The Connection Between Coronal Shock Wave Dynamics and Early SEP Production

ISSI International Science Team Proposal

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Abstract

A slew of recent remote observations have shown that sufficiently fast coronal mass ejections (CMEs) can drive shock waves very low in the solar atmosphere. Collisionless shocks are known to produce solar energetic particles (SEPs), but it is presently not known to what energies they accelerate particles efficiently, or how that efficiency varies in time and space. The evolution of SEP fluxes in the early stages of coronal eruptions is of considerable interest to heliophysics, since it allows us to study processes of particle acceleration and radio emission, probe interplanetary magnetic fields, and to understand the origins of particle radiation that poses significant risks for space exploration. Despite considerable progress in observations and modeling in recent years, however, we still do not understand the connection between the global coronal field configuration, observed shock wave dynamics, and their efficiency at producing SEPs. We propose an ISSI working team to unravel this connection. We will identify a number of events to analyze in detail, using both remote and in situ observations. Comparisons will be made with simulated data and current theory and models, in order to explore the parameter space of coronal shock waves, their interaction with the coronal magnetic fields and their association with SEP events. The proposed team has the required expertise in observations, theory, and modeling of solar eruptions and the associated particle acceleration and radio emission.

Research Domains

Space Sciences (Solar and Heliospheric Physics, Solar and Terrestrial Sciences)

Scientific Rationale

Solar Energetic Particles (SEPs) consist of electron, proton and ion populations with energies in the range of tens of keV to a few GeV. SEP events can be loosely categorized into impulsive and gradual events, distinguished by the timescales of their intensity profiles and properties such as composition and ionization states (Reames, 1999). Impulsive events are attributed to particle acceleration in the magnetic reconnection process of solar flares, and gradual events to propagating CME shocks. However, a number of events exhibit characteristics of both impulsive and gradual events (i.e. timing of intensity profiles and ratios of heavy ions at high energies with hybrid characteristics), blurring the distinction between acceleration at flare reconnection sites and CME shocks (Kallenrode et al., 1992; Torsti et al., 2002).

In-situ observations of CME-driven shocks and their associated energetic particle signatures have shown that particle acceleration in propagating shocks results from shock drift acceleration in the quasi-perpendicular regime and diffusive shock acceleration in the quasi-parallel regime (Lee, 2005; Cohen, 2006). Here the two regimes are defined in terms of θ_{BN}, the angle between the upstream magnetic field and the normal to the shock surface, in such a way that the quasi-perpendicular (quasi-parallel) regime corresponds, for example, to $\theta_{BN}>60°(\theta_{BN}<50°)$. Without the ability to obtain in situ measurements of shocks in the corona, determining which acceleration processes take place close to the Sun is very challenging. The ability of the shock to accelerate particles to high energies is related to the length of time particles are present in the shock. While quasi-perpendicular shock acceleration has been shown to efficiently accelerate particles to high energies (GeV) (Zank et al., 2006), such shock geometry may be short lived. However, in the low corona, two types of CME evolution - lateral over-expansion, and self-similar expansion, can produce regions of stronger, or longer, respectively, quasi-perpendicularity in the portions of the shock driven by the CME flanks. Yet another possibility is that regions of significant compression (but smoother than plasma shocks) within the CME sheath may also accelerate SEPs to high energies (Kozarev et al., 2013). This may occur if the particles have diffusion lengths larger than the compression scale, which causes them to feel the compression sufficiently abruptly.

White light and EUV observations, supported by radio imaging and radio type II dynamic spectra, have found that shocks can form as low in the corona as 1.2 to 2.2 $R_\odot$ (Bain et al., 2012; Gopalswamy et al., 2013; Carley et al., 2013; Nitta et al., 2014). Multi-frequency mapping of type II bursts has shown that the sources at different frequencies are aligned along a direction that is often strongly inclined to the radial (Nelson & Robinson, 1975; Klein et al., 1999). This is not expected if the radiating electrons are accelerated at a quasi-parallel shock driven by the outward motion of a CME, but is consistent with a shock generated by lateral expansion. Several mechanisms can give rise to shock formation in the corona, including blast waves, caused by a sudden release of flare-related energy (Vršnak et al., 2006), or erupting CMEs which drive the shock as they propagate outwards (Dauphin et al., 2006; Zimovets et al., 2012). Recent high-cadence observations of transient EUV waves[1] suggest that they are formed by magnetosonic waves or shocks (Kozarev et al., 2011; Downs et al., 2012). These large-scale coronal fronts have been widely studied in the last several years due largely to the signficantly improved EUV images in terms of spatial and temporal resolution, and spectral coverage (the Solar Dynamics Observatory (SDO)), and of multipoint views (Solar and Terrestrial Relations Observatory (STEREO)). We now know that EUV waves are very common during solar eruptions, and several studies have characterized them in detail (Veronig et al., 2010; Patsourakos et al., 2010; Hoililjoki et al., 2013).

The ubiquity of EUV waves during solar eruptions has raised the question of whether they may signify shock or compression waves responsible for accelerating particles observed during the early stages of SEP events. Recent analysis of the temporal relation between the evolution of EUV waves on the solar disk and the in situ onset of particle fluxes for a large sample of events during cycle 23 has shown a general consistency with wave/shock acceleration for protons, but not for electrons (Miteva et al., 2014). This discrepancy points to the likely complexity of the interaction between the wave/shock and the global coronal magnetic field during its evolution - both in terms of acceleration efficiency, and coronal magnetic connectivity to the observer. An example of an event that generated an EUV wave, a radio shock, and significant proton fluxes at both STEREO spacecraft is shown in Figure 1.

With the advent of the STEREO mission, for the first time EUV waves could be observed simultaneously from two different vantage points (e.g., Kienreich et al., 2009; Patsourakos & Vourlidas, 2009). These new observations showed that EUV waves are very likely initiated by the dynamic evolution of the associated CME in the lower corona. Using SDO data, Cheng et al. (2012) observed in detail the formation and separation of an EUV wave from the expanding CME. These results support the idea that

[1]Different authors refer to them as "EIT waves", "coronal bright fronts (CBFs)", "large-scale coronal propagating fronts (LCPFs)", etc., but we consistently use "EUV waves" to avoid unnecessary confusion.

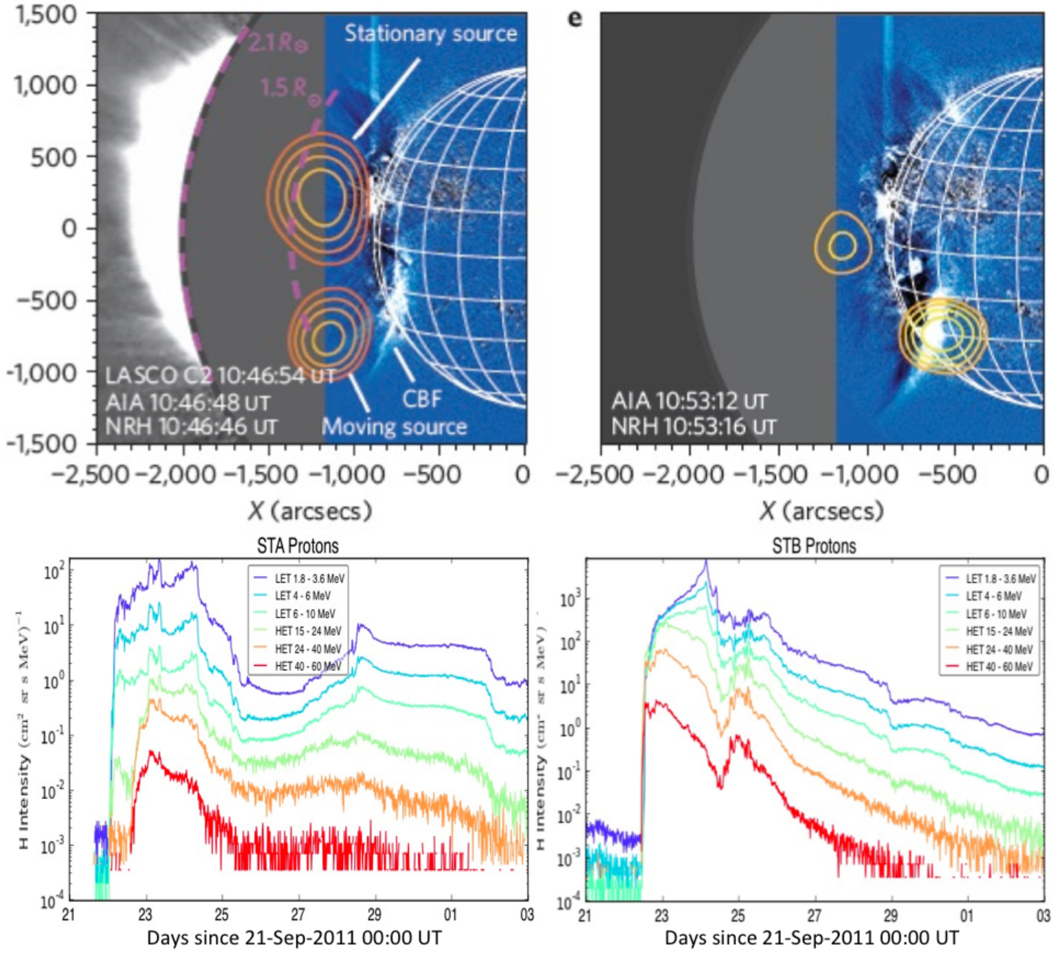

Figure 1: **Top, left.** An image showing a composite image from the eastern limb event of September 22, 2011, with overlaid: EUV (blue) difference image of the Sun from SDO/AIA highlighting an EUV wave; metric radio emission contours (orange) from the Nançay Radioheliograph (NRH); white light emission from the LASCO coronagraph (grayscale) outlining the outermost CME surface (shock front). **Top, right.** A snapshot 7 minutes later shows the overlap between the radio and EUV emission. The large scale EUV wave is easily seen. Both panels are taken from Carley et al. (2013). **Bottom.** STEREO A (left) and B (right) observed significant increases in 1.8-60 MeV proton fluxes for this event.

the flanks of the CME would initially drive EUV waves and as the impulsive lateral expansion of the CME stops or slows down the wave detaches and propagates freely, comparable to results from MHD modeling (e.g., Pomoell et al., 2008). With the two STEREO spacecraft and near-Earth observers we can also study SEP events from multiple vantage points. The observation of the same event from a broad range of longitudes (e.g. Dresing et al., 2014; Lario et al., 2014; Gómez-Herrero et al., 2015) allows us to test the longitudinal extent of particle acceleration by coronal shocks.

Modeling efforts have begun to unravel the complexity of interaction between coronal shocks and solar magnetic fields by developing advanced numerical simulations of CMEs, radio emissions, and the acceleration and transport of particles in the corona (Afanasiev & Vainio, 2013; Kozarev et al., 2013; Schmidt et al., 2013). Global three-dimensional modeling of time-dependent coronal dynamics has matured to the point that they combine a sufficiently realistic description of the plasma in the solar atmosphere, including impulsive and driven shocks. Two important parameters that likely affect shock dynamics (and thus particle acceleration efficiency) are the Alfven speed profile in the corona and the lateral expansion of the CME driver (Temmer et al., 2013). Zucca et al. (2014) have recently used density diagnostics from

SDO/AIA and SOHO/LASCO, combined with a PFSS extrapolation of the coronal magnetic field to construct 2D Alfven speed maps of the corona, confirming the existence of Alfven speed minima in the corona predicted by models (Warmuth & Mann, 2005). Shocks are likely to occur in these minima, so knowledge of their position can help determine the shock formation location, i.e., near the CME nose or flank. Furthermore, suprathermal particle spectra and efficiency of injection into shocks need to be further taken into account (Battarbee et al., 2013), as well as the amount of pre-existing and self-generated turbulence (Vainio et al., 2014). In situ SEP measurements have shown a large variability in the ratio of heavy ions (Fe/C, Fe/O) as function of energy, especially in the >1 MeV/nuc ranges. Such characteristics may be the net result of specific shock geometries accelerating a seed population (Tylka et al., 2005). In-situ observations of relativistic electron release times may hold a clue to the acceleration efficiency and interplanetary diffusion (Agueda et al., 2014). A definitive answer to the question of whether and how efficiently coronal shocks accelerate SEPs will require carefully combining in situ and remote sensing observations with realistic global modeling. In addition, remote EUV and radio observables (e.g., type II bursts) that can be related, directly or through models, to 1 AU measurements, may help to dramatically improve space weather forecasting capabilities (Schmidt et al., 2013; Kozarev et al., 2015). The proposed team will review the current understanding of the interrelatedness of the relevant phenomena, and outline a direction for improving our understanding through a balanced approach combining observations and modeling. This step will be important in preparing for the Solar Probe Plus and Solar Orbiter missions.

Team Expertise and Duties

Team Member	Expertise	Project Duties
Neus Agueda	In-situ particle data analysis	Modeling of electron acceleration, comparison to observables
Hazel Bain	Radio & X-ray data analysis	Analysis of Type II observations
Rositsa Miteva	Radio diagnostics & SEP analysis	Analysis of solar origin of SEP events
Astrid Veronig	EUV, X-ray and H-alpha analysis	Kinematics and plasma diagnostics of EUV waves
Iver Cairns	Radio burst theory & modeling	CME, shock, and radio emission modeling, comparisons with data
Raul Gomez Herrero	SEP multi-point observations	Analysis of multi-point SEP observations for selected events
Ludwig Klein	Coronal acceleration & transport of particles	Study of connection between electromagnetic observations and solar origin of SEPs
Kamen Kozarev	EUV/radio observations SEP modeling	Analysis of EUV wave magnetic field interaction, modeling proton acceleration
David Lario	SEP observations	Analysis of SEP events' longitudinal extent, onset and release times
Nariaki Nitta	Multi-wavelength solar data, in-situ data	Analysis of EUV waves, examination of magnetic field connection
Jens Pomoell	Dynamics and characteristics of shocks and CMEs in the corona	MHD modeling of CME-initiated shock waves
Rami Vainio	Assessment of self-generated waves at shocks	Modeling & analysis of coronal wave/shock properties

Expected Output

The main goal of this team is to establish the connection between the properties of coronal shock waves and the production of solar energetic particles, using some of the most sophisticated observational and modeling techniques available. To accomplish this task, we will first review the theoretical basis for particle acceleration by shocks and evidence from in situ observations on the energy range and species of the accelerated particles. We will identify the observables which can characterize the processes relevant to particle acceleration and diffusion in the low corona. We will also review the major statistical studies relating remote observations of solar eruptions to in situ observations. We will then study a list of pre-selected recent events with observational and modeling tools, in order to examine the validity of the theories, and how much these observables influence SEP production in solar coronal shocks. These studies will be published in a review article and multiple joint research papers.

Added Value from ISSI

The ISSI gives a unique opportunity for teams comprising researchers from different countries worldwide to gather and do focused work on topics at the forefront of contemporary space sciences. The proposed team of international scholars holds the necessary varied expertise on the topic of coronal shocks, SEP acceleration, and radio emission needed to approach this problem in a comprehensive way, theoretically and observationally. That is why an ISSI workshop would be an important step in significantly improving our knowledge and setting the future direction of research on this important topic.

Schedule

We propose to hold two five-day meetings at ISSI-Bern - the first to be held in late 2015, and the second in mid-2016. During the first meeting the team will review and discuss the theories for shock acceleration of SEPs applicable to the solar corona, and determine the relevant remote observables that may be useful for characterizing shock parameters in the corona. In addition, the team will assess the results from previous studies connecting remote and in-situ signatures of shocks and SEPs - single-case, as well as statistical - as a basis and a 'null hypothesis', on which to build and advance our knowledge with the help of higher spatial and temporal resolution observations from the current solar cycle. This work will be published in an overview paper. The team will also identify a short list of events for in-depth study, using the identified observables. Between the first and second meetings, team members will perform their tasks on the data analysis and modeling efforts discussed during the first meeting. Bi-monthly telecons will be held in order to ensure the continuity of the effort and cooperation in event analysis. At the second meeting, the team will have joint discussions of the results and interpretation of event studies. We will also draft the overview and research papers. We will invite external experts on shock SEP acceleration to participate in the second meeting, perhaps using Skype or an equivalent alternative. We will use the remote observables identified at the first meeting, and determine their applicability to characterizing the shock evolution. In addition, the team will study the effect of the overall coronal structure and its solar cycle variation on shock evolution and heliospheric connectivity. The team will write up the results during the meeting, and publish them in peer-reviewed journals.

Requested Facilities and Financial Support

We request a meeting room for two five-day periods, internet access, white board, and a multimedia projector. In addition, we request financial support for the 12 team members for lodging (10 days×12 ppl×€140 = €16,800) and meals (10 days×12 ppl×€50 = €6000) for the two five-day periods. We also request financial support for the travel of one team leader (€1,500). Total requested amount is €24,300. If selected, we will make use of ISSI's 'young scientist' funding scheme to include Dr. Eoin Carley.

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