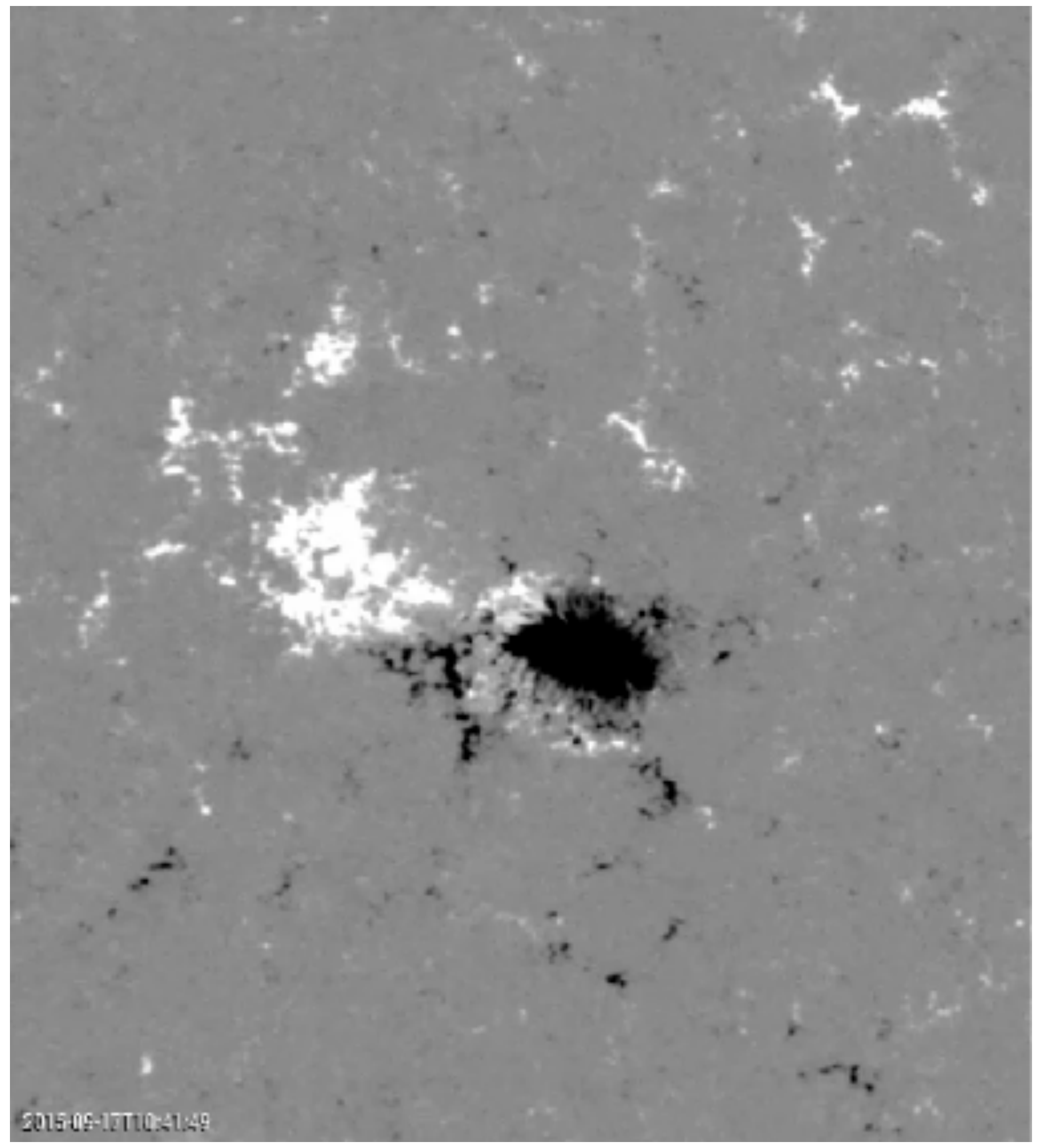
# Flux rope formation: flux cancellation

- van Ballegooijen & Martens, 1989
- Slow & ongoing tether-cutting-like photospheric reconnection
- A key mechanism for pre-CME flux rope formation
- The most robustly tested model for flux rope formation?



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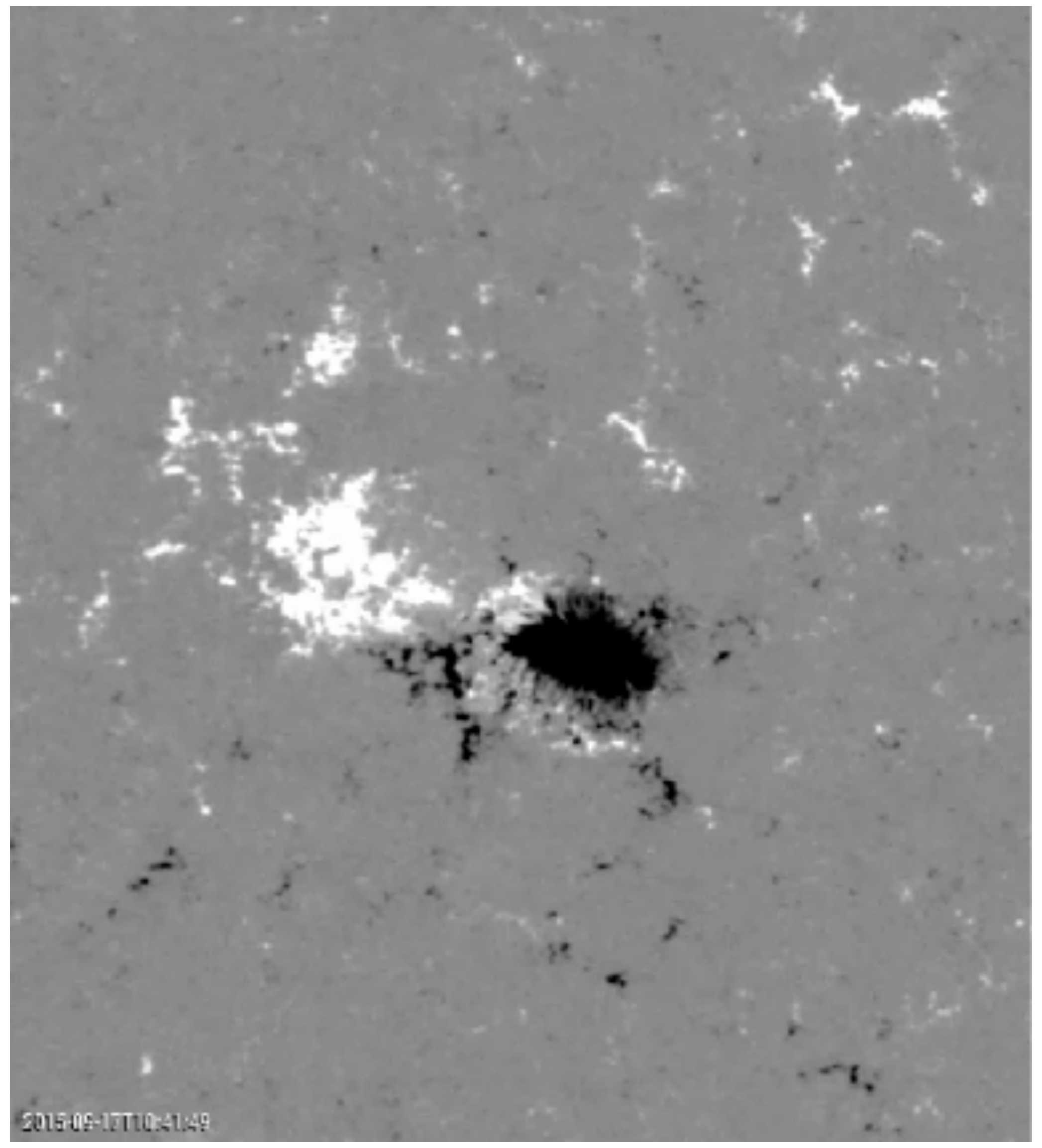

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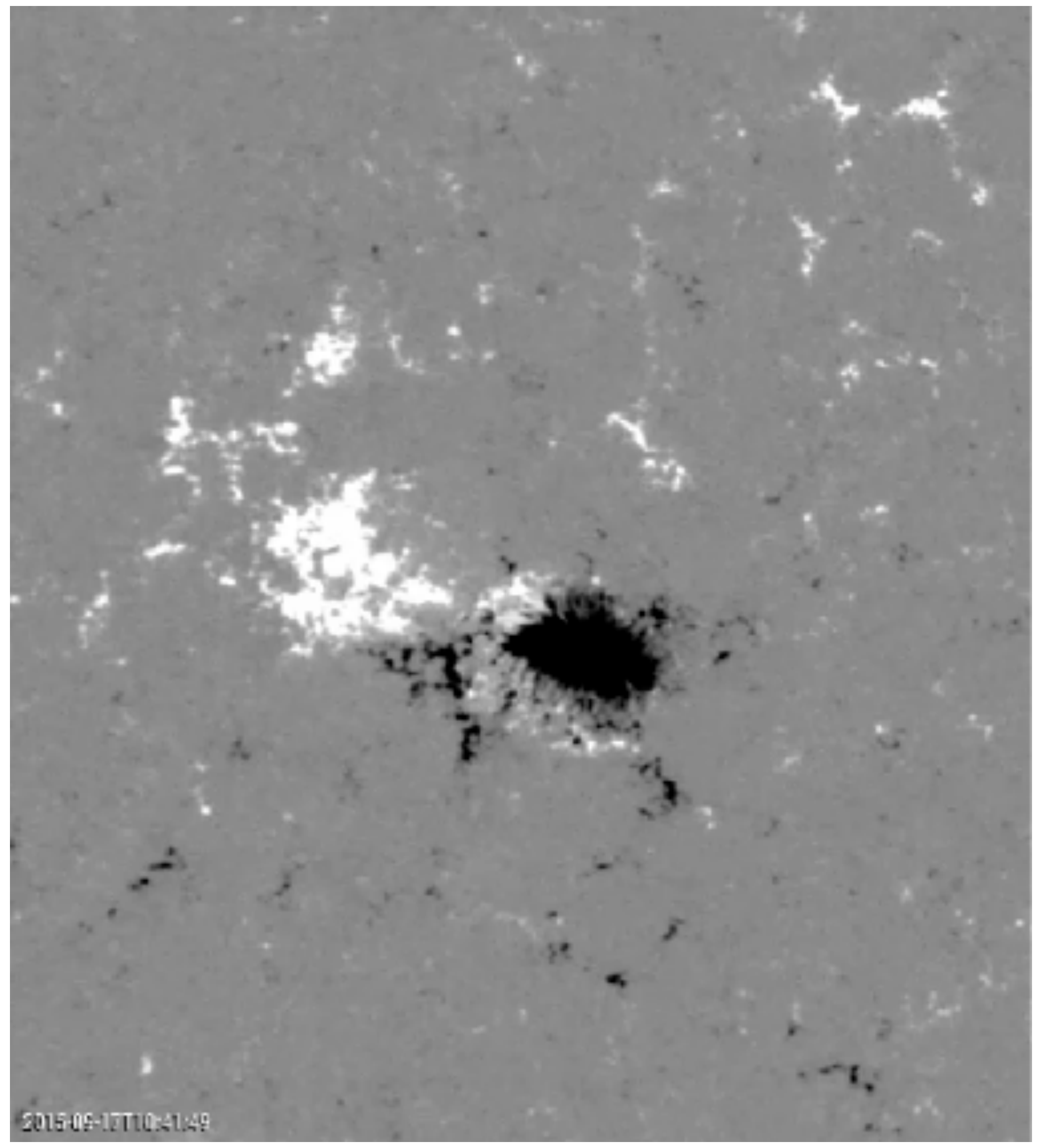

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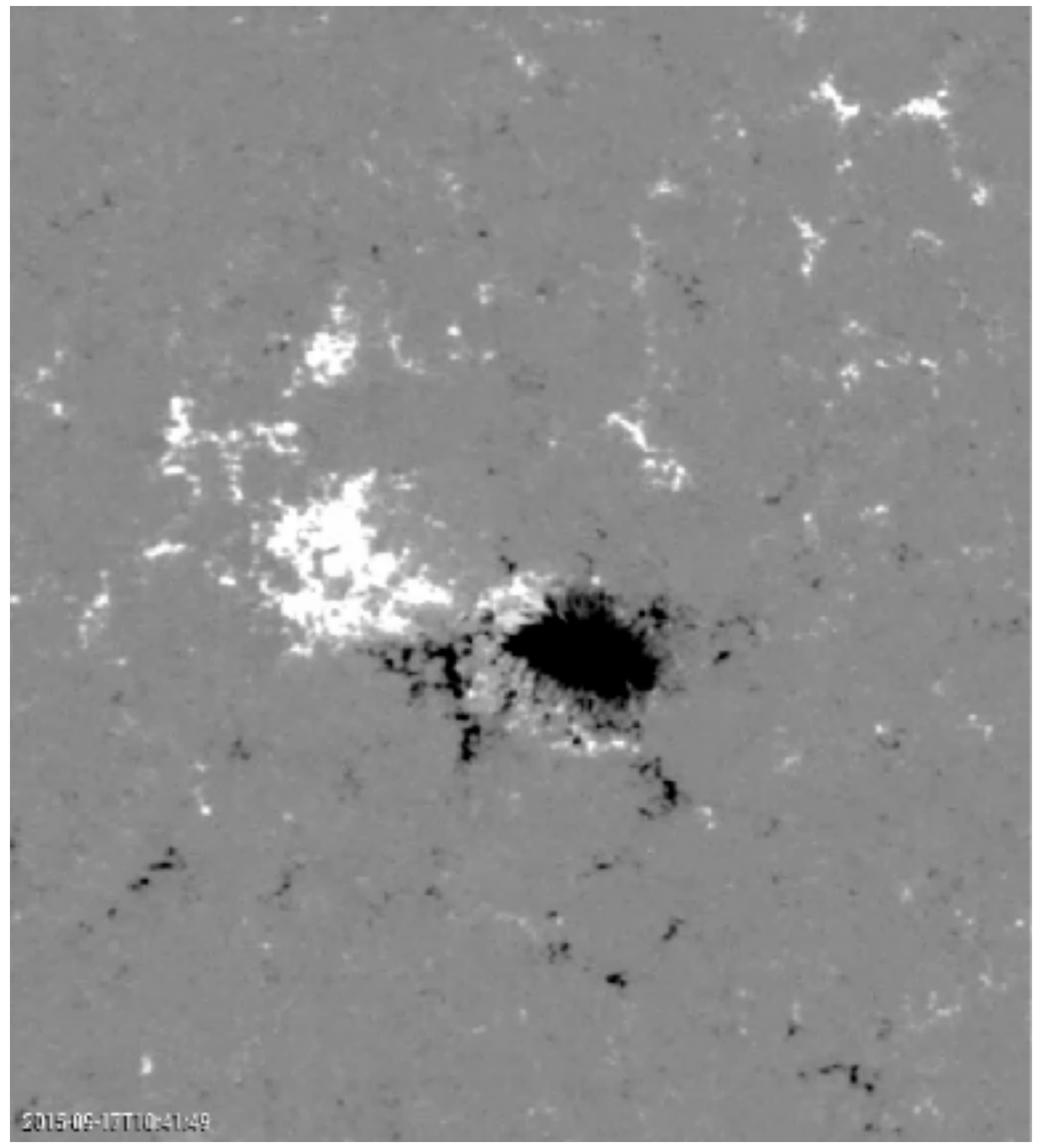
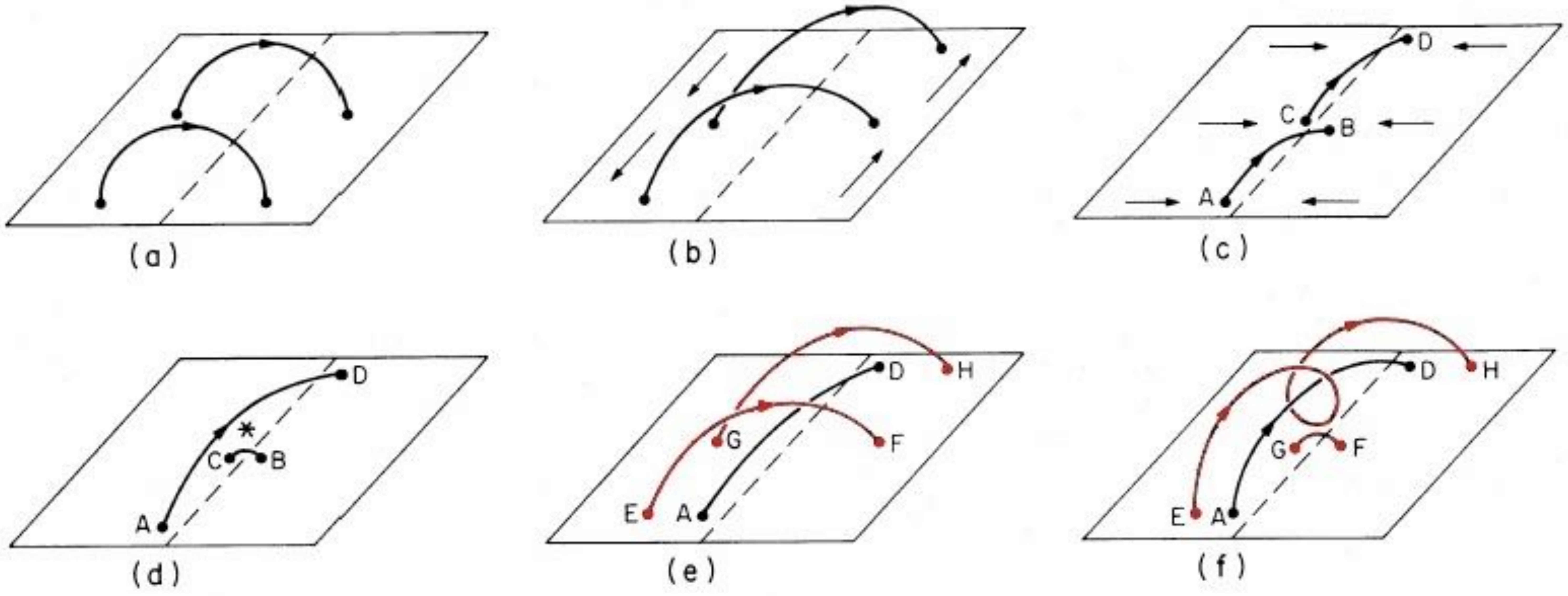




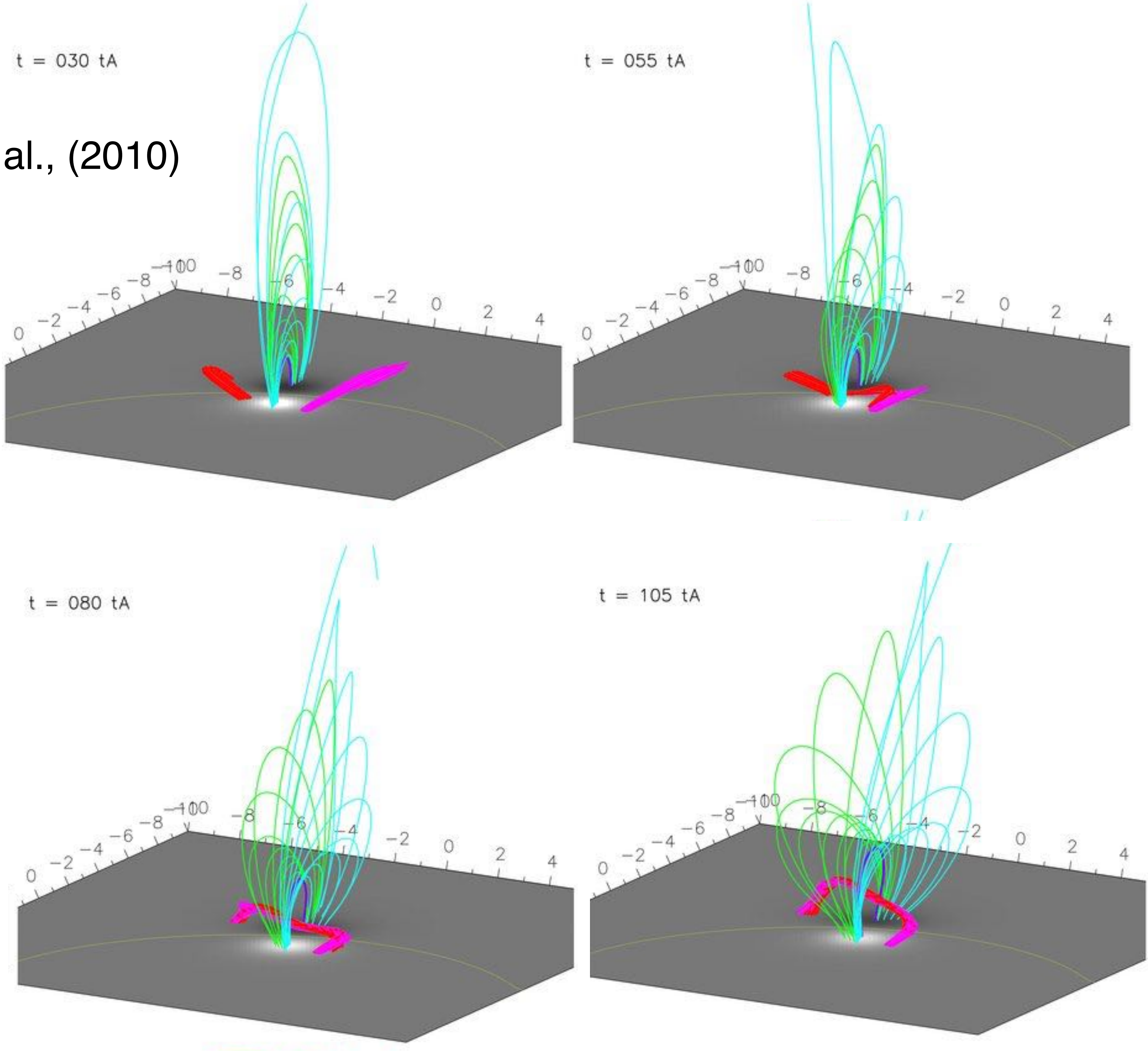

Modified from van Ballegooijen & Martens, 1989

# Flux rope formation: flux cancellation & modelling

For example:

- Amari et al. (2003, 2010, 2011)
- Lionello et al. (2002)
- Aulanier et al. (2010)
- Zuccarello et al (2012)
- *Gibb et al., (2014)*
- *Yardley et al. (2018)*

Aulanier et al., (2010)

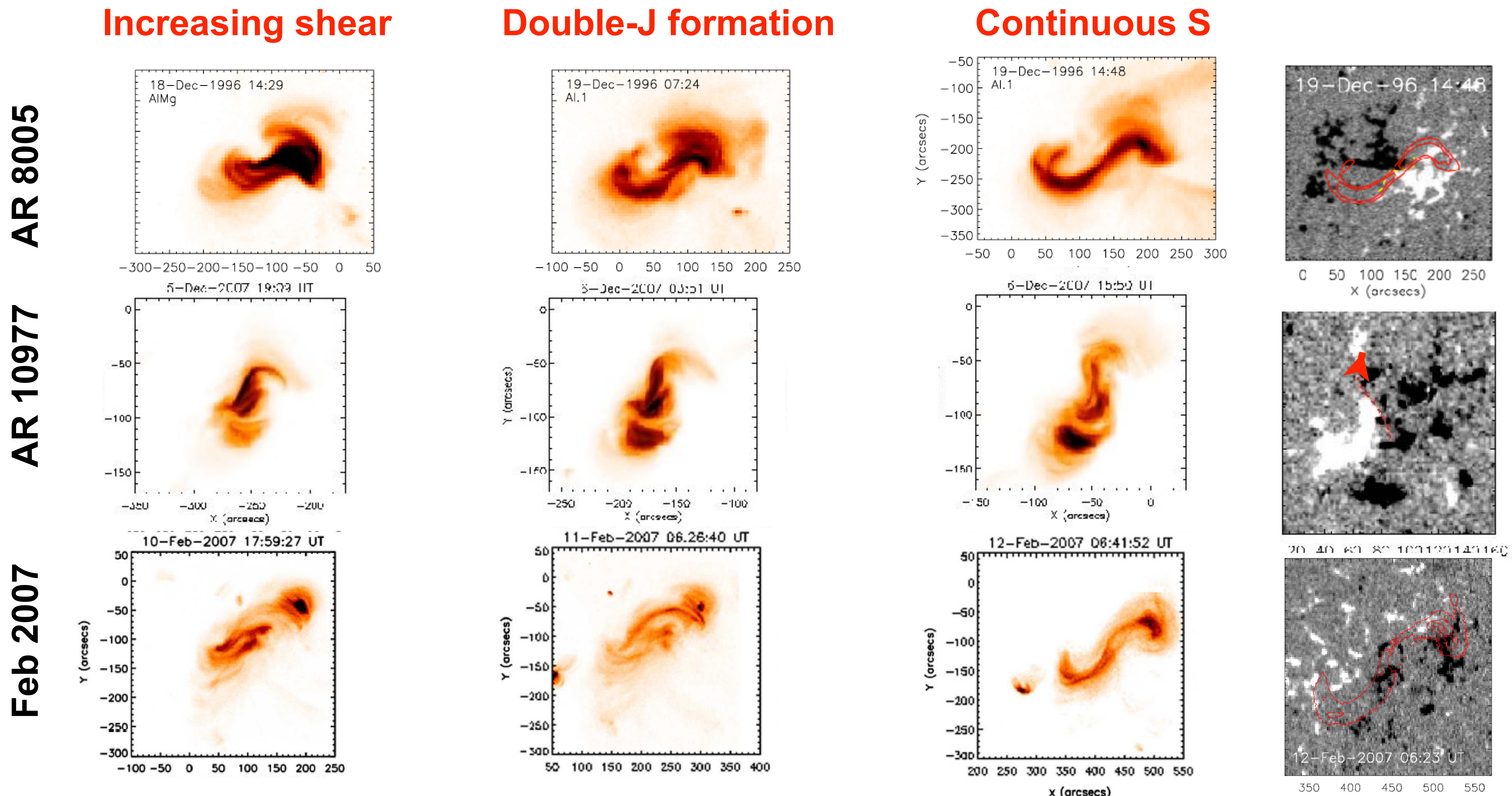



Red & magenta: Forming & erupting weakly twisted flux rope

Cyan & green: moderately sheared overlying arcade

# Flux rope formation: flux cancellation & observations

- Evolutionary stages in isolated bipolar regions
- Driven by photospheric field evolution



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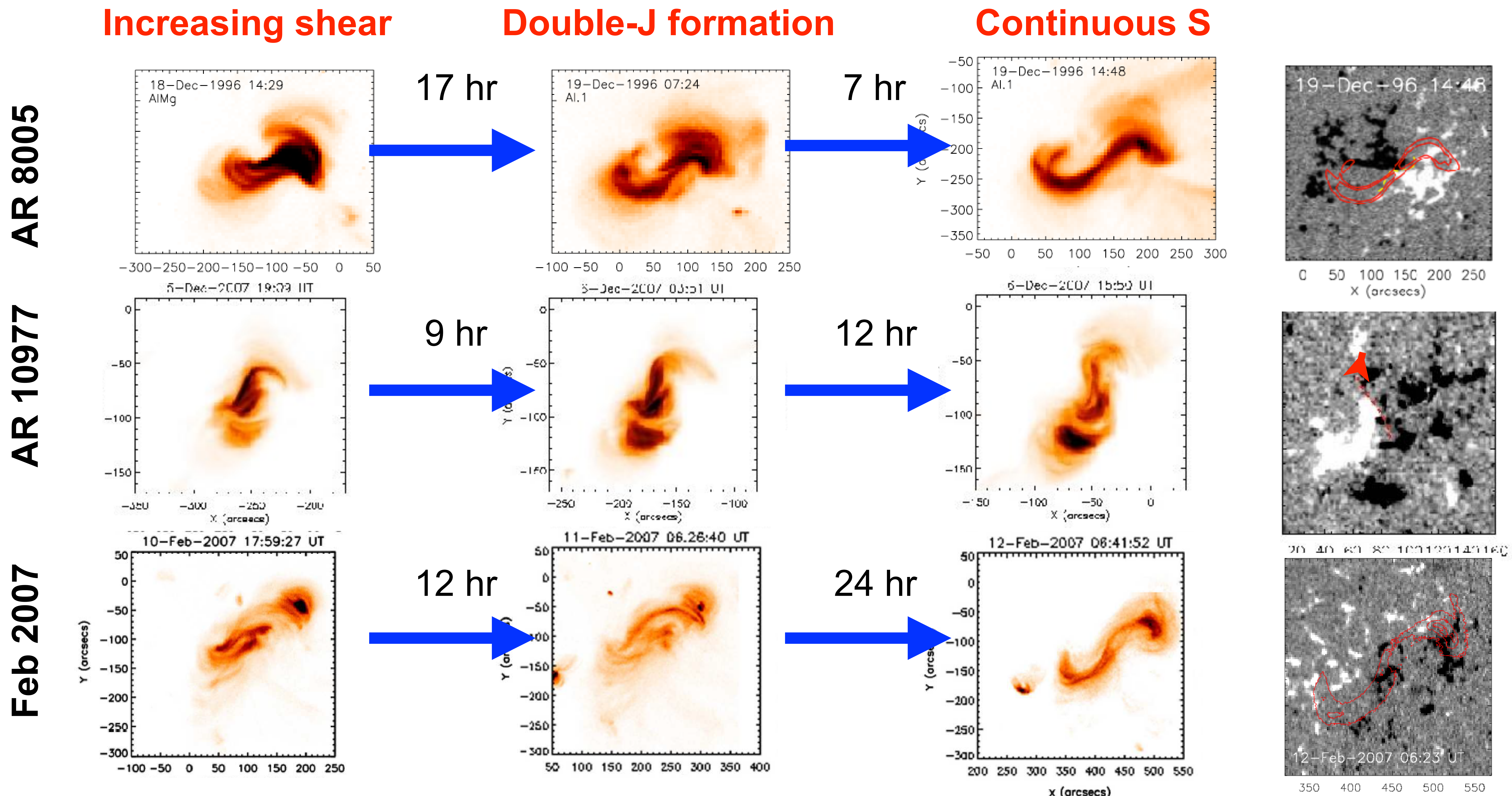

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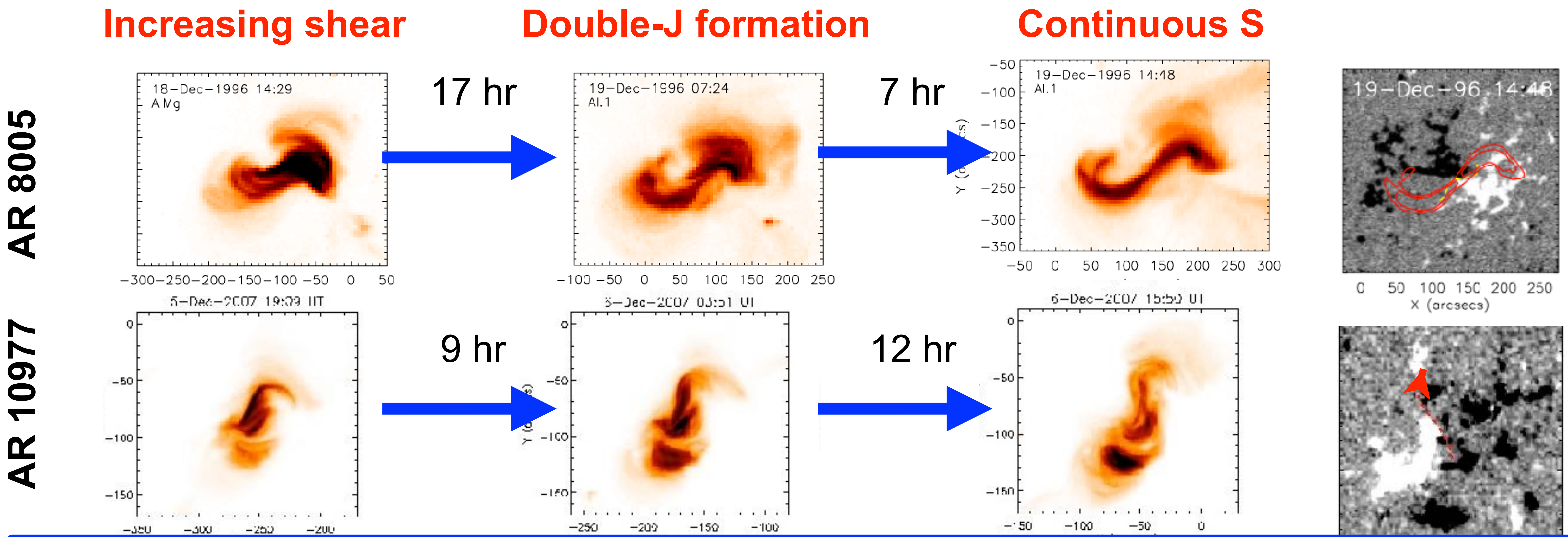


Observations show these flux ropes form on a timescale of ~ few days up to 14 hours prior to their eruption. But sigmoids are only observed in a sub-set of eruptive active regions.

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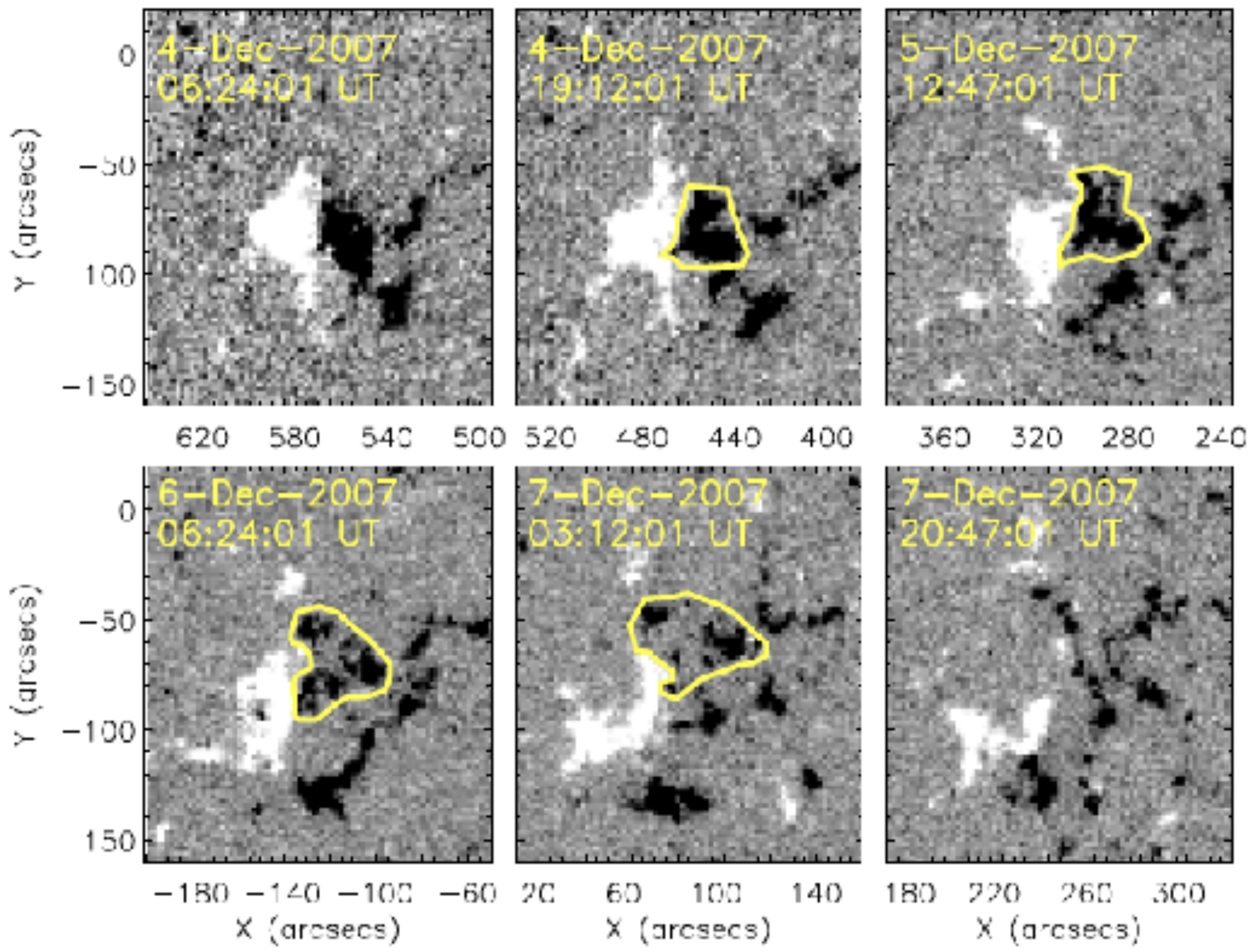
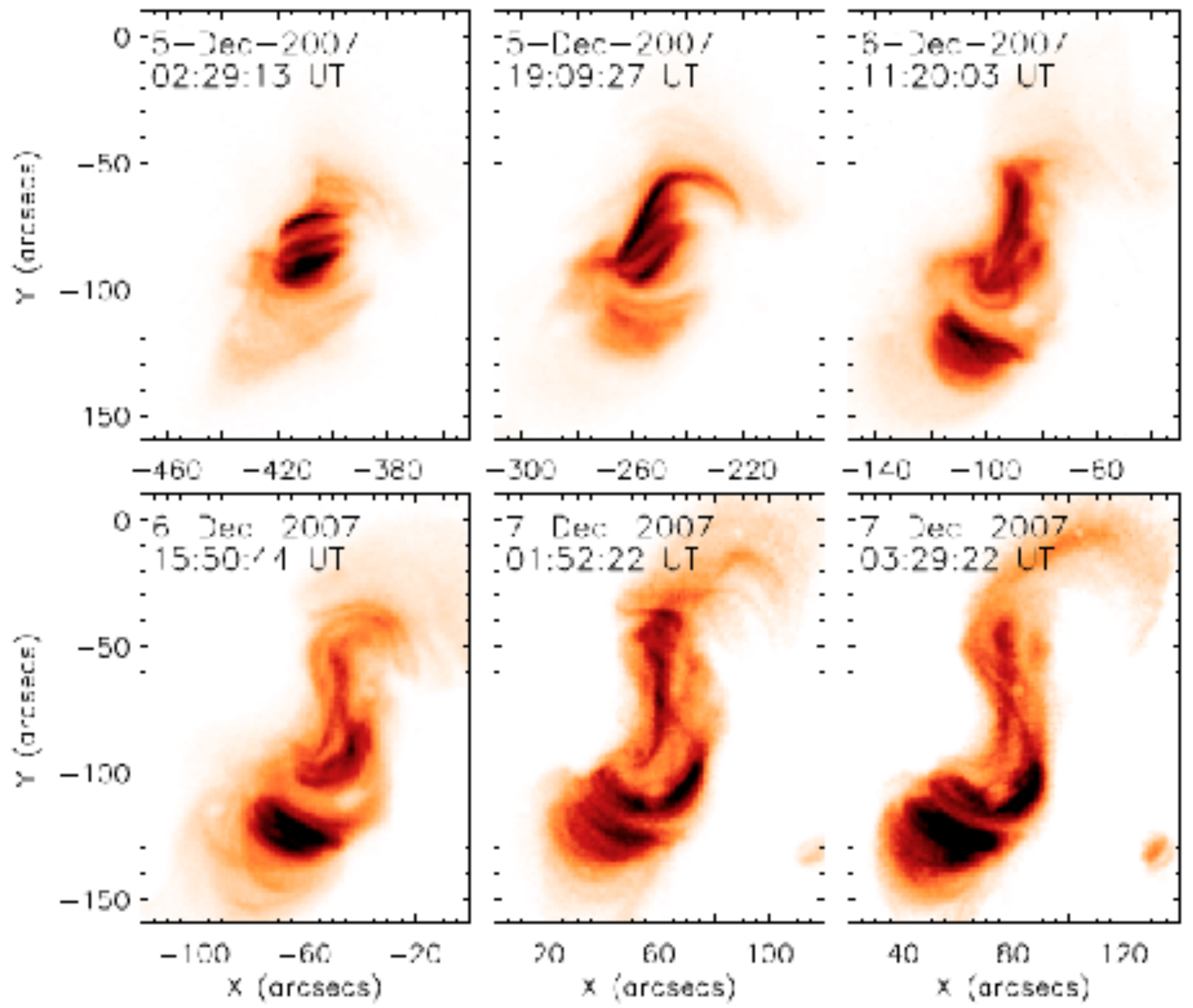
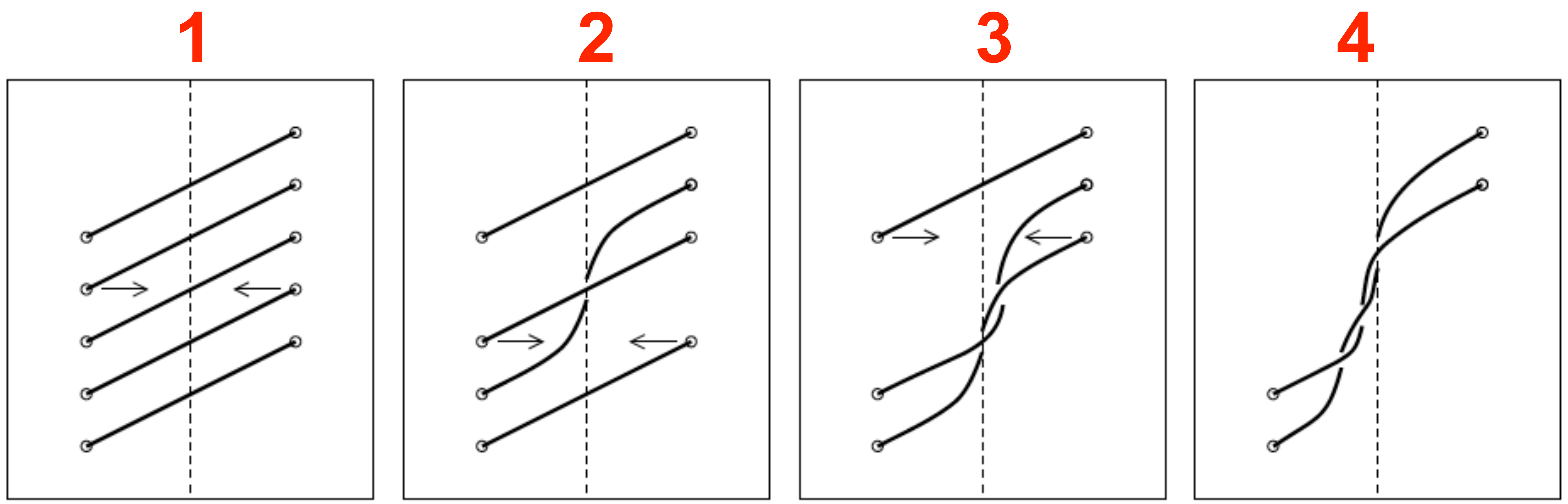



| **Date (2007)** | **Observed cancelled flux (10^20 Mx)** |
|---|---|
| Dec. 4 | 0 |
| Dec. 5 | 2.75 |
| Dec. 6 | 5.15 |
| Dec. 7 | 7.07 |

# “Added value” of the flux cancellation process




Green, Kliem, Wallace (2011)

- But: cancellation can only create a flux rope from sheared fields, in fact it is concentrating free energy along the PIL (Welsch, 2006).

- The above example shows that only 2/3 cancellations were forming a flux rope out of the sheared arcade.

- Flux in **the flux ropes** amounts to about **60%-70% of the cancelled flux** (Savcheva et al., 2012).

# “Added value” of the flux cancellation process

AND - these flux ropes are likely to be only partially formed, only building their coherency during the flare reconnection as the eruption takes place. So consideration must be made as to the overlying arcade!

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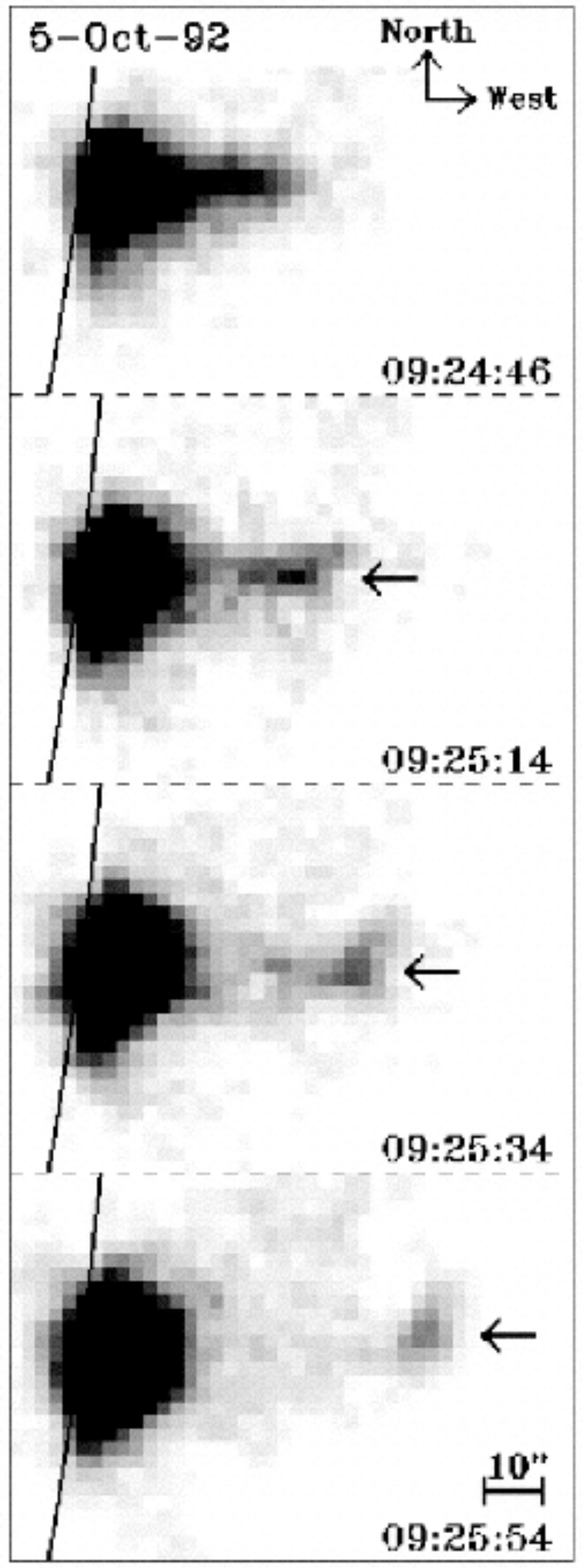
# Flux rope formation: coronal recon'n (hot flux ropes)

- Seen at the solar limb. Line-of-sight is ~parallel with the flux rope axis




Ohyama & Shibata (1995)

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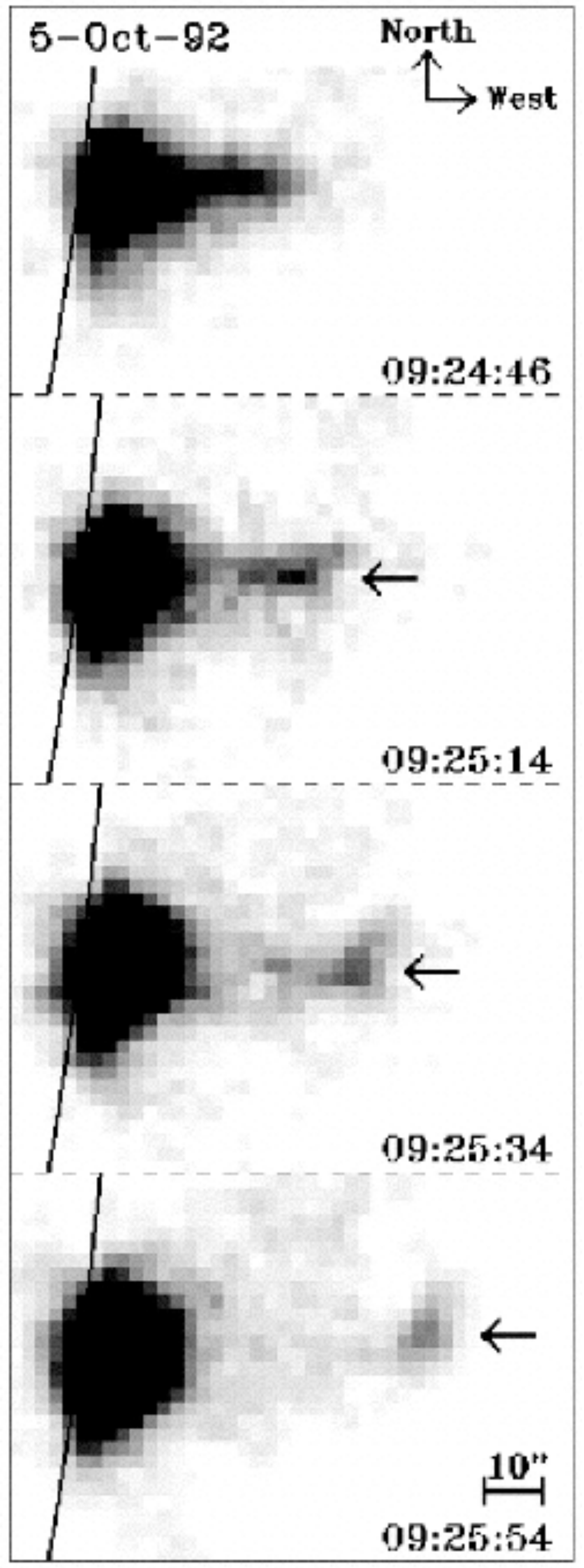


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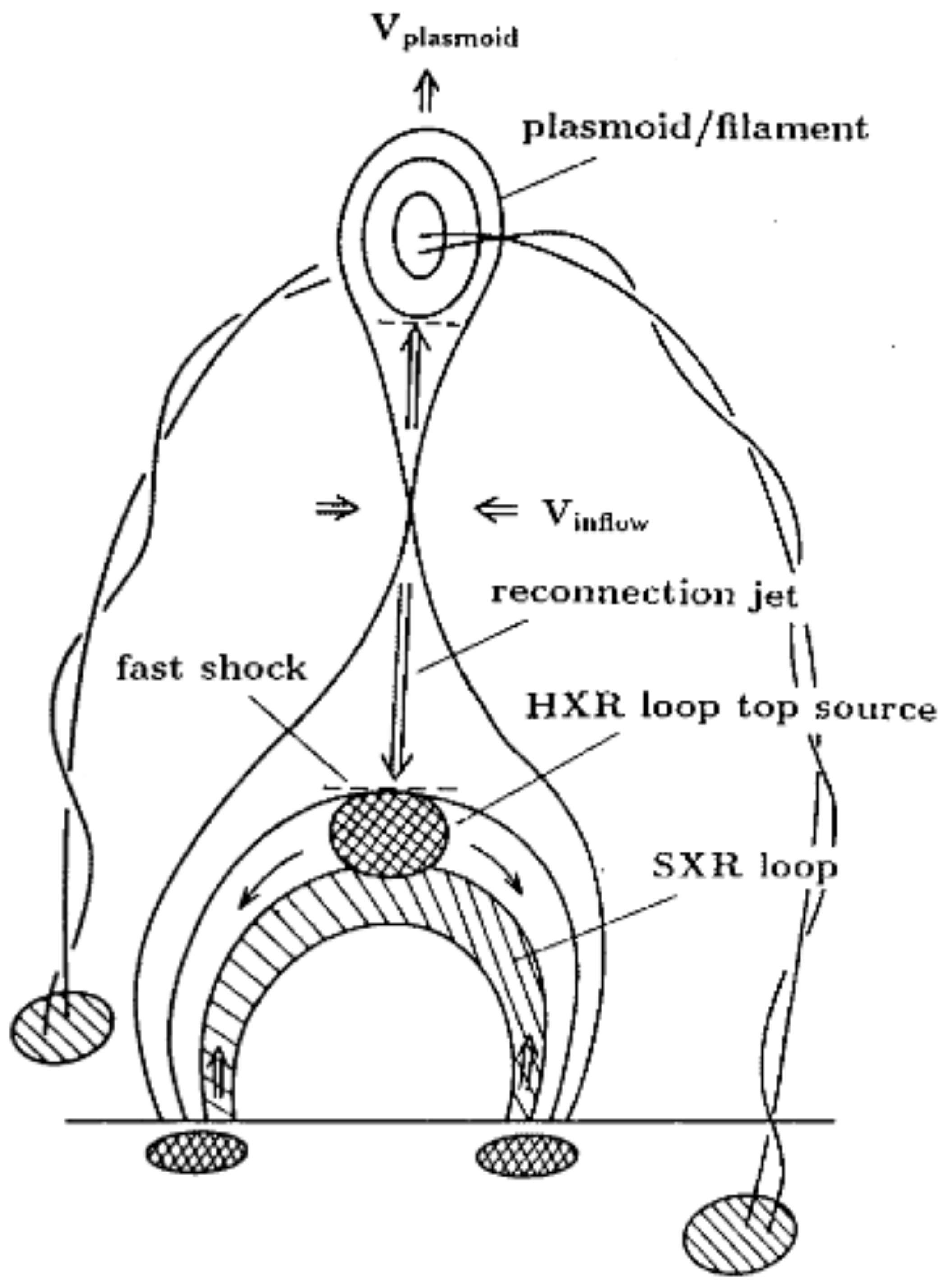


Fig. 1. A unified model of flares: *plasmoid-induced-reconnection model* (Shibata *et al.*, 1995). This is an extention of a classical model of eruptive solar flares, called the CSHKP model.

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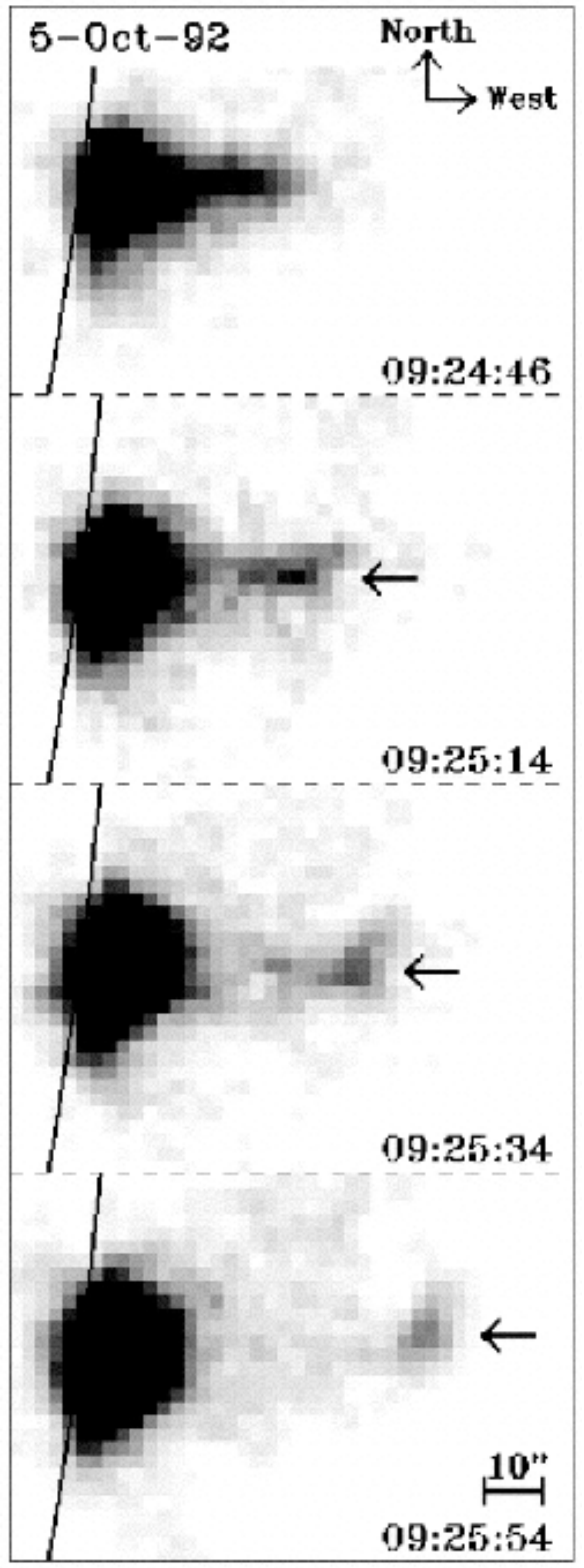


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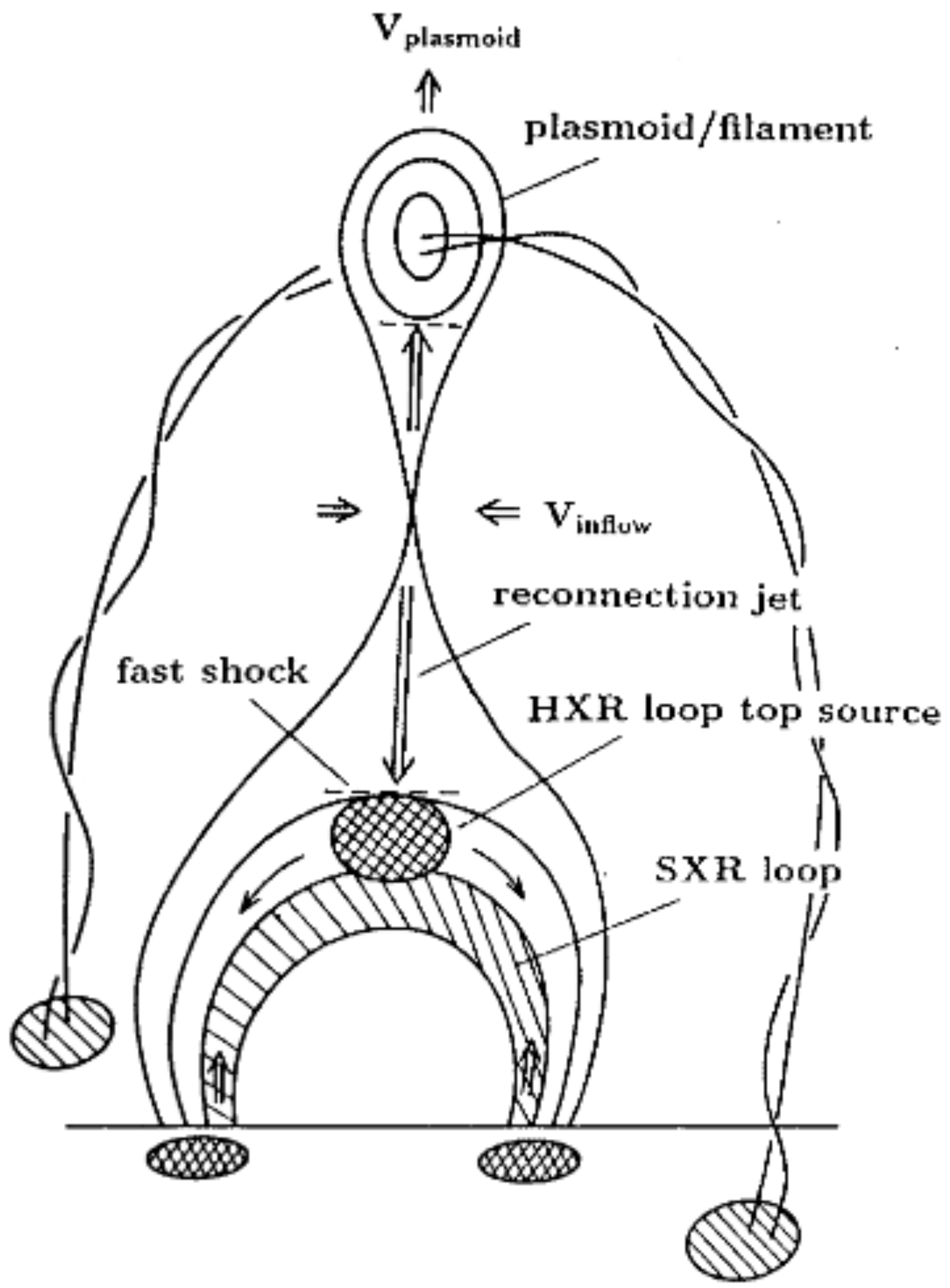


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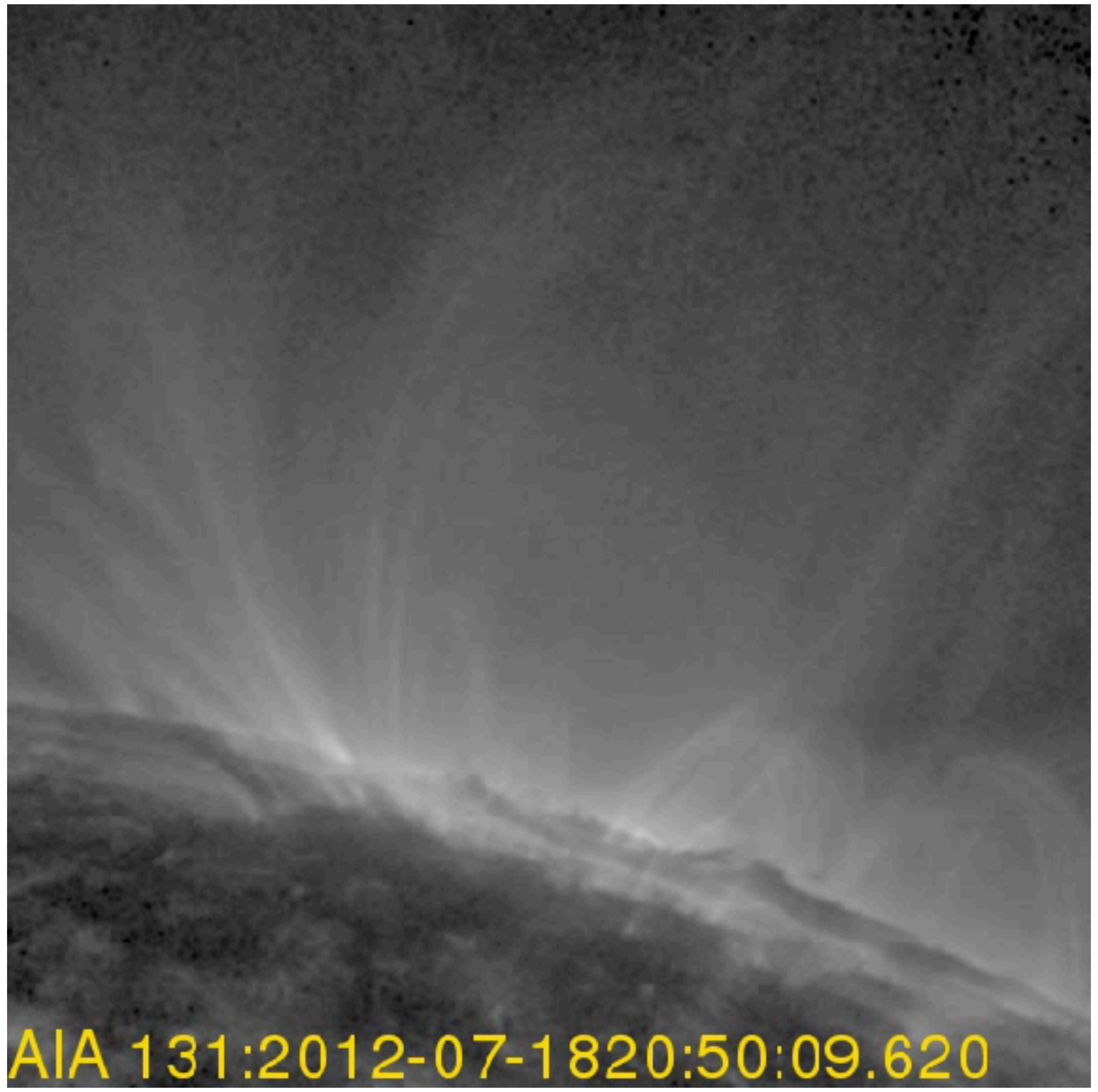


Patsourakos, Vourlidas, Stenborg (2013)

See also:

Cheng et al., 2011
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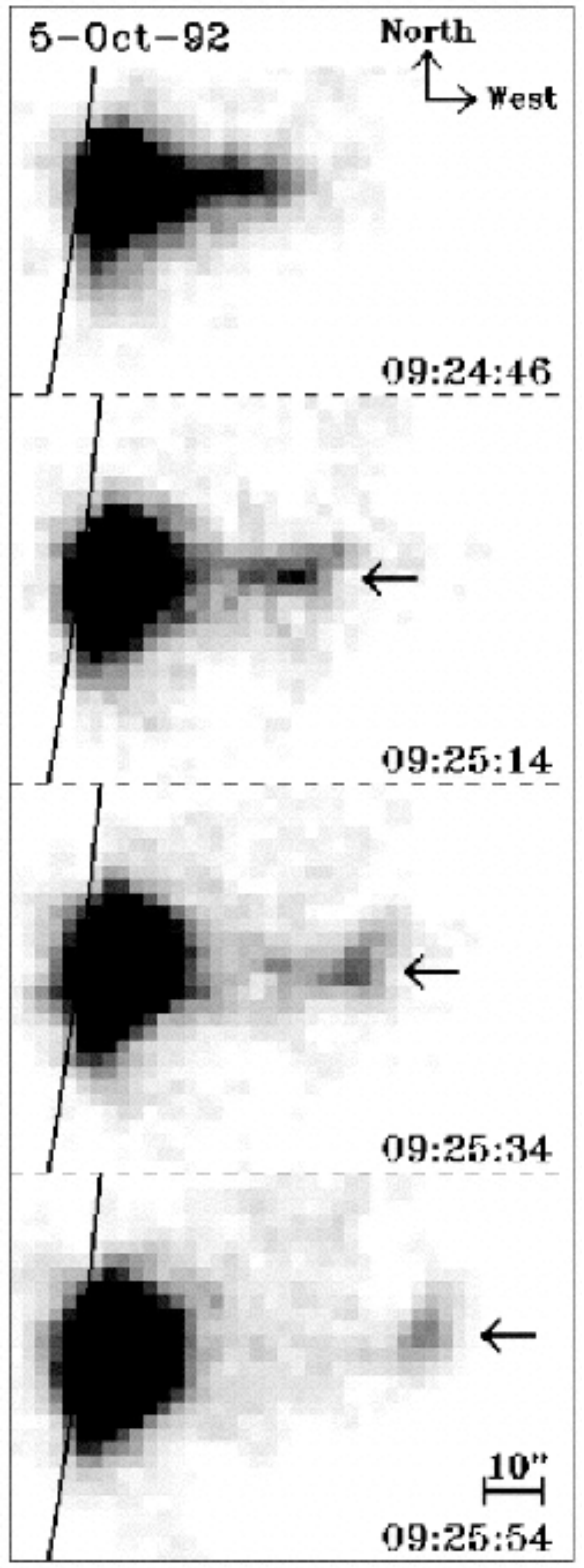


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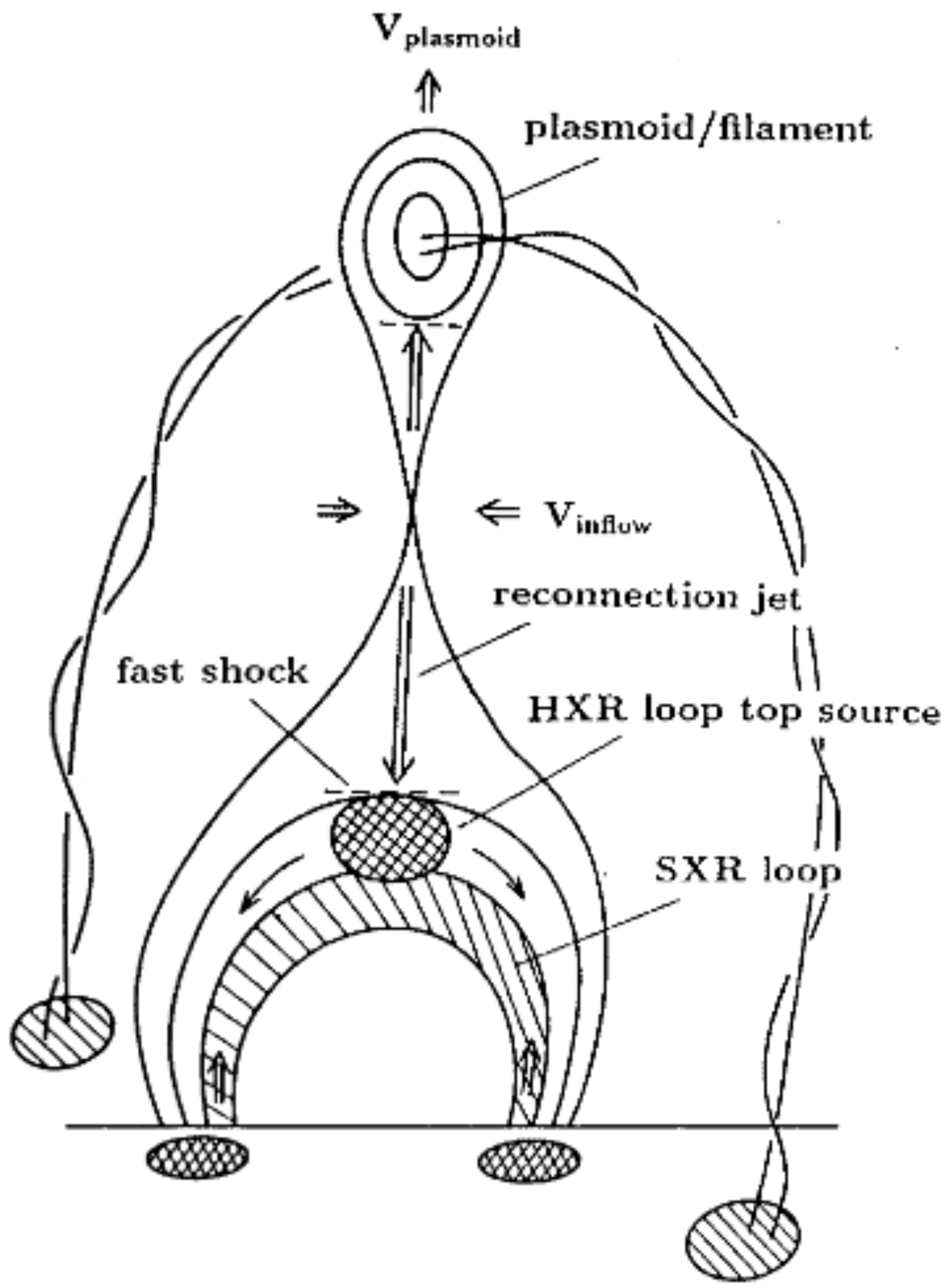


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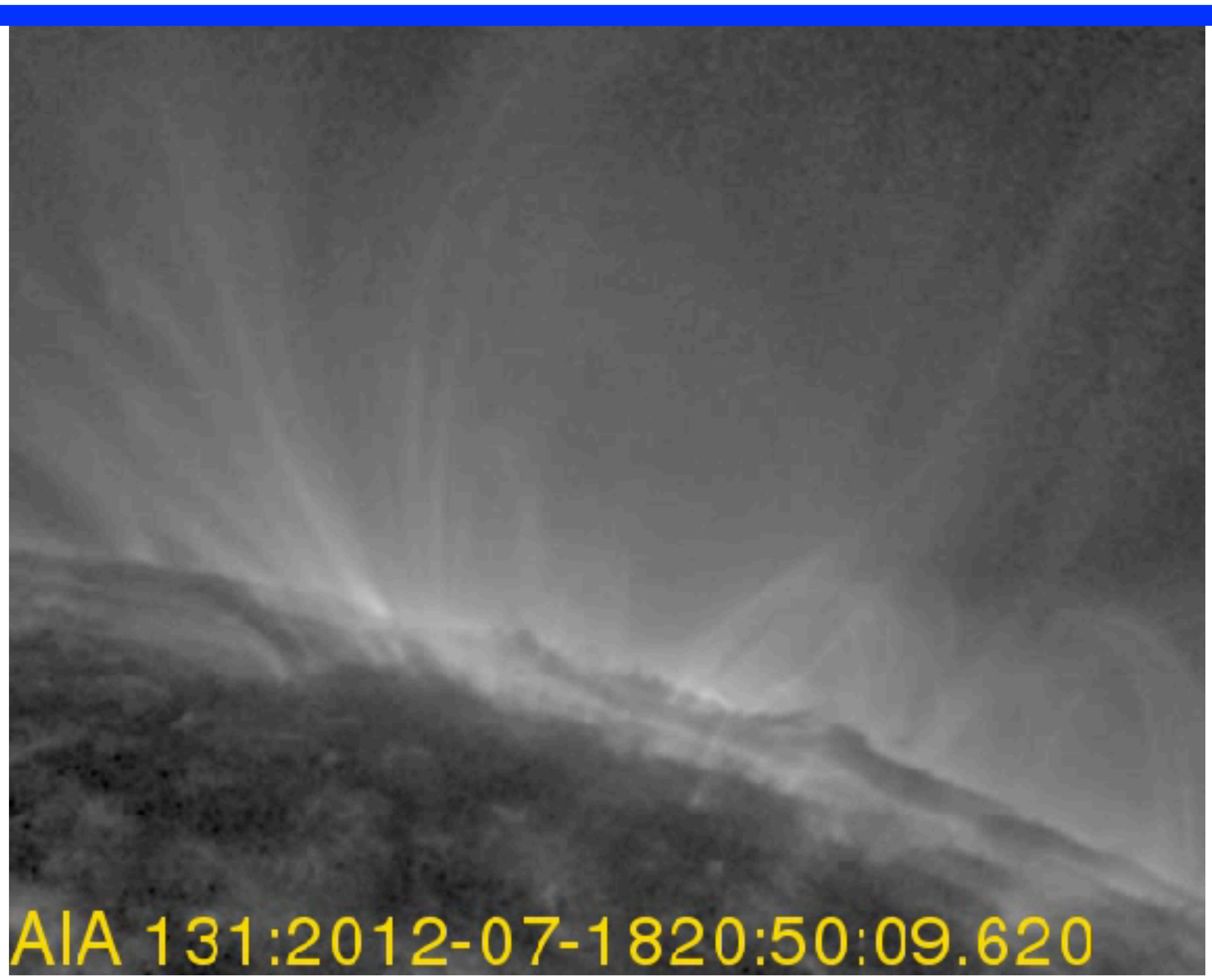
Patsourakos, Vourlidas, Stenborg (2013): Flux rope formed on a timescale of 20 minutes around 7 hours prior to its eruption

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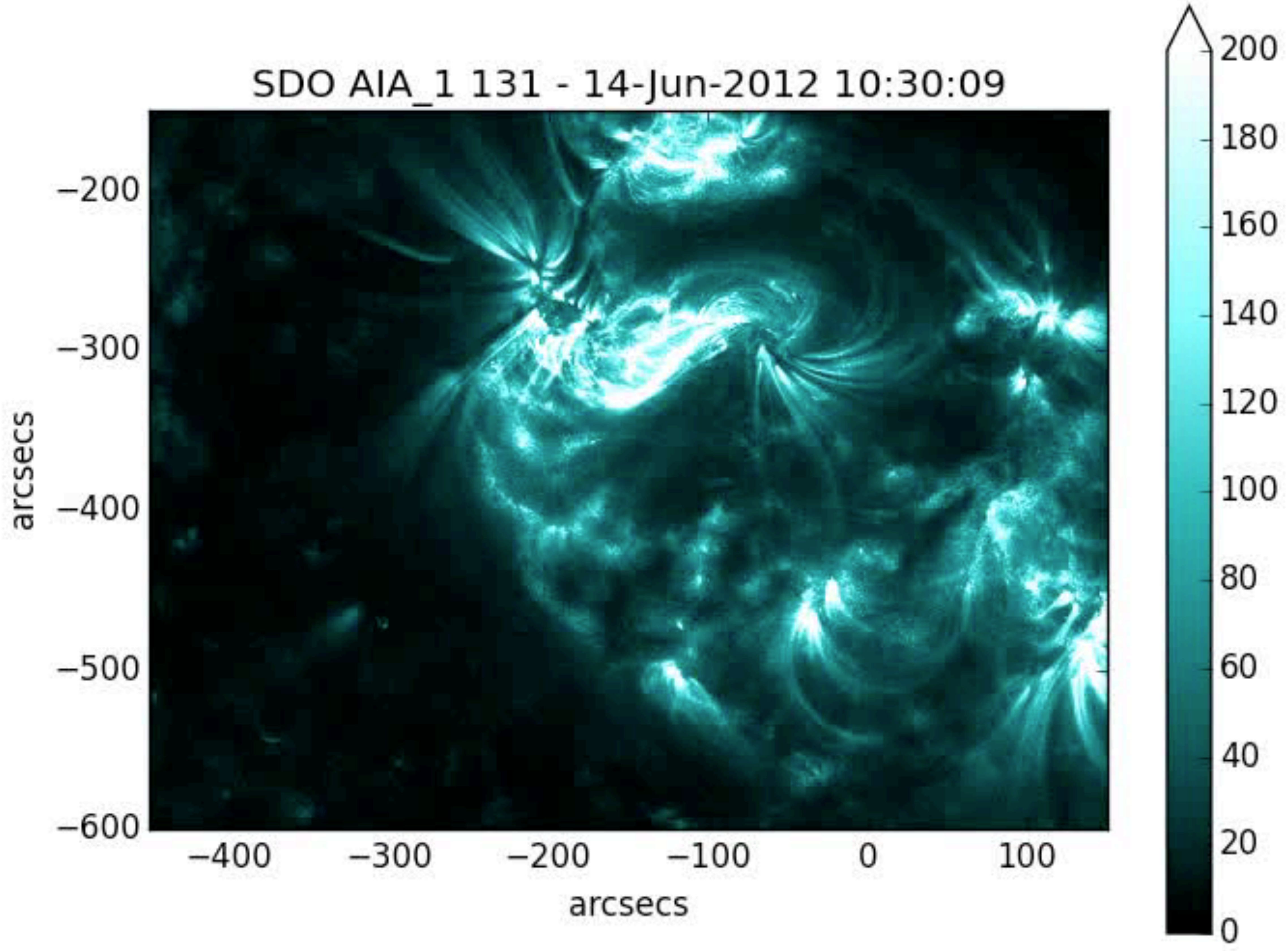
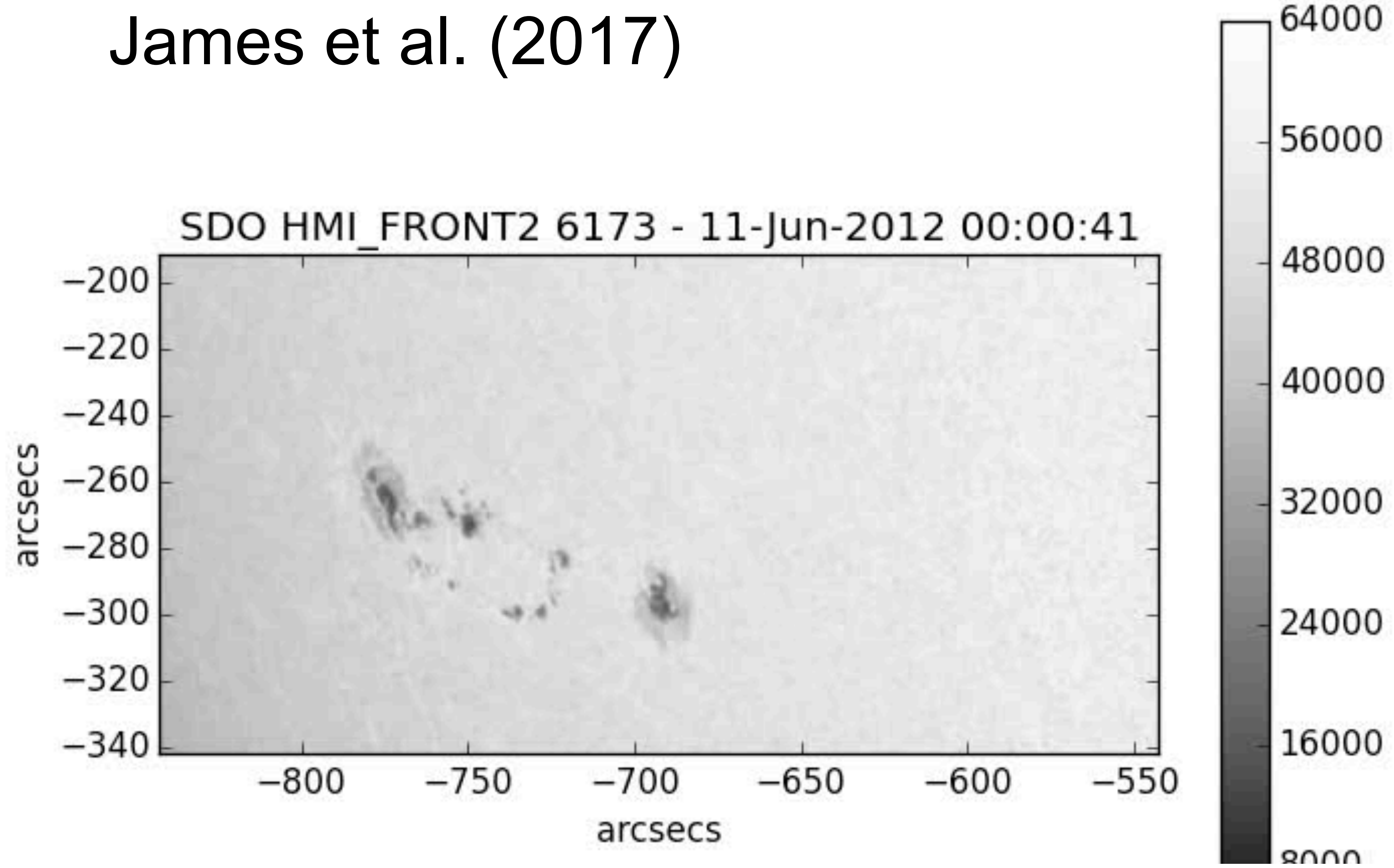
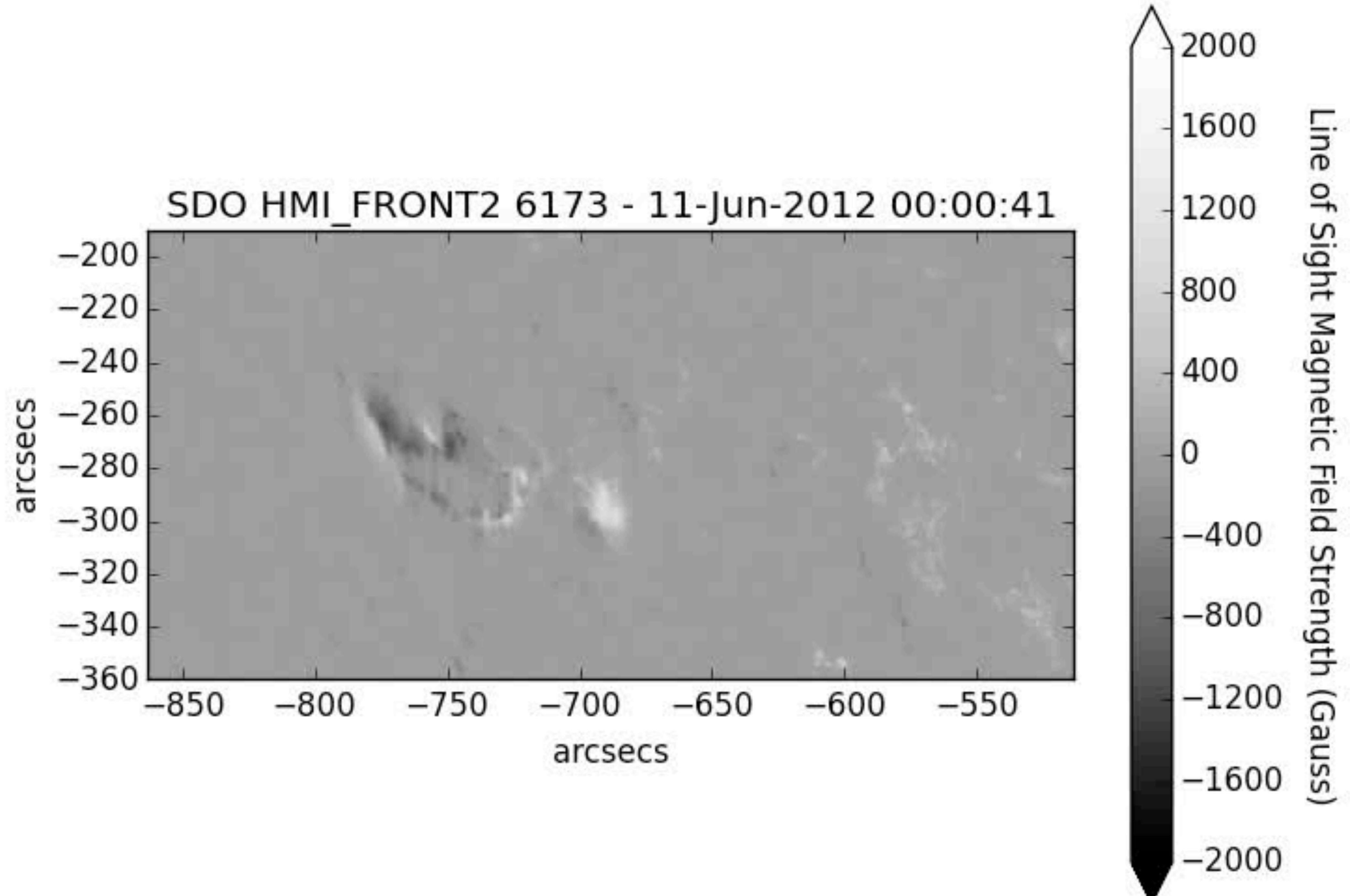
James et al. (2017)



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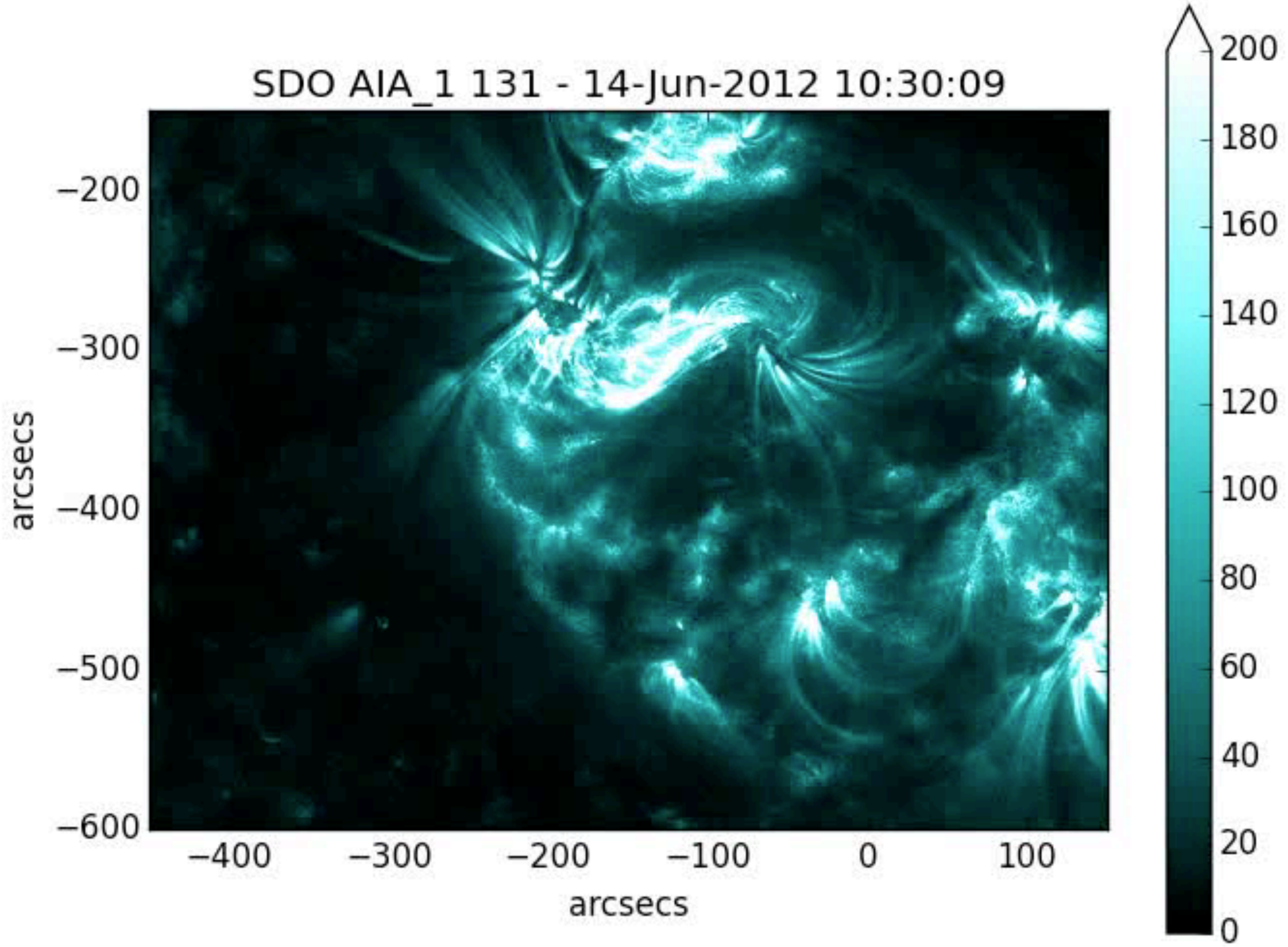


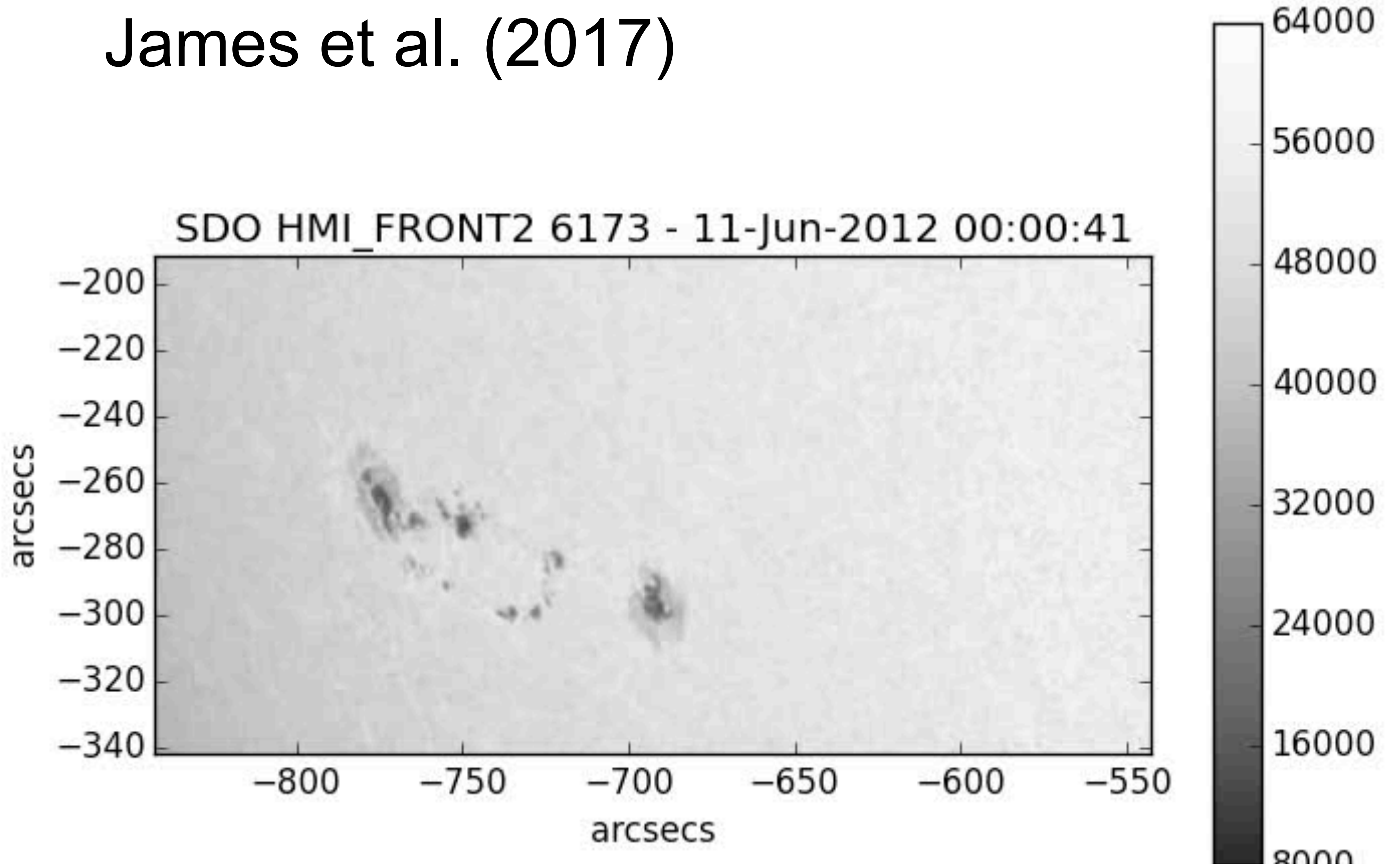


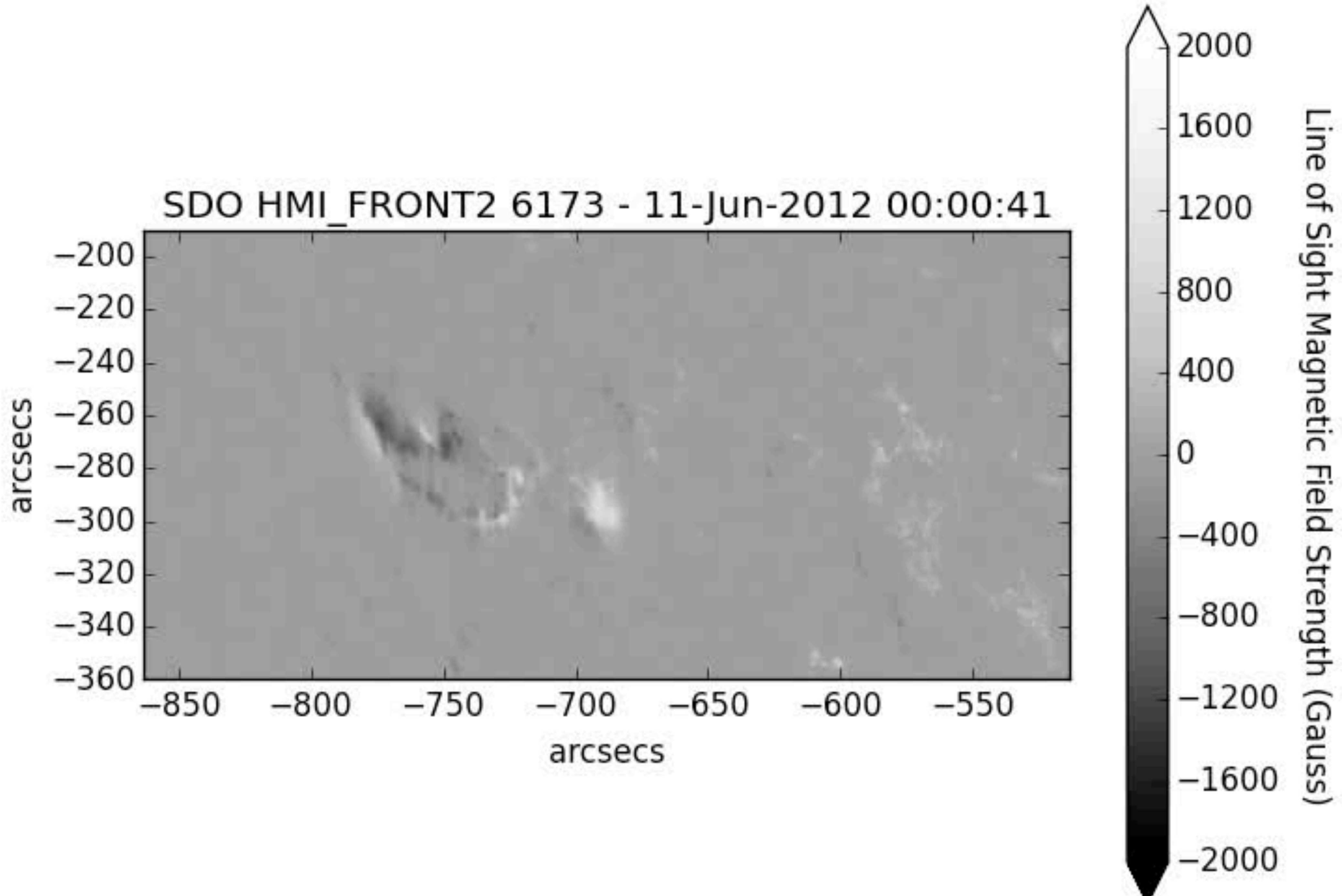

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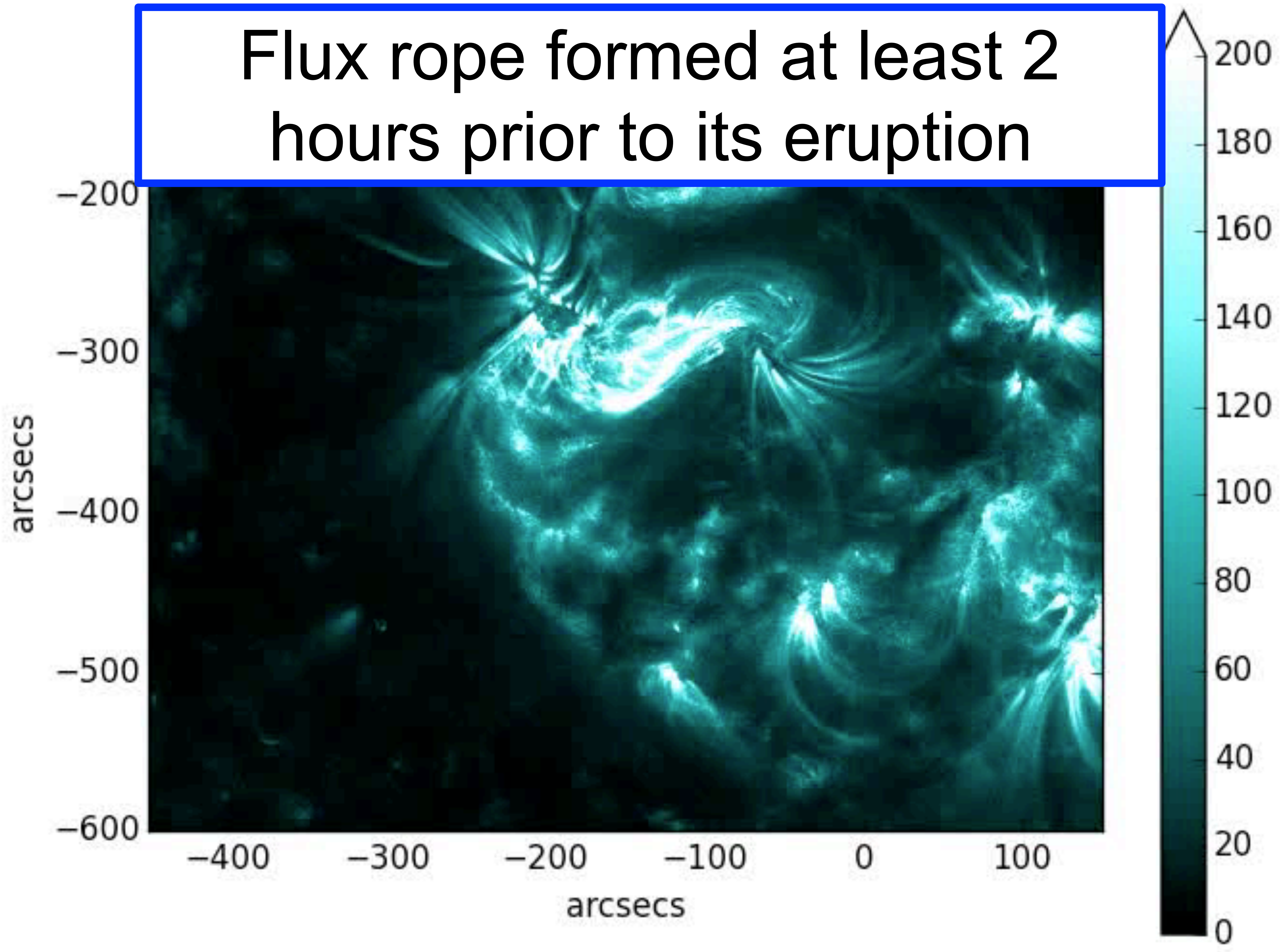
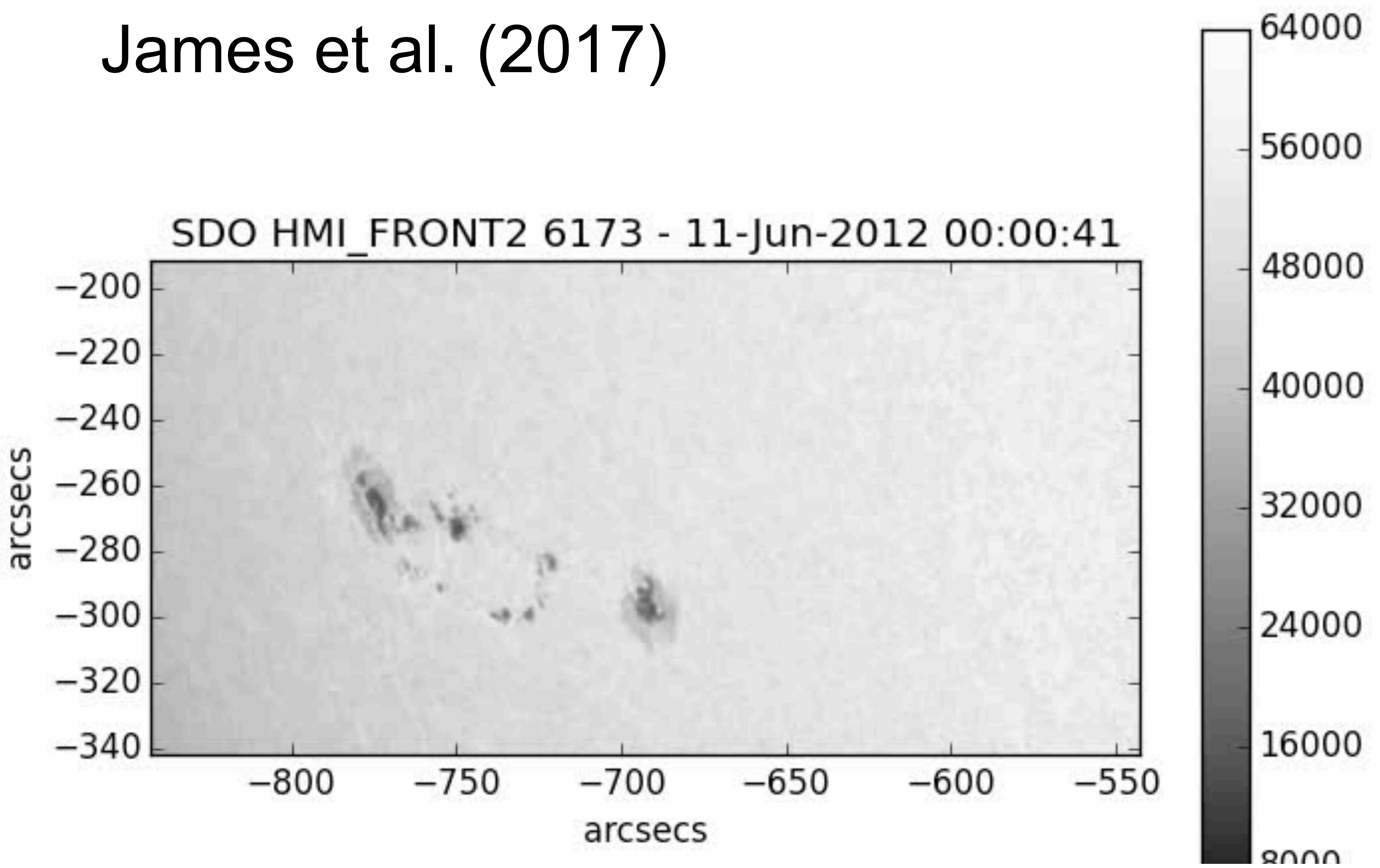
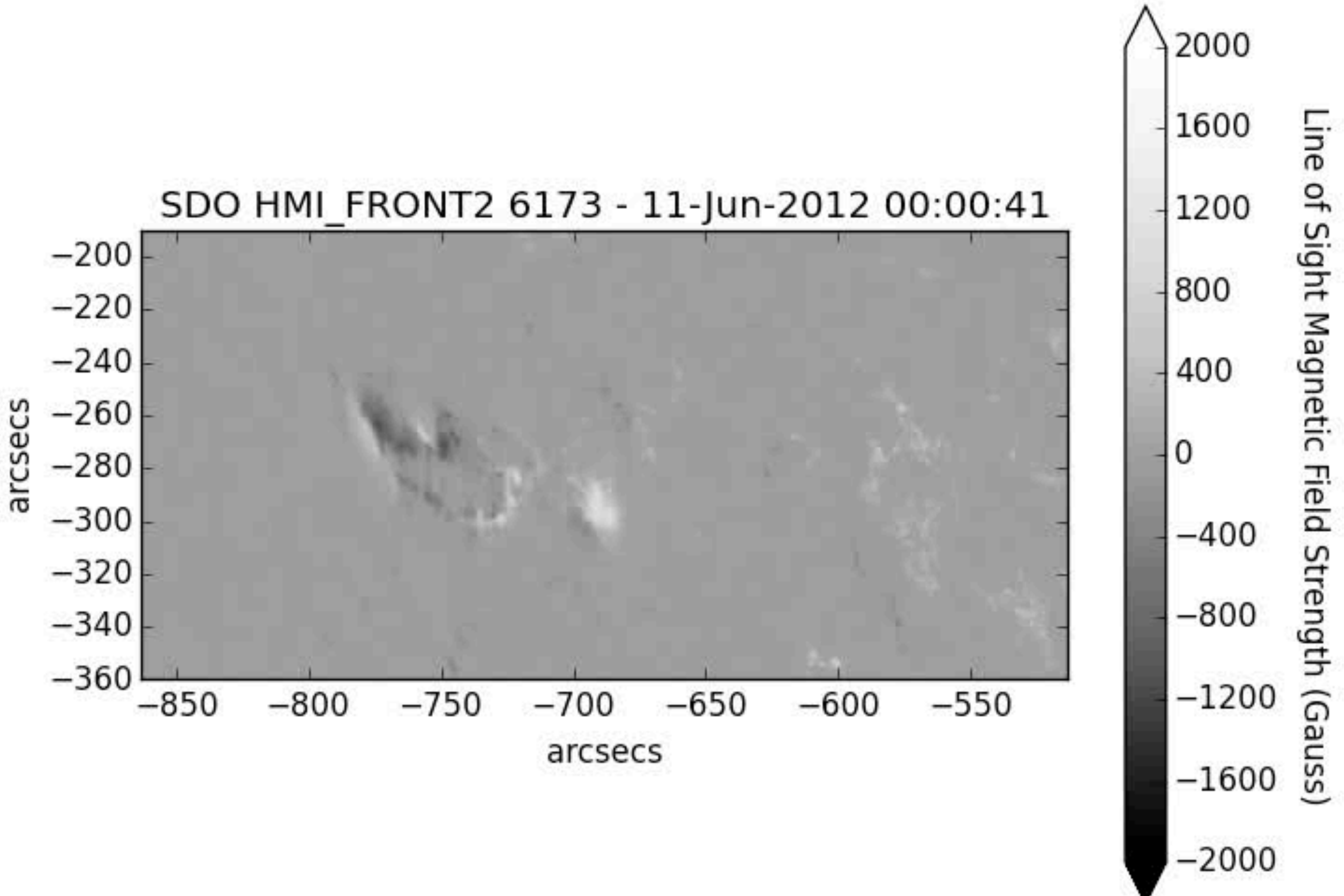
Flux rope formed at least 2 hours prior to its eruption



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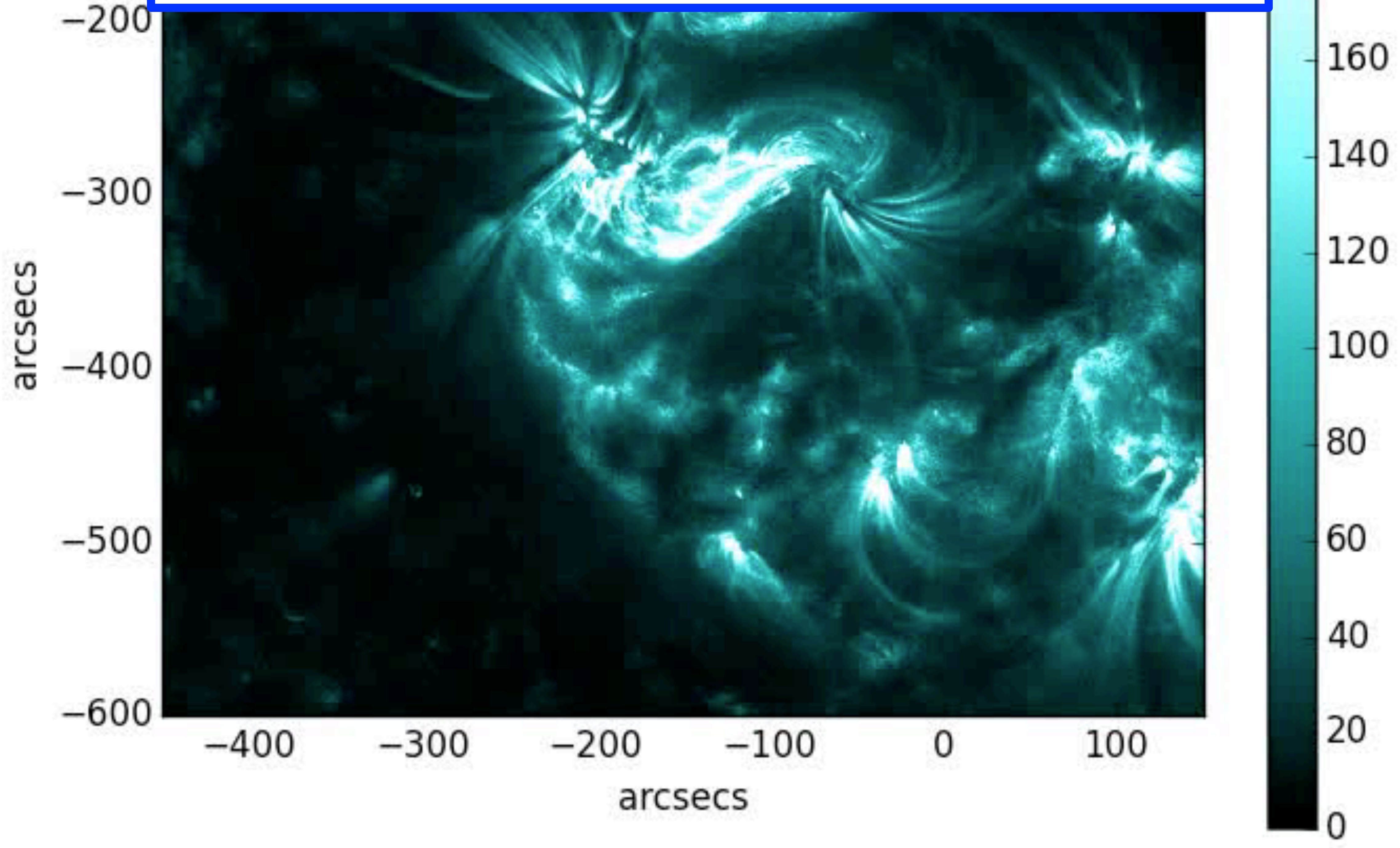


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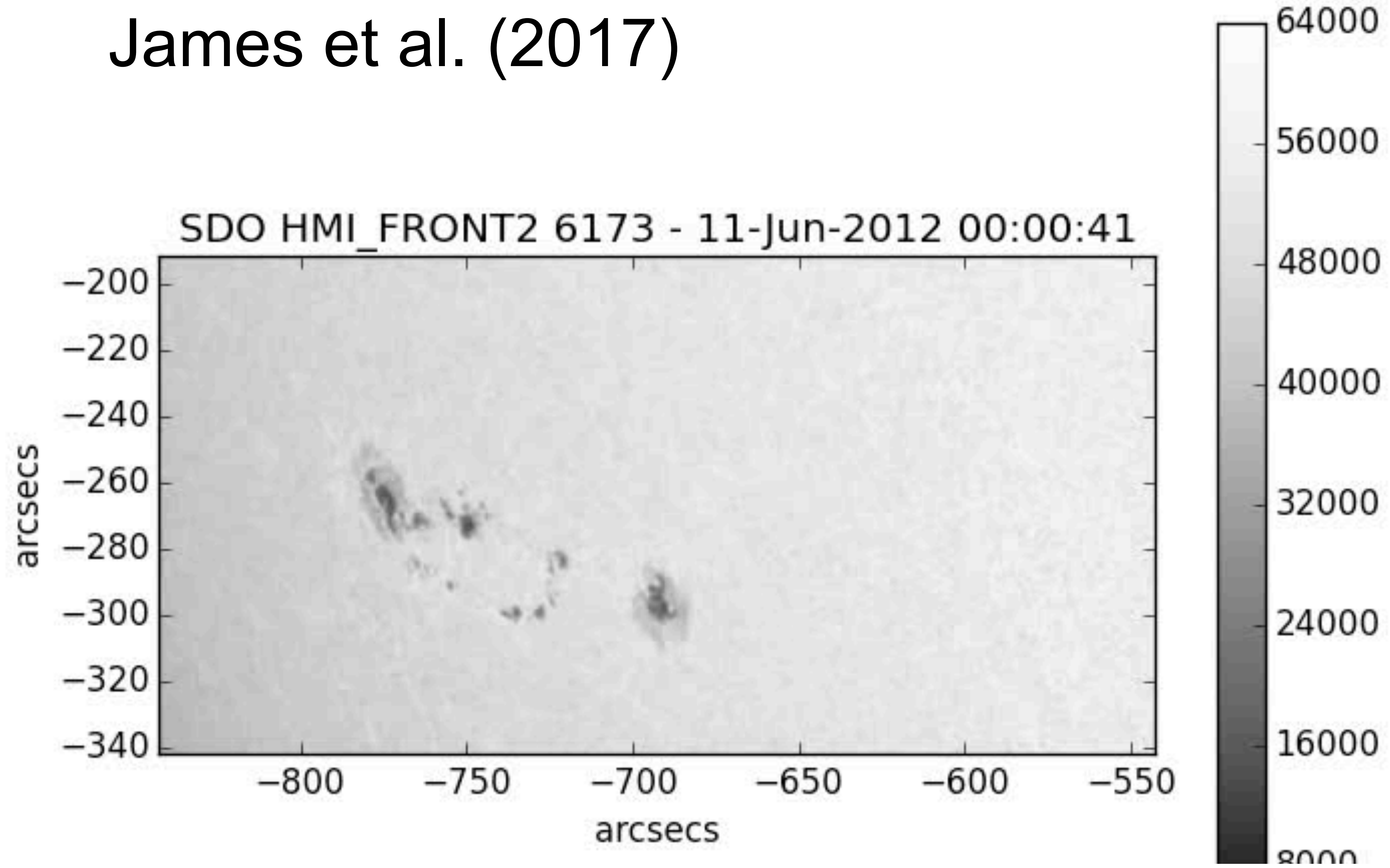


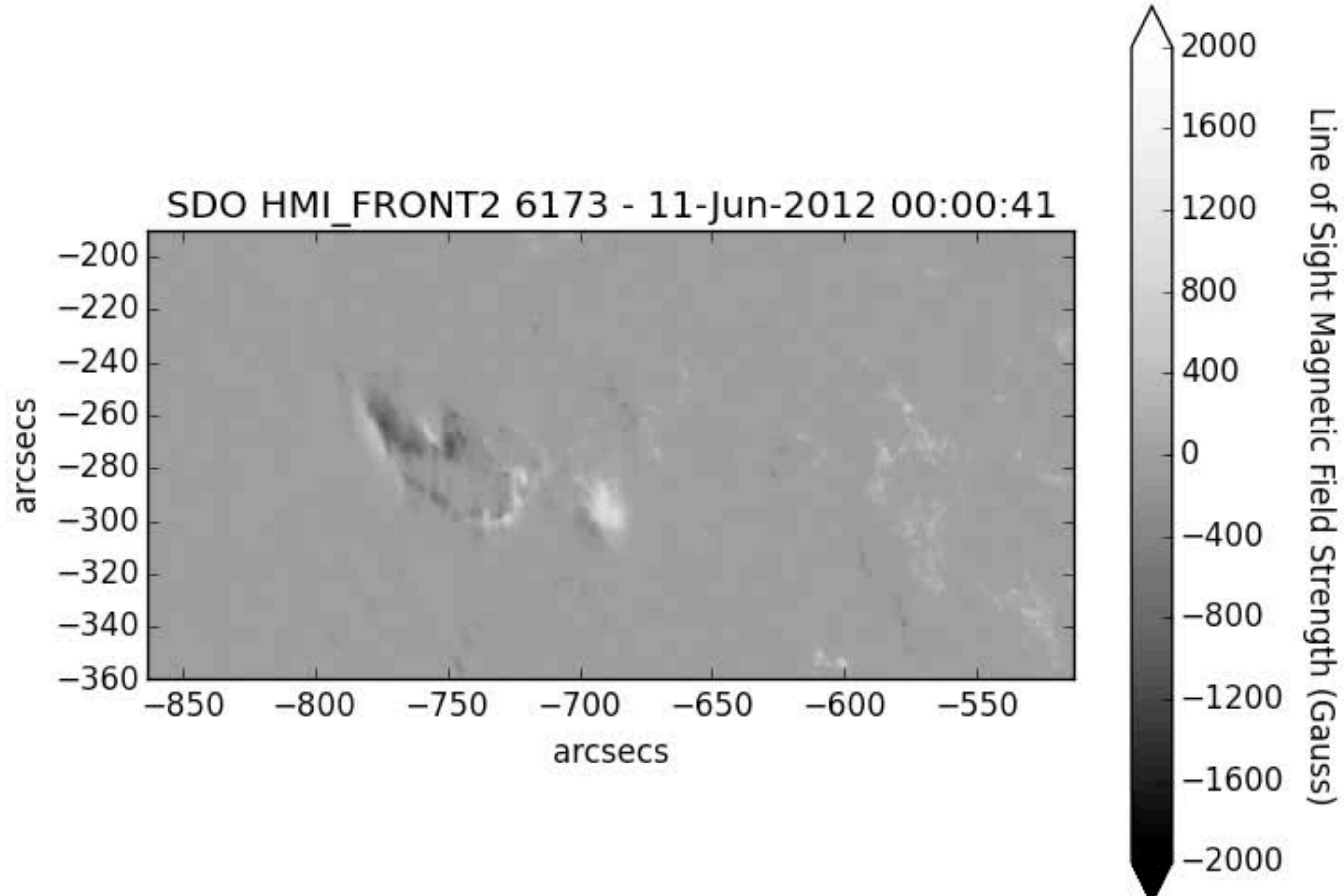

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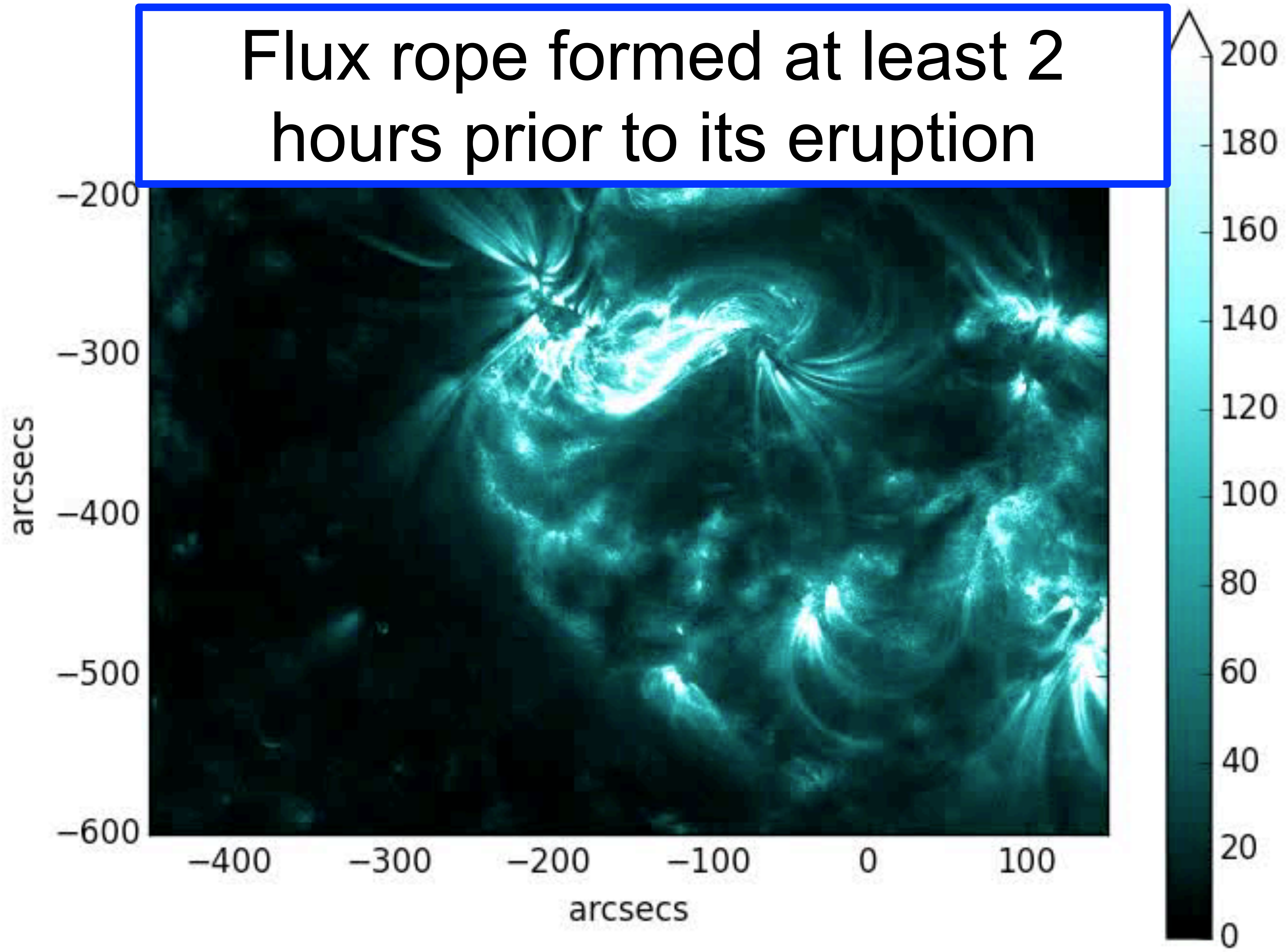


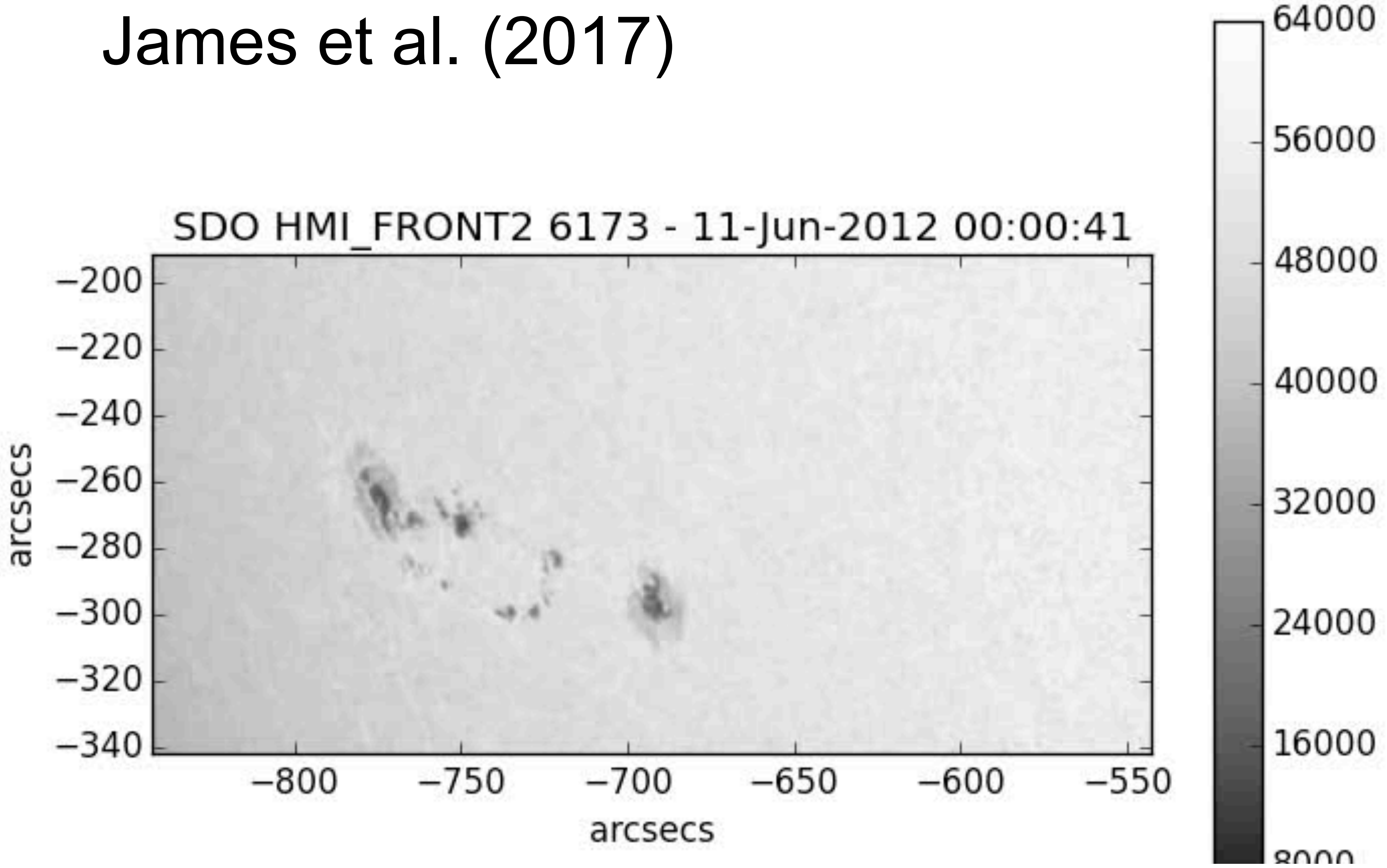


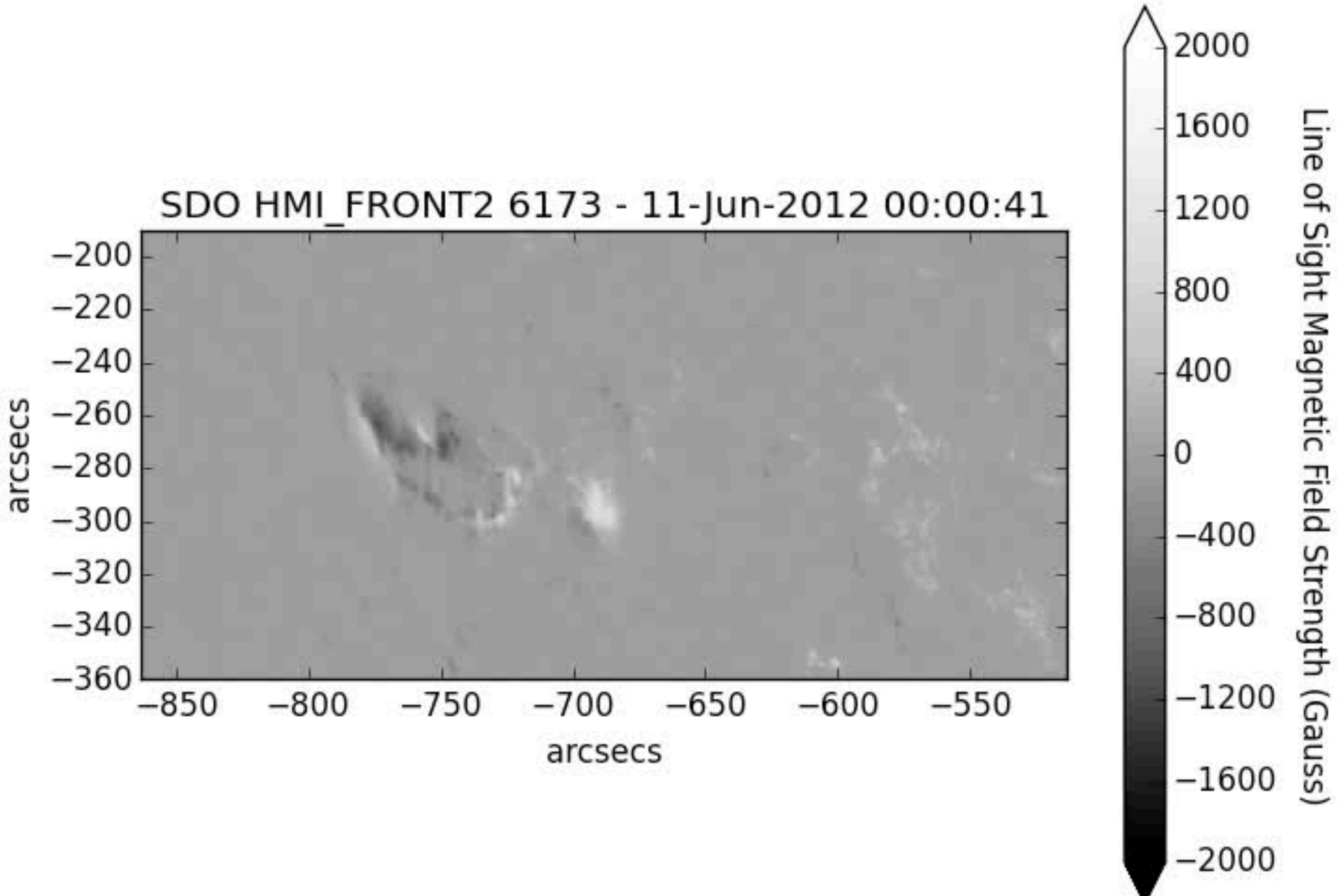

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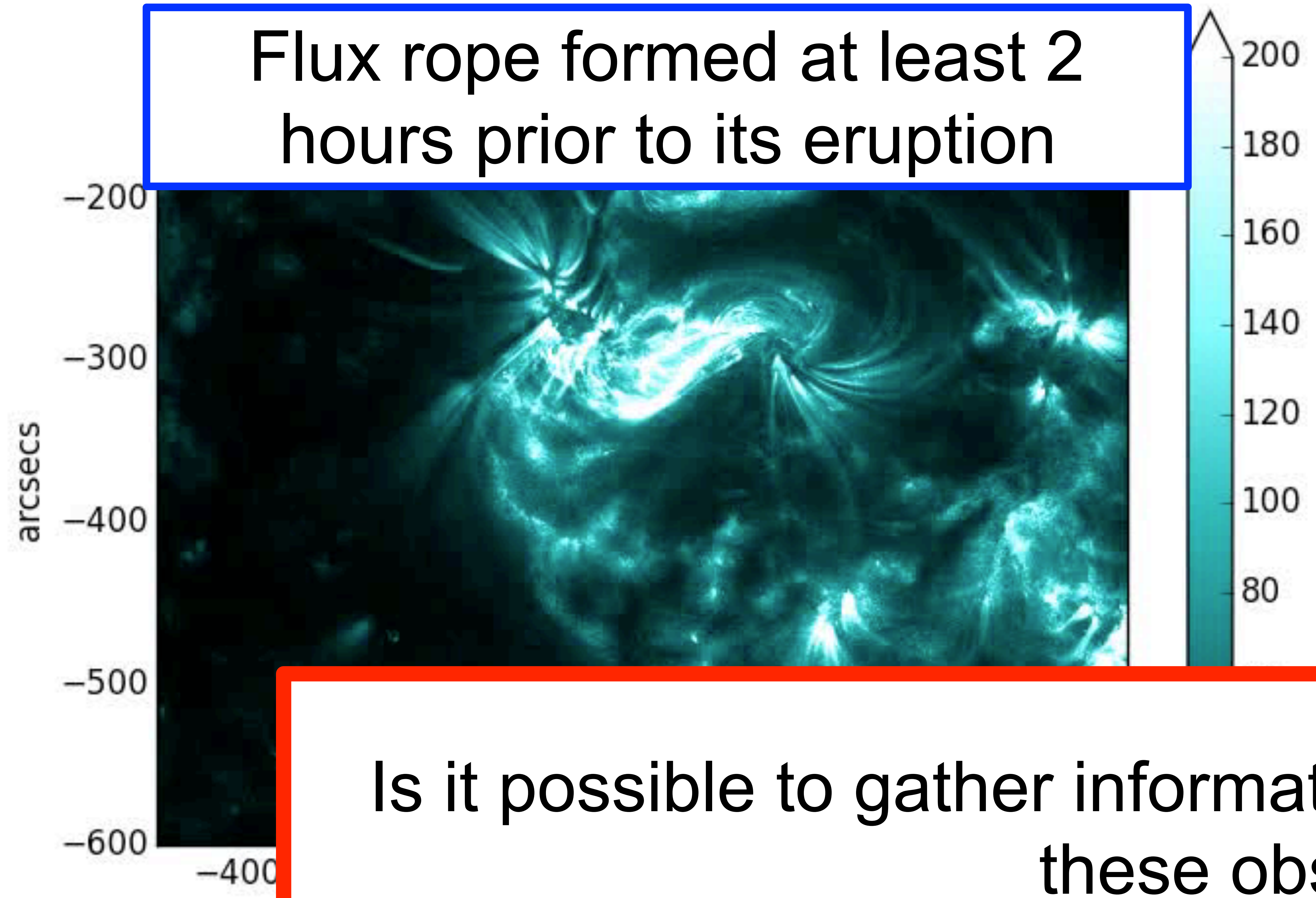
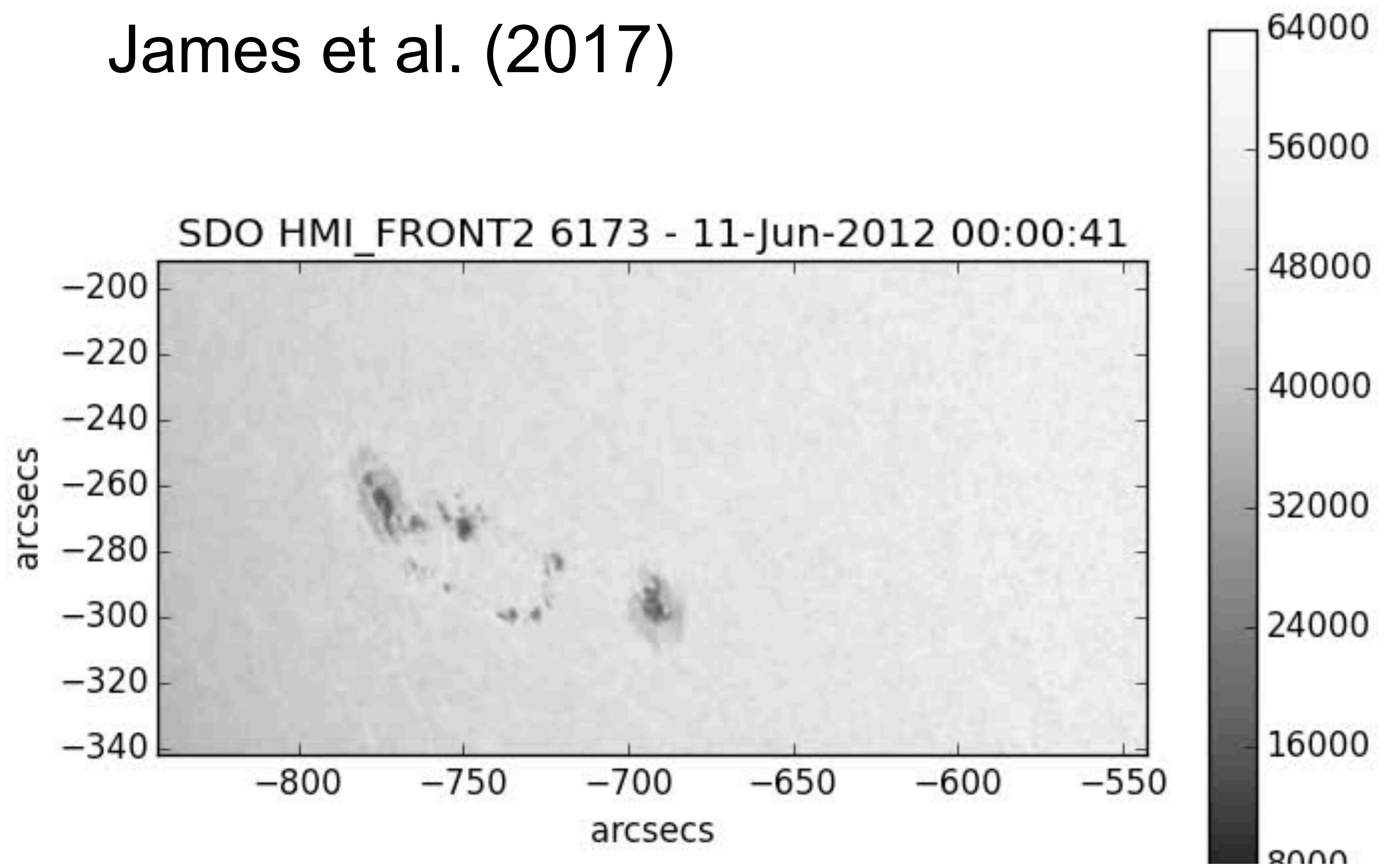
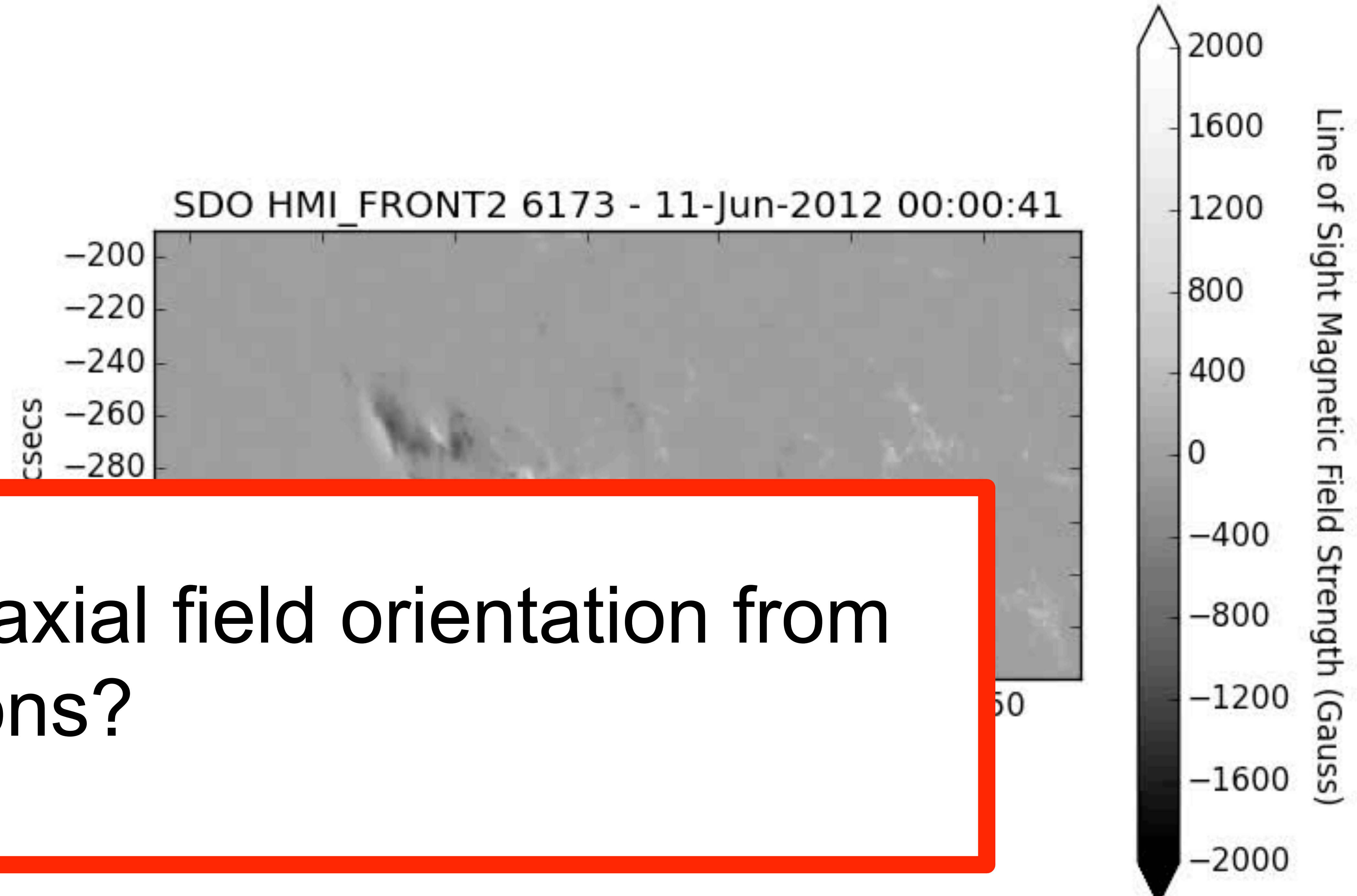
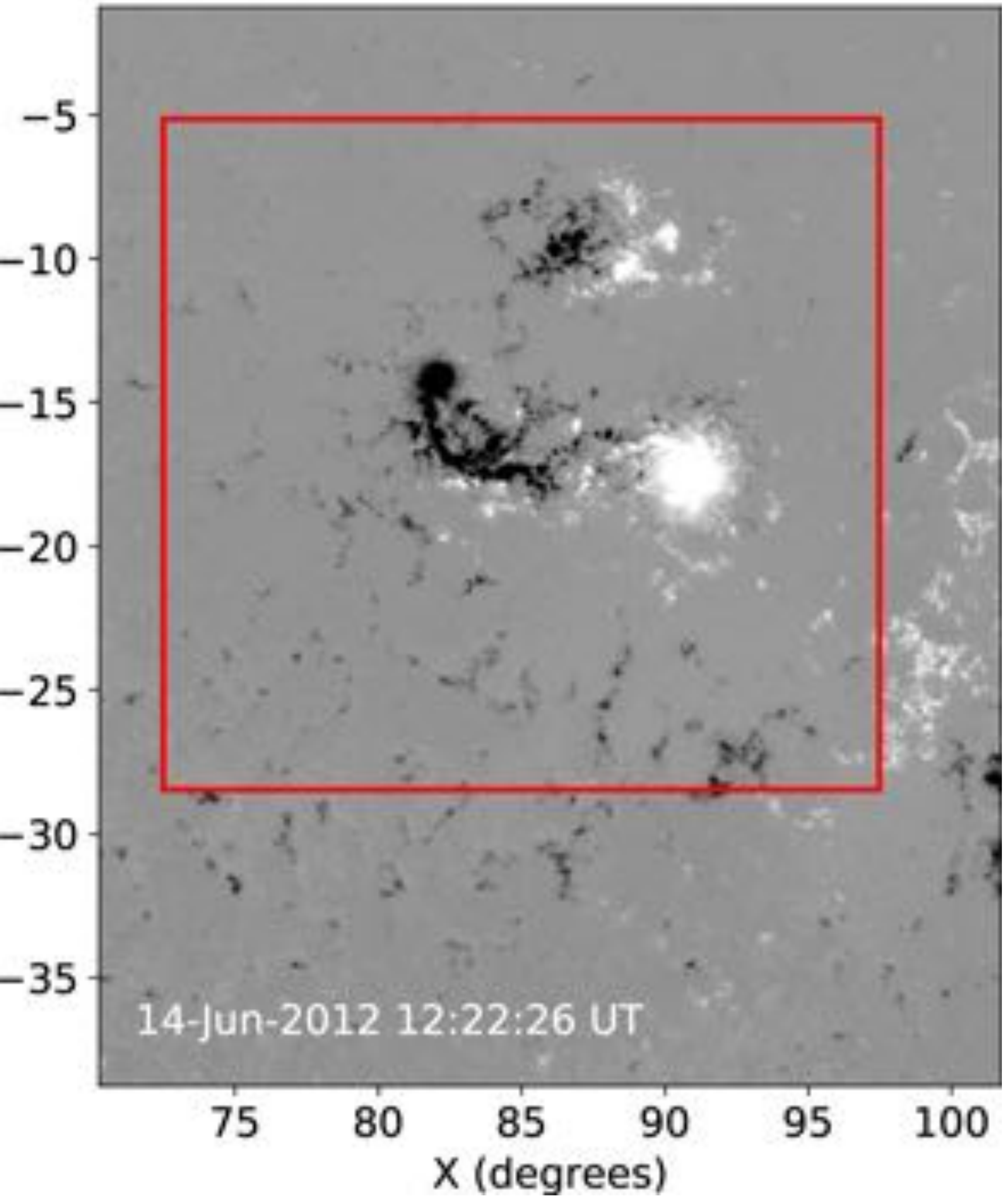


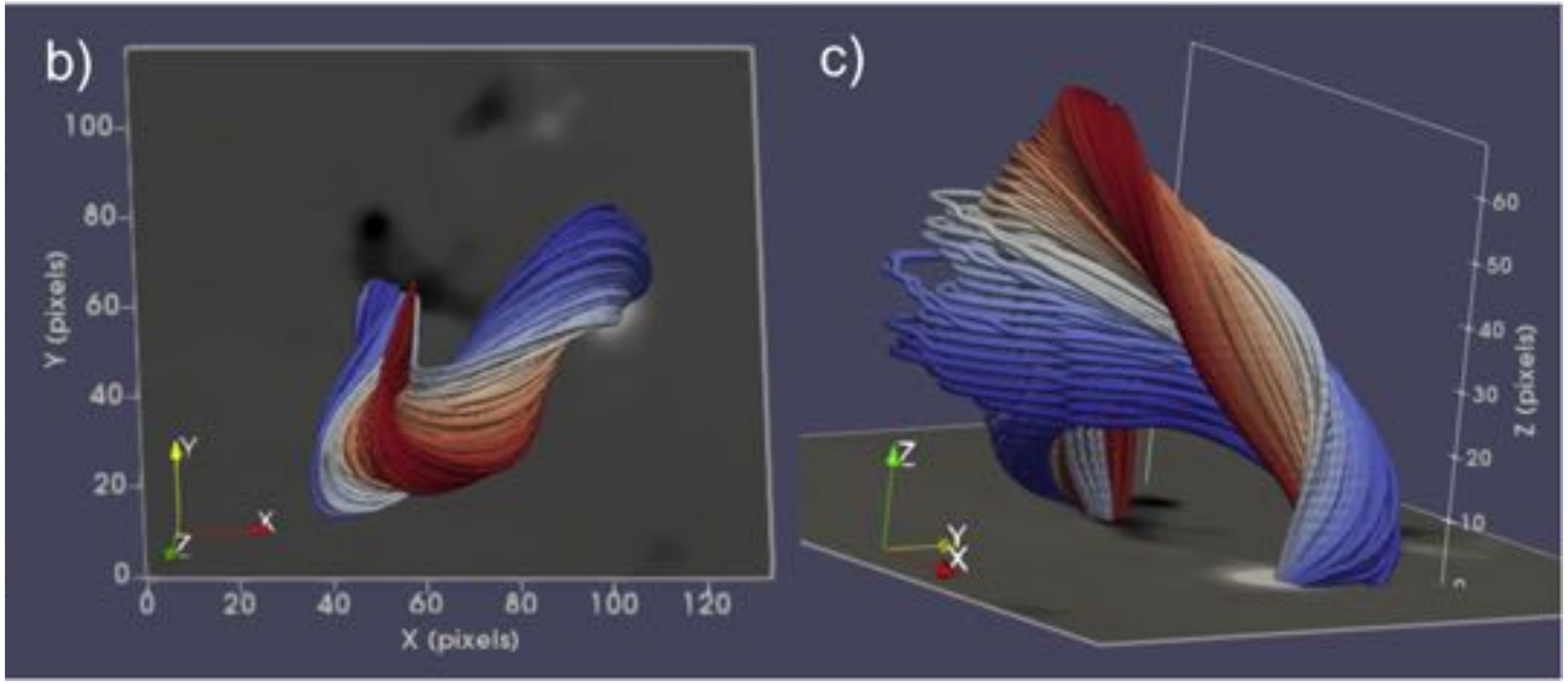




Is it possible to gather information on axial field orientation from these observations?

# Flux rope formation: coronal reconnection




- The flux rope extends high in the corona, with its highest point reaching ≈ 150 Mm (≈ 0.2 $R_S$) above the photosphere
- The flux rope contains $4 \times 10^{20}$ Mx of magnetic flux (≈3% of that in AR)

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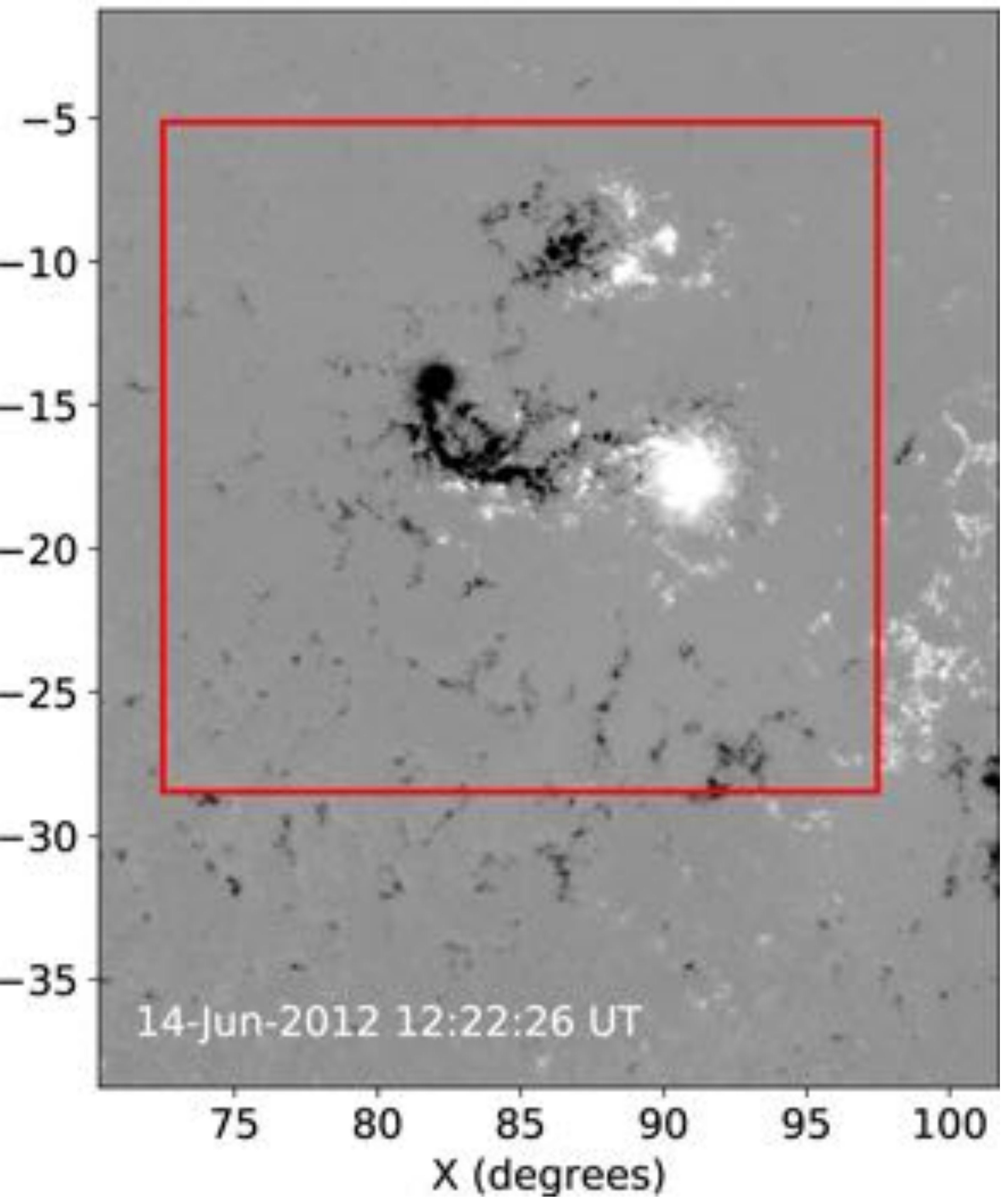
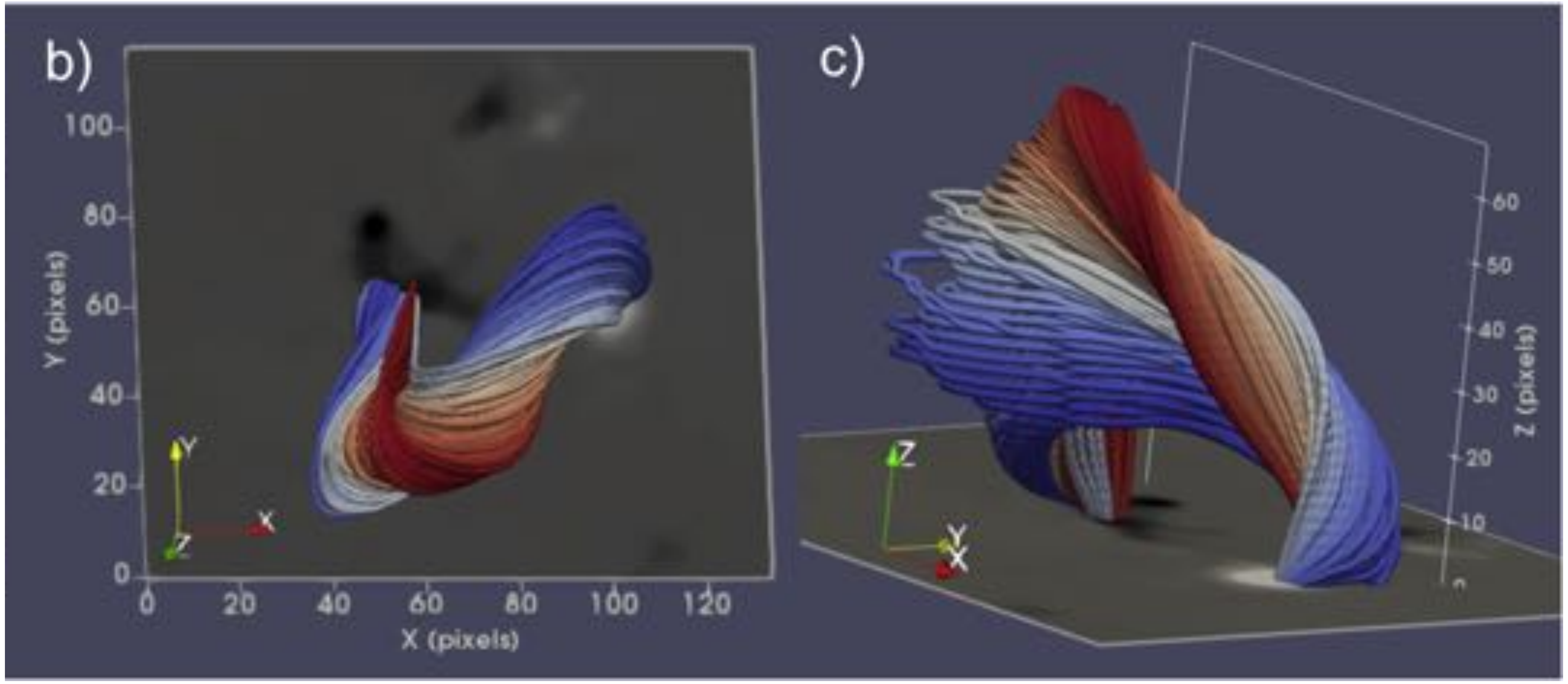
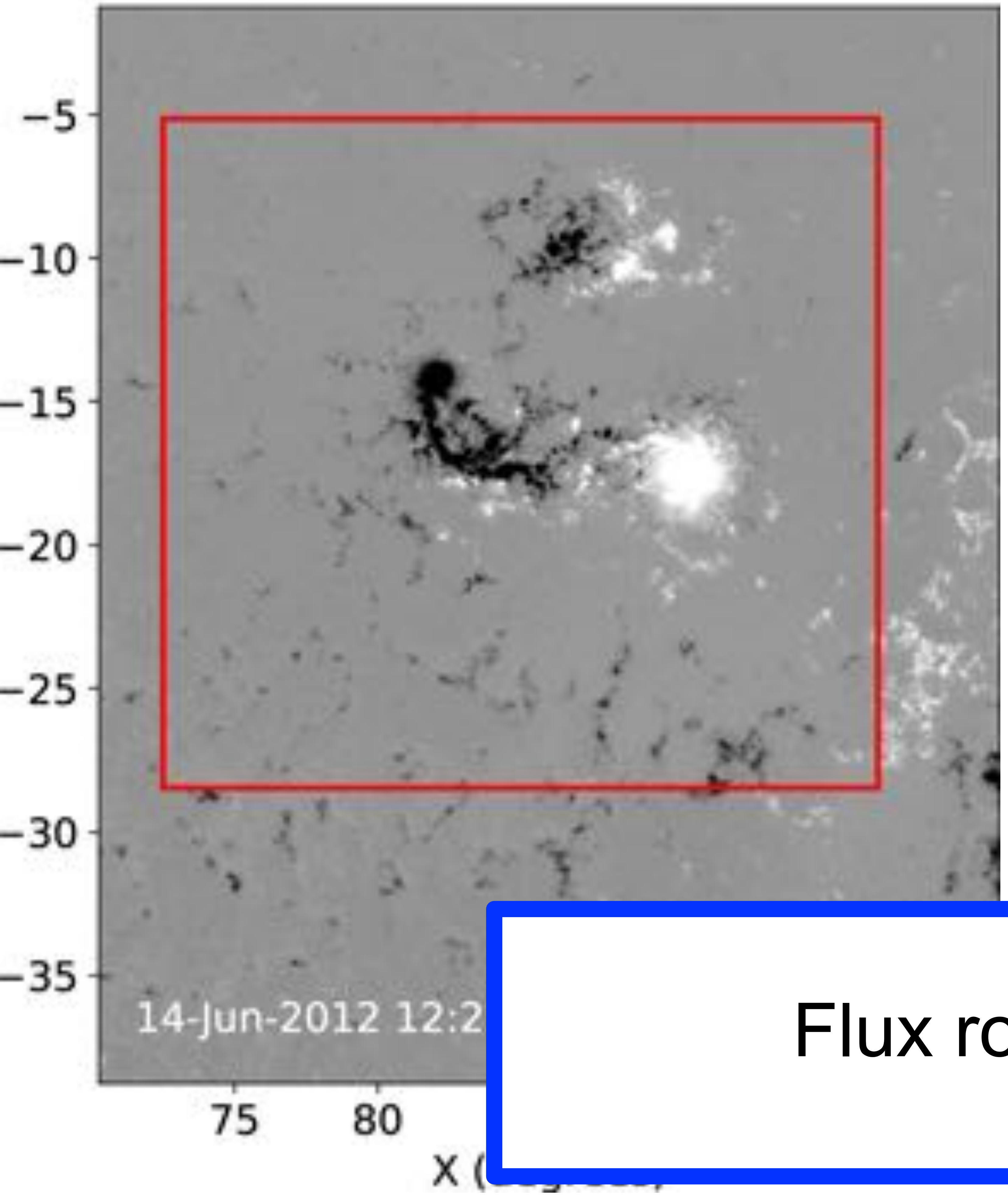


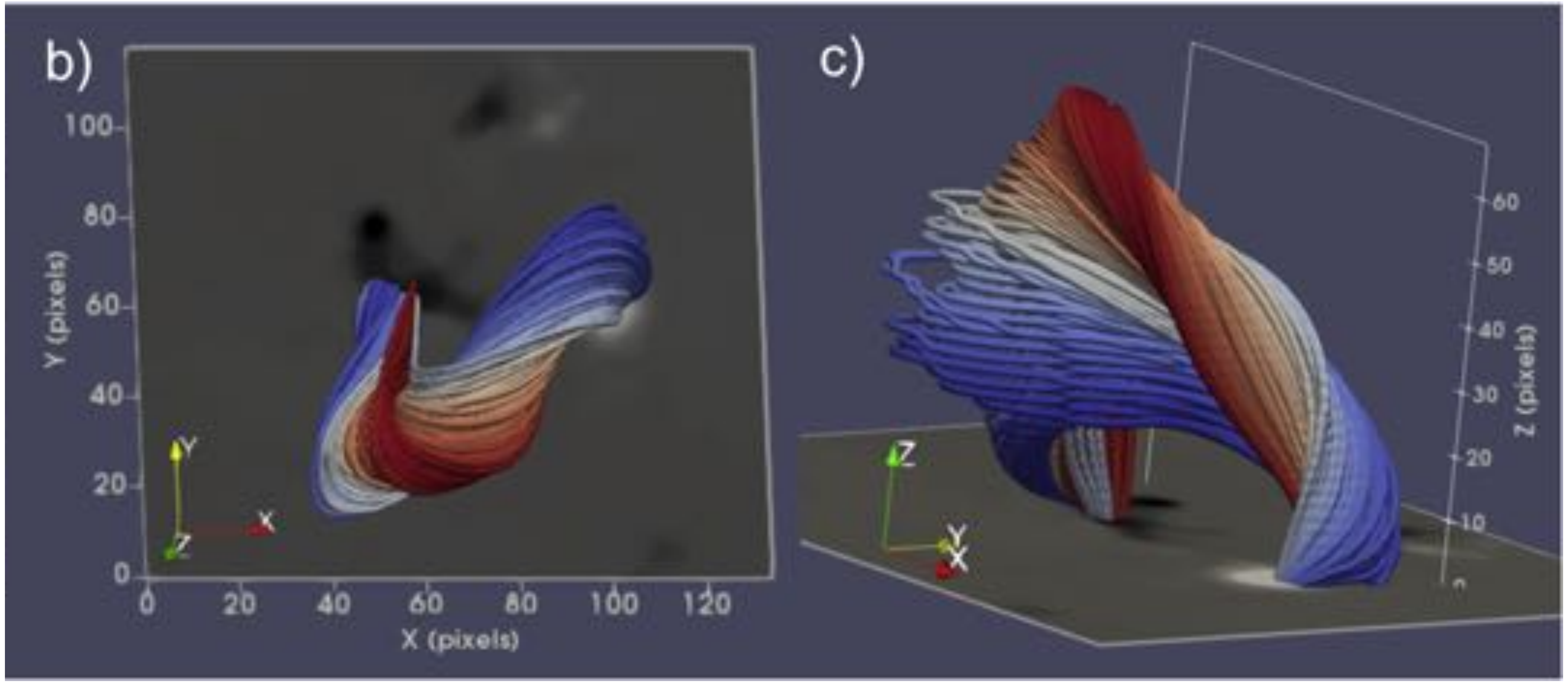




- The flux rope extends high in the corona, with its highest point reaching ≈ 150 Mm (≈ 0.2 $R_S$) above the photosphere
- The flux rope contains $4 \times 10^{20}$ Mx of magnetic flux (≈3% of that in AR)

# Flux rope formation: coronal reconnection

James et al. (2018)

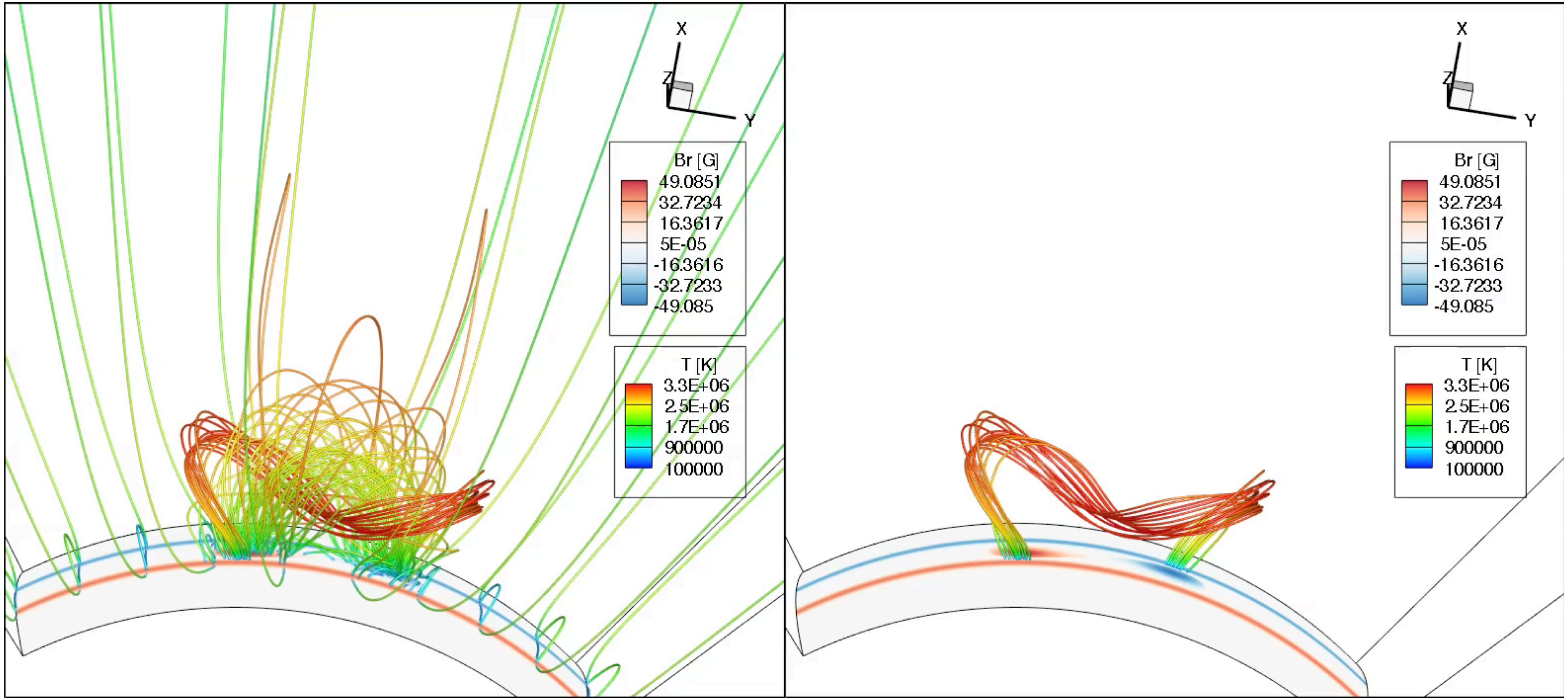


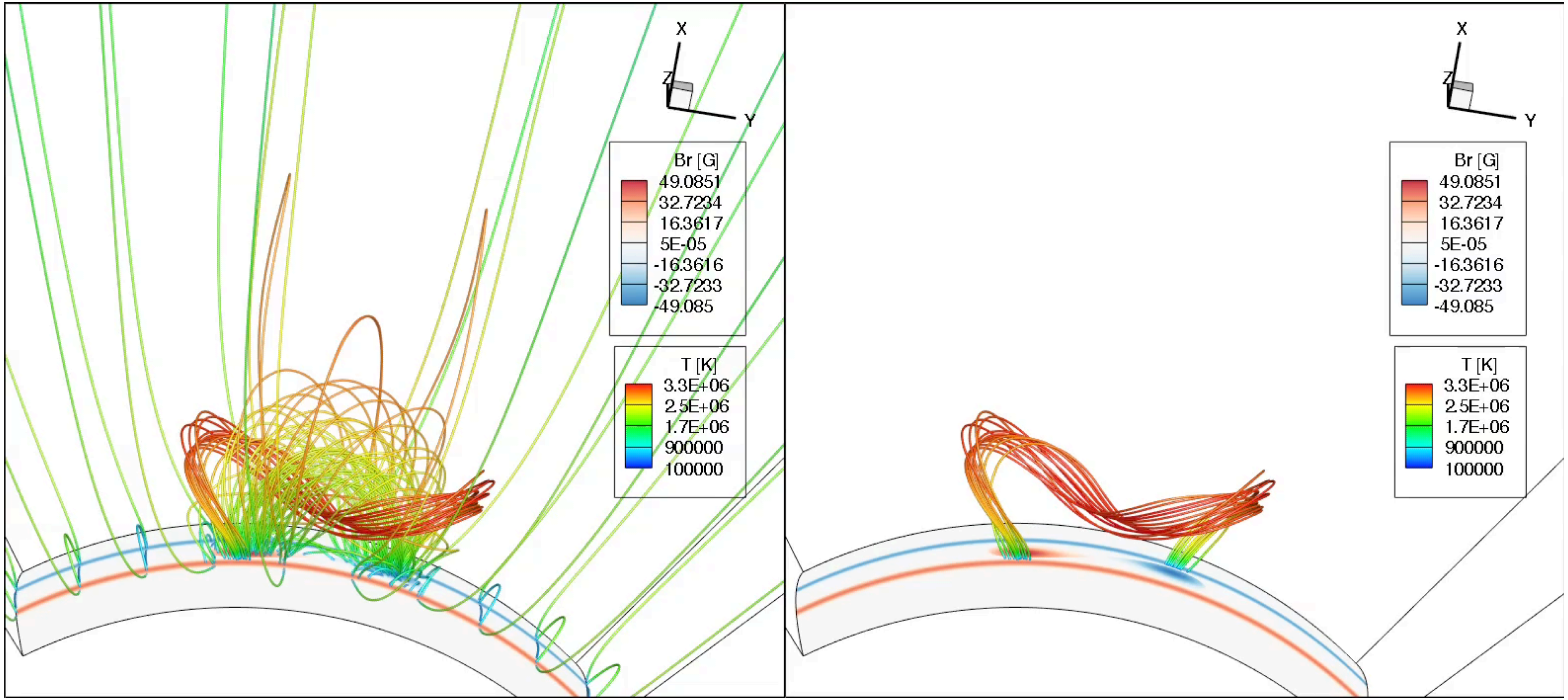

aching ≈

Flux rope axis runs along the polarity inversion line

in AR)

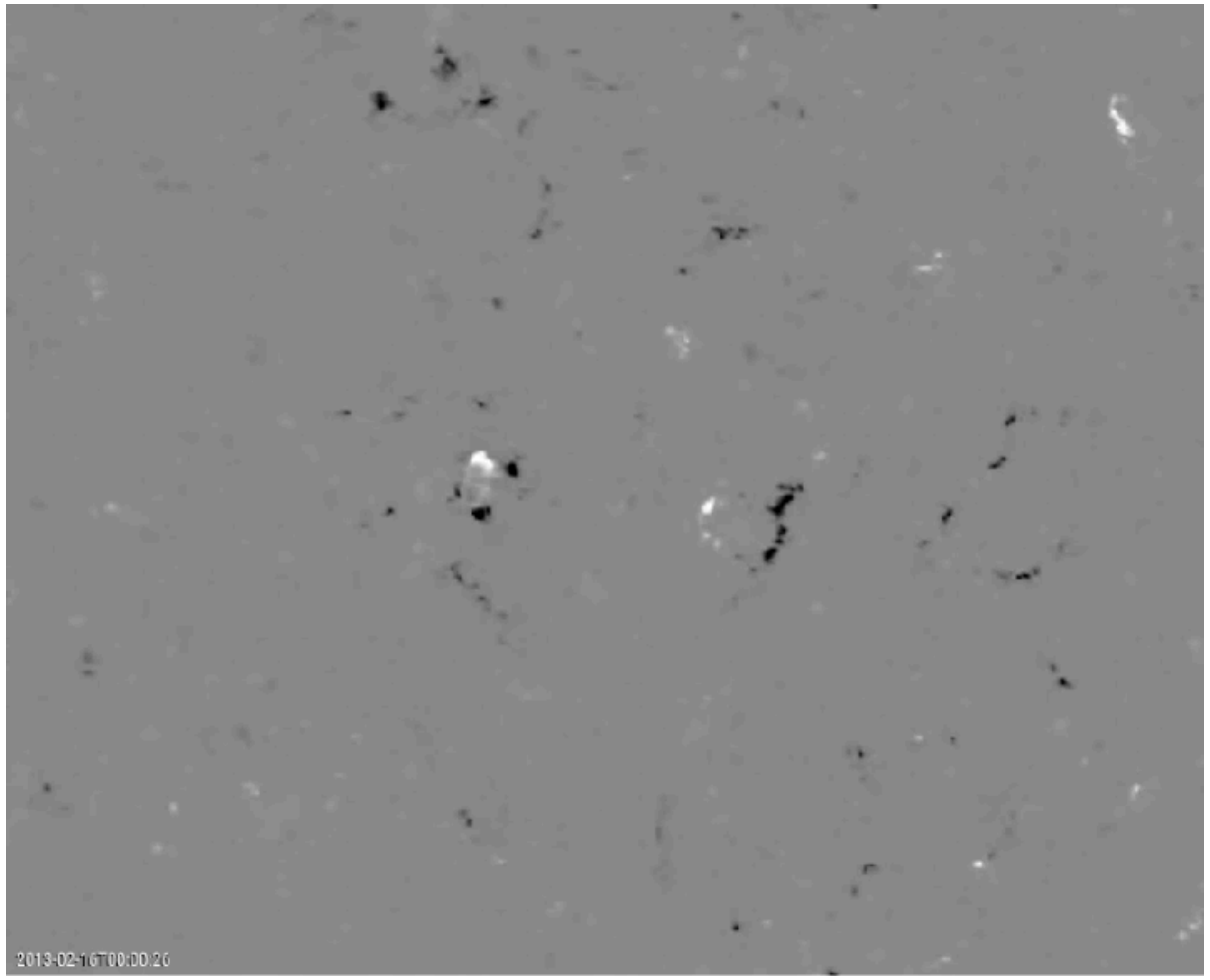



Movie associated with figure 8 in Fan (2017)



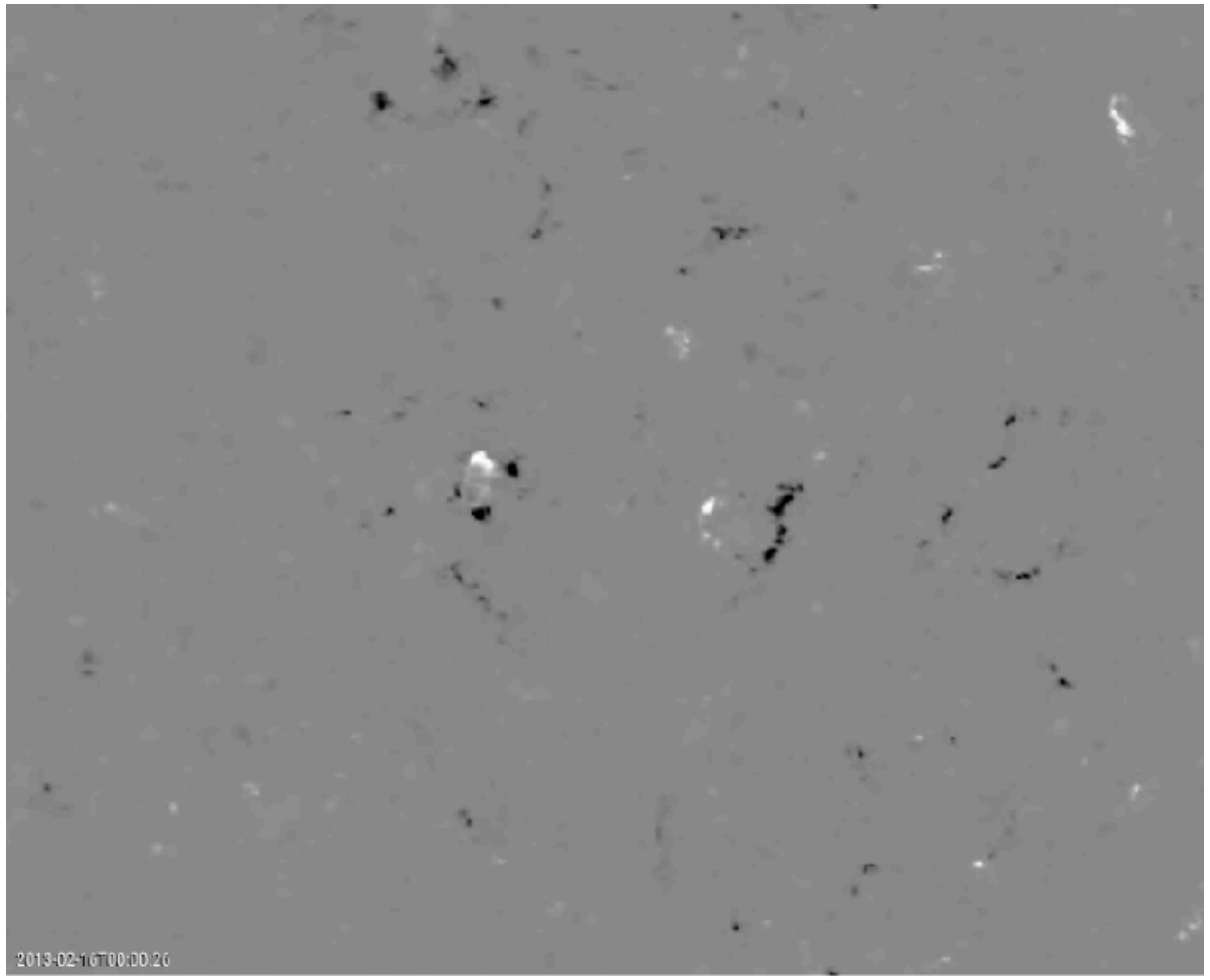

Movie associated with figure 8 in Fan (2017)

# Case study: AR 11675



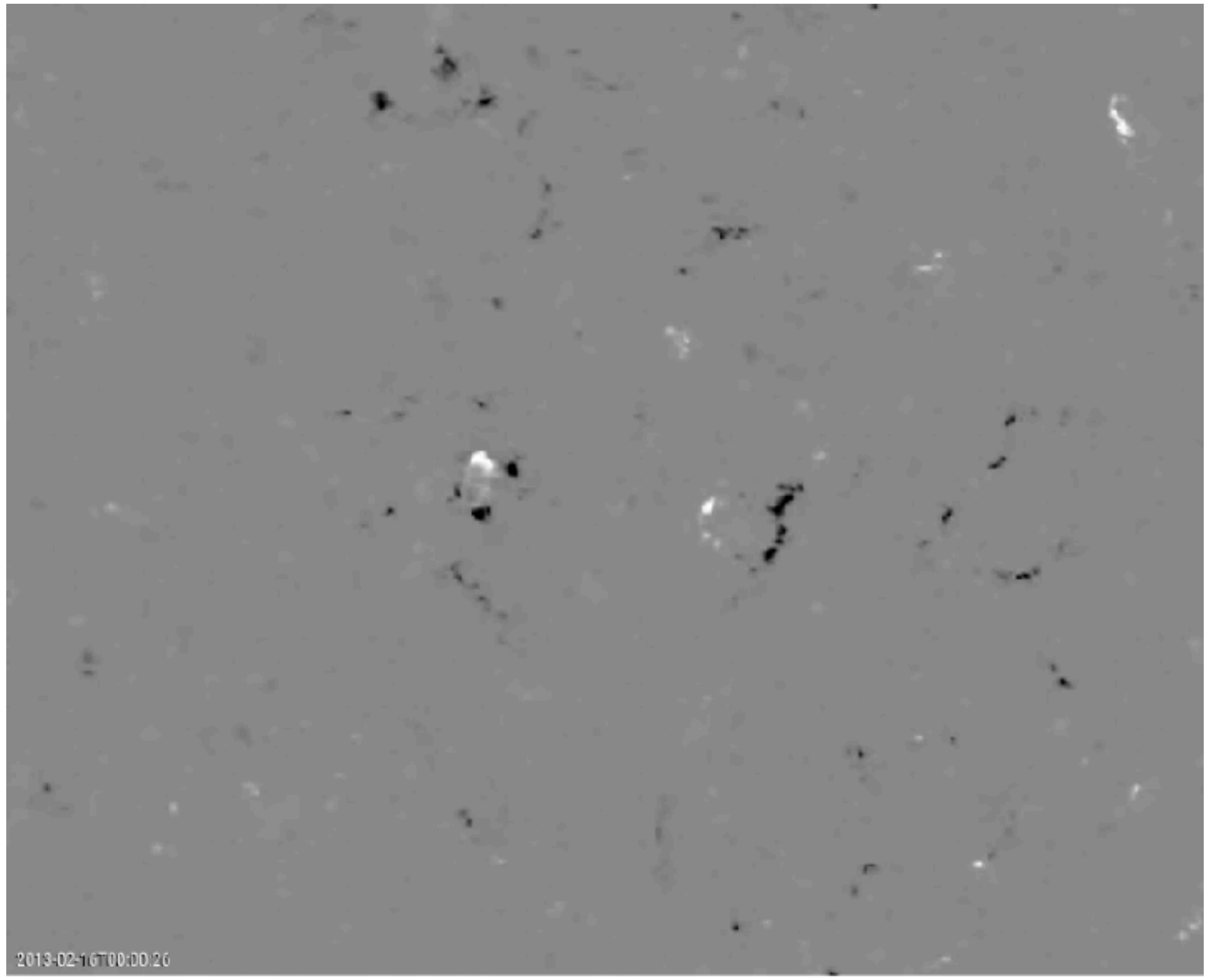

Green et al. (2017)

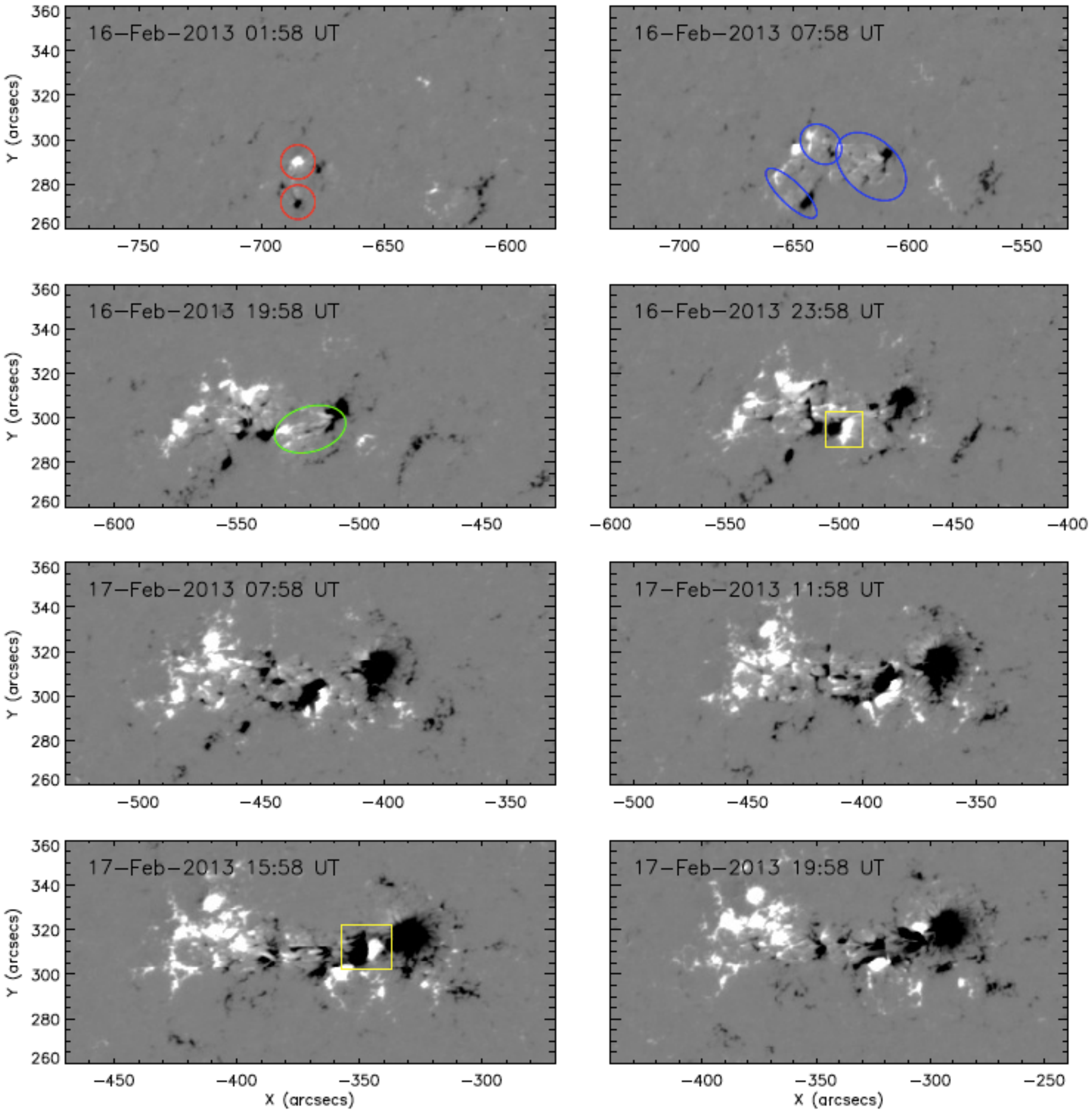
# Case study: AR 11675




Green et al. (2017)

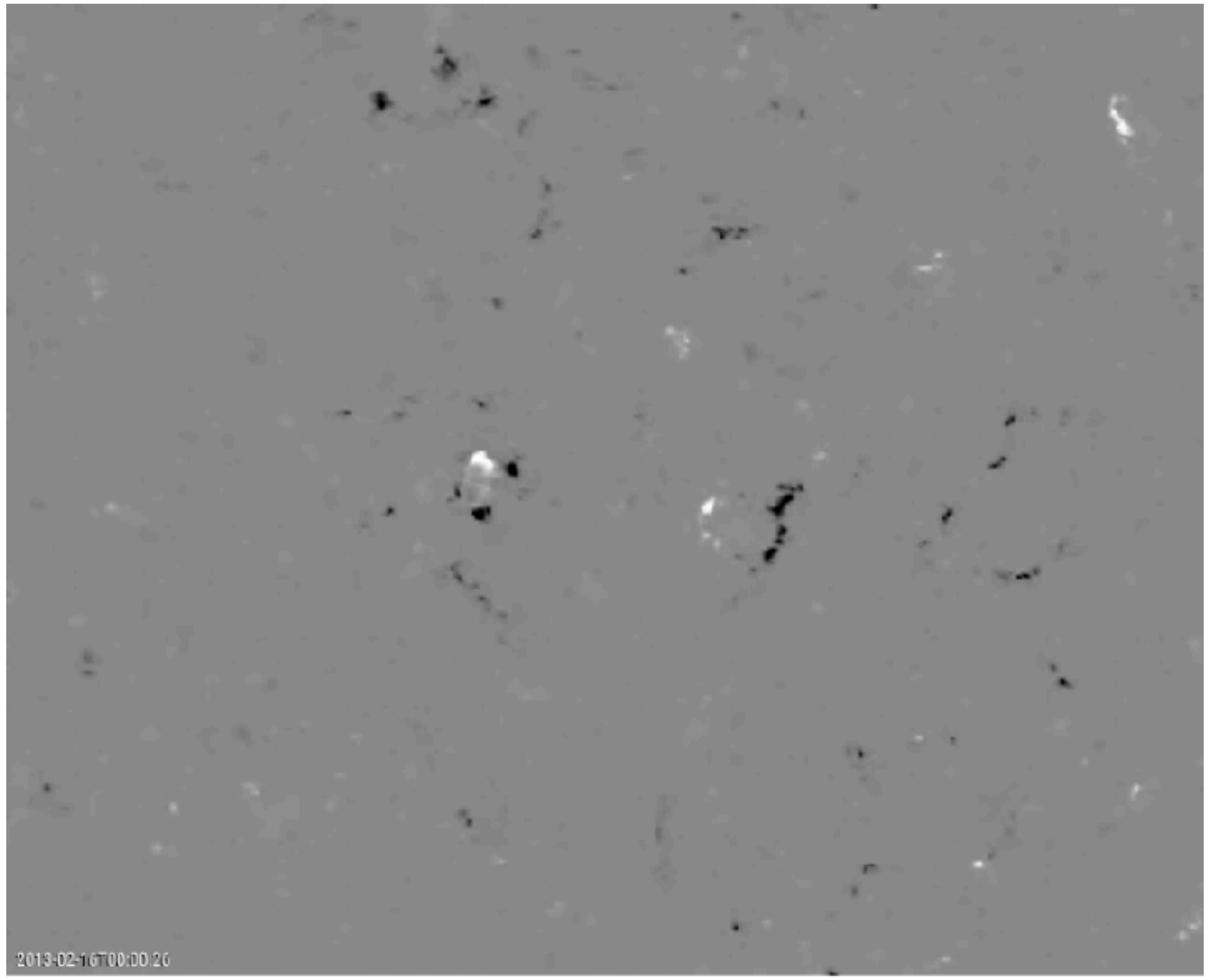
# Case study: AR 11675

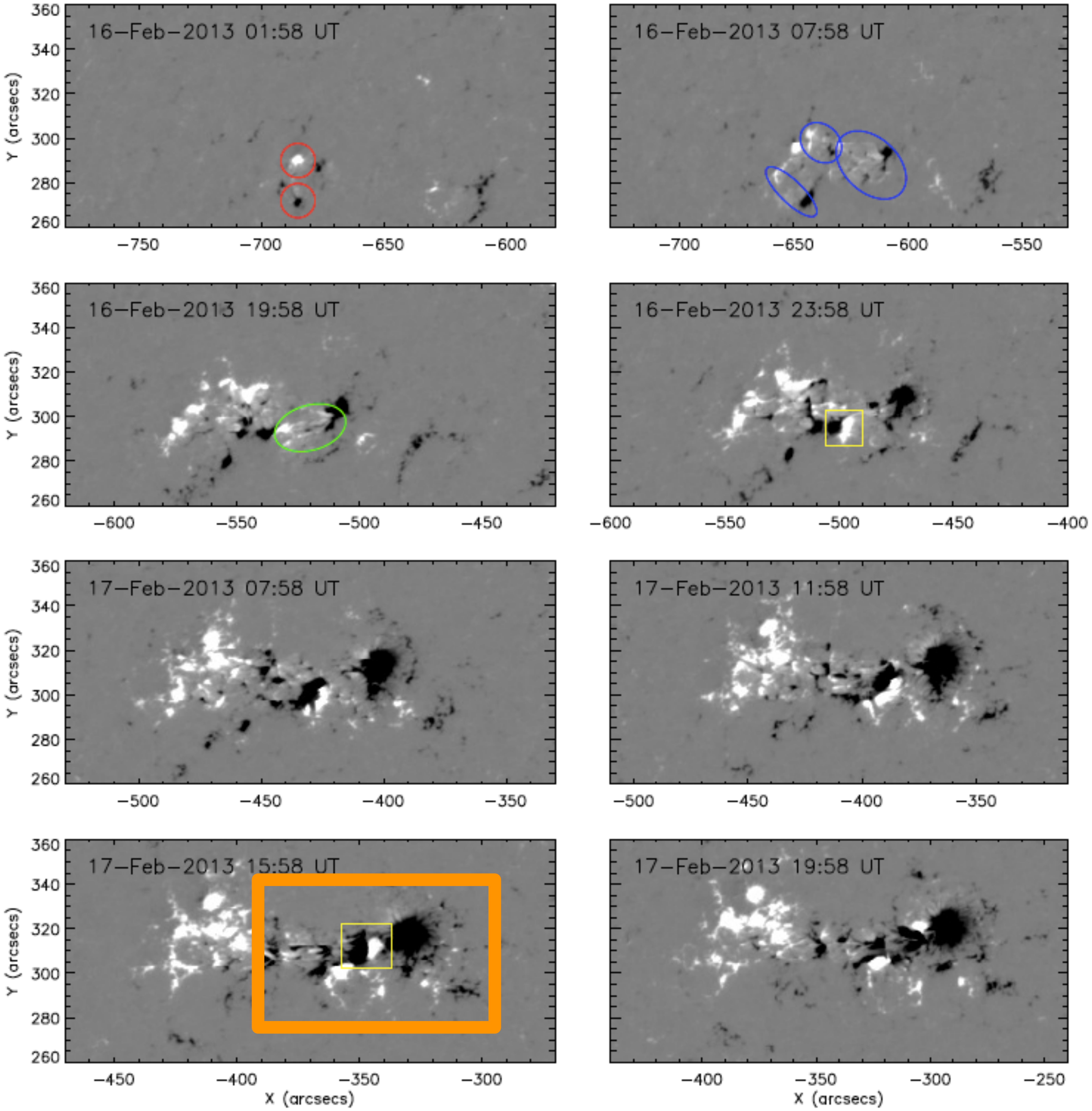


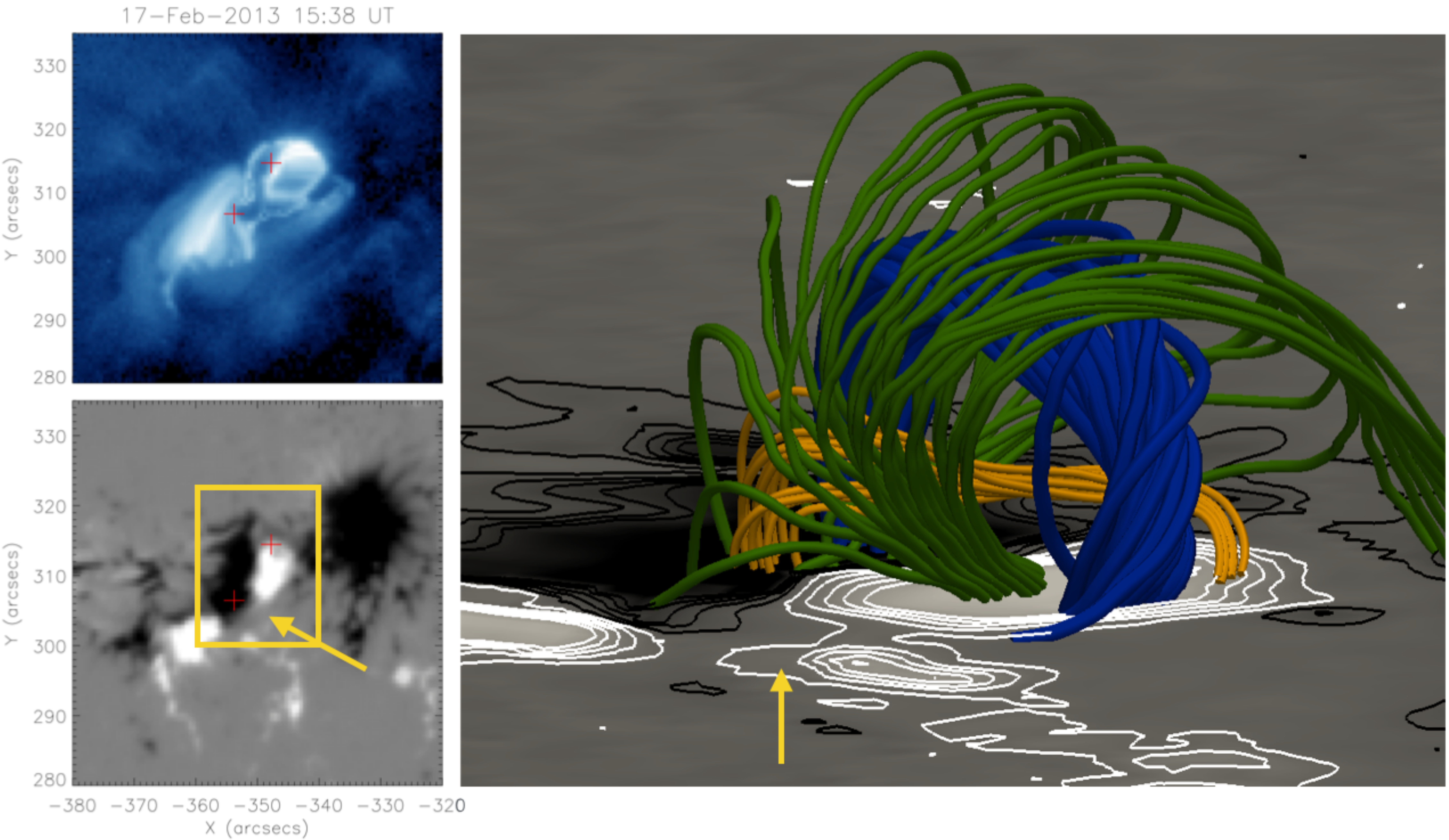

Green et al. (2017)

# Case study: AR 11675




Green et al. (2017)



17−Feb−2013 15:38 UT
330
320
310
300
290
280
Y (arcsecs)
−380 −370 −360 −350 −340 −330 −320
X (arcsecs)

# Using remote sensing to predict in situ

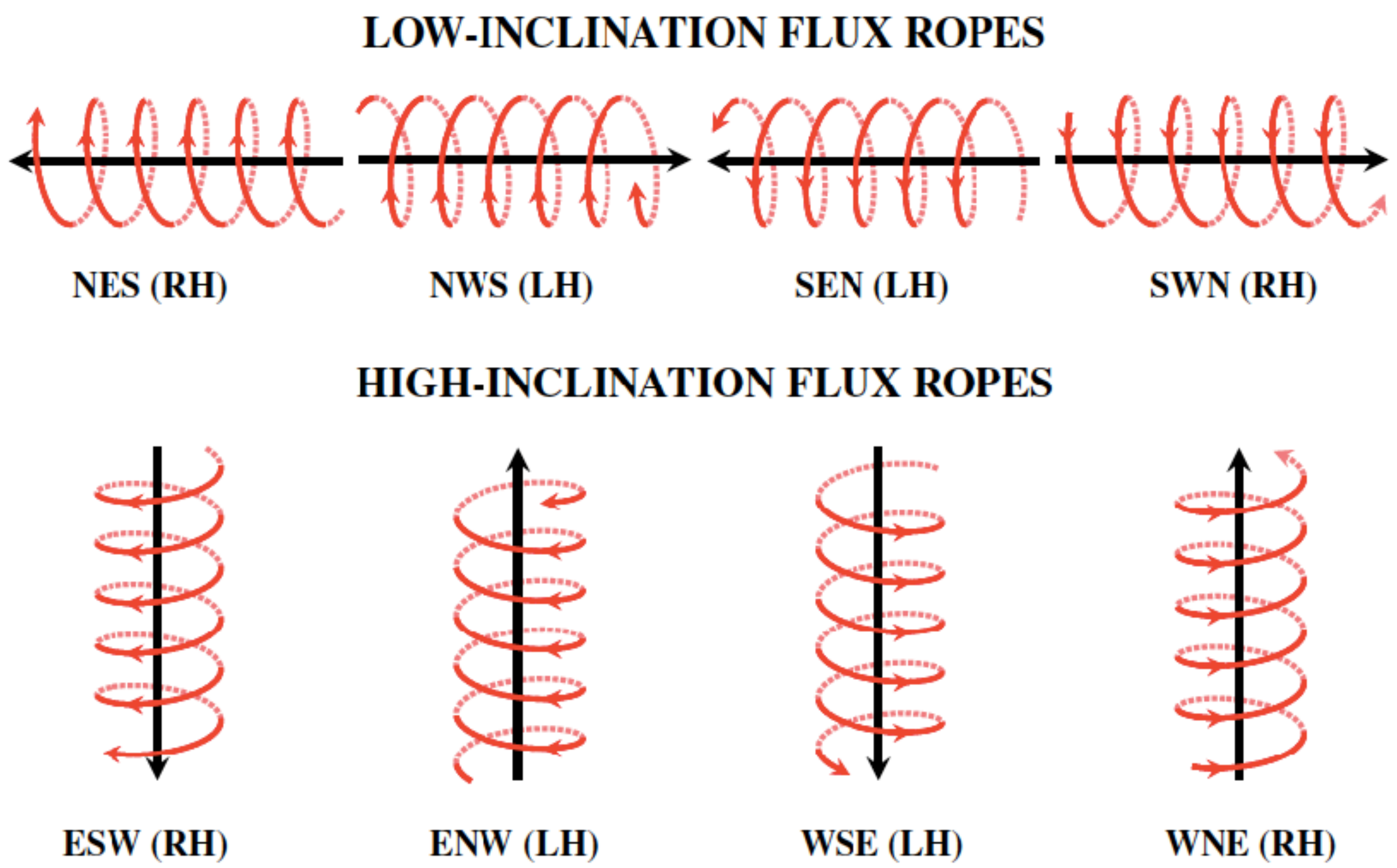



Figure 1 in Palmerio et al., 2018
(See earlier work by Bothmer & Schwenn, Mulligan et al.)

# Using remote sensing to predict in situ

**Mixed results!**

e.g. Palmerio et al., 2018

- 20% of the events have a match between the intrinsic and in situ flux rope types
- 55% match when intermediate cases (where the orientation at the Sun and/or in situ is close to 45°) are considered
- Difficulties in disentangling flux rope rotation from spacecraft crossing location
- You can be far from the axis & far from the nose even for Sun-centred eruptions

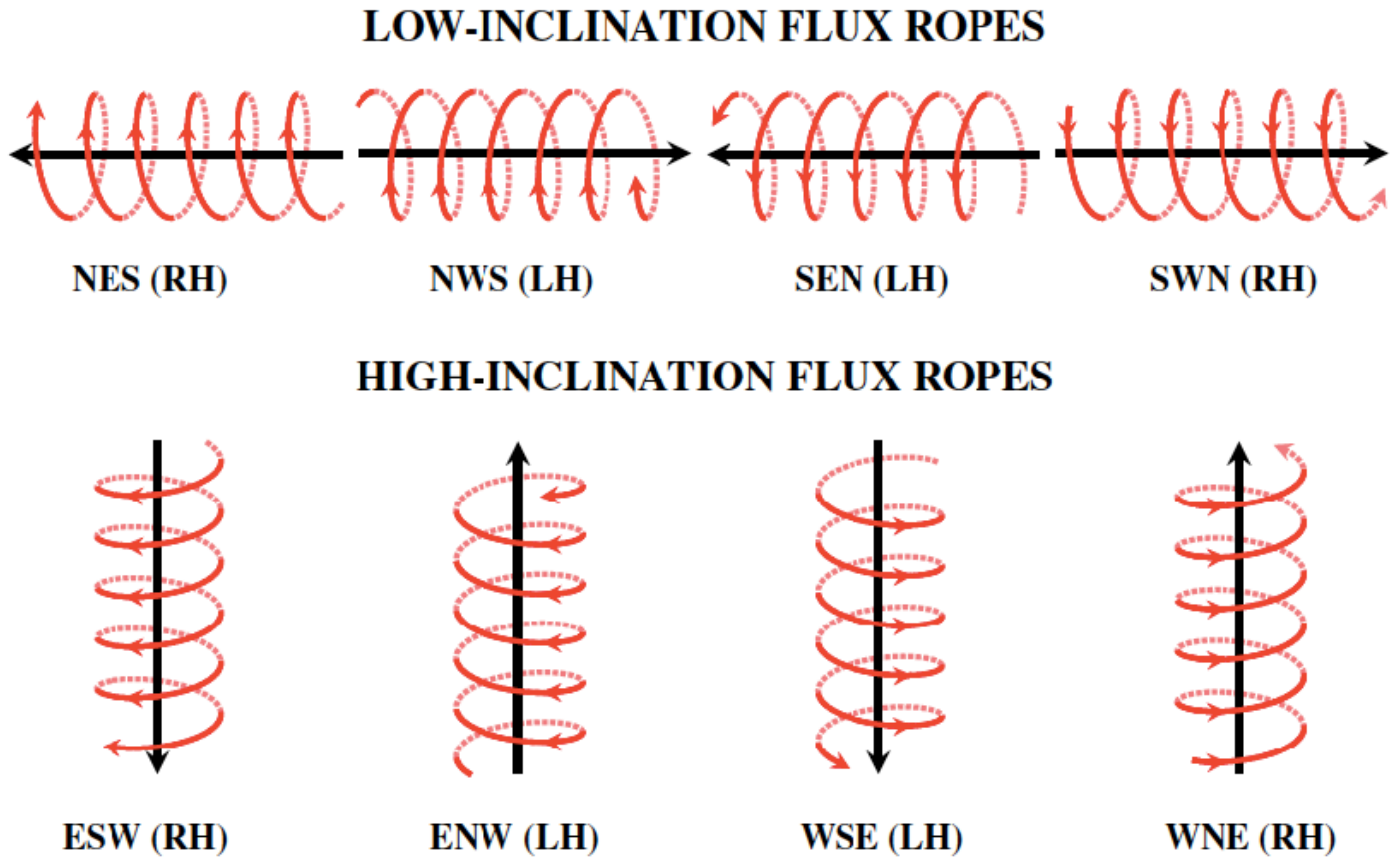



Figure 1 in Palmerio et al., 2018
(See earlier work by Bothmer & Schwenn, Mulligan et al.)

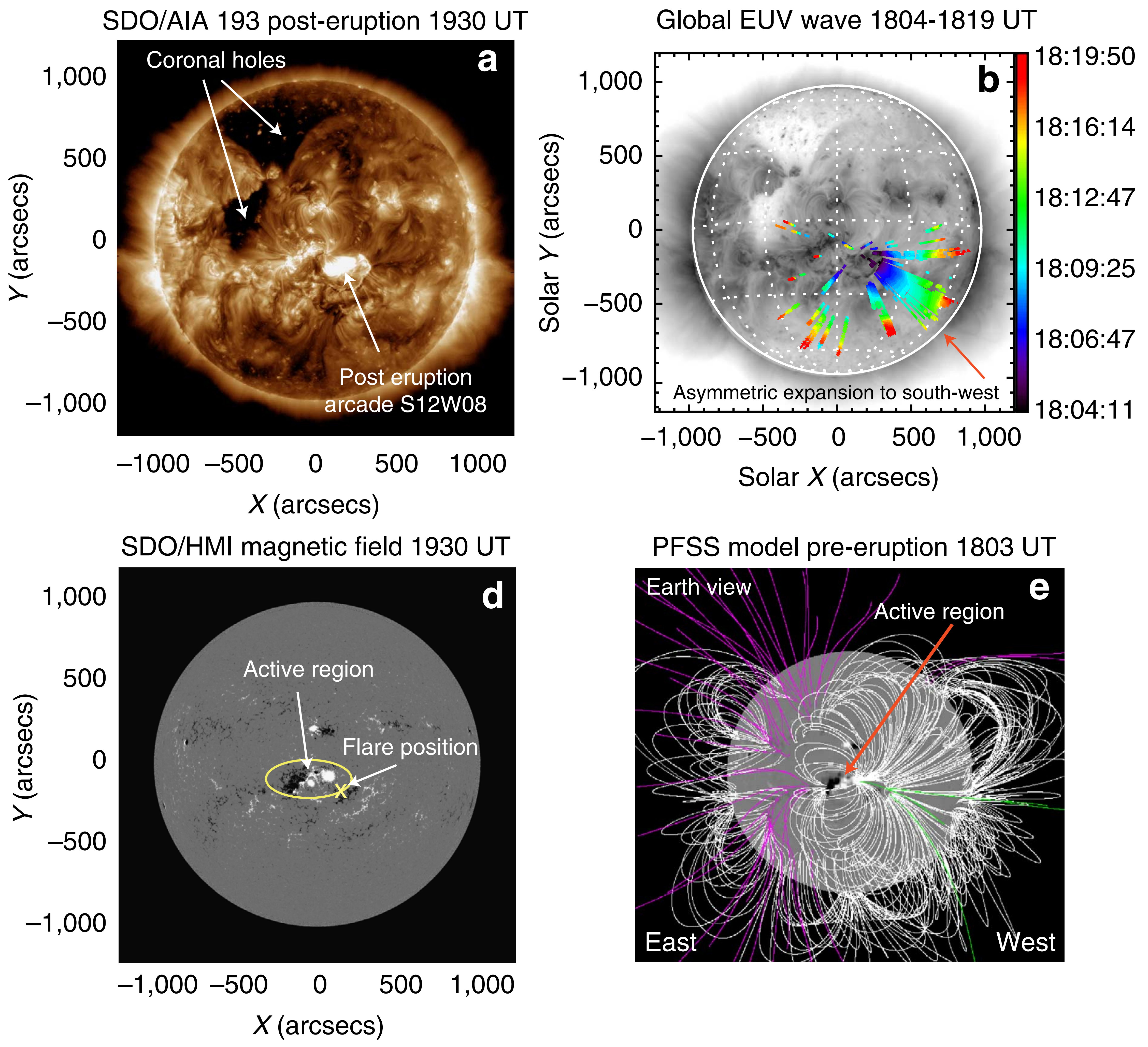
# What next?

# 1. Connecting solar and in situ structures

Möstl et al. (2015)

- Deflection and rotation of CMEs largely take place during about first 10% of their journey from the Sun to the Earth (e.g., Isavnin et al., 2014; Kay et al., 2016)
- Deflection can be found from EUV wave prominent direction in some cases
- Rotation can be found from EUV waves in some cases (Attrill et al., 2014)

i.e. better use of EUV data combined with magnetic field modelling (global and local)



# 2. Stealth CMEs

- CMEs with no obvious lower corona signatures
- They originate at altitudes of > 0.1 R_s (Robbrecht et al.,  2009)
- 30% of all CMEs? (solar minimum study, Ma et al., 2010)

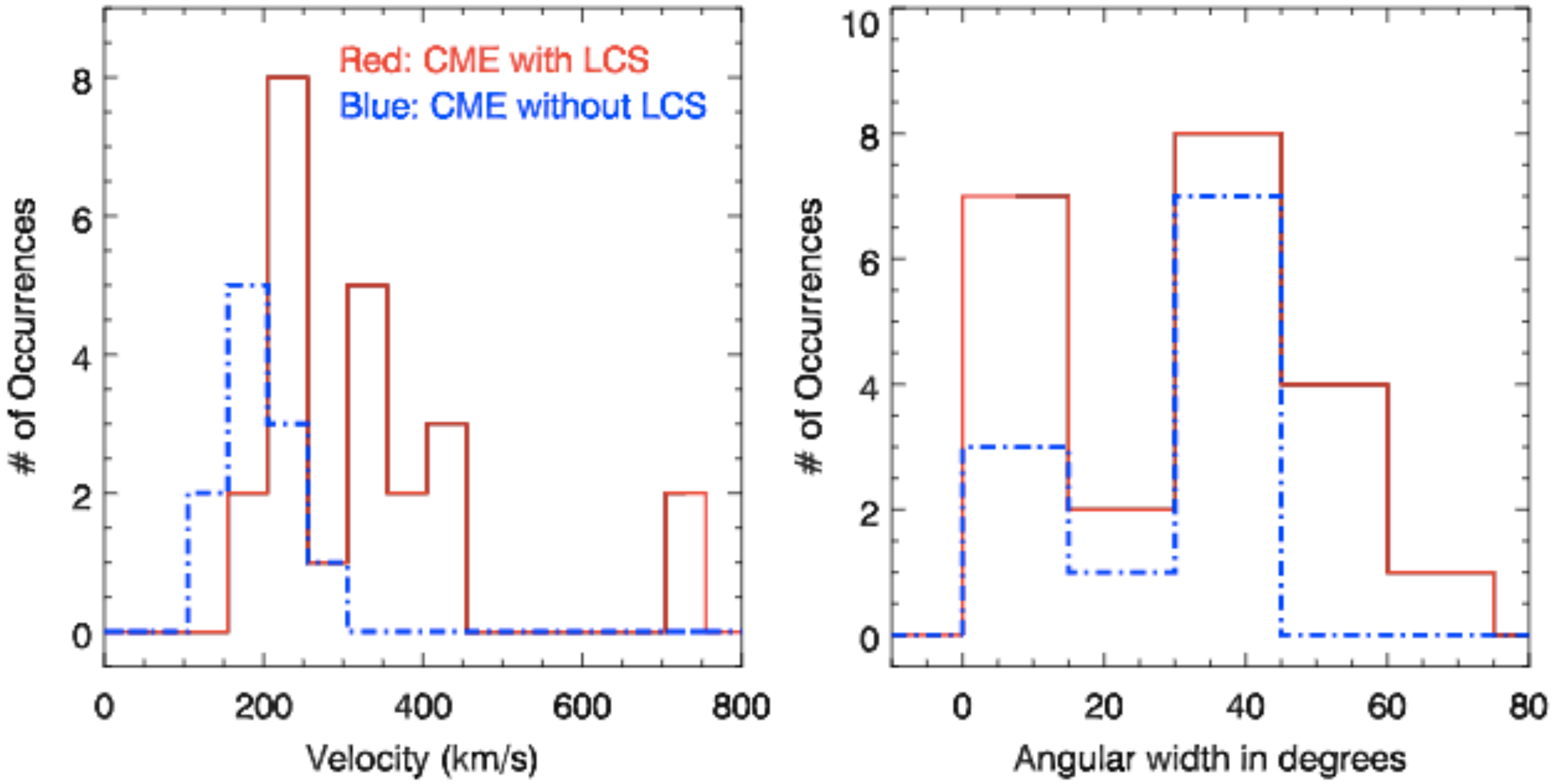
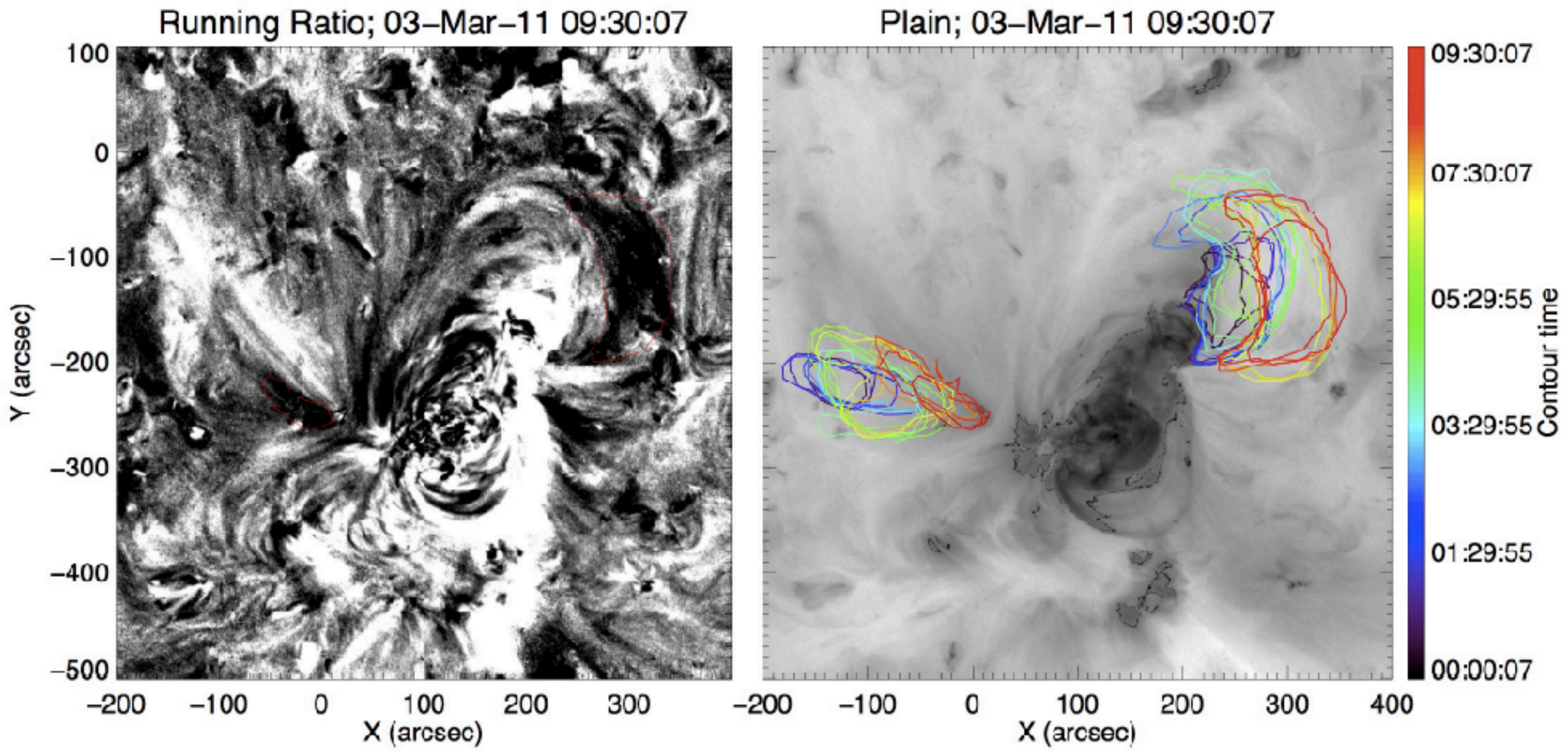



Fig. 4: Ma et al., 2010

# 2. Stealth CMEs

Imaging processing techniques are enabling post-event analysis:

- How do we/should we take knowledge of lower atmospheric flux rope formation/evolution and apply it to stealth CMEs?
- Can photospheric field data be used to predict axial field orientation?
- Can we determine the handedness/shear of the erupting magnetic field?




Event included in Nitta & Mulligan, 2017

Image from O’Kane et al. (in prep)

# 3. Bringing in plasma

Four main stages of evolution

1. 12:00 - approx. 13:00 UT (flux cancellation)
2. a rise phase (13:00 – 01:00 UT)
3. a shallow-exponential phase (01:00 – 04:40 UT, rope marginally unstable, **large mass unloading starts** at 04:00 UT)
4. a steep-exponential phase (04:40 onwards)

*See Fan (2018) for a complementary MHD simulation*

Jenkins et al. (2018)