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Active Region evolution prior to magnetic flux rope ejections

P. Pagano and D. H. Mackay
University of St Andrews - St Andrews, UK

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Summary. — Magnetic flux rope ejections from the Sun are the main progenitors of Coronal Mass Ejections and thus driver of the Space Weather. To study and understand these phenomena is key to tackle the challenges of Space Weather and to do so we need tools to identify where and when magnetic flux ropes are ejected. We run a non-linear force-free field magnetofrictional simulation of the active region AR11261 over the two days prior to an observed magnetic flux rope ejection. We analyse the distribution of three quantities from the numerical model at the time of the flux rope ejections and we verify that in this application they highlight the location where the flux rope ejection originates.

1. – Introduction

To predict the occurrence of solar eruptions is one of the current challenges for the solar physics community. Solar eruptions are the most violent driver for the space weather and a number of observed phenomena in the solar corona are generated in the aftermath of solar eruptions.

In this scenario, a technique that can track the occurrence of solar eruption would bring a significant contribution. In our work we focus on the ejection of magnetic flux rope, a subset of what is being referred as solar eruptions, but certainly a key phenomenon to address especially in connection with space weather, where magnetic flux rope ejections are the most common progenitors of Coronal Mass Ejections (CMEs). Magnetic flux rope are twisted magnetic structures connecting opposite polarities in the solar photosphere. They form during a sequence of quasi equilibrium stages where the magnetic field slowly evolves responding to photospheric changes that inject twist in the coronal magnetic field [1]. Magnetic flux ropes are most commonly found in active regions.

In this work we address the properties of the evolution of the 3D magnetic configuration of the active region AR11261 where a magnetic flux rope ejection occurred and we illustrate some quantities derived from such evolution that can indicate the build up of the eruption phase. To do so, we use the non-liner force-frree field (NLFFF) magnetofrictional model introduced in [2] that describes the evolution of the 3D configuration of the magnetic field of an active region. We then proceed with the investigation of the magnetic configuration, identifying the possible signatures of the build up to a magnetic flux rope ejection, i.e. the presence of magnetic flux ropes and the Lorentz force that is ultimately responsible to expel magnetic structures in the corona.

2. – Model and Observation

In order to investigate the properties of the magnetic configuration of an active region prior to a magnetic flux rope ejection we study the specific case of the AR11261 [3]. In this study a time series of 3D magnetic configurations are obtained from a corresponding time series of magnetograms [2, 4].

In this model the time dependent magnetic field configuration is derived from dynamic reconstruction of the magnetic field as result of two simultaneous processes. One is the evolution of the vertical component of the magnetic field at the lower boundary. The other is the simultaneous relaxation of the magnetic field in the computational domain that is done using a magnetofrictional technique. This model has been already successfully used to generate realistic magnetic configurations that can reproduce observed dynamic phenomena in the solar corona, e. g. the synthesis of AIA observations of magnetic flux rope ejections [5], the initiation of a CME [3], or reproducing sigmoids and the formation of magnetic flux ropes [4, 6].

Our computational box is defined in a cartesian coordinate system, where z is the vertical direction and x and y the horizontal ones. The bottom boundary represents the solar surface and evolves to match the vertical component of the magnetic field from the observed magnetograms. In this model the initial magnetic configuration is assumed to be potential and a non-potential component of the magnetic field develops during the evolution and thus magnetic flux ropes can form. Fig.1 (left panels) shows the initial magnetic configuration, i.e. the potential magnetic field and the final one that is around the time when the magnetic flux rope ejection occurred. In our model, before this time a magnetic flux rope forms along the polarity inversion line (PIL) and is about 0.03 $R_\odot$ long, centred at the heliographic coordinates x = 0 , y = 0.02 $R_\odot$ in Fig.1. The initial magnetic field configuration is potential and thus force-free, however as the simulation progresses, the relaxation of the magnetic field is continuously perturbed by the changing boundary conditions, and the magnetic field is no longer force-free and a non-zero Lorentz force appears especially near the lower boundary. Fig.1 (right hand side panels) shows the z component of the Lorentz force (LF_z) at the lower boundary at the beginning of the simulation (upper right panel) and at the end around the flux rope ejection time (lower right panel). Positive and negative values of the Lorentz force appear throughout the domain and not only in the region where the magnetic flux rope forms.

3. – Properties of the magnetic configuration before eruption

The first quantity we take into consideration is the function that is a proxy for the development of magnetic flux ropes already used in [3] and [7]:

$$\Omega_{x,y,z} = \frac{|B \times \nabla B_{x,y,z}|}{|\nabla B_{x,y,z}|} \tag{1}$$

The function Ω is dependent on the twist of the magnetic field and its strength. Such a function peaks at the spatial locations where magnetic flux ropes have formed or are

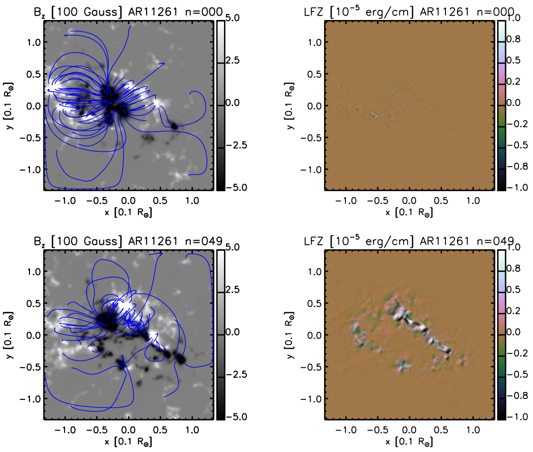

Fig. 1. – On the left hand side column, maps of the vertical component of the magnetic filed (B_z) at the lower boundary of the magnetofrictional simulations at the beginning of the simulation (upper panels) and near the time of eruption (lower panels) for AR11261 with some significant magnetic field lines over plotted. On the right hand side corresponding maps of the vertical components of the Lorentz force (LF_z).

about to form. In order to have time dependent 2D maps of the active regions, we take into account the vertical integral of Ω.

$$\omega\left(x,y,t\right)=\int_{z=0}^{z=z_{max}}\sqrt{\Omega_x^2+\Omega_y^2+\Omega_z^2dz} \tag{2}$$

where $z=0$ is the lower boundary and $z=z_{max}$ is the upper boundary.

Second, we focus on the vertical component of the Lorentz force. A key aspect of this approach is to consider its vertical integral in order to identify where a positive Lorentz force is not balanced by negative ones at different layers. Additionally, because of the heterogeneity of the Lorentz force distribution as shown in Fig.1 we average its value around a circle $C(x,y)_{0.7Mm}$ of radius 0.7 Mm and centred in x,y.

$$\mu\left(x,y,t\right)=\frac{\int_{C(x,y)_{0.7Mm}}\int_{z=0}^{z=z_{max}}LF_z\left(x',y',z,t\right)dzdx'dy'}{C_{0.7Mm}} \tag{3}$$

The function $\mu\left(x,y,t\right)$ is closely correlated with the vertical Lorentz force. At the same time, positive values of $\mu\left(x,y,t\right)$ are not necessarily followed up by an ejection, as these occurrences can get balanced in a smooth rearrangement.

Finally, unstable regions are where the Lorentz forse is highly heterogeneous and we consider the mean quadratic departure from the average as it is defined by Eq.3.

$$\sigma\left(x,y,t\right)=\frac{\int_{C(x,y)_{0.7Mm}}\sqrt{\left[\int_{z=0}^{z=z_{max}}LF_z\left(x',y',z,t\right)dz-\mu\left(x,y,t\right)\right]^2}dx'dy'}{C_{0.7Mm}} \tag{4}$$

The quantity $\sigma\left(x,y,t\right)$ is a measure of how heterogeneous the Lorentz force is within the circle $C(x,y)_{0.7Mm}$. We find that the distribution of $\sigma\left(x,y,t\right)$ may or may not be

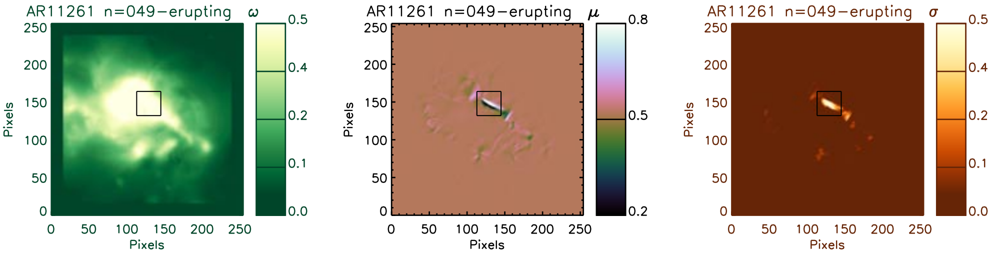

Fig. 2. – Maps of ω, μ, and σ at the time of the magnetic flux rope ejection.

correlated to the distribution of $\mu\,(x, y, t)$, but interestingly there are regions where both functions show high values. In this regions, the integral of the Lorentz force is positive and heterogeneous, thus there can be locations where the the Lorentz force is significantly higher or lower than its mean value.

Fig.2 shows the value of ω, μ, and σ at the end of the magnetofrictional simulation normalised between 0 and 1 that roughly corresponds to the time of the magnetic flux rope ejection in AR11261. We find that the patter of ω identifies a broad region that includes the polarity inversion line, that μ is strongly positive or negative in the part of the PIL where a magnetic flux rope was identified, and values of σ are found in the same region.

4. – Conclusions

In this work we model the evolution of the active region AR11261 in the two days prior to an observed magnetic flux rope ejection that has been studied and analysed in details in [3]. We focus our analysis on the 3D magnetic configuration and we show that some properties of such configuration can highlight where the magnetic flux rope ejection originates from. In particular we have studies the functions ω, μ and σ that concern in different way the region of the ejection. This study suggests some quantities that are relevant to be modelled or measured in order to identify the location of a magnetic flux rope ejection.

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