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SOLPENCO: A solar particle engineering code

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Abstract

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.

Keywords: Space weather; Solar energetic particle events; Shocks; Coronal mass ejections

1. Introduction

The current paradigm for solar energetic particle (SEP) events states that there are two basic types of events, impulsive and gradual events (Reames, 1999). This paradigm assumes that particles in impulsive events are accelerated during the flaring process while particles in gradual events are accelerated by shocks driven by coronal mass ejections (CMEs). Recent observations, however, challenge this simple picture (Cliver and Cane, 2002). Whether there are two completely separated types of events or a continuous change from one type to the other is still being debated (Cliver et al., 2002). Under these circumstances, the task of building reliable applications to forecast SEP events, i.e., to predict, where and when the SEP events might occur and determine their flux profile or their fluence, is extremely difficult. For example, the poor knowledge of the initial conditions for the physical mechanisms that accelerate 'ambient' particles to high energy is a strong constraint for modeling. In spite of this situation, models leading to a prediction of specific time-flux or fluence profiles for individual gradual SEP events are being developed. These models are based on observations and analysis of SEP events, and rely on simplified theoretical assumptions. A recent review of their characteristics can be found in Lario (2005).

In order to obtain reliable predictions of the flux and fluence profiles for SEP events, it is necessary to consider the contribution of particles accelerated by CME-driven shocks, as well as the transport effects due to the energetic particle streaming along the interplanetary magnetic field (IMF). We have built an operative code (Aran et al., 2004) called SOLPENCO (SOlar Particle ENgineering COde) that is based on the first model that combined magnetohydrodynamic shock simulations and energetic

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particle transport simulations (Lario et al., 1998). In Section 2, we present the main characteristics of the latest working version of this code, with a complete set of scenarios at 1 and 0.4 AU. For a given SEP event, SOLPENCO is able to provide a prediction of the time profile of the proton flux and of the cumulative fluence, from the onset of the event near the Sun up to the shock arrival at the observer's location. Its applicability for space weather forecasting has still to be validated. We are now working on this. This type of operative code is needed to quantitatively predict the hazard that an SEP event may eventually pose to, for instance, space-borne instruments and manned interplanetary missions. We expect that this code will be useful to achieve this purpose. Further, it will also be useful for inner heliospheric missions where the heliocentric radial dependence of the flux and fluence of SEP events is practically unknown due to the lack of observations. Currently, we can already perform a direct comparison between the synthetic flux profiles provided by SOLPENCO and those observational fluxes at similar energies for different events. Here, we present the case of the 4–6 April 2000 SEP event.

2. The tool SOLPENCO

2.1. Upgrade of the code

SOLPENCO is the present version of a preliminary code described in Aran et al. (2004, 2005). Here, we focus our description on the last improvements performed in the code. Two important factors that contribute to the large variety of SEP flux profiles are the particle energy and the spacecraft angular position with respect to the heliolongitude of the parent solar activity (e.g., Cane et al., 1988). In order to analyze the energy dependence, we have extended the energy range of the synthetic flux and cumulative fluence profiles originally presented in Aran et al. (2005) up to 90 MeV. In this way, we take into account those energies which mostly affect instruments onboard satellites and probes, and that can be also a hazard to astronauts. The user of SOLPENCO can choose from ten values of the energy, that is, the mean value of each energy interval considered by the code: 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32 and 64 MeV. Regarding the heliolongitude of the solar source activity, we have extended the angular positions of the observers at 1 AU from the western limb (W90) to far eastern locations (E75) and completed the set of scenarios at 0.4 AU. Therefore, the database contains synthetic profiles for observers located each 15° from W90 to E75, for both 1 and 0.4 AU locations, as well as two more intermediate spacecraft sites, W22.5 and E22.5.

For a given gradual SEP event, SOLPENCO interpolates among the four pre-calculated gradual SEPs in the database which have the closest angular positions and initial shock velocities to the values chosen by the user. This database contains the upstream flux and cumulative fluence profiles of 10 energy channels for each of the 448 combined shock-plus-particle scenarios (8 shocks, 14 observer's angular positions and 4 particle transport conditions), both at 1 AU and at 0.4 AU. SOLPENCO can thus, provide predictions, in less than 1 min, for a large set of SEP events (at least 697,864 possibilities, if only integer values of shock initial speed and angular position are considered).

2.2. The injection rate of shock-accelerated particles

To build up the database of SOLPENCO we use the empirical relation derived from modeling several SEP events by Lario et al. (1998). This relation states that there is an exponential dependence between the injection rate of shock-accelerated particles, Q, and the normalized downstream-to-upstream plasma velocity jump (VR) at the point of the shock front magnetically connected to the observer (also called the cobpoint (Heras et al., 1995)). For values $\mathrm{VR} > 0.1$, the injection rate is given by

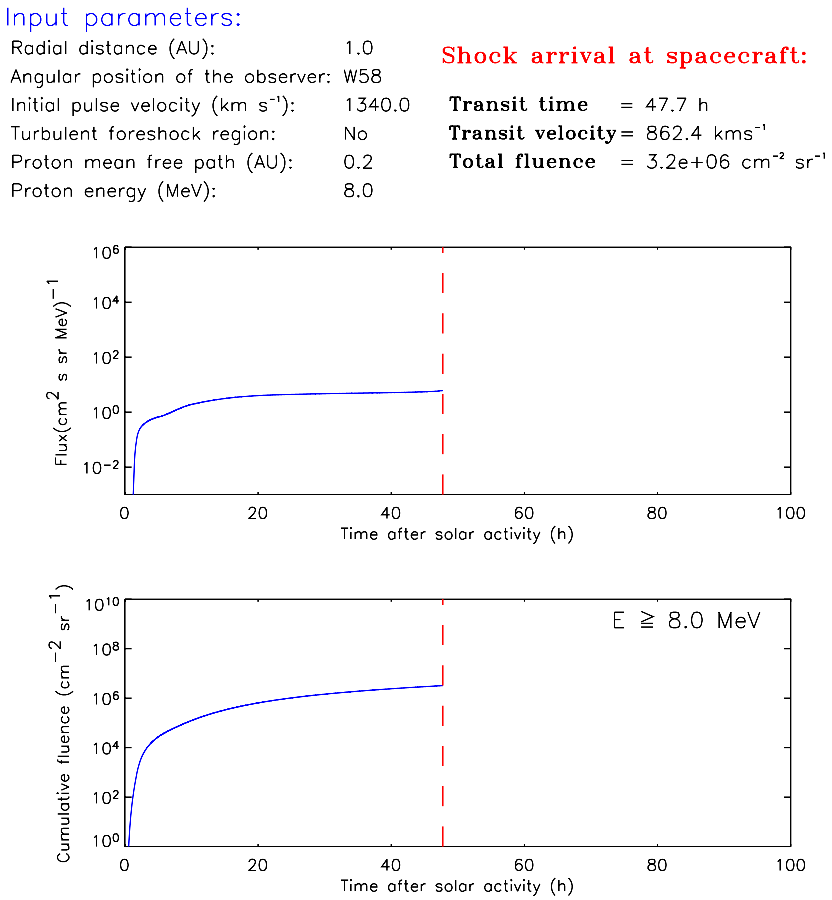
$$\log Q = \log Q_0 + k\,\mathrm{VR}. \tag{1}$$

This expression allows us to relate the dynamic evolution of the shock strength at the cobpoint to the rate at which shock-accelerated particles are injected into the interplanetary medium. To set the values of the proportionality factor, k, and of Q_0 we have assumed average conditions. The factor k has been taken as $k = 0.5$, the average value derived from modeling several SEP events for 0.5 MeV protons (Aran et al., 2004 and references therein). As a first approximation, we assume that this value is the same for all energies because in the majority of the analyzed events the derived values of k only vary slightly with the energy. We also assume that Q_0 scales as a power law with energy, with a spectral index $\gamma = 2$ for $E < 2$ MeV and $\gamma = 3$ for $E \geqslant 2$ MeV. These are average values derived from the literature (e.g., van Nes et al., 1984; Cane et al., 1988) and from our modeled SEP events. The values of Q_0 are taken from those obtained from the simulation of the 24–26 April 1981 SEP event since this event presents an almost constant value of $k \sim 0.5$ (Lario, 1997) (for a thorough discussion on this subject see Aran et al. (2004)). This procedure to obtain the injection rate, Q, clearly improves former attempts (Aran et al., 2005) because it assures a soft transition of the evolution of the proton flux profiles from low to high energies and from eastern to western events. Moreover, to translate the fluxes from the arbitrary units obtained by the model to the physical units observed by spacecraft a unique scaling factor is needed for all the events in the database, and thus, the number of free parameters of the code is reduced. The adopted scaling factor corresponds to the value of the 0.5 MeV proton flux at the shock arrival of the 12–15 September 2000 event, using data from the ACE/EPAM instrument (Gold et al., 1998); for a description of this SEP event see Aran et al. (2004, 2005). This assumption is a first step; in order to establish a definitive value for the scaling factor, we must perform a statistical analysis of a large set of SEP events.

Figs. 1 and 2 show two examples of the output display provided by SOLPENCO. The upper left panels list the input values selected by the user: (1) the radial distance of the probe's location (1 or 0.4 AU), (2) the initial shock speed (from 750 to 1800 km s^{-1}), (3) the observer's angular longitude with respect the parent solar activity site (from E75 to W90), (4) the mean free path for 0.5 MeV protons (0.2 or 0.8 AU), scaled to different energies as $\propto P^{0.5}$, where P is the proton rigidity, (5) the existence of a turbulent foreshock region able to keep particles confined around the shock (Yes/No), and (6) the proton energy (one of the ten energy values mentioned above). The top right panels give: the upstream duration of the event (i.e., the time from the onset of the activity at the Sun up to the shock arrival at the spacecraft), the shock transit speed, and the total upstream fluence of the event, integrated for all the energies over that selected by the user. The flux profile is plotted in the middle panel and the cumulative fluence profile at the bottom. The vertical dashed lines indicate the time of the shock arrival at the observer. The SOLPENCO output interface allows the user to plot the flux and/or the fluence, and to store the output data in an ASCII file and/or the graphical display in Portable Network Graphics (PNG) format.

3. Results and discussion

SOLPENCO is a first step towards an operative tool for the prediction of the proton flux and the fluence of individual gradual SEP events. To evaluate its usefulness for space weather purposes, it is necessary to validate its outputs by comparing the synthetic profiles with the corresponding values of a reasonable number of observed SEP events. We have started this process by comparing the output flux profiles of SOLPENCO with those of the SEP events that we have already modeled. As an example of such comparison, we present the case of the 4–6 April 2000 event. This SEP event is associated with a strong interplanetary shock detected by ACE at 16:00 UT on April 6, driven by a full halo CME observed by SOHO/LASCO at 16:32 UT on April 4. The CME was in temporal association with a C9.7/2F flare observed at 15:11 UT on April 4, located in the AR 8933 region (N18 W66). Therefore, the transit time of the shock from the Sun to ACE is 48.82 h and the average transit speed is 843 km s^{-1}. We classify this SEP event as a western event: the observer is magnetically well connected to the central part of the expanding interplanetary shock at the beginning of the event.



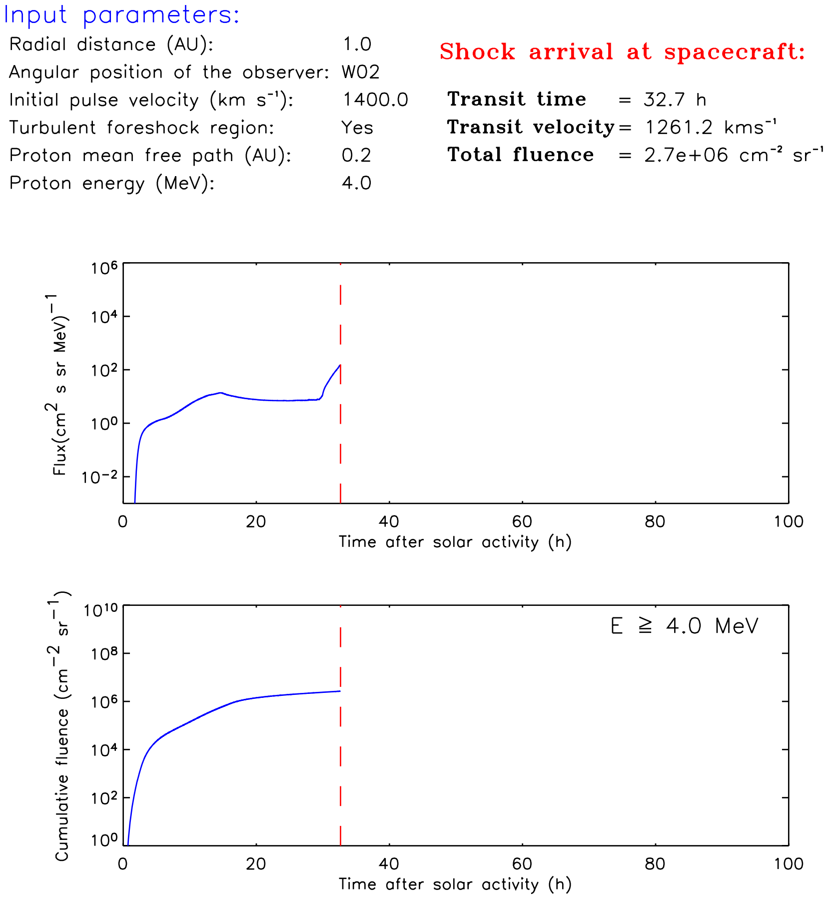
Input parameters:

Radial distance (AU): 1.0
Angular position of the observer: W58
Initial pulse velocity (km s^{-1}): 1340.0
Turbulent foreshock region: No
Proton mean free path (AU): 0.2
Proton energy (MeV): 8.0

Shock arrival at spacecraft:

Transit time = 47.7 h
Transit velocity = 862.4 kms^{-1}
Total fluence = 3.2e+06 cm^{-2} sr^{-1}

Fig. 1. Example of the output display: flux and fluence profiles for 8 MeV protons associated with a shock with an initial speed of 1340 km s^{-1}, for a western SEP event (W58) with the observer located at 1 AU. The dashed vertical line indicates the time of the shock passage.



Input parameters:

Radial distance (AU): 1.0

Angular position of the observer: W02

Initial pulse velocity (km s^{-1}): 1400.0

Turbulent foreshock region: Yes

Proton mean free path (AU): 0.2

Proton energy (MeV): 4.0

Shock arrival at spacecraft:

Transit time = 32.7 h

Transit velocity = 1261.2 kms^{-1}

Total fluence = 2.7e+06 cm^{-2} sr^{-1}

Fig. 2. Example of the output display: flux and fluence profiles for 4 MeV protons associated with a shock with an initial speed of 1400 km s^{-1}, of a central meridian SEP event (W02) with the observer located at 1 AU. The dashed vertical line indicates the time of the shock passage.

To obtain the flux profiles of this event from SOLPENCO, we have taken into account the spacecraft location and the transit time of the shock; hence, the inputs for this event are the following: (1) radial distance: “1”; (2) initial shock speed: “1445”; (3) heliolongitude: “*W*66”; (4) mean free path: “0.2”; (5) existence of turbulence: “*Yes*”; and (6) energy: “0.5” (for example). From the data set of SOLPENCO, we have chosen the initial shock speed that closely matches the transit time for an observer at 1 AU and at W66. With these inputs the code provides ten proton flux profiles, between 88 and 90 MeV. Fig. 3 shows the flux profiles observed by the EPAM instrument (Gold et al., 1998) onboard the ACE spacecraft (dotted lines) and six of the flux profiles obtained by SOLPENCO (solid lines). The energy values, although similar, do not exactly match. Table 1 lists these seven energy intervals of SOLPENCO (top block) and ACE/EPAM (bottom block); top value of each block is the geometric mean of the energy channel, the two bottom values are the minimum and maximum energy of each channel. The arrow in each of the panels of Fig. 3 marks the time of the parent solar activity, and the dashed vertical line the time of the shock passage. The predicted shock transit time is 48.5 h, 19 min shorter than the actual transit time. Comparing the synthetic and observed flux profiles shown in Fig. 3, we can say that SOLPENCO is able to reproduce the peak flux at the shock arrival: it is well fitted for most of the energies (Fig. 3b, c, e and f). Whereas the flux profiles at the high energies (Fig. 3d, e and f) are reasonably well fitted by the synthetic profiles, at low energies they are overestimated (Fig. 3a, b and c). On the other hand, the predicted flux for the highest energy channel (Fig. 3g) is smaller than the observed flux profile.

Despite the simplifying assumptions made to build the synthetic flux profiles, SOLPENCO performs well in predicting the peak fluxes of this SEP event and the flux for the intermediate and high energy channels. The overestimation of the flux at low energies is due to the average values of k and Q_0 used in Eq. (1). SOLPENCO uses $k = 0.5$ for all energies; this value is slightly higher than the values of k assumed to model this event at different energies. In Aran et al. (2004), we run the MHD shock propagation-plus-particle transport model of Lario et al. (1998) and we fit the observed fluxes and anisotropies at different energies. For instance, the simulation yields a value $k = 0.26$ for the 0.25 MeV channel. Since VR decreases from 2.8 to 0.5, from the beginning of the event to the arrival of the shock at ACE (see Aran et al., 2004), the difference between the values of k assumed in the simulation and in SOLPENCO leads SOLPENCO to consider an

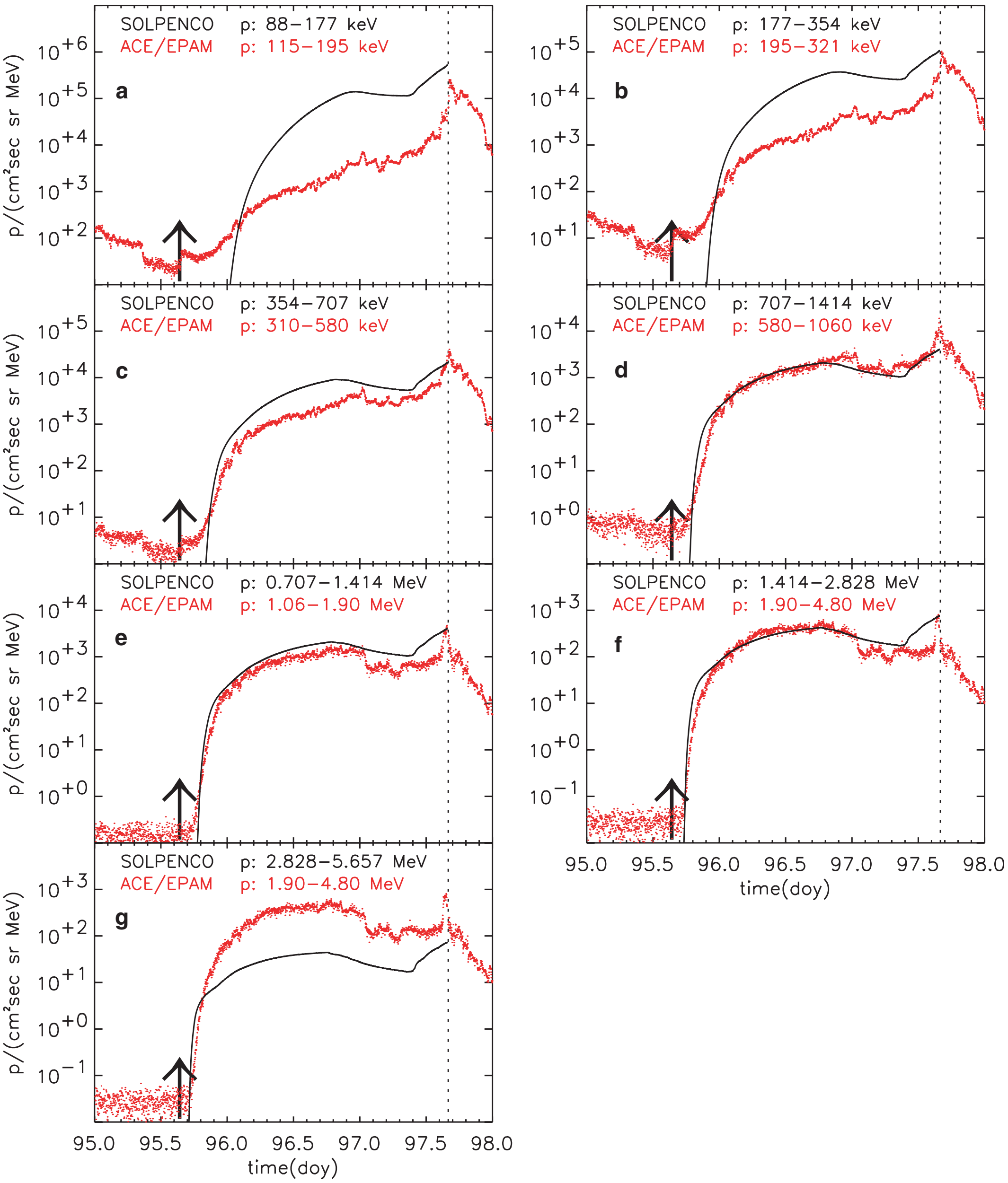


Fig. 3. Flux profiles for the 4–6 April 2000 event. Comparison between synthetic flux profiles produced by SOLPENCO (solid line) and those observed by ACE/EPAM (dotted trace), for seven energy ranges, as indicated in the top of each panel. The dashed line marks the time of the shock arrival at the spacecraft and the arrow indicates the onset of the parent solar activity.

Table 1
Energy (in MeV) channels shown in Fig. 3

Plots	*a*	*b*	*c*	*d*	*e*	*f*	*g*
SOLPENCO	0.125	0.250	0.500	1.000	1.000	2.000	4.000
Energy interval	0.09–0.18	0.18–0.35	0.35–0.71	0.71–1.41	0.71–1.41	1.41–2.83	2.83–5.66
ACE/EPAM	0.150	0.250	0.424	0.784	1.419	3.020	3.020
Energy channel	0.16–0.20	0.20–0.32	0.32–0.58	0.58–1.06	1.06–1.90	1.90–4.80	1.90–4.80

overestimated injection rate of shock accelerated particles at low energy. In addition, for western events the cobpoint slides from the strongest central part of the shock front (the most efficient particle acceleration region) at the onset of the event, to the weaker (less efficient) part of the eastern wing of the shock late in the event. Therefore the extreme changes of VR makes our results sensitive to our selection of k.

A second factor which has an important influence is the initial injection rate, Q_0. The value adopted in SOLPENCO for 0.25 MeV protons is 1.8×10^{-34} cm^{-6} s^3 s^{-1}. While the simulation of the event (applying the shock-plus-particle model) yields 3.7×10^{-35} cm^{-6} s^3 s^{-1}. The combination of these two factors results in a clear overestimation of Q at low energy (a factor 23 at the beginning of the event which reduces to 6 at the shock arrival). These differences largely reduce when comparing energy channels better adjusted. For example, to a factor 5 and 2 at the onset of the event and at the shock arrival, respectively, when comparing the 1 MeV channel of SOLPENCO with the 0.789 MeV channel of ACE/EPAM. Moreover, the underestimation of the flux profile at high energy (Fig. 3g) is an expected result because the flux profile of SOLPENCO is derived for $E > 2.8$ MeV, while the energy channel of ACE/EPAM used for comparison (1.9–4.8 MeV) includes protons of lower energies; the contribution of low energy particles represents a noticeable fraction of the observed flux (a factor 1.5–3, depending on the spectral energy dependence). Note that the observed flux is much better fitted assuming a mean energy of 2 MeV (Fig. 3f).

The dependence of the injection rate of shock-accelerated particles, Q, on the energy can also produce differences between the synthetic and observed flux profiles. SOLPENCO assumes a constant spectral index for the energy dependence throughout the event, which is an over-simplification as derived from modeling this event (Aran et al., 2004). Fig. 4 shows how the spectral index evolves from the beginning of the event up to the shock arrival. It is easy to see that the spectral indices assumed in SOLPENCO are almost the same as those derived from the modeling of this event at the shock arrival ($\gamma = 1.85$ for $E < 2$ MeV and $\gamma = 2.77$ for $E \geqslant 2$ MeV); nevertheless, they are quite different at the beginning of the event ($\gamma = 1.35$ for $E < 2$ MeV and $\gamma = 2.27$ for $E \geqslant 2$ MeV). For the 0.25 MeV energy interval, these variations lead SOLPENCO to use at the beginning of the event a Q-value 2.5 higher than that derived from the modeling. This factor decreases to 1.2 at the shock arrival. It is worth noting that the changes in the spectral index are less relevant than those of the parameters discussed in the previous paragraphs.

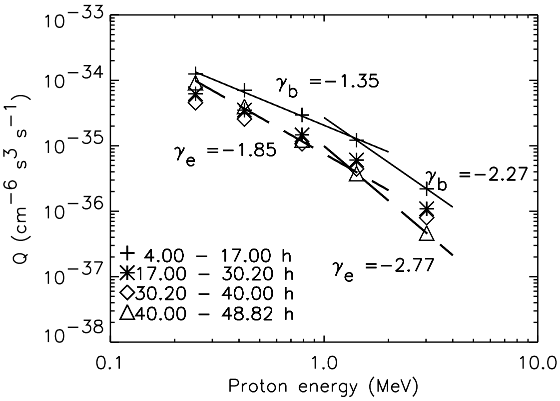


Fig. 4. Spectra of the particle injection rate, Q, as derived from modeling the 4–6 April 2000 event. Each point is the average value of Q over the time interval indicated for each energy channel. The solid line shows the fit at low ($E < 2$ MeV) and at high ($E \geqslant 2$ MeV) energy for the first period and the dashed line shows the fit for the last period (ending at the shock arrival). The values of the spectral index, at the beginning, γ_b, and at the end, γ_e, of the event, derived from the fittings are also shown.

Summing up, the most relevant variables that have to be considered in the validation of SOLPENCO are the values taken for k, Q_0, and the spectral index; the possible time variation of the spectral index during the development of the event, and the scaling factor adopted to express in physical units the flux and fluences of the code.

4. Conclusions

SOLPENCO allows the user to obtain flux and fluence predictions of gradual SEP events originating from the solar western limb to far eastern locations as seen at two heliocentric radial distances: 1 and 0.4 AU. The proton energy channels considered now extend up to 90 MeV, to accommodate the range of energy relevant to space weather purposes. SOLPENCO can provide quick predictions for the proton flux and cumulative fluence profiles for gradual SEP events by interpolating among the 448 scenarios contained in the database at each heliocentric distance. Estimations of the transit time, shock speed and total fluence of the SEP event (measured from the onset of the event up to the shock passage by the observer) are also provided for the selected event. We have started the validation of the outputs of the code by comparing the flux profiles for several SEP events. The main differences between both synthetic and observed profiles arise from the range of energies compared and from the values of the parameters k and Q_0 adopted to compute the injection rate of shock accelerated particles: average values that are not necessarily representative of the possible solar-interplanetary scenarios. As can be seen in different cases (Aran et al., 2004), these values are sensitive to the change of the variables that describe the evolution of the plasma regime at the shock front (specifically VR). Better estimations of the influence of k and Q_0 would be achieved if SEP events were measured by spacecraft at different locations (such as Helios-1, Helios-2, ISEE-3 and IMP-8 missions in the late 1970s and early 1980s). Despite the simplicity of the assumptions, the output flux profiles of SOLPENCO fit well the peak flux for several energy channels in different SEP events. Keeping in mind that there are no two SEP events alike, a statistical validation of SOLPENCO has to be undertaken, comparing its outputs with a large set of SEP events. We are currently working on this task.

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