12th European Solar Physics Meeting
8 - 12 September 2008
Freiburg, Germany

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3.3-41

Simulations of the CME-Flare Relationship

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Observations of coronal mass ejections (CMEs) and solar flares have revealed a high correlation between the acceleration of the ejecta and the plasma heating and particle acceleration signified by the soft and hard X-ray emissions of the associated flare. The latter are generally thought to result from magnetic reconnection. This finding has stimulated the discussion of the CME-flare relationship, but at the same time it has made it difficult to find a conclusive answer as to whether magnetic reconnection or an ideal MHD instability is the prime cause of the eruptions.

Numerical simulations of unstable flux ropes will be presented that are in very satisfactory quantitative agreement with erupting filaments, both, confined to the corona and ejective (i.e., developing into a CME). Some of these simulations indeed show a high degree of synchronization between the initial exponential acceleration of the flux rope, due to the ideal MHD instability, and the development of reconnection flows. However, others show a very delayed onset of reconnection, even after the flux rope's acceleration peak. In addition, the reconnection flows generally lag behind the motions driven by the ideal instability as the flux rope rise velocity nears the saturation phase. Both findings indicate that the ideal MHD process is the primary driver of the coupled CME-flare phenomenon.

The strong differences in the degree of synchronization, which the simulated systems show in the main rise phase of the eruption, are related to the magnetic topology prior to the eruption. Given the observational result of a high correlation between CME and flare development (Zhang & Dere 2006), these simulations yield constraints on the topology and lead us to conclude that a seed for a reconnecting current sheet must typically be present already at the onset of the eruption.

The CME-Flare Relationship on the Computer

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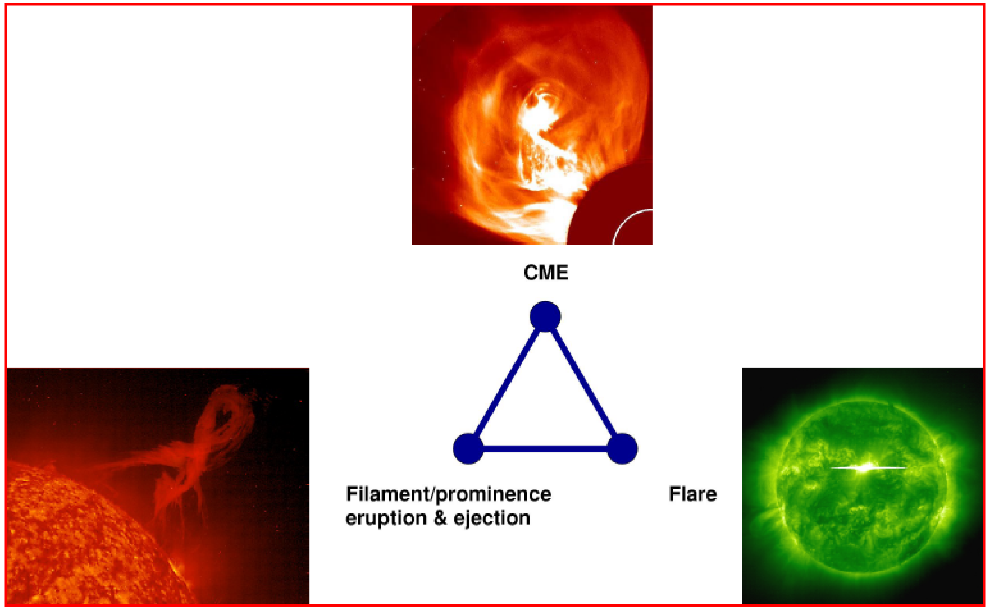
Abstract

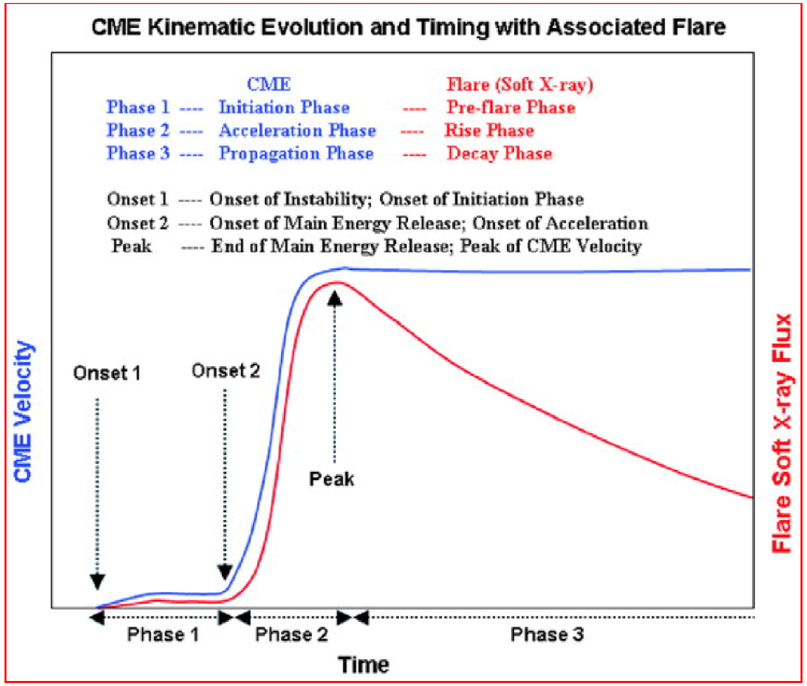
Observations of coronal mass ejections (CMEs) and solar flares have revealed a high correlation between the acceleration of the ejecta and the plasma heating and particle acceleration signified by the soft and hard X-ray emissions of the associated flare. The latter are generally thought to result from magnetic reconnection. This finding has stimulated the discussion of the CME-flare relationship, but at the same time it has made it difficult to find a conclusive answer as to whether magnetic reconnection or an ideal MHD instability is the prime cause of CMEs and flares. Numerical simulations of unstable flux ropes are presented that are in very satisfactory quantitative agreement with erupting filaments, both, confined to the corona and ejective (i.e., developing into a CME). Some of these simulations indeed show a high degree of synchronization between the initial exponential acceleration of the flux rope, due to an ideal MHD instability, and the development of reconnection flows. However, others show a very delayed onset of reconnection, even after the flux rope's acceleration peak. In addition, the reconnection flows generally lag behind the motions driven by the ideal instability as the flux rope rise velocity nears the saturation phase. Both findings indicate that the ideal MHD process is the primary driver of the coupled CME-flare phenomenon. The strong differences in the degree of synchronization, which the simulated systems show in the main rise phase of the eruption, are related to the magnetic topology prior to the eruption. Given the observational result of a high correlation between CME and flare development (Zhang & Dere 2006), these simulations yield constraints on the topology and lead us to conclude that a seed for a reconnecting current sheet must typically be present already at the onset of the eruption.

Introduction



Filament or prominence eruptions, CMEs, and flares are the three basic elements of large-scale solar eruptions. They often occur jointly and are thought to be different observational signatures of one (complex) process. The heating and particle acceleration observed in flares is generally believed to be due to magnetic reconnection in a vertical current sheet located below the erupting filament or CME. However, it is not fully clear what causes the acceleration of the ejected plasma: Is it the reconnection in the vertical current sheet or is it an instability or loss of equilibrium of the pre-eruptive sheared/twisted fields? Are both processes at work, and if so, how are they related and which one is dominant?

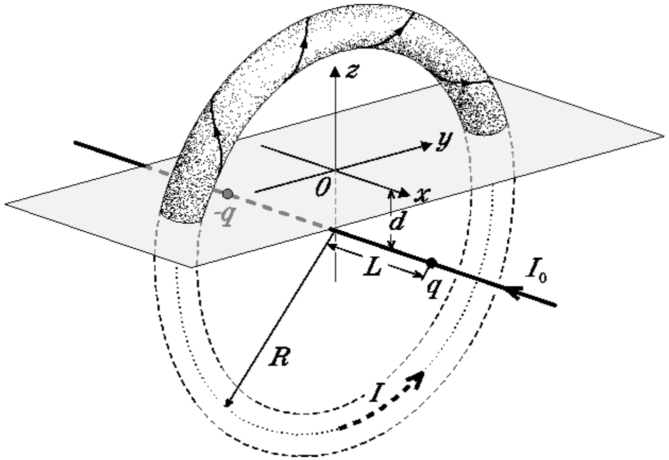
The CME-flare relationship



Zhang & Dere 2006

There have been many discussions in the past on how CMEs and flares are related and which one might cause the other. However, recent observations have shown that the main acceleration phase of CMEs and the main energy release phase of flares typically possess a high temporal correlation, indicating that: “CMEs and flares do not cause each other; instead, they both are the results of more fundamental processes. ... They are driven by the same physical process or by multiple processes that are physically coupled in the corona.” (Zhang et al. 2004)

Numerical simulations



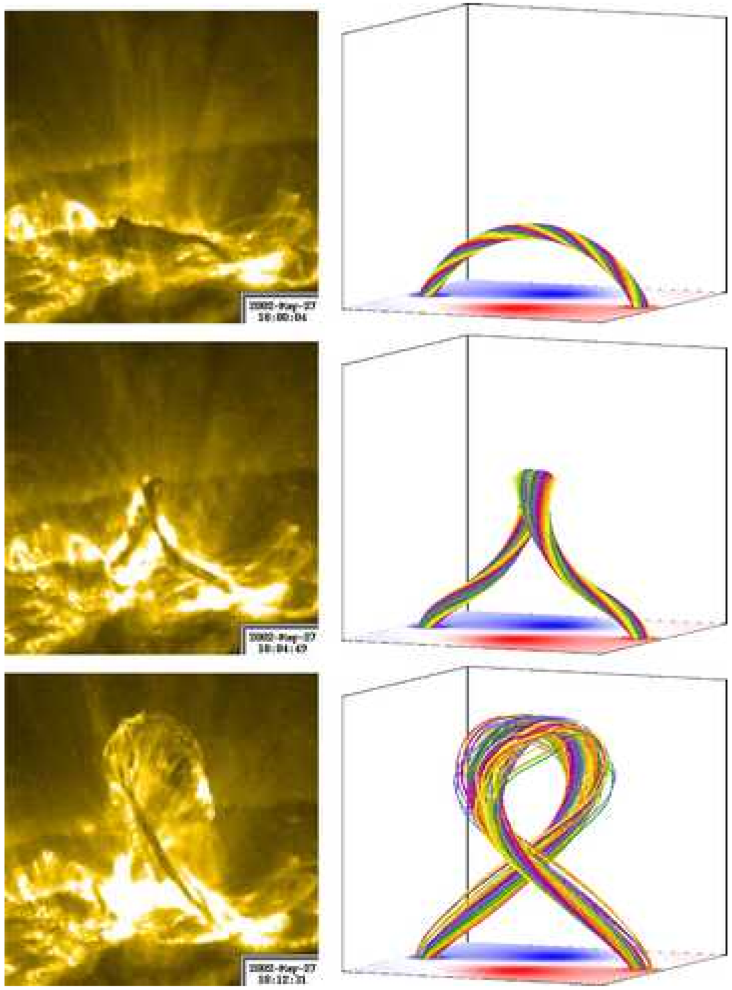
Titov & Démoulin 1999

In order to investigate the relationship between CMEs and flares, we present further diagnostics of our ideal MHD simulations (Török & Kliem 2005; Schrijver et al. 2008) of erupting magnetic flux ropes subject to the helical kink instability and the torus instability (Kliem & Török 2006). The coronal flux rope model by Titov & Démoulin *(left)* was used as initial condition in these simulations. The results reported here are supported by a wider parametric study (to be published separately).

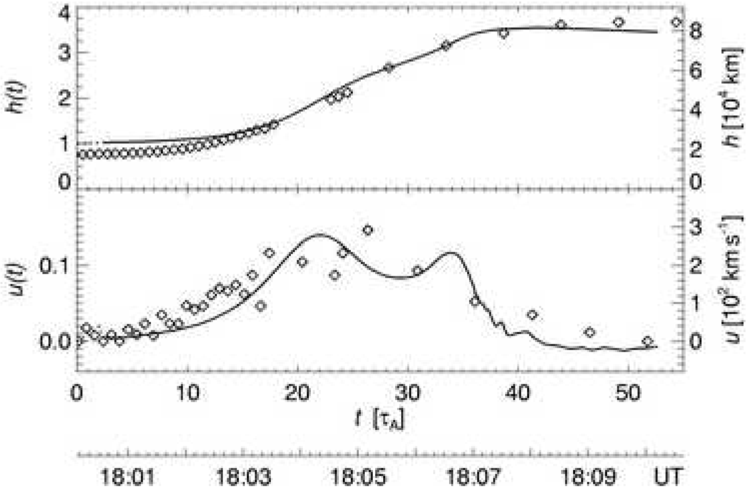
Here we ask the following questions:

- How close is the coupling between ideal flux rope instability (CME) and reconnection in the vertical current sheet below the rising flux rope (flare)?
- How does the coupling depend on magnetic topology and parameters?

Confined eruption

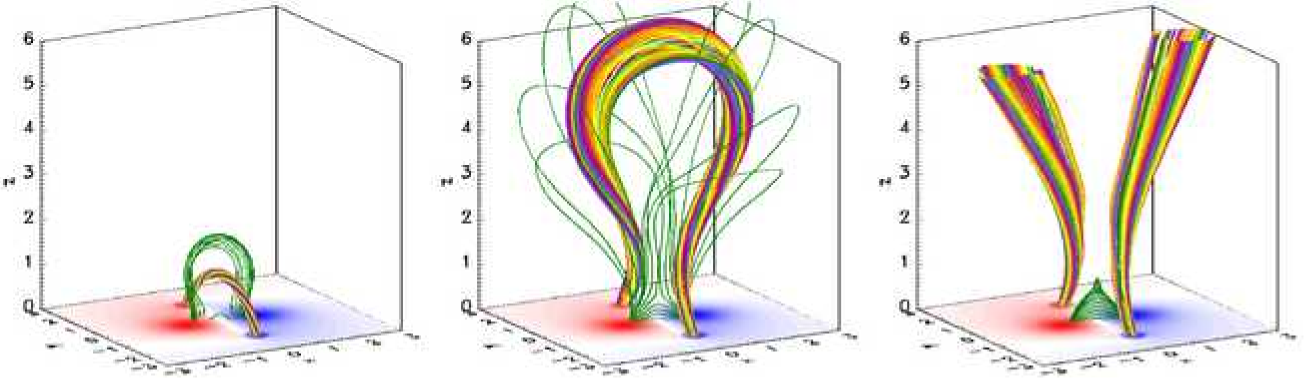


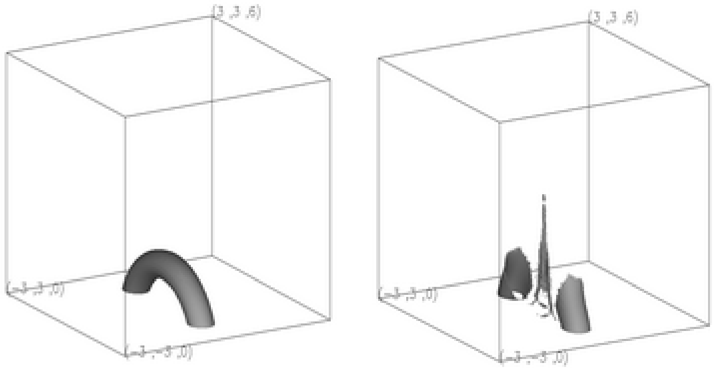
Török & Kliem 2005

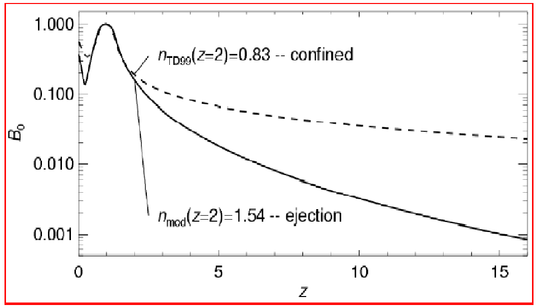


Left: simulation of the confined filament eruption on 2002 May 27. The flux rope eruption is driven by the kink instability. *Top:* apex heights and velocities of the flux rope (*solid lines*), scaled to the corresponding measurements of the filament (diamonds; data from Ji et al. 2003). We find a moderate correlation between the flux rope acceleration and the reconnection below it: the reconnection outflow sets in when the flux rope nears its peak velocity (at t > 18 and a height less than twice its initial height).

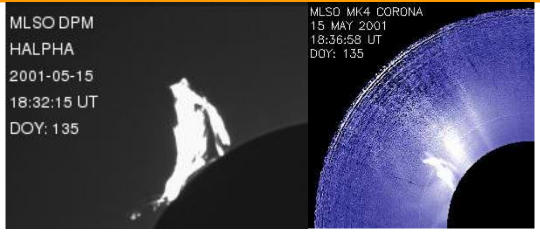
Ejective eruption

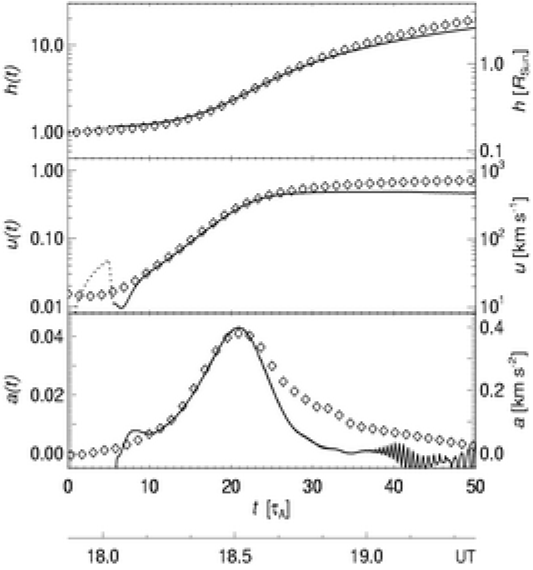






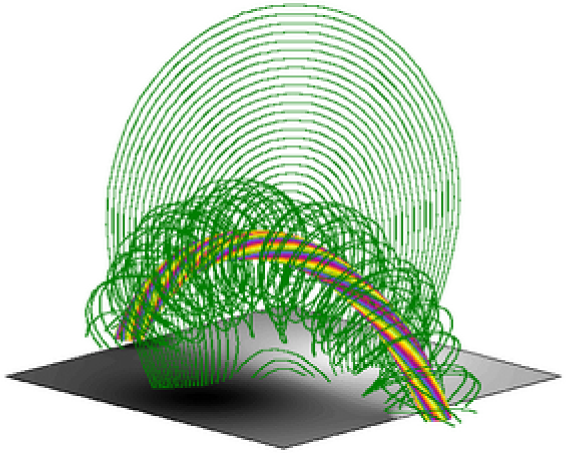
Török & Kliem 2005

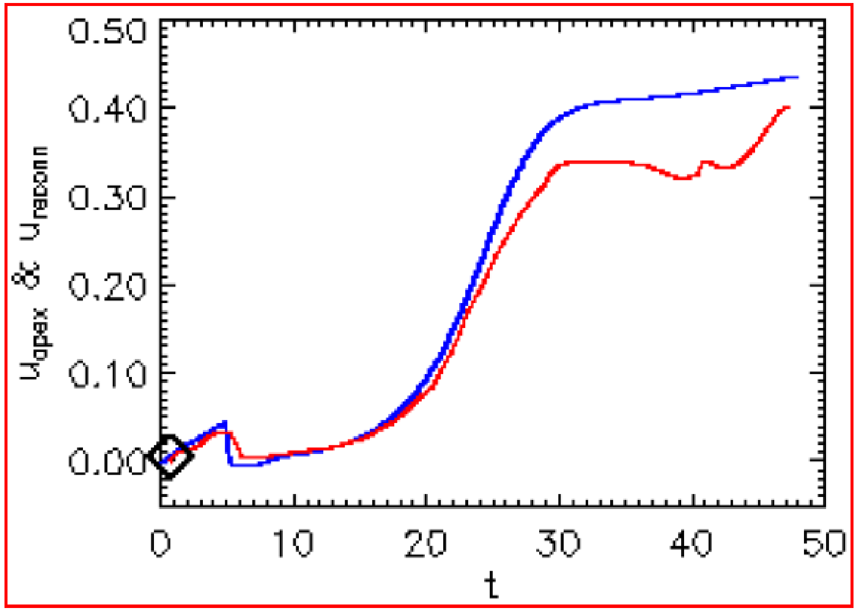




Ejective eruption of the TD flux rope driven by the combined action of the kink and torus instabilities. *Top left:* magnetic field lines outlining the flux rope core and the formation of a cusp. *Bottom left:* iso-surfaces of current density, showing the vertical current sheet below the rising rope. The flux rope has the same twist as in the confined eruption, but the overlying potential field drops faster *(bottom middle).* The rope kinematics were successfully scaled to a CME observed by Maricic et al. (2001) *(right)*.

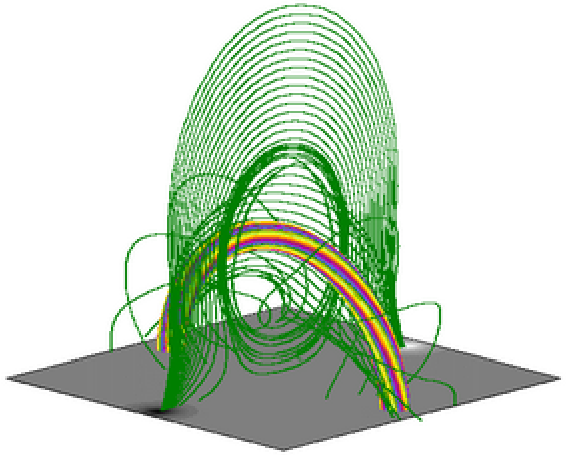
Instability vs. Reconnection --- with HFT

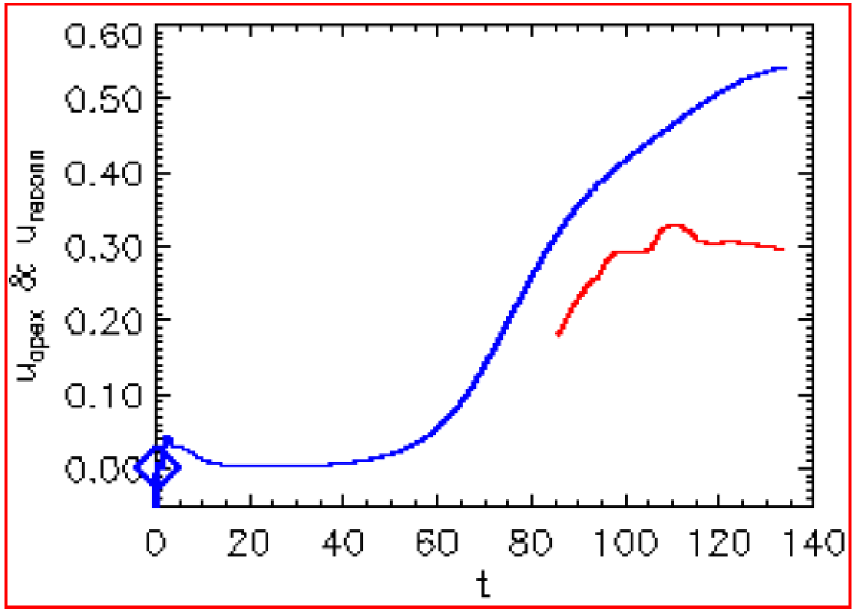




Left: magnetic field lines of the initial configuration of the ejective simulation, showing the ambient potential field and outer flux surfaces of the TD rope in green. An HFT (Hyperbolic Flux Tube --- a generalization of a magnetic X-line in 3D) is present below the rope. The vertical current sheet forms at the position of the HFT.
Right: flux rope apex velocity (blue) and peak velocity of the upward reconnection outflow below the rope (red) vs. time. Here we find a high correlation between flux rope acceleration and reconnection. However, it is also evident that the reconnection flow starts to lag behind the flux rope velocity as the latter approaches the saturation phase (t > 23).

Instability vs. Reconnection --- without HFT





Left: magnetic field lines (as on the former slide) of the initial configuration of a torus instability simulation described in Schrijver et al. (2008). This configuration has no HFT, but a ‘‘Bald Patch Separatrix Surface’’ (BPSS) topology. The vertical current sheet forms only after the flux rope has expanded considerably (see also Fan & Gibson 2006). *Right:* flux rope apex velocity (blue) and peak velocity of the upward reconnection outflow below the rope (red) vs. time. Here we find no correlation between flux rope acceleration and reconnection. The reconnection flow is clearly delayed and *starts only after the flux rope has reached its peak acceleration*.

Summary

- In configurations with an HFT, the ideal flux rope instability and the reconnection below the rising rope are closely coupled (positive feedback). The simulations suggest that the instability is the primary effect for the acceleration of the rope.

- In configurations without an HFT, the eruption is mainly driven by the instability. The onset of reconnection follows the onset of the instability with a clear delay. The peak acceleration of the rope can be reached without reconnection.

- These results suggest that the CME-flare timing allows to draw conclusions about the pre-eruptive topology (HFT vs. BPSS).

- They also suggest that CME/flare events are *not* exclusively due to “runaway reconnection” (as suggested by the Tether Cutting model).

- Given the observed high correlation of CME and flare development, the simulations indicate that the seed for current sheet formation is typically present already at eruption onset.

References

Fan Y. & Gibson S.E., ApJ ***637****, L65 (2006)*

Ji H., et al., ApJ ***595****, 135 (2003)*

Kliem B. & Török T., PRL ***96****, 255002 (2006)*

Maricic D.,et al., 2004, et al., SP ***225****, 337 (2004)*

Schrijver C., et al., ApJ ***674****, 586 (2008)*

Titov V.S. & Démoulin P., A&A ***351****, 707 (1999)*

Török T. & Kliem B., ApJ ***630****, L97 (2005)*

Zhang J., et al., ApJ ***604****, 420 (2004)*

Zhang J. & Dere K.P., ApJ ***649****, 1100 (2006)*