Coronal Shock Acceleration and Heliospheric Transport of Solar Energetic Protons

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Abstract. The aim of this dissertation is to give insight into the generation and evolution of solar energetic proton fluxes in the heliosphere, starting at the Sun and extending beyond 1 AU. This is done in two ways - by characterizing the dynamics and particle acceleration efficiency of shocks very low in the solar corona from remote observations; and by performing physics-based, consistent numerical modeling studies of proton acceleration in a realistic CME-driven shock, as well as in the inner heliosphere. Currently, it is commonly thought that solar flares mostly accelerate SEPs low in the corona, while CME-driven shocks are responsible for the acceleration in the higher corona and interplanetary space. This dissertation challenges that paradigm by showing that shocks can be very efficient accelerators throughout the corona (1.3-7 R_S), and may be responsible for most of the SEP acceleration. In addition, Interplanetary simulations suggest that SEP transport in the heliosphere is mostly modulated by the transport conditions, and traveling shocks are not necessary to reproduce the observed fluxes.

1 Summary of Results

In Chapter 2 I have presented high cadence remote observations of CME-related shocks and waves in the corona. I have analyzed two coronal shock events using extreme ultraviolet (EUV) observations of coronal bright fronts from the Advanced Imaging Assembly (AIA) instrument on the Solar Dynamics Observatory (SDO), as well as radio and in situ observations. I characterized the shock dynamics, and showed that those fronts were consistent with MHD shocks. I also showed that the magnetic field topology in which the shock propagates is very important for determining the acceleration location and subsequent direction of release and propagation of the accelerated particles.

In order to explore further the relationship between coronal shock dynamics, the magnetic field topology, and particle acceleration, I combined a simple geometric model for the propagation of an idealized spherical shock through a coronal potential field source surface model (PFSS), and estimated the energization of protons with initial energies of 0.01 MeV Kozarev et al.(2012). I show that even the weak shocks may efficiently accelerate protons to tens of MeV very low in the corona, below 2 R_S. This is because CMEs that drive them are quite fast and carry a lot of kinetic energy shortly after their onset, and also because of the sharp drop of the Alfven speed to values below the typical shock propagation speeds. Since the density of particles available to be accelerated is much higher than in interplanetary space, these shocks can energize larger numbers of them. What is more, the shock speed, strength, and orientation to the magnetic fields control entirely the amount of energization. Thus, constraining the dynamics and morphology of coronal shocks and CMEs that drive them is crucial if we are to realistically model particle acceleration.

The characterization of energetic particle fluxes and radiation doses is an important topic in heliospheric physics. For the study of global SEP transport in large events simultaneously in different locations in the heliosphere in a realistic and physics-based manner, I present in Chapter 3 a modern, versatile and robust three dimensional particle transport model, which can be used for scientific studies and space weather predictions alike. The Energetic Particle Radiation Environment Module (EPREM)Schwadron et al.(2010) is a parallelized numerical kinetic code for the global propagation and acceleration of highly energetic charged particles of solar origin in the heliosphere. The model solves for the acceleration and transport of a distribution of protons with a dependence on pitch angle, momentum, time, and position, solving a modified version of the field aligned transport equation Kóta et al.(2005). EPREM can be used over a wide range of energies. It has been verified and shown to be consistent with expectations of particle transport theory. The model has been used to study SEP transport beyond 1 AU in large historical events Kozarev et al.(2010), Dayeh et al.(2010). The modular design of EPREM allows for the model of interplanetary magnetic field to be changed easily. In its original formulation, EPREM employs a time independent Parker spiral magnetic field, a constant solar wind speed, and density falling off as the inverse square of radial distance.

In order to study the acceleration of SEPs in shocks close to the Sun with fidelity, a much more detailed model for the solar corona and wind is required, which takes into account the dynamic nature of CMEs and shocks. I have created and present in Chapter 4 a coronal version of the EPREM model with an inner boundary at $\sim 1.8\,R_S$, which includes a diffusive solver treating explicitly particle acceleration at traveling shocks, and can readily incorporate detailed and time dependent models of the corona and wind. I have developed a dynamic coupling between results from a state-of-the-art 3D MHD time-dependent coronal and CME model and the EPREM model. A modified Titov-Demoulin flux rope Roussev et al.(2004) was used to reproduce a CME eruption. Using a realistic model of CME propagation has allowed the particle propagation model to take into account the ever changing properties of traveling shocks, magnetic field orientations, and local solar wind parameters when solving for particle acceleration. I have applied this coupled model to particle acceleration in the corona for a particular event, the May 13, 2005 CME. I have found that: 1. During a CME/shock event, SEP spectra vary greatly in longitude and latitude in the solar corona. 2. The spectra are very dynamic; consequently they do not in general follow a power law in energy. 3. The shape of the CME dictates the shape of the shock and the pile-up compression region, which in turn modulates the SEP acceleration profiles. 4. The spectra on the east side of this CME-driven shock show more acceleration due to the much faster expansion and compression there. 5. The variations in the coronal spectra in longitude and latitude cause very different SEP profiles on different field lines at 1 AU for steady solar wind conditions. 6. The PUC seems to be very efficient in containing and further enhancing the particles accelerated at the shock, due to the compressive nature of these flows. 7. The shock acceleration efficiency varies with time, and depends on how the shock speed changes with time.

We have performed a study of the transport of energetic protons between 1-5 AU during the 2003 Halloween SEP events, presented in Chapter 6. The

EPREM model was run for a variety of interplanetary conditions, in order to find the best agreement with the observations by the Ulysses spacecraft. I have found that a detailed global model of the solar wind parameters or a CME-driven traveling shock are not necessary in this case in order to predict the onset and reach the peak fluxes observed at 5 AU. From the results, I constructed radial gradients of peak and event integrated fluxes, as well as gradients of particle radiation dose rates and accumulated doses. These are very useful quantities for characterizing the heliospheric radiation environment, and for planning radiation protection for future exploratory missions. I found that the gradients had steeper slopes than previously reported. This is probably due to the disturbed conditions in interplanetary space during these events, which caused the proton fluxes to diffuse more efficiently in the three dimensional heliosphere.
Key words: CME SEP GCR solar corona Sun mass-ejection shock heliosphere

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