A proposal to NASA

Coronal injection sites of SEP beam events

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Rs → R_s

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2.1 Introduction

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Processes in the solar corona are prodigious accelerators of near-relativistic electrons. Only a small fraction of these electrons escape the low corona, yet are by far the most abundant species observed in Solar Energetic Particle (SEP) events. The vast majority of these electrons remain at the Sun, loosing energy, as they generate hard X-rays (HXR) through interactions with the dense solar material. HXR and other electromagnetic emissions produced by electrons give information about the acceleration, injection, intensity, spectra, and transport of energetic electrons at the Sun. These electromagnetic emissions can be directly compared with in situ observation of electrons sampled in interplanetary space. Priest and Forbes (2002) summarized various particle acceleration scenarios: Reconnection sites containing strong electric fields accelerate electrons and ions to high energy; MHD shocks are known to accelerate ions to high energy; in a highly turbulent environment, transit-time acceleration and cyclotron acceleration may accelerate electrons and ions respectively. We propose a study that will help to determine whether field-line reconnection, CME-driven shocks, both, or some other mechanism is responsible for the near-relativistic electron populations observed near 1 AU.

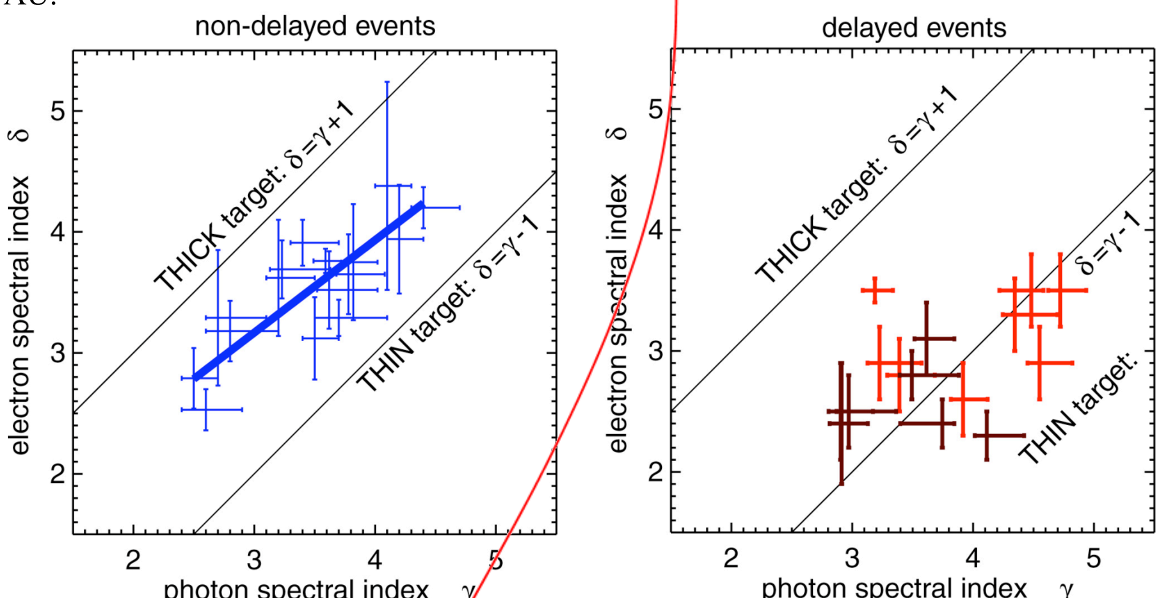

Figure 1. RHESSI observed photon spectra compared to in situ electron spectra for non-delayed events (left), and for delayed events (right). Non-delayed events correlate well with the photon spectra while events that show a timing delay are not well correlated with the HXR spectra (figures courtesy of Sam Krucker et al., ApJ, submitted).

Recent studies of HXR spectra sampled by RHESSI provide new possibilities to understand the mechanism by which solar flares accelerate electrons and help us to understand the associated electrons at 1 AU. We have reported that many electron events observed near 1 AU appear to be injected onto open coronal fields on average 8 minutes after the associated electromagnetic emissions (HXR, Radio, Hα flare, etc: see Haggerty et al., 2003; Haggerty and Roelof 2002, Krucker et al., 1999). Figure 1 show results from a statistical survey [Krucker and Lin, 2006, Krucker et al. (~2007)] where near-

Consistency in references

relativistic electron events were classified as either non-delayed events (left panel) or delayed events (right panel). In Figure 1 the power-law spectral index of electron events at 1 AU is compared with the HXR spectra for the associated events in the corona. For events where the electrons appear to be injected at or very near the time the photons are emitted, the spectra are well correlated (although not strictly according to either a thick or thin target model). For those events where the electrons appear to be injected significantly after the associated photon emission, the in situ electron spectra are not well correlated with the low coronal photon spectra.

The near-relativistic electrons that escape the sun transmit much more information than just the onset time and spectra (although both provide good diagnostics of the acceleration process). Haggerty and Roelof (2006) presented new results that show beam-like electron events exhibit a continuum of profiles, from a Gaussian-like “spike” that has a symmetric and rapid rise and fall (lasting as little as 20 minutes), through a “pulse” that has a rapid rise, but a slower fall (lasting about and hour), to a “ramp” that rises to an intensity plateau (that can endure for many hours). These different temporal profiles, examples shown in Figure 2, must be definitive signatures of the acceleration and injection processes.

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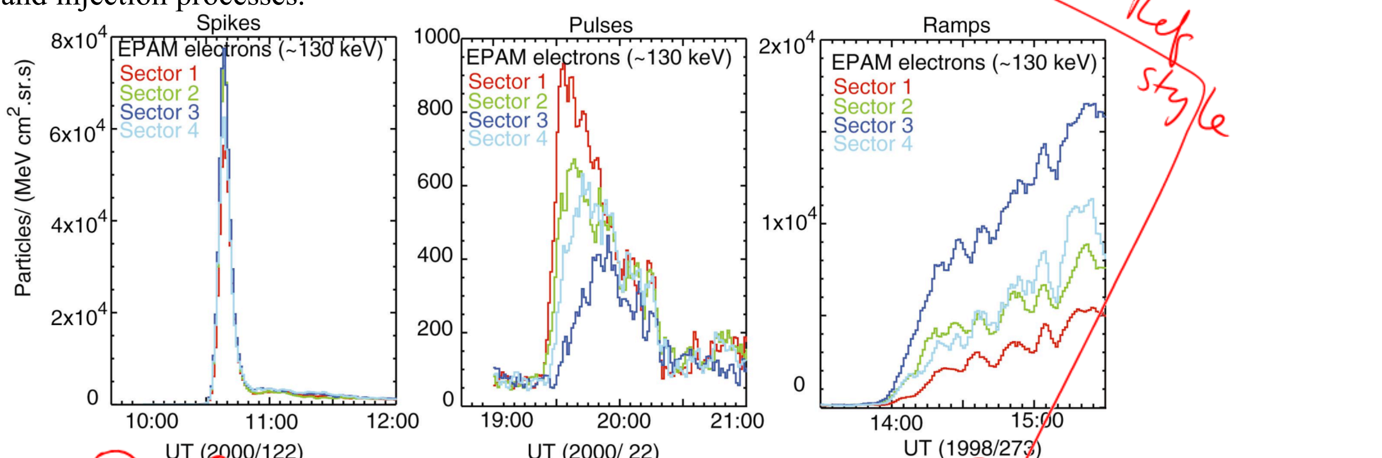

Figure 2 ~~shows~~ one example for each of the three phenomenological groups (spikes: May 1, 2000; Pulses: Jan 22, 2000; and Ramps: Nov 13, 1997). At 1 AU each of these events has strong anisotropy throughout their peaks and velocity dispersion that implies energy independent injection at the Sun.

Additional information about the acceleration and injection mechanism can be obtained from examining events originating from the same active region. Gosling [2004] reported that at very low energy (E < 1.4 keV) solar electron bursts tend to organize themselves in sequences of events. A significant number of near-relativistic electron events observed near 1 AU also tend to be members of sequences of events [Simnett, 2005; Haggerty and Roelof, 2006]. The definition of an event sequence is somewhat arbitrary, but we used a time window of 18 hours. In other words if an event occurs within a 18 hour window of a previous event, then both events are deemed to be part of a sequence. Early estimates from 203 beam-like events indicate that ~48% of the events are part of an event sequence according to this constraint. Figure 3 shows an event sequence consisting of at least 5 events on February 25, 2002. The events occur within only a few hours of each other. This sequence of events consists of both spikes and pulses but no ramps. Strong type-III radio drift events were observed for each of the events in this sequence by the WAVES experiment on the WIND spacecraft. There are indications (based on the longitude of the Hα flare) that for those events within a given sequence, the field lines are connecting into the same active region. These sequence events may be a direct observation of the flare accelerated electron population. In Figure 3 we show the Hα location (both longitude and latitude) for the 5 events in the sequence. One of these events (indicated in red) may have come from a different active region from the other 4 events.

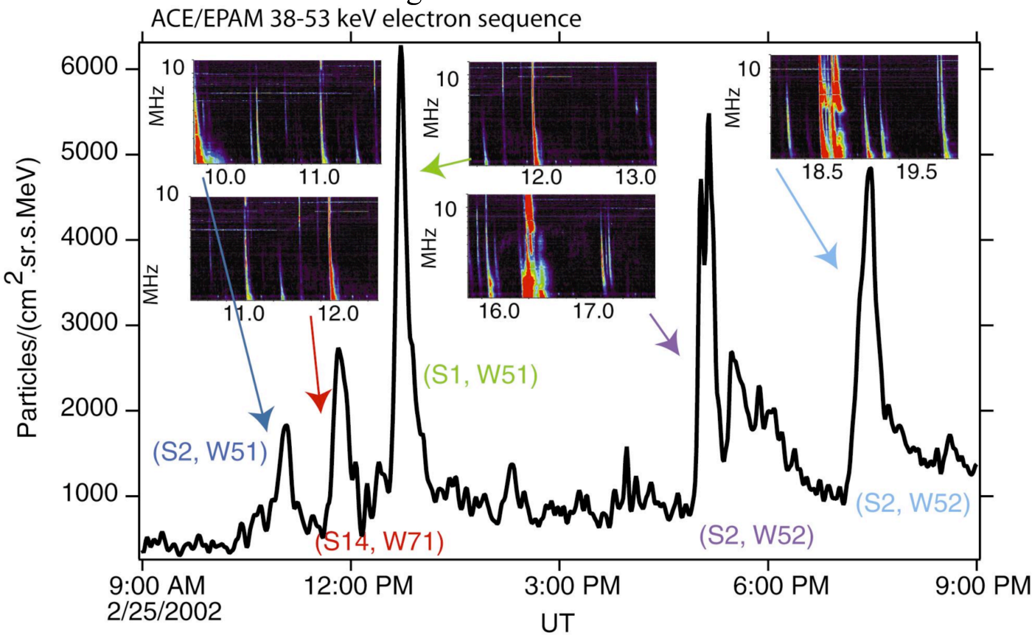

Figure 3. A sequence of near-relativistic electron events (left) observed on Feb 25, 2002. Each of these events was associated with a high-coronal type-III radio burst (inset) and ~~was associated with~~ chromospheric Hα flares from apparently the same active region. There was a small CME (492 km/s) observed near the injection time of the first event, no subsequent CMEs were observed in association with any of the following events.

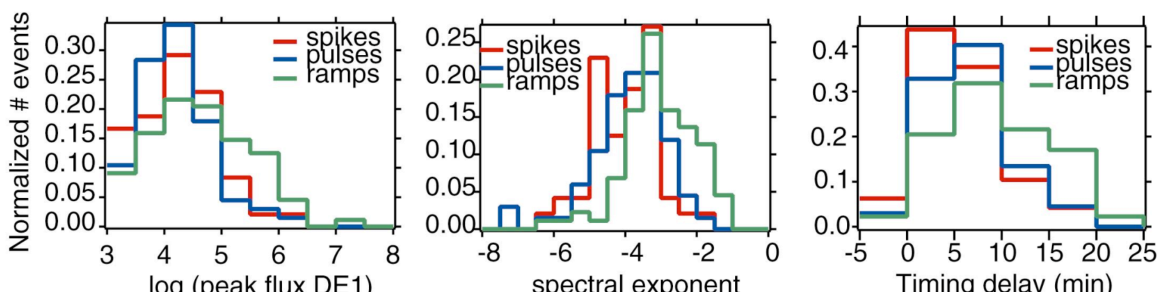

Figure 4. The three different phenomenological groupings (spikes in red, pulses in blue; and ramps in green) show differences in peak intensity, spectra, and injection time with respect to the 14 MHz type-III emission time. The peak flux (shown on the left) and the spectral exponent (shown in the middle) indicates that the spikes and pulses are both lower in intensity and softer then the more intense, longer-lived, and harder ramp type events. The timing delay (shown on the right) indicates that a spectrum of delays is observed, but more spikes tend to have short delays while more ramps tend to have larger delays.

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The spike and pulse events differ significantly from the ramp events. The spike and pulse events tend to be lower intensity events, tend to have softer spectra, and tend to have smaller injection delays with respect to associated electromagnetic emissions. The larger, longer-lasting ramp events tend to have larger intensity, harder spectra, and longer injection delays (figure 4). ***These simple phenomenological groupings order the data!***

These groupings exhibit themselves in sequence events with both spikes and pulses involved in sequence events (64% of the sequence events consist of spikes and pulses), yet sequence events are deficient in ramps (only 36%). The events involved in a sequence therefore tend to have a lower intensity, softer spectra, and are injected closer to the emission time of 14 MHz type-III radio bursts than isolated events. Spike and pulse events and the sequences of which they are part, represent an interesting sub-set of near-relativistic electron events as any particular sequence may map back to the same active region. Ramp events may represent an entirely different class of events (66% are isolated events while only 34% are contained within an event sequence). These ramp events may have a different acceleration mechanism than spikes and pulses.

To significantly advance this topic we require more information: we need to understand where and how the interplanetary field lines (on which the electrons are observed) connect to the region on the sun where they are accelerated; we need to understand the state of the corona through which these energetic electrons propagate; and for those events that have an associated CME, we need to know if conditions in the corona are favorable for the formation of a shock.

We propose to use global MHD models to predict the state of the corona and to connect in situ observations of near-relativistic electrons to their associated electromagnetic emissions on the Sun.

The fundamental questions we want to investigate are:

- Can we identify near-relativistic electron events accelerated by strong electric fields at reconnection sites?
- Can we identify electron events accelerated by CME-driven shocks?
- Are the RHESSI HXR observations and the in situ ACE/WIND observations consistent with different acceleration mechanisms and can we distinguish between them?

These <u>fundamental questions</u> can be addressed systematically through an extensive study of the observations and use of advanced modeling techniques. A <u>practical objective</u> is to understand the state of the solar corona and its magnetic field prior to the acceleration and injection of energetic particles, and thereby be in a position to make predictions of SEP events.

2.2 Global Modeling of the Solar Corona and Inner Heliosphere

Potential Field Source Surface (PFSS) model calculations have long been used in the discussion of SEP events [e.g. Schatten et al., 1969; Altschuler and Newkirk, 1969]. The method is to solve Laplace's equation within an annular volume above the photosphere in terms of a spherical harmonic expansion, the coefficients of which are derived from the synoptic Carrington maps of the photospheric magnetic field (i.e., maps assembled over an entire solar rotation from Earth-based observations). Coronal currents are neglected so as to allow unique solutions in closed form. To circumvent the problem that such simple harmonic expansions would result in all of the magnetic field lines returning to the Sun (i.e. potential solutions), an outer radial boundary is introduced at

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which point the coronal field is required to become radial, leading to what ~~is commonly~~ known as the PFSS model. Above this so-called “source surface”, typically at 2.4 Rs, the field is prescribed according to the Parker spiral. Another technique to map the solar wind observations back to the Sun relies on a simple ballistic mapping from the point of observation back to 2.4 Rs. From 2.4 Rs a PFSS solution is used to complete the plasma’s trajectory back to the solar surface along a particular magnetic field line (Neugebauer et al., 2002). In spite of its simplicity, this approach has been quite successful. By tracking the composition of the plasma, Neugebauer et al. were able to distinguish a 3rd component (in addition to the standard “slow” and “fast” solar wind) that apparently originated from within (or near) active regions and contained a distinct compositional signature. in studying the origin of the Solar Wind

Global MHD models are a more recent development. Relying on solutions to more complex equations and requiring significantly more computational power, the first global solutions incorporating ~~observed photospheric fields into the boundary~~ conditions were produced some 10 years ago [Mikić et al., 1996; Usmanov et al., 1996]. Although models can be run on single processor machines, the codes in use today (e.g. Linker et al., 1999, Riley et al., 2001, Roussev et al., 2003) typically use the Message Passing Interface to run on massively parallel architectures. MHD solutions describe not only the magnetic structure of the corona and solar wind, but also the properties of the plasma. Thus they can be used to study a wide variety of topics. They have been used to interpret and connect a wide variety of both solar and in situ observations (e.g. Linker 1999) for specific campaign intervals, as well as to interpret the three-dimensional heliosphere made possible by observations from the ACE and Ulysses spacecraft [Riley et al., 2002b].

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Riley et al. (2003) have developed a global MHD ~~model of the solar corona and inner heliosphere driven by observations of the photospheric magnetic field (Riley et al., 2000; Riley et al., 2002a). They numerically solve a system of partial differential equations, in spherical coordinates. The details of the algorithms used to advance the MHD equations are given elsewhere (Mikić et al., 1994; Lionello et al., 1998). They use a finite difference approach with staggered meshes that have the effect of preserving ∇ • **B** = 0 to within round-off errors for the duration of the simulation.~~ Computationally, it is more efficient to split the MHD modeling region into two domains: A coronal region, spanning 1 Rs to 30 Rs and a heliospheric region, spanning 30 Rs to 1 AU. The outer-radial coronal solution directly drives the inner-radial boundary of the heliospheric model. The lower boundary of the coronal model is based on the observed line-of-sight measurements of the photospheric magnetic field, assuming uniform and characteristic values for the plasma density and temperature. An initial estimate of the field and plasma parameters is found from a potential field model and a Parker transonic solar wind solution, respectively. This initial solution is advanced in time until a dynamic, steady-state equilibrium is achieved. The steady state solution should be sufficient for our study of SEP injection: ~~because~~ The first-arriving SEPs must propagate out of the corona through an essentially undisturbed magnetic field, because the energetic particles out-run any shock or reconnection front.

Results from MHD simulations for specific time periods of interest, provide a global context for interpreting a wide variety of disparate observations, and, in particular, for connecting in situ observations with their solar sources. For the purposes of the proposed investigation, we describe two specific applications: Tracing along field lines from the point of measurement at the spacecraft back to the Sun; and (2) computing Alfvén-speed profiles for inferring the likely spatial location of CME-driven shocks in the corona. Other potentially useful applications exist and we would be happy to work with the TR&T team on such projects.

2.2.1 Mapping Technique

A number of techniques have been developed to connect in situ observations of various solar features. Typically these involve some kind of mapping procedure to extrapolate solar wind observations from the point of measurement back to the Sun. They ~~These~~ range from the simplest “constant speed”, or “ballistic” mapping [Nolte, 1973] (where it is assumed that the plasma maintains constant radial velocity from the Sun to the point of observation) to more sophisticated global, time-dependent MHD simulations that can trace field lines all the way from the solar surface to the point of observation [e.g. Riley et al., 2001].

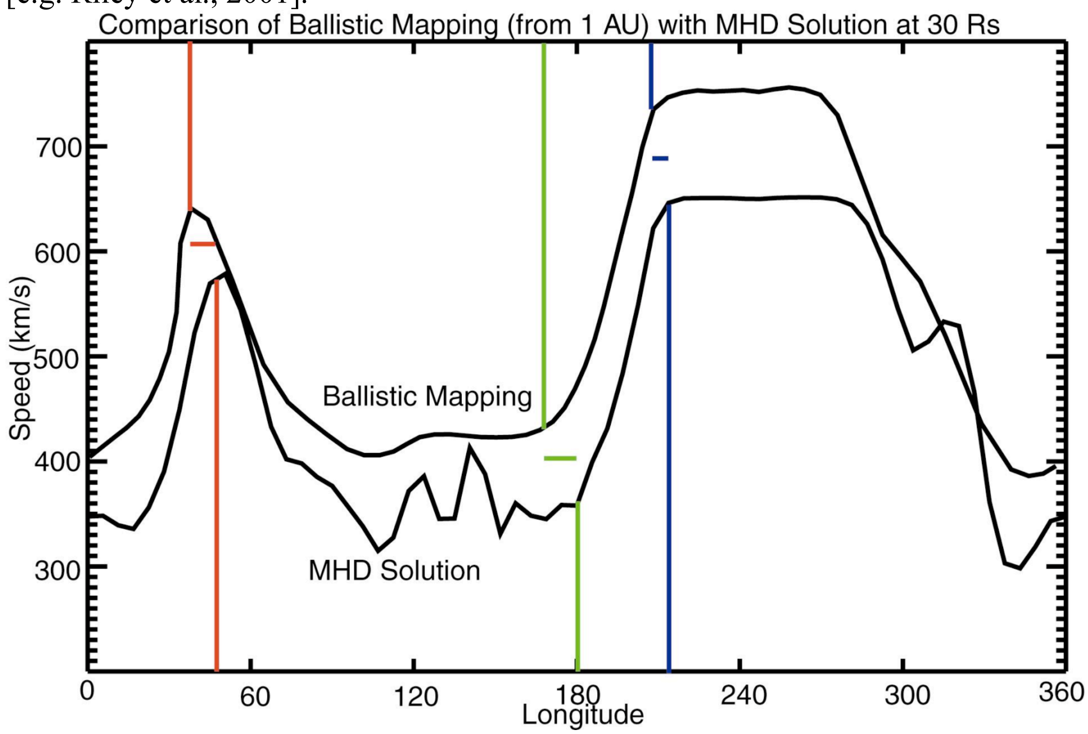

Figure 5. Comparison of the solar wind velocity at 30 Rs between the inward ballistic mapping with the MHD solution of the solar wind measured at 1 AU. Vertical lines and short horizontal bars indicate differences in longitude for 3 distinct points in the stream profile. The ballistic mapping tends to give velocity values < 15% higher than the MHD solution, leading to proportionate eastward errors in the footpoints (e.g. < 10° out of 70° for an MHD velocity of 350 km/s, or < 5° out of 40° for 650 km/s)

Riley et al., (2002b) investigated the errors associated with several of these approaches and found that a combination of ballistic mapping (30 Rs < r < 1 AU), together with a realistic MHD model for the coronal magnetic field (r < 30 Rs) is often as accurate or more accurate than using the heliospheric MHD solution. In figure 1 we show results from a global MHD model to illustrate the errors introduced by the ballistic mapping procedure. The two curves compare the MHD solution at 30 Rs with the MHD solution at 1 AU, which has been ballistically mapped back to 30 Rs. Differences of 5°-10° are

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apparent, and may represent the limit in longitudinal accuracy for the mapping process. While one might suppose that 3-D MHD solutions driven by solar observations would provide a more accurate way to map the in situ data, relatively small errors of ~ 40 km/s in the solution at 1 AU lead to longitudinal offsets of ~ 8° at 30 Rs. Although the heliospheric MHD models have been very successful as a tool to investigate the large-scale structure of the solar wind (e.g. Riley et al. (2001) improved specification of the boundary conditions will be necessary before they can be used as a reliable mapping tool. We believe that investigations currently underway aimed at improving the global MHD models, and specifically the boundary conditions, will lead to the best mapping solution.

For the purposes of the proposed investigation (given the current uncertainties) we will apply all 3 techniques: (1) Ballistic mapping + PFSS solution; (2) Ballistic mapping + coronal MHD solution; and (3) coronal + heliospheric MHD solution, and we will quantify the errors associated with each of them. Thus either the ballistic mapping or the heliospheric solution may be used to bring the data from the point of observation (1 AU) to 30 Rs where the flow is essentially radial. Between 1 and 30 Rs, on the other hand, latitudinal variations are most significant and the PFSS or MHD model is used to trace along magnetic field lines back to the solar surface.

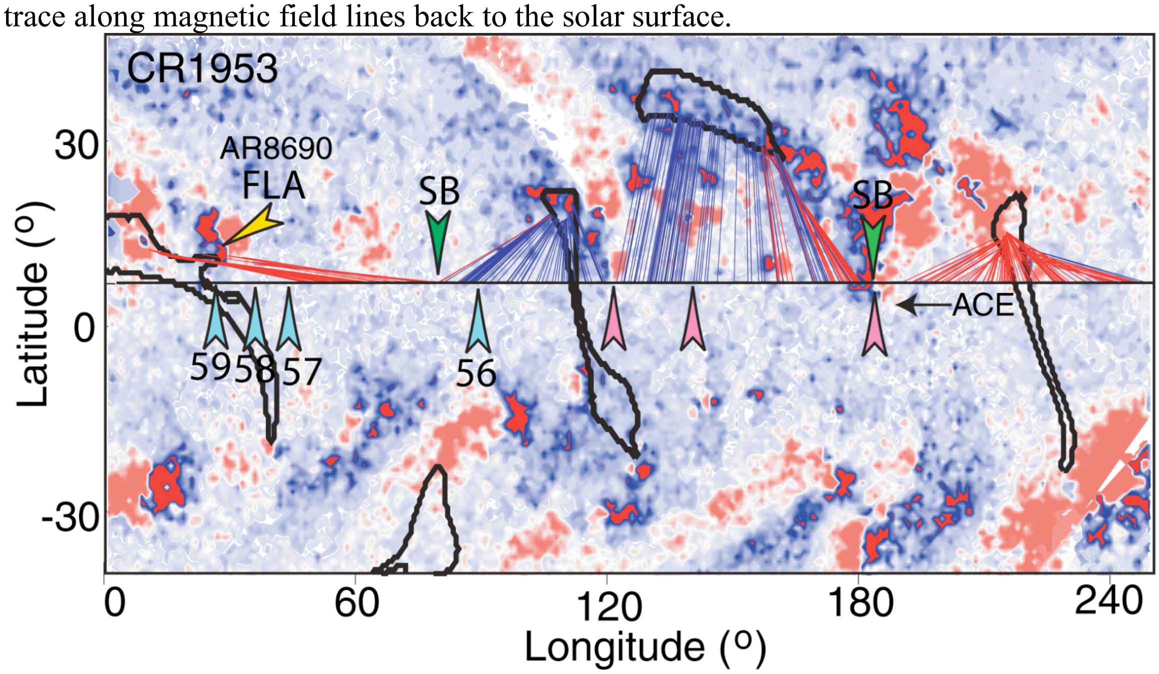

Figure 6. ACE (close to equator) mapped back to the Sun for a segment of CR 1953. Coronal holes are outlined in black. Trajectories are color-coded according to the measured in situ polarity of the IMF (red/blue corresponds to outward/inward polarity). Superimposed on the map are pointers indicating: four near-relativistic beam-like electron events (light blue – event numbers 56-59 from Haggerty and Roelof, 2002); three electron events not classified as beams (pink); an Hα flare associated with electron events 57 and 58 from AR8690 (yellow); and two sector boundary crossings (SB – green).

We illustrate the mapping technique in Figure 6, which combines data and modeling results. The closed regions represent coronal holes, as computed by the coronal MHD solution for this time period (Carrington Rotation (CR) 1953 – Ending September 14th 1999). These are often similar, but not identical to the coronal holes inferred from Kitt Peak He I 1083 nm observations. Superimposed onto the map is the trajectory of ACE. At the time, ACE was located at 1 AU and 6.6° above the heliographic equator. The starting points of the trajectory (already mapped to 30 Rs) is a straight-line trace moving from right to left (with increasing time) and all points map back to origins within coronal holes (by definition). These mappings have been color-coded according to the measured polarity of the interplanetary magnetic field. Given the approximations in the mapping procedure and the relatively high level of solar activity during this time period, the strong correlation between the mapped in situ polarities and the polarity of the coronal holes is quite remarkable, providing strong support that the mapping procedure has been successful.

To illustrate our technique to integrate the in situ observations with the MHD mapping technique we have superimposed on Figure 6 a number of color-coded pointers. We show the locations of four near-relativistic beam-like electron events in light blue. These events are #(56-59) from Haggerty and Roelof (2002). Our technique is to: First use the measured solar wind speed at the time of the electron event onset to ballistically map to a location on the 30 Rs source surface; then convert that to a Carrington longitude. We show the locations of three electron events that because broad angular distributions and lack of clear velocity dispersion were not classified as beam-like events (pink pointers). We show the location of AR8690 (yellow pointer) that was responsible for two Hα flares associated with electron events 57 and 58. We show the location of two sector boundary crossings (SB – green pointers).

2.2.2 Alfvén speed radial profiles

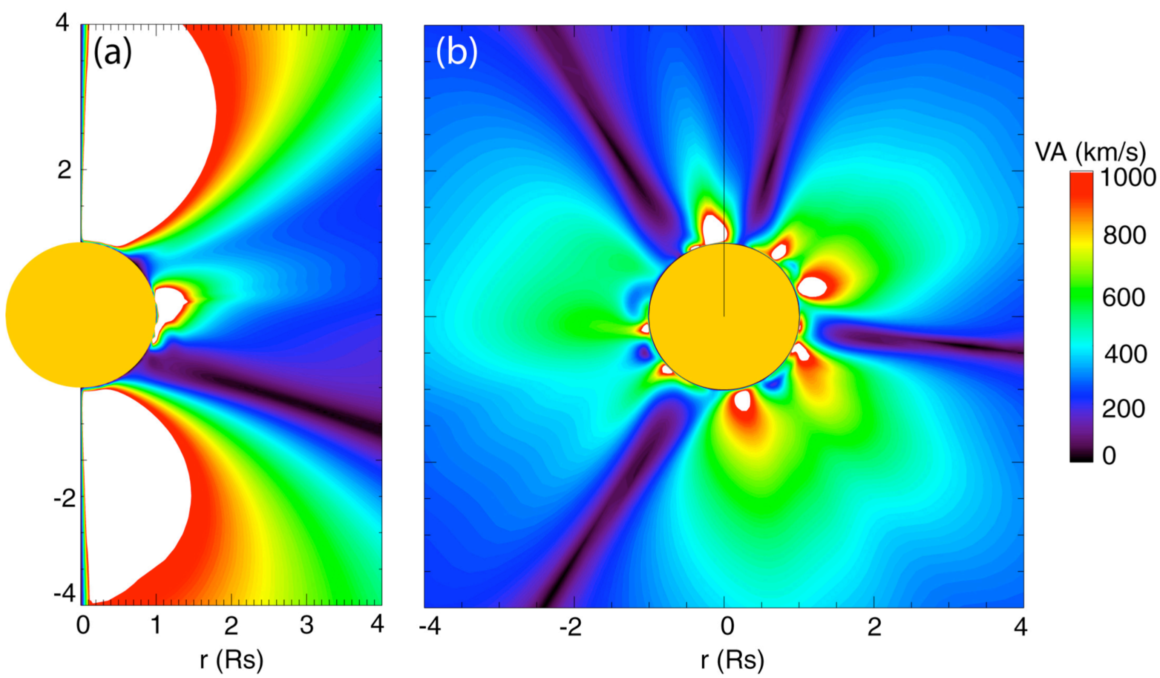

Figure 7. (a) Meridional cross section of the Alfvén speed during the interval bounding the 20th January, 2005 MCE event (Carrington Rotation 2025) at a longitude of 0°. (b) Equatorial cross section of the Alfvén speed. The solar line at 180° coincides with the location of active region 720, from which the CME erupted.

To illustrate the significance of the Alfvén speed to SEP-related issues, we have computed the Alfvén speed VA from a simulation of the January 20, 2005 SEP event. The simulation included full thermodynamics and thus represents the most sophisticated steady-state solution. Similar cases run using the polytropic approximation yielded markedly different results. Figure 7 (a) shows the equatorial cross section of the Alfvén speed while (b) shows a Meridional cross section at 180° longitude. The color bar has been saturated at 1,000 km/s to emphasize variations near AR 720, which produced the CME and energetic particle event. These profiles (derived from a simulation driven by photospheric observations) allow us to explore the underlying coronal and heliospheric structure prior to the launch of a CME as it relates to the acceleration of particles. Consider a CME, for example that is observed to propagate away from the Sun driving a wave ahead of it in the ambient medium. The wave will steepen into a shock only when its speed is in excess of the local Alfvén speed (strictly speaking we should consider the directional fast-mode speed; however, for simplicity, we will ignore the contribution from the sound speed). Depending on the location of the eruption, this could occur at considerably different radial distances. Moreover, the finite angular extent of the CME will ensure that different parts of the wave front will shock at different locations. Thus we can elaborate on the suggestion by Mann et al., [2003] that a single wave might encounter two distinct regions where the wave's speed is in excess of the local Alfvén speed. Whether this occurs depends sensitively on the ambient plasma and magnetic field structure into which the wave propagates. Moreover, we have a likely scenario that a wave propagating in an inhomogeneous region will shock at different distances along its front. Finally, given some information about the CME (such as inferred from LASCO observations), we can predict where the likely sites for particle acceleration will occur. In this proposed investigation, we will consider not only the Alfvén speed, but also the directional magnetosonic (fast) mode speed, which will allow us to more accurately describe the likely evolution of the shock.

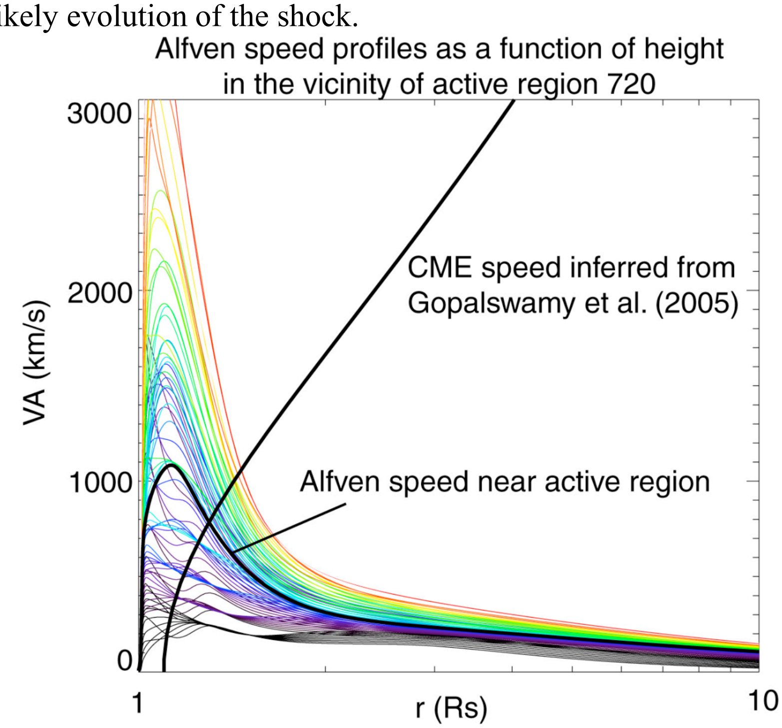

Figure 8. Alfvén speed as a function of height for a selection of radial profiles surrounding AR 720. The profile lying closest to AR 720 is shown in thick black. Also shown is the inferred speed of the January 20th, 2005 CME based on limited LASCO observations.

In the case of the January 20th, 2005 CME, LASCO observations showed a fast, and rapidly accelerating CME. Figure 8 shows the inferred speed/height profile of the CME, together with a selection of Alfvén speed – height profiles surrounding active region 720. It is clear from the intercept between these lines that a coronal shock likely formed at 1.2-1.5 Rs and then rapidly increased in strength. By ~ 3 Rs, the Alfvén Mach number of the shock had exceeded 7. By 5 Rs it had increased to 15.

2.3 Proposed Work

Advanced MHD models of the configuration of the corona and inner-heliosphere prior to the energetic particle acceleration and injection allow us to estimate the path along which the energetic particles propagate and thus better refine our estimates of the particle injection times. Detailed models of the Alfvén speed and the directional magnetosonic (fast) mode speed will allow us to more accurately describe the likely evolution of a CME-driven shock. Because of the ubiquitous nature of electron acceleration in the corona and their resulting electromagnetic emissions, the near-relativistic electrons are ideally suited for a study of how flares accelerate particles near the Sun. We propose this quantitative investigation of SEP events that combines new analytical techniques of dealing with energetic particle observations with high-resolution observations of the solar flares electromagnetic emissions. We integrate these detailed observations with advanced MHD models to significantly enhance our understanding of the very complex and dynamic acceleration processes near the Sun and surrounding corona.

2.3.1 Data analysis

We will begin our investigation by identifying a selection of beam-like near-relativistic events. These will consist of spikes, pulses, and ramps. We will select events from event series as well as events that occur in isolation. Studies during the current solar cycle have demonstrated the crucial information contained in SEP events with beam-like strongly anisotropic rise phases for near-relativistic electrons and protons [Haggerty and Roelof, 2002, Simnett et al., 2002, Haggerty and Roelof, 2005, etc.] Of the 668 electron events observed on ACE by the Electron, Proton, and Alpha Monitor (EPAM, see Gold et al., 1998) from August 1997 through mid 2006, nearly 33% of the events are beam-like. Careful event selection is essential for obtaining clear observational results for three reasons:

i) There is no quantitative understanding of how particles from flares outside the preferred connection longitudes (W30° - W90°) are injected onto IMF lines that connect to Earth. Many propagation studies in the literature have not made a clean separation of events on the basis of magnetic field connection, relying instead of less spatially restrictive characterizations such as “impulsive” and “gradual”, terms that became associated more with composition (elemental and isotopic) than with intensity and anisotropy histories. Indeed, if we can first understand the coronal channeling of well-connected (beam-like) events, we can then take the next step in understanding the magnetic connection for the more remote events.

ii) With nearly “scatter-free” beam-like SEP events, we can have the maximum confidence in our association of the particle event with particular solar flare events. Beam-like events allow us to estimate within a few minutes the injection time of SEPs

into the low corona [e.g. Tylka, 2006 on the January 20, 2005 event]. This injection time can be closely correlated with the onsets of electromagnetic emissions from the flare.
iii) Selection of events based on phenomenological groups tends to order the data. There are clear differences in spectra, intensity, and timing. Our initial results using this technique are promising and may represent a way to differentiate between electron events accelerated by reconnection, events accelerated by a CME-driven shock, or events accelerated by a different technique.

Haggerty and Roelof [2005] have developed a 4-parameter function (based on the hyperbolic sine) that properly describes the intensity rise-to-maximum phase.

$$\frac{j}{j_0} = 2\sinh\left[\frac{a}{\alpha}\left(1 - \exp\left(-\alpha\left(t - t_0\right)\right)\right)\right]$$

For each selected event we will characterize the profile of the rise phase of the near-relativistic electrons and protons (spike, pulse, or ramp) with this quantitative function that defines the initial rise rate as well as the transition to the maximum intensity. We will also compute the peak spectra, the fluence spectra, and the temporal evolution of the spectra for each event.

2.3.2 Modeling

For each beam-like SEP event that we study, we will model the coronal structure and magnetic field connection between the photosphere and 1 AU. We will apply all 3 mapping techniques: (1) Ballistic mapping + PFSS solution; (2) Ballistic mapping + coronal MHD solution; and (3) coronal + heliospheric MHD solution, and we will quantify the errors associated with each of them.

The boundary conditions for the MHD and PFSS models will be driven from synoptic maps of the radial component of the photospheric magnetic field. These are assembled from a sequence of images taken over the course of a solar rotation (~27 days as viewed from Earth). To improve the accuracy of the boundary conditions (particularly for Earth-directed events), we will carefully ingest daily (and potentially hourly) magnetograms into these synoptic maps, resulting in boundary conditions that evolve in time.

For each event in this study where an associated CME is observed, we will use the MHD results to examine the spatial variability of the Alfvén velocity as well as the directional magnetosonic (fast) mode speed to accurately describe the likely evolution of the shock. We will compute if, when, and where a CME-driven, fast-mode shock would form, and if so its altitude and the evolution of its associated Mach number.

As shown by Neugebauer et al. (2002), in situ composition data can provide important clues about the source region of the mapped plasma. Thus as part of the mapping process we will also map composition data from ACE/SWICS back to its solar origin. This will provide additional clues about the thermal environment of the corona.

2.3.3 Integrate modeling and analysis

For each event we will utilize the mapping results from the MHD model to determine the injection time of the energetic electrons and protons. Haggerty and Roelof (2004, 2003) described a quantitative method to measure the strong anisotropy of energetic particle distributions. This method, when coupled with a guiding center transport model (Nolte and Roelof, 1975), or a transport model that includes scattering in the interplanetary medium (e.g. Li, et al., 2005), can estimate the electron injection history for near-relativistic beam-like electron events. We will apply our technique to each event selected in this study to determine the injection profile at the Sun.

We will examine the estimated injection profile at the Sun and compare it with energetic electrons in the low corona using RHESSI observations of HXRs. We will do a detailed comparison between the injection profile and the temporal evolution of the HXRs. We will compute the peak photon spectra, the integrated photon spectra, and the temporal evolution of the photon spectra and compare that with electron spectra observed at 1 AU.

For each event we will examine observations of the Soft X-rays measured by GOES, the microwave emission by ground-based receivers, the metric type-III observations from ground-based receivers, and the decametric type-III radio bursts from WIND/WAVES to place each event in context with all its associated emissions.

For each event we will determine if there was an associated CME using SOHO (and if available STEREO), and both space based and ground based observations of type-II bursts. For those events with a CME we will use these observations to determine location of the CME and its velocity.

We will directly compare the CME observations with the computed Alfvén velocity and the directional magnetosonic (fast) mode speed. We will compare the mapping technique of taking ACE/SWICS back to its solar origin with estimates of plasma heating observed by SOHO/EIT.

2.3.4 Results of the investigation

With this compilation of unique information, we can answer specific questions that will address the fundamental scientific questions of this proposed investigation:

1. *Where do energetic electrons observed at 1 AU map back to in the low corona, and what were the electromagnetic signatures in the vicinity of that location at that time?*

By identifying a specific location where an event originates we will remove a host of ambiguities associated with associating electromagnetic emissions with electron events. For example, there are frequently multiple Hα events at different locations that occur within a reasonable time window of the calculated electron injection time. By knowing precisely where and when to look, we can be much more effective in using RHESSI, TRACE, SOHO, (and if available STEREO, SDO, Solar-B) observations. Corrections to the path length are unlikely to significantly alter the estimated injection time as the electrons are near-relativistic. However, the injection time relative to electromagnetic emission will be significantly altered by any change in event association. We can take advantage of the sequences of events (and their possible implications) by knowing if these sequences of events map back to specific active regions.

2. *Which events are likely to form shocks?*

We have reported [Haggerty et al., 2003; Simnett et al., 2002] that a large fraction of near-relativistic beam-like electron events are associated with SOHO/LASCO observed CMEs or CME-like transient events. However, 75% of these transients are slow (v < 1000 km/s), narrow, and are not associated with type-II radio events. A detailed analysis of the Alfvén speed and the directional magnetosonic (fast) mode speed will provide us with a quantitative estimate on which of these events is likely to form a shock. Are CMEs associated with spike and pulse type events likely to form shocks? Are CMEs associated with long-lived ramp-type events likely to form shocks? Is the calculated injection times (relative to electromagnetic emission) consistent with the time shocks would form? Or are these relative times consistent with an impulsive injection near a reconnection region? Is there a pattern in the calculated temperature, density, Alfvén speed that is more consistent with one acceleration mechanism or another?

3. *For which events do the energetic electron spectra correlate with the photon spectra observed by RHESSI?*

The observation that the spectra in some events correlate with the low-coronal photon spectra (Krucker et al., ApJ, submitted) is strong evidence that these events may be accelerated by reconnection. Are the spikes produced by reconnection? Obviously due to their velocity dispersion, angular distribution, and symmetrical profile they require essentially scatter-free propagation. Are the spectra of spike and pulse events correlated with the HXR spectra? Are ramp-type events those events whose spectra are uncorrelated with the HXR photon spectra? For those events is there a likely shock that could explain the long-lived anisotropy? Are there electromagnetic signatures of long-lived reconnection that could indicate long-lived acceleration and injection onto open field lines?

2.3.5 Investigation timeline

The modeling to be performed as part of this investigation can be done at two levels, both at low resolution (taking hours to complete) and at high resolution (taking days to complete). During the first year we will select a combination of spike, pulse, and ramp events to be addressed with the low-resolution MHD simulations and the PFSS calculations. We will analyze the in situ energetic particle observations to determine the SEP injection history. We will use observations from WIND/WAVES, GOES, SOHO, and ground based receivers to examine the evolution of each event near the Sun. We will present the results at scientific meetings and will publish the initial results in a peer-reviewed scientific journal.

During the second year we will gather a selection of promising events that were examined in the first year and use the high resolution MHD solutions to compute the magnetic connection in detail. We will use observations from RHESSI (and if available Solar-B and SDO) to determine the intensity of each event, the photon spectra, and the spatial and temporal evolution. We will present and publish the results in scientific journals.

In the third year we will continue the high resolution MHD modeling and will assemble the Alfvén/fast-mode velocity maps determined from the model for each of our events. We will examine observations from SOHO (and if available STEREO) and combined with observations from WIND/WAVES and other ground based receivers determine the velocity of the CME and its associated type-II radio burst. We will then examine if, when and where the CME was likely to shock. We will compare these datasets to the in situ observations and the optical observations to produce a detailed picture of SEP acceleration in the low corona. We will present the results of this investigation at scientific meetings and publish the results in scientific journals.

The proposed period of performance will include the rise-to-maximum of Solar Cycle 24. Assuming the availability of data from ACE/EPAM, WIND/3DP, and observations from STEREO, we anticipate adding valuable additional beam-like electron events to our active catalog. These events during the rising phase of the cycle carry the signature of rapid evolution of the coronal magnetic field due to the eruption of new active regions and the recession of polar coronal holes. For example, the ACE launch caught the first great active region of Solar Cycle 23 in the sequence of flares in November 1997. Within less than 3 years, the Sun produces the giant geoeffective "Bastille Day" event of 14 July, 2000. We will seize the opportunity of applying our accumulated knowledge to the events expected in the upcoming Solar Cycle 24.

2.4 Expected Impact and Relevance to NASA

This proposal directly addresses the LWS TR&T focus science topic (FST) 3(e), to understand how flares accelerate particles near the Sun and how they contribute to large SEP events. It addresses the interpretation of energetic electron and proton spectra, associated electromagnetic emissions, and their relative timing at both at 1 AU and in the low corona. The energetic electron and proton observations from ACE, WIND, GOES and SOHO will be combined with radio observations from WIND and ground-based receivers, as well as other optical observations from RHESSI, SOHO. This investigation will take advantage of future observations if available from both STEREO (both in situ energetic particles and optical observations) and from SOLAR-B (X-ray observations). These observations will be carefully compared with a detailed MHD model (that uses photospheric observations as a boundary condition) of the structure of the solar corona and its connectivity to the active regions responsible for the acceleration and injection of the energetic particles and the associated ~~coronal mass ejection~~. CME

In 2005 the PI of this proposed investigation was selected to participate in the Heliospheric Magnetic Fields Focus Research Team (Rust/APL PI) lead by T. Zurbuchen. That specific investigation has the scientific goal: to understand the topology and evolution of the magnetic fields that originate at the Sun and open into the heliosphere. There are several points of view advocated within the team. For example, open flux could be (1) concentrated in a few regions (coronal holes) with quasi-steady conditions, as predicted by the PFSS model, or it could be (2) distributed more evenly over the Sun with many open fields and closed loops able to collide frequently and reconnect so that open field becomes closed while an adjacent closed field opens. The team's focus is on the evolution of the open flux distribution.

Two major timescales are of interest: ~ 40 hours, the time it takes the photosphere to replenish its magnetic field, and 11 years, the approximate time for each global reversal in magnetic polarities. Can the model (2) based on frequent reconnections involving loops, account for the cyclic redistribution of open flux at the magnetic poles of the Sun every eleven years? Or, as in model (1) does the open flux at each pole stampede across the equator as a continent-size patch toward the opposite pole? Answering these questions will require a closer look at the coronal origins of open fields. Our role in the team is to map open heliospheric fields back to the Sun, using the ACE electron beam event catalog, and to determine which of the models, if any, gives an adequate description of open magnetic field distribution and evolution. The work is complementary to what we propose here since we are mapping open field distributions and do not consider the detailed structure of the fields at the beam injection sites. In this proposal we place a large emphasis on the MHD models, we include critical observations from RHESSI, and we are proposing to investigate a different selection of events based on their temporal intensity history and their relative timing to other events. In addition to investigations selected for this opportunity, this proposed effort would significantly enhance the Heliospheric Magnetic Fields Focused Research Team by adding a selection of events that have been extensively investigated through both in situ observations of near-relativistic particles including the associated electromagnetic emissions and have been investigated with a global MHD model. In addition, the 2005 Focus group (SEPs) lead by M. Desai would greatly benefit by the quantitative analysis we propose here.

The physical conditions of the corona and inner heliosphere are a major focus of this investigation and as such are of great value to a future Sentinels mission. The recently released LWS Solar Sentinels report suggests that an asset be placed to observe the magnetic fields on the far-side of the Sun. One justification for these observations (among many) is that observations and models of the coronal magnetic field structure are required for understanding the acceleration and injection of energetic particles. This proposed effort is focused explicitly on this topic and will not only significantly quantify these arguments, but will provide essential information on how these models can be improved.

The research proposed here addresses only a portion of focus topic 3(e) and could be enhanced by other efforts on this topic. Specifically this effort deals with energetic electrons and protons, their acceleration and injection, and the heliospheric and coronal magnetic field connection between 1 AU and the associated active regions. Of benefit would be a transport model for the energetic protons and perhaps a transport model that could be adapted to include near-relativistic electrons. In addition, studies that provides reconnection models, models of electron acceleration at shocks, models of both type-III and type-II emission, and models of HXR and gamma ray production from the low corona and chromosphere.

The research proposed here supports the research focus areas defined in the Heliophysics Roadmap, namely, Objective F (space environment prediction); Objective H (nature of our home in space); and Objective j (safeguard the journey of exploration). Specific research focus areas that this proposal addresses are: plasma processes that accelerate and transport particles; to understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment; and to Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

Cost Plan. Investigators at APL have funding for the analysis of energetic particle data using the EPAM instrument on ACE. This funding has supported the development of routines required to analyze the energy spectra and detailed timing of energetic electrons in SEP events and it is presumed that funding for routine analysis of ACE data will continue. As of early 2007, there will be no funding in place at either institution to support the analysis of RHESSI, SOHO, Wind or GOES data. The support requested at APL will cover the additional effort needed to assemble these data sets and to provide the spectra and detailed temporal profiles from RHESSI ACE, SOHO, Wind and GOES that are needed to support the proposed analysis and simulation efforts.

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4. Summary of Personnel and Work Efforts

Dr. D. K. Haggerty is the Principal Investigator of this proposal. He will be responsible for the overall conduct of the investigation and for the coordination of the investigation teams activities. He is also responsible for analysis of energetic particle observations and the associated electromagnetic emissions. *Dr. P. Riley* (Co-I) is primarily responsible for the modeling in this investigation (MHD and PFSS) and is responsible for the analysis of in situ magnetic field and solar wind plasma observations. *Dr. E. C. Roelof* (Co-I) will provide theoretical support for this investigation in addition to the analysis of energetic particle observations. *Dr. J. Linker* (Collaborator) will assist the modeling effort at SAIC and will provide additional experience in obtaining and utilizing various datasets of solar emissions. *Dr. S. Krucker* (Collaborator) will provide data and support for the RHESSI analysis.

Name	FY 07*	FY 08*	FY 09*	Total*
Dennis K. Haggerty (PI) JHU/Applied Physics Laboratory	2.0	2.0	2.0	6.0
Edmond C. Roelof (Co-I) JHU/Applied Physics Laboratory	1.0	1.0	1.0	3.0
Pete Riley (Co-I) SAIC	3.0	3.0	3.0	9.0

* in person-months of work year;

5. Facilities and Equipment

The work at the PI institution will be ~~done~~ accomplished using the existing Linux cluster that will adequately meet the needs of this investigation. SAIC maintains a 64-processor cluster, together with a number of Linux and Mac OS X workstations, which are capable of performing the data analysis and the majority of the simulations described here. In addition, SAIC maintains and anticipates receiving additional allocations of time on a variety of supercomputers, including NASAs "Columbia", which will more than adequately meet the needs of this investigation.

6. Budget Justification

7. Biographical Sketches

7.1 Dennis K. Haggerty (Principal Investigator)

Johns Hopkins University, Applied Physics Laboratory (240) 228-7886
Johns Hopkins Rd. Dennis.Haggerty@jhuapl.edu
Laurel, MD 20723

Education
Ph.D. Physics, University of Kansas, December 1996
M.S. Physics, University of Kansas, 1993
B.S. Physics, Weber State University, 1991
B.S. Applied Mathematics, Weber State University, 1990

Professional Experience
1997-present: APL, Space Department
Solar and Heliospheric research focusing on energetic electrons and ions, solar electromagnetic emissions, plasma and fields. GEANT4 model developer for many in-flight instruments including Ulysses/HISCALE, ACE/EPAM, CASSINI/LEMS, and MESSENGER/EPS, Neutron spectrometers and instrument concept development.

Honors, Awards and professional Activities:
NASA Group Achievement Award: ACE (1997).
Editor's Citation for Excellence in Refereeing, AGU Space Weather (2004).
NASAs LWS Heliospheric Strategy Panel, Co-chair, (2002-2004).
NASAs LWS Sentinels Science and Technology Definition Team, (2004-2006).

Selected publications
Haggerty, D. K., E. C. Roelof, Solar Proton and Near-relativistic Electron Events: What is the Relationship, proc. Solar Wind 11/SOHO 16, 2005
Haggerty, D. K., E. C. Roelof, Leading Edge and Peak Flux Density Exciter Speeds For Well Connected Type-III Bursts, *Adv. Space Res.*, in press, 2006
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7.2 Curriculum Vitae for Edmond C. Roelof (Co-Investigator)

Johns Hopkins University, Applied Physics Laboratory (240) 228-5411
Johns Hopkins Rd. Edmond.Roelof@jhuapl.edu
Laurel, MD 20723

Education
Ph.D. Physics, University of California Berkeley, 1966
A.B. Physics, University of California, Los Angeles, 1959

Professional Experience
JHU/APL, 1974-present: (Principal Professional Staff); Assis. Prof. of Physics, UNH, 1969-74; NAS/NASA Postdoctoral Res. Assoc., GSFC, 1967-69; Staff, Boeing Scientific Research Labs., Seattle 1964-67; Visiting Scientist: Observatoire de Paris, Dept. Solaire, Meudon, France, 1988, 1989; ESA European Space Technology Centre, Noordwiik, The Netherlands, 1980, 1983, 1984; Christian-Albrechts Universitaet, Kiel, Germany, 1973; NOAA Space Environment Lab., Boulder, CO 1971, 1972, 1974.

Honors, Awards and professional Activies:
Fellow, American Geophysical Union; NASA Group Achievement Awards: IMAGE, Galileo, Ulysses, ISTP, Geotail; Editor's Citation for Excellence in Refereeing, Geophys. Res. Lett.

Relevant Experience:
Mission Co-Investigator on energetic particles and neutral imaging: Pioneer 10/11, 1972; Galileo, Mars Express, 2003; TWINS, 2004; IBEX 2005. Mission Science Team for ACE, 1997; IMAGE, 2000; Venus Express, 2004, BepiColombo, 2004. Principal and Co-Investigator NASA, NSF, and AFOSR Research Grants and Contracts since 1970.

Professional Services (selected list):
NASA Working Groups: Two Sun-Earth Connections Roadmap (2003-2028 and 2005-2035) Strategic Planning Committees, (2002-03 and 2004-05); Inner Magnetospheric Imager Mission Science Definition Team, 1990-95; Lunar Observatory Steering Group, 1994-95; Solar and Heliospheric Pysics, 1980-83; Atmospheric and Space Physics, 1978-83. AGU: Secretary, Solar-Heliospheric Subsection, 1994-98; Honors Committee, Solar-Planetary Relationships Section, 1990-92; Secretary, Cosmic-Ray Subsection, 1970-74.

Selected publications from 2005-2006 relevant to this proposal (from over 300)
Haggerty, D. K., E. C. Roelof, Solar Proton and Near-relativistic Electron Events: What is the Relationship, proc. Solar Wind 11/SOHO 16, 2005
Haggerty, D. K., E. C. Roelof, Leading Edge and Peak Flux Density Exciter Speeds For Well Connected Type-III Bursts, *Adv. Space Res*., in press, 2006
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7.3 Curriculum Vitae for Pete Riley (Co-Investigator)

Science Applications International Corporation (858) 826-9550
10260 Campus Point Dr. Pete.Riley@saic.com
San Diego, CA 92121

<u>Education</u>
Ph.D. Physics, Rice University, 1994
M.Sc. Physics, University of Sussex, Brighton, England, 1989
B.Sc. Physics, College Cardiff, Cardiff, Wales, 1988

<u>Professional Experience</u>
Pete Riley obtained his Ph.D. (title: "Electrodynamics of the low latitude ionosphere") from the department of Space Physics and Astronomy at Rice University under R. A. Wolf in May 1994. After spending two year at the University of Arizona, he became a postdoctoral research fellow, and subsequently technical staff member, at Low Alamos National Laboratory. Currently, he is a senior scientist in the Solar and Heliospheric Physics group at Science Applications International Corporation in San Diego. He is particularly interested in 3-D, time-dependent MHD simulations of large-scale heliospheric processes, including solar wind stream and coronal mass ejections but also enjoys working on the micro-scale physics of Alfven wave propagation, discontinuities, shocks, and turbulence. Pete analyzes a variety of solar and interplanetary datasets, and is a team member of the STEREO, Ulysses, and ACE plasma instrument teams.

<u>Honors, Awards and professional Activities:</u>
Editor for Reviews of Geophysics
Associate editor for Geophysical Research Letters
Editors' citation for excellence in refereeing for the Journal of Geophysical Research.
Chair of NFS's SHINE steering committee
Member of the CCMC operations working group committee
Member of NASAs Sentinels Science Definition Team

<u>Selected publications</u>
Riley, P., et al., (2006), On the Rates of Coronal Mass Ejections: Remote Solar and in situ Observations, *Ap. J.* in press.
Riley, P., (2005), Modeling Interplanetary Coronal Mass Ejections, *IAU Symposium,* ***226***, 389-402.
Riley, P., et al., (2004), Ulysses Observations of the Magnetic Connectivity between CMEs and the Sun, *Ap. J,* ***608***, 1100-1105.
Riley, P., et al., (2004), Fitting Flux Ropes to a Global MHD solution: A comparison of techniques, *Journal of Atmospheric and Solar-Terrestial Physics,* ***66***, I 15-16, 1321-1331.
Riley, P., and N. U. Crooker, (2004), Kinematic treatment of CME evolution in the solar wind, *Ap. J.,* ***600***, I2, 1035-1042.
Riley, P., et al., (2004), Magnetohydrodynamic modeling of Interplanetary MCEs, *IEEE Transactions on Plasma Science: Space Weather Dynamics and effects on Technology*.

8. Statements of Commitment

8.1 Co-Investigator Commitment for Edmond C. Roelof

From: Edmond.Roelof@jhuapl.edu
Subject: **Letter of Commitment**
Date: August 9, 2006 4:24 PM EDT
To: Dennis.Haggerty@jhuapl.edu

Dear Dennis--

I acknowledge that I am identified by name as Co-Investigator to the investigation, entitled "Coronal injection sites of SEP beam events", that is submitted by Dennis Haggerty to the NASA Research Announcement under the ROSES 2006 NRANNH06ZDA001N-LWS and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

With best regards.....Ed.
(Edmond C. Roelof, Principal Professional Staff)

8.2 Co-Investigator Commitment for Pete Riley

From: Pete.Riley@saic.com
Subject: **LWS TR&T Letter of Commitment**
Date: August 9, 2006 3:23 PM EDT
To: Dennis.Haggerty@jhuapl.edu

Dear Dennis,

I acknowledge that I am identified by name as Co-Investigator to the investigation, entitled "Coronal injection sites of SEP beam events", that is submitted by Dennis Haggerty to the NASA Research Announcement under the ROSES 2006 NRANNH06ZDA001N-LWS and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Sincerely, Pete

Pete Riley, Senior Scientist
SAIC
10260 Campus Point Dr., San Diego, CA 92121.
Email: Pete.Riley@saic.com
Tel: 858-826-9550
Fax: 858-826-6261

8.3 Collaborator Commitment for J. A. Linker

From: linker@saic.com
Subject: letter of commitment
Date: August 9, 2006 4:01 PM EDT
To: Dennis.Haggerty@jhuapl.edu

Dear Dennis,

I acknowledge that I am identified by name as Collaborator to the investigation, entitled "Coronal injection sites of SEP beam events", that is submitted by Dennis Haggerty to the NASA Research Announcement under the ROSES 2006 NRANNH06ZDA001N-LWS and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Regards,

Jon Linker

8.4 Collaborator Commitment for S. Krucker

From: krucker@ssl.berkeley.edu
Subject: Re: LWS TR&T letter of commitment
Date: August 9, 2006 4:01 PM EDT
To: Dennis.Haggerty@jhuapl.edu

Dear Dennis,

I acknowledge that I am identified by name as Collaborator to the investigation, entitled "Coronal injection sites of SEP beam events", that is submitted by Dennis Haggerty to the NASA Research Announcement under the ROSES 2006 NRANNH06ZDA001N-LWS and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Regards,

Sam Krucker

9. Current and Pending Support

9.1 Current and Pending Support for Dennis K. Haggerty

A. Current Support – Dennis K. Haggerty

FUNDING SOURCE	TITLE-ABSTRACT	AWARD AMOUNT	AWARD PERIOD	COMMITMENT
		See **Commitment**		
NASA ACE mission	Science Team/EPAM	FG1GF3	1997-	2.0 PM/year
NASA Grant	HIRACE spectrometer	FG987	2003-2006	2.0 PM/year
NSBRI Grant	Neutron/Ion spectrometer	FG1FJ	2004-	2.0 PM/year
NASA Grant	Heliospheric Fields	FG1MN	2006-	1.0 PM/year
NASA Grant	Spectral Breaks	FG1XB	2006-	0.6 PM/year

B. Pending Support – Dennis K. Haggerty

FUNDING SOURCE	TITLE-ABSTRACT	AWARD AMOUNT	AWARD PERIOD	COMMITMENT
		See **Commitment**		
NASA (this proposal)	SEP coronal injection		2007-2010	2.0 PM/year
NASA Grant	SEP propagation		2007-2010	< 0.1 PM/year
NASA MoO BepiColombo	STROFIO		2007-	0.5 PM/year

9.2 Current and Pending Support for Edmond C. Roelof

A. Current Support – Edmond C. Roelof

FUNDING SOURCE	TITLE-ABSTRACT	AWARD AMOUNT	AWARD PERIOD	COMMITMENT
		See **Commitment**		
NASA ACE mission	Science Team/EPAM	FG1GF3	1997-	3.0 PM/year
NASA Ulysses mission	Co-I/HI-SCALE	FG885	1990-	1.0 PM/year
NASA Voyager missio	Science Team/LECP	FG1EQ	2000-	2.0 PM/year
NASA IMAGE mission	Science Team/HENA	FF725	2000-	1.0 PM/year
NASA Cassini mission	Co-I/MIMI	IBS01	1996-	2.0 PM/year
NASA MoO MarsExpr	Co-I (Winningham PI)	IJH01	2003-	0.5 PM/year
NASA IBEX mission	Co-I (D. McComas, PI)	I6RXX3	2005-	0.5 PM/year
NASA Grant (VEX)	Co-I (P. C. Brandt, PI)	FG1RY	2006-	1.0 PM/year
NASA TWINS mission	Co-I (D. McComas, PI)	ITY01	2006-	1.0 PM/year

B. Pending Support – Edmond C. Roelof

FUNDING SOURCE	TITLE-ABSTRACT	AWARD AMOUNT	AWARD PERIOD	COMMITMENT
		See **Commitment**		
NASA (this proposal)	SEP coronal injection		2007-2010	1.0 PM/year
NASA MoO BepiColombo	STROFIO		2007-	0.5 PM/year

9.3 Current and Pending Support for Pete Riley

A. Current Support – Pete Riley

FUNDING SOURCE	TITLE-ABSTRACT	AWARD AMOUNT	AWARD PERIOD	COMMITMENT
		See **Commitment**		
NSF/Boston University	CISM	ATM-0120950	2002-2007	1.0 PM/year
NASA/SEC	Coronal Structure	$1,125k	2005-2008	1.0 PM/year

B. Pending Support – Pete Riley

FUNDING SOURCE	TITLE-ABSTRACT	AWARD AMOUNT	AWARD PERIOD	COMMITMENT
		See **Commitment**		
NASA (this proposal)	SEP coronal injection		2007-2010	2.5 PM/year
NASA/SupportingR&T	CMEs and counterpart		2006-2009	4.2 PM/year
NASA/LWS capability	Next-gen coronal model		2006-2009	1.0 PM/year
NASA/GI	CME structure		2007-2009	4.2 PM/year
NASA GI	Structure of flux ropes		2007-2009	4.0 PM/year
NSF/SHINE	Open Magnetic Flux		2007-2009	3.0 PM/year