Changes in the photospheric magnetic field produced by flares

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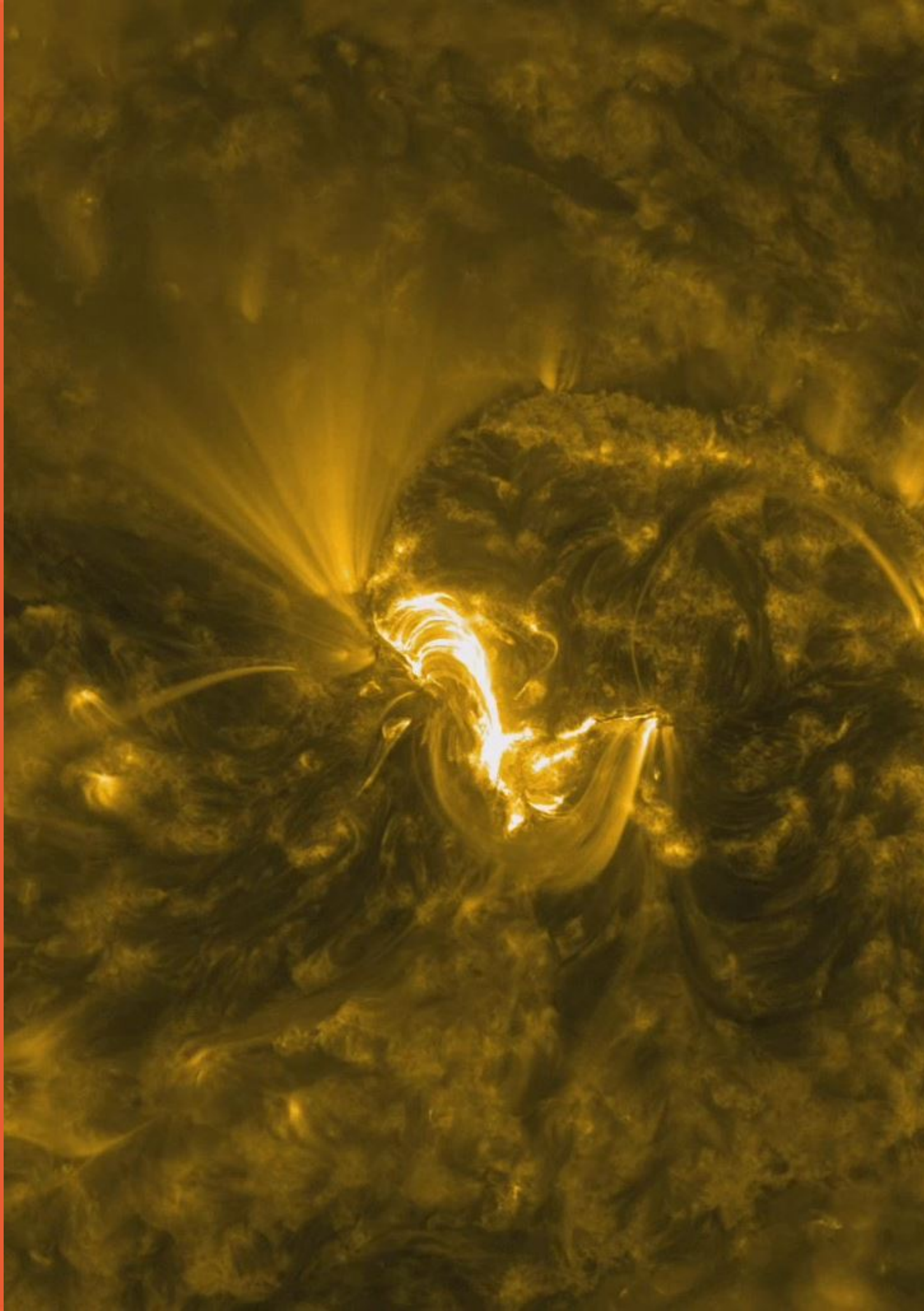


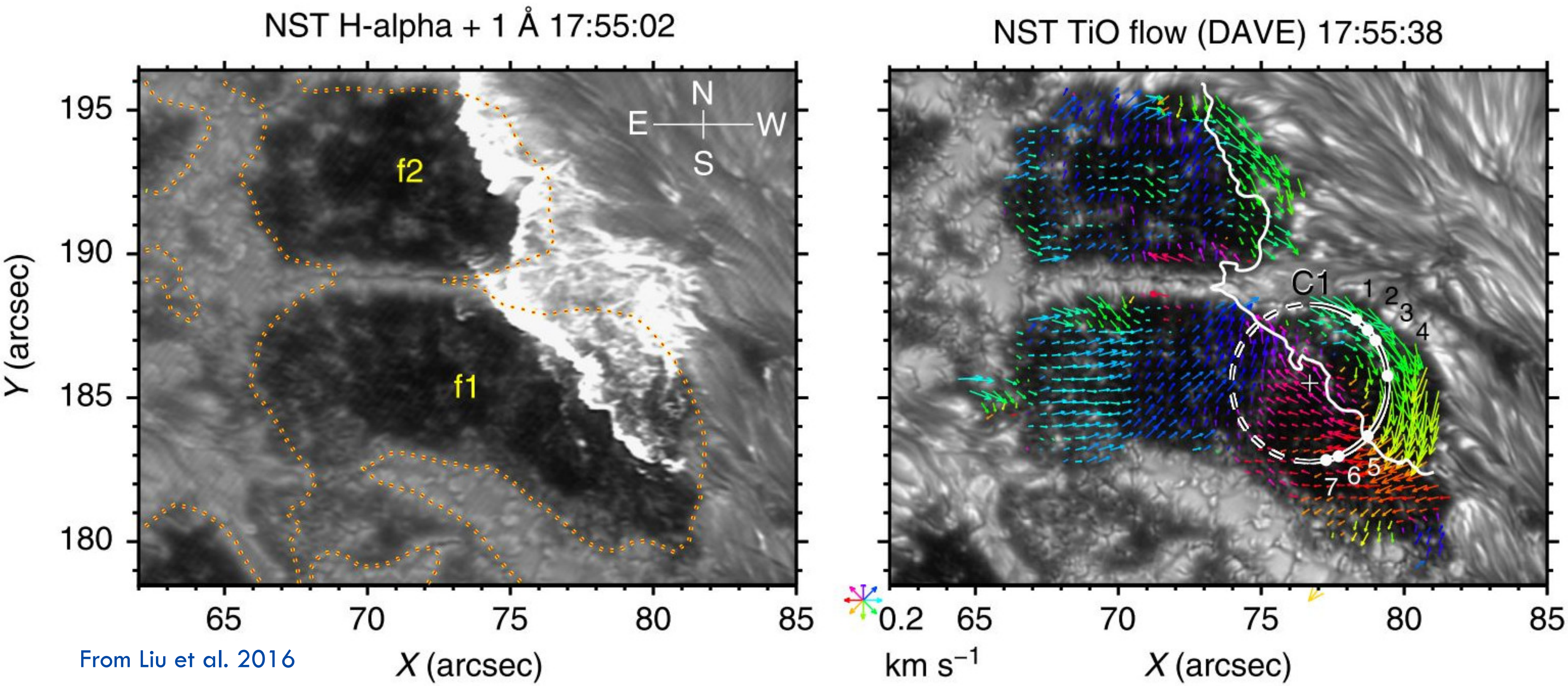
Background

- Flares involve conversion of magnetic energy into other forms in the corona
  - including acceleration of 10-100 keV electrons
- Sudden and permanent changes are observed in the photospheric magnetic field (e.g. Sudol and Harvey 2005)
  - vector magnetograms show the predominant change is in $\boldsymbol{B}_h$
  - shear tends to increase along the neutral line (e.g. Wang et al. 2012; Petrie 2012)
  - a change in the net Lorentz force is implied (e.g. Fisher et al. 2012)
- The changes are interpreted as a response to coronal magnetic restructuring

Observations

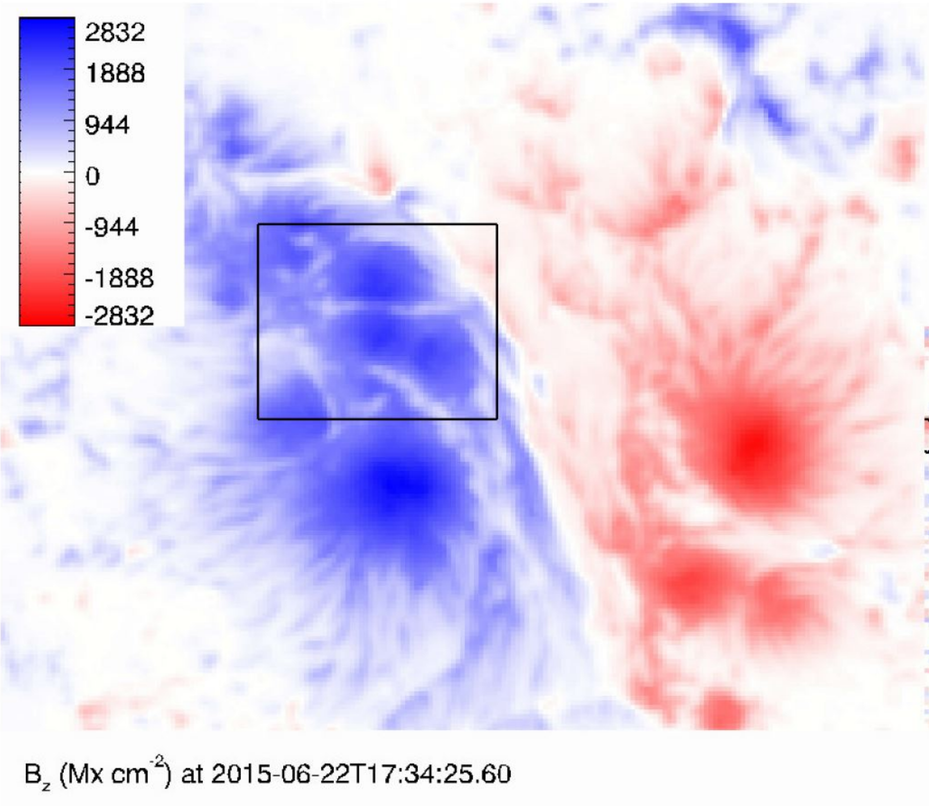
– 22 June 2015 M6.5 flare/CME (e.g. Liu et al. 2016; Jing et al. 2017; Wang et al. 2018)

  – sudden rotation of a sunspot in response to a flare
  – coincident with passage of flare ribbons

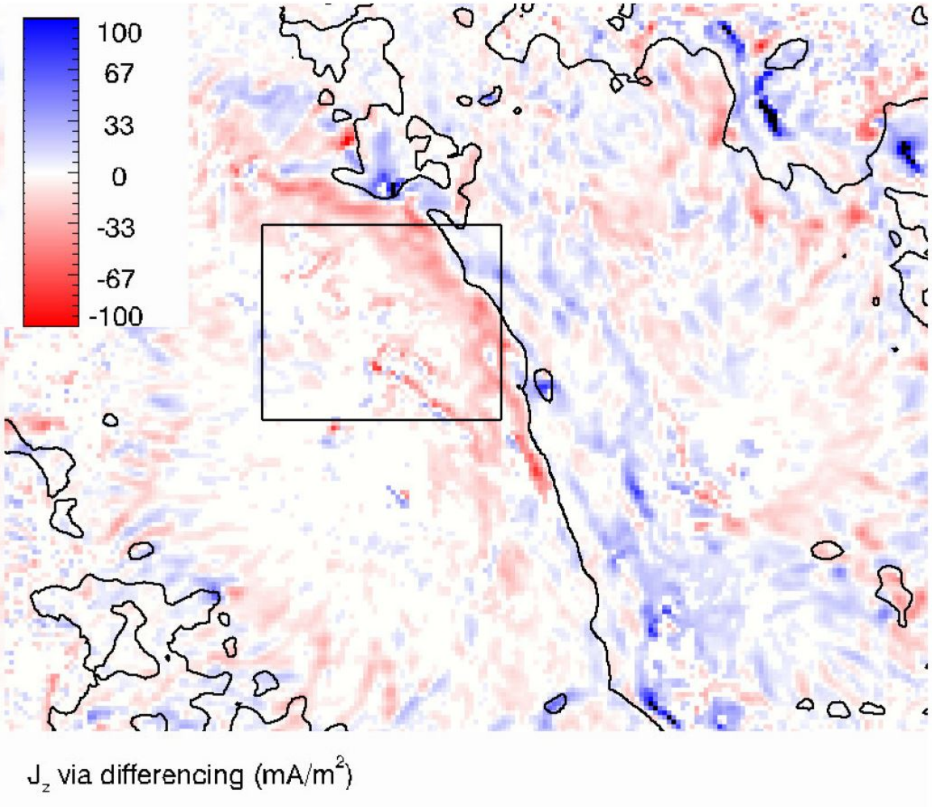


From Liu et al. 2016

– SDO/HMI SHARP data at 17:34

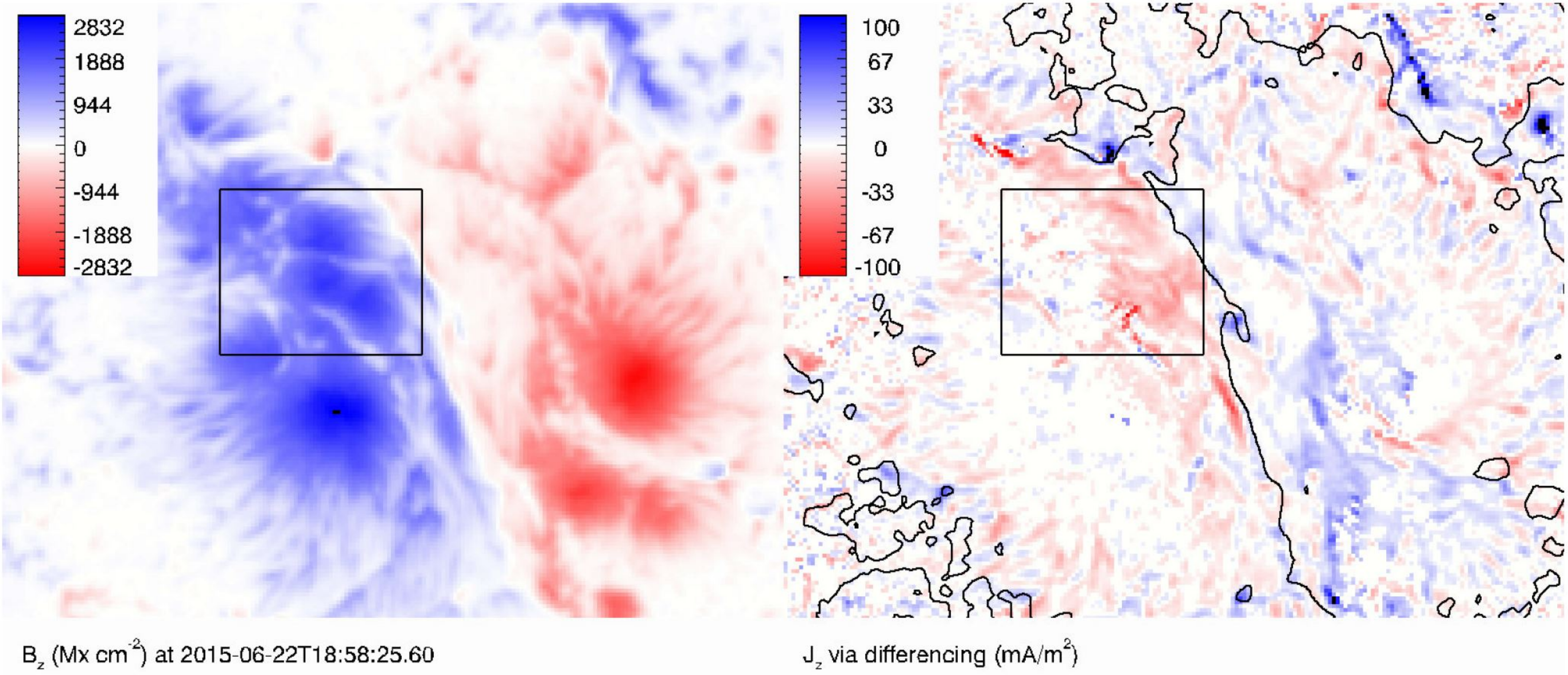


B_z



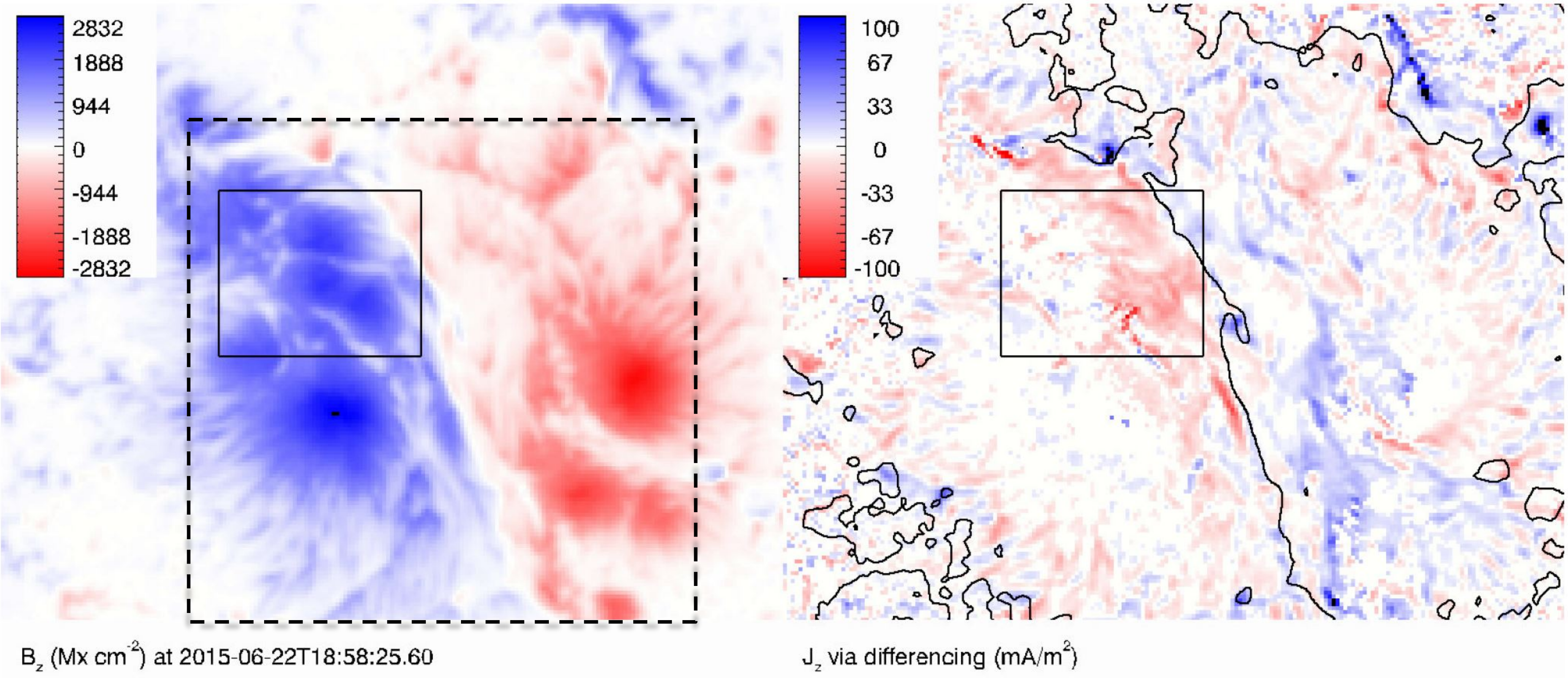
J_z

– SDO/HMI SHARP data at 18:58

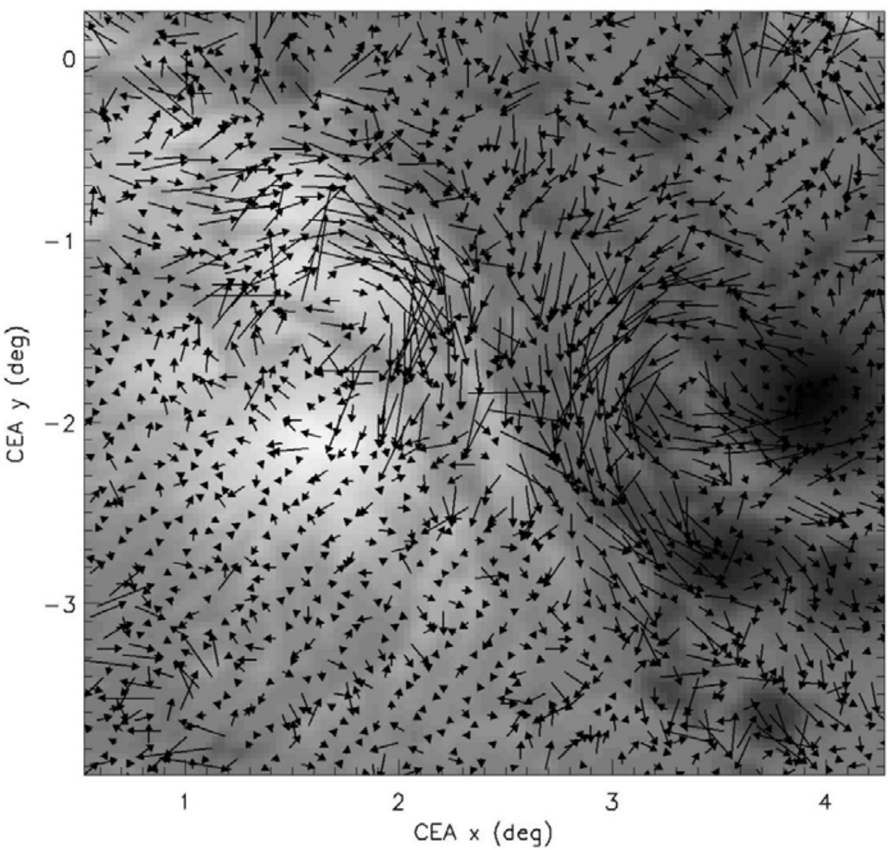


B_z J_z

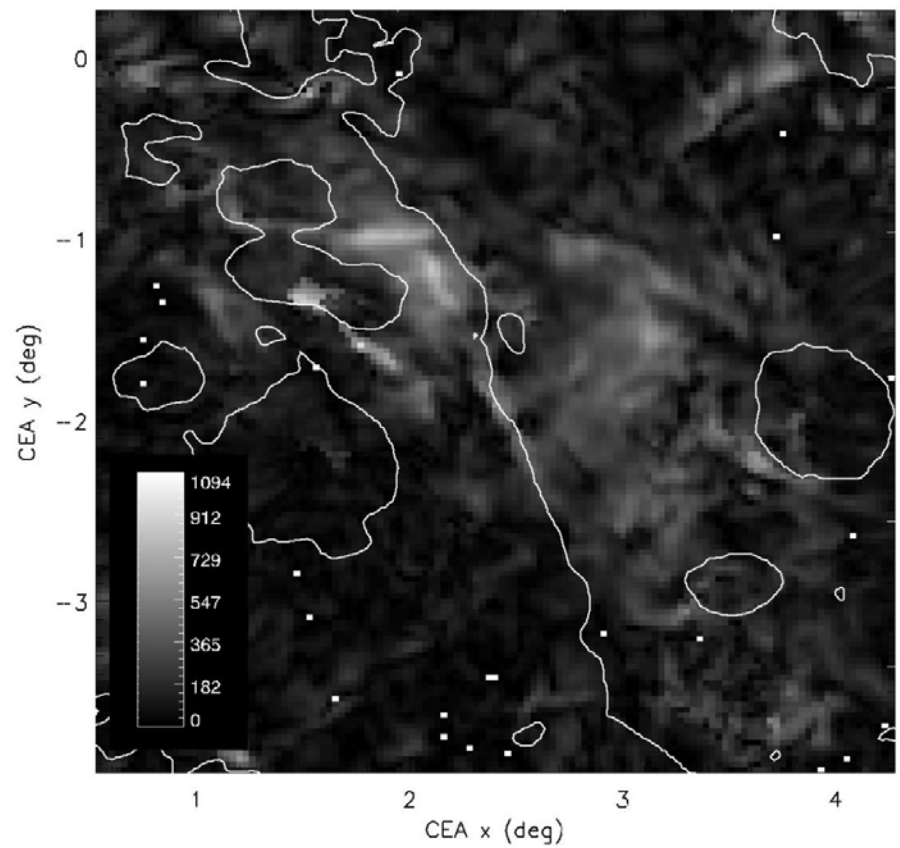
– SDO/HMI SHARP data at 18:58



– Change in SDO/HMI SHARP data 18:58 – 17:34

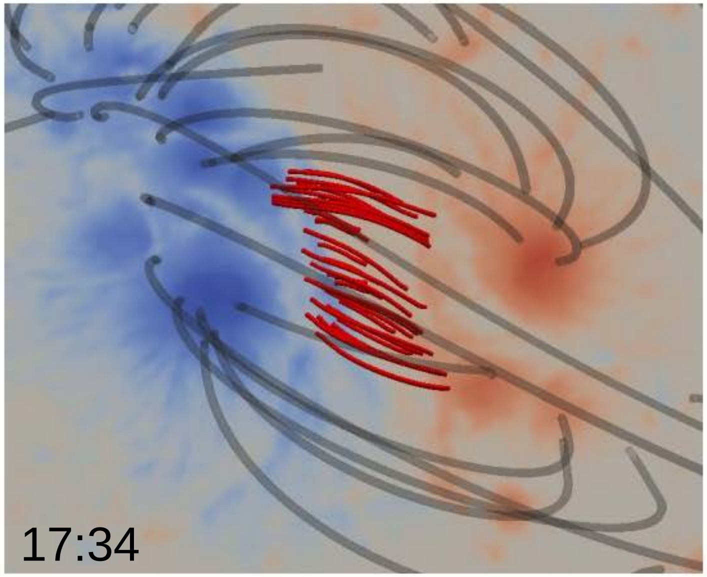


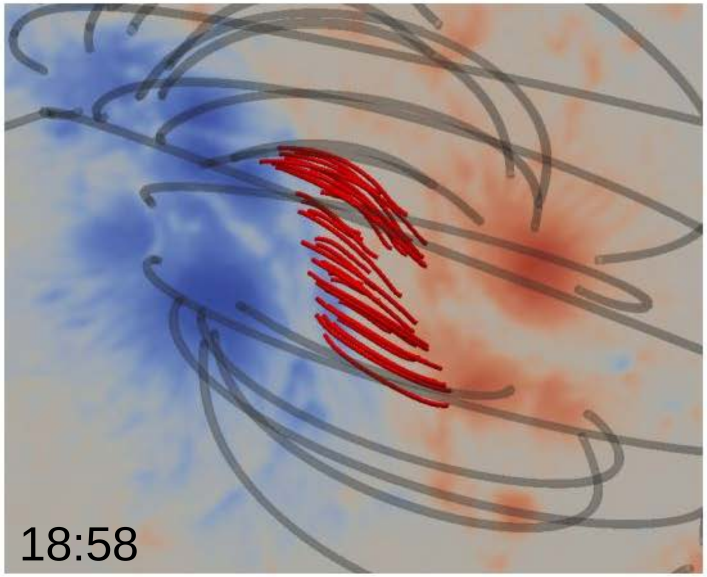
$\boldsymbol{B}_h$



$|\boldsymbol{B}_h|$

- The flare introduces a strong southward shear component in the field along the NL
- There are also oppositely directed shear flows on either side of the NL (Wang et al. 2018)
- NLFFF reconstructions show an increase in shear in the corona

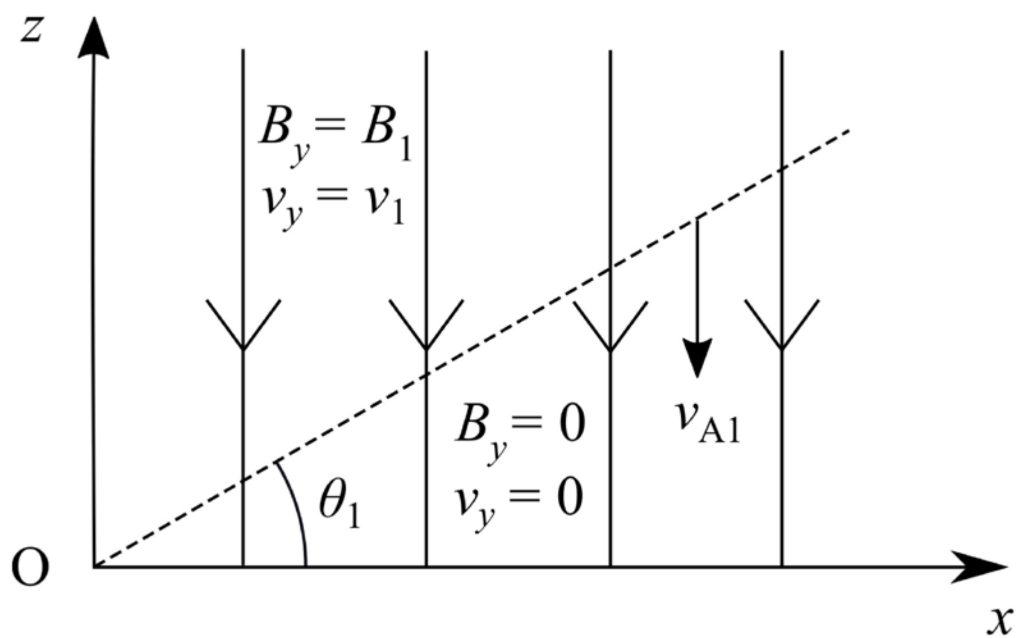




Model (Wheatland, Melrose, & Mastrano 2018)

Large amplitude shear Alfvén wave

- We consider a 2-D model of an Alfvénic front incident on the photosphere ($z = 0$) from above
  - the front introduces a shear field component B_1 and shear flow v_1
  - the front is oblique, so shear appears behind a propagating line

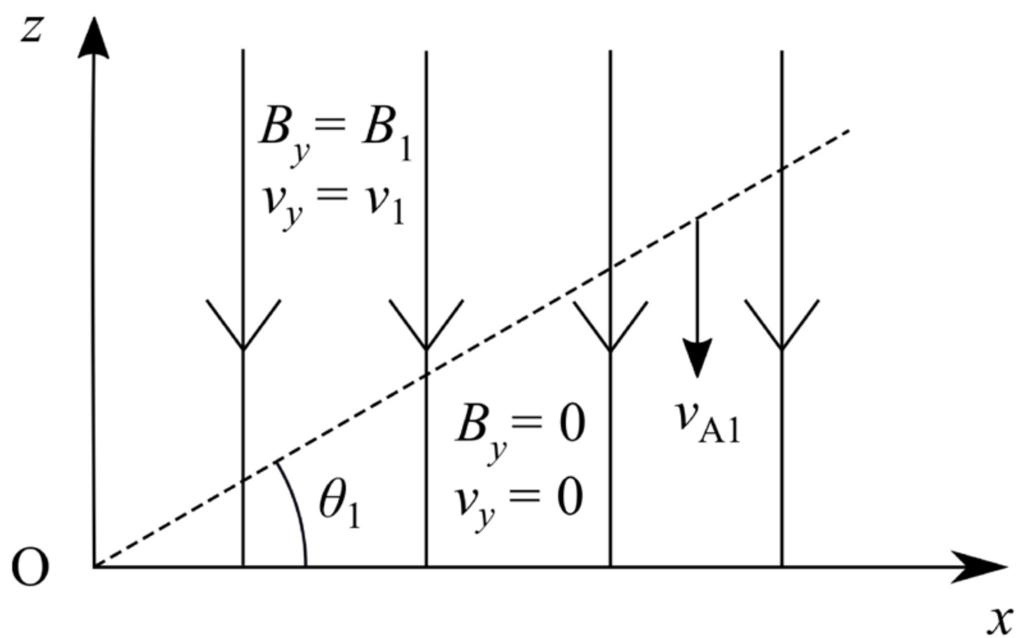


– Solutions to the ideal MHD equations in 2-D:

$$B_y(x,z,t) = B_1\theta(z + v_{\mathrm{A}1}t - \tan\theta_1 x)$$

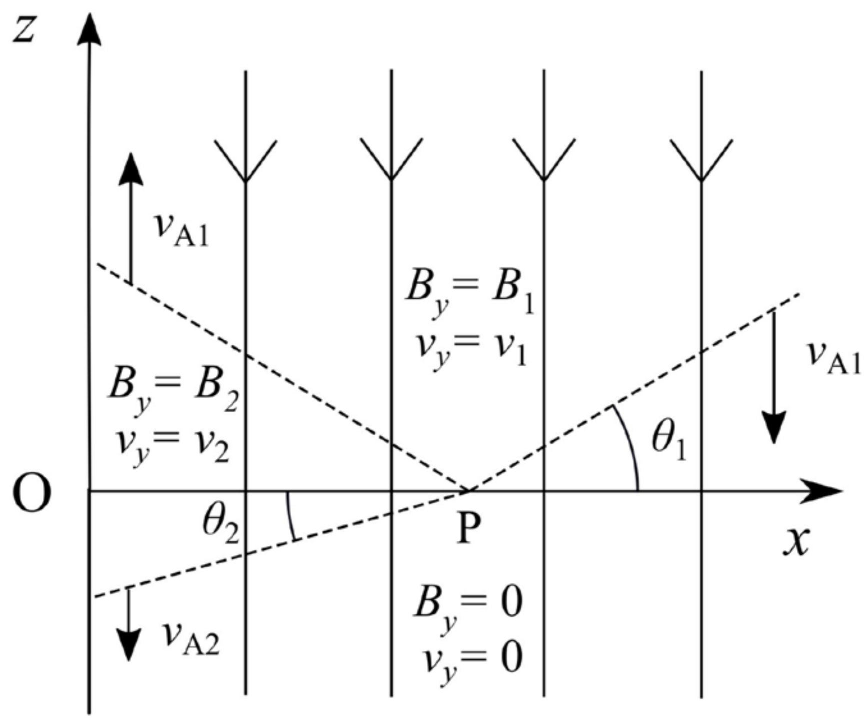
$$v_y(x,z,t) = -v_{\mathrm{A}1}\frac{B_1}{B_0}\theta(z + v_{\mathrm{A}1}t - \tan\theta_1 x)$$

– Walén relation: $v_1 = -v_{\mathrm{A}1}\dfrac{B_1}{B_0}$



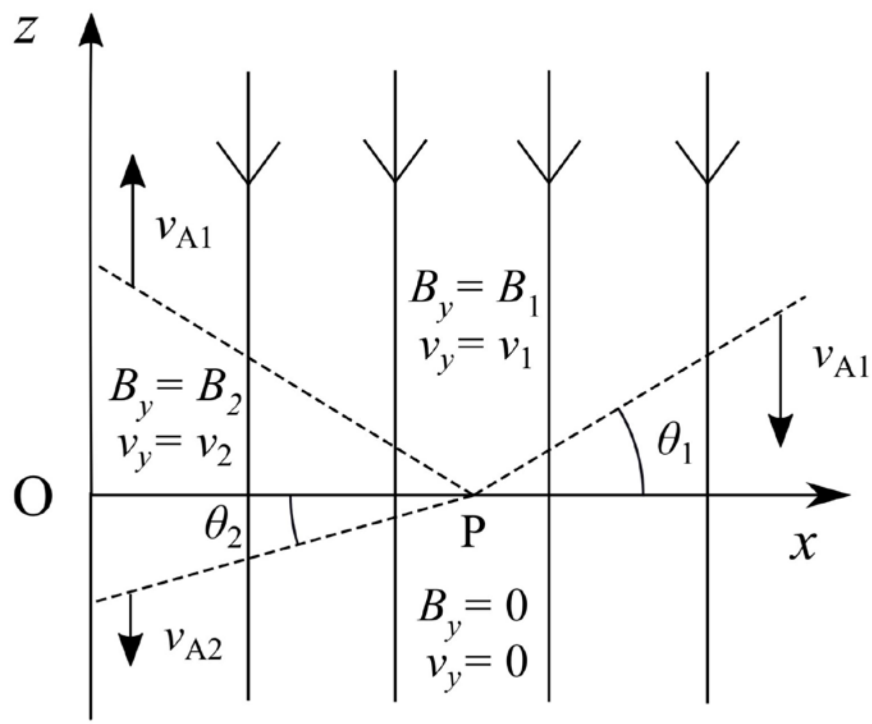
Photospheric response

- We represent the sub-photosphere as a uniform ideal region with Alfvén speed v_{A2}
  - the front is partially transmitted and partially reflected



- The shear values between the reflected and transmitted fronts are B_2, v_2
- The MHD equations and continuity imply:

$$B_2 = \frac{2v_{\rm A1}}{v_{\rm A1} + v_{\rm A2}} B_1 \quad \text{and} \quad v_2 = \frac{2v_{\rm A2}}{v_{\rm A1} + v_{\rm A2}} v_1$$



Model predictions

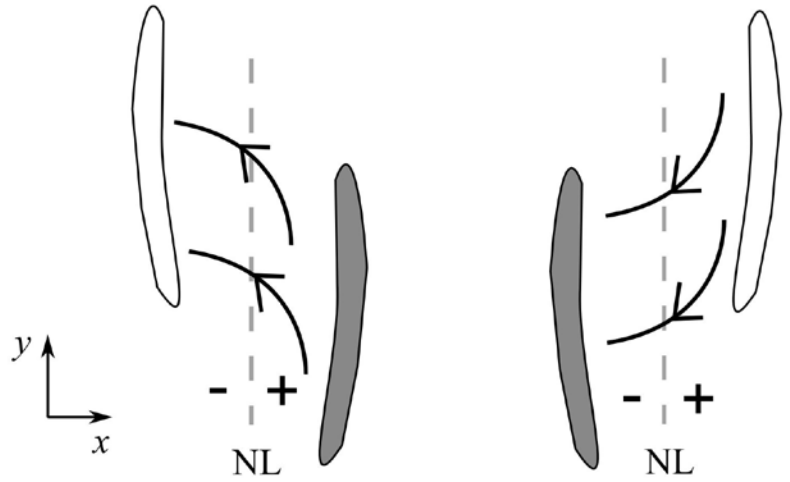
- If $v_{A2} \to 0$ then $B_2 \to 2B_1$ and $v_2 \to 0$ (perfect reflection)
  - otherwise reflection and transmission ($B_2 > B_1$ and $v_2 < v_1$)
- Walén relation for the transmitted front:

$$v_2 = -v_{\mathrm{A2}} \frac{B_2}{B_0}$$

  - for photospheric values: $\rho_2 = 5 \times 10^{-4} \mathrm{kg/m^3}$, $B_0 = 1000$ G we have $v_{\mathrm{A2}} = 4 \times 10^3 \mathrm{m/s}$
  - assuming $v_2 = 0.1 - 1 \times 10^3 \mathrm{m/s}$ (Wang et al. 2018) $\Rightarrow |B_2| = 25 - 250$ G, consistent with observations
- The Poynting flux $P_P = -v_y B_y B_z$ must be downwards
  - if $B_z > 0$ then $v_y B_y > 0$ and if $B_z > 0$ then $v_y B_y < 0$
  - the magnetic shear has the same sign, the velocity shear the opposite sign, across the NL

Particle acceleration

- The flare ribbons coincide with hard X-ray emission
- The front in the model represents a surface current
  - which implies a field-aligned electric field if the conductivity is finite
  - above a critical value $E_{\|}$ can cause runaway
  - we estimate this requires a front thickness $\approx 10\mathrm{m}$
- The electric field direction is determined by the direction of B_1
  - which implies an asymmetry in the HXR production



Summary

- Flares produce permanent changes in the photospheric field
- A well-observed flare (SOL2015-06-22T18:23) shows:
  - the introduction of a shear component of ***B*** along the neutral line
  - the introduction of oppositely-directed shear flows
- A simple model is presented involving a shear Alfven wave impacting on the photosphere (Wheatland, Melrose, & Mastrano 2018)
  - a shear field B_1 and shear flow v_1 are introduced behind a front
  - the front is reflected and transmitted at the photosphere
- The model, although idealised, can account for the observed field change and flows