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SEP spectra derived from neutron monitor data and from EPHIN space detector data during recent GLEs and sub-GLEs

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Abstract
The Electron Proton Helium Instrument (EPHIN) aboard the Solar Heliospheric Observatory (SOHO) observed several SEP events with protons accelerated to energies E>500 MeV, whereas no neutron monitor (NM) of the worldwide network showed a significant increase in their counting rate. For instance, the SEP event on 8 November 2000 with maximum proton intensity at 500 MeV of >0.1 $(cm^2\ s\ sr\ MeV)^{-1}$ is outstanding, as this maximum proton flux is comparable with the GLEs on 14 July 2000 and on 15 April 2001 (max. count rate increase in 5-min data of 225% at South Pole NM). In a first step we applied a forward modelling approach of the SEP event on 8 November 2000, i.e. we computed the expected NM count rate increases for selected NM stations, utilizing as input parameters the SEP spectra determined from EPHIN data as well as anticipated pitch angle distribution and apparent source direction. The simulated count rate increases for selected NM stations showed that this SEP event should have be seen as a clear GLE. To further understand this situation, we investigated in a next step recent GLEs and sub-GLEs. Consequently, a total of four SEP events were selected, two clearly identified GLEs and two sub-GLEs. We performed a "GLE analysis" based on the data of the worldwide network of NMs for each of the four SEP events and then compared the derived SEP spectra with the proton spectra as determined from EPHIN measurements.

1. Introduction

When solar energetic particles (SEPs), which originate either from a solar flare or are accelerated by shock waves associated with coronal mass ejections (CMEs), are detected at Earth by ground based cosmic ray detectors (neutron monitors (NMs)) then such an event is called GLE, for Ground Level Enhancement or Ground Level Event. Since the first observation of a GLE in 1942 a total of 72 GLEs have been observed, i.e. about one GLE per year. The occurrence rate of SEP events is much higher. More than 20 SEP events may be observed per year during years with high solar activity. Recently, Kühl et al. (2017) investigated 42 SEP events between 1995 and 2015 with protons accelerated to energies $E > 500$ MeV based on measurements of the EPHIN instrument onboard SOHO. NMs at sea level and at high latitude with magnetic cutoff rigidity, Rc, ≤ 1 GV, are sensitive to primary cosmic ray protons with energies $E > 500$ MeV. The atmospheric cutoff energy of the

KIEL-UP • 10.38072/2748-3150/p11

polar, high altitude NM stations SOPO (2820 m asl) and DOMC (3233 m asl) is ~300 MeV. Therefore, many of the 42 SEP events, investigated by Kühl et al. (2017), should have been observed also by the NM network, mainly if the SEP spectrum is not too soft at energies E > 500 MeV, i.e. at energies where NMs become sensitive. On 8 November 2000 an outstanding large SEP event occurred which was observed by EPHIN (Kühl et al. 2017) and by detectors on GOES at energies E > 700 MeV (Thakur et al. 2016), but by none of the NMs of the worldwide network. The maximum intensity during this SEP event at 500 MeV was larger than 0.1 $(cm^2\ s\ sr\ MeV)^{-1}$ which is comparable with the GLEs on 14 July 2000 (max. NM increase in 5-min data of almost 60% at South Pole NM) and on 15 April 2001 (max. NM increase in 5-min data of 225% at the South Pole NM).

In a first step we applied a forward modelling of the SEP event on 8 November 2000, i.e. we computed the expected count rate increases for selected high latitude NM stations. As input parameters we used the SEP spectrum as derived by Kühl et al. (2017) based on EPHIN measurements, as well as, an anticipated pitch angle distribution and an apparent source direction which corresponds to the direction of the interplanetary magnetic field during this SEP event. Our analysis showed that the simulated NM count rates led to a clear increase during the SEP event of 8 November 2000, mainly at high latitudes (> 100%). However, the actual NM measurements did not demonstrate such a behaviour. As a result, we further analysed in a next step two recent GLEs (GLE71 & GLE72) and two sub-GLEs (events on 2013-03-07 & 2014-01-06) (Poluianov et al. 2017) based on NM data, comparing the obtained SEP spectra from this analysis with the spectra derived from EPHIN data by Kühl et al. (2017).

2. Analysis

2.1 EPHIN detector

The Electron Proton Helium Instrument (EPHIN) on board the ESA/NASA spaceprobe SOHO is part of the COSTEP (Comprehensive Suprathermal and Energetic Particle Analyzer) experiment that studies the suprathermal and energetic particle populations of solar, interplanetary, and galactic origin. EPHIN is a telescope for the measurement of energy spectra of electrons from 250 keV to more than 8.7 MeV and of hydrogen and helium isotopes from 4 MeV/nucleon to more than 53 MeV/nucleon. Charged particles are registered in the sensor by ionisation. The EPHIN sensor consists of a semiconductor stack with five layers. They are enclosed by different detectors operating as anticoincidence system (Müller-Mellin et al. 1995). Kühl et al. (2015) showed that EPHIN is capable to measure proton energy spectra up to 1 GeV. However, the EPHIN channels at energies above ~800 MeV may be corrupted by the contribution of electrons (Kühl et al. 2017). Therefore, SEP spectra derived from EPHIN are only reliable up until 800 MeV. For penetrating particles the EPHIN detector has an angle of aperture of about 65°. Nominal the symmetry axis of EPHIN has an angle towards the Sun of 45° along the nominal Parker spiral. Due to technical problems, SOHO is rotated since 2003 several times per year within a few hours by 180°. As a consequence, EPHIN is looking with an angle of 90° to the Parker spiral but still in the ecliptic plane for some months. The data on this roll maneuver are listed under: https://soho.nascom.nasa.gov/data/ancillary/attitude/roll/nominal_roll_attitude.dat (last accessed April 13, 2021).

The determination of the SEP spectra in the work of Kühl et al. (2017) is taking place as follows: for each SEP event a two hours time interval (due to the statistical limitations of the EPHIN data) is selected, with the start of this two hour time interval being 30 minutes after the SEP onset, so that the different travel times of lower (100 MeV) and higher (1 GeV) proton energies are considered.

2.2 GLE analysis with neutron monitor data

Neutron monitors can be used to determine the SEP characteristics (proton spectra, pitch angle distribution, direction of anisotropy) during a GLE in the energy range ~500 MeV – 15 GeV. For this analysis, the NM count rate increases are computed by assuming an SEP spectrum, pitch angle distribution, and apparent source direction. By a trial and error procedure the SEP characteristics

KIEL-UP • 10.38072/2748-3150/p11

are determined by changing the different parameters to minimize the difference between simulated and measured NM count rate increases (for details see, e.g., Smart, Shea, & Tanskanen 1971; Debrunner & Lockwood 1980; Bütikofer & Flückiger 2015; Mishev et al. 2018).

The definition of a GLE specifies that an observed SEP event is registered as a GLE when the count rates of at least two differently located NMs observe a significant increase, with at least one NM being located near sea level (Poluianov et al. 2017). One should note that in the GLE definition there are no restrictions given, concerning the time resolution of the investigated count rate increases. Typically the sampling interval in the GLE analysis is in the order of a few minutes up to about half an hour. This is because the duration of the interesting part of a GLE as measured with NMs lasts up to a few hours. However, in the present analysis, which is driven by the 2-hour averaged EPHIN values, it is mandatory to compare with NM data with identical time resolution, i.e. the “GLE analysis”, carried out in this work utilized a 2-hour time interval. As expected, the statistical errors of a 2-hour NM count rate is by about a factor five lower as for a 5-minute value, hence, much smaller count rate increases may be statistically significant. On the other hand, an SEP is defined as sub-GLE when at least two high altitude, high latitude NM stations at different locations measure a simultaneous, significant count rate increase, with no near sea level NM station recording a significant count rate increase (Poluianov et al. 2017). It is self-explanatory that the results of a *GLE analysis* where only two NM stations observed a significant count rate increase is afflicted by large uncertainties.

2.3 Investigated SEP events

The SEP event on 8 November 2000 was associated with an M7.4 class solar flare with onset at 22:42 UT and was produced at N10W77 (Lario et al. 2003; Agueda et al. 2012). LASCO onboard SOHO identified a wide (>170°) and fast (1738 km/s) CME at 23:06 UT[1]. These eruptive events were further associated to a type III radio burst starting at 22:55 UT (see Cane, Erickson & Prestage 2002), as well as, an intense type II burst that was identified extending from metric to decametric radio waves, starting at ~23:15-23:20 UT (Agueda et al. 2012). As a result, the SEP event on 8 Novenber 2000 was driven by a set of complicated and strong eruptive events. A clear increase of this SEP can be identified up until >700 MeV in GOES/HEPAD; however, this SEP event was not seen by any of the NMs of the worldwide network.

To check possible differences between the SEP spectra as derived by EPHIN and by NM measurements, we further investigated four recent SEP events that were observed by the NM network as GLEs or as sub-GLEs. In particular, in chronological order we investigated: sub-GLE on 7 March 2012, GLE71 on 17 May 2012, sub-GLE on 6 January 2014, and GLE72 on 10 September 2017.

According to the official sub-GLE definition (Poluianov et al. 2017), the SEP event on 7 March 2012 is not a sub-GLE as this event was significantly seen in the 5-minute count rates only by the high altitude NM station South Pole with maximal relative count rate increase of ~3% in the 5-minute data (Mishev et al. 2017). However, one should note that the Dome C NMs started operating only in February 2015. As a result, it can be assumed that Dome C would have seen this SEP event as well. Therefore this SEP event is listed as a sub-GLE in the official GLE database, hosted and managed by the Oulu Cosmic Ray Station of the University of Oulu, Finland (Official GLE database 2014 | https://gle.oulu.fi/).

On 17 May 2012 GOES observed a moderately strong M5.1 class flare at 01:25 UT. The Earth was well connected to the active region at the Sun (N07 W88). Near 01:50 UT the worldwide network of NM detected a clear enhancement with maximum relative count rate increase in the 5-minute data of about 17% at South Pole NM station. The near sea-level, high latitude NM stations Apatity and Oulu were in excellent positions for this event with a rapid count rate increase of ~15% (Papaioannou et al. 2014). Further high-latitude NM stations measured a count rate of maximal 4% in the 5-minute data (e.g. Pewanuck, Thule, Fort Smith, Terre Adelie, Kerguelen, Inuvik). This event is labeled as GLE71 and is a GLE with a quite short duration. The time to the half-maximum of the count rate increase is significantly less than one hour. The increased NM count rates remained above background during about 2 hours.

1 https://cdaw.gsfc.nasa.gov/CME_list/sepe/ (last accessed April 13, 2021).

KIEL-UP • 10.38072/2748-3150/p11

The SEP event on 6 January 2014 occurred during a period of active Sun and during disturbed geomagnetospheric conditions. The C2.1 class flare was located behind the west limb (> W90) (whose emission was therefore most probably underestimated) was registered at 07:55 UT and a Halo and fast (1402 km/s) CME, that was marked at 08:00 UT, were the drivers of this SEP event. Typical to such active situations, a type III burst was marked at around 07:50 UT and a type II were clearly identified starting at 07:45 UT (at metric radio waves)[2]. A non-null response was observed only by the South Pole NMs (SOPO, the common NM with lead producer and the bare NM SOPB, i.e. NM without lead producer) with maximum relative count rate increase in the 5-minute values of about 3%.

Close to the end of solar cycle 24, i.e. a period with low solar activity, an interval of high solar activity occurred between 4 and 10 September 2017. A large number of bright eruptions were observed, including four associated with X-class flares. The X8.2 solar flare on 10 September 2017, peaking at 16:06 UT, situated behind the western limb (> W90), was linked to an abnormaly fast (3163 km/s) CME, giving rise to a strong SEP event measured by near-Earth spacecraft. This western limb event triggered also GLE72 with an onset at about 16:10 UT, which occurred however, during the decaying phase of a major Forbush decrease (FD) (Belov 2009) that started on 8 September 2017 and lasted for several days. The maximum relative count rate increase in the 5-minute values at the Dome C NM station was about 10%, whereas it was only about 5% at the South Pole NM. GLE72 was observed by more than 10 high latitude NM stations with count rate increases between ~2-5% in the 5-minute data.

3. Results

3.1 Backward modelling of GLEs & sub-GLEs

For the “GLE analysis” in this investigation, the data of 30-40 NM stations were available for each SEP event. The number of NM stations that observed a significant count rate increase is one NM station for the two sub-GLEs and ~15-20 NM stations for the GLEs, under investigation. However, it must be noted that also the data of NM stations with no significant count rate increase give important information for the determination of the SEP spectrum, mainly the NM stations at high geomagnetic latitudes. Figure 1 depicts the obtained rigidity spectra for the selected four SEP events as determined by Kühl et al. (2017) based on EPHIN measurements and as based on NM data of the worldwide network. The derived rigidity spectra were computed in each case for a two hours interval that starts 30 minutes after the SEP event onset. Mishev et al. (2014) investigated the sub-GLEs on 2013-03-07 and on 2014-01-06 based on NM data. Their results are shown in Figure 1 together with the spectra derived by Bütikofer within this analysis. For GLE71 the rigidity SEP spectra were investigated based on NM data by different groups (Balabin et al. 2013; Apatity/IZMIRAN, http://pgia.ru:81/cosmicray/GLE/ 2012, last accessed April 7, 2021; Kuwabara et al. 2013; Mishev et al. 2014; Plainaki et al. 2014), the results are shown in the top right graph of Figure 1 for selected time intervals (see the legend in the top right graph). The spectra derived from the NM data show the SEP intensity in the direction of the largest solar proton flux (direction of anisotropy), whereas the spectra based on EPHIN data correspond to the average fluence in the direction in which EPHIN was looking during the corresponding SEP event. Thereby, the expectation is that the SEP fluence derived from NM data should be larger than the corresponding value deduced from EPHIN measurements. However, it must also be considered that with the starting time of 30 minutes after the SEP onset and the two-hour length of the time interval, the SEP flux may already be quite isotropic and thus the expected difference in the SEP spectra derived from EPHIN and NM data could vanish. Figure 1, shows that the best agreement of the simulated NM count rate increases to the measured ones were achieved for: (a) a pure power law in rigidity for the two sub-GLEs and (b) a modified power law for the two GLEs, investigated in this work.

2 http://secchirh.obspm.fr/spip.php?page=survey&hour=day&survey_type=4&dayofyear=20140106 (last accessed April 13, 2021).

KIEL-UP • 10.38072/2748-3150/p11

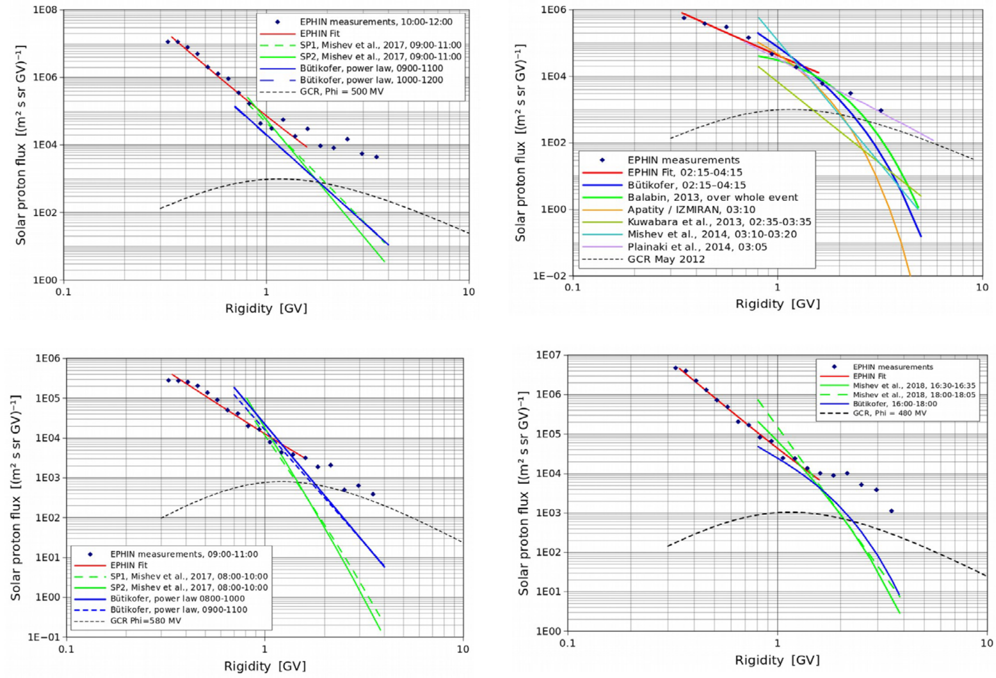

Figure 1: SEP rigidity spectra as derived from EPHIN measurements (dark blue diamonds with fits (red lines) up to 800 MeV) and determined based on NM data. **Top left:** sub-GLE on 2012-03-07, **top right:** GLE71 on 2012-05-07, **bottom left:** sub-GLE on 2014-01-06, and **bottom right:** GLE72 on 2017-09-10. For details see the text.

3.2 Significant count rate increases in hourly NM data

The plotting of hourly count rates of the NM data available during the two sub-GLEs and the two GLEs instead of higher time resolutions made apparent that more NM stations measured a significant count rate increase. Figure 2 shows as an example the relative hourly count rates of the high latitude NM stations Kerguelen, South Pole, Inuvik, and Fort Smith for 6/7 March 2012. The geomagnetic cutoff rigidity at all these four NM stations is below the respective atmospheric cutoff rigidity. The red vertical dashed line at 2012-03-07 09:00:00 gives the onset time of the SEP event in the hourly values. From figure 2 one may assume that the sub-GLE on 7 March 2012 has to be upgraded to a GLE, i.e. the data of NM stations fulfil the GLE criterion. However, Figure 2 should be treated with caution, since it is unclear if the cause of the increased count rates are indeed SEPs, as in some NM stations this raised measured cosmic ray intensity lasted for several hours. This is atypical for SEP events at the energies where NMs are sensitive. In addition, clear count rate increases were observed also at some mid-latitude NM stations as e.g. the two Moscow NM stations MCRL and MOSC with a maximum increase of about 2% in the hourly data. In fact many of the NM stations of the worldwide network showed a tendency of increasing count rate starting around beginning of 7 March 2012 which may be the pre-increase of galactic cosmic rays as it is often observed in advance of FDs (Leerungnavarat, Ruffolo, & Bieber 2003). That said, late on 7 March 2012, i.e. about one day after the SEP occurrence, a considerable FD of maximum NM count rate decline by more than 10% started.

4. Conclusions

The comparison of the derived SEP rigidity spectra as determined by Kühl et al. (2017) based on EPHIN data and as computed based on NM data by different groups does not show large discrepancies in all four SEP events investigated in the present analysis. These results show that EPHIN and

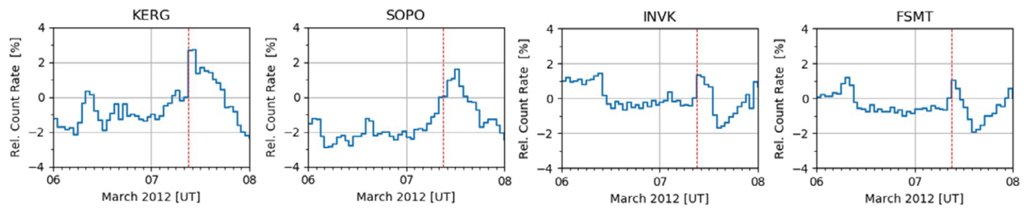

Figure 2: Relative hourly count rates of the NM stations Kerguelen (KERG), South Pole (SOPO), Inuvik (INVK), and Fort Smith (FSMT), for 6-7 March 2012. The red vertical dashed line at 2012-03-07 09:00:00 indicates the onset time in the hourly values at most NM stations.

NM data as well as the data analysis seem to result in reliable outcomes. However, this does not answer why the large SEP on 8 November 2000 was seen by EPHIN but not by the worldwide NM network. It must be investigated, if the SEP flux during that event was very anisotropic over a long time duration and if the direction of the anisotropy was not covered by the asymptotic directions of the high latitude NM stations in operation during this SEP event. Another explanation may be the greater height above the Sun of the CME formation which reduced the efficiency of the particle acceleration and therefore resulted in a steeper spectrum above 700 MeV (Thakur et al. 2016). As a consequence, the polar NMs would in this case not detect enough SEPs to observe a significant count rate increase. So far the GLE definition (Poluianov et al. 2017) does not give a criterion on the time resolution of the NM data. Based on this study, the question arises whether the GLE definition should be adapted in this regard.

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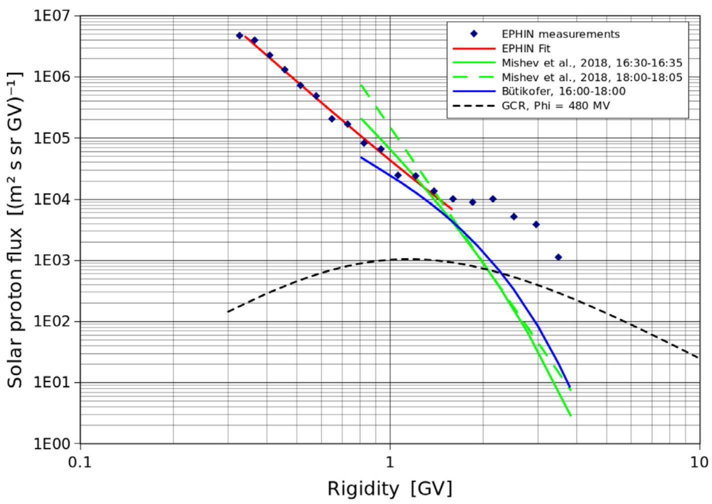
Questions and answers

Ilya Usoskin: In one of the last plots, EPHIN data above 1 GV shows a strange bump (GLE 72)



Answer: Kühl et al. (2017) pointed out that the electron contribution to the proton spectrum is negligible below about 500 MeV and is less than 20 % in the energy range between 500 and 800 MeV, but the proton energy bins above 800 MeV can be corrupted by electrons. Therefore, proton intensities >500 MeV should not be considered during SEP events.

Alexander Mishev: Just a comment. This maverick GLE on 8 November 2000 can be very anisotropic.
Answer: The SEP on 08.11.2000 was not observed by any NM station and therefore it is neither a GLE nor a sub-GLE.

James Ryan: What was the connection for the 8 November 2000?
Answer: The source is W77, thus it was a well-connected event.

Alexander Mishev: Did you try all apparent source position posibilities for the maverick event?
Answer: No, not yet. We plan to make a more comprehensive analysis of the SEP event on 8 November 2000 as well as of the other SEP events investigated in this study.