Validation of currents in coronal magnetic field models

Michael S. Wheatland
Sydney Institute for Astronomy
School of Physics

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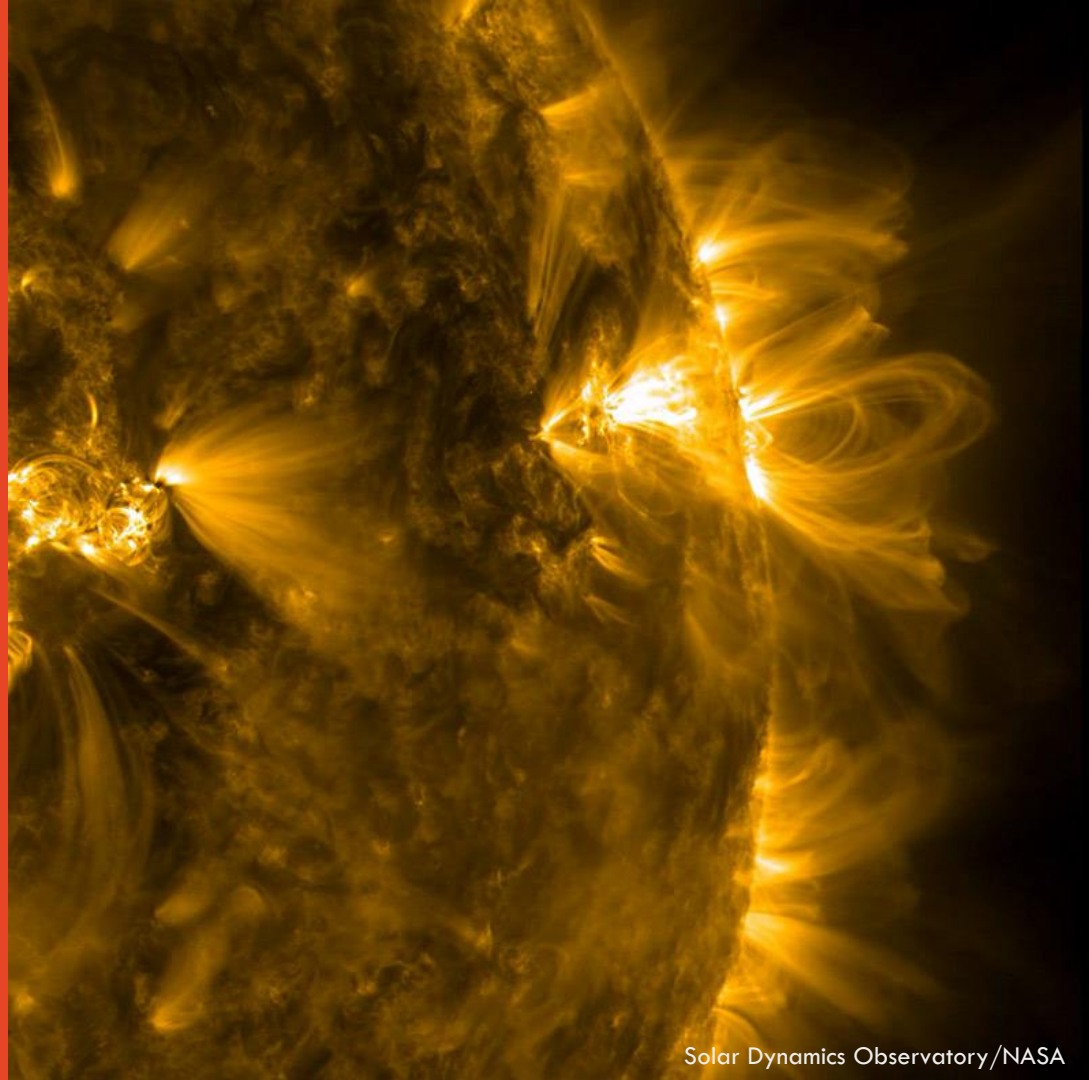
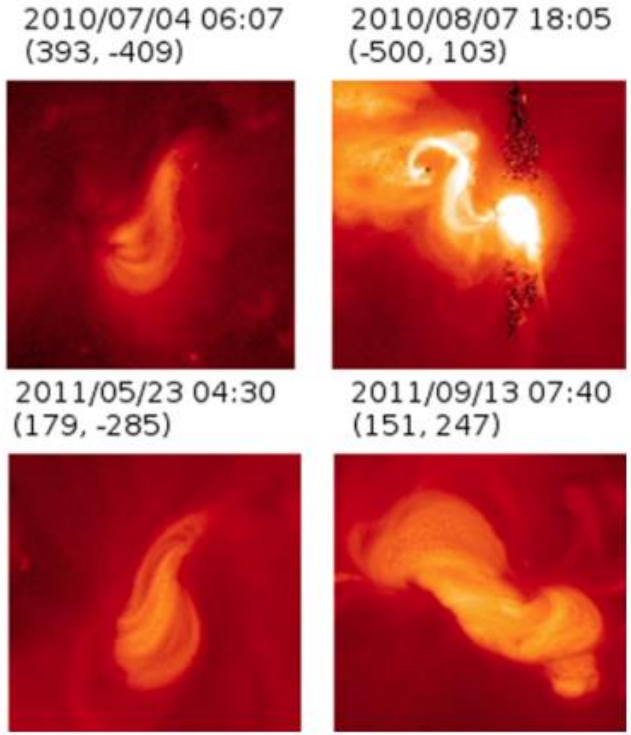


Currents in coronal magnetic fields

- Flares and CMEs are powered by the energy stored in coronal electric currents
  - observed structures in the corona imply the presence of currents
- The energy of the field depends on the geometry of the currents:

$$E = \frac{1}{2}\sum_{i=1}^{N} L_i I_i^2 + \sum_{i=1}^{N}\sum_{j>i} M_{ij} I_i I_j$$

- It is not possible to directly infer coronal currents
  - we rely on models based on photospheric data



Savcheva et al. 2014

A hierarchy of coronal field models

Static/data-constrained | **Time-dependent/data-driven**

Nonlinear force-free (NLFF)
a boundary value problem for **B**

Magneto-hydrostatic (MHS)
a boundary value problem for **B**, p and ρ

Magneto-frictional (MF)
a boundary value problem for **B** or an initial value/ boundary value problem for **B**

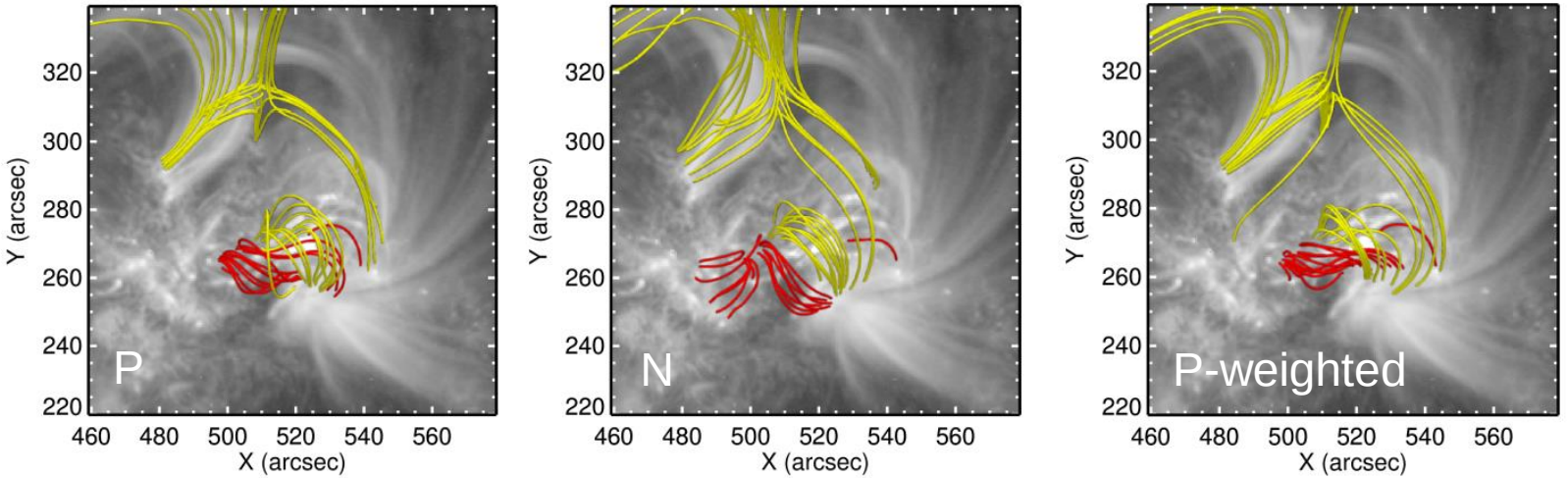
Zero-β magneto-hydrodynamic (MHD)
an initial value/boundary value problem for **B**, **v** and ρ

Full MHD
an initial value/ boundary value problem for **B**, **v**, p and ρ

Increasing physics and computational cost →

Uncertainty in modelling 1

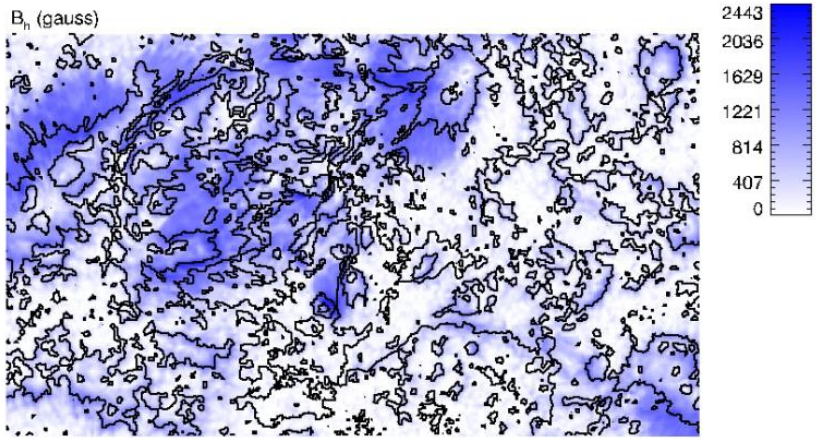
- In practice the models may produce very different results due to:
  - different choices of model
  - uncertainties in the data and model assumptions
  - inconsistencies between the model and the boundary data

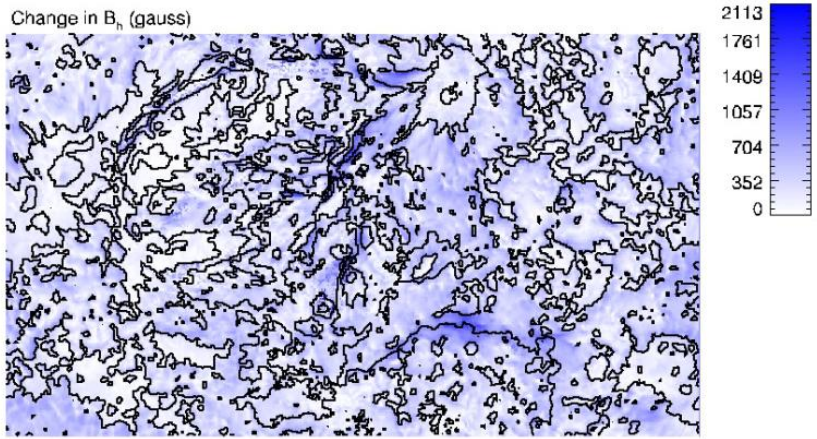


Mastrano, Yang & Wheatland 2020

Uncertainty in modelling 2

- Generally models change the BCs substantially
- In particular the horizontal field $\mathbf{B}_h$
  - corresponding to J_z at the photosphere

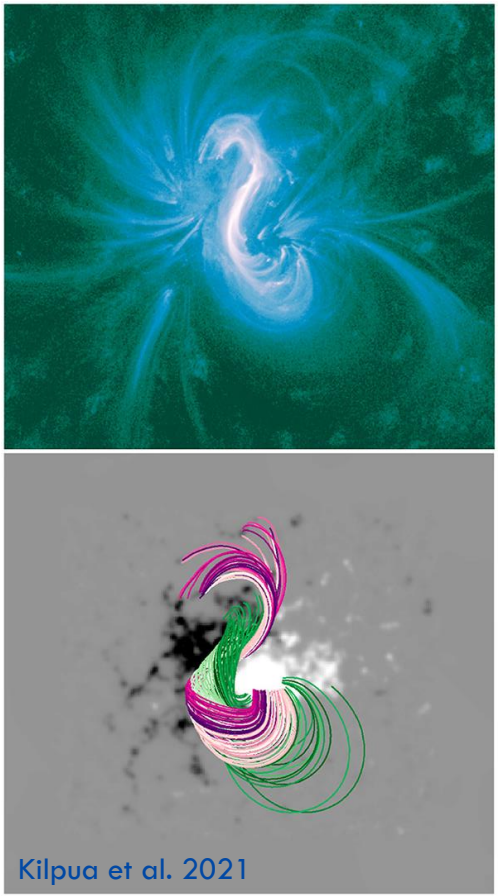




De Rosa et al. 2015

How can we validate currents in a model?

- Qualitative methods have included:
  - comparison of model field lines with observed coronal/chromospheric structures
  - comparison of line-of-sight integrated model current with observed emission e.g. De Rosa et al. 2009
  - inter-comparison of models
- However, coronal currents in models are significantly uncertain
  - which constrains the determination of free energy



Gaussian separation method

- Remarkably, the components of the boundary field due to coronal currents can be identified Schuck et al. 2022, Welsch 2022
  - this is a well-known result in terrestrial/planetary magnetism due to Gauss (1830) e.g. Olsen et al. 2010
- Basic idea:

$$\mathbf{B}(x,y,0) = \mathbf{B}^{\mathrm{rot}}(x,y) + \mathbf{B}^{<}(x,y,0) + \mathbf{B}^{>}(x,y,0)$$

Due to currents crossing the photosphere

Due to currents below the photosphere

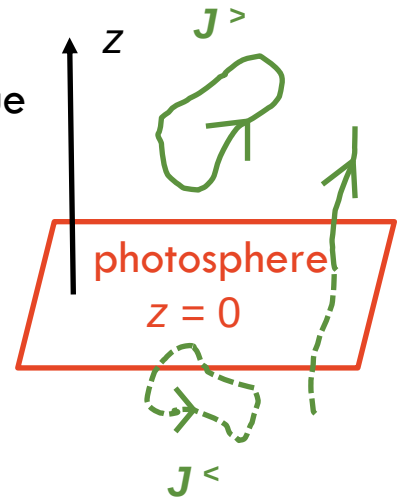
Due to currents above the photosphere

  - where:

$$\mathbf{B}^{\mathrm{rot}}(x,y) = \nabla \times [T(x,y)\hat{\mathbf{z}}]\,,$$

$$\mathbf{B}^{<}(x,y,z) = -\nabla\chi^{-}(x,y,z), \quad z \geq 0$$

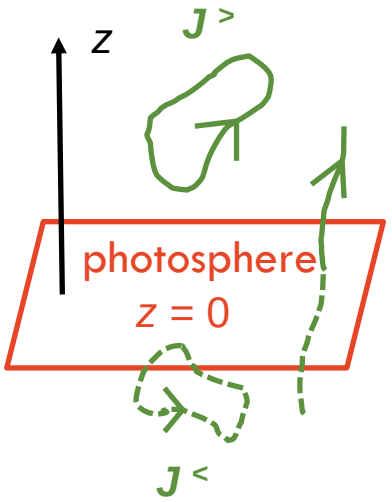
$$\mathbf{B}^{>}(x,y,z) = -\nabla\chi^{+}(x,y,z), \quad z \leq 0$$



Gaussian separation method

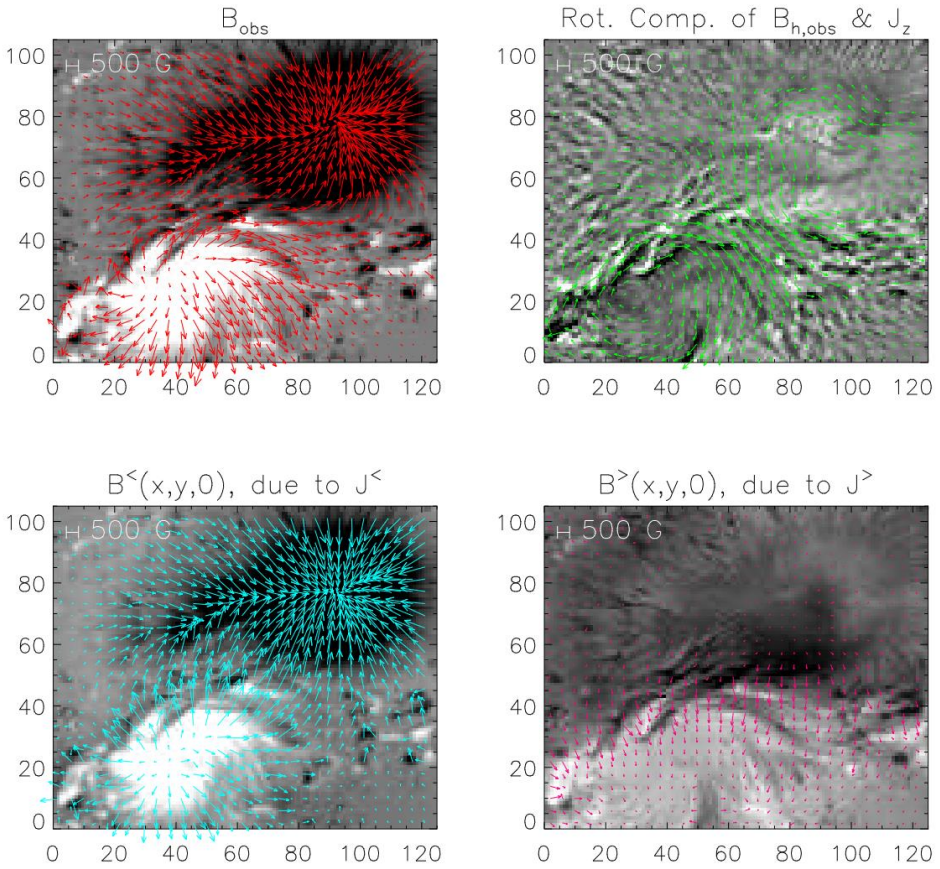
Schuck et al. 2022, Welsch 2022

- $B_z(x,y,0)$ can be expressed using the difference of $\chi^{\pm}(x,y,0)$ and $\nabla_h \cdot \mathbf{B}_h(x,y)$ using the sum
  - hence the potentials can be determined
  - i.e. the components due to currents above, below, and crossing the photosphere can be determined
- Welsch (2022) presents a Fourier solution for $\chi^{\pm}(x,y,z)$
- The method potentially allows validation of coronal currents in a model
  - by comparison of the fields at the boundary due to currents in the model with the Gaussian separation results



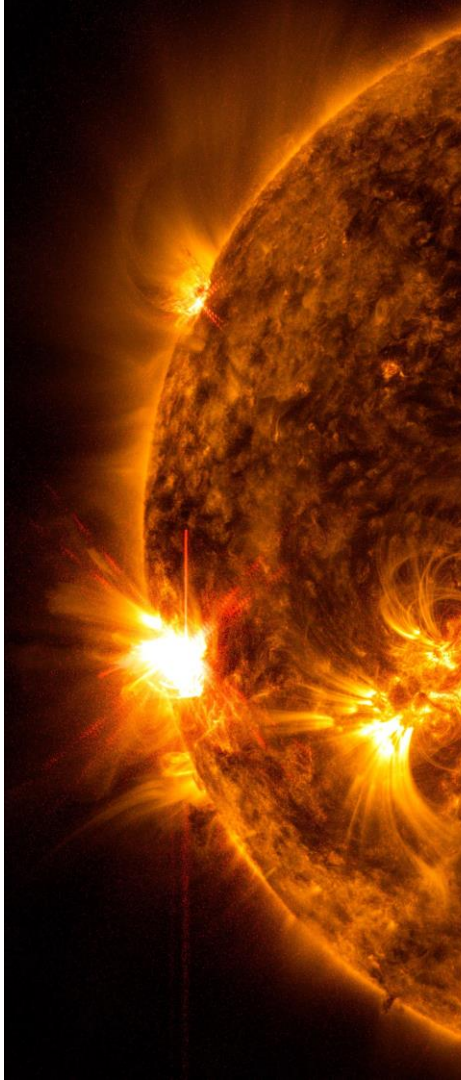
Application to data Welsch 2022

- Method applied to observations from Hinode SP for AR 10930 from Dec 2006
  - total unsigned flux about half as large for $B_z^{>}(x,y,0)$ versus $B_z^{<}(x,y,0)$
  - ~6 x as much energy in the potential field due to interior currents versus coronal currents
- The patterns in $\mathbf{B}_h^{>}(x,y,0)$ imply a coronal current R to L above the neutral line



Other considerations

- The coronal currents alter $B_z(x,y,0)$ – hence the usual Neumann BC potential field is not the energy corresponding to a current-free corona see Welsch 2022
- In principle the Gaussian separation method can be applied directly to data to investigate flare-related changes in coronal currents see Welsch 2022
- The method could also be used for model validation:
  - by comparing $\mathbf{B}_{model}^{>}(x,y,0)$ with $\mathbf{B}_{obs}^{>}(x,y,0)$
- Or, better: the extra constraint of $\mathbf{B}_{obs}^{>}(x,y,0)$ could be incorporated into models during construction



Summary

- Coronal currents provide the energy for flares and CMEs
- Determination of coronal currents requires modelling and there are various uncertainties
  - which limit e.g. ability to determine free energies
- The Gaussian separation method provides information on coronal currents directly from the data
  - in principle it provides a new test for model results
  - or additional information to incorporate directly in models
- This method should be used!