Project Details

ROSES ID: NNH13ZDA001N
Selection Year: 2013
Program Element: Targeted Science Team

Topic: Magnetic Flux Ropes from the Sun to the Heliosphere

Project Title:
Investigating the Origin and Evolution of Magnetic Flux Ropes in the Heliosphere

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Summary:
We propose a Targeted Science Team to attack the Living with a Star

Focused Science Topic "Flux Ropes from the Sun to the Heliosphere."

Our interdisciplinary team will address the fundamental

aspects of flux rope formation and evolution, including the emergence of

magnetic flux from the solar interior, the formation of flux ropes in the

solar atmosphere, their eventual eruption and subsequent evolution as coronal

mass ejections (CMEs), and their propagation as interplanetary

coronal mass ejections (ICMEs).

We will closely couple observations, models, and simulations to develop

a deep understanding of the properties of CME flux ropes from their birth

in the solar atmosphere to their arrival at Earth and beyond. The expertise of

our team members covers all the disciplines needed to track a CME flux rope during

its life cycle.

Objectives and Methods:

Our investigation focuses on answering three key questions:

1) How do magnetic flux ropes form in emerging active regions?
We propose to combine active region observations, including photospheric vector magnetic field and velocity measurements, with state-of-the-art magnetohydrodynamic (MHD) simulations of flux emergence and flux rope formation, to significantly improve the ability to characterize the properties of coronal flux ropes.

2) How does flux emergence lead to the eruption of CME flux ropes?
Our demonstrated ability to study CME events with unprecedented realism, together with our recent advances in coupling MHD simulations of flux emergence with the evolution of flux ropes in the corona, will lead to a richer understanding of the conditions that determine when flux ropes erupt. These theoretical investigations will be guided by the analysis of multi-wavelength observations of CME eruptions associated with flux emergence.

3) How are ICME flux ropes distorted by their interaction with the interplanetary medium? We propose to combine MHD simulations, white-light observations and modeling, flux rope reconstruction, and in-situ charge state measurements to understand the coronal origin of the features we measure at 1 AU. We will investigate how to combine CME morphology and flux rope reconstruction techniques to estimate the fields embedded in ICMEs prior to their arrival at Earth.

Significance to solicitation and NASA interests:

Understanding the life cycle of CME flux ropes is a critical challenge, not only from a purely scientific perspective, but because of the crucial role these structures play in space weather. Our proposed research combines detailed observational studies, state-of-the-art simulations, and practical empirical models

to answer fundamental questions about the origin and evolution of CME flux ropes.

The successful completion of our project will pave the way for a capability to

predict geoeffective magnetic fields hours to days in advance of the arrival of

Earth-targeted ICMEs

Publication References:

Summary: This paper explores the catastrophe versus instability formulations for coronal mass ejections in three dimensional magnetohydrodynamical simulations of toroidal flux rope eruptions.

Reference: Kliem B.; Lin J.; Forbes T. G.; Priest T.; (2014). Catastrophe versus Instability for the Eruption of a Toroidal Solar Magnetic Flux Rope. Astrophysical Journal, 789, 46, doi: 10.1088/0004-637X/789/1/46

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper explores the eruption of two vertically co-aligned fluxropes for various external toroidal (shear) field strengths, finding that toroidal field above a certain strength inhibits eruption.

Reference: Kliem B.; Torok T.; Titov V. S.; Lionello J. A.; Liu R.; Liu C.; Wang H.; (2014). Slow Rise and Partial Eruption of a Double-decker Filament. II. A Double Flux Rope Model. Astrophysical Journal, 792, 107, doi: 10.1088/0004-637X/792/2/107

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper investigates a 23 June 2010 CME eruption using EUV, AIA, GOES X-ray, and radio observations. It investigates the CME expansion along the ejecta nose and flanks as a source for shock compression and associated radio bursts.

Reference: Kouloumvakos A.; Patsourakos S.; Hillaris A.; Preka-Papadema P.; Moussas C.; Tsitsipis P.; Kontogeorgos A.; (2014). CME Expansion as the Driver of Metric Type II Shock Emission as Revealed by Self-consistent Analysis of High-Cadence EUV Images and Radio Spectrograms. Solar Physics, 289, 2123-2139, doi: 10.1007/s11207-013-0460-z

- **Investigation Type:** Data Analysis
- **Data Sources:** SDO:AIA GOES:X-RAY ARTEMIS:RADIO

Summary: This paper explores the stability of a Chen-Shibata (2000) type flux rope - coronal mass ejection configuration. It finds that the system changes from a stable state at high background pressure (magnetic and /or plasma) to unstable at low background pressure.

Reference: Lee E.; Lukin V. S.; Linton M. G.; (2014). On flux rope stability and atmospheric stratification in models of coronal mass ejections triggered by flux emergence. Astronomy and Astrophysics, 569, A94, doi: 10.1051/0004-6361/201423739

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper reports on a new method, developed by the authors, for initializing pre-eruptive arched flux rope equilibria in solar coronal simulations.

Reference: Titov V. S.; Torok T.; Mikic Z.; Linker J. A.; (2014). A Method for Embedding Circular Force-free Flux Ropes in Potential Magnetic Fields. Astrophysical Journal, 790, 163, doi: 10.1088/0004-637X/790/2/163

- **Investigation Type:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** Torus instability theory, Titov-Demoulin flux rope model
- **Domains:** Sun

Summary: This paper explores the generation of writhe in three dimensional simulations of the kink instability, with the goal of using solar observations of writhing filaments to understand the extent of their magnetic twist.

Reference: Torok T.; Kliem B.; Berger M. G.; Demoulin P.; van Driel-Gesztelyi L.; (2014). The evolution of writhe in kink-unstable flux ropes and eruptingfilaments. Plasma Physics and Controlled Fusion, 56, 064012, doi: 10.1088/0741-3335/56/6/064012

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper reports on observations and simulations of reconnection during a coronal mass ejection eruption.

Reference: van Driel-Gesztelyi L.; Baker D.; Torok E.; Green L. M.; Williams D. R.; Carlyle G.; Demoulin P.; Kliem B.; Long S. A.; Malherbe J.-M.; (2014). Coronal Magnetic Reconnection Driven by CME Expansion-the 2011 June 7 Event. Astrophysical Journal, 788, 85, doi: 10.1088/0004-637X/788/1/85

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** Torus instability model.
- **Datasources:** SDO:AIA SDO:HMI STEREO A:EUVI

Summary: This paper reports on a study of the field line twists and lengths in observed interplanetary magnetic flux ropes, as reconstructed using both a Grad-Shafranov method and a Gold-Hoyle model.

Reference: Hu Q.; Qiu J.; Krucker S.; (2015). Magnetic field line lengths inside interplanetary magnetic flux ropes. Journal of Geophysical Research (Space Physics), 120, 5266-5283, doi: 10.1002/2015JA021133

- **Investigation Type:** Data Analysis
- **Data Sources:** WIND:MAGNETIC FIELD DETECTOR

Summary: This paper reports on research on the role of flux emergence in generating and destabilizing eruptive coronal flux ropes.

Reference: Leake J. E.; Linton M. G.; Antiochos S. K.; (2014). Simulations of Emerging Magnetic Flux. II. The Formation of Unstable Coronal Flux Ropes and the Initiation of Coronal Mass Ejections. Astrophysical Journal, 787, 46, doi: 10.1088/0004-637X/787/1/46

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper presents a theoretical and simulation based study of the formation of flux ropes via twisting motions in solar active regions. The study reports on the structure and evolution of the field aligned currents which are generated by these motions, and how those are distributed to form the structure of the twisted flux rope.

Reference: Dalmasse K.; Aulanier G.; Demoulin B.; Torok T.; Pariat E.; (2015). The Origin of Net Electric Currents in Solar Active Regions. Astrophysical Journal, 810, 17, doi: 10.1088/0004-637X/810/1/17

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper reports on studies of particle acceleration in CME shocks formed in the low corona, using analytical methods and numerical magnetohydrodynamic simulations.

Reference: Schwadron N. A.; Lee M. A.; Gorby M.; Lugaz H. E.; Desai M.; Torok C.; Linker J.; Lionello R.; Mikic P.; Giacalone J.; Jokipii J. R.; Kota K.; (2015). Particle Acceleration at Low Coronal Compression Regions and Shocks. Astrophysical Journal, 810, 97, doi: 10.1088/0004-637X/810/2/97

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper reports on a remote sensing observation of two coronal mass ejections with prominences embedded in them. It reports on the evolution of the prominence material within the inferred CME flux rope structure. This analysis relies on multi-viewpoint STEREO observations to infer and analyze the three dimensional structure and evolution of the prominences and CMEs.

Reference: Wood B. E.; Howard R. A.; Linton M. G.; (2016). Imaging Prominence Eruptions out to 1 AU. Astrophysical Journal, 816, 67, doi: 10.3847/0004-637X/816/2/67

- **Investigation Type:** Data Analysis
- **Data Sources:** STEREO A:COR1 STEREO A:COR2 STEREO A:HI STEREO B:COR1 STEREO B:COR2 STEREO B:HI

Summary: This paper investigates, via magnetohydrodynamical simulations, the coronal mass ejection (CME) of 15 March, 2013 as a source of solar energetic particles (SEPs). The paper presents simulations of the solar wind with a pressure-pulse initiated CME through it. The simulation follows the fast mode shock produced by the CME, and the paper analyzes the SEPs which should be produced by this shock. It finds that the observed high energy SEP profile can be explained by such a CME produced shock.

Reference: Wu C.-C.; Liou K.; Vourlidas A.; Plunkett M.; Wu S. T.; Mewaldt R. A.; (2016). Global magnetohydrodynamic simulation of the 15 March 2013 coronal mass ejection event-Interpretation of the 30-80 MeV proton flux. Journal of Geophysical Research (Space Physics), 121, 56-76, doi: 10.1002/2015JA021051

- **Investigation Type:** Simulations
- **Domains:** Interplanetary space or solar wind
- **Model Types:** MHD

Summary: This paper investigates the observable consequences of impulsive heating on coronal loops. This advances this Living with a Star project by advancing our understanding of the thermodynamic state of the corona. Simulations of coronal mass ejections (CMEs) find that the background thermodynamic state of the corona has a significant effect on CME eruptions, and so advancing our models of this state is an important component of studying CME eruptions.

Reference: Lionello R.; Alexander C. E.; Winebarger J. A.; Mikic Z.; (2016). Can Large Time Delays Observed in Light Curves of Coronal Loops Be Explained in Impulsive Heating?. Astrophysical Journal, 818, 129, doi: 10.3847/0004-637X/818/2/129

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper presents an overview of instensive magnetohydrodynamical modeling of the coronal mass ejection (CME) event of July 14, 2000, also known at the "Bastille Day event." This paper reports on significant advances in our capability to model CME events. It discusses the initial and driving conditions used for the event, both of which are based on the solar observations of that event. It then compares the eruptive behavior of the event with coronal and coronagraphic observations of the event. Event studies such as this one represent a direct test of CME modeling methods against observations, and present an important method for investigating the physics of CMEs, as well as for testing and improving the numerical models.

Reference: Linker J.; Torok T.; Downs C.; Lionello V.; Caplan R. M.; Mikic Z.; Riley P.; (2016). MHD simulation of the Bastille day event. , 1720, 020002, doi: 10.1063/1.4943803

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper presents results of an investigation into the effect that coronal mass ejection (CME) shocks in the low corona have on the acceleration of energetic particles, and their potential contribution to the generation os solar energetic particle events.

Reference: Schwadron N. A.; Lee M. A.; Gorby M.; Lugaz H. E.; Desai M.; Torok C.; Linker J.; Lionello R.; Mikic P.; Giacalone J.; Jokipii J. R.; Kota K.; (2015). Broken Power-law Distributions from Low Coronal Compression Regions or Shocks. Journal of Physics Conference Series, 642, 012025, doi: 10.1088/1742-6596/642/1/012025

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This paper presents a new toroidal Grad-Shafranov based flux rope reconstruction method. The method is applied first to a known numerical solution, and is then applied to several in-situ observed magnetic cloud events. This method provides a promising way for investigating flux rope coronal mass ejections in cases where the flux rope axis deviates from a straight (cylindrical) condition.

Reference: Hu Q.; (2016). On the Grad-Shafranov reconstruction of toroidal magnetic flux ropes. , 1720, 040005, doi: 10.1063/1.4943816

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** Toroidal Grad Shafranov model.
- **Datasources:** WIND:MAGNETIC FIELD DETECTOR

Summary: This paper reports on a study of the evolution of sunspot pair tilt angle, footpoint separation, and total area during the flux emergence and decay phase of small, midsize and large active regions. This work is important for understanding the process of active region formation, as well as the process of coronal flux rope formation, from flux emergence.

Reference: McClintock B. H.; Norton A. A.; (2016). Tilt Angle and Footpoint Separation of Small and Large Bipolar Sunspot Regions Observed with HMI. Astrophysical Journal, 818, 7, doi: 10.3847/0004-637X/818/1/7

- **Investigation Type:** Data Analysis
- **Data Sources:** SDO:HMI

Summary: This paper reports on an extensive analysis of observations relevant to the March 7-11, 2012 geomagnetic storm. The paper follows the eruption (with SDO) and Earthward propagation (with STEREO) of the associated coronal mass ejection (CME), followed by in situ measurements of it's arrival at 1AU (with WIND), and its effect on the magnetospheric environment, (with THEMIS and GOES). This gives a comprehensive Sun to Earth view of the processes leading up to this CME-driven geomagnetic storm.

Reference: Patsourakos S.; Georgoulis M. K.; Vourlidas A.; Sarris T.; Anagnostopoulos A.; Chintzoglou G.; Daglis C.; Hatzigeorgiu N.; Iliopoulos C.; Kouloumvakos A.; Moraitis T.; Pavlos G.; Sarafopoulos P.; Tsironis C.; Tziotziou K.; Vogiatzis G.;

Georgiou M.; Karakatsanis O. E.; Papadimitriou C.; Odstr\v cil E. G.; Podlachikova O.; Sandberg D. L.; Xenakis M. N.; Sarris E.; Tsinganos L.; (2016). The Major Geoeffective Solar Eruptions of 2012 March 7: Comprehensive Sun-to-Earth Analysis. Astrophysical Journal, 817, 14, doi: 10.3847/0004-637X/817/1/14

- **Investigation Type:** Data Analysis
- **Data Sources:** SDO:AIA STEREO A:COR1 STEREO A:COR2 STEREO B:COR1 STEREO B:COR2 THEMIS:ESA GOES:X-RAY

Summary: This paper reports on an observational study of hot coronal flux ropes with SDO AIA. The goal was to assess the frequency with which such observations show the presence of hot flux rope signatures in flare events. Of the 141 flare events studies, roughly a third showed hot flux ropes, and of the flares which produced an eruption, roughly half showed the presence of hot flux ropes.

Reference: Nindos A.; Patsourakos S.; Vourlidas A.; Tagikas C.; (2015). How Common Are Hot Magnetic Flux Ropes in the Low Solar Corona? A Statistical Study of EUV Observations. Astrophysical Journal, 808, 117, doi: 10.1088/0004-637X/808/2/117

- **Investigation Type:** Data Analysis
- **Data Sources:** SDO:AIA

Summary: This work uses MHD simulations to model coronal jets in the outer corona and to estimate their contribution to the mass and energy content of the solar wind. This is work is timely in light of the upcoming Solar Orbiter and Solar Probe Plus missions.

Reference: Lionello R.; Torok T.; Titov V. S.; Leake J. E.; Mikic Z.; Linker J. A.; Linton M. G.; (2016). The Contribution of Coronal Jets to the Solar Wind. Astrophysical Journal, 831, L2, doi: 10.3847/2041-8205/831/1/L2

- **Investigation Type:** Simulations
- **Domains:** Sun Interplanetary space or solar wind
- **Model Types:** MHD

Summary: This work investigates predictive signatures of solar eruptions by analyzing a series of MHD simulations. The work found that the ratio of the coronal mutual helicity to the full relative helicity shows a distinct signature for those simulations which are about to erupt relative to those which are not about to erupt. This points in a promising direction for developing observational measures for predicting eruptions.

Reference: Pariat, E.; Leake, J. E.; Valori, G.; Linton, M. G.; Zuccarello, F. P.; Dalmasse, K.; (2017), Relative magnetic helicity as a diagnostic of solar eruptivity, Astronomy & Astrophysics, Volume 601, id.A125, 16 pp, doi: 10.1051/0004-6361/201630043

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This article describes the coupling between two MHD codes which model the solar corona (MAS) and the inner heliosphere (LFM), respectively. Such a coupling is required to efficiently simulate the propagation of CMEs from the low corona to Earth and beyond, in light of the potential use of MHD simulations for future operational space-weather-forecast. A number of test cases is presented.

Reference: Merkin V. G.; Lionello R.; Lyon J. G.; Linker J.; Torok T.; Downs C.; (2016). Coupling of Coronal and Heliospheric Magnetohydrodynamic Models: Solution Comparisons and Verification. Astrophysical Journal, 831, 23, doi: 10.3847/0004-637X/831/1/23

- **Investigation Type:** Simulations
- **Domains:** Interplanetary space or solar wind
- **Model Types:** MHD

Summary: This article reviews observations, theoretical models, and MHD simulations of coronal jets, including a description of work that was done in the course of this LWS project.

Reference: Raouafi N. E.; Patsourakos S.; Pariat E.; Young P. R.; Sterling A. C.; Savcheva A.; Shimojo M.; Moreno-Insertis F.; DeVore C. R.; Archontis V.; Torok T.; Mason H.; Curdt W.; Meyer K.; Dalmasse K.; Matsui Y.; (2016). Solar Coronal Jets: Observations, Theory, and Modeling. Space Science Reviews, 201, 1-53, doi: 10.1007/s11214-016-0260-5

- **Investigation Type:** Other Investigations
- This is a review paper that contains several investigation types.

Summary: This article describes the first thermodynamic MHD simulations of coronal jets. These ubiquitous events are believed to contribute mass and energy to the corona and solar wind, but it is not yet known how large these contributions are. It is therefore important to constantly improve the realism of jet simulations, to which this work contributes.

Reference: Torok T.; Lionello R.; Titov V. S.; Leake J. E.; Mikic Z.; Linker J. A.; Linton M. G.; (2016). Modeling Jets in the Corona and Solar Wind. , 504, 185

- **Investigation Type:** Simulations
- **Domains:** Sun
- **Model Types:** MHD

Summary: This article describes a detailed analysis of the coronal magnetic field around the time of a series of sympathetic (coupled) CMEs that occurred on 2010 August 1-2. Such a detailed analysis is required for understanding how solar eruptions can trigger one another.

Reference: Titov V. S.; Mikic Z.; Torok T.; Linker J. A.; Panasenco O.; (2017). 2010 August 1-2 Sympathetic Eruptions. II. Magnetic Topology of the MHD Background Field. Astrophysical Journal, 845, 141, doi: 10.3847/1538-4357/a81ce

- **Investigation Type:** Tools and Analysis Techniques
- **Names of the tools and techniques:** Tools developed at Predictive Science Inc. for analyzing the topology of coronal magnetic fields.

Summary: This article describes an investigation of the distribution of electric currents in solar active regions. The degree of current-neutralization in such regions appears to be related with their capability to produce CMEs. This quantity may thus provide a means of predicting large-scale eruptive activity on the Sun.

Reference: Liu Y.; Sun X.; Torok T.; Titov V. S.; Leake J. E.; (2017). Electric-current Neutralization, Magnetic Shear, and Eruptive Activity in Solar Active Regions. Astrophysical Journall, 846, L6, doi: 10.3847/2041-8213/a861e

- **Investigation Type:** Data Analysis
- **Data Sources:** SDO:HMI

Summary: This paper reviews recent progress in data analysis and numerical simulations of the processes that govern the evolution of CMEs and ICMEs in the corona and interplanetary space. It therefore as an educational purpose for young solar and heliospheric physicists and it improves our understanding of these processes by "putting the dots together".

Reference: Manchester W.; Kilpua E. K. J.; Liu Y. D.; Lugaz N.; Riley P.; Torok T.; Vrsnak B.; (2017). The Physical Processes of CME/ICME Evolution. Space Science Reviews, 212, 1159-1219, doi: 10.1007/s11214-017-0394-0

- **Investigation Type:** Other Investigations
- This is a review paper that addresses several investigation types.

Summary: The model described in this article improves previous flux-rope models in that it allows one to construct flux ropes of arbitrary shape. It has been designed for application in numerical simulations of CMEs and will improve the initial conditions for

pre-eruptive configurations used in such simulations.

Reference: Titov V. S.; Downs C.; Mikic Z.; Torok T.; Linker J. A.; Caplan R. M.; (2018). Regularized Biot-Savart Laws for Modeling Magnetic Flux Ropes. Astrophysical Journall, 852, L21, doi: 10.3847/2041-8213/aa3da

- **Investigation Type:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** This article describes a new analytical model for coronal flux ropes.
- **Domains:** Sun