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Prospects for Modeling and Forecasting SEP Events with ENLIL and SEPMOD

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Abstract. One view of major Solar Energetic Particle (SEP) events is that these (proton-dominated) fluxes are accelerated in heliospheric shock sources created by Interplanetary Coronal Mass Ejections (ICMEs), and then travel mainly along interplanetary magnetic field lines connecting the shock(s) to the observer(s). This places a particular emphasis on the role of the heliospheric conditions during the event, requiring a realistic description of the latter to interpret and/or model SEP events. The well-known ENLIL heliospheric simulation with cone model generated ICME shocks is used together with the SEPMOD particle event modeling scheme to demonstrate the value of applying these concepts at multiple inner heliosphere sites.

Keywords. Space weather, solar energetic particles, interplanetary shocks

1. Introduction

The desire to interpret and forecast Solar Energetic Particle (SEP) events as part of space weather research has spawned a number of schemes for both source and particle transport descriptions (e.g. Marsh *et al.* 2015). One school of thought favors approaches with near-Sun sources and diffusive propagation, while another emphasizes the evolving geometry and properties of the coronal mass ejection driven shock sources and regards shock-connected interplanetary field lines as highways for their transport into the heliosphere (Heras *et al.* 1992; Kallenrode *et al.* 1997; Lario *et al.* 1997). Each of these have advantages and weaknesses, but the latter has the best prospects for describing the global nature of these events including those involving multiple shock sources. One well-exercised way of describing the necessary heliospheric conditions is the WSA-ENLIL-cone model (e.g. Odstrcil *et al.* 2005), which we refer to as ENLIL here. This MHD simulation bases its solar wind and interplanetary field description on inner boundary conditions set by global magnetic maps obtained with solar magnetographs (e.g. see Arge *et al.* 2004), while its coronal mass ejection (CME)-driven shocks are driven by localized injections of high pressure outflows into the solar wind with directions, stream widths, and initial speeds dictated by coronagraph images of CMEs (e.g. see Mays *et al.* 2015). Together, this combination can sometimes produce good matches to the plasma parameters observed at 1 AU, including high speed solar wind streams and interplanetary CME (ICME) shock arrivals (e.g. Taktakishvili *et al.* 2009).

SEPMOD takes the next step by using the results from ENLIL to time-integrate assumed SEP injections of energetic protons at the shocks onto magnetic field lines connecting to an observer located anywhere in the ENLIL domain (see Luhmann *et al.* 2017 for a more detailed description of SEPMOD). The result for any observer is a companion time series of SEP proton fluxes for the period of the ENLIL run, including all of the ICME shock source contributions present in ENLIL during that run. Sample results from this scheme are shown here, together with the corresponding available data, for SEP observer outposts at Earth, STEREO, Venus and Mars. The results demonstrate the extent to which a heliosphere-wide perspective of SEP events associated with sometimes highly complex heliospheric conditions can be obtained with the application of the combined ENLIL/SEPMOD approach.

2. Examples of ENLIL/SEPMOD Applications

Here we use a straw-man set of 5 inner heliosphere observers located at Earth, STEREO, Venus and Mars to illustrate the application of ENLIL with SEPMOD to the diagnosis of two cases of multipoint SEP observations. For 1 AU observations we use a combination of EPAM on ACE and EPS on GOES for Earths location (e.g. Gold *et al.* 1998), and LET and HET (Mewaldt *et al.* 2008, Von Rosenvinge *et al.* 2004) on STEREO-A and B at their changing heliocentric positions with respect to Earth. We also use an ASPERA IMA detector background from Venus Express (VEX) for Venus at 0.7 AU, and a similar detector background from Mars Express (MEX) at Mars at 1.5 AU (see Futaana *et al.* 2008).

Although the assumptions in SEPMOD of parallel (to the field), non-diffusive transport are best suited to 10-100 MeV energy protons, we apply the ENLIL/SEPMOD scheme to the energy range from a few MeV to 100 MeV to assess its usefulness at the lower energies. It should be mentioned here that the injected SEP protons are each initially isotropic bursts that have energy spectra determined by the ENLIL shock compression jump at the point of the observers magnetic connection, which change with the 5 minute cadence of SEPMODs adoption of ENLIL time-dependent field and shock geometries (see Luhmann *et al.* 2017). The injected SEP fluxes are determined using a semi-empirical formula derived by Lario *et al.* (1998) based on those authors observer field line backmapping to a modeled shock in a large number of SEP events. SEPMOD also includes an ad-hoc Energetic Storm Particle (ESP) component that is added to the injected flux when the observer is located within a few tenths of an AU of a strong shock. This component has a flux level that is a fixed fraction of the baseline flux and falls off with distance from the shock location. It also has a softened spectrum relative to the baseline flux. The construction of this component was based on a survey of ESP event phenomenology in the literature (e.g., Cohen 2006 and references therein).

The results shown illustrate a variety of issues and features that contribute to the complexity of SEP event analysis and modeling. For each case we first show the geometry of the various observers during the period under analysis. We then show the observed time series of SEP fluxes at each of the 5 observer sites, for the duration of the ENLIL run, and then the model counterparts to these time series calculated with the ENLIL results and SEPMOD. ENLIL runs of several weeks duration are typically used because in many cases multiple ICME shocks are present in the ENLIL domain at one time, and must all be considered in interpreting what is observed. In concert with this, it is found that ENLIL simulations out to 5 AU are desirable because of both contributions of shock

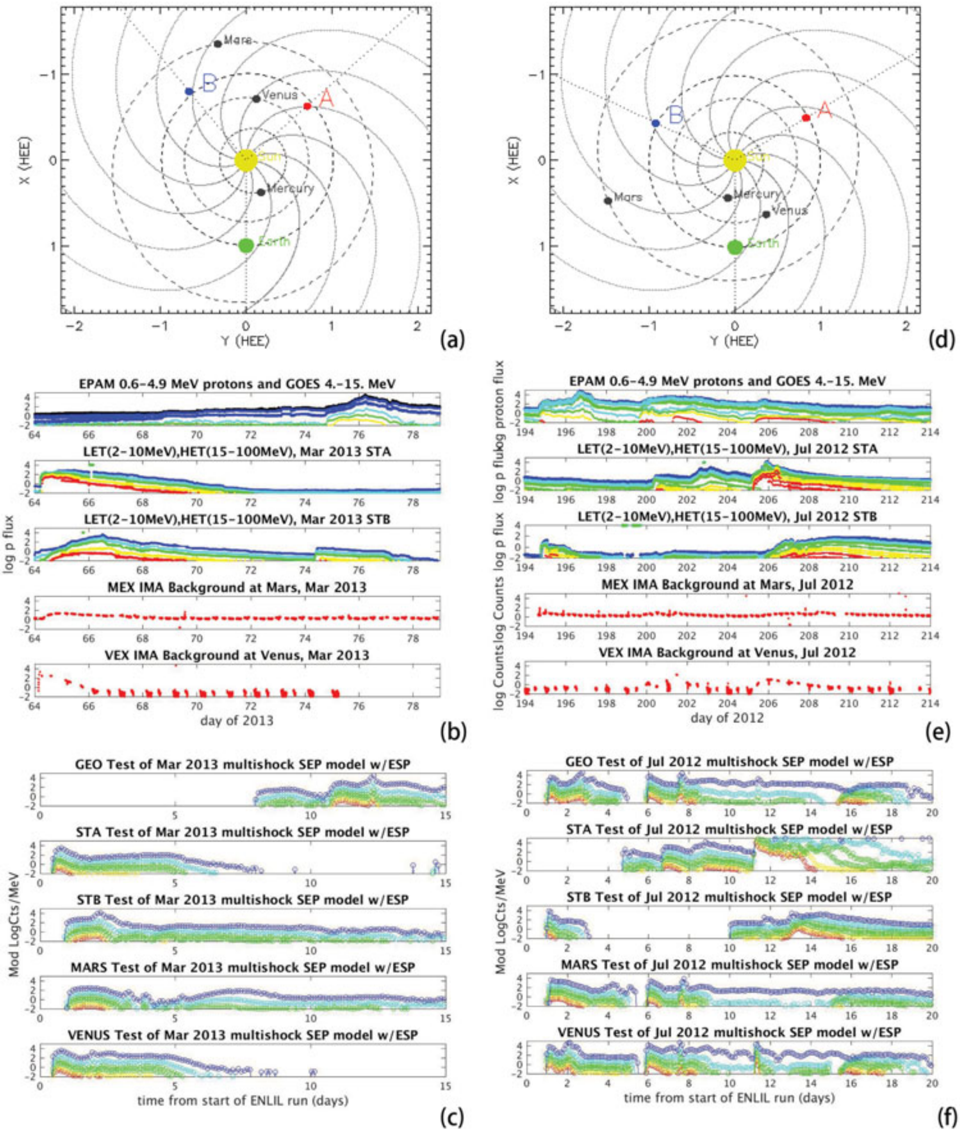

Figure 1. (a) Ecliptic plane locations of the observers at the Earth, STEREO-A and B sites, Venus and Mars from which SEP and supporting observations are available in March 2013. (b) Stacked SEP flux time profiles for days 64-79 (March 5-20) of 2013 from ACE/GOES at Earth, STEREO-A and B, and background in the Mars Express and Venus Express ASPERA-IMA detectors. (c) SEP flux time profiles calculated with ENLIL and SEPMOD for this period. (d-f) Same as (a-c) but for a period of high solar activity in July 2012 (July 12-31).

sources that have passed the observer, and SEP mirroring in the structured interplanetary magnetic field. Although many details of the observer shock connections could be shown, the modeled time series represent the ultimate test of the SEPMOD/ENLIL scheme, which is why we focus on them in this brief report.

We chose a period of relatively simple solar activity in March 2013, when only two major ICME shocks were present, well-separated in time and space, and another in July 2012 when there was exceptionally strong, complex activity with multiple overlapping

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shocks. The results for the former case are shown in the left column of Figure 1 (Figure 1 a-c), while the latter case is shown on the right (Figure 1 d-f). Both events had combinations of well-separated and more closely spaced observers as seen in the top panels from the STEREO Science Center website. The observed widespread SEP activity for March 5-20, 2013 and July 12-31, 2012 in the middle panels exhibits a variety of distinctive flux time profiles, which according to the SEPMOD assumptions, are the result of each observers unique heliospheric shock connection history. The corresponding SEPMOD results in the bottom panels generally reproduce both the flux time series trends including flux magnitudes for both time periods. The results suggest that SEPMOD using current ENLIL is useful for both retrospectively interpreting observed SEP events and possibly for making forecasts.

3. Prospects for SEP Forecasting

The above examples illustrate that with a fixed set of assumptions, the ENLIL/SEPMOD scheme can provide first-order descriptions of gradual SEP proton event fluxes for the few MeV to 100 MeV energy range of interest to users of space weather information. To apply this scheme in a forecasting mode is straightforward but requires the availability of updated coronagraph images and solar magnetic synoptic maps on a near-real-time basis. The speed with which these can be obtained, and ENLIL models run with the needed derived information for the cone models of the CME(s), is a critical factor because of the relative immediacy (within 10s of minutes) of SEP event onsets following major CME occurrence. While the ESP SEP flux enhancement arrives with the ICME shock several days after the CME onset, the initial flux onset can be intense and with a harder spectrum than the bulk of the sometimes several-day-long SEP event because it originates in the ICME shock while it is still close to the Sun. This includes the hard GLE (Ground Level Event) fluxes which are often generated in association with a strong coronal shock connection near the west limb (e.g. Gopalswamy *et al.* 2012). Nevertheless, if such near-real-time ENLIL runs can be realized (as are provisionally posted at the NASA Goddard Space Flight Center Space Weather Research Center website (http://ccmc.gsfc.nasa.gov/mssionsupport) or the NOAA Space Weather Prediction Center (http://www.swpc.noaa.gov/pproducts/wsa-enlil-solar-wind-prediction)), the subsequent running of SEPMOD using these results is a fast process that can provide related SEP flux time profile predictions for the sometimes several-day-long events duration.

Needless to say, the infrastructure required for model calculations SEPMOD to run must be a first priority of those invested in the goal of interplanetary radiation environment forecasting, including both the coronal and solar magnetic field observations and the continual improvement of heliospheric models like ENLIL. The availability of multiperspective imaging such as that possible with SOHO and ACE makes determination of CME properties much more realizable than images from only Earths perspective. In addition, while current ENLIL appears to provide a usable first order description of heliospheric shocks and fields, it does not include the region of strongest shocks inside 21 Rs (inside ENLILs inner boundary) -where GLE SEPs are generated. Nor does current ENLIL include the magnetic fields of the coronal ejecta in its cone model CMEs. The magnetic fields of the latter both influence the radial evolution and interactions of the ICME shocks, as well as alter the magnetic field line and hence connectivity descriptions in the post shock regions of the ICMEs. SEPMOD upgrades, in terms of physics included, can also be made, but these can only improve the outcomes if the underlying heliospheric simulations are also improved. Thus one has to regard any implementation or validation of the scheme described here in its entirety. These issues notwithstanding, modeled SEP flux time profiles like those above can be obtained for retrospective studies on a regular basis today. The CCMC at Goddard Space Flight Center is currently taking steps toward that goal.

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References

C. N., Luhmann, J. G., Odstrcil, D., Schrijver, C. J. & Li, Y. 2004, *J. Atmosph. Solar Terr. Phys.*, 66, 1295-1309

Cohen, C. M. S. 2006, *Geophys. Monograph Ser., 165, eds. N. Gopalswamy, R. Mewaldt and J. Torsti*, 275-282, AGU, Washington DC

Futaana, Y., *et al.* 2008, *Planet. Space Sci.*, 56, 873-880

Gold, R. E., Krimigis, S. M., Hawkins, S. E., Haggerty, D. K., Lohr, D. A., Fiore, E., Armstrong, T. P., Holland, G. & Lanzerotti, L. J. 1998, *Space Sci. Rev.*, 86, 541-562

Gopalswamy, N., Xie, H., Yashiro, S., Akiyama, S., Makela, P. & Usoskin, I. 2012, *Space Sci. Rev.*, 171, 23-60

Heras, A. M., Sanahuja, B., Smith, Z. K., Detman, T. & Dryer, M. 1992, *Astrophys. J.*, 391, 359-369

Kallenrode, M.-B. & Wibberenz, G. 1997, *J. Geophys. Res.*, 102, 22,311-11,334

Lario, D., Sanahua, B. & Heras, A. M. 1997, *Adv. Space Res.*, 20, 121-126

Lario, D., Sanahuja, B. & Heras, A. M. 1998, *ApJ* 509, 415

Luhmann, J. G., *et al.* 2017, *Space Weather*, 15, 1-21, doi:10.1002/2017SW001617

Mays, M. L., *et al.* 2015, *Sol. Phys.*, 290, 1775-1814

Marsh, M. S., Dalla, S., Dierckxsens, M., Laitinen, T. & Crosby N. B. 2015, *Space Weather*, 13, 386-394

Mewaldt, R. A., *et al.* 2008, *Space Sci. Rev.*, 136, 285-362

Odstrcil, D., Pizzo, V. J. & Arge, C. N. 2005, *J. Geophys. Res.*, 110, 2004JA010745

Taktakishvili, A., Kuznetsova, M., MacNeice, P., Hesse, M., Rastaetter, L., Pulkkinenen, A., Chulaki, A. & Odstrcil, D. 2009, *Space Weather*, 7, doi:10.1029/2008SW000448

Von Rosenvinge, T. T., *et al.* 2008, *Space Sci. Rev.*, 136, 391-436