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 $B_h$
  - 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

$B_z$ (Mx cm$^2$) at 2015-06-22T17:34:25.60

$J_z$ via differencing (mA/m$^2$)
SDO/HMI SHARP data at 18:58
- SDO/HMI SHARP data at 18:58

\[ B_z \ (Mx \ cm^2) \] at 2015-06-22T18:58:25.60

\[ J_z \] via differencing (mA/m^2)
Change in SDO/HMI SHARP data 18:58 – 17:34
– 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
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:

\[ B_y(x, z, t) = B_1 \theta(z + v_{A1} t - \tan \theta_1 x) \]

\[ v_y(x, z, t) = -v_{A1} \frac{B_1}{B_0} \theta(z + v_{A1} t - \tan \theta_1 x) \]

– Walén relation: \( v_1 = -v_{A1} \frac{B_1}{B_0} \)
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:

\[
B_2 = \frac{2v_{A1}}{v_{A1} + v_{A2}} B_1 \quad \text{and} \quad v_2 = \frac{2v_{A2}}{v_{A1} + v_{A2}} v_1
\]
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:
  \[ v_2 = -v_{A2} \frac{B_2}{B_0} \]

- for photospheric values: $\rho_2 = 5 \times 10^{-4} \text{kg/m}^3$, $B_0 = 1000 \text{ G}$ we have $v_{A2} = 4 \times 10^3 \text{ m/s}$
- assuming $v_2 = 0.1 - 1 \times 10^3 \text{ m/s}$ (Wang et al. 2018) $\Rightarrow |B_2| = 25 - 250 \text{ G}$, 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 $E_\parallel$ can cause runaway
  - we estimate this requires a front thickness $\approx 10\text{m}$
- 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 Alfvén 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