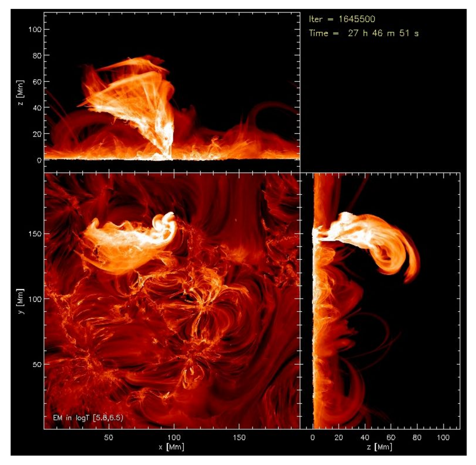
Numerical MHD Coronal Simulations: Energy Statistics and FORWARD Analysis

Kenzie Nimmo[1], Matthias Rempel[2], Feng Chen[2], Sarah Gibson[2], Yuhong Fan[2]
[1] *School of Physics & Astronomy, University of Glasgow, Glasgow, Scotland*
[2] *High Altitude Observatory, NCAR, Boulder, CO, USA.*

Introduction

The solar corona is the outer part of the Sun's atmosphere. Temperatures rise rapidly from the chromosphere through the transition region, reaching temperatures of the order of 1×10^6 Kelvin in the corona. Simultaneously, the high densities in the lower atmosphere fall rapidly in the transition region and result in a low density plasma in the corona. Numerical simulations of the solar corona are important to develop our understanding of, for example, the energetics and magnetic structure, which can be difficult to interpret using observations alone. We present here the analysis of 118 solar events from a magnetohydrodynamic simulation of the solar atmosphere, that describes the upper convective zone of the Sun through the corona. This simulation shows an "extreme" active region of the Sun, with a number of flares and a coronal mass ejection (CME). We provide here statistics of the energetics of the events in the simulation.

The FORWARD code is a tool used for the purpose of coronal magnetometry. It compares physical properties of models with observable quantities, which helps to interpret observations of the Sun from instruments like the High Altitude Observatory's CoMP instrument. The CoMP (COronal Multi-channel Polarimeter) instrument measures the intensity and the linear and circular polarisation of Fe XIII at 1074.7nm. We discuss some important limitations of the FORWARD code when simulating an extremely active solar region, and investigate the evolution of a CME event from the coronal simulation.



Identifying Simulated Flare Events

Regions of the Sun with a strong electric current (known as a *current sheet*) has very efficient dissipation which can cause the magnetic field topology to alter. This is a phenomena called *magnetic reconnection* and results in the magnetic energy stored in the corona being converted to kinetic and internal energy. Magnetic reconnection causes the sudden release of magnetic energy in the solar atmosphere, resulting in a flare or similar solar event.
Simulated flares and flare-like phenomena can be observed in Figure 1, with sudden releases of magnetic energy into a combination of the work done by the Lorentz force and the resistive heating.
By studying Figure 1, 118 simulated solar events were identified, and each event's duration and energy was estimated.

The analysis: The full energy time series is divided into subsections, and each of these shorter profiles are smoothed by a combination of boxcar averaging and Lee filtering. The smoothing parameters are dependent upon the solar activity in each time interval.

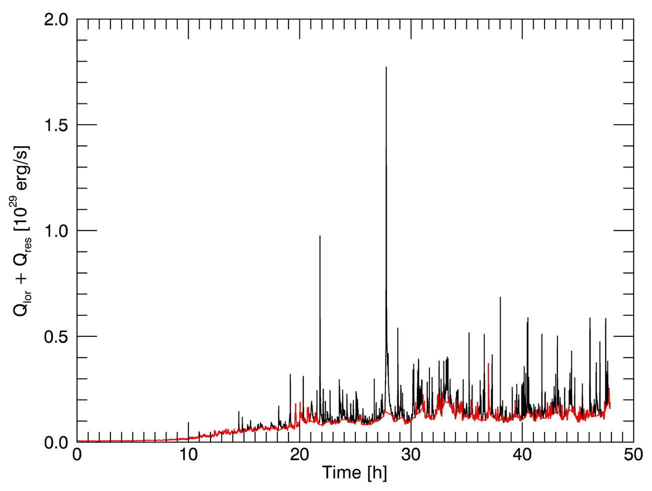


Figure 1: Black: Rate of work done by the Lorentz force (Q_{lor}) plus rate of resistive heating (Q_{res}) time series for the coronal simulation. Sudden releases of magnetic energy indicating solar flares. Red: The time series resulting from omitting every identified event.

By considering the locations where the sign of the gradient changes, the peak value on the smoothed profile, and the beginning and end indices of the event are determined.
The beginning and end indices, and their corresponding value on the original profile, are then fitted by a straight line to model the background of the event.
The energy is estimated by subtracting the background linear fit from the original profile and integrating over time from the beginning of the event to the end.

Energetics of Simulated Flare Events

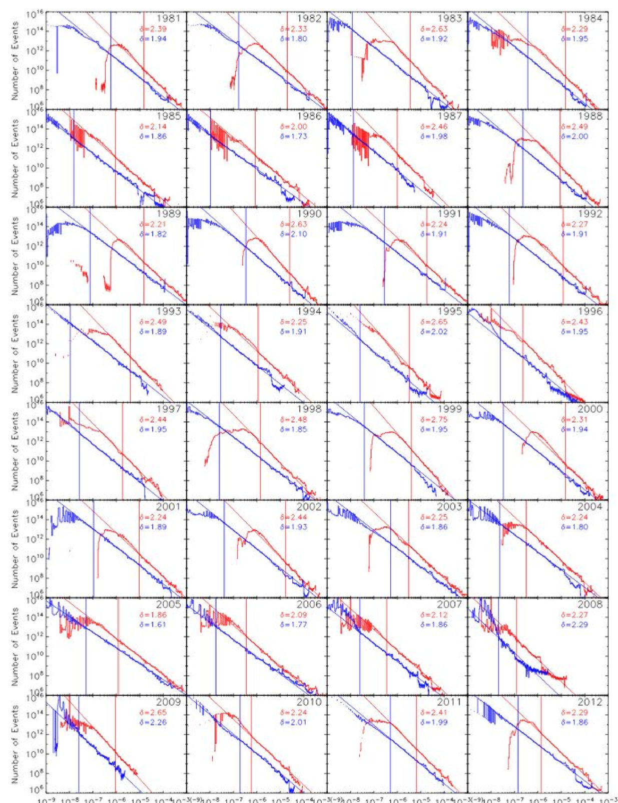


Figure 2: Observations of the GOES X-ray flux. Red plots are the ones to compare (1-8Å range). *Y.-P. Li et al., 2016.*

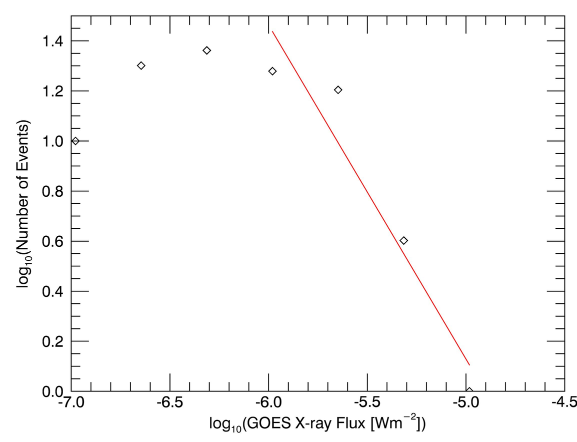
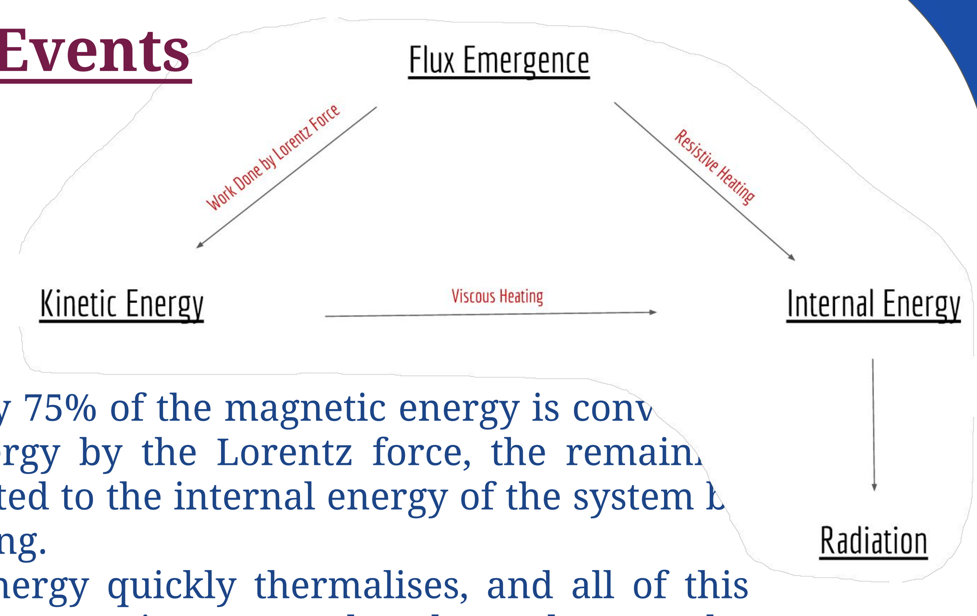


Figure 3: Histogram of the simulated GOES X-ray flux for flares of class B and above. The red line is a linear fit of flares of class C and above, with gradient 1.33452.



- Approximately 75% of the magnetic energy is converted to kinetic energy by the Lorentz force, the remaining 25% is converted to the internal energy of the system by resistive heating.
- The kinetic energy quickly thermalises, and all of this excess kinetic energy is converted to thermal energy by viscous heating.
- About 60% of the internal energy is immediately released as radiation.

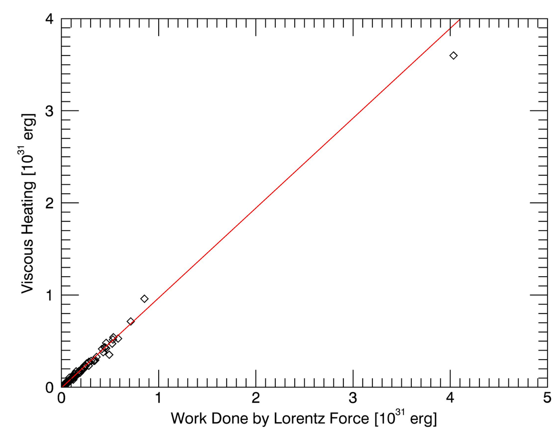


Figure 4: Scatter plot of the work done by the Lorentz force vs. viscous heating.
The red line shows the line of best fit of the data (not including the CME), with gradient 0.97528309.

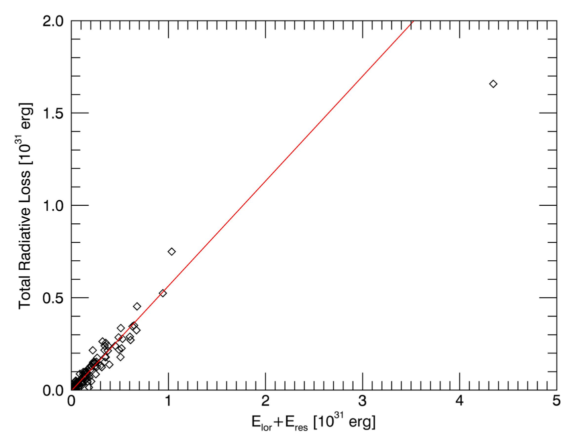


Figure 5: Scatter plot of the work done by the Lorentz force (E_{lor}) plus the resistive heating (E_{res}) vs. the total radiative loss in the corona. The red line shows the line of best fit of the data (not including the CME), with gradient 0.567776.

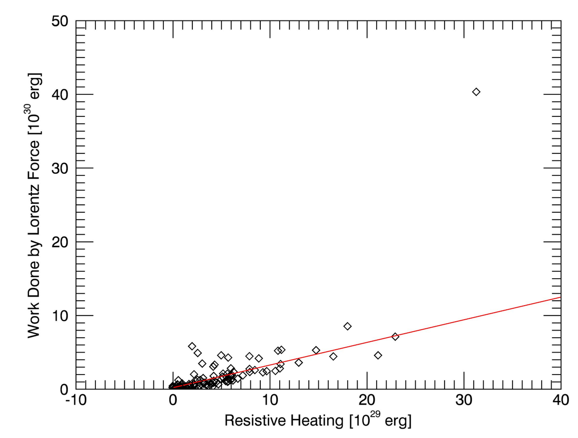


Figure 6: Scatter plot of the resistive heating vs. the work done by the Lorentz force. The red line shows the line of best fit of the data (not including the CME), with gradient 3.06987.

Limitations of the FORWARD Analysis

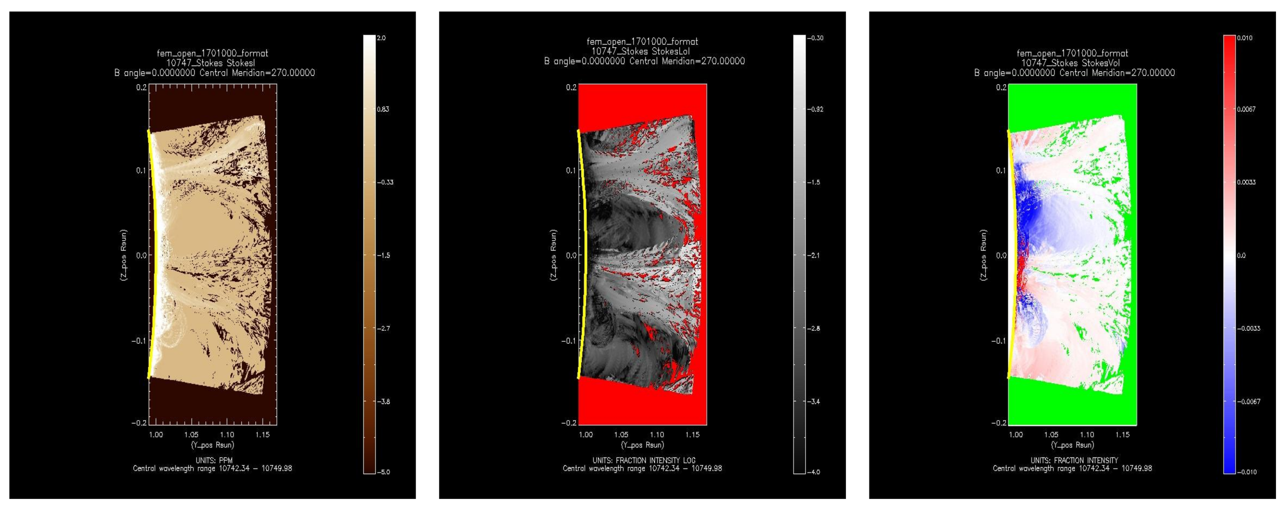


Figure 8: Left: Stokes I map calculated by FORWARD around the time of the CME in the simulation. Middle: Stokes L/I map at the same time step. Right: Stokes V/I map at the same time step. In the middle and right maps, the null pixels have been shown in red and green, respectively.

- Large velocities cause Fe XIII line to be shifted out of the viewing window, leaving a null pixel.
- High (and low) temperatures cause the Fe XIII line to be scaled down (not necessarily zero), due to the response function of the CoMP instrument.
- Circular polarisation depends only on the direction of the magnetic field. Linear polarisation, however, depends on the direction of the magnetic field, **and** the density. Therefore, high densities suppress collisions and, as a result, suppress the linear polarisation.

Conclusions

- This sophisticated numerical MHD model of the solar atmosphere simulates an extremely active region of the Sun with a range of different solar events that all follow a similar energy distribution.
- This indicates that the geometry of a particular event does not influence how the magnetic energy is distributed after magnetic reconnection.
- The CME outlier does not follow the same distribution as the other events in the simulation.
- Since this simulation is a very "extreme" case, it has been useful to develop an understanding of the limitations of the FORWARD code, which could, in theory, help explain similar issues that occur in observations from instruments like CoMP.
- If observing a solar event or active region similar to that of the simulation, it is possible that CoMP would not be able to see the event at all.

References

M. Rempel (2016). Extension of the MURaM radiative MHD code for coronal simulations. *Astrophys. J.*
K. Shibata and T. Magara (2011). Solar flares: magnetohydrodynamic processes. *Living Rev. Solar Phys.*
S. Gibson, T. Kucera, et al., (2016). FORWARD: a toolset for multiwavelength coronal magnetometry. *Frontiers in Astronomy and Space Sciences.*
Y.-P. Li, P. Zhang, et al., (2016). On the power-law distributions of X-ray fluxes of solar flares observed with the GOES. *Research in Astron. Astrophys.*
F. Chen, M. Rempel, et al., (2017). Emergence of magnetic flux generated in a solar convective dynamo.i: formation of sunspots and active regions, and origin of their asymmetries.

Acknowledgements

Special thanks to Matthias Rempel, Feng Chen, Sarah Gibson, and Yuhong Fan for their guidance and advice. I would like to thank Martin Snow, and the LASP REU Program for giving me this opportunity. Thanks are also due to the High Altitude Observatory for hosting me.