Project Details

ROSES ID: NNH11ZDA001N
Selection Year: 2012
Program Element: NSF Partnership

Project Title:
Corona-Solar Wind Energetic Particle Acceleration (C-SWEPA) Modules

PI Name: Nathan Schwadron
PI Email: n.schwadron@unh.edu
Affiliation: Boston University
Summary:
The 3-D Coronal-Solar Wind Energetic Particle Acceleration (C-SWEPA) modules provide tools for taking the critical next step in understanding Solar Energetic Particle (SEP) events and characterizing their hazards through physics-based modeling from the low corona through the inner heliosphere. C-SWEPA s central objective is to develop and validate a numerical framework of physics-based modules that couple the low corona and CMEs with solar wind, shocks, acceleration and composition of energetic particles, and the fluctuations and turbulence within solar wind that buffet terrestrial and planetary magnetospheres. Using pre-existing EMMREM modules, we characterize time- dependent radiation exposure in interplanetary space environments. Simulated observers (e.g., spacecraft near L1, Earth, moon, Mars, etc.) provide basis for comparison with spacecraft and tools to explore simulated mission datasets (e.g., Solar Probe Plus, SPP, and Solar Orbiter, SolO).

C-SWEPA fulfills the need for a transformative synthesis of LWS capabilities by bringing together an exceptional team of leading experts from five institutions in solar, heliospheric and magnetospheric physics and two successful LWS strategic capabilities: the Earth-Moon-Mars Radiation Environment Modules (EMMREM), and the Next Generation Model for the Corona and Solar Wind. C-SWEPA leverages new advancements in High Performance Computing (HPC) through the use of heterogeneous architectures (Graphical Processing Units; GPUs) and develops an innovative approach to delivering complex models that enables the CCMC to use dedicated GPU-enabled and massively parallelized systems for C-SWEPA simulations.

C-SWEPA is a transformational project providing: an integration between observationally-driven modeling of CMEs, solar wind, shocks and energetic particles from the low corona through the heliosphere; incorporation of seed populations and associated compositional dependencies; new fundamental information via highly- resolved inertial node-lines vital to studies of the magnetosphere (e.g., by the upcoming Radiation Belt Storm Probes mission, RBSP), other planetary magnetospheres and the microstates and turbulence within solar wind; and detailed models that probe the steady and disturbed corona thus paving the way for Solo and SPP studies.

C-SWEPA deliverables include: two numerical systems (one at the CCMC and one at UNH) that run C-SWEPA; documentation; and an intuitive interface. These systems provide: on-line availability and event scenarios from Sun-to-Earth; runs that include solar wind, CMEs and associated shock(s), SEP flux time series, dose & dose-equivalent rates, integrated doses behind various layers of shielding; and results of runs made for specific campaign events of interest to the science community at large. Both EMMREM and CORHEL run at the CCMC and the associated teams have a strong history of partnering with the CCMC.

C-SWEPA answers fundamental scientific questions via four science subgroups that study the corona, solar wind, CME initiation, shocks, solar energetic particle acceleration and propagation, and solar wind waves and turbulence. Core team members have experience working together and leverage developments from CISM, EMMREM, CORHEL, NSF s FESD Sun-to-Ice project, and existing Focus Science Teams (FSTs) of NASA's Living With a Star (LWS) Program.

C-SWEPA provides broad impacts by advancing discovery and understanding while also promoting teaching, training of graduate students, undergraduate involvement, and participation of under-represented groups. C-SWEPA enhances the infrastructure for research and education through development of computing capabilities for the science community. By advancing tools for understanding and predicting space weather, C- SWEPA provides important societal benefits enabling expansion of space technologies.

Publication References:

Summary: The acceleration of protons and electrons to high (sometimes GeV/nucleon) energies by solar phenomena is a key component of space weather. These solar energetic particle (SEP) events can damage spacecraft and communications, as well as present radiation hazards to humans. In-depth particle acceleration simulations have been performed for idealized magnetic fields for diffusive acceleration and particle propagation, and at the same time the quality of MHD simulations of coronal mass

ejections (CMEs) has improved significantly. However, to date these two pieces of the same puzzle have remained largely decoupled. Such structures may contain not just a shock but also sizable sheath and pileup compression regions behind it, and may vary considerably with longitude and latitude based on the underlying coronal conditions. In this work, we have coupled results from a detailed global three-dimensional MHD time-dependent CME simulation to a global proton acceleration and transport model, in order to study time-dependent effects of SEP acceleration between 1.8 and 8 solar radii in the 2005 May 13 CME. We find that the source population is accelerated to at least 100 MeV, with distributions enhanced up to six orders of magnitude. Acceleration efficiency varies strongly along field lines probing different regions of the dynamically evolving CME, whose dynamics is influenced by the large-scale coronal magnetic field structure. We observe strong acceleration in sheath regions immediately behind the shock.

Reference: Kozarev K. A.; Evans R. M.; Schwadron N. A.; Dayeh M. A.; Opher M.; Korreck K. E.; Holst van der, B.; (2013). Global Numerical Modeling of Energetic Proton Acceleration in a Coronal Mass Ejection Traveling through the Solar Corona. Astrophysical Journal, 778, 43, doi: 10.1088/0004-637X/778/1/43

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

Summary: It is now well established that many bulk properties of the solar wind rise and fall with the solar cycle, and the heliospheric magnetic field (HMF) intensity is no exception. The HMF intensity is seen to be maximum around the time of solar maximum, lowest during solar minimum, and lower still during the recent protracted solar minimum 2006-2009. One explanation of this behavior can be found in the theory of Schwadron et al. (2010) that argues magnetic flux is injected into interplanetary space by coronal mass ejection eruptions and removed by reconnection in the low solar atmosphere. This produces an HMF intensity that is correlated with sunspot number, and the rapid injection of flux followed by the slow removal by reconnection results in a hysteresis effect that is readily evident in the observations. Here for the first time we apply this theory to the sunspot record going back to 1749 and compare favorably our predictions to the results derived from10Be observations. We also make a prediction for the coming solar minimum based on results from the Dalton Minimum. The results of this paper provide the basis to understand how CME injection regulates the interplenary magnetic field, which in turn regulates cosmic ray fluxes, the strength of shocks, etc. Understanding and predicting the HMF is ultimately critical for its foundational role in regulating space weather.

Reference: Goelzer M. L.; Smith C. W.; Schwadron N. A.; McCracken K. G.; (2013). An analysis of heliospheric magnetic field flux based on sunspot number from 1749 to today and prediction for the coming solar minimum. Journal of Geophysical Research (Space Physics), 118, 7525-7531, doi: 10.1002/2013JA019404

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** Schwadron magnetic flux model
- **Datasources:** ACE:MAG

Summary: The last solar minimum, which extended into 2009, was especially deep and prolonged. Since then, sunspot activity has gone through a very small peak while the heliospheric current sheet achieved large tilt angles similar to prior solar maxima. The solar wind fluid properties and interplanetary magnetic field (IMF) have declined through the prolonged solar minimum and continued to be low through the current mini solar maximum. Compared to values typically observed from the mid-1970s through the mid-1990s, the following proton parameters are lower on average from 2009 through day 79 of 2013: solar wind speed and beta (~11%), temperature (~40%), thermal pressure (~55%), mass flux (~34%), momentum flux or dynamic pressure (~41%), energy flux (~48%), IMF magnitude (~31%), and radial component of the IMF (~38%). These results have important implications for the solar wind's interaction with planetary magnetospheres and the heliosphere's interaction with the local interstellar medium, with the proton dynamic pressure remaining near the lowest values observed in the space age: ~1.4 nPa, compared to ~2.4 nPa typically observed from the mid-1970s through the mid-1990s. The combination of lower magnetic flux emergence from the Sun (carried out in the solar wind as the IMF) and associated low power in the solar wind points to the causal relationship between them. Our results indicate that the low solar wind output is driven by an internal trend in the Sun that is longer than the ~11 yr solar cycle, and they suggest that this current weak solar maximum is driven by the same trend.

Reference: McComas D. J.; Angold N.; Elliott H. A.; Livadiotis G.; Schwadron N. A.; Skoug R. M.; Smith C. W.; (2013). Weakest Solar Wind of the Space Age and the Current "Mini" Solar Maximum. Astrophysical Journal, 779, 2, doi: 10.1088/0004-637X/779/1/2

- **Investigation Type:** Data Analysis
- **Data Sources:** ACE:SWEPAM ACE:MAG

Summary: The interplanetary magnetic field (IMF) is determined by the amount of solar magnetic flux that passes through the top of the solar corona into the heliosphere, and by the dynamical evolution of that flux. Recently, it has been argued that the total flux of the IMF evolves over the solar cycle due to a combination of flux that extends well outside of 1 AU and is associated with the solar wind, and additionally, transient flux associated with coronal mass ejections (CMEs). In addition to the CME eruption rate, there are three fundamental processes involving conversion of magnetic flux (from transient to wind-associated), disconnection, and interchange reconnection that control the levels of each form of magnetic flux in the interplanetary medium. This is distinct from some earlier models in which the wind-associated component remains steady across the solar cycle. We apply the model of Schwadron et al. that quantifies the sources, interchange, and losses of magnetic flux to 50 yr of interplanetary data as represented by the Omni2 data set using the sunspot number as a proxy for the CME eruption rate. We do justify the use of that proxy substitution. We find very good agreement between the predicted and observed interplanetary magnetic flux. In the absence of sufficient CME eruptions, the IMF falls on the timescale of ~6 yr. A key result is that rising toroidal flux resulting from CME eruption predates the increase in wind-associated IMF.

Reference: Smith C. W.; Schwadron N. A.; DeForest C. E.; (2013). Decline and Recovery of the Interplanetary Magnetic Field during the Protracted Solar Minimum. Astrophysical Journal, 775, 59, doi: 10.1088/0004-637X/775/1/59

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** Schwadron heliospheric magnetic flux model
- **Datasources:** ACE:MAG

Summary: (Predictions of Radiation from Release, EMMREM, and Data Incorporating the CRaTER, COSTEP and other SEP measurements, prediccs.sr.unh.edu) is an online system designed to provide a near real-time characterization of the radiation environment of the inner heliosphere. PREDICCS utilizes data from various satellites in conjunction with numerical models such as the Earth-Moon-Mars Radiation Environment Module (EMMREM) to produce dose rate and particle flux data at the Earth, Moon and Mars. The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument launched aboard the Lunar Reconnaissance Orbiter (LRO) spacecraft in 2009 and designed to measure energetic particle radiation, offers an opportunity to test the capability of PREDICCS to accurately describe the lunar radiation environment. We provide comparisons between dose rates produced by PREDICCS with those measured by CRaTER during three major solar energetic particle (SEP) events that occurred in 2012. In addition, using EMMREM data products together with our archive of measured CRaTER dose rates, we compute the modulation potential at the Moon throughout the LRO mission and, using this, compute the background GCR dose rate during each event. We demonstrate reasonable agreement between PREDICCS and CRaTER dose rates and come to the conclusion that PREDICCS provides credible characterization of the lunar radiation environment. This study represents the first multi-event validation, via in situ measurement, of radiation models such as EMMREM, which should prove to be valuable in future efforts in risk assessment and in the study of radiation in the inner heliosphere.

Reference: Joyce C. J.; Schwadron N. A.; Wilson J. K.; Spence H. E.; Kasper J. C.; Golightly M.; Blake J. B.; Mazur J.; Townsend L. W.; Case A. W.; Semones E.; Smith S.; Zeitlin C. J.; (2013). Validation of PREDICCS using LRO/CRaTER observations during three major solar events in 2012. Space Weather, 11, 350-360, doi: 10.1002/swe.20059

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** EMMREM and PREDICCS
- **Datasources:**

Summary: This special issues combines results of EMMREM, PREDICCS and compares them with observations from LRO/CRaTER and other platforms to quantify our understanding of the space radiation environment in the extended cycle 23-24.

Reference: Schwadron N. A.; Smith S.; Spence H. E.; (2013). The CRaTER Special Issue of Space Weather: Building the observational foundation to deduce biological effects of space radiation. Space Weather, 11, 47-48, doi: 10.1002/swe.20026

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** EMMREM and PREDICCS
- **Datasources:** ACE:MAG

Summary: We describe a new MHD model for the propagation of interplanetary coronal mass ejections (ICMEs) in the solar wind. Accurately following the propagation of ICMEs is important for determining space weather conditions. Our model solves the MHD equations in spherical coordinates from a lower boundary above the critical point to Earth and beyond. On this spherical surface, we prescribe the magnetic field, velocity, density, and temperature calculated typically directly from a coronal MHD model as time-dependent boundary conditions. However, any model that can provide such quantities either in the inertial or rotating frame of the Sun is suitable. We present two validations of the technique employed in our new model and a more realistic simulation of the propagation of an ICME from the Sun to Earth.

Reference: Lionello R.; Downs C.; Linker J. A.; Torok T.; Riley P.; Mikic Z.; (2013). Magnetohydrodynamic Simulations of Interplanetary Coronal Mass Ejections. Astrophysical Journal, 777, 76, doi: 10.1088/0004-637X/777/1/76

- **Investigation Type:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** PSI ICME model
- **Domains:** Sun Interplanetary space or solar wind

Summary: This research provides new insights into the emergence of CMEs, which is critical to the development of predictive models. We present results from three-dimensional visco-resistive magnetohydrodynamic simulations of the emergence of a convection zone magnetic flux tube into a solar atmosphere containing a pre-existing dipole coronal field, which is orientated to minimize reconnection with the emerging field. We observe that the emergence process is capable of producing a coronal flux rope by the transfer of twist from the convection zone, as found in previous simulations. We find that this flux rope is stable, with no evidence of a fast rise, and that its ultimate height in the corona is determined by the strength of the pre-existing dipole field. We also find that although the electric currents in the initial convection zone flux tube are almost perfectly neutralized, the resultant coronal flux rope carries a significant net current. These results suggest that flux tube emergence is capable of creating non-current-neutralized stable flux ropes in the corona, tethered by overlying potential fields, a magnetic configuration that is believed to be the source of coronal mass ejections.

Reference: Leake J. E.; Linton M. G.; Torok T.; (2013). Simulations of Emerging Magnetic Flux. I. The Formation of Stable Coronal Flux Ropes. Astrophysical Journal, 778, 99, doi: 10.1088/0004-637X/778/2/99

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

Summary: Understanding CME interaction is essential for being able to predict the conditions at 1 AU that lead to major space weather storms. We report on a numerical investigation of two coronal mass ejections (CMEs) that interact as they propagate in the inner heliosphere. We focus on the effect of the orientation of the CMEs relative to each other by performing four different simulations with the axis of the second CME rotated by 90° from one simulation to the next. Each magnetohydrodynamic simulation is performed in three dimensions with the Space Weather Modeling Framework in an idealized setting reminiscent of solar minimum conditions. We extract synthetic satellite measurements during and after the interaction and compare the different cases. We also analyze the kinematics of the two CMEs, including the evolution of their widths and aspect ratios. We find that the first CME contracts radially as a result of the interaction in all cases, but the amount of subsequent radial expansion depends on the relative orientation of the two CMEs. Reconnection between the two ejecta and between the ejecta and the interplanetary magnetic field determines the type of structure resulting from the interaction. When a CME with a high inclination with respect to the ecliptic overtakes one with a low inclination, it is possible to create a compound event with a smooth rotation in the magnetic field vector over more than 180°. Due to reconnection, the second CME only appears as an extended "tail," and the event may be mistaken for a glancing encounter with an isolated CME. This configuration differs significantly from the one usually studied of a multiple-magnetic-cloud event, which we found to be associated with the interaction of two CMEs with the same orientation.

Reference: Lugaz N.; Farrugia C. J.; Manchester W. B.; Schwadron N.; (2013). The Interaction of Two Coronal Mass Ejections: Influence of Relative Orientation. Astrophysical Journal, 778, 20, doi: 10.1088/0004-637X/778/1/20

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

Summary: This work develops new capabilities for nowcasting and forecasting the radiation environment down to aircraft altitudes. We expand upon the efforts of Joyce et al. (2013), who computed the modulation potential at the Moon using measurements from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument on the Lunar Reconnaissance Orbiter (LRO) spacecraft along with data products from the Earth-Moon-Mars Radiation Environment Module (EMMREM). Using the computed modulation potential, we calculate galactic cosmic ray (GCR) dose and dose equivalent rates in the Earth and Mars atmospheres for various altitudes over the course of the LRO mission. While we cannot validate these predictions by directly comparable measurement, we find that our results conform to expectations and are in good agreement with the nearest available measurements and therefore may be used as reasonable estimates for use in efforts in risk assessment in the planning of future space missions as well as in the study of GCRs. PREDICCS (Predictions of radiation from REleASE, EMMREM, and Data Incorporating the CRaTER, COSTEP, and other solar energetic particles measurements) is an online system designed to provide the scientific community with a comprehensive resource on the radiation environments of the inner heliosphere. The data products shown here will be incorporated into PREDICCS in order to further this effort and daily updates will be made available on the PREDICCS website (http://prediccs.sr.unh.edu).

Reference: Joyce C. J.; Schwadron N. A.; Wilson J. K.; Spence H. E.; Kasper J. C.; Golightly M.; Blake J. B.; Townsend L. W.; Case A. W.; Semones E.; Smith S.; Zeitlin C. J.; (2014). Radiation modeling in the Earth and Mars atmospheres using LRO/CRaTER with the EMMREM Module. Space Weather, 12, 112-119, doi: 10.1002/2013SW000997

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** EMMREM, PREDICCS
- **Datasources:**

Summary: We develop a tool that will be needed to forecast the radiation environment. Described here is the development of a new project, the Coronal-Solar Wind Energetic Particle Acceleration (C-SWEPA) Modules, which couples the CORHEL MHD models within the low corona with EMMREM for characterizing energetic particle acceleration and subsequent formation of energetic particle hazards. We have shown initial results of the coupling, in which an extreme SEP event with a broad longitudinal extent was formed from a fast CME at 2–5 solar radii. This model showed large enough differential energy fluxes to approach 30 day radiation limits even behind thick spacecraft shielding (10 g/cm2). The fact that the event was so abrupt, with high-energy fluxes formed within only 2 h after CME onset, demonstrates the significant potential hazard for astronauts and spacecraft. The development of accurate predictive models, response strategies, and an understanding of the statistical probability for this type of prompt and extreme SEP event is the focus of C-SWEPA research in the NASA/NSF Space Weather Modeling Collaborative.

Reference: Schwadron N. A.; Gorby M.; Torok T.; Downs C.; Linker J.; Lionello R.; Mikic Z.; Riley P.; Giacalone J.; Chandran B.; Germaschewski K.; Isenberg P. A.; Lee M. A.; Lugaz N.; Smith S.; Spence H. E.; Desai M.; Kasper J.; Kozarev K.; Korreck K.; Stevens M.; Cooper J.; MacNeice P.; (2014). Synthesis of 3-D Coronal-Solar Wind Energetic Particle Acceleration Modules. Space Weather, 12, 323-328, doi: 10.1002/2014SW001086

- **Investigation Type:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** EPREM, C-SWEPA
- **Domains:** Sun Interplanetary space or solar wind

Summary: The Sun and its solar wind are currently exhibiting extremely low densities and magnetic field strengths, representing states that have never been observed during the space age. The highly abnormal solar activity between cycles 23 and 24 has caused the longest solar minimum in over 80 years and continues into the unusually small solar maximum of cycle 24. As a result of the remarkably weak solar activity, we have also observed the highest fluxes of galactic cosmic rays in the space age and relatively small solar energetic particle events. We use observations from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter to examine the implications of these highly unusual solar conditions for human space exploration. We show that while these conditions are not a show stopper for long-duration missions (e.g., to the Moon, an asteroid, or Mars), galactic cosmic ray radiation remains a significant and worsening factor that limits mission durations. While solar energetic particle events in cycle 24 present some hazard, the accumulated doses for astronauts behind 10 g/cm2 shielding are well below current dose limits. Galactic cosmic radiation presents a more significant challenge: the time to 3% risk of exposure-induced death (REID) in interplanetary space was less than 400 days for a 30 year old male and less than 300 days for a 30 year old female in the last cycle 23-24 minimum. The time to 3% REID is estimated to be ˜20% lower in the coming cycle 24-25 minimum. If the heliospheric magnetic field continues to weaken over time, as is likely, then allowable mission durations will decrease correspondingly. Thus, we estimate exposures in extreme solar minimum conditions and the corresponding effects on allowable durations.

Reference: Schwadron N. A.; Blake J. B.; Case A. W.; Joyce C. J.; Kasper J.; Mazur J.; Petro N.; Quinn M.; Porter J. A.; Smith C. W.; Smith S.; Spence H. E.; Townsend L. W.; Turner R.; Wilson J. K.; Zeitlin C.; (2014). Does the worsening galactic cosmic radiation environment observed by CRaTER preclude future manned deep space exploration?. Space Weather, 12, 622-632, doi: 10.1002/2014SW001084

- **Investigation Type:** Data Analysis
- **Data Sources:** LRO:CRATER

Summary: Recent papers have linked the heliospheric magnetic flux to the sunspot cycle with good correlation observed

between prediction and observation. Other papers have shown a strong correlation between magnetic flux and solar wind proton flux from coronal holes. We combine these efforts with an expectation that the sunspot activity of the approaching solar minimum will resemble the Dalton or Gleissberg Minimum and predict that the magnetic flux and solar wind proton flux over the coming decade will be lower than at any time during the space age. Using these predictions and established theory, we also predict record high galactic cosmic ray intensities over the same years. The analysis shown here is a prediction of global space climate change within which space weather operates. It predicts a new parameter regime for the transient space weather behavior that can be expected during the coming decade.

Reference: Smith C. W.; McCracken K. G.; Schwadron N. A.; Goelzer M. L.; (2014). The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum. Space Weather, 12, 499-507, doi: 10.1002/2014SW001067

- **Investigation Type:** Data Analysis
- **Data Sources:** ACE:MAG

Summary: We propose a method for constructing approximate force-free equilibria in pre-eruptive configurations in which a thin force-free flux rope is embedded into a locally bipolar-type potential magnetic field. The flux rope is assumed to have a circular-arc axis, a circular cross-section, and electric current that is either concentrated in a thin layer at the boundary of the rope or smoothly distributed across it with a maximum of the current density at the center. The entire solution is described in terms of the magnetic vector potential in order to facilitate the implementation of the method in numerical magnetohydrodynamic (MHD) codes that evolve the vector potential rather than the magnetic field itself. The parameters of the flux rope can be chosen so that its subsequent MHD relaxation under photospheric line-tied boundary conditions leads to nearly exact numerical equilibria. To show the capabilities of our method, we apply it to several cases with different ambient magnetic fields and internal flux-rope structures. These examples demonstrate that the proposed method is a useful tool for initializing data-driven simulations of solar eruptions.

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:** MAS
- **Domains:** Sun Interplanetary space or solar wind

Summary: There has been a long-standing debate on the question of whether or not electric currents in solar active regions are neutralized. That is, whether or not the main (or direct) coronal currents connecting the active region polarities are surrounded by shielding (or return) currents of equal total value and opposite direction. Both theory and observations are not yet fully conclusive regarding this question, and numerical simulations have, surprisingly, barely been used to address it. Here we quantify the evolution of electric currents during the formation of a bipolar active region by considering a three-dimensional magnetohydrodynamic simulation of the emergence of a sub-photospheric, current-neutralized magnetic flux rope into the solar atmosphere. We find that a strong deviation from current neutralization develops simultaneously with the onset of significant flux emergence into the corona, accompanied by the development of substantial magnetic shear along the active region's polarity inversion line. After the region has formed and flux emergence has ceased, the strong magnetic fields in the region's center are connected solely by direct currents, and the total direct current is several times larger than the total return current. These results suggest that active regions, the main sources of coronal mass ejections and flares, are born with substantial net currents, in agreement with recent observations. Furthermore, they support eruption models that employ pre-eruption magnetic fields containing such currents.

Reference: Torok T.; Leake J. E.; Titov V. S.; Archontis V.; Mikic Z.; Linton M. G.; Dalmasse K.; Aulanier G.; Kliem B.; (2014). Distribution of Electric Currents in Solar Active Regions. Astrophysical Journall, 782, L10, doi: 10.1088/2041-8205/782/1/L10

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

Summary: Coronal mass ejections (CMEs) erupt and expand in a magnetically structured solar corona. Various indirect observational pieces of evidence have shown that the magnetic field of CMEs reconnects with surrounding magnetic fields, forming, e.g., dimming regions distant from the CME source regions. Analyzing Solar Dynamics Observatory (SDO) observations of the eruption from AR 11226 on 2011 June 7, we present the first direct evidence of coronal magnetic reconnection between the fields of two adjacent active regions during a CME. The observations are presented jointly with a data-

constrained numerical simulation, demonstrating the formation/intensification of current sheets along a hyperbolic flux tube at the interface between the CME and the neighboring AR 11227. Reconnection resulted in the formation of new magnetic connections between the erupting magnetic structure from AR 11226 and the neighboring active region AR 11227 about 200 Mm from the eruption site. The onset of reconnection first becomes apparent in the SDO/AIA images when filament plasma, originally contained within the erupting flux rope, is redirected toward remote areas in AR 11227, tracing the change of large-scale magnetic connectivity. The location of the coronal reconnection region becomes bright and directly observable at SDO/AIA wavelengths, owing to the presence of down-flowing cool, dense (1010 cm-3) filament plasma in its vicinity. The high-density plasma around the reconnection region is heated to coronal temperatures, presumably by slow-mode shocks and Coulomb collisions. These results provide the first direct observational evidence that CMEs reconnect with surrounding magnetic structures, leading to a large-scale reconfiguration of the coronal magnetic field.

Reference: van Driel-Gesztelyi L.; Baker D.; Torok T.; Pariat E.; Green L. M.; Williams D. R.; Carlyle J.; Valori G.; Demoulin P.; Kliem B.; Long D. M.; Matthews 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 Analysis
- **Data Sources:** SDO:AIA SDO:HMI

Summary: The helical kink instability of a twisted magnetic flux tube has been suggested as a trigger mechanism for solar filament eruptions and coronal mass ejections (CMEs). In order to investigate if estimations of the pre-emptive twist can be obtained from observations of writhe in such events, we quantitatively analyze the conversion of twist into writhe in the course of the instability, using numerical simulations. We consider the line tied, cylindrically symmetric Gold-Hoyle flux rope model and measure the writhe using the formulae by Berger and Prior which express the quantity as a single integral in space. We find that the amount of twist converted into writhe does not simply scale with the initial flux rope twist, but depends mainly on the growth rates of the instability eigenmodes of higher longitudinal order than the basic mode. The saturation levels of the writhe, as well as the shapes of the kinked flux ropes, are very similar for considerable ranges of initial flux rope twists, which essentially precludes estimations of pre-eruptive twist from measurements of writhe. However, our simulations suggest an upper twist limit of ˜6? for the majority of filaments prior to their eruption.

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

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

Summary: The onset of a solar eruption is formulated here as either a magnetic catastrophe or as an instability. Both start with the same equation of force balance governing the underlying equilibria. Using a toroidal flux rope in an external bipolar or quadrupolar field as a model for the current-carrying flux, we demonstrate the occurrence of a fold catastrophe by loss of equilibrium for several representative evolutionary sequences in the stable domain of parameter space. We verify that this catastrophe and the torus instability occur at the same point; they are thus equivalent descriptions for the onset condition of solar eruptions.

Reference: Kliem B.; Lin J.; Forbes T. G.; Priest E. R.; Torok 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:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** Torus Instability Model for solar eruptions
- **Domains:** Sun

Summary: Force-free equilibria containing two vertically arranged magnetic flux ropes of like chirality and current direction are considered as a model for split filaments/prominences and filament-sigmoid systems. Such equilibria are constructed analytically through an extension of the methods developed in Titov & Démoulin and numerically through an evolutionary sequence including shear flows, flux emergence, and flux cancellation in the photospheric boundary. It is demonstrated that the analytical equilibria are stable if an external toroidal (shear) field component exceeding a threshold value is included. If this component decreases sufficiently, then both flux ropes turn unstable for conditions typical of solar active regions, with the lower rope typically becoming unstable first. Either both flux ropes erupt upward, or only the upper rope erupts while the lower rope reconnects with the ambient flux low in the corona and is destroyed. However, for shear field strengths staying somewhat above

the threshold value, the configuration also admits evolutions which lead to partial eruptions with only the upper flux rope becoming unstable and the lower one remaining in place. This can be triggered by a transfer of flux and current from the lower to the upper rope, as suggested by the observations of a split filament in Paper I. It can also result from tether-cutting reconnection with the ambient flux at the X-type structure between the flux ropes, which similarly influences their stability properties in opposite ways. This is demonstrated for the numerically constructed equilibrium.

Reference: Kliem B.; Torok T.; Titov V. S.; Lionello R.; Linker 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: There is a recurring question in solar physics regarding whether or not electric currents are neutralized in active regions (ARs). This question was recently revisited using three-dimensional (3D) magnetohydrodynamic (MHD) numerical simulations of magnetic flux emergence into the solar atmosphere. Such simulations showed that flux emergence can generate a substantial net current in ARs. Other sources of AR currents are photospheric horizontal flows. Our aim is to determine the conditions for the occurrence of net versus neutralized currents with this second mechanism. Using 3D MHD simulations, we systematically impose line-tied, quasi-static, photospheric twisting and shearing motions to a bipolar potential magnetic field. We find that such flows: (1) produce both direct and return currents, (2) induce very weak compression currents—not observed in 2.5D—in the ambient field present in the close vicinity of the current-carrying field, and (3) can generate force-free magnetic fields with a net current. We demonstrate that neutralized currents are in general produced only in the absence of magnetic shear at the photospheric polarity inversion line—a special condition that is rarely observed. We conclude that photospheric flows, as magnetic flux emergence, can build up net currents in the solar atmosphere, in agreement with recent observations. These results thus provide support for eruption models based on pre-eruption magnetic fields that possess a net coronal current.

Reference: Dalmasse K.; Aulanier G.; Demoulin P.; Kliem 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: We present a study on particle acceleration in the low corona associated with the expansion and acceleration of coronal mass ejections (CMEs). Because CME expansion regions low in the corona are effective accelerators over a finite spatial region, we show that there is a rigidity regime where particles effectively diffuse away and escape from the acceleration sites using analytic solutions to the Parker transport equation. This leads to the formation of broken power-law distributions. Based on our analytic solutions, we find a natural ordering of the break energy and second power-law slope (above the break energy) as a function of the scattering characteristics. These relations provide testable predictions for the particle acceleration from low in the corona. Our initial analysis of solar energetic particle observations suggests a range of shock compression ratios and rigidity dependencies that give rise to the solar energetic particle (SEP) events studied. The wide range of characteristics inferred suggests competing mechanisms at work in SEP acceleration. Thus, CME expansion and acceleration in the low corona may naturally give rise to rapid particle acceleration and broken power-law distributions in large SEP events.

Reference: Schwadron N. A.; Lee M. A.; Gorby M.; Lugaz N.; Spence H. E.; Desai M.; Torok T.; Downs C.; Linker J.; Lionello R.; Mikic Z.; Riley P.; Giacalone J.; Jokipii J. R.; Kota J.; Kozarev 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:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** Analytical solutions to the Parker transport equation for energetic particles
- **Domains:** Sun Interplanetary space or solar wind

Summary: Recent in situ observations of the solar wind show that charge states (e.g., the $O^{7+}/O^{6+}$and C^{6+}/C^{5+}abundance ratios) evolved through the extended, deep solar minimum between solar cycles 23 and 24 (i.e., from 2006 to 2009) reflecting cooler electron temperatures in the corona. We extend previous analyses to study the evolution of the coronal electron temperature through the protracted solar minimum and observe not only the reduction in coronal temperature in the cycles

23-24 solar minimum but also a small increase in coronal temperature associated with increasing activity during the "mini maximum" in cycle 24. We use a new model of the interplanetary magnetic flux since 1749 to estimate coronal electron temperatures over more than two centuries. The reduction in coronal electron temperature in the cycles 23-24 protracted solar minimum is similar to reductions observed at the beginning of the Dalton Minimum (˜1805-1840). If these trends continue to reflect the evolution of the Dalton Minimum, we will observe further reductions in coronal temperature in the cycles 24-25 solar minimum. Preliminary indications in 2013 do suggest a further post cycle 23 decline in solar activity. Thus, we extend our understanding of coronal electron temperature using the solar wind scaling law and compare recent reductions in coronal electron temperature in the protracted solar minimum to conditions that prevailed in the Dalton Minimum.

Reference: Schwadron N. A.; Goelzer M. L.; Smith C. W.; Kasper J. C.; Korreck K.; Leamon R. J.; Lepri S. T.; Maruca B. A.; McComas D.; Steven M. L.; (2014). Coronal electron temperature in the protracted solar minimum, the cycle 24 mini maximum, and over centuries. Journal of Geophysical Research (Space Physics), 119, 1486-1492, doi: 10.1002/2013JA019397

- **Investigation Type:** Data Analysis
- **Data Sources:** ACE:SWICS

Summary: Specification of radiation environment.

Reference: Cooper John F.; King Joseph H.; Papitashvili Natalia E.; Lal Nand; Sittler Edward C.; Sturner Steven J.; Hills H. Kent; Lipatov Alexander S.; Kovalick Tamara J.; Johnson Rita C.; Leckner Howard A.; McGuire Robert E.; Narock Thomas W.; Szabo Adam; Roberts D. Aaron; Armstrong Thomas P.; Manweileri Jerry W.; Patterson J. Douglas; McKibben Robert B.; Tranquille Cecil; (2012). Space weathering investigations enabled by NASA's virtual heliophysical observatories. AIP Conference Proceedings, 1500, 204-209, doi: http://dx.doi.org/10.1063/1.4768767

- **Investigation Type:** Data Analysis
- **Data Sources:** SOHO:ERNE STEREO A:IMPACT STEREO B:IMPACT ACE:CRIS ACE:SIS ACE:ULEIS ACE:SEPICA ULYSSES:COSPIN ULYSSES:HISCALE VOYAGER 1-2:LECP VOYAGER 1-2:CRS

Summary: The Cosmic Ray Telescope for the Effects of Radiation (CRaTER), an instrument carried on the Lunar Reconnaissance Orbiter spacecraft, directly measures the energy depositions by solar and galactic cosmic radiations in its silicon wafer detectors. These energy depositions are converted to linear energy transfer (LET) spectra. High LET particles, which are mainly high-energy heavy ions found in the incident cosmic ray spectrum, or target fragments and recoils produced by protons and heavier ions, are of particular importance because of their potential to cause significant damage to human tissue and electronic components. Aside from providing LET data useful for space radiation risk analyses for lunar missions, the observed LET spectra can also be used to help validate space radiation transport codes, used for shielding design and risk assessment applications, which is a major thrust of this work. In this work the Monte Carlo transport code HETC-HEDS (High-Energy Transport Code-Human Exploration and Development in Space) is used to estimate LET contributions from the incident primary ions and their charged secondaries produced by nuclear collisions as they pass through the three pairs of silicon detectors. Also in this work, the contributions to the LET of the primary ions and their charged secondaries are analyzed and compared with estimates obtained using the deterministic space radiation code HZETRN 2010, developed at NASA Langley Research Center. LET estimates obtained from the two transport codes are compared with measurements of LET from the CRaTER instrument during the mission. Overall, a comparison of the LET predictions of the HETC-HEDS code to the predictions of the HZETRN code displays good agreement. The code predictions are also in good agreement with the CRaTER LET measurements above 15 keV/μm but differ from the measurements for smaller values of LET. A possible reason for this disagreement between measured and calculated spectra below 15 keV/μm is an inadequate representation of the light ion spectra in HETC-HEDS and HZETRN code calculations. It is also clear from the results of this work that Vavilov distributions need to be incorporated into the HETC-HJEDS code before it will be able to recreate the observed LET spectra measured by the CRaTER instrument.

Reference: Porter J. A.; Townsend L. W.; Spence H.; Golightly M.; Schwadron N.; Kasper J.; Case A. W.; Blake J. B.; Zeitlin C.; (2014). Radiation environment at the Moon: Comparisons of transport code modeling and measurements from the CRaTER instrument. Space Weather, 12, 329-336, doi: 10.1002/2013SW000994

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** EMMREM and HZETRN
- **Datasources:** LRO:CRATER