# Project Details

**ROSES ID:** NRA-00-OSS-01
**Selection Year:** 2001
**Program Element:** Independent Investigation: LWS

**Project Title:**
Solar Energetic Particle Events in the Inner Heliosphere and Deep Space: A Model for Forecasting Proton Fluxes and Anisotropies

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**Summary:**
Solar Energetic Particle (SEP) events pose a threat to spacecraft components, materials, and operations. Accurate models for their occurrence, flux profiles, and durations are an important component of space weather. SEP events originate at shocks driven by coronal mass ejections (CMEs) propagating through interplanetary space. Such models must simulate the shock propagation and the injection and transport of shock-accelerated particles. We have developed a model that incorporates these processes. We simulate shock propagation with a magnetohydrodynamic (MHD) time-dependent code, and energetic particle propagation by solving a 1st-order complete transport equation that includes the source of particles accelerated continuously at the moving shock. This model departs from previous particle prediction schemes in that we account for the continuously changing relationship of the observer to the propagating shock. The model reproduces 50 keV-20 MeV SEP proton flux and anisotropy profiles and provides a relationship between the MHD parameters of the shock and the injection rate of shock-accelerated particles. We will use this relationship to create a catalog of simulated SEP events to determine the acceleration efficiency of shocks and to predict the evolution of SEP events. In Year 1 we will build the catalog of SEP events at 1 AU simulated under different heliospheric conditions and configurations. In Year 2 we will extend this catalog to radial distances from 0.3 AU to ~2 AU to provide particle fluences for future NASA missions such as the Inner Heliospheric Sentinels. In Year 3 we will make our results available through the WWW and will study other possibilities for shock modeling and for the injection rate of shock-accelerated particles. Throughout this 3-year project we will build and update a data base of SEP events observed by ACE, IMP-8, Helios-1/2 and compare our calculated fluxes with SEP events in this data base. Our proposed work is central to NASA's Living With a Star program. We will model the evolution of SEP events at Earth and in the inner and outer heliosphere and provide a firm scientific basis for forecasting a key aspect of space weather.

# Publication References:

**Summary:** One of the most energetic and most intense energetic storm particle (ESP) events (the 1989 October 20 event) was not due to local acceleration of particles at 1 AU, but rather to a population of particles confined to a plasma structure with depressed magnetic field and solar wind density.

**Reference:** Lario D.; Decker R. B.; (2002). The energetic storm particle event of October 20, 1989. Geophysics Research Letters, 29, 31-1, doi: 10.1029/2001GL014017
- **Investigation Type:** Data Analysis
- **Data Sources:** IMP-8:CPME  GOES:EPS

**Summary:** Survey of the effects of interplanetary shocks on energetic >47 keV ions and >38 keV electrons as observed by the field, plasma and energetic particle experiments on the ACE spacecraft. Our survey of the proton and electron intensity-time profiles has revealed the following: (1) intensity increases associated with a shock passage are more frequently observed in the low-energy ion fluxes; (2) electron shock events, which occur less frequently than ion shock events, are mainly spikes or step-like post-shock increases; and, (3) peak intensities are usually observed within ~2 minutes of the shock passage with a clear trend towards occurrence in the downstream region of the shock.

**Reference:** Lario D.; Ho G. C.; Decker R. B.; Roelof E. C.; Desai M. I.; Smith C. W.; (2003). ACE Observations of Energetic Particles Associated with Transient Interplanetary Shocks. , 679, 640-643, doi: 10.1063/1.1618676
- **Investigation Type:** Data Analysis
- **Data Sources:** ACE:EPAM  ACE:SWEPAM  ACE:MAG

**Summary:** Review paper on the classification, origin, intensity and properties of the solar energetic particle events, in terms of both energetic ions and electrons. We review the long-term databases created to compare the occurrence frequency and intensity distribution of events among the solar cycles. Models for the production of the largest gradual solar energetic particle events are also discussed.

**Reference:** Lario D.; Simnett G. M.; (2004). Solar Energetic Particle Variations. , 141, 195, doi: 10.1029/141GM14

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** SEP transport and acceleration models
- **Datasources:**
  ACE:EPAM  ACE:SWEPAM  ACE:MAG  ULYSSES:COSPIN  ULYSSES:HISCALE  IMP-8:CPME  GOES:EPS

**Summary:** Preliminary version of a potential tool for real time proton flux prediction which provides proton flux profiles and cumulative fluence profiles at 0.5 and 2 MeV of solar energetic particle events, from their onset up to the arrival of the interplanetary shock at the spacecraft position (located at 1 or 0.4 AU). Based on the proton transportation model by Lario et al. [Lario, D., Sanahuja, B., Heras, A.M. Energetic particle events: efficiency of interplanetary shocks as 50 keV E < 100 MeV proton accelerators. Astrophys. J. 509, 415-434, 1998] and the magnetohydrodynamic shock propagation model of Wu et al. [Wu, S.T., Dryer, M., Han, S.M. Non-planar MHD model for solar flare-generated disturbances in the Heliospheric equatorial plane. Sol. Phys. 84, 395-418, 1983], we have generated a database containing "synthetic" profiles of the proton fluxes and cumulative fluences of 384 solar energetic particle events.

**Reference:** Aran A.; Sanahuja B.; Lario D.; (2005). A first step towards proton flux forecasting. Advances in Space Research, 36, 2333-2338, doi: 10.1016/j.asr.2004.06.023

- **Investigation Type:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** Preliminary version of a potential tool for real time proton flux prediction which provides proton flux profiles and cumulative fluence profiles at 0.5 and 2 MeV of solar energetic particle events, from their onset up to the arrival of the interplanetary shock at the spacecraft position (located at 1 or 0.4 AU). Based on the proton transportation model by Lario et al. [Lario, D., Sanahuja, B., Heras, A.M. Energetic particle events: efficiency of interplanetary shocks as 50 keV E < 100 MeV proton accelerators. Astrophys. J. 509, 415-434, 1998] and the magnetohydrodynamic shock propagation model of Wu et al. [Wu, S.T., Dryer, M., Han, S.M. Non-planar MHD model for solar flare-generated disturbances in the Heliospheric equatorial plane. Sol. Phys. 84, 395-418, 1983].
- **Domains:** Interplanetary space or solar wind

**Summary:** SOLPENCO (for SOLar Particle ENgineering COde) is a tool for rapid predictions of proton flux and fluence profiles observed during gradual solar energetic particle (SEP) events and upstream of the associated traveling interplanetary shocks. SOLPENCO contains a data base with a large set of interplanetary scenarios under which SEP events develop. These scenarios are basically defined by the solar longitude of the parent solar activity, ranging from E75 to W90, and by the position of the observer, located at 0.4 AU or at 1.0 AU, from the Sun. We analyze how the peak flux and the fluence of the synthetic profiles generated by SOLPENCO vary as a function of the strength of the CME-driven shock, the heliolongitude of the solar parent activity and the particle energy considered.

**Reference:** Aran A.; Sanahuja B.; Lario D.; (2005). Fluxes and fluences of SEP events derived from SOLPENCO. Annales Geophysicae, 23, 3047-3053, doi: 10.5194/angeo-23-3047-2005

- **Investigation Type:** Theory and Model Development
- **Existing theories/models/datasets which the study is based:** SOLPENCO (for SOLar Particle ENgineering COde)
- **Domains:** Interplanetary space or solar wind

**Summary:** Solar energetic particles pose one of the most serious hazards to space probes, satellites and astronauts. The most intense and largest solar energetic particle events are closely associated with fast coronal mass ejections able to drive interplanetary shock waves as they propagate through interplanetary space. The simulation of these particle events requires knowledge of how particles and shocks propagate through the interplanetary medium, and how shocks accelerate and inject particles into interplanetary space. Several models have appeared in the literature that attempt to model these energetic particle events. Each model presents its own simplifying assumptions in order to tackle the series of complex phenomena occurring during the development of such events. The accuracy of these models depends upon the approximations used to describe the physical processes involved in the events. We review the current models used to describe gradual solar energetic particle

events, their advances and shortcomings, and their possible applications to space weather forecasting.

**Reference:** Lario D.; (2005). Advances in modeling gradual solar energetic particle events. Advances in Space Research, 36, 2279-2288, doi: 10.1016/j.asr.2005.07.081

- **Investigation Type:** Tools and Analysis Techniques
- **Names of the tools and techniques:** Simulation models used to describe gradual solar energetic particle events

**Summary:** Forecasting the arrival of solar-generated shocks and accelerated protons anywhere in the heliosphere presents an awesome challenge in the new field of space weather. Currently, observations of solar wind plasmas and interplanetary magnetic fields are made at the sun–Earth libration point, L1, about 0.01 astronomical units sunward of our planet. An obvious analogy is the pitot tube that protrudes ahead of a supersonic vehicle. The Advanced Composition Explorer and Solar and Heliospheric Observatory spacecraft, currently performing this function, provide about 0.5–1 h advance notice of impending arrival of interplanetary disturbances. The signatures of these disturbances may be manifested as interplanetary shock waves and/or coronal mass ejecta. We describe a first-generation procedure, based on first-principles numerical modeling, that provides the key links required to increase the advance notice (or lead time) to days, or even weeks. This procedure, instituted at the start of the present solar cycle 23, involves three separate models, used in real time, to predict the arrival of solar-event initiated interplanetary shock waves at the L1 location. We present statistical results, using L1 observations as "ground truth" for 380 events.We also briefly discuss how one of these models (Hakamada–Akasofu–Fry version 2) may be used with a model that predicts the flux and fluence of energetic particles, for energies up to 100 MeV, that are generated by these propagating interplanetary shock waves.

**Reference:** Fry C.; Akasofu S.; Aran A.; Deehr C.; Detman T.; Dryer M.; Lario D.; Sanahuja B.; Smith Z.; Sun W.; (2005). Key Links to Space Weather: Forecasting Solar-Generated Shocks and Proton Acceleration. AIA Journal, 43, 987-993, doi: 10.2514/1.11470

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** How the Hakamada–Akasofu–Fry model may be used to predict the flux and fluence of solar energetic particles, for energies up to 100 MeV.
- **Datasources:** ACE:EPAM  SOHO:ERNE  SOHO:COSTEP

**Summary:** Monte-Carlo technique to study the time-dependent transport of energetic particles in the interplanetary medium. We use the guiding center approximation between discrete finite pitch-angle scatterings to quantify the competing effects of focusing and pitch-angle scattering on energetic particles propagating along a Parker spiral magnetic field. We consider that the pitch-angle scattering process is produced by small-scale magnetic field irregularities frozen in the expanding solar wind. We also include the effects of both solar wind convection and adiabatic deceleration. The results of our simulations are pitch-angle distributions and time-intensity profiles that can be directly compared to spacecraft observations. Comparison of our simulations with near-relativistic (45-290 keV) electron events observed by the Electron, Proton and Alpha Monitor on board the Advanced Composition Explorer allows us to estimate both the time dependence of the injection of near-relativistic electrons into the interplanetary medium and the conditions for electron propagation along the interplanetary magnetic field.

**Reference:** Agueda N.; Lario D.; Roelof E. C.; Sanahuja B.; (2005). Modeling the effects of pitch-angle scattering processes on the transport of solar energetic particles along the interplanetary magnetic field. Advances in Space Research, 35, 579-585, doi: 10.1016/j.asr.2005.04.069

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** MonteCarlo SEP transport model
- **Datasources:** ACE:EPAM  ACE:SWEPAM  ACE:MAG

**Summary:** We present SOLPENCO (SOLar Particle ENgineering COde), the first step towards an operational tool able to quantitatively predict proton flux and fluence profiles of solar energetic particle (SEP) events associated with interplanetary shocks. The main components of this code are the following: a data base containing synthetic proton flux and fluence profiles for a set of 448 different scenarios at 1 AU and at 0.4 AU, for proton energies ranging from 0.125 to 64 MeV; and a user-friendly interface which permits rapid acquisition, by interpolation, of the flux and cumulative fluence profiles in the upstream part of an SEP event for a given solar-interplanetary scenario selected by the user (from among 697,800 cases). SOLPENCO also provides an estimate for the transit time and average speed of the CME-driven shock. We have started the validation of the outputs of this code by comparing them with several observed and modeled SEP events. As an example, we discuss here the case of the 4 6 April 2000 event. The main conclusions are that the code fits well the peak flux for several energy channels, and that the average parameters used to synthesize the flux and fluence profiles must be studied in more detail by performing a statistical study with a large set of observed and modeled SEP scenarios.

**Reference:** Aran A.; Sanahuja B.; Lario D.; (2006). SOLPENCO: A solar particle engineering code. Advances in Space Research, 37, 1240-1246, doi: 10.1016/j.asr.2005.09.019

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** SOLPENCO (SOLar Particle ENgineering COde), the first step towards an operational tool able to quantitatively predict proton flux and fluence profiles of solar energetic particle (SEP) events associated with interplanetary shocks.
- **Datasources:** ACE:EPAM

**Summary:** We study the radial and longitudinal dependence of 4-13 and 27-37 MeV proton peak intensities and fluences measured within 1 AU of the Sun during intense solar energetic particle events. Simultaneous measurements of individual events by at least two spacecraft show that the dominant parameter determining the total event fluence and the event peak intensity is the longitudinal separation (?) between the parent active region and the footpoint of the field line connecting each spacecraft with the Sun, rather than the spacecraft radial distance (R). We provide functional forms to describe these radial and longitudinal dependences.

**Reference:** Lario D.; Kallenrode M.-B.; Decker R. B.; Roelof E. C.; Krimigis S. M.; Aran A.; Sanahuja B.; (2006). Radial and Longitudinal Dependence of Solar 4-13 MeV and 27-37 MeV Proton Peak Intensities and Fluences: Helios and IMP 8 Observations. Astrophysical Journal, 653, 1531-1544, doi: 10.1086/508982

- **Investigation Type:** Data Analysis
- **Data Sources:** HELIOS:E6  IMP-8:CPME

**Summary:** We model an intense solar energetic particle event observed simultaneously on the 6 of March 1989 by the near-Earth orbiting spacecraft IMP-8 and by the Phobos-2 spacecraft in orbit around Mars (located 72° to the East of the Earth and at 1.58 AU from the Sun). We use an MHD code to model the propagation of the associated shock to both spacecraft and a particle transport code to model the proton intensities measured by IMP-8 and Phobos-2. By assuming that energetic particles are continuously accelerated by the traveling shock, and that the injection rate of these particles, Q, into the interplanetary medium is related to the upstream-to-downstream velocity ratio, VR, at the point of the shock front that connects with the observer, we perform predictions of the solar energetic particle intensities observed at Mars from those measured at Earth. We reproduce not only the arrival times of the shock at both spacecraft but also the measured jump discontinuity of solar wind speed, density and magnetic field. Also, we reproduce the 0.5-20 MeV proton intensities measured by both spacecraft. Functional dependences such as the Q(VR) relation deduced here allow us to predict the proton intensities measured at Phobos-2 for this event. Applications of this model for future predictions of solar energetic particle fluxes at Mars are discussed.

**Reference:** Aran A.; Lario D.; Sanahuja B.; Marsden R. G.; Dryer M.; Fry C. D.; McKenna-Lawlor S. M. P.; (2007). Modeling and forecasting solar energetic particle events at Mars: the event on 6 March 1989. Astronomy and Astrophysics, 469, 1123-1134, doi: 10.1051/0004-6361:20077233

- **Investigation Type:** Data Model Comparison
- **Names of models being tested or validated:** The Lario et al. (1998) model that combines SEP transport and MHD simulation of shock propagation to describe gradual solar energetic particle (SEP) events.
- **Datasources:** IMP-8:CPME  PHOBOS-2:LET

**Summary:** SOLPENCO provides proton differential flux and cumulated fluence profiles from the onset of the event up to the arrival of the associated traveling interplanetary shock at the observer's position (either 1.0 or 0.4 AU). SOLPENCO considers a variety of interplanetary scenarios where the SEP events develop. These scenarios include solar longitudes of the parent solar event ranging from E75 to W90, transit speeds of the associated shock ranging from 400 to 1700 km s-1, proton energies ranging from 0.125 to 64 MeV, and interplanetary conditions for the energetic particle transport characterized by specific mean free paths. We compare the results of SOLPENCO with flux measurements of a set of SEP events observed at 1 AU that fulfill the following four conditions: (1) the association between the interplanetary shock observed at 1 AU and the parent solar event is well established; (2) the heliolongitude of the active region site is within 30° of the Sun Earth line; (3) the event shows a significant proton flux increase at energies below 96 MeV; (4) the pre-event intensity background is low. The results are discussed in terms of the transit velocity of the shock and the proton energy. We draw conclusions about both the use of SOLPENCO as a prediction tool and the required improvements to make it useful for space weather purposes.

**Reference:** Aran A.; Sanahuja B.; Lario D.; (2008). Comparing proton fluxes of central meridian SEP events with those predicted by SOLPENCO. Advances in Space Research, 42, 1492-1499, doi: 10.1016/j.asr.2007.08.003

- **Investigation Type:** Tools and Analysis Techniques
- **Names of the tools and techniques:** SOLPENCO: An operational code that can be used for space weather prediction schemes of solar energetic particle (SEP) events. SOLPENCO provides proton differential flux and cumulated fluence profiles from the onset of the event up to the arrival of the associated traveling interplanetary shock at the observer’s position (either 1.0 or 0.4 AU).