Numerical MHD Coronal Simulations: Energy Statistics and FORWARD Analysis

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Introduction

- 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.

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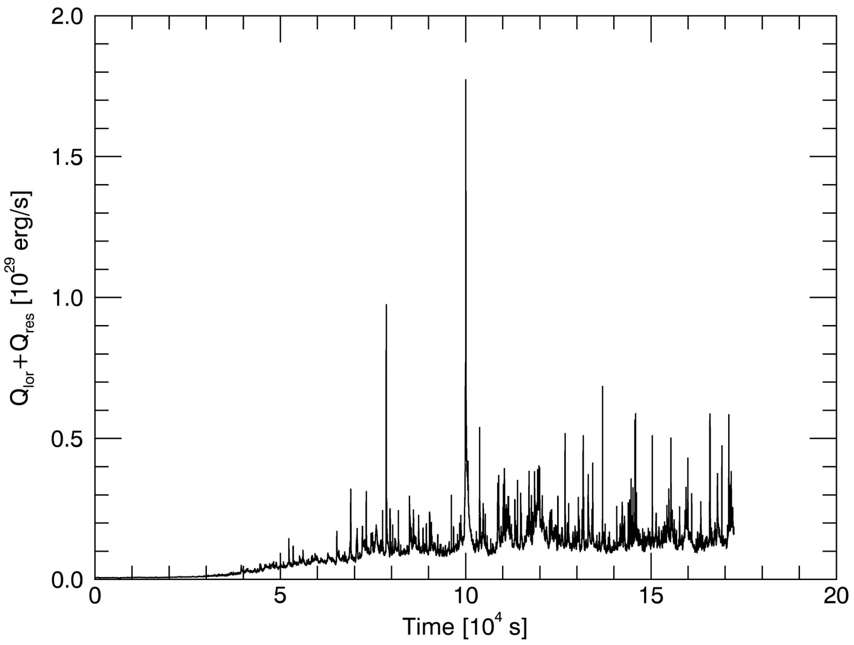
- The FORWARD code is a tool used for the purpose of coronal magnetometry. It compares physical properties of models with observable quantities, which helps to interpret observations of the Sun from instruments like the High Altitude Observatory’s CoMP instrument.
- The CoMP (COronal Multi-channel Polarimeter) instrument measures the intensity and the linear and circular polarisation of Fe XIII at 1074.7nm.

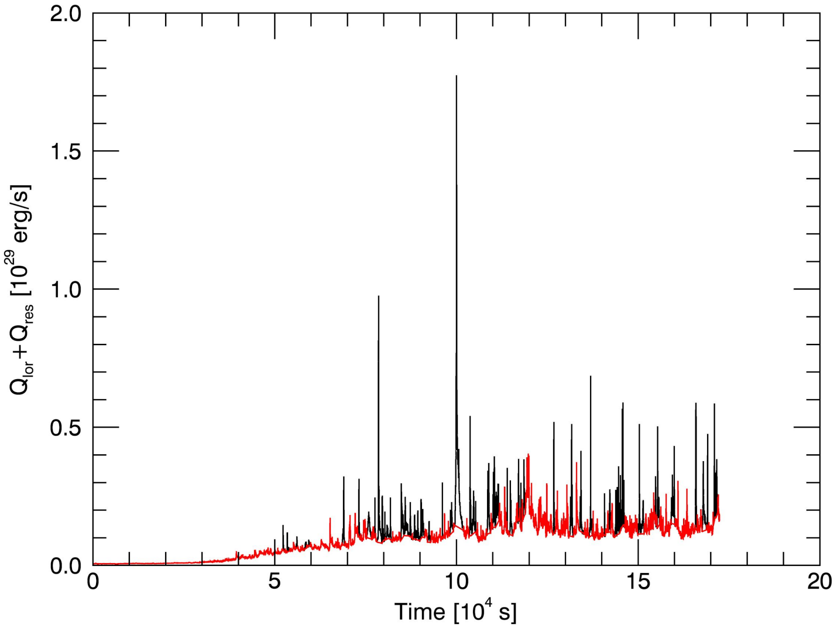
Identifying Flare Events in the Simulation



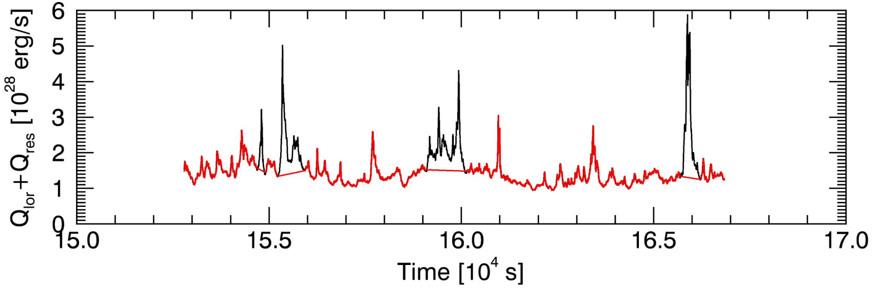
The Analysis...

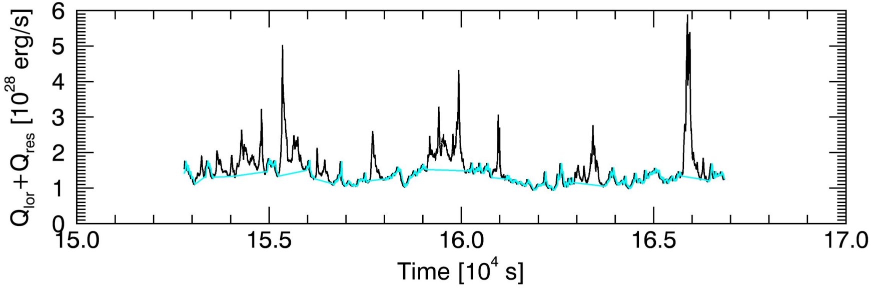
Input Parameters:

- Beginning and end indices of a subsection of the overall energy rate profile.
- The number of flares to identify in the subsection.
- The width of the smoothing window.
- The Lee filter box size.



Improvements to the Analysis



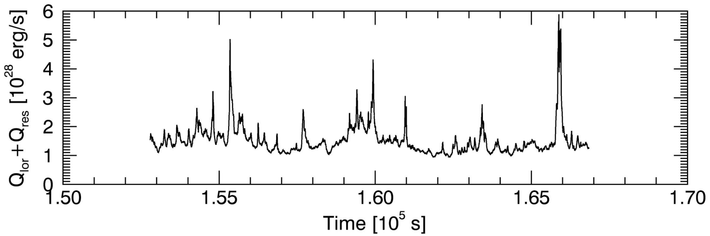


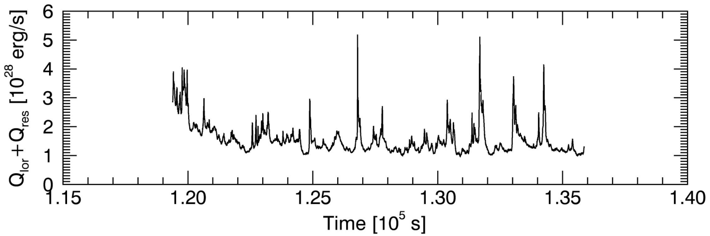
By considering smaller subsections of the overall profile and using the appropriate smoothing parameters, we can identify more of the smaller events.

Filtering: Three Cases

(a) Considering a subsection of the energy time series with multiple tall peaks (relative to the surrounding values in the time interval) separated by a lot of smaller peaks, requires a smoothing window width that is twice or three times as large as the Lee filter box size.

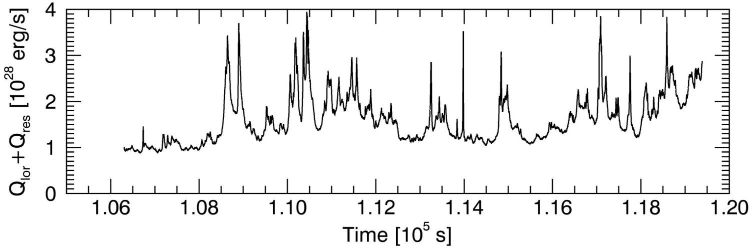
The top plot uses a Lee filter box size of 39 and a smoothing window width of 100, and identifies the four largest flares in the plot.
The bottom plot uses a lee filter box size of 85 and a smoothing window width of 190, and identifies the three largest flares in the plot.

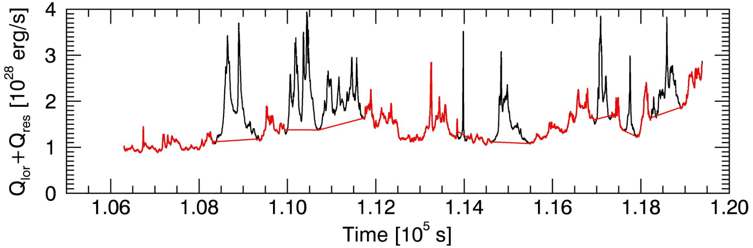




Filtering: Three Cases

(b) Regions of the time series that are made up of a lot of tall peaks, with very few smaller peaks separating them require a smoothing window width that is slightly smaller than the Lee filter box size.

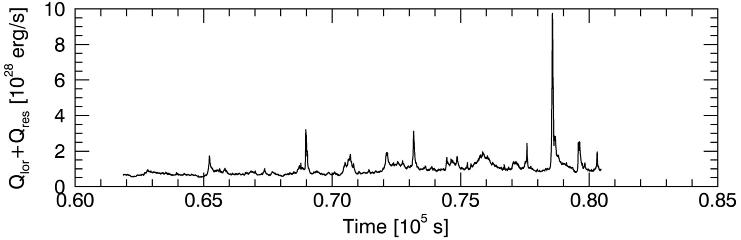


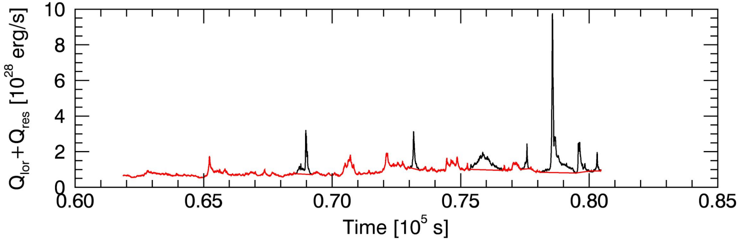


The Lee filter box size for this example is 65 and the smoothing window width is 50. The bottom plot shows the 8 identified events.

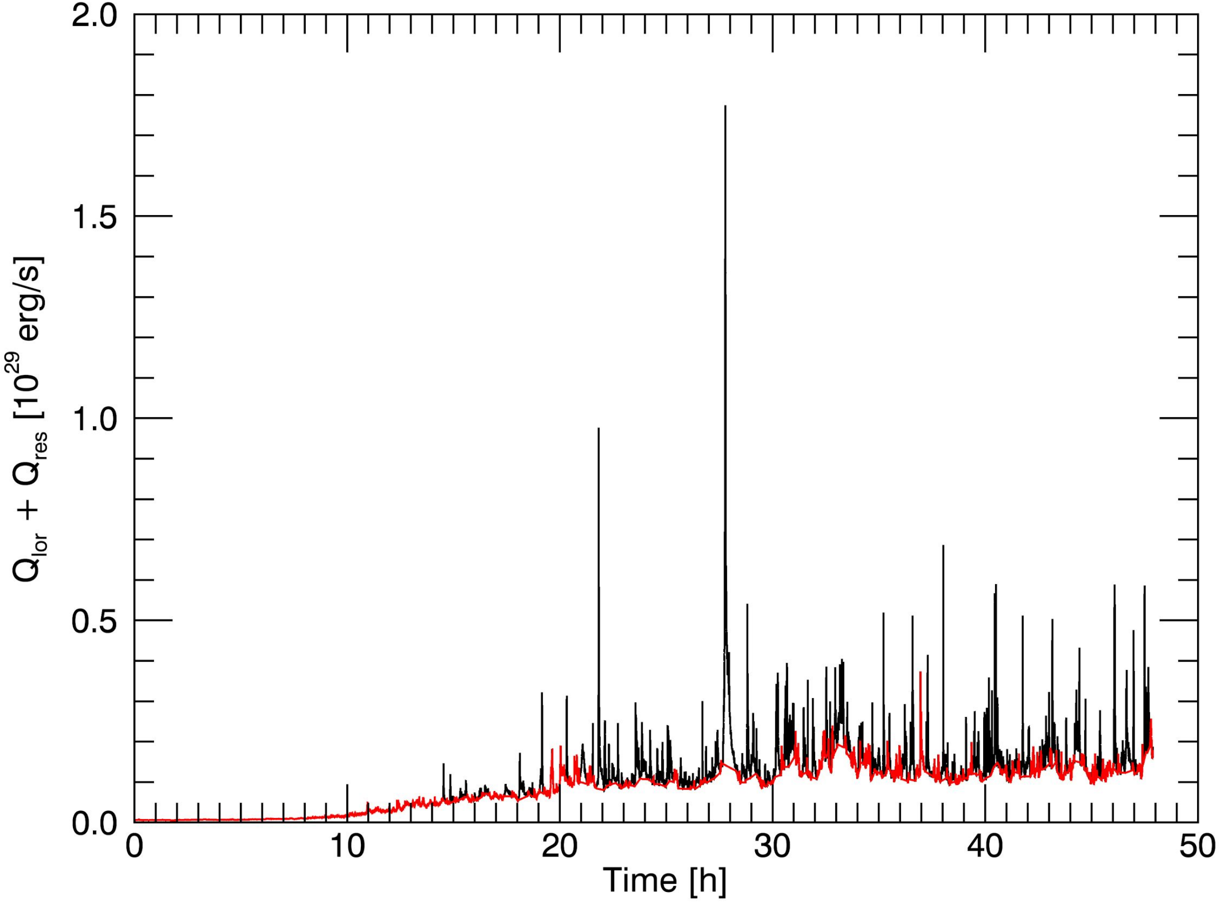
Filtering: Three Cases

(c) Regions of the energy time series that have clear, distinct peaks require a Lee filter box size that is slightly smaller than the smoothing window width.

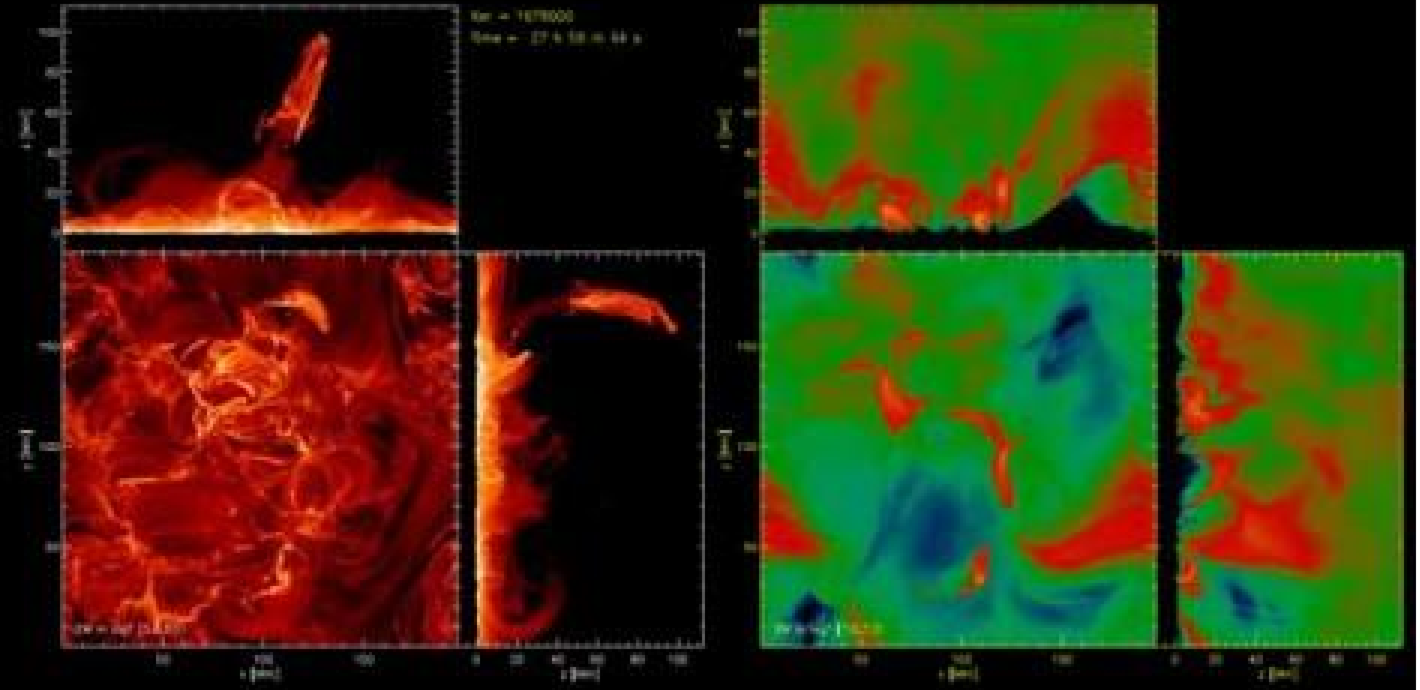




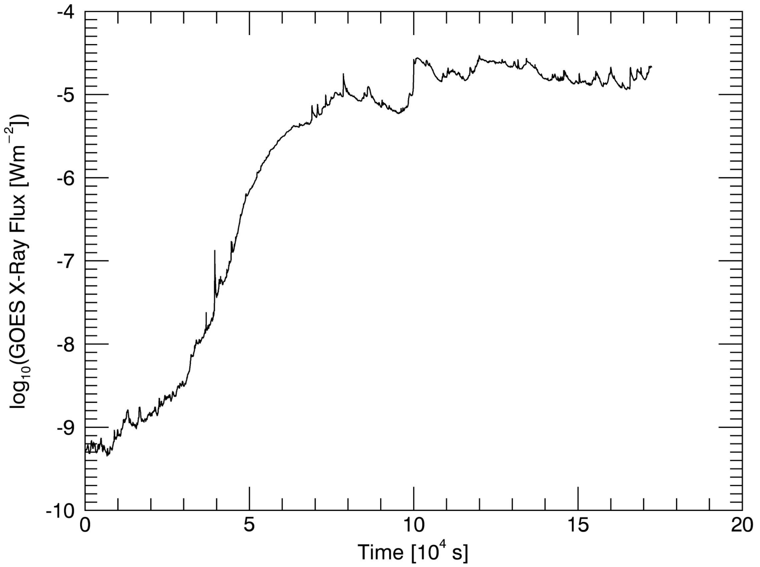
The Lee filter box size for this example is 43 and the smoothing window width is 50. The bottom plot shows the 7 identified events.



2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
Time [h]
Q_{lor} + Q_{res} [10^{29} erg/s]


50
100
150
0
20
40
60
80
100

GOES X-ray Flux

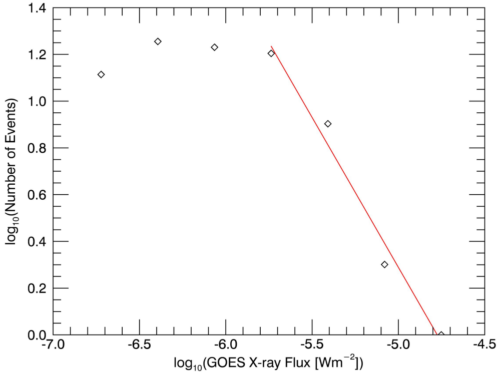


The simulation creates an X-ray flux mimicking observations by the GOES (Geostationary Operational Environmental Satellite) satellite in the wavelength range 1-8 Å.

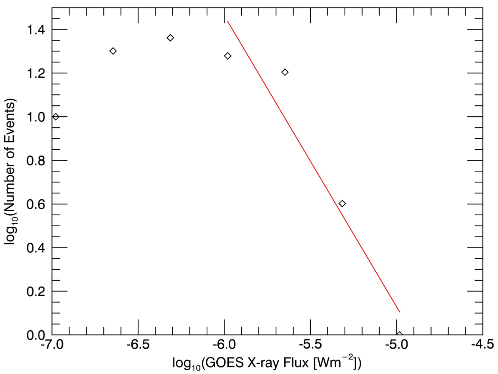
Two methods of determining the background:

1. Defining the background as the value of the GOES X-ray flux at the beginning of the flare.
2. Fitting a straight line between the beginning and end of the flare and defining the background as the value of the GOES X-ray flux on that line at the peak index.

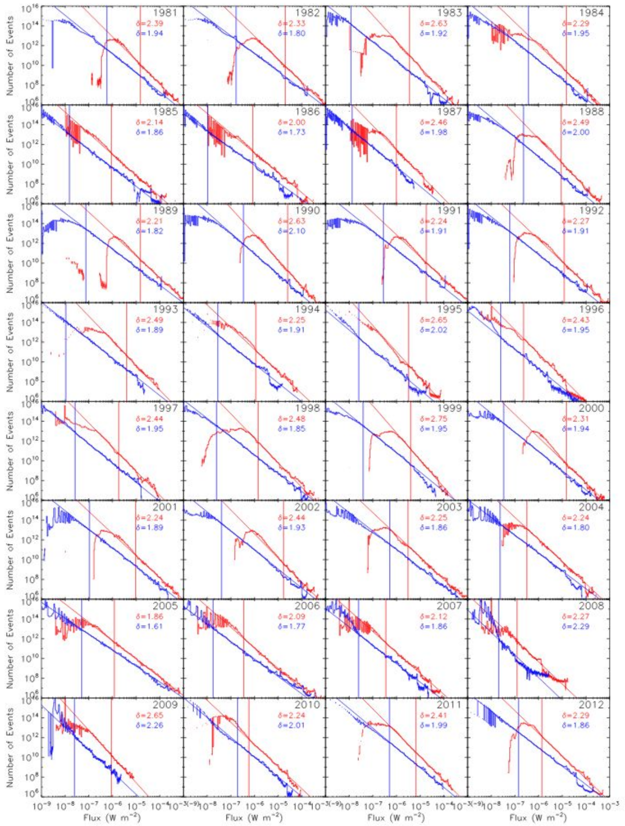
Power Law Relationship



Example 1. Gradient 1.28323.



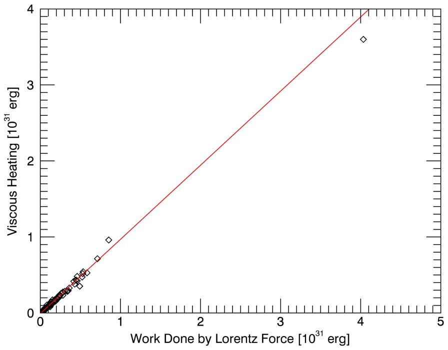
Example 2. Gradient 1.33452.



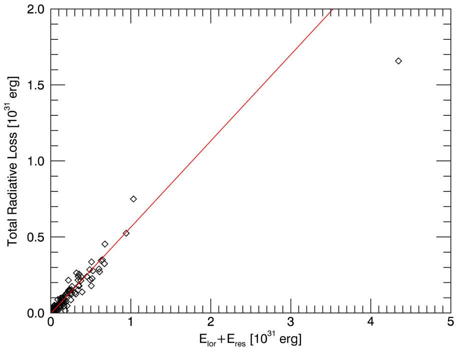
Y.-P. Li et al. (2016)

Overall shape of histogram matches observations pretty well.
Gradient of linear fit for flares of class C and above is slightly smaller than what observations have shown. This could be due to the lack of events in the simulation.

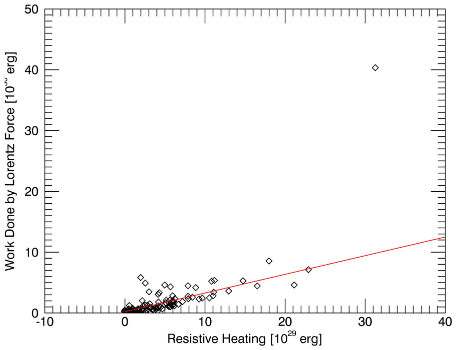
Energetics of the Simulated Flare Events



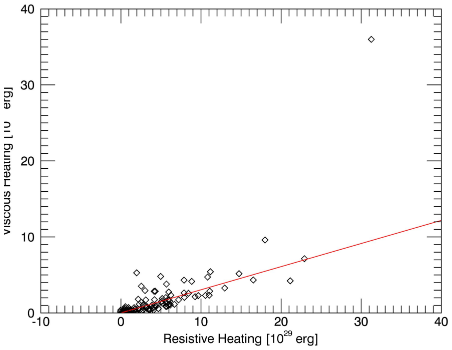
Gradient = 0.97528309



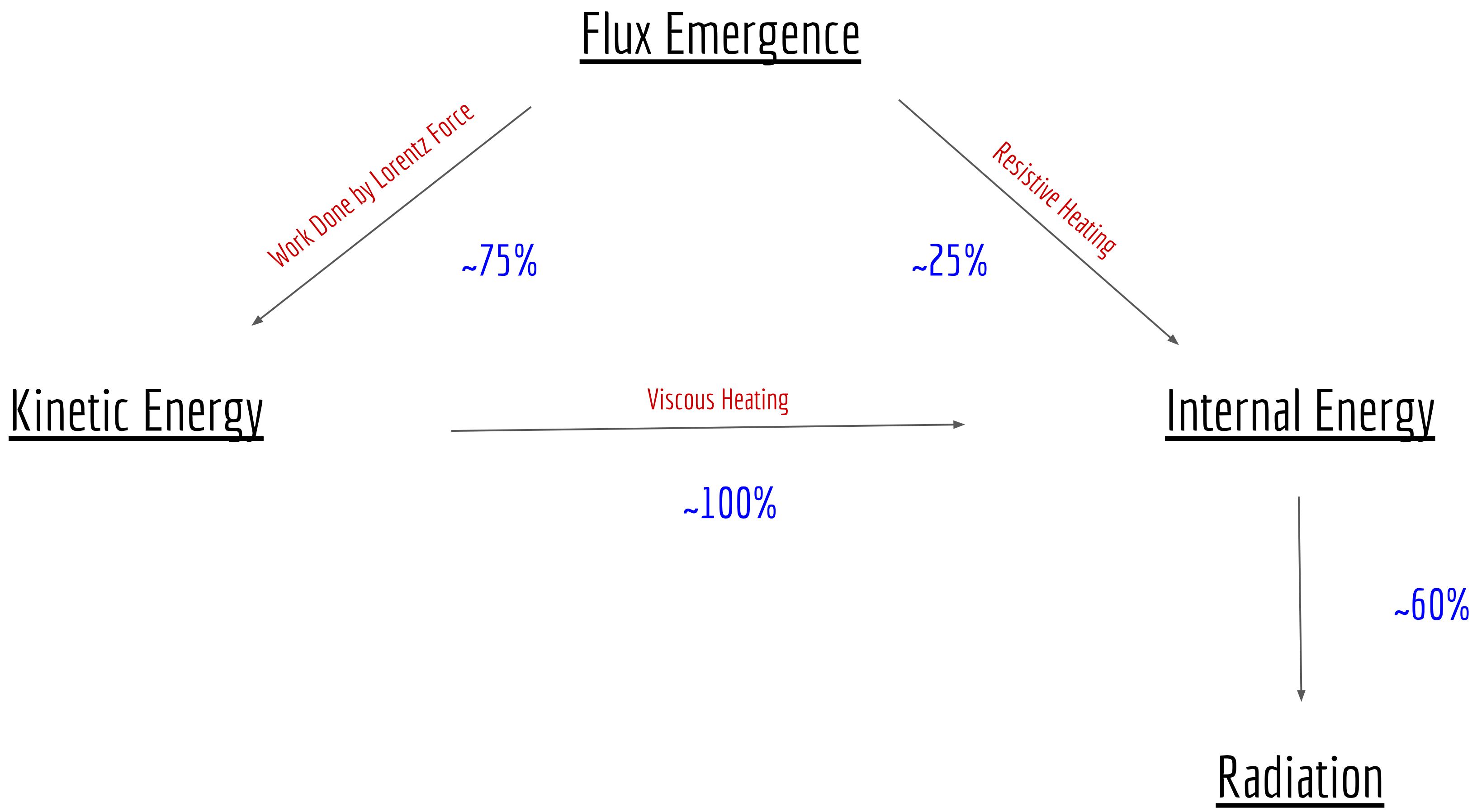
Gradient = 0.567776



Gradient = 3.06987



Gradient = 3.04253



Flux Emergence
Work Done by Lorentz Force
~75%
Resistive Heating
~25%
Kinetic Energy
Viscous Heating
~100%
Internal Energy
~60%
Radiation

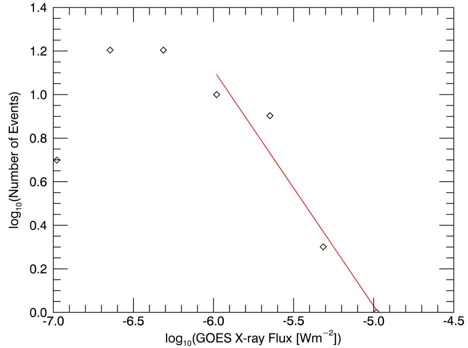
Complicated Events

Maybe more improvements needed to filter out these complicated system of events.

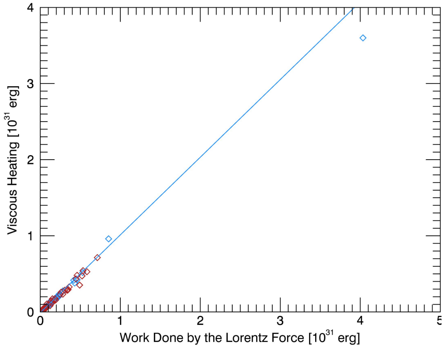
Clear Single Peak Events

GOES X-ray flux histogram changes.

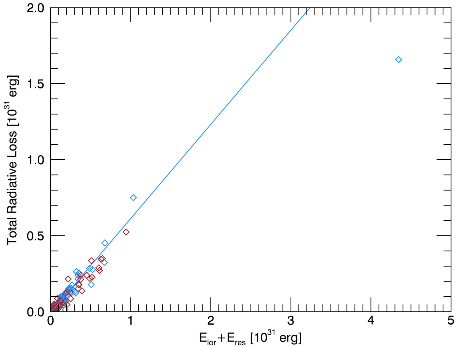
The four plots below of the energy distributions do not change too much when only considering the single peak events.



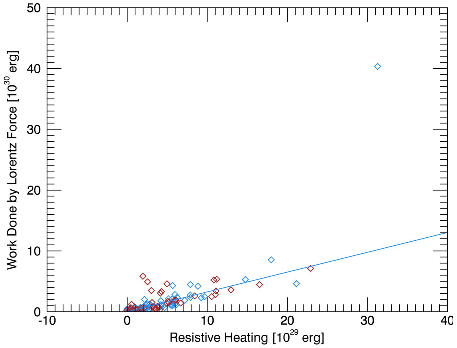
Gradient = 1.08307



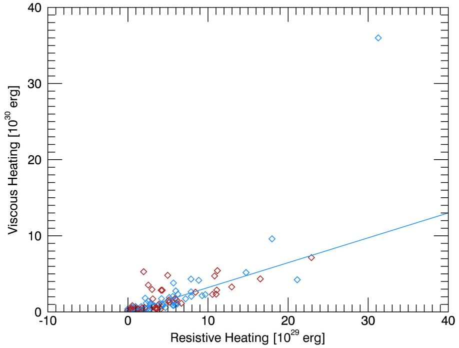
Gradient = 1.0203803



Gradient = 0.619405



Gradient = 3.2556782



Gradient = 3.2658238

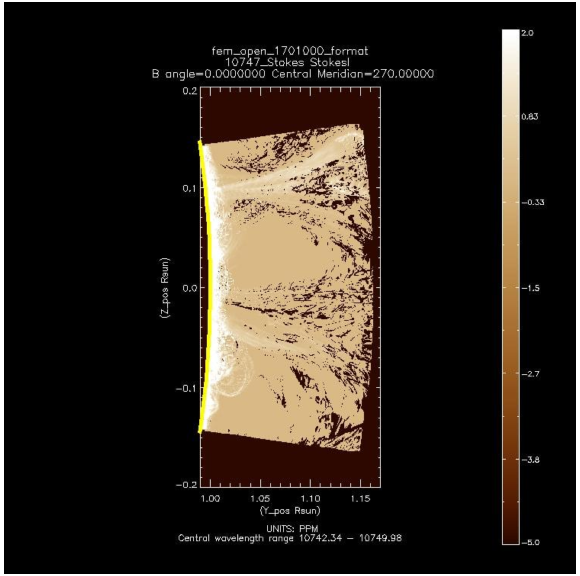
FORWARD Analysis

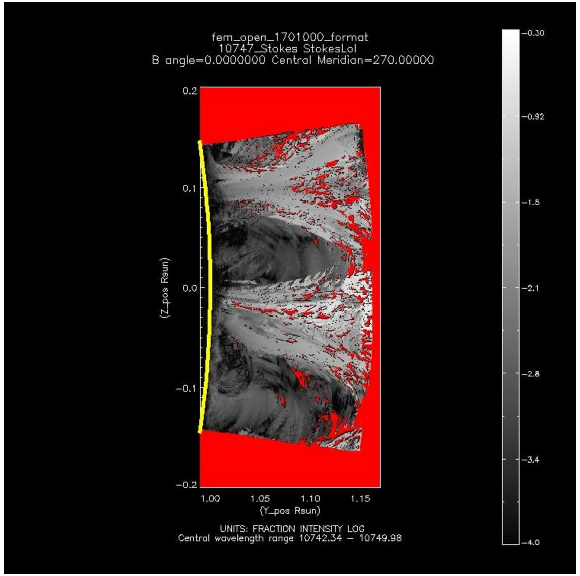
FORWARD is a tool used to compare the physical properties of models with observable quantities.

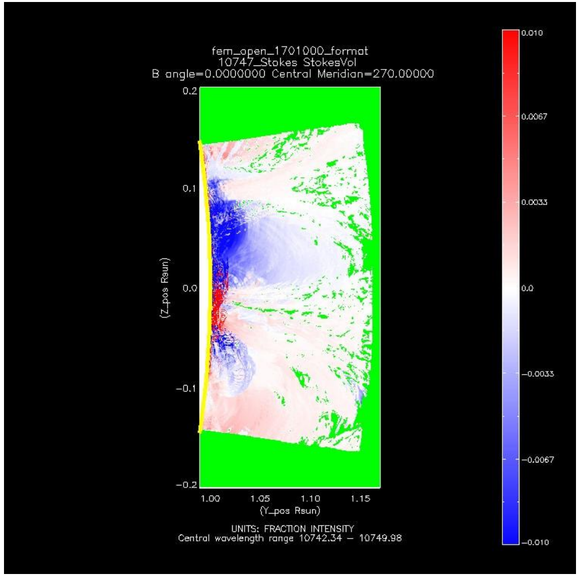
For this study, we focus on the interpretation of HAO's CoMP observations. We consider the linear and circular polarised light, as well as the intensity.

- Circular polarisation depends on the direction of the magnetic field in the line of sight.
- Linear polarisation depends on the direction of the magnetic field in the plane of sky.

FORWARD



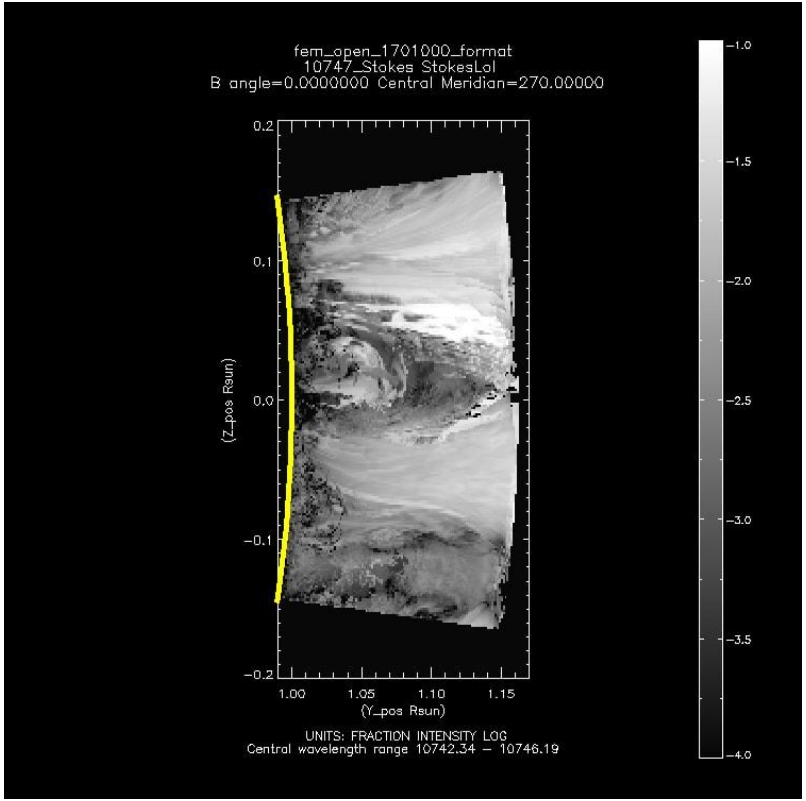




- High velocities?
- High temperatures?
- High densities?

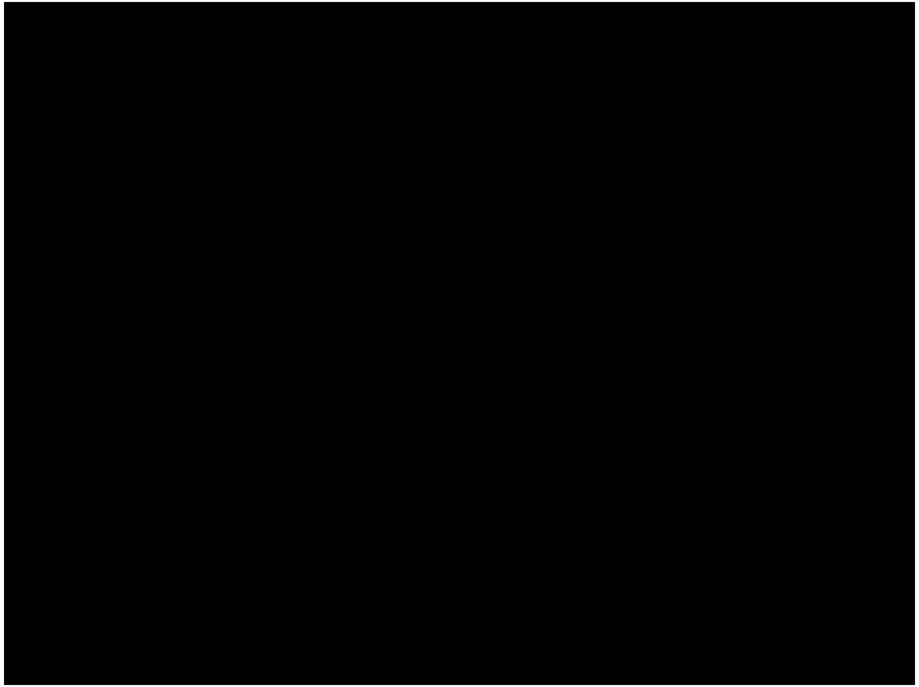
High Velocities Causing Null Pixels

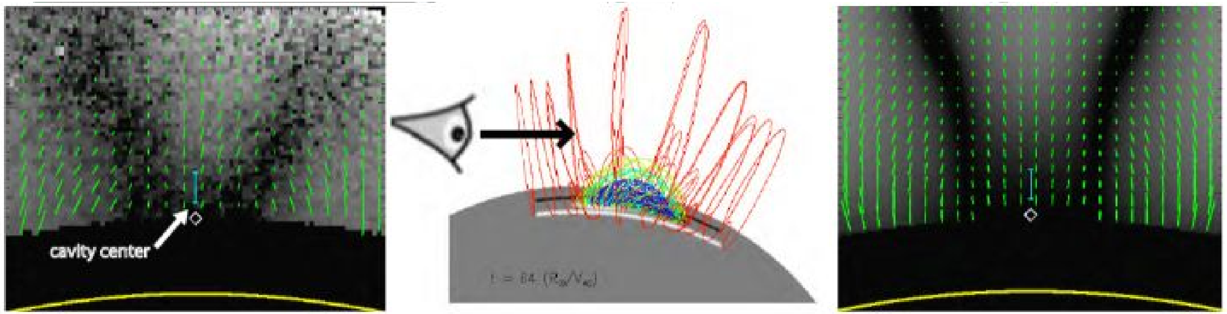
Large velocities cause Fe XIII line to be shifted out of the viewing window, leaving a null pixel.
By artificially setting the velocity to zero, the majority of the null pixels vanish.



High Temperatures and High Densities Causing Small Pixel Values

- 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 the linear polarisation.



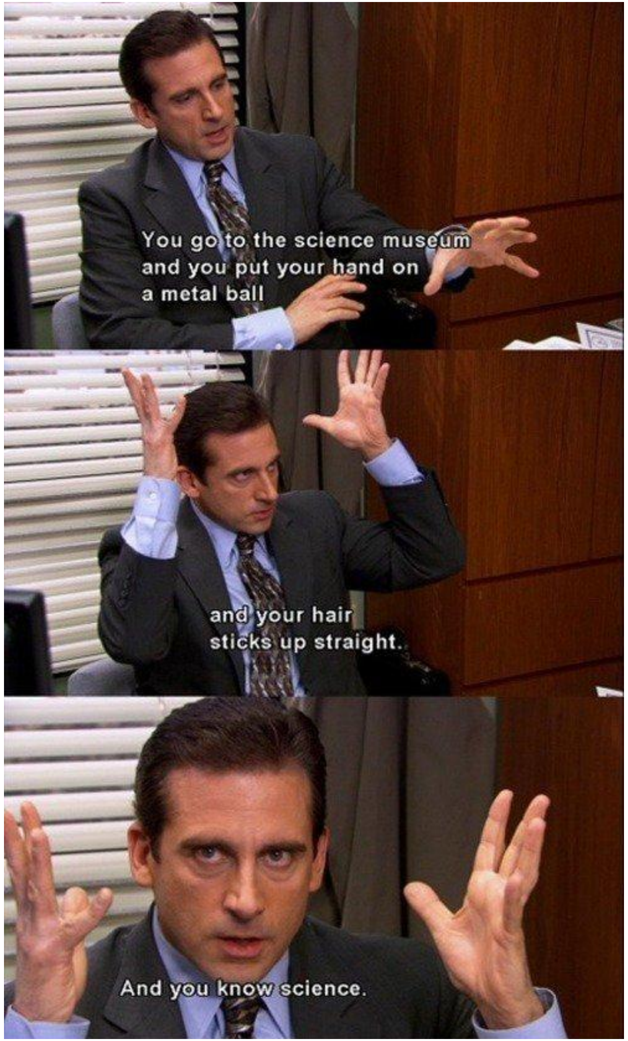


Bak-Steslicka et al. (2013)

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.

Questions?


You go to the science museum
and you put your hand on
a metal ball
and your hair
sticks up straight.
And you know science.

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.