Galactic cosmic ray hydrogen spectra and radial gradients in the inner heliosphere measured by the HELIOS Experiment 6

J. Marquardt and B. Heber

Christian-Albrechts-Universität zu Kiel, Germany
e-mail: marquardt@physik.uni-kiel.de

Received 6 March 2019 / Accepted 24 April 2019

ABSTRACT

Context. The HELIOS solar observation probes provide unique data regarding their orbit and operation time. One of the onboard instruments, the Experiment 6 (E6), is capable of measuring ions from 4 to several hundred MeV nucleon$^{-1}$.

Aims. In this paper we aim to demonstrate the relevance of the E6 data for the calculation of galactic cosmic ray (GCR), anomalous cosmic ray (ACR), and solar energetic particle (SEP) fluxes for different distances from the sun and time periods.

Methods. Several corrections have been applied to the raw data: determination of the Quenching factor of the scintillator, correction of the temperature dependent electronics, degradation of the scintillator as well as the effects on the edge of semi-conductor detectors.

Results. Fluxes measured by the E6 are in accordance with the force field solution for the GCR and match models of the anomalous cosmic ray propagation. GCR radial gradients in the inner heliosphere show a different behaviour than in the outer heliosphere.

Key words. Sun: heliosphere – solar-terrestrial relations – cosmic rays

1. Introduction

In October 2011, the European Space Agency (ESA) announced the selection of Solar Orbiter as one of the Cosmic Vision M missions, with the launch envisioned for 2019/2020. On August 12, 2018 the National Aeronautics and Space Administration (NASA) Parker Solar Probe was launched and reached its first perihelion on November 9, 2018. Thus, we have again spacecraft that determine in-situ the properties and dynamics of plasma, fields, and particles in the inner heliosphere. Ng et al. (2016) showed recently a solar cycle variation of 1–10 GeV γ-rays measured by the Fermi satellite, which is caused by galactic cosmic ray (GCR) particles interacting with the solar atmosphere. In order to investigate such temporal evolution it is worthwhile revisiting the energetic particle measurements by the HELIOS Experiment 6 (E6) performed in the 1970s within 0.4 AU in the light of advanced analysis and modelling techniques.

It has been recently shown that the E6 instrument is capable of measuring the distribution of anomalous cosmic ray (ACR), and GCR ions from carbon ($z = 6$) to silicon ($z = 14$) in the energy range from a few mega-electron-volt (MeV) nucleon$^{-1}$ to several tens of MeV nucleon$^{-1}$ in the inner heliosphere during solar minimum (Marquardt et al. 2018), resulting in the first measurement of the radial gradient of anomalous oxygen within the Earth orbit. Bialk (1996) and Droge (1999) showed that the energy range of the instrument can be extended to above several 100 MeV nucleon$^{-1}$, allowing us to determine the energy spectra and the radial gradient of GCRs’ hydrogen in the inner heliosphere from 0.3 to 1 AU.

GCRs encounter a turbulent solar wind with the embedded heliospheric magnetic field (HMF) when entering the heliosphere. This leads to significant global and temporal variations in their intensity and in their energy as a function of position inside the heliosphere. This process is identified as the solar modulation of GCRs (see for example Potgieter 2013, and references therein). The analysis of the radial gradient of ACR oxygen in the inner heliosphere within 0.5 AU by Marquardt et al. (2018) shows the need to improve particle transport models towards the Sun.

In what follows we show that the measurement capabilities of HELIOS E6 allow us to determine the hydrogen spectra up to above 800 MeV nucleon$^{-1}$. Figure 1 from Christian (1989) displays the quiet-time energy spectra for H, He, C, N, and O taken during quiet times from 1974 to 1978 1 AU by Interplanetary Monitoring Platform (IMP) 8. We validate our results against the GCR hydrogen measurements shown there. The accuracy of the instrument allows us to give upper limits of the radial gradient that are consistent with the ones reported by McDonald et al. (1977) and Webber et al. (1981) between 1 and 4.5 AU.

2. Instrumentation

HELIOS A and HELIOS B were launched on December 10, 1974 and January 15, 1976, respectively. The two almost identical spinning space probes were sent into ecliptic orbits around the Sun. The orbital period around the Sun was 190 days for HELIOS A and 185 days for HELIOS B, and their perihelia were 0.3095 AU and 0.290 AU, respectively.

A sketch of the E6 sensor is shown in Fig. 2. It consists of a stack of five silicon semiconductor detectors (SSD: D1 to D5) and one Sapphire Cherenkov detector surrounded by a plastic anti-coincidence detector. The five SSDs function as a “standard” $dE/dx$ − $E$ telescope (Brunstein 1964) with the Cherenkov detector used as anti-coincidence (see for example Marquardt et al. 2018, and references therein) allowing us to measure hydrogen to silicon energy spectra in the energy range from a few to several tenths of MeV nucleon$^{-1}$. This method is based on at least two energy deposits, one in a thin detector transmitting ($dE/dx$) and another one in a thick detector.
Fig. 1. Quiet-time H, He, C, N, and O energy spectra measured at 1 AU over the period from 1974 to 1978. The ACR component is reflected in the spectra by an enhancement at low energies for He, N, and O (Fig. 1.2 of Christian 1989). The GCR component dominates at energies above 30 MeV nucleon$^{-1}$ for N and O and 50 MeV nucleon$^{-1}$ for He, respectively.

The stopping the incident particle ($E$) (more details can be found in Marquardt et al. 2015, and references therein). At energies above ∼50 MeV protons trigger the sapphire Cherenkov detector. In order to increase the geometric factor, both detectors D1 and D2 are not required for a valid coincidence. These integral channels are called P51 for protons and A48 for heavier ions and the identification of ions is based on the $dE/dx - dE/dx$ and $dE/dx - C$ method (Kühl et al. 2016; Linsley 1955).

The $dE/dx - dE/dx$ method is based on the energy loss in two detectors allowing us to identify different particle species in certain energy ranges. However, this method has two major disadvantages, which are (1) some areas of the two dimensional energy loss plane are populated by different elements and (2) the signal from particles that penetrate the instrument from the back cannot no longer be distinguished from the ones that penetrate the instrument from the front. By adding a Cherenkov detector the overlap of different species can be minimized and one can discriminate against backward penetrating particles. This so called $dE/dx - C$-method (Linsley 1955) is applied to charged particles that completely penetrate a semi-conductor detector 5 and a Cherenkov detector C, which is placed underneath (see inset in Fig. 3). If they penetrate C faster in the dielectric material than light can propagate, they produce a measurable light flash (Cherenkov radiation). The threshold speed of $v > c/n$ depends on the refractive index $n$ of the material. Plotting the energy-loss by ionization, $\Delta E$ in A, as a function of the Cherenkov detector signal results in characteristic curves, clearly separated for different atomic numbers, with their slopes depending on particle speed. Thus, the method allows an identification of the penetrating particles and a determination of their energy above a threshold speed. Figure 3 shows measurements by Helios E6, where the Cherenkov detector is made of sapphire, which is also a scintillator responding to the ionization energy loss of the particle in the detector. The different ion tracks are identified in the figure and the orange and blue circles mark those points along the track where the particles penetrate the sapphire and where the Cherenkov light production starts, respectively. Thus, the $dE/dx - dE/dx$ method is used along the tracks starting at the orange point and ending at the blue point, and the $dE/dx - C$ method after the blue point. As is evident from Fig. 3, charged particle measurements can suffer from various...
imperfections. Therefore, modelling of the physical processes and of the instrument geometry, as well as the environment, is essential to understand such measurements (e.g. Heber et al. 2005; Kühl et al. 2015; Marquardt et al. 2015).

3. Experiment 6 modelling

In order to understand the Helios E6 response to penetrating ions, a GEometry And Tracking (GEANT) 4 simulation (Agostinelli et al. 2003) has been setup that has to include optical photon tracking as well as Birks’ quenching (Birks 1951) in the sapphire detector, as discussed in what follows.

While usual anorganic scintillation counters reach a typical scintillation yield of one photon per 100 eV deposited energy, the sapphire Cherenkov detector scintillates with an efficiency of one photon per 50 keV deposited energy. The reason for this is the self-absorption of the emitted light inside the scintillator and the emitted photons being of higher energy than the photon energy at which the photo-multiplier reaches peak efficiency. In common anorganic scintillators those effects are bypassed by doping the base material. Due to the low scintillation efficiency of the detector, the light output from scintillation falls in the same order of magnitude as the light output from Cherenkov radiation. Otherwise it wouldn’t be possible to measure the Cherenkov effect and scintillation light with the same detector. The sum of the emitted photons can be seen in Fig. 3. Cherenkov radiation is emitted as soon as particles have a higher speed than light in the medium; in the case of the sapphire $v_n = V_0/n = 0.566 \cdot c$ with $n = 1.77$ has been used. Cherenkov radiation is always emitted anisotropically while scintillated photons are isotropic.

In Fig. 3 it is also noticeable that neither the orange nor the blue points align. This is due to quenching (Birks 1951). The higher the energy deposit per path length, $\frac{dE}{dx}$, the lower the number of photons per energy deposit. Furthermore, the upper side of the detector C has been blackened to avoid the reflection of light. For speeds much larger than $v_n$ the light output is dominated by Cherenkov light that reflects the direction of the incoming particles. Thus, Cherenkov light from particles entering the detector from behind gets absorbed, while photons from the scintillation process are still counted. This leads to a separation of forward and backward penetrating particle tracks in Fig. 3. However, particles with speed $v < v_n$ lead to a photon distribution that is isotropic resulting in insufficient discrimination between forward and backward particles below $0.566 \cdot c$. In order to improve the rejection of backwards penetrating ions, we calculated the expected distributions for forward and backward penetrating protons as well as the ones for backward penetrating helium in Figs. 4 and 5. In all our simulations, quenching in the sapphire detector has been taken into account, by using Birks’ formula

$$\frac{dL}{dx} = S \frac{dE}{dx} \left( 1 + \kappa_0 \frac{dE}{dx} \right)^{-1}$$

using as parameter $S = \frac{20}{MeV}$ and $\kappa_0 = 50 \cdot 10^{-6} \frac{mm}{MeV}$. Taking the above-mentioned effects into account, we performed a simulation with one Billion protons in the energy range from 40 MeV nucleon$^{-1}$ up to 10 GeV nucleon$^{-1}$ impinging isotropically on the E6 sensor. Results for protons that cross the sensor from the front are summarized in the left panel of Fig. 4 and in the top panel of Fig. 5. The first of the two figures displays the minimum logarithmic energy loss $\Delta E$ in SSD 4 and SSD 5 as a function of the light output of the Cherenkov detector C in six different energy bands from 50–83 MeV nucleon$^{-1}$.
In that case, Eq. (2) reduces to
\[ R(E) = \begin{cases} 
0 & \text{for } 0 < E < E_i \\
R_i & \text{for } E_i \leq E \leq E_U \\
0 & \text{for } E > E_u 
\end{cases} 
\]
(3)

In that case, Eq. (2) reduces to
\[ C_i = R_i \cdot (E_u - E_i) \cdot I(\langle E \rangle), \]
(4)
where \( E \) is the mean energy of channel \( i \) and \( J_i(\langle E \rangle) \) can be easily computed by
\[ J_i(\langle E \rangle) = \frac{C_i}{R_i \cdot (E_u - E_i)}. \]
Although the response function for each box is deviating from the ideal ones described by Eq. (3), we approximate $R \cdot (E_u - E_i)$ by the integral of the response function $\int R_i(E) dE$ and $(E)$ is the energy $E$ for which the response function has a maximum. The results are visualized in Fig. 7. In this figure we added three channels for stopping protons to extend the energy range down to about 10 MeV (see Marquardt et al. 2018, and references therein). While the $y$ errors account for statistical errors only, the $x$ errors mark the energies when the response has been decreased to $\frac{1}{\text{e}}$ of the maximum response of each box. This simple method has been chosen since it shows in an intuitive way the results applicable to a response function that has a box or a gaussian shape, respectively. For comparison the green symbols display the hydrogen measurements from Fig. 1. Taking into account the different measurement times from 1974 to 1978 for IMP 8 and from the end of 1974–1977 for Helios A, the agreement between both data sets is remarkably good. Taking these uncertainties into account, our analysis shows that the E6 can be utilized to determine proton energy spectra in the range from 10–50 MeV from energy channels of stopping particles and from 60 to about 600 MeV for penetrating particles. During quiet times the energy spectra of protons can be approximated by the force field solution (FFS, see Gleeson & Axford 1968; Caballero-Lopez & Moraal 2004, and references therein). As local interstellar spectrum (LIS) we used a gaussian shape, respectively. For comparison the green symbols are the fluxes measured by IMP 8 taken from Fig. 1. The results are visualized in Fig. 7. In this figure we added three channels for stopping protons to extend the energy range down to about 10 MeV (see Marquardt et al. 2018, and references therein). While the $y$ errors account for statistical errors only, the $x$ errors mark the energies when the response has been decreased to $\frac{1}{\text{e}}$ of the maximum response of each box. This simple method has been chosen since it shows in an intuitive way the results applicable to a response function that has a box or a gaussian shape, respectively. For comparison the green symbols display the hydrogen measurements from Fig. 1. Taking into account the different measurement times from 1974 to 1978 for IMP 8 and from the end of 1974–1977 for Helios A, the agreement between both data sets is remarkably good. Taking these uncertainties into account, our analysis shows that the E6 can be utilized to determine proton energy spectra in the range from 10–50 MeV from energy channels of stopping particles and from 60 to about 600 MeV for penetrating particles. During quiet times the energy spectra of protons can be approximated by the force field solution (FFS, see Gleeson & Axford 1968; Caballero-Lopez & Moraal 2004, and references therein). As local interstellar spectrum (LIS) we used a gaussian shape, respectively. For comparison the green symbols are the fluxes measured by IMP 8 taken from Fig. 1. The results are visualized in Fig. 7. In this figure we added three channels for stopping protons to extend the energy range down to about 10 MeV (see Marquardt et al. 2018, and references therein). While the $y$ errors account for statistical errors only, the $x$ errors mark the energies when the response has been decreased to $\frac{1}{\text{e}}$ of the maximum response of each box. This simple method has been chosen since it shows in an intuitive way the results applicable to a response function that has a box or a gaussian shape, respectively. For comparison the green symbols display the hydrogen measurements from Fig. 1. Taking into account the different measurement times from 1974 to 1978 for IMP 8 and from the end of 1974–1977 for Helios A, the agreement between both data sets is remarkably good. Taking these uncertainties into account, our analysis shows that the E6 can be utilized to determine proton energy spectra in the range from 10–50 MeV from energy channels of stopping particles and from 60 to about 600 MeV for penetrating particles.
solar cycle variation in the 1–10 GeV γ-rays measured by the Fermi satellite in the vicinity of the Sun. Thus in contrast to our current understanding, cosmic rays penetrate deeply into the Sun’s corona. In order to advance our understanding, it is important to know the radial variation of the GCR flux within 1 AU. With the improved data analysis of the E6 experiment, we investigate in what follows the radial gradient of galactic cosmic ray protons in the energy range from about 250 to about 700 MeV, combining boxes 6–8. We investigate the radial variation using a two-step approach. Since the flux obtained in this channel results from the product of the integral channel and the number of entries in boxes 6–8, we first determine the radial variation in the integral channel and then the one in the box channel. The integral channel is the channel that measures forward and backward penetrating protons and electrons and backward penetrating helium above 50 MeV nucleon\(^{-1}\) for ions and above 10 MeV for electrons. Figure 9 displays in the top and middle panels the radial distance to the Sun and the count rate in the integral proton channel for the fifth orbit of Helios 1 from December 30, 1976 (mission day 750) to July 18, 1977 (mission Day 950). Marked by different colours are Bartels rotation averages centred around the closest approach, allowing us to determine the radial dependence of this count rate. In the lowest panel, the mean of the Bartels average of the count rates prior and after closest approach are displayed as a function of radial distances for all orbits, which occurred during quiet times from launch of the satellite to July 18, 1977. In order to compare the different orbits to each other all count rates are normalized to the ones observed between 0.9 and 1 AU. Although we find a wide spread, a clear trend of decreasing flux with radial distance is obtained. In order to minimize the influence of temporal variations we average the normalized values for all five orbits. They are shown in Fig. 9 by the black bullets. By fitting a line to the logarithms of the three outer bins we obtain a radial gradient of 6.6 ± 4% AU\(^{-1}\).

This value is consistent with the one obtained by Bialk (1996) but larger than the ones published by McDonald et al. (1977) and Webber & Lockwood (1981) summarized in Table 1. We note that the flux at 0.35 AU is much lower than the expected one from our fit. This is in agreement with the observation of the radial gradient of anomalous oxygen increasing in the inner heliosphere (Marquardt et al. 2018).

In the second step we used the same approach as for the integral channel for the differential proton channel sensitive to protons between 250 and ~700 MeV. Here we binned the data so that we get a radial resolution of 0.05 AU per bin as displayed in Fig. 10. The values have been normalized to the maximum value at a distance of 0.6 AU. Details can be found in the text.

This study.

Table 1. Selected radial gradients obtained in the heliosphere by McDonald et al. (1977), Webber et al. (1981), Bialk (1996), and this study.

| Distance range | \(G_r\) | Energy |
|----------------|---------|--------|
| (AU)           | (% AU\(^{-1}\)) | (MeV)  |
| From McDonald et al. (1977) |         |        |
| 1.25–4.2       | 4.1 ± 3.7 | 210–275 |
| 1.25–4.2       | 2 ± 4    | 275–380 |
| 1.25–4.2       | 1.3 ± 5  | 380–460 |
| 1–3.8          | 0 ± 4    | 210–275 |
| 1–3.8          | 2.5 ± 4  | 275–380 |
| 1–3.8          | 3.8 ± 5  | 380–460 |
| From Webber & Lockwood (1981) |         |        |
| 2–28           | 2.5 ± 0.5 | > 60   |
| 0.4–1          | 6.6 ± 4  | > 50   |
| 0.3–1          | 2 ± 2.5  | 250–700 |

Fig. 9. Top panel: radial distance to sun versus time. We colour-coded the length of one Bartels rotation centred around the closest point to sun. Middle panel: corresponding count rates. Lowest panel: averaged count rates for different revolutions versus the distance.

Fig. 10. Flux in the energy range from 250 to 700 MeV as a function of radial distance using a bin width of 0.05 AU. The values have been normalized to the maximum value at a distance of 0.6 AU. Details can be found in the text.
gradient of $G_R = 2 \pm 2.5\%\text{AU}^{-1}$ that is in good agreement with the one published by McDonald et al. (1977), Bialk (1996), and Webber et al. (1981). Because of the limited E6 capabilities the uncertainties in the differential flux measurements do not indicate any increase of the radial gradient towards the Sun. Although the count rate profile of the integral channel as well as the anomalous oxygen indicate an increase of the radial gradient within 0.5 AU, only the measurements from the Parker Solar Probe will validate or disprove the Helios observations presented here.

5. Summary and conclusions

The Experiment 6 (E6) aboard the Helios space probes was designed to measure ions and electrons in the energy range from a few MeV nucleon$^{-1}$ to above 50 MeV nucleon$^{-1}$ and 0.15 and above 10 MeV for electrons. In order to compute the proton energy spectrum above 50 MeV nucleon$^{-1}$, the instrument utilizes the $dE/dx - C$ method. A sophisticated model of the instrument has been developed on the basis of the GEometry And Tracking (GEANT)-4 package. We computed the response of the instrument not only to forward penetrating protons but also to hydrogen and helium that penetrate the sensor from behind. In order to reduce the background to these unwanted contributions, the energy loss distributions in the two silicon detectors have been evaluated. By adding a simple mask the background of backward protons below 130 MeV could be reduced significantly. For energies between 130 and 250 MeV, backward and forward penetrating protons cannot be distinguished from the signal of the last three detectors. At higher energies from above 250 MeV the Cherenkov effect sets in and forward and backward penetrating particle tracks separate again (see Fig. 5).

Applying the “background” rejection derived from simulations an energy response (lower panel in Fig. 6) for different masks shown in the upper two panels of Fig. 6 were computed. These response functions were used to compute the GCR spectrum during quiet times from December 1974 to July 1977. The flux in each mask (box) was determined by applying a simple inversion. Taking into account the different measurement periods used in the study by Christian (1989) and our analysis, the spectra derived from Helios and IMP 8 measurements agree very well with each other. Our analysis resulted in $\phi = 440\text{MV}$, which is in very good agreement with mean $\phi = 435\text{MV}$ derived from the values published by Usoskin et al. (2005). Thus we conclude that Helios E6 can be used to determine the proton spectra up to above 600 MeV. However, not only the intensity close to Earth can be determined but also the radial gradient within 1 AU. In contrast to Webber & Lockwood (1981) who determined a radial gradient of $2.5 \pm 0.5\%\text{AU}^{-1}$ between 2 and 28 AU, we found a radial gradient of $6.6 \pm 4\%\text{AU}^{-1}$ between 0.3 and 1 AU for above 50 MeV protons. Our analysis indicates an increasing radial gradient within 0.5 AU. The analysis from Bialk (1996) using an integral channel with energies above 135 MeV results in somewhat lower gradients. This trend is continued when we determine the radial gradient for protons in the energy range between 250 and 600 MeV protons to $2 \pm 2.5\%\text{AU}^{-1}$, which is in good agreement with the values found by McDonald et al. (1977) obtained between about 1 to about 4 AU. The Parker Solar Probe has explored the inner heliosphere on its first orbit during the same magnetic polarity of the Sun as in the 1970s and during solar minimum conditions. Therefore the results from the Parker Solar Probe will enable us to find out the following information: (1) whether the radial gradient during the current solar cycle is consistent with the one obtained in the 1970s between 0.5 and 1 AU; (2) whether the radial gradient increases with decreasing distance to the Sun within 1 AU; and (3) in the event that the Parker Solar Probe results confirm the HELIOS results, we can ascertain the implications for cosmic ray propagation models.

References

Agostinelli, S., Allison, J., Amako, K., et al. 2003, Nucl. Instrum. Methods Phys. Res. Sect. A, 506, 250
Bialk, M. 1996, PhD Thesis, Christian-Albrechts-Universität zu Kiel
Birks, J. B. 1951, Proc. Phys. Soc. Sect. A, 64, 874
Brunstein, K. A. 1964, Phys. Rev., 133, 1520
Burger, R. A., Potgieter, M. S., & Heber, B. 2000, J. Geophys. Res., 105, 27447
Caballero-Lopez, R. A., & Moraal, H. 2004, J. Geophys. Res. (Space Phys.), 109, A01101
Christian, E. R. 1989, PhD Thesis, California Institute of Technology, Pasadena
Droege, W. 1999, Proceedings of the 26th International Cosmic Ray Conference, August 17–25, 232
Gieseler, J., Heber, B., & Herbst, K. 2017, J. Geophys. Res. (Space Phys.), 122, 10
Gloeson, L. J., & Axford, W. I. 1968, ApJ, 154, 1011
Heber, B., Kopp, A., Fichtner, H., & Ferreira, S. E. S. 2005, AdsPr, 35, 605
Kühl, P., Banjac, S., Dressing, N., et al. 2015, A&A, 576, A120
Kühl, P., Gómez-Herrero, R., & Heber, B. 2016, Sol. Phys., 291, 965
Lansley, J. 1955, Phys. Rev., 97, 1292
Marquardt, J., Heber, B., Höröck, M., Kuhl, P., & Wimmer-Schweingruber, R. F. 2015, J. Phys. Conf. Ser., 632, 012016
Marquardt, J., Heber, B., Potgieter, M. S., & Strauss, R. D. 2018, A&A, 610, A42
McDonald, F. B., Lal, N., Trainor, J. H., Van Hollebeke, M. A. I., & Webber, W. R. 1977, ApJ, 216, 930
Ng, K. C. Y., Beacom, J. F., Peter, A. H. G., & Rott, C. 2016, Phys. Rev. D, 94, 023004
Potgieter, M. S. 2013, Liv. Rev. Sol. Phys., 10, 3
Richardson, I. G. 2004, Space Sci. Rev., 111, 267
Richardson, I. G., & Cané, H. V. 2011, Sol. Phys., 270, 609
Strauss, R. D., & Potgieter, M. S. 2010, J. Geophys. Res. (Space Phys.), 115, A12111
Sullivan, J. D. 1971, Nucl. Instrum. Methods, 95, 5
Usoskin, I. G., Alanko-Huotari, K., Kovaltsov, G. A., & Mursula, K. 2005, J. Geophys. Res. (Space Phys.), 110, A12108
Webber, W. R., & Lockwood, J. A. 1981, J. Geophys. Res., 86, 11458
Webber, W. R., McDonald, F. B., von Rosenvinge, T. T., & Mewaldt, R. A. 1981, Int. Cosmic Ray Conf., 10, 92

A153, page 7 of 7