Decoding the Pre-eruptive Magnetic Configurations of Coronal Mass Ejections

A Proposal for an ISSI International Team in Space Science

Abstract

Coronal Mass Ejections (CMEs) are transient expulsions of large amounts of coronal plasma and magnetic flux into the Heliosphere. They represent a key energy release process in the solar corona, and a major driver of space weather. A largely unresolved and fiercely debated problem of the CME physics concerns the nature of their pre-eruptive magnetic configurations. Namely, which magnetic configurations are most prone to destabilization and subsequent CME formation and how do they form? There exist two largely orthogonal models/theories asserting that the pre-eruptive magnetic configuration has the form of either a magnetic flux rope (MFR) or that of a sheared magnetic arcade (SMA). Moreover, a diversity of physical mechanisms (e.g., shearing, flux emergence, flux cancellation, etc.) have been proposed to explain the formation of pre-eruptive configurations. Elucidating on the pre-eruptive configurations and how they form has important implications for the physical understanding of CMEs, the origin and evolution of CME-prolific active regions, and for space-weather prediction purposes.

The current wealth of observational data from the Solar Dynamics Observatory mission (i.e., AIA observations of both pre-eruptive and eruptive structures in hot channels and HMI vector magnetograms), coupled with the latest capabilities in MHD modeling, make it timely to undertake a comprehensive, systematic study of pre-eruptive magnetic configurations. Our team contains expertise in all facets of the problem. We propose to approach the problem as follows.

(1) Combine MHD theory and modeling to generate a pre-eruptive structure diagnostics matrix.

(2) Juxtapose the pre-eruptive structure diagnostics matrix with observations to determine the dominant pre-eruptive configuration.

(3) Determine the dominant physical mechanism(s) behind the formation of the observed pre-eruptive configurations.

(4) Compile a list of recommendations for observational set-ups of future solar instrumentation.

Introduction and scientific rationale

In spite of significant progress in our physical understanding of CMEs, one of the most challenging problems is the nature of their pre-eruptive magnetic configurations that eventually destabilize and lead to CMEs (see the recent review of Aulanier (2014)). There are CME models that require an MFR prior to the eruption onset (e.g., Kliem & Török 2006) while others require a SMA instead (e.g., Antiochos, Klimchuk & Devore 1999). Both MFRs and SMAs run along polarity inversion lines (PILs) of the photospheric magnetic field. An MFR is a coherent magnetic structure characterized by twisted field lines coiled around its axis. A SMA is an arrangement of magnetic loops with planes deviating significantly from the local normal to the PIL. Observationally limited in the photosphere, magnetic PILs per se are not sufficient to distinguish between MFRs and SMAs. Currently, the issue of whether pre-eruptive configurations involve MFRs, SMAs, or a combination of them, is far from being settled. This is a "hot" and strongly debated topic. Settling this issue might be the only avenue to test the realism of different CME initiation models. This is because practically *all* CME initiation models involve a MFR once the CME is underway. The MFR is either formed on-the-fly (e.g., Lynch et al. 2008) or exists before the eruption (e.g., Kliem & Török 2006). In addition, coronographic observations of CMEs in the outer corona show that a MFR geometry is common (Vourlidas 2014), and this is also the case for CMEs observed in-situ at 1 AU (e.g., Jian et al. 2006).

Another largely outstanding question concerns the *physical mechanism(s)* responsible for the *formation of the pre-eruptive structures*, be them MFRs or SMAs. Proposed formation mechanisms include flux emergence, flux cancellation, magnetic reconnection and shearing, acting independently or in conjunction (e.g., Antiochos et al. 1999; Yurchyshyn et al. 2006; Archontis & Török 2008; Lynch et al. 2008; Archontis et al. 2009; Aulanier et al. 2010; Georgoulis et al. 2012; Leake, Linton & Török 2013; Tziotziou, Georgoulis & Liu 2013). Note that most of these mechanisms predict plasma heating to high temperatures during flaring events of various magnitudes (e.g., Aulanier et al. 2010; Tziotziou et al. 2013). Plasma heating to flare temperatures during either confined or eruptive flaring events highlights and uncovers the elusive MFRs or SMAs (e.g., Green et al. 2011; Zhang et al. 2012; Patsourakos et al. 2013). Thus imaging of high temperature plasmas during flaring events is a key observational element in our study of pre-eruptive configurations.

Our ability to address the aforementioned problems is challenged by a number of observational and theoretical factors. In particular, fast CMEs originating from active regions (ARs), known to drive intense space weather phenomena, have small initial sizes and heights ($< 0.1R_{\odot}$) and evolve very rapidly ($\approx$ few minutes) in the low corona (e.g., Patsourakos, Vourlidas, Kliem 2010; Cheng et al. 2013). This makes it difficult to identify the elusive pre-eruptive structure against the forest of low-lying background structures in the optically-thin corona and to discriminate between pre-existing MFRs and those formed on the fly. Moreover, most CME models predict significant plasma heating to flare-like temperatures (and subsequent cooling) during the formation of the pre-eruptive structures and during the initial stages of the eruption. On the cooler end of the temperature range, filaments/prominences are often considered as proxies of pre-eruptive MFRs, with the cool plasma collected at their dips acting as an MFR marker. Finally, we have to rely on mainly non-linear force-free (NLFF) extrapolations of the photospheric magnetic field into the corona, and more recently to data-driven MHD simulations as well, to calculate the magnetic field distribution in the solar atmosphere. Both these methods require high-quality observations of the photospheric magnetic field and flow (in the case of data-driven MHD simulations) vectors.

Thefore, for this study we require high temporal and spatial resolution, multi-wavelength imaging, spectroscopic observations of hot plasmas, and vector magnetic field observations. We now have numerous such datasets thanks to recent missions such as STEREO, Hinode and IRIS, and mainly SDO. In particular, the high-cadence EUV data from AIA, in both low temperatures (304 Å $\approx$ 0.05 MK) to probe filament/prominence structures and determine their relationship with MFRs, and at high temperatures (94 and 131 Å $\approx$ 6 and 10 MK respectively) channels, to observe hot MFRs, are considered key capabilities when combined with the HMI photospheric vector magnetograms. Note also that to date, observational analyses of pre-eruptive configurations are typically case-studies and consider only few of the available diagnostic tools (e.g., Green et al. 2011; Inoue et al. 2012; Zhang et al. 2012; Cheng et al. 2013; Patsourakos, Vourlidas & Stenborg 2013).

CME initiation models often fall short in supplying concrete observational diagnostics (e.g., synthetic EUV and SXR images, magnetic twist maps, etc.) that could be directly compared against observations. Furthermore, several CME models invoke *weakly-twisted* rather than multi-turn MFRs, which makes the understanding of MFR-SMA differences more challenging. Finally, multiple mechanisms may be at work either concurrently or sequentially during the formation of a given pre-eruptive configuration (e.g., Aulanier et al. 2010). All things considered, CME models should supply detailed observational signatures to compare with observations. Recently developed capabilities in CME modeling, for example the calculation of realistic synthetic EUV images (e.g., Mikic, Török et al. 2014), the resolution of steep gradients (e.g., Karpen, Antiochos, Devore 2012) and the incorporation of data-constrained initial conditions (e.g., Kliem et al. 2013) are thus key assets in the study of the aforementioned problems.

Timeliness of the team

Our proposal is timely since our effort will: (1) address in a comprehensive manner a currently "hot" and much disputed problem in coronal physics that is attracting significant community attention, (2) allow to fully harness the data steam from current missions such as Hinode, STEREO, SDO and IRIS, (3) support international programmes with similar objectives such as NASA's LWS 2013 TR&T Steering Committee recommendation for "Physics-based Predictive Capabilities for Solar Eruptions" and EU's Horizon 2020 research program ("Protection of European assets in and from Space-2014-LEIT SPACE"), and (4) provide important guidance for the planning of future solar instrumentation on CMEs physics and space weather forecasting.

Proposed research

The proposed research plan consists of the following four major tasks.

(1) Combine MHD theory and modeling to generate a pre-eruptive structure diagnostics matrix

Tools commonly used in the analysis of observations of pre-eruptive structures include: (1) determination of the horizontal field direction at the polarity inversion line in filament channels and flux emergence regions (e.g., Lites 2009); (2) NLFF magnetic field extrapolations (e.g., Canou et al. 2009; Nindos, Patsourakos & Wiegelmann 2012; Cheng et al. 2013; Guo et al. 2013); (3) flux-rope insertion calculations (e.g., Savcheva et al. 2012); (4) magnetic twist and helicity maps (Pariat et al. 2006; Inoue et al. 2013; Tziotziou et al.

2013); (5) quasi-separatrix layer maps (e.g., Aulanier et al. 2002; Titov et al. 2012; Savcheva et al. 2012); (6) magnetogram stacking (Chintzoglou & Zhang 2012); (7) EUV and SXR movies in multiple wavelengths and views (e.g., Green & Kliem 2009; Cheng et al. 2011; Green, Kliem & Wallace 2011; Zhang et al. 2012; Cheng et al. 2013; Patsourakos, Vourlidas & Stenborg 2013) and (8) density, differential emission measure, and bulk and non-thermal flow maps (e.g., Cheng et al. 2013; Harra et al. 2013; Patsourakos, Vourlidas & Stenborg 2013).

These tools have been applied to observations, but often lack connection to detailed model predictions. Moreover, the robustness of a given signature is not scrutinized regularly. For example, the observation of hot EUV emission channels, prior to or during CME onsets, is often taken as evidence of a pre-eruptive MFR but what are the expected plasma temperatures and observational features anticipated for an SMA? Likewise, do twist maps of weakly-twisted MFRs and SMAs exhibit significant differences? Do data-driven MHD simulations (currently being developed by several groups represented in our team) substantiate the MFR or SMA signatures obtained with these tools?

For each of the observational tools above, we plan to generate synthetic observables from the appropriate models in our team's arsenal. The team has representatives from the pre-eruptive MFR and SMA "camps", as well as from all major pre-eruptive configuration formation mechanisms. They can consider all tools. This ensures that each observational tool will be thoroughly scrutinized against all possibilities, and thus its robustness as a pre-eruptive configuration and formation diagnostic will be fully assessed. Note that a large number of the required model runs are already available from previous work of the team members. We mainly plan to post-process the outputs of these simulations and construct synthetic observables. However, new custom-made runs can be also considered (for example the data-driven MHD simulations currently developed by several team members), if deemed necessary. The end result will be encapsulated in a *Pre-eruptive Structure Diagnostics Matrix*, that will assess the merit and relevant range for each possibility (MFR or SMA). This will allow us to determine which diagnostic(s) supply the most unambiguous means of determining the nature of the pre-eruptive magnetic configurations.

(2) Juxtapose the pre-eruptive structure diagnostics matrix with observations to determine the dominant pre-eruptive configuration

With this task we will achieve closure between the theoretical predictions of the previous task and the observations. We will first gather a set (around a dozen) of major AR-hosted CMEs. We will consider first CMEs launched not very far from disk center (as seen from Earth), since the magnetic field measurements are less susceptible to projection effects. Emphasis will be given to observations in both hot and cool AIA channels to probe multimillion and prominence pre-eruptive structures. For the latter task, IRIS and ground observations will be also considered. Later, we will consider additional events, launched from locations closer to the solar limb. This would allow for a more comprehensive morphological analysis of the pre-eruptive configurations over a wider range of viewpoints, starting from direct views close to disk center to side views once they approach the limb. Complementary, non-terrestrial points of view, supplied by the STEREO spacecraft will be also considered. Our sample will mostly cover the SDO era, but we may also consider pre-SDO observations. Various sources of pertinent data are available including space-borne Hinode/EIS,XRT,SOT, STEREO/SECCHI, SDO/AIA,HMI and IRIS, as well as ground-based resources like the recently upgraded 1.5-m BBSO optical telescope (e.g., Yurchyshyn, Abramenko & Goode 2013). For each event we will consider dataset time series prior and during the onset of the CME eruption.

(3) Determine the dominant physical mechanism(s) behind the formation of the observed pre-eruptive configurations

For a smaller number of events (e.g., about half a dozen), we will consider longer intervals, spanning several days before eruption. This will allow us to study in detail the route(s) and to pinpoint, given the meticulous application of *all* available diagnostic tools to a decent data-set (i.e., not either using only few of the available tools nor analyzing a case-study as it is done by most related studies to date) the physical mechanisms towards the formation of the corresponding pre-eruptive structures. Once more we will apply our diagnostics matrix to the observations, but this time to the extended time series. Given the close connection between pre-eruptive structure visibility and flaring, discussed in the Introduction, we will place particular emphasis to periods of flaring activities.

After assembling the various pertinent datasets, and for both tasks 2 and 3, we will run them against the diagnostics matrix and assess, whether MFR, SMA, or maybe a combination of them is the most common pre-eruptive structure occurrence. We expect we will eventually settle the pre-eruptive MFR vs SMA dilemma by virtue of sufficient event statistics and our scrutiny of the various diagnostics tools. In addition, our analysis of the formation path of pre-eruptive configurations could possibly lead to the identification of typical, or even universal, pre-eruptive structure formation patterns and mechanisms. Our findings, therefore, may (i) enhance our physical understanding of the genesis of CMEs and (ii) significantly benefit future space-weather forecasting, via the advance detection of CME-prolific ARs.

(4) Compile a list of recommendations for observational set-ups for future solar instrumentation

Our results on the nature of pre-eruptive configurations will supply important guidance into the design of future solar instrumentation aimed at the study of CMEs. The solar physics community is currently in the stage of conception of new missions with significant space weather applications. Having determined what are the best diagnostics of pre-eruptive structures (e.g., which temperature domain is most appropriate for the detection of currently elusive pre-eruptive configurations and their formation process) would be an important information for the instrument teams designing new missions. The tools and expertise of our team can be used to easily generate and explore synthetic observables in spectral domains which are currently under evaluation for implementation in future missions. An example of our study's importance to future mission design, are the L4 and L5 missions. These mission concepts, currently under study in both Europe and the USA, are mainly focused in space-weather forecasting and will be observing parts of the Sun which are ahead/behind the east/west limb (L5 and L4 respectively) as seen from the Earth. The determination by our team of the best observables of pre-eruptive structures can be considered in the design of the scientific payload, especially for the L5 mission, which will supply a significant lead of several days in the observational coverage of magnetic configurations prone to generate Earth-directed CMEs.

Expected output

The team will prepare a review paper, presenting and assessing the validity of the various pre-eruptive structure diagnostics, as well as one or more papers on comparisons of the diagnostics matrix with actual observations. The review paper with the diagnostics matrix is expected to become an important community resource, not only because such a critical and comprehensive compilation is currently missing from the literature but also as a guideline for future instrumentation. Moreover, the comparison of our diagnostics matrix with observations of an extended set of events can help resolve the problem of determining the nature and the formation mechanism(s) of pre-eruptive magnetic field configurations—a central problem in CME physics. The planned activities will significantly enhance the visibility of the team and thus of ISSI.

Added value from ISSI support

Determining the nature and formation mechanisms of pre-eruptive magnetic configurations represents an important, and intensely debated problem in solar physics. A small team's approach, as offered by ISSI, is ideally suited to make progress in this problem. Running such a team in the productive environment of ISSI would bring observers together with modelers from different 'camps' in a synergistic forum. This will enable discussions in all necessary detail of the relevant problems and particularly of the sometimes subtle but potentially important differences between different models and interpretations. This cannot be achieved in large-format meetings and workshops. ISSI importantly provides the necessary and sufficient conditions to tackle these issues.

Program, Facilities and Financial Support

We plan to have two week-long meetings during winter of 2015 and winter of 2016. The first meeting will be dedicated to an overview of the existing problems, the set-up of the MFR/SMA diagnostics, the assembly of the datasets, and the task assignment to each team member. The results from these tasks will be the focus of the second meeting. A meeting room with video projector, white-board and internet access would be sufficient. Standard ISSI support covering the living and accommodation expenses of the team members is requested.

Team

We assembled an international team of experts to perform the above research tasks. The team has observers with extensive experience in multi-wavelength CME studies and modelers from the entire spectrum of CME initiation models and mechanisms. We have identified three young scientists, two PhD students (UK, USA) and an early-career post-doc (China) who will participate in at least one of the two team meetings, working on key aspects of the proposed investigation. The team has the following line-up.

1. S.K. Antiochos, NASA/GSFC, USA (MHD theory and modeling)
2. V. Archontis, Univ of St Andrews, UK (MHD theory and modeling)
3. G. Aulanier, LESIA, France (MHD theory and modeling; magnetic field observations)
4. M. K. Georgoulis, RCAAM, Greece (MHD theory, magnetic field observations, optical imaging observations)
5. L. M. Green, MSSL/UCL, UK (magnetic field observations, SXR and EUV imaging and spectroscopic observations)
6. B. Kliem, Univ of Potsdam, Germany (MHD theory and modeling)
7. J. Leake, GMU, USA (MHD theory and modeling)
8. A. Nindos, Univ of Ioannina, Greece (magnetic field observations; SXR, EUV and optical imaging observations)
9. S. Patsourakos **(team leader)**, Univ of Ioannina, Greece (SXR and EUV imaging and spectroscopic observations)
10. T. Török, PSI, USA (MHD theory and modeling)
11. V. Yurchyshyn, BBSO, USA (magnetic field observations, optical imaging observations, instrumentation)
12. A. Vourlidas **(team leader, self-funded)**, JHU/APL, USA (EUV and WL imaging observations, instrumentation, NASA L5 representative)
13. J. Zhang, GMU, USA (SXR, EUV and WL imaging observations, magnetic field observations).

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