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Simulations of shock structures of a flare/CME event in the low corona

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Abstract. We study the MHD processes related to a flare/CME event in the lower solar corona using numerical simulations. Our initial state is an isothermal gravitationally stratified corona with an embedded flux rope magnetic field structure. The eruption is driven by applying an artificial force to the flux rope. The results show that as the flux rope rises, a shock structure is formed, reaching from ahead of the flux rope all the way to the solar surface. The speed of the shock quickly exceeds that of the driving flux rope, and the shock escapes from the driver. Thus, the shock exhibits characteristics both of the driven and blast wave type. In addition, the temperature distribution behind the shock is loop-like, implying that erupting loop-like structures observed in soft X-ray images might be shocks. Finally, we note that care must be taken when performing correlation analysis of the speed and location of type II bursts and ejecta.

Keywords. Sun: coronal mass ejections (CMEs); flares; radio radiation, shock waves, plasmas

1. Introduction

Large-amplitude waves and shocks launched by coronal mass ejections (CMEs) and flares are believed to play an important role in the generation of a number of solar transient phenomena such as type II radio bursts, Moreton waves, EIT waves and SEP events (see, e.g., Warmuth 2007 for an overview). However, the exact mechanisms linking the eruptions with the observed disturbances continue to be elusive. For instance, for type II radio bursts and Moreton waves, the debate continues whether the shock responsible for the disturbance is a flare-generated blast wave or instead driven by mass motions related to CME lift-off (see Vršnak & Cliver 2008 for a recent review).

In this study, we employ MHD simulations of CME lift-off to study the shock structures induced by the eruption. We focus especially on the shock formation process, and point out features that are of importance when interpreting observations.

2. Model

We perform ideal-MHD simulations of an erupting CME in a local model of the low corona. The coronal plasma is assumed to be isothermal with an exponentially decreasing density profile balancing gravity, while the potential background magnetic field is quadrupolar. Thus, the Alfvén speed of the model corona increases as a function of height. In addition, we superpose a flux rope with increased density on top of the background plasma. Fig. 1 shows the density and Alfvén speed of the initial state. The filament-like structure is then made to erupt by invoking an artificial force that acts on the filament plasma during the simulation. For details of the model, consult Pomoell *et al.* (2008).

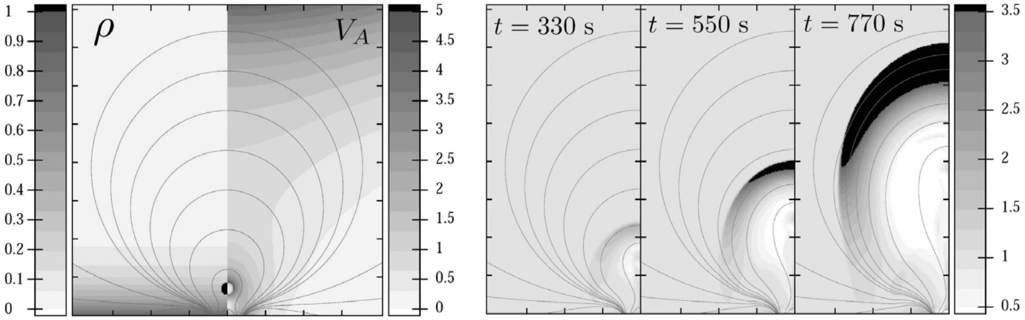

Figure 1. Left: The initial state of the simulation: density (left half) and Alfvén speed (right half). The lines depict magnetic field lines. The tick marks are drawn at intervals of 5×10^4 km. The units in the color bars are for the density (left bar) 1.67×10^{-12} kg m^{-3} and for the Alfvén speed (right bar) 91 km s^{-1}. Right: Temperature at three different times of the eruption. The unit in the color bar is 0.636×10^6 K. Note the clipping of the color bar; a black (white) color indicates values larger (smaller) than the color bar maximum (minimum).

3. Results

The dynamics of the eruption is as follows:

(*a*) A perturbation surrounding the flux rope is quickly formed as the flux rope starts to rise under the influence of the artificial force.

(*b*) As the driving flux rope picks up speed, the outward propagating wave surrounding the flux rope develops to a shock ahead of the flux rope. The speed and strength of the shock are highest at the leading edge, and decrease towards the flanks, degenerating to a fast-mode wave close to the solar surface.

(*c*) The speed of the shock quickly exceeds that of the driving flux rope, and the shock escapes from the flux rope as its speed continues to increase due to the increasing Alfvén speed of the ambient corona. However, the shock starts to lose strength once it escapes from the driver.

(*d*) At the end of the simulation, when the shock approaches the upper boundary, the eruption has evolved into a large global structure. However, the driving flux rope has remained roughly the same size during the eruption.

4. Discussion

4.1. *Shock formation: a driven blast wave*

The flux rope motion launches a coronal shock wave, which propagates in all directions from the driver. It nevertheless remains strongest near the leading edge of the shock, which emphasizes the role of the driver. However, due to the increasing Alfvén speed of the corona, the shock starts to escape from the driver. In this sense, the shock expands more like a freely propagating than a driven wave. Thus, caution must be practised in labeling shocks as being either driven waves or blast waves, as low cadence observations could lead one to make an erroneous conclusion about the mechanism responsible for generating the shock.

4.2. *Shocks and soft X-ray observations*

The temperature plot (Fig. 1) reveals an arc of extremely hot plasma (downstream of the shock front), which could easily be interpreted as a hot erupting coronal loop. However, the feature is not a loop but a wave. Thus, one must be careful when interpreting propagating loop-like features in coronal soft X-ray images, some of them might actually be

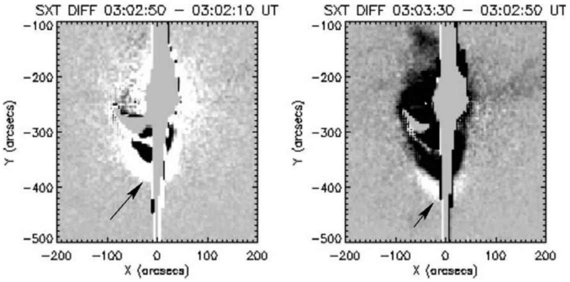

Figure 2. SXT difference images (AlMg filters) at 03:02:50 UT and 03:03:30 UT, 13 May 2001, showing a loop-like eruption front in soft X-rays. See Pohjolainen *et al.* (2008) for details.

shock waves. For instance, in an event studied by Pohjolainen *et al.* (2008), SXT difference images (Fig. 2) show a loop-like eruption front, which could in fact be the signature of a shock wave. Similar structures have been identified as shocks in Yohkoh SXT images in conjunction with Moreton waves, see Khan & Aurass (2002) and Narukage *et al.* (2002).

4.3. *Ejecta and type II burst correlations*

Recently, Shanmugaraju *et al.* (2006) analysed 18 events of X-ray plasma ejections associated with coronal shocks inferred from metric type II bursts, and concluded that the absence of correlation between the speeds of ejecta and type IIs as well as the sub-Alfvénic speeds of the ejections are factors not in favor of the ejecta to be the main driver of all coronal shocks. Our results suggest a number of important points to note when performing such an analysis of observations. First, a sub-Alfvénic ejection is capable of launching a shock, since a wave can steepen to a shock due to nonlinear evolution of the wave profile. Also, if a wave enters a region with low Alfvén speed, the wave can quickly steepen to a shock. Such behaviour of the shock has actually been proposed to cause fragmented high-frequency type II emission (Pohjolainen *et al.* 2008).

Furthermore, depending on the variations of the Alfvén speed in the corona, the ejection can at times act as the driver, while at other times the shock may propagate freely. If we assume that type II bursts are generated at the leading edge of the shock, where the shock is strongest, the speeds and locations of the ejecta and burst may not be correlated in any simple way. Thus, we conclude that observations in conjunction with modeling are needed in order to resolve such correlation issues.

References

Khan, J. I. & Aurass, H. 2002, *A&A*, 383, 1018

Narukage, N., Hudson, H. S., Morimoto, T., Akiyama, S., Kitai, R., Kurokawa, H., & Shibata, K. 2002, *ApJ*, 572, L109

Pohjolainen, S., Pomoell, J., & Vainio, R. 2008, *A&A*, 490, 357

Pomoell, J., Vainio, R., & Kissmann, R. 2008, *Solar Phys.*, 253, 249

Shanmugaraju, A., Moon, Y.-J., Kim, Y.-H., Cho, K.-S., Dryer, M., & Umapathy, S. 2006, *A&A*, 458, 653

Vršnak, B. & Cliver, E. W. 2008, *Solar Phys.*, 253, 215

Warmuth, A. 2007, in: Klein, K.-L. & MacKinnon, A. L. (eds.), *The High Energy Solar Corona: Waves, Eruptions, Particles*, Lecture Notes in Physics, vol. 725, p. 107