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Comparing solar energetic particle events from ~ 0.3 AU to ~ 1 AU

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Abstract. Proton fluxes recorded in the energy range ~ 4 MeV - 40 MeV by Helios and IMP-8 spacecraft (SC) during 1974-1978 are used to analyze several solar energetic particle (SEP) events. In particular, the problem of the flux radial dependence is faced, by selecting events for which at least two SC have nominal magnetic footpoints within 20° in heliographic longitude. For each event, the data were previously calibrated by comparing measurements from channels with equivalent energy aboard the different space vehicles. Results for the radial dependence between ~ 0.3 AU and ~ 1 AU provide a realistic scaling of SEP fluxes at Mercury orbit.

1. Introduction

The Sun emits transient fluxes of nonthermal particles in the interplanetary space, ranging from suprathermal to relativistic energies. Solar energetic particles (SEPs) have been routinely detected by space vehicles since the descending phase of the 19th solar cycle and, before that time, only relativistic solar proton events were identified at the Earth (ground level enhancements since 1942; Forbush 1946). It is believed that the most powerful sources of SEP fluxes observed at 1 AU are flares and shock waves driven by fast coronal mass ejections (CMEs). Flares are known to provide efficient particle acceleration, as inferred from gamma-ray, hard X-ray and microwave observations. CME driven shock waves are thought to accelerate electrons and ions within a large volume of the corona and interplanetary space during SEP events.

Energetic particle measurements mostly identified two solar particle populations (called gradual and impulsive events) also in terms of their abundances, ionization states, and time and longitude distributions (Reames 1999). Nevertheless, a more complex scenario was underlined by Kocharov & Torsti (2002). To notice that all major SEP events associated with fast CMEs are also accompanied by solar flare occurrences.

SEP event profiles depend on the heliographic distance at which they are recorded. Their radial dependence is a fundamental issue to understand the conditions for both particle propagation in the interplanetary space and particle acceleration at the front of the propagating interplanetary shocks. Moreover, the knowledge of the expected SEP fluxes at a given radial distance allows to investigate not only their interaction with planets but also the SEP impact on interplanetary missions traveling into the inner solar system (such as Messenger and BepiColombo).

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Most of the available SEP data bases consist of measurements made on spacecraft (SC) orbiting near the Earth; only limited data exist at radial distances (R) of ~ 0.3-1.0 AU. Hence, a great amount of the performed SEP analyzes are based on data recorded at 1 AU (and near the ecliptic plane) and their extrapolation to other positions in the heliosphere by using transport models. Shea et al. (1988), for example, proposed to estimate SEP fluxes by using the diffusive transport model reported by Hamilton (1988). In particular, they suggested that to extrapolate proton fluxes from R = 1 AU to R < 1 AU, the functional dependence $R^{-\alpha}$ (with α ranging from 3 to 2) should be used for the proton flux. Later on, Ng & Reames (1994) deduced an R^{-3} dependence by performing numerical calculations able to follow the spatial and temporal evolution of the particle spectra. Reames & Ng (1998) confirmed this theoretical result for 3-6 MeV protons from Helios-1 and 2 and 4.2-8.7 MeV protons from GOES. In general, attempts to use multiple SC data to estimate the SEP radial gradient for individual events are complicated by the different longitudes of the space vehicles. This means that the longitudinal separation existing between the solar active region (at the origin of the SEP event) and the footpoint of the field line connecting each SC with the Sun produces an additional gradient (longitudinal gradient).

Performed work demonstrated that SEP event measurements are generally consistent with an α dependence that is rigorously predicted by the diffusion theory (Zwickl & Webber 1977; Mason Reames & Ng 1991; Reames Barbier & Ng 1996), if shock peak fluxes are excluded from the analysis.

Recently, Lario et al. (2006) found that the SEP radial dependence is less steep than the one deduced from the diffusion transport model to extrapolate SEP fluxes from R=1 AU to R < 1 AU. The radial distribution of SEP events observed by at least two SC shows ensemble-averaged variations ranging from $R^{-2.7}$ to $R^{-1.9}$ for 4-13 MeV and 27-37 MeV proton peaks flux.

In this paper we examine the available proton fluxes for several SEP events recorded during 1974-1978, to explore the SEP maximum flux variation with the radial distance for different proton energies in the whole range of ~ 4-40 MeV. We selected SEP events recorded by Helios-1, Helios-2 and IMP-8 when at least two SC were located on the same line of the magnetic connection with the Sun, to avoid the contribution given by the longitudinal flux gradient. We also face the problem of calibration between data coming from different space vehicles, being otherwise affected the radial gradient evaluation.

2. Database

We use 1-h averaged data from the two Helios SC (whose heliocentric radial distances are included in the R range of ~ 0.3-1.0 AU) and the 5-min averaged data from the Earth-orbiting spacecraft IMP-8 (with R ~ 1 AU). Helios-1 and Helios-2 particle data were obtained by the Identical cosmic-ray instruments of the University of Kiel (Kunow et al. 1977). The IMP-8 data were recorded by the Charged Particle Measurement Experiment (CPME) (Sarris et al. 1976).

The proton channels P1, P2 and P3 of the University of Kiel experiments correspond to a nominal energy range of 4-13 MeV, 13-27 MeV and 27-37 MeV, respectively; proton channels P5, P7 and P8 of CPME aboard IMP-8, to a nominal energy range of 4.6-15 MeV, 15-25 MeV and 25-48 MeV, respectively. Hereafter, we will refer to the different channels with comparable energy between Helios-1/2 and IMP-8 as three single equivalent ones (ch1, ch2, and ch3).

The 1-h averaged spacecraft trajectories data of Helios-1 and Helios-2 were provided by http://nssdcftp.gsfc.nasa.gov/. When those data were not available and for the IMP-8 ones, we used the 1-day averaged trajectory data coming from http://cohoweb.gsfc.nasa.gov/.

The following parameters are used for each spacecraft:

- R, the radial distance from the Sun to the SC;

- ϕ_{sc}, the heliographic inertial longitude of the SC, as defined by Burlaga (1984);

Table 1. The selected SEP events.

Event N.	Event date dd/mm/yy	SC	R [AU]	SC	R [AU]
1	22/12/74	Helios-1	0.98	IMP-8	0.99
2	27/12/77	Helios-2	0.90	IMP-8	0.98
3	01/01/78	Helios-2	0.93	IMP-8	0.98
4	13/02/78	Helios-2	0.96	IMP-8	0.99
5	28/03/76	Helios-2	0.51	IMP-8	1.00
6	28/04/78	Helios-1	0.29	IMP-8	1.01

- ϕ_{foot}, the heliographic inertial longitude of the footpoint of the magnetic field line connecting each SC with the Sun;

- ϕ_{fl}, the heliographic inertial longitude of the flare site.

To compute the nominal footpoint of each SC on the Sun, we assumed a Parker spiral for the interplanetary magnetic field configuration, with a constant solar wind speed of 450 km/s. The time for the interplanetary shock passages at Helios-1 and Helios-2 were taken from Volkmer & Neubauer (1985). Finally, the SEP association with specific solar flares was based on either previous works or on the temporal coincidence with intense solar flares listed in the Solar Geophysical Data (SGD).

3. The selected SEP events

To infer the radial dependence of the particle peaks flux for R < 1 AU, we restricted our SEP event selection to those for which the nominal footpoints of at least two of the three space vehicles were close in longitudinal distance. Thus, we selected SEP events satisfying the following conditions:

1. at least two of the three SC were operative throughout the event, i.e., with a good data coverage to allow the identification of the peak flux.
2. the considered event was isolated from others that might have contributed to the peak flux.
3. the nominal footpoints of at least two SC were less than 20° apart.

Before proceeding with the analysis of the selected events, we considered another group of events in order to obtain a first intercalibration between Helios-1 or Helios-2 data and IMP-8 ones. For this auxiliary group we added another requirement:

4. The radial distance of the SC from the Sun should be close to 1 AU.

Table 1 lists the selected SEP events, and their principal characteristics, i.e.:
- column 1: the SEP event number;
- column 2: the date (dd: day; mm: month; yy: year) of the SEP onset;
- column 3: the first spacecraft used;
- column 4: the heliocentric radial distance of the first SC;
- column 5: the second spacecraft used;
- column 6: the heliocentric radial distance of the second SC.

We first analyzed events 1 to 4 for the data calibration of the different SC; then we derived the radial dependence of the particle peak flux for R < 1 AU by using all the events listed in Table 1.

4. Data calibration

As stated in Sect. 3, we compared SEP events in each nearly equivalent energy channel (ch1, ch2, and ch3) when the Helios-1 or Helios-2 SC were close to IMP-8 both in heliographic distance (~ 1 AU) and in the footpoints longitude separation (less than 20° apart).

Fig. 1 shows, as an example, the SEP event N. 1, recorded by the ch1 proton channel on both Helios-1 and IMP-8 at ~ 1 AU. A similar trend can be seen for the SEP event from both SC. Inspection of Fig. 2, reporting SEP event

Table 2. Proton data calibration for the three energy channels.

SC-Number	Name	ch1-Energy [MeV]	ch2-Energy [MeV]	ch3-Energy [MeV]
SC-1	Helios-1/2	4.0-13	13-27	27-37
SC-2	IMP-8	4.6-15	15-25	25-48
Ratio	SC-1/SC-2	2	1	2

N. 2 for the same energy channel, suggests that the IMP-8 P5 channel is saturated; thus, the recorded peak flux of the event could be lower than the real one. Hence, we considered this channel not valid for data calibration as far as SEP event N. 2 is concerned. Generally, by using all the channels from SEP events N. 1 to N. 4, we determined the ratio between the peak fluxes, as observed by the instruments aboard Helios-1/2 and IMP-8 SC. Table 2 lists such ratio for the three proton energy channels.

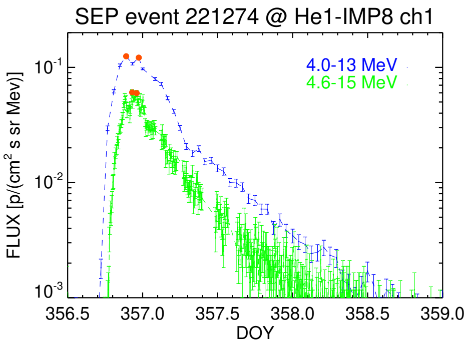

Fig. 1. 1-min average of the 4-13 MeV and 5-min average of the 4.6-15 MeV proton channels as measured by Helios-1 (blue line) and IMP-8 (green line) respectively, for the 22 December 1974 SEP event. Red dots are used points to perform the data calibration.

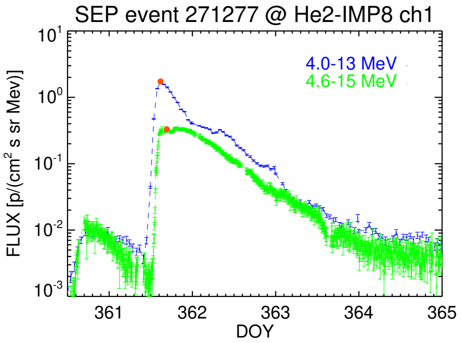

Fig. 2. As in Fig. 1 for the 27 December SEP event. Red dots indicate the peaks flux.

5. Radial dependence derived for the proton flux

The relevance of the performed data calibration can be checked in the following. The SEP event N. 6 (see Fig. 3 and Table 1) was used as a case study to derive the radial dependence of the event peak flux (points A in Fig. 3). Fig. 4 shows the proton flux (dots) for the three energy channels before (ch) and after (cch) the application of the calibration factor derived in section 4. The obtained α parameter resulted to be 2.4 (ch1), 1.7 (ch2) and 2.5 (ch3) before the data calibration and 1.8 (cch1), 1.7 (ch2) and 1.9 (cch3) after it.

The above case study was based only on two data points (from Helios-1 and IMP-8) for each energy channel. The obtained small variability, from one channel to the other, of the α parameter (0.2) suggests that the functional radial dependence could be the same for solar protons in the whole considered energy range. To check this possibility, data from the six selected SEP events were considered together. To notice that data from ch2 and ch3 of SEP event N. 1 could not be used because no clear event effects have been found (low energy event) while for SEP event N. 6 two points for each channel were selected (see red dots in Fig. 3). Hence, an ensemble of 38 data points (19 points for IMP-8 and 19 for Helios SC at different positions) was used to evaluate the relationship between the proton *flux ra-*

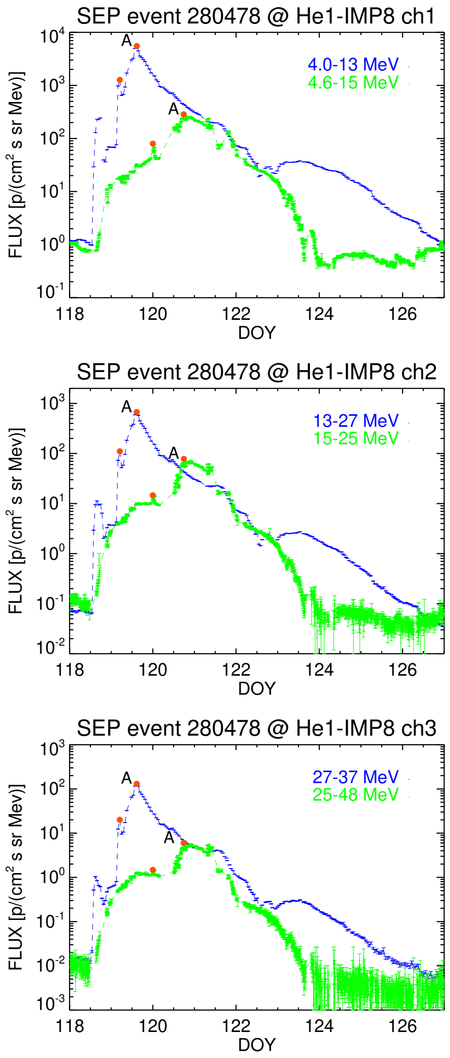

Fig. 3. 1-min average and 5-min average of the three proton channels as measured by Helios-1 (blue line) and IMP-8 (green line) respectively, during the 28 April 1978 SEP event. Red dots indicate the points used to compute the proton flux variation with the radial distance (Fig. 5). Red points labeled by 'A' refer to those used in Fig. 4

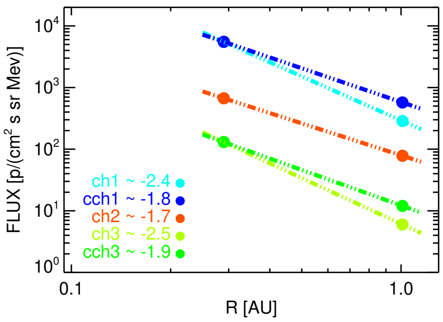

Fig. 4. Proton peak flux dependence with the radial distance for the 28 April 1978 SEP event, for the three channels before (ch) and after (cch) the calibration.

tio (F[SC-1]/F[SC-2]) and the radial *distance ratio* (R[SC-1]/R[SC-2]). Fig. 3 shows the obtained plot in logarithmic scale. To notice that while most of the data points cluster together (in fact, there is a clear data overlay) the points labeled by 5S are outside the linear trend. This is because the maximum flux of the SEP event N. 5 might be underestimated due to saturation in the three IMP-8 channels. Such feature can be derived also observing that the computed *flux ratio* is decreasing with the increasing of the proton energy, but it is always above the line connecting the other data points in Fig. 5. Also ch1 of the SEP event N. 2 (see IMP-8 data reported in Fig. 2) is above the line.

To recover this data point, the mean *flux ratio* in a not IMP-8 saturated region (but before the declining phase of the event) was evaluated (data point labeled as 2 in Fig. 5). As can be seen in Fig. 5 the evaluated data point 2 moves to the right place in the scatter plot.

The final result showed that the derived radial dependence was the same ($\alpha = 1.7$) for the three channels, when data from SEP event N. 5 were excluded.

6. Conclusion

Several SEP events recorded during 1974-1978 onboard Helios and IMP-8 SC were analyzed by using similar proton energy channels. The variable (∼ 0.3-1 AU) heliocentric radial distance of the Helios SC, compared to the stable IMP-8 one, allowed to compare the same SEP event at different radial distances. Only SC positions whose the nominal footpoints are within 20° apart were considered in order to

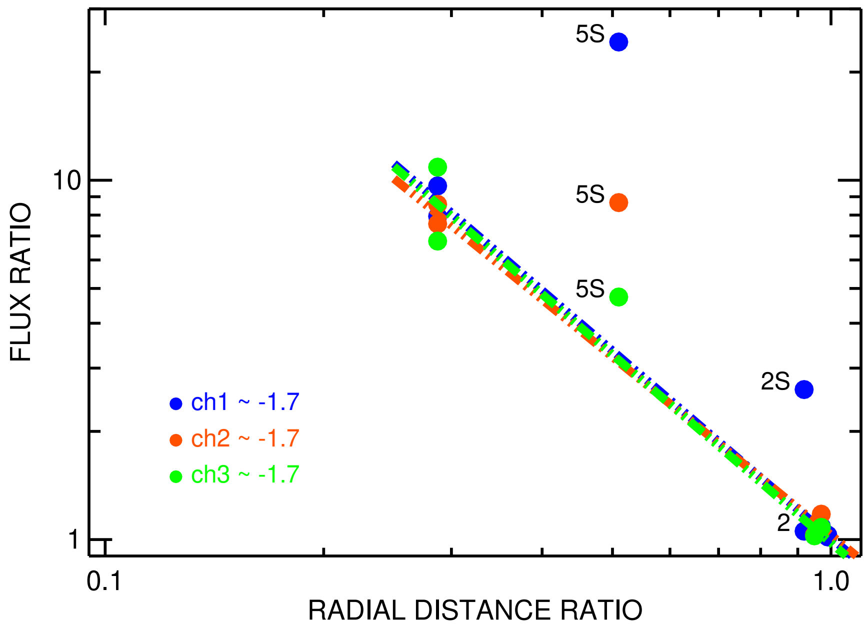

Fig. 5. Calibrated peak flux ratio as function of the radial distance ratio, for all the channels and SEP events. Labels '5S' are used for SEP event N. 5 (IMP-8 data saturated) and '2S' for ch1 of SEP event N. 2 (IMP-8 data saturated), while '2' for the derived mean flux ratio, outside the IMP-8 saturated region.

avoid the longitudinal flux gradient and to focus on the radial flux dependence.

We confirm Lario et al. (2006) finding that the radial flux dependence is less than the one recommended in the past by Shea et al. (1988). Moreover, we show that with an appropriate data calibration the functional parameter to be used for a realistic scaling of SEP fluxes at the Mercury's orbit is α = 1.7 for the investigated proton energy range. This implies that for SEP events the maximum proton flux in the whole energy range of ~ 4-40 MeV should be at Mercury around ten times higher than at the Earth's orbit.

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