# Solar wind $\mathrm{H}^{+}$fluxes at 1 AU for solar cycles 23 and 24 

Maciej Sznajder*<br>PW Sznajder, P3RUN - Radiation Hardness Assurance and Data Science Expertise, Dolina Zielona 19A, 65-154, Zielona Góra, Poland

DLR Institute of Space Systems, Mechanics and Thermal Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany

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#### Abstract

The solar wind consists of electrons and ion species having kinetic energy $\lesssim 10 \mathrm{keVs}$. Ion stream is mainly composed of protons. Their flux magnitude is especially important for radiation hardness assurance scientists who qualify materials for future space missions. Materials irreversibly degrade as soon as are exposed to solar radiation. Hence, proton differential and integral flux spectra play a crucial role in properly estimating radiation loads deposited within satellite functional components. Up to now, the wind fluxes were read out, e.g., from figures made for specific periods of a solar cycle. This method is not effective and is a source of a flux, and further on, a fluence uncertainty. The objective of this work was to calculate and tabulate the solar wind differential and integral proton fluxes, which can be used further on to evaluate space mission proton fluence spectra. Solar wind proton bulk velocity and number density from four space solar observatories (SOHO, ACE, WIND, and DSCOVR) were numerically processed to achieve that goal. Fluxes were tabulated and represented in calendar year periods. Now, the radiation hardness assurance community can quickly access, compute and compare SW proton fluxes from different energy ranges, calendar years, and satellite data sources. Proton fluxes presented here indicate magnitude variations along with the solar cycle period. A correlation between the number of sunspots and the proton average flux was found, i.e., the larger the number of spots, the larger the flux magnitude. More importantly, it was discovered that proton fluxes indicate huge variations in magnitude for a selected year based on different satellite data sources. For some years, the difference reaches $240 \%$. This value is reported for the first time and shows that to have a complete picture of the SW proton stream population, one must compare data from all four satellites. Also, it is reported that satellites, for a given calendar year, record different ranges of proton velocity and number density values. This finding, even stronger, suggests a necessity of comparing SW data from as many solar observatories as possible. The spread in the proton flux magnitude ( $240 \%$ ) has a direct implication for planning and executing satellite material on-ground radiation test campaigns. Not carefully choosing a proton flux may result in a false impression of how examined material would degrade under an interplanetary space radiation environment. In this article, recommendations for selecting proper proton spectra are given.


Keywords - solar wind, radiation hardness assurance, material aging

## 1 Introduction

The solar wind (SW) is a magnetized plasma emitted from the solar corona, the most outer part of the Sun's atmosphere. Its variability in composition and flow intensity is dictated by the $\sim 11$-years solar cycle (SC). The kinetic energy of the SW protons can obtain values up till 10 keV . However, within that range, one can distinguish the so-called slow SW (SSW) as well as fast SW (FSW) flows. FSW flows originate from the so-called coronal holes (Krieger et al., 1973, Zirker, 1977). Those are regions mainly located at the Sun's poles, where the corona has much lower density and temperature than surrounding plasma (Harvey \& Recely, 2002). On the other hand, the origin of the SSW is still under debate. Studies of Sakao et al. (2007)

[^0]and Brooks et al. (2015) show that the primary source of the SSW is most likely associated with the edge of active regions. Those are Sun atmosphere structures with complex magnetic field formation associated with sunspots (van Driel-Gesztelyi \& Green, 2015, Cheung et al., 2017, Stansby et al., 2021). However, Bale et al. (2019) using data collected by the Parker Solar Probe (PSP) reveals that coronal holes located at low latitudes are a key source of the SSW. Most importantly, Larrodera \& Cid (2020) using all available historical data from the Advanced Composition Explorer (ACE) spacecraft show that bulk SW has a bi-modal distribution of speed, density, temperature as well as magnetic field strength. Hence, as the authors strongly emphasized, SW at 1 AU has a truly bi-modal nature consisting of both fast and slow components.

Many authors classify the SSW and the FSW in different proton speed ranges. For example, Schwenn (2006) defines the SSW for proton speeds below 400 km $\mathrm{s}^{-1}$ and the FSW for speeds greater than the mentioned value. On the other hand, for Brooks et al. (2015) the

FSW has proton speeds larger than $700 \mathrm{~km} \mathrm{~s}^{-1}$. Lastly, for Abbo et al. (2016) and Bale et al. (2019) the SSW is defined for proton speeds smaller than $500 \mathrm{~km} \mathrm{~s}^{-1}$. Those four examples indicate that authors choose the velocity range to classify SW flows rather freely. Hence, when scientific results are compared, one has to carefully review how authors classify the SSW and the FSW flow velocity range. Then, above 10 keV , one can distinguish the so-called Interstellar Pickup Protons (IPPs) and the Suprathermal Proton Tail (SPT). Further on, above approx. 0.1 MeV , a population of the solar energetic particles (SEP) is present. IPPs originate from interstellar neutral hydrogen atoms, which penetrate the heliosphere and are split of electrons by photoionization and charge exchange with SW ions. Then they are picked by the SW magnetic field and convected outwards from the Sun (Gloeckler et al. 1993, Whang et al., 1996, Intriligator et al., 2012) eventually constituting the tail (Dayeh et al.| 2009; Lazar et al., 2012; Mason \& Gloeckler, 2012 | Desai et al., 2016). A differential proton spectrum showing magnitude of combined proton species, i.e., the SW, the IPPs, and its SPT is shown in Fig. 1. The plot is taken from the work of Gloeckler et al. (2008). The spectrum was calculated from the ACE spacecraft data set and averaged for the calendar year 2007, that is, at the solar minimum activity state. The author considered only SSW flow from the SW proton population. Please note that Gloeckler et al. (2008) did not depict SEP population on the figure. The SEP proton flux is approx. 3 to 4 orders of magnitude higher than the proton flux of the SPT protons. SEPs are generated by the Coronal Mass Ejections (CMEs) and the Solar Flares (SFs) Reames, 2015).

The interstellar neutral gas is an origin not only for the IPPs but also for the so-called anomalous cosmic rays (ACR). When neutral atoms are ionized, they can be sped up by a mechanism called the diffusive shock acceleration. In that process, particles are accelerated by plasma compression, such as the termination shock. The particles' energy gain depends on how effectively they are trapped near the shock. A review paper of Giacalone et al. (2022) gives an in-depth overview of the ACRs.

Corpuscular radiation, when trapped by a celestial magnetic field, constitutes a unique zone in its close vicinity. Trapped are SW electrons and ions, SEP, and ACR (Klecker et al., 1998, Cummings \& Stone, 2013). However, galactic cosmic rays (GCR) penetrate both the heliosphere and the zone. All constitute a unique radiation environment. For the Earth, trapped particles form the so-called inner and the outer Van Allen radiation belts (Freden, 1969, Li \& Hudson, 2019, Ripoll et al., 2020). The inner belt spans approximately 2.4 Earth radii $R_{\mathrm{E}}$, while the outer one spans from 2.8 $R_{\mathrm{E}}$ up to $12 R_{\mathrm{E}}$. Both are separated from each other by the so-called slot (Holmes-Siedle \& Adams, 2012). Occasionally, however, a third belt is formed, which is mainly filled with MeV range electrons (Baker et al., 2013). Distances stated above are given in the equatorial plane. Also, in the literature, one can find belt


Figure 1: Differential proton flux spectrum evaluated out of measurements performed by the ACE satellite for the calendar year 2007. Both the SWICS and the ULEIS detectors (Stone et al. 1998) were used to calculate flux values for a broad proton energy range reaching approx. 4 MeVs . The spectrum is transferred to 1 AU distance from the Sun. The plot is taken from Gloeckler et al. (2008).
dimensions defined by the use of the $L$-shell parameter. Its definition can be found, e.g., in the work of Freden (1969). The inner belt is populated with electrons and ions, which consist mainly of protons, while in the outer belt, the electrons dominate the radiation environment. There were multiple missions probing the radiation composition and spatial variability of the belts. One could list, for example, the Sputnik-2, the Explorer -1, -3 , and -4 satellites, the Pioneer $-1,-3$ and -4 satellites, the Combined Release and Radiation Effects Satellite (CRRES) (Johnson \& Kierein, 1992), the Van Allen Probes (VAP) (Fox \& Burch, 2014) or the Exploration of energization and Radiation in Geospace (ERG, also nicknamed Arase) Miyoshi et al., 2017, 2022). Multiple radiation models were developed based on data collected by those satellites, e.g. the AP-8 and the AE8 for protons and electrons, respectively (Jordan, 1989); the CRRESPRO and the CRRESELE for protons and electrons, respectively (Meffert \& Gussenhoven, 1994, Brautigam \& Bell, 1995); the SAMPEX/PET for protons and altitudes below 600 km (Heynderickx et al., 1999); the AE9/AP9 model (Ginet et al. 2013) or the GREEN model (Sicard et al., 2018) for protons and electrons having energies down to 1 keV . Overall, the Van Allen radiation belt models provide differential and integral particle fluxes and cover a wide energy range from 1 keV up to hundreds of MeVs .

There is a slightly different situation with radiation models developed for interplanetary space (IS). The IS radiation environment has been probed by many satellites, e.g. the Interplanetary Monitoring Platform-8 (IMP-8, also known as the EXPLORER 50) Paularena
\& King, 1999), both the Voyager-I and -II pioneers, the Comprehensive Solar Wind Laboratory for LongTerm Solar Wind Measurements (WIND) (Lin et al., 1995. Ogilvie et al., 1995), the Solar and Heliospheric Observatory (SOHO) (Domingo et al., 1995; Ipavich et al., 1998), the ACE (Stone et al., 1998), the Solar Terrestrial Relations Observatory (STEREO-A and B), the Solar Orbiter (Müller et al., 2020), the Deep Space Climate Observatory (DSCOVR) (NOAA, 2021), or the PSP. There are also two satellites that are planned to be launched in 2025 which will extend our knowledge about the radiation conditions of the interplanetary medium, i.e., the Interstellar Mapping and Acceleration Probe (IMAP) and the Space Weather Follow On-Lagrange 1 (SWFO-L1). Based on the collected data, many models of corpuscular radiation of the IS were developed. Those models are used by radiation hardness assurance (RHA) scientists who predict how much radiation loads are deposited within satellite components, and how to ultimately design a radiation shield to protect mission payloads and preserve the onboard electronics during the desired duration of the space mission. Here, in the case of on-board electronics, the MeV range SEPs and GCRs, heavy ions, protons, and neutrons have the main destructive potential, see e.g. ESCC (2014, 2016). There are two classes of radiation models: so-called solar peak flux models and average proton and ion models. The energy range covered by these models starts from $\sim 100$ keV . The first class gives differential and integral fluxes, which are commonly used to evaluate what is known as single event effect (SEE) rates. SEEs are all kinds of events that can occur within satellite electronics which are caused by incident energetic particles and result in their malfunction, or, ultimately, permanent damage (ESCC, 2014). The models are the Cosmic Ray Effects on Micro-Electronics model (CREME -86 and -96) Adams, 1986 Tylka et al., 1997), the Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment model (SAPPHIRE) (Jiggens et al., 2018), the Xapsos et al. (2000) model, or the Mission Specific Solar Radiation Environment Model (MSSREM) (Robinson et al., 2020). The second class gives integral and differential particle fluence spectra for a predefined satellite mission time. Hence, divided by that time, a flux can be calculated. Those are, for instance, the King (1974) model, the Jet Propulsion Laboratory model (JPL-91) Feynman et al., 1993), the Emission of Solar Protons model (ESP) (Xapsos et al., 1999, 2000), the Rosenqvist et al. (2005) model, or again, the SAPPHIRE model.

Clearly, there is an energy spectrum of solar corpuscular radiation with particle energies $\lesssim 100 \mathrm{keV}$ which is not covered by standards used in the space industry, i.e., the European Cooperation for Space Standardization (ECSS), the American Society for Testing and Materials (ASTM), nor the International Organization for Standardization (ISO). Moreover, it must be pointed out that some of the models, e.g. SAPPHIRE, incorporate extrapolation down to 100 keV based on an assumed spectral form. Furthermore, publicly available
tools such as the SPENVIS (Heynderickx et al. 2004 SPENVIS, 2018), the OMERE (TRAD, 2022), or the OLTARIS (Singleterry et al., 2011) do not offer such spectra. However, it must be strongly emphasized that spectra with particle energies $\lesssim 100 \mathrm{keV}$ exist, see e.g. Gloeckler (1984); Yu \& Zhang (1990); Lin et al. (1995); Mewaldt et al. (2001) or Gloeckler et al. (2008). In the case of SW protons ( $\mathrm{E}<10 \mathrm{keV}$ ), available spectra differ in flux magnitude at their peaks, so for the energy of $\sim 1$ keV , by approx. two orders of magnitude. Such a difference has strong implications for predicting material aging mechanisms. A differential flux is used to calculate an integral flux, a quantity necessary to perform a radiation test. An energy range for the integration depends on a target material specification, i.e., in the case of a multi-layer film, it is important which layer is studied. In such a case, one must consider particle energies whose penetration depths within the material correspond to the studied layer. Then, particle fluxes shall be integrated over these energies. A problem occurs when the integration is done around the mentioned 1 keV . A fluence is calculated by knowing an effective material exposition time in space. Next, a radiation test can be planned and performed. However, the conclusions of such a test can be highly misleading. If a differential flux is chosen from one source, which may be, e.g., an order of magnitude smaller (or higher) than from another source, then material aging results may suggest that a certain degradation effect appears slower (or faster) than it would in radiation conditions of the IS. Hence, such test results may give a false impression about an examined material's aging mechanism timescale. It is of great importance to write in test reports or scientific manuscripts a full list of irradiation test parameters, i.e., a particle flux, a fluence, an energy, and an acceleration factor used during the test.

It is worth annotating that in the problematic of a satellite surface charging, there are recommendations regarding radiation testing for particle energies smaller than 10 keV . For example, in the ECSS-E-ST-20-06C (2019) standard, it is stated that for a Geostationary Orbit (GEO) environment, a flux of $250 \mathrm{pA} \mathrm{cm}^{-2}$ shall be used in case of electrons with an energy between 0 keV and 50 keV . However, no particle spectra are provided.

Estimation of particle integral flux and fluence requires, preferably, a particle differential flux in the form of a table where data can be easily read out. Instead, spectra are available, e.g., as plots (Fig. 1), where a flux readout is already accompanied by uncertainty. Additionally, published differential spectra are not supplemented with data processing procedures. One cannot follow computational steps to re-calculate the spectra. Hence, one cannot use another data source, follow the same procedure and calculate its own spectra. This situation leaves too many degrees of freedom when radiation loads of satellite components need to be calculated. Arguments given above were the main motivation for the work presented here. However, it must be pointed out that only SW protons ( $\mathrm{E}<10 \mathrm{keV}$ ) were studied here.

The SW particles have too little energy to pass through a satellite radiation shield and cannot harm the onboard electronics. This can be verified e.g. by performing a simple simulation by use of the SRIM software (Ziegler et al., 2010). After taking a 1 mm aluminum plate as a target material, one finds that protons with energies smaller than $\approx 14 \mathrm{MeV}$ are stopped within its structure. Hence, the radiation shield will also stop SW protons with energies lower than 10 keV . Estimation of its thickness and design are key results of the RHA study. Here, the driving parameter is the radiation environment. Also equally important are the mission duration, location, and type of the onboard electronics (Zeynali et al., 2012). The typical shield thickness is a few millimeters (Palmerini \& Pizzirani, 2002, Daneshvar et al., 2021). However, it must be emphasized that the shield thickness estimation is performed for every new space mission. However, a class of satellite components is especially vulnerable to low energy solar ions, that is, ions having energy lower than 10 keV . Those are solar reflectors, the so-called second surface mirrors, and all kinds of optical satellite elements. For those applications, common use is a thin stack of coatings of just a few $\mu \mathrm{m}$ or even tens of nm . Coatings in a stack can be made with different materials and have different thicknesses. A pair of two parameters define thermo-optical properties of those materials, the socalled solar absorptance $\alpha$ and the thermal emittance $\epsilon$. The former is defined as the ratio of the solar radiant flux absorbed by a material to that incident upon it, while the latter is defined as the ratio of the radiant intensity of the specimen to that emitted by a black body radiator at the same temperature and under the same geometric and wavelength conditions (ECSS-Q-ST-7009C, 2008). Each coating layer slows down or stops the SW particles. A coating material is ionized and implanted by the SW ions as soon as it is exposed to the solar plasma. Hence, during exposure, such materials are irreversibly aged, and hence, a coating's pre-defined physical properties are changed. Especially fragile are front material surfaces as well as interfaces between the coatings. When exposed to SW protons, metallic surfaces indicate the formation of blisters filled with hydrogen and helium molecular gas (Sznajder et al., 2015 Sznajder et al., 2018; Pelizzo et al., 2018; Pelizzo et al., 2021). The gas results from recombination processes (Hagstrum, 1954, Sols \& Flores, 1984) of SW protons and alpha particles with metal electrons. The blistering effect leads to a change of thermo-optical properties and decreases the reflectance of exposed metallic surfaces (Pelizzo et al., 2018; Sznajder et al., 2021). Also, non-metallic materials like polyimide-based films suffer after being irradiated by low energy protons (3 keV and 5 keV$)$. Solar absorptance of such materials increases, which causes their temperature to increase while being aged and operated in space (Dembska et al. 2020). Especially fragile to SW protons are materials composed of a stack of coatings such as Extreme-UV mirrors. Pelizzo et al. (2011) shows that stack layers can delaminate from each other while being exposed to low energy protons $(1 \mathrm{keV})$. That mechanism causes
permanent mechanical damage to such mirrors. Also, Nardello et al. (2013) and Sertsu et al. (2015) show that such materials, while being exposed to low energy alpha particles ( 4 keV ), exhibit a drop of reflectivity performance. However, Wappaus (1971) experiments proved that, contrary to protons ( 5 keV ), low energy electrons ( 5 keV ) and UV radiation bring a smaller impact to the degradation of thermo-optical properties of second surface mirrors. On the other hand, corpuscular radiation with particle kinetic energy in the MeV range travels through material structure, causing its ionization and simultaneous creation of interstitials and vacancies (Damask \& Dienes, 1971). Those, however, can accelerate other degradation mechanisms like blistering (Condon \& Schober, 1993; Lu \& Kaxiras, 2005, Li et al., 2019), which for thin films, is primarily generated by low energy protons and alpha particles. It must be kept in mind that materials in space are exposed to a broad spectrum of electromagnetic and corpuscular radiation (Holmes-Siedle \& Adams, 2012). Examples listed above report aging mechanisms of materials irradiated by mono-energetic particles and a fraction of the electromagnetic radiation spectrum, i.e., the UV light. Hence, the true response of materials to the interplanetary space radiation environment is to a great extent unknown.

A differential particle flux is required to calculate the number of particles implanted in a coating layer. Then, it must be integrated over an energy range which can be translated to specific particle penetration depths within a stack material.

Here, the differential and integral fluxes of the SW protons were calculated by use of data from four satellites: SOHO, WIND, ACE, and DSCOVR. All four orbit in the close vicinity of the Lagrangian-L1 point of the Earth-Sun system, which is located $1.5 \times 10^{6} \mathrm{~km}$ sunwards from the Earth. Hence, the flux numbers computed here were transformed to 1AU distance from the Sun by use of the inverse square law. Such a transformation method is suggested by the ECSS (2020) standard. The results are organized in two blocks, first for the SC 23, which started in August 1996 and ended in December 2008, and second, the SC 24 followed the SC 23, and it ended in December 2019. Additionally, fluxes are given for 2020 for those satellites where the SW data was available.

A subsystem that measures SW protons in all four satellites records the incident particle current. It is measured, e.g., from different proton grazing angles and energy windows. The current is then used to estimate basic SW proton plasma parameters. More information about this procedure can be found, e.g., in the B. The SOHO subsystem is called the Proton Monitor, and it is a part of the Charge, Element, and Isotope Analysis System (CELIAS) and Mass Determining Time-of-Flight Sensor (MTOF) compartments (Hovestadt et al., 1995). The WIND subsystem is simply a Faraday cup, and it is part of the Solar Wind Experiment (SWE) set of sensors (Ogilvie et al. 1995). Next, the ACE spacecraft is using the so-called Solar Wind Electron Proton Alpha Particle Monitor (SWEPAM)
(McComas et al. 1998). Finally, the DSCOVR satellite is equipped with a Faraday cup to measure the SW proton current (Loto'aniu et al., 2022).

The manuscript is organized as follows. In Section 23 average, differential, and integral proton flux values are reviewed from the literature. Then, in Section 3, mathematical methods and computed SW fluxes based on the satellite SW data are given. Fluxes were tabulated for each calendar year in two considered two SC periods. The resulting discussion is provided in Section 4 Conclusions are drawn in Section 5. Next, in A. the evolution of proton speed and density histograms and differential proton flux spectra approaching solar minimum based on SOHO, ACE, WIND and DSCOVR SW data is presented. As already mentioned, in B a principle of measuring SW proton current by a responsible satellite subsystem is introduced. Also here, a scaling factor from an omni-directional to a directional SW proton flux is discussed. In C, a simple use case of presented proton spectra is shown. A proton fluence spectrum for an exemplary space mission is calculated and discussed. Finally, in D, in addition to the Section (3) tables with integral proton fluxes are given. The fluxes are integrated into a descending length of energy range, for example from 0.2 keV ... 5.0 keV , then from 0.3 keV ... 5.0 keV , till 4.9 keV ... 5.0 keV , where the energy step between the lower boundary of the ranges equals 0.1 keV .

## 2 Solar wind average, differential and integral proton fluxes

An average proton flux $\bar{f}$ is defined by the use of a set of two physical quantities, i.e., proton number density $n$ with a dimension of $\mathrm{cm}^{-3}$ and a proton bulk velocity $v$ with dimension of $\mathrm{cm} \mathrm{s}^{-1}$. The set consists of a pair of numbers within a time period of one calendar year. Here, the $\bar{f}$ is defined as:

$$
\begin{equation*}
\bar{f}=\frac{\sum n_{\mathrm{i}} v_{\mathrm{i}}}{\left|\left\{n_{\mathrm{i}} v_{\mathrm{i}}\right\}\right|} \tag{1}
\end{equation*}
$$

Where, $\left|\left\{n_{\mathrm{i}} v_{\mathrm{i}}\right\}\right|$ denotes the length of a set $\left\{n_{\mathrm{i}} v_{\mathrm{i}}\right\}$. The flux $\bar{f}$ can be used as an indicator for the Sun activity state, see Section 3. The flux was reported by many authors. For example, Feldman et al. (1977) using Helios satellite SW data collected between 1971 and 1974 estimated average flux to $\bar{f}=2.7 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. This time period is allocated to the SC 20 just after the solar maximum, which fell on the calendar year 1970. Schwenn (1983, 1990) also based his calculations on Helios satellite measurements made between $12^{\text {th }}$ Dec. 1974 and $31^{\text {st }}$ of Dec. 1976, and calculated the flux to $\bar{f}=2.66 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. It is worth mentioning that the measurement time range was allocated during the solar minimum between the SC 20 and the SC 21. Both mentioned values are already transformed to 1 AU by use of the inverse square law transformation. Reisenfeld et al. (2013) estimated the average flux to $f=2.57 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. The data originated from the Genesis satellite (Burnett et al., 2003) collected in
a period between $24^{\text {th }}$ of Aug. 2001 until $1^{\text {st }}$ of Apr. 2004, just after the solar maximum activity in the SC 23. There was, however, a period when the satellite was switched into safe mode for 11.26 days due to a solar super storm called Halloween Event of 2003 (Skoug et al., 2004). Another SW average flux was reported by Gosling (2014). There, the flux at the ecliptic plane and at 1 AU was estimated to be $\bar{f}=3.8 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. The number includes alpha particles as well as heavier ion elements. However, it is not mentioned in which time frame the SW data was collected, nor by which satellite.

The RHA study process requires information on a differential and an integral particle flux to estimate the amount of radiation deposited within a material being exposed to the SW plasma. A differential flux of $f$ is defined as a number of particles crossing a unit area within a unit time at a given energy, namely $\mathrm{cm}^{-2} \mathrm{~s}^{-1} \mathrm{keV}^{-1}$, while the integral flux $f^{\mathrm{I}}$ is a differential flux integrated above a given energy threshold (ECSS, 2020):

$$
\begin{equation*}
f^{\mathrm{I}}(\geq E)=\int_{\mathrm{E}}^{\mathrm{E}_{\max }} f d E^{\prime} \tag{2}
\end{equation*}
$$

Here, $E_{\max }$ corresponds to the highest kinetic energy of a particle recorded within a given period. However, in case, e.g., of a stack of many layers made of different materials and having different thicknesses, the differential flux must be integrated over energies in which the corresponding penetration depth reflects the selected layer thickness. Using this method, one can calculate a proton fluence magnitude deposited in each stack layer.

In the RHA study phase, there are in common use the so-called directional- and omni-directional- differential fluxes. The former are given, in addition, per unit solid angle $\mathrm{cm}^{-2} \mathrm{~s}^{-1} \mathrm{sr}^{-1} \mathrm{keV}^{-1}$ while the latter are integrated over a fraction or a whole sphere solid angle ( $4 \pi$ ), i.e., $\mathrm{cm}^{-2} \mathrm{~s}^{-1} \mathrm{keV}^{-1}$. In the work presented here, omni-directional differential proton fluxes are calculated, and these are hereafter called just differential proton fluxes.

There are literature sources for the SW protons that can be used to estimate integral proton flux. For example, Gloeckler (1984) reported a directional differential proton flux spectrum at 1 AU distance from the Sun from 0.5 keV up to 10 MeV where its peak at 1 keV has a magnitude of $\sim 10^{11} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1} \mathrm{sr}^{-1} \mathrm{keV}^{-1}$. Then integrating it around the peak, i.e., $1 \pm 0.1 \mathrm{keV}$, and a hemisphere, one ends up with an integral proton flux of $f^{\mathrm{I}}(0.9 \mathrm{keV} \leq E \leq 1.1 \mathrm{keV}) \sim 10^{11} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. The author, however, does not report which data source was used nor in which time frame data was collected. SW protons shall be integrated over a hemisphere. It is related due to the fact that SW particle stream has mostly radial components and that almost no SW particles are coming from the Sun with grazing angles higher than $\pm 90^{\circ}$. Detail explanations can be found in the B Yu \& Zhang (1990) estimated the SW integral ion flux above 1 keV to $f^{\mathrm{I}}(\geq 1 \mathrm{keV}) \sim 6 \times 10^{9}$ particles $\mathrm{cm}^{-2} \mathrm{~s}^{-1}$. This number includes protons, alpha particles as well as other ions present in the SW. Knowing


Figure 2: The top row, from left to right, shows a set of mesh grids of the SW proton differential fluxes recorded by the SOHO, the WIND, the ACE, and the DSCOVR satellites, respectively. Color-coded information is related to a number of records indicating how many times a given flux was recorded per calendar year. The bottom row shows a set of minimum (blue), average (green), and maximum (red) SW proton differential fluxes estimated from the mesh grid plots. Fluxes are based on data recorded in the calendar year 2017. The blue background color denotes the SSW proton energy range, while the red one the FSW energy range.
the SW composition, i.e., the ratio between the number of alpha particles and protons in the ecliptic plane and neglecting the traceable number of the other elements in the wind, the integral proton flux would then be $\sim 5.8 \times 10^{9} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. However, it is not clear rather the spectrum was estimated for the Sun-Earth L1 point or 1AU distance from the Sun. Another example is Lin et al. (1995), who published directional differential spectra of the SW protons at 1AU distance from the Sun based on the data taken from the WIND spacecraft and outside of the magnetosphere. There, the flux peak at 1 keV is $\sim 8 \times 10^{9} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1} \mathrm{sr}^{-1} \mathrm{keV}^{-1}$. Hence, integrating over a hemisphere and an energy plateau of roughly 0.2 keV around 1 keV , the integral proton flux is $f^{\mathrm{I}}(0.9 \mathrm{keV} \leq E \leq 1.1 \mathrm{keV}) \sim 10^{10}$ $\mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. Another value was reported by Minow et al. (2007). The authors presented their numerical reconstruction of a radiation environment of the GENESIS mission (Burnett et al., 2003). A spectrogram was presented where protons for energies of $1 \pm 0.1 \mathrm{keV}$ have a directional differential flux magnitude of $\sim 10^{11} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1} \mathrm{sr}^{-1} \mathrm{keV}^{-1}$. Integrating the value over a hemisphere and an energy band of 0.2 keVs as well as transferring the numbers from the Sun-Earth L1 point to 1AU by an inverse square law, the integral proton flux would be higher than $f^{\mathrm{I}}(0.9 \mathrm{keV} \leq E \leq 1.1 \mathrm{keV}) \sim 10^{11} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. Also Gloeckler et al. (2008) reported directional differential proton flux spectra, see Fig. 11 One can carefully digitalize the spectrum and integrate for proton energies lower than 10 keV . Then one obtains a value of $\approx 5.41 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$.

Those values may suggest that when all energies are
used for the integration procedure, the integral flux $f^{\mathrm{I}}(\lesssim 10 \mathrm{keV})$ would be larger than the magnitude of at least $10^{10} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. The work presented here reveals that number.

## 3 Results

In order to calculate a differential proton flux, i.e., $\mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1} \mathrm{keV}^{-1}$, a series of two values, the socalled moments, were taken from a publicly available satellite data set (NASA, 2021, ESA/NASA, 2021). Those are the proton bulk velocity and the proton number density (Verscharen et al., 2019 Case et al. 2020). Both values were averaged and stored by a satellite storage system within different time intervals. Here, by the system, it is meant that a satellite is performing SW proton current measurements while on-ground operations compute raw data to obtain, e.g., the proton speed or the number density. Raw data were recorded at $30 \mathrm{~s}, 64 \mathrm{~s}, 92 \mathrm{~s}$, and 60 s for SOHO, ACE, WIND, and DSCOVR, respectively. It shall be pointed out that using moments for calculating the differential proton flux, a thermal component of the SW is neglected. However, SW thermal speed has a magnitude of just a few percent of the radial component of the SW speed (Němeček et al., 2021). Also, the influence of the thermal component will average out for a large data set used to calculate the flux.

In the following Tables 14 the presented fluxes are organized in calendar year periods, i.e., from $1^{\text {st }}$ of January till the last day of a selected year. Such an approach allows space scientists to identify fluxes for a selected activity phase of the Sun. Hence, radiation anal-


Figure 3: Integral proton flux $f^{\mathrm{I}}$ spectra of the SW protons calculated by integrating minimum, average, and maximum differential fluxes based on the SOHO, the WIND, the ACE, and the DSCOVR satellites data sets. Fluxes are based on data recorded in the calendar year 2017.
ysis of space components can be made for a maximum, a minimum, or an intermediate Sun activity state. All fluxes are calculated for SSW as well as FSW flows, assuming, after Abbo et al. (2016) and Bale et al. (2019), that SSW is classified for proton speeds $<500 \mathrm{~km} \mathrm{~s}^{-1}$ while FSW covers proton speeds $\geq 500 \mathrm{~km} \mathrm{~s}^{-1}(\geq 1.3$ $\mathrm{keV})$. In addition, average proton flux was also calculated for the SSW, the FSW and the whole energy range recorded within a given calendar year.

Proton bulk velocity and number density were processed as follows. First, both values were excluded from empty records, i.e., records where velocity or number density were flagged, e.g., in the case of the SOHO satellite, by a number of -1 . Such a number informs that, for a specific time, the data is not present. Next, a mesh grid of a proton differential flux was compiled, see Fig. 2 (top row). The Y-axis denotes a product of a proton velocity $v$, a number density $n$, and a kinetic energy $E$, i.e., the differential flux, namely $f=n v / E$, while on the X-axis, the proton kinetic energy is set. A single grid cell with coordinates $i j$ provides colorcoded information on the number of records $N_{\mathrm{ij}}$. It represents an aggregated number of differential fluxes having a magnitude in the range $\{f, f+d f\}$ recorded for a kinetic energy range $\{E, E+d E\}$. Here, in this representation (Eq. 3), the $f_{i, j}$ and the $E_{\mathrm{j}}$ are representing a mean value of $<\{f, f+d f\}>$ and $<\{E, E+d E\}>$ for a $i j$ cell of the mesh grid, respectively. Using matrix notation, the grid can be presented as follows:

$$
\left\{\mathbf{N}_{\mathrm{ij}}\right\}=\left[\begin{array}{cccccc}
E_{1} & E_{2} & \cdots & E_{\mathrm{j}} & \cdots & E_{1}  \tag{3}\\
N_{\mathrm{k} 1} & N_{\mathrm{k} 2} & \cdots & N_{\mathrm{kj}} & \cdots & N_{\mathrm{k} 1} \\
\vdots & \vdots & \ddots & \vdots & . & \vdots \\
N_{\mathrm{i} 1} & N_{\mathrm{i} 2} & \cdots & N_{\mathrm{ij}} & \cdots & N_{\mathrm{il}} \\
\vdots & \vdots & . & \vdots & \ddots & \vdots \\
N_{21} & N_{22} & \cdots & N_{2 \mathrm{j}} & \cdots & N_{21} \\
N_{11} & N_{12} & \cdots & N_{1 \mathrm{j}} & \cdots & N_{11}
\end{array}\right] \begin{aligned}
& \\
& f_{\mathrm{k}, \mathrm{j}} \\
& \vdots \\
& f_{\mathrm{i}, \mathrm{j}} \\
& \vdots \\
& f_{2, \mathrm{j}} \\
& f_{1, \mathrm{j}}
\end{aligned}
$$

It must be pointed out that the number $N_{\mathrm{ij}}$ depends on a grid dimension. For the calculations presented here, 250x250 cells were used. All grids shown in Fig. 2 (top row) are based on the data recorded in the calendar year 2017. Columns, from left to right, correspond to data sets collected by the SOHO, the WIND, the ACE, and the DSCOVR satellite, respectively. The SSW energy range is marked with blue and the FSW energy range with a red background color. The color-coded scale is set from 1 to 365 . It corresponds to a number of records $N_{\mathrm{ij}}$ per cell of a mesh grid. Its lower boundary value (1) shall be interpreted as a single occurrence of a flux $f_{\mathrm{i}, \mathrm{j}}$ for a proton kinetic energy $E_{\mathrm{j}}$ recorded in a given year. The upper boundary value has a slightly different function. Here, it means that (within a year) a flux $f_{\mathrm{i}, \mathrm{j}}$ for a proton kinetic energy $E_{\mathrm{j}}$ is recorded 365 times or more. Hence, the flux is recorded statistically at least once a day in a year. The year 2017 was chosen since DSCOVR has more available SW data than in 2016. Also, 2017 is a year when data from all four satellites could be directly compared. The advantage of a grid representation of the SW data, given by the Eq. 3 . is to identify how often a differential flux $f_{\mathrm{i}, \mathrm{j}}$ is recorded within a given calendar year. Hence, it shall be interpreted simply as a 2D-histogram of the flux. Data from the WIND and the ACE satellite may suggest that most of the fluxes were recorded below $\sim 1.5 \mathrm{keV}$. A closer look at the SOHO and the DSCOVR grid plot reveals that there is much larger FSW flux population around $\sim 2 \mathrm{keV}$ than for the WIND and the ACE satellites. Therefore, it is of greatest importance to analyze SW data from multiple solar observatories. It can be noticed that fluxes computed by use of the SOHO data have much broader magnitudes than those computed from the other three satellites. This is because the proton number density recorded by the SOHO satellite is lower or higher than the corresponding numbers recorded by the other three satellites. For example, proton number density from SOHO for the very first data entry in 2016 equals $1.01 \mathrm{p}^{+} \mathrm{cm}^{-3}$, while for the WIND it is $1.87 \mathrm{p}^{+} \mathrm{cm}^{-3}$ and for the ACE it is 1.85 $\mathrm{p}^{+} \mathrm{cm}^{-3}$. On the other hand, proton number density from SOHO for the very last data entry in 2016 equals $7.72 \mathrm{p}^{+} \mathrm{cm}^{-3}$, while for the DSCOVR it is $5.87 \mathrm{p}^{+} \mathrm{cm}^{-3}$ and for the WIND it is $6.91 \mathrm{p}^{+} \mathrm{cm}^{-3}$. However, proton velocity recorded by the SOHO and the other three satellites for those two mentioned points in time differs within just a few percent. Hence, the estimated differential flux from SOHO data is lower or higher than

Table 1: Average and integral proton fluxes are listed from the data collected by the SOHO satellite for the SC 23 (1996-2008), the SC 24 (2009-2019), and additionally for the calendar year 2020. The first column gives the calendar year. Then, two columns give the minimum and a maximum energy recorded by a satellite within a given calendar year, stated in keV units. Next, the average proton flux $\bar{f} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ calculated for the whole energy range and for the SSW and the FSW energy range is given, followed by three integral fluxes $f^{1} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. They are based on the minimum, the average and the maximum differential fluxes for the SSW and FSW flows. The FSW integral flux is calculated for an energy range of $1.3 \mathrm{keV} \leq E<E_{\max }$ and the second, stored in parenthesis, for the proton energy range of $1.3 \mathrm{keV} \leq E<3.3 \mathrm{keV}$. The last column contains the number of sunspots. Furthermore, each SC data collection is summarized by an average set of fluxes.

| Date | $E_{\text {min }}$ | $E_{\max }$ | $\bar{f}_{\text {S }}$ | $\bar{f}_{\text {S,SSW }}$ | $\bar{f}_{\text {S, FSW }}$ | $f_{\text {S,SSW }}^{\text {I,MIN }}$ | $f_{\text {S,SSW }}^{\text {I, A }}$ | $f_{\text {S, SSW }}^{\text {I,MAX }}$ | $f_{\text {S, FSW }}^{\text {I,MIN }}$ | $f_{\text {S, FSW }}^{\text {I, A }}$ | $f_{\text {S, FSW }}^{\text {I,MAX }}$ | NSS |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1996 | 0.38 | 2.82 | 2.95 | 3.08 | 2.40 | 1.44 | 4.20 | 13.54 | 0.90 (0.90) | 1.84 (1.84) | 4.22 (4.22) | 12 |
| 1997 | 0.39 | 2.93 | 3.10 | 3.12 | 2.53 | 0.59 | 3.81 | 18.29 | 1.05 (1.05) | 2.09 (2.09) | 6.02 (6.02) | 29 |
| 1998 | 0.39 | 5.00 | 2.94 | 2.96 | 2.79 | 0.54 | 3.76 | 15.17 | 2.55 (0.92) | 5.46 (3.65) | 11.96 (9.93) | 88 |
| 1999 | 0.40 | 5.03 | 2.62 | 2.80 | 2.10 | 0.57 | 3.62 | 16.43 | 0.72 (0.23) | 2.52 (1.92) | 11.69 (10.92) | 136 |
| 2000 | 0.39 | 5.26 | 2.66 | 2.69 | 2.60 | 0.36 | 3.62 | 19.41 | 0.45 (0.13) | 4.07 (2.59) | 22.27 (18.07) | 174 |
| 2001 | 0.39 | 5.26 | 2.62 | 2.55 | 3.03 | 0.47 | 3.30 | 20.57 | 0.52 (0.21) | 7.58 (3.38) | 37.67 (24.37) | 170 |
| 2002 | 0.40 | 5.17 | 2.86 | 2.85 | 2.89 | 0.34 | 3.45 | 21.45 | 0.62 (0.12) | 3.13 (2.45) | 14.01 (13.08) | 164 |
| 2003 | 0.40 | 5.27 | 2.73 | 2.65 | 2.79 | 0.24 | 3.01 | 15.83 | 0.20 (0.04) | 3.68 (2.65) | 27.89 (24.56) | 99 |
| 2004 | 0.39 | 5.27 | 2.12 | 2.07 | 2.28 | 0.10 | 2.44 | 16.73 | 0.26 (0.11) | 3.25 (2.34) | 23.30 (19.63) | 65 |
| 2005 | 0.39 | 5.27 | 2.14 | 2.11 | 2.19 | 0.31 | 2.57 | 19.60 | 0.28 (0.10) | 3.75 (2.11) | 32.34 (22.35) | 46 |
| 2006 | 0.38 | 5.22 | 1.84 | 1.84 | 1.86 | 0.14 | 2.29 | 18.67 | 0.84 (0.27) | 3.62 (1.81) | 13.09 (9.46) | 25 |
| 2007 | 0.38 | 3.86 | 1.65 | 1.58 | 1.83 | 0.17 | 1.99 | 21.09 | 0.96 (0.46) | 2.27 (1.75) | 7.24 (6.70) | 13 |
| 2008 | 0.38 | 3.58 | 1.53 | 1.49 | 1.61 | 0.18 | 1.86 | 15.00 | 0.63 (0.48) | 1.70 (1.54) | 6.27 (6.11) | 4 |
| $\begin{aligned} & \text { Average } \\ & \text { '96-'08 } \\ & \hline \end{aligned}$ | - | - | 2.44 | 2.45 | 2.38 | 0.42 | 3.07 | 17.83 | 0.77 (0.39) | 3.46 (2.32) | 16.77 (13.49) | - |
| 2009 | 0.38 | 2.46 | 1.36 | 1.36 | 1.26 | 0.11 | 1.70 | 13.59 | 0.53 (0.53) | 0.94 (0.94) | 1.97 (1.97) | 5 |
| 2010 | 0.38 | 3.85 | 1.60 | 1.60 | 1.58 | 0.16 | 1.99 | 18.03 | 0.90 (0.53) | 2.36 (1.95) | 8.53 (8.08) | 25 |
| 2011 | 0.38 | 4.87 | 1.68 | 1.66 | 1.83 | 0.15 | 2.09 | 20.93 | 0.86 (0.25) | 2.30 (1.89) | 14.52 (13.67) | 81 |
| 2012 | 0.38 | 5.13 | 1.74 | 1.72 | 1.89 | 0.14 | 2.13 | 22.57 | 1.80 (0.28) | 3.85 (2.05) | 20.45 (18.20) | 84 |
| 2013 | 0.38 | 4.96 | 1.64 | 1.63 | 1.67 | 0.08 | 2.07 | 22.78 | 0.35 (0.10) | 2.01 (1.62) | 12.46 (11.72) | 94 |
| 2014 | 0.38 | 5.02 | 1.81 | 1.79 | 2.00 | 0.18 | 2.23 | 15.18 | 0.95 (0.37) | 2.76 (2.11) | 10.82 (10.08) | 114 |
| 2015 | 0.38 | 4.96 | 2.15 | 2.14 | 2.18 | 0.22 | 2.53 | 20.57 | 1.08 (0.34) | 2.98 (2.18) | 19.16 (18.29) | 70 |
| 2016 | 0.38 | 4.11 | 1.87 | 1.86 | 1.89 | 0.19 | 2.22 | 15.56 | 1.11 (0.50) | 2.51 (1.85) | 7.77 (7.05) | 40 |
| 2017 | 0.38 | 4.00 | 1.64 | 1.56 | 1.86 | 0.19 | 1.84 | 16.52 | 0.46 (0.17) | 2.28 (1.84) | 8.96 (8.36) | 22 |
| 2018 | 0.38 | 3.00 | 1.38 | 1.37 | 1.47 | 0.15 | 1.70 | 12.22 | 0.27 (0.27) | 1.14 (1.14) | 4.05 (4.05) | 7 |
| 2019 | 0.38 | 4.72 | 1.20 | 1.17 | 1.61 | 0.15 | 1.44 | 11.92 | 1.20 (0.54) | 2.33 (1.66) | 5.14 (4.45) | 4 |
| $\begin{aligned} & \text { Average } \\ & \text { '09-'19 } \end{aligned}$ | - | - | 1.64 | 1.62 | 1.75 | 0.16 | 1.99 | 17.26 | 0.86 (0.35) | 2.31 (1.75) | 10.35 (9.63) | - |
| 2020 | 0.38 | 3.25 | 1.07 | 1.05 | 1.43 | 0.14 | 1.34 | 9.11 | 0.44 (0.44) | 1.24 (1.24) | 3.82 (3.82) | 9 |

Table 2: Average and integral proton fluxes are listed from the data collected by the WIND satellite for the SC 23 (1996-2008), the SC 24 (2009-2019), and additionally for the calendar year 2020 . The first column gives the calendar year. Then, two columns give the minimum and the maximum energy recorded by a satellite within a given calendar year, stated in keV units. Next, the average proton flux $\bar{f} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ calculated for the whole energy range and for the SSW and the FSW energy range is given, followed by three integral fluxes $f^{\mathrm{I}} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. They are based on the minimum, the average and the maximum differential fluxes for the SSW and FSW flows. The FSW integral flux is calculated for an energy range of $1.3 \mathrm{keV} \leq E<E_{\max }$ and the second, stored in parentheses, for the proton energy range of $1.3 \mathrm{keV} \leq E<3.3 \mathrm{keV}$. The last column contains the number of sunspots. Furthermore, each SC data collection is summarized by an average set of fluxes.

| Date | $E_{\text {min }}$ | $E_{\text {max }}$ | $\bar{f}_{\mathrm{W}}$ | $\bar{f}_{\mathrm{W}, \mathrm{SSW}}$ | $\bar{f}_{\text {W,FSW }}$ | $f_{\text {W,SSW }}^{\text {I,MIN }}$ | $f_{\text {W, }{ }^{\text {I, }} \text {, }}$ | $f_{\text {W,SSW }}^{\text {I,MAX }}$ | $f_{\text {W, FSW }}^{\text {I,MIN }}$ | $f_{\text {W, }{ }^{\mathrm{I}, \mathrm{A}} \mathrm{FW}}$ | $f_{\text {W, FSW }}^{\text {I,MAX }}$ | NSS |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1996 | - | - | - | - | - | - | - | - | - | - | - | 12 |
| 1997 | - | - | - | - | - | - | - | - | - | - | - | 29 |
| 1998 | - | - | - | - | - | - | - | - | - | - | - | 88 |
| 1999 | - | - | - | - | - | - | - | - | - | - | - | 136 |
| 2000 | - | - | - | - | - | - | - | - | - | - | - | 174 |
| 2001 | - | - | - | - | - | - | - | - | - | - | - | 170 |
| 2002 | - | - | - | - | - | - | - | - | - | - | - | 164 |
| 2003 | - | - | - | - | - | - | - | - | - | - | - | 99 |
| 2004 | 0.27 | 6.04 | 2.71 | 2.69 | 2.78 | 0.88 | 3.41 | 11.90 | 5.11 (1.69) | 7.25 (3.44) | 11.58 (7.36) | 65 |
| 2005 | 0.34 | 6.00 | 2.77 | 3.00 | 2.33 | 1.54 | 4.32 | 15.14 | 2.01 (0.52) | 4.39 (2.16) | 12.41 (9.19) | 46 |
| 2006 | 0.36 | 5.66 | 2.70 | 2.92 | 2.06 | 0.94 | 3.73 | 13.92 | 4.43 (1.01) | 5.43 (1.92) | 8.04 (4.44) | 25 |
| 2007 | 0.31 | 3.11 | 2.35 | 2.52 | 1.94 | 0.99 | 3.67 | 14.76 | 0.92 (0.92) | 1.73 (1.73) | 3.78 (3.78) | 13 |
| 2008 | 0.36 | 3.63 | 2.11 | 2.28 | 1.76 | 1.13 | 2.92 | 10.80 | 0.90 (0.77) | 1.67 (1.54) | 3.61 (3.48) | 4 |
| $\begin{aligned} & \text { Average } \\ & \text { '96-'08 } \end{aligned}$ | - | - | 2.53 | 2.68 | 2.17 | 1.10 | 3.61 | 13.30 | 2.67 (0.98) | 4.09 (2.16) | 7.88 (5.65) | - |
| 2009 | 0.28 | 2.61 | 2.16 | 2.18 | 1.61 | 1.44 | 3.41 | 11.41 | 0.86 (0.86) | 1.10 (1.10) | 1.48 (1.48) | 5 |
| 2010 | 0.35 | 3.65 | 2.18 | 2.26 | 1.74 | 0.93 | 3.00 | 10.95 | 2.24 (1.64) | 2.99 (2.38) | 4.89 (4.27) | 25 |
| 2011 | 0.29 | 4.15 | 2.22 | 2.26 | 2.04 | 1.14 | 3.55 | 14.50 | 1.08 (0.81) | 1.99 (1.72) | 5.86 (5.59) | 81 |
| 2012 | 0.37 | 3.57 | 2.28 | 2.31 | 2.09 | 0.62 | 2.95 | 11.63 | 1.46 (1.09) | 2.67 (2.30) | 6.59 (6.22) | 84 |
| 2013 | 0.30 | 3.57 | 2.22 | 2.26 | 1.91 | 0.83 | 3.23 | 12.80 | 0.68 (0.61) | 1.76 (1.68) | 4.63 (4.55) | 94 |
| 2014 | 0.32 | 4.71 | 2.44 | 2.44 | 2.52 | 1.10 | 3.46 | 12.94 | 1.52 (1.07) | 2.79 (2.33) | 5.45 (4.99) | 114 |
| 2015 | 0.32 | 3.95 | 3.05 | 3.20 | 2.59 | 1.56 | 4.63 | 17.64 | 2.14 (0.96) | 3.50 (2.31) | 8.36 (7.17) | 70 |
| 2016 | 0.35 | 3.30 | 2.88 | 3.13 | 2.26 | 1.49 | 4.38 | 15.07 | 1.19 (1.19) | 2.12 (2.12) | 4.81 (4.81) | 40 |
| 2017 | 0.36 | 3.86 | 2.78 | 3.01 | 2.28 | 1.13 | 3.85 | 14.56 | 1.26 (0.87) | 2.55 (2.15) | 5.36 (4.95) | 22 |
| 2018 | 0.37 | 2.77 | 2.82 | 2.92 | 2.11 | 1.50 | 3.60 | 10.73 | 0.95 (0.95) | 1.51 (1.51) | 2.60 (2.60) | 7 |
| 2019 | 0.34 | 3.44 | 2.57 | 2.62 | 2.20 | 1.41 | 3.40 | 11.52 | 1.45 (1.37) | 2.14 (2.06) | 3.64 (3.56) | 4 |
| $\begin{aligned} & \hline \text { Average } \\ & \text { ‘09-'19 } \\ & \hline \end{aligned}$ | - | - | 2.51 | 2.60 | 2.12 | 1.20 | 3.59 | 13.07 | 1.35 (1.04) | 2.28 (1.97) | 4.88 (4.56) | - |
| 2020 | 0.34 | 3.07 | 2.43 | 2.48 | 1.90 | 2.02 | 3.13 | 9.42 | 1.14 (1.14) | 1.66 (1.66) | 2.67 (2.67) | 9 |

Table 3: Average and integral proton fluxes are listed from the data collected by the ACE satellite for the SC 23 (1996-2008), and the SC 24 (2009-2019). The first column gives the calendar year. Then, two columns give the minimum and the maximum energy recorded by a satellite within a given calendar year. It is stated in keV units. Next, the average proton flux $\bar{f} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ calculated for the whole energy range and for the SSW and the FSW energy range is given, followed by the three integral fluxes $f^{\mathrm{I}} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. They are based on the minimum, the average and the maximum differential fluxes for the SSW and FSW flows. The FSW integral flux is calculated for an energy range of $1.3 \mathrm{keV} \leq E<E_{\max }$ and the second, stored in parentheses, for the proton energy range of $1.3 \mathrm{keV} \leq E<3.3 \mathrm{keV}$. The last column contains the number of sunspots. Furthermore, each SC data collection is summarized by an average set of fluxes.

| Date | $E_{\text {min }}$ | $E_{\max }$ | $\bar{f}_{\text {A }}$ | $\bar{f}_{\text {A,SSW }}$ | $\bar{f}_{\text {A,FSW }}$ | $f_{\text {A }, \text { SSW }}^{\text {I,MIN }}$ | $f_{\mathrm{A}, \mathrm{SSW}}^{\mathrm{I}, \mathrm{A}}$ | $f_{\text {A , SSW }}^{\text {I,MAX }}$ | $f_{\text {A, FSW }}^{\text {I,MIN }}$ | $f_{\text {A , FSW }}^{\text {I, A }}$ | $f_{\text {A, FSW }}^{\text {I, MAX }}$ | NSS |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1996 | - | - | - | - | - | - | - | - |  | - | - | 12 |
| 1997 | - | - | - | - | - | - | - | - | - | - | - | 29 |
| 1998 | 0.39 | 4.19 | 3.22 | 3.30 | 2.74 | 1.86 | 4.09 | 9.60 | 3.73 (2.72) | 4.40 (3.38) | 5.39 (4.37) | 88 |
| 1999 | 0.47 | 4.09 | 2.81 | 2.92 | 2.46 | 0.89 | 2.85 | 7.86 | 2.48 (1.21) | 3.30 (2.02) | 4.59 (3.31) | 136 |
| 2000 | 0.50 | 5.01 | 2.88 | 2.90 | 2.82 | 1.08 | 2.75 | 7.82 | 2.57 (1.43) | 3.73 (2.58) | 6.16 (5.00) | 174 |
| 2001 | 0.50 | 4.24 | 2.73 | 2.70 | 2.88 | 0.86 | 2.60 | 7.81 | 2.27 (1.88) | 3.35 (2.95) | 5.12 (4.71) | 170 |
| 2002 | 0.50 | 5.09 | 2.91 | 2.98 | 2.69 | 1.30 | 2.99 | 7.95 | 3.55 (1.38) | 4.40 (2.22) | 5.76 (3.56) | 164 |
| 2003 | 0.52 | 5.38 | 2.64 | 2.83 | 2.52 | 1.53 | 2.89 | 5.35 | 3.29 (1.14) | 4.47 (2.28) | 7.05 (4.81) | 99 |
| 2004 | 0.49 | 5.61 | 2.55 | 2.53 | 2.57 | 1.18 | 2.40 | 5.20 | 2.71 (1.44) | 3.75 (2.44) | 5.52 (4.18) | 65 |
| 2005 | 0.51 | 5.49 | 2.71 | 2.96 | 2.28 | 1.28 | 2.99 | 7.54 | 3.28 (1.09) | 4.36 (2.06) | 6.13 (3.71) | 46 |
| 2006 | 0.39 | 4.54 | 2.50 | 2.81 | 1.94 | 1.70 | 3.16 | 6.91 | 2.69 (1.20) | 3.23 (1.73) | 4.22 (2.72) | 25 |
| 2007 | 0.51 | 3.11 | 2.28 | 2.52 | 1.94 | 1.09 | 2.42 | 5.92 | 1.21 (1.21) | 1.76 (1.76) | 2.72 (2.72) | 13 |
| 2008 | 0.42 | 3.63 | 1.86 | 2.08 | 1.63 | 1.26 | 2.21 | 4.41 | 1.12 (0.99) | 1.59 (1.46) | 2.45 (2.32) | 4 |
| $\begin{aligned} & \text { Average } \\ & \text { '96-'08 } \end{aligned}$ | - | - | 2.64 | 2.78 | 2.41 | 1.28 | 2.85 | 6.94 | 2.63 (1.43) | 3.49 (2.26) | 5.01 (3.76) | - |
| 2009 | 0.44 | 2.56 | 1.87 | 1.92 | 1.40 | 1.35 | 2.26 | 4.16 | 0.86 (0.86) | 0.94 (0.94) | 1.05 (1.05) | 5 |
| 2010 | 0.50 | 3.42 | 1.84 | 1.97 | 1.39 | 0.99 | 1.86 | 3.37 | 1.81 (1.71) | 2.01 (1.91) | 2.25 (2.15) | 25 |
| 2011 | 0.50 | 3.53 | 1.98 | 2.09 | 1.59 | 1.23 | 1.89 | 2.93 | 1.38 (1.29) | 1.54 (1.45) | 1.73 (1.64) | 81 |
| 2012 | 0.47 | 2.59 | 1.99 | 1.97 | 2.41 | 1.13 | 2.00 | 3.47 | 1.59 (1.59) | 1.70 (1.70) | 1.81 (1.81) | 84 |
| 2013 | 0.50 | 3.43 | 1.82 | 1.84 | 1.75 | 0.79 | 1.78 | 3.88 | 1.32 (1.28) | 1.64 (1.60) | 2.05 (2.01) | 94 |
| 2014 | 0.49 | 4.22 | 2.05 | 2.05 | 2.00 | 1.04 | 2.11 | 4.35 | 1.82 (1.57) | 2.11 (1.86) | 2.45 (2.20) | 114 |
| 2015 | 0.49 | 3.68 | 2.24 | 2.36 | 1.91 | 1.17 | 2.35 | 4.94 | 1.49 (1.29) | 1.96 (1.75) | 2.73 (2.52) | 70 |
| 2016 | 0.54 | 3.40 | 2.13 | 2.30 | 1.67 | 1.04 | 2.02 | 4.02 | 1.50 (1.39) | 1.77 (1.77) | 2.16 (2.05) | 40 |
| 2017 | 0.54 | 3.82 | 2.18 | 2.37 | 1.79 | 0.98 | 2.00 | 4.35 | 1.58 (1.30) | 2.00 (1.72) | 2.67 (2.39) | 22 |
| 2018 | 0.53 | 2.43 | 2.28 | 2.38 | 1.54 | 1.55 | 2.19 | 3.06 | 0.88 (0.88) | 0.92 (0.92) | 0.97 (0.97) | 7 |
| 2019 | 0.54 | 1.96 | 1.93 | 1.96 | 1.74 | 1.37 | 1.88 | 2.57 | 0.69 (0.69) | 0.73 (0.73) | 0.78 (0.78) | 4 |
| $\begin{aligned} & \text { Average } \\ & \text { '09 - '19 } \end{aligned}$ | - | - | 2.03 | 2.11 | 1.74 | 1.15 | 2.03 | 3.74 | 1.36 (1.26) | 1.57 (1.49) | 1.88 (1.78) | - |

Table 4: Average and integral proton fluxes are listed from the data collected by the DSCOVR satellite for the SC 24 (2009-2019). The first column gives the calendar year. Then, two columns give the minimum and the maximum energy recorded by a satellite within a given calendar year. It is stated in keV units. Next, the average proton flux $\bar{f} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ calculated for the whole energy range and for the SSW and the FSW energy range is given, followed by the three integral fluxes $f^{1} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. They are based on the minimum, the average and the maximum differential fluxes for the SSW and FSW flows. The FSW integral flux is calculated for an energy range of $1.3 \mathrm{keV} \leq E<E_{\max }$ and the second, stored in parentheses, for the proton energy range of $1.3 \mathrm{keV} \leq E<3.3 \mathrm{keV}$. The last column contains the number of sunspots. Furthermore, each SC data collection is summarized by an average set of fluxes.

| Date | $E_{\text {min }}$ | $E_{\text {max }}$ | $\bar{f}_{\mathrm{D}}$ | $\bar{f}_{\text {D, SSW }}$ | $\bar{f}_{\text {D, FSW }}$ | $f_{\text {D,SSW }}^{\text {I,MIN }}$ | $f_{\text {D,SSW }}^{\text {I,A }}$ | $f_{\text {D,SSW }}^{\text {I,MAX }}$ | $f_{\mathrm{D}, \mathrm{FSW}}^{\mathrm{I}, \mathrm{MIN}}$ | $f_{\mathrm{D}, \mathrm{FSW}}^{\mathrm{I}, \mathrm{A}}$ | $f_{\text {D, FSW }}^{\text {I, MAX }}$ | NSS |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2009 |  |  |  |  |  |  |  |  |  |  |  | 5 |
| 2010 | - | - | - | - | - | - | - | - | - | - |  | 25 |
| 2011 | - | - | - | - | - | - | - | - | - |  |  | 81 |
| 2012 | - | - | - | - | - | - | - | - | - | - | - | 84 |
| 2013 | - | - | - | - | - | - | - | - | - | - | - | 94 |
| 2014 | - | - | - | - | - | - |  |  | - |  |  | 114 |
| 2015 |  | - | - | - | - |  |  |  |  |  |  | 70 |
| 2016 | 0.33 | 3.67 | 2.66 | 3.03 | 1.95 | 1.29 | 4.07 | 14.50 | 1.54 (1.31) | 2.32 (2.09) | 4.48 (4.25) | 40 |
| 2017 | 0.35 | 3.86 | 2.70 | 2.99 | 2.05 | 1.17 | 3.95 | 17.36 | 1.98 (1.15) | 2.96 (2.13) | 5.73 (4.89) | 22 |
| 2018 | 0.39 | 2.84 | 2.81 | 2.94 | 1.97 | 1.23 | 3.63 | 11.37 | 0.92 (0.92) | 1.39 (1.39) | 2.27 (2.27) | 7 |
| 2019 | 0.36 | 2.20 | 2.46 | 2.51 | 2.03 | 1.26 | 3.29 | 9.14 | 0.72 (0.72) | 1.03 (1.03) | 1.56 (1.56) | 4 |
| $\begin{aligned} & \hline \text { Average } \\ & \text { '09-'19 } \end{aligned}$ |  |  | 2.66 | 2.87 | 2.00 | 1.24 | 3.73 | 13.09 | 1.29 (1.03) | 1.90 (1.66) | 3.51 (3.24) |  |

the one computed from data taken from the other three satellites. Here, the calendar year 2016 was used as an example, since, for the first and the last day of that year, the proton number density and the proton velocity were present for all four satellites, except DSCOVR (the $1^{\text {st }}$ day of the year) and ACE (the last day of the year).

A comparison of proton number density and velocity from all four satellites and four calendar years is given in the A. It can be observed that the SOHO satellite records protons with a slightly wider velocity range and wider density values than the other three satellites. This can be explained by the fact that SOHO has the smallest data value used by the on-ground operations to calculate both plasma quantities. Pairs of numbers $(n, v)$ are derived from the SW proton current measured within just 30 seconds. The other three satellites perform two- or three-times longer measurements of the current. Hence, SOHO may provide the numbers with larger uncertainty than the other three satellites. Also, it must be kept in mind that two decades of SOHO operation in space may have degraded its subsystems responsible for SW proton current measurements. Also, all four satellites were made with different technologies and at different times, which may explain the observed differences in plasma parameters. The explanations given above are speculative and will be a part of the next study campaign.

The second row in Fig. 2 aggregates plots of maximum, average, and minimum differential proton fluxes from the SOHO, the WIND, the ACE, and the DSCOVR satellite, respectively. The minimum and the maximum ones are simply the lowest and highest fluxes recorded for the given proton kinetic energy $E_{\mathrm{j}}$, while the average differential flux is defined as:

$$
\begin{equation*}
f_{\mathrm{j}}=\frac{\sum_{i=1}^{\mathrm{K}} N_{i} f_{i, j}}{\sum_{i=1}^{\mathrm{K}} N_{i}}, \quad 1 \leq j \leq L, \quad 1 \leq i \leq K \tag{4}
\end{equation*}
$$

Here, the unclustered data were used, i.e., the differential flux is defined as $f_{i, j}=\{n v\}_{i, j} / E_{j} . L$ is the number of all individual proton kinetic energies recorded by a satellite within a given calendar year, while $K$, on the other hand, is a number of all differential proton fluxes calculated for the $j$ 'th kinetic energy. Hence, $f_{\mathrm{j}}$ builds a set of values for a corresponding set of proton kinetic energies $E_{\mathrm{j}}$. Hereafter, for simplicity, $f_{\mathrm{j}}$ is denoted as $f$. Clearly, data recorded by the WIND and the DSCOVR satellite are comparable, i.e., trends in the maximum, the average, and the minimum fluxes indicate similar patterns throughout the whole energy range. This is contrary to the data collected by the ACE satellite. There, the patterns, such as the flux spikes below $\sim 1 \mathrm{keV}$, cannot be noticed. Also, one can spot an order of magnitude smaller fluxes, i.e., $\sim 10^{7}$ $\mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$, between $\sim 1.2 \mathrm{keV}$ and $\sim 2.5 \mathrm{keV}$ from the WIND and the ACE based differential spectra. However, such values cannot be spotted in the data set collected by the DSCOVR satellite. It must be emphasized that all data, including the mentioned artifacts,
were taken for the differential proton flux magnitude calculations.

Followed by Eq. 2, the minimum, the average, and the maximum differential fluxes $f$ were used to calculate corresponding integral fluxes $f^{\mathrm{I}}$. The result of that procedure is presented in Fig. 3. The fluxes are computed from data sets from the calendar year 2017. Clearly, $f^{\mathrm{I}}$ based on the average and the maximum differential fluxes from the WIND and the DSCOVR data sets indicates a comparable descending trend. For the integral flux based on the minimum differential flux, computation of the WIND and the ACE data sets reveal their comparable magnitudes along with the whole energy range. In the case of the SOHO data set, maximum integral flux indicate the highest magnitude when compared to the other three. Conversely, the minimum flux is lower than for the other three up to an energy of 3.2 keV . The highest integral flux was recorded by the SOHO satellite and is equal to $\sim 2.5 \times 10^{9} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$.

The average as well as the integral proton fluxes calculated for all years in the SC 23 , the SC 24 , and additionally for the calendar year 2020, are listed in Tables 1, 2, 3 and 4. It should be noted that data from the SOHO satellite were processed from August 1996, since the SC 23 had started from that date. For the WIND satellite, the data were processed from May 2004, since from that date the satellite reached its destination at the Sun-Earth L1 point. Since differential proton flux spectra have non-uniform energy steps, they were linearly interpolated with a step of $10^{-5} \mathrm{keV}$ and integrated to calculate the integral proton fluxes. Tables aggregate calculated fluxes based on the data from the SOHO, the WIND, the ACE, and the DSCOVR satellites. Data are presented throughout all tables with the same format. The first column contains a calendar year. Next, two columns give a minimum $E_{\text {min }}$ and a maximum energy $E_{\max }$ of the SW protons recorded within that period. The energies are given in the keV unit. Then an average proton flux $\bar{f} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ calculated for the whole energy range and for the SSW and the FSW energy range is listed and is followed by the three integral fluxes $f^{1} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ also calculated for the SSW and the FSW energy range. The fluxes have subscripts $S, W, A$, and $D$, which stand for four considered satellite names. They are based on the minimum (MIN), the average (A), and the maximum (MAX) differential fluxes. The last column in tables contains an average number of sunspots $N S S$ (SILSO, 2021) for a given calendar year. Each SC is representatively characterized by a set of average values for the fluxes. Table cells where no data is given are marked with a horizontal bar.

From the mesh grid differential flux spectra it can be noticed that for years close to the solar maximum, FSW has just a few records, please see Fig. 2 for energies $\gtrsim 3 \mathrm{keV}\left(\gtrsim 760 \mathrm{~km} \mathrm{~s}^{-1}\right)$. In fact, some authors, e.g., Schwenn (2000) calculate FSW proton flux magnitude only up to $800 \mathrm{~km} \mathrm{~s}^{-1}(\sim 3.3 \mathrm{keV})$. Above such a value the Coronal Mass Ejections (CMEs) are mostly responsible for generating the protons (Sheeley et al. 1999, Papaioannou et al. 2016). This data was not ex-


Figure 4: The upper left plot shows the number of sunspots averaged over a calendar year (SILSO, 2021) together with an average proton flux per calendar year calculated by the use of the SOHO, the WIND, the ACE, and the DSCOVR SW data. The upper right plot shows a direct relationship between these two quantities. Here, average proton flux was calculated by use of the whole energy range of the protons within a given calendar year. The lower left plot depicts average proton flux as a function of the calendar year for the SSW (solid-) and the FSW (dotted- color-coded lines). The lower right plot shows integral proton flux based on average differential proton flux as a function of the calendar year. Here, similarly, the SSW and the FSW fluxes are drowned by color-coded solid and dotted lines, respectively. Here, for the FSW the whole proton energy was considered.

Table 5: The table gives a coefficient of determination $R^{2}$ and fitted curve equations for the relation between the average proton flux and the number of sunspots. Estimated quantities are given for the four satellites. $1^{\text {st }}, 2^{\text {nd }}$ and $3^{\text {rd }}$ order polynomials were considered as candidates for fitting curves. Also, for the SOHO satellite, data was taken for all calendar years as well as from (inclusively) 1999. $R^{2}$ coefficient values for the SOHO satellite where data was reduced is denoted by the $R D$ phrase. In case of ACE, WIND and DSCOVR satellites, data from all calendar years were used for $R^{2}$ estimation.

| $R^{2}$ | $R^{2}$ <br> Satellite data source | $R^{2}$ <br> $\left(2^{\text {st }}\right)$ | $R^{2}$ <br> $\left(3^{\text {rd }}\right)$ | Fitted curve equation <br> $\left(3^{\text {rd }}\right)$ |
| :--- | :---: | :---: | :---: | :---: | :---: |

cluded from the analysis since such protons contribute to degradation of materials under the IS radiation environment. Hence, columns in Tables 1, 2, 3, and 4 related to the FSW integral proton flux have a pair of values, i.e., the first for the FSW integral flux calculated for the energy range of $1.3 \mathrm{keV} \leq E<E_{\max }$ and the second, stored in a parentheses, for the FSW integral flux calculated for the proton energy range of 1.3 keV $\leq E<3.3 \mathrm{keV}$. Obviously, such energy range reduction results in a decrease in the FSW integral flux magnitude. Here, a fixed energy limit was chosen. However, the following procedure can be used to pick any upper limit for the reduction. First, mesh differential flux spectra for a specified calendar year can be visually reviewed, and the SW data energy range for the exclusion can be identified. Next, an integral flux spectrum can be calculated directly by integrating the differential flux spectrum. Another possibility is to use tables given in the D. For example, for the calendar year 2016 and the DSCOVR satellite, one can exclude the FSW records above 3.3 keV . The average integral proton flux calculated from 3.3 keV up to the end of the energy range is $0.23 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. This value can be directly read out from Table 15. Also, this value shall be then subtracted from the average integral proton flux calculated from 1.3 keV , which is $2.32 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. Hence, the FSW proton flux without SW records above 3.3 keV is $2.09 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. Please note that all necessary tools to perform such a procedure are provided, so the mesh differential flux spectra are stored as PNG files and the minimum, the average, and the maximum differential flux spectra are stored as CSV files within the GitHub repository (Sznajder, 2022).

Information stated in Tables 1, 2, 3 and 4 are graphically presented in Fig. 4. The upper left plot shows sunspot numbers NSS and average proton fluxes $\bar{f}$ as a function of the calendar year. The upper right plot presents the direct relation between these two quantities. Here, additionally, fitting curves are drawn. It was examined whether there is a linear (or non-linear) relationship between these two quantities. Average fluxes based on the SSW (solid lines) and the FSW (dotted lines) flows are presented in the lower left plot of the figure. Integral flux spectra based on the average differential fluxes are given in the lower right plot of the figure. Here, the whole energy range for the FSW flow was used. Also, solar cycle periods were indicated by different background colors. A correlation between the Sun's activity represented by the NSS and the flux magnitudes is indicated. The stronger the Sun's activity, the larger the fluxes, which has been confirmed by fitting different order polynomial functions to the relation of the average proton flux calculated over the whole energy range and the number of sunspots. It was compiled by applying the following procedure. First, the average proton flux values and the number of sunspots were interpolated for the same points in time. Then, a relation of both quantities was fitted by a polynomial function and the so-called coefficient of determination $R^{2}$ (Igual \& Seguí, 2017) was evaluated. Its value can vary between 0 and 1 . In the study examined here,
$R^{2}=0$ would mean that a hypothesis of a linear (or a non-linear) relationship between the average proton flux and the number of sunspots is false. On the other hand, $R^{2}=1$ would mean that all data points lie on a fitted line, hence such $R^{2}$ value represents a perfect fit situation. In reality, data points are scattered along a trend line and the $R^{2}$ value has a magnitude close to one. Here, it would mean that a hypothesis of a linear (or a non-linear) relationship between the average proton flux and the number of sunspots can be confirmed. Table 5 summarizes results from the fitting procedure. The first column gives the satellite name, then the $R^{2}$ values are listed. The last column gives fitted curve equations. The $R^{2}$ coefficient was calculated for polynomials from the $1^{\text {st }}$ till the $3^{\text {rd }}$ degree. When data from all calendar years is taken for calculation the $R^{2}$ coefficients for the $1^{\text {st }}$ order polynomial is lower than 0.5 . However, when SOHO data is taken from (inclusively) 1999, then the corresponding $R^{2}$ coefficient rises to 0.7 . Such a reduction was made since a visual data inspection revealed an anti-correlation between the examined quantities for years before 1999, see Fig. 4 upper left plot. Here, it means that when the number of sunspots increases, the proton flux magnitude decreases. The reduction was performed only to check whether there is an impact on the $R^{2}$ coefficient. The hypothesis turned out to be true. However, the nature of the anti-correlation of the quantities is unknown. It will be a part of a future study campaign. However, similar data reduction for the ACE satellite does not bring the $R^{2}$ increase. $R^{2}$ coefficients for which data was reduced are marked within the table by the $R D$ phrase. From the fitting procedure, one may conclude that, at least based on the SOHO reduced data, there is a strong relation $\left(R^{2}=0.7\right)$ between the average proton flux and the number of sunspots. The higher the number of sunspots, the larger the average proton flux. Also, it may be observed that when the number of data thrown into analysis decreases, the $R^{2}$ coefficient also decreases. Hence, one has to analyze data from at least two solar cycles to indicate the mentioned relation between the examined quantities. A third-order polynomial degree results in the highest set of $R^{2}$ coefficients. Further increase of polynomial degree results in a decrease of coefficient values. Fitted curve equations plotted in the right upper panel of Fig. 4 are given in the last column of the table. A similar study was made by Feldman et al. (1978) who analyzed average proton flux as a function of time. Please see Figure 5 from the mentioned manuscript. There, the conclusion was that the average proton flux is constant along the considered period of six calendar years. Data from 1971 till 1976 inclusively were analyzed. That period fell at the end of the SC 20. Possibly such a conclusion was drawn since a too small data set was processed, i.e., six years are roughly half of a SC period, which, by the analysis of the SOHO and the ACE data presented here, shows that it is required to process data from at least two SC to verify the hypothesis of the relation between the quantities. Also, a similar study was made by Larrodera \& Cid (2020). However, there, the au-
thors examined a linear correlation between the proton number density and the NSS using of all historical data from the ACE spacecraft. A correlation was qualified by the use of the Pearson's coefficient Aggarwal, 2015), which was $\sim 0.65$ for the SSW and the FSW flows.

It can also be recognized that the proton energy range at the solar maximum is approx. 2 -times wider than at the solar minimum. That observation is valid for both SC 23 and SC 24.
Integral proton fluxes, based on the minimum, the average, and the maximum differential fluxes, were also calculated for a descending set of energy ranges with a step of 0.1 keV . Tabulated values for each calendar year of the SC 23, SC 24, and calendar year 2020 are provided in the D .

## 4 Discussion

Magnitude values of the average proton flux as well as the integral proton flux calculated from data collected by the four satellites require further discussion. For example, for calendar year 2017, the average proton flux $\bar{f}$ based on the whole energy range is $1.64 \times, 2.78 \times$, $2.18 \times$, and $2.70 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ from the SOHO, the WIND, the ACE and the DSCOVR, respectively. Low flux values calculated from the SOHO data can be explained by the fact that the number density values measured by the satellite deviate substantially from the corresponding quantity recorded by the other three satellites, see Section 3 and A. Please note that the WIND and the DSCOVR satellites record protons from the energy of $\sim 0.3 \mathrm{keV}$, while the ACE records protons from the energy of $\sim 0.5 \mathrm{keV}$, see proton energy ranges in the Tables 1, 2, 3, and 4. Hence, a wider energy range results in potentially higher average proton flux, since more data is available for the analysis. In fact, the average proton flux calculated from the WIND and the DSCOVR data varies just within a few percent. In the case of SSW flows, the magnitude of the average proton flux $\bar{f}_{\text {SSW }}$ throughout the data between all four satellites indicates higher variations than fluxes from the FSW flow $\bar{f}_{\text {FSW }}$, please see bottom left plot on the Fig. 4 . The average proton flux is calculated based on the Eq. 1. The plot has one flux value for SSW and FSW flows and a selected calendar year. The maximum deviation between flux magnitudes from the SSW flow is recorded for the calendar year 2020, the $\bar{f}_{\mathrm{S}, \mathrm{SSW}}$ from the SOHO satellite is approx. $240 \%$ smaller than $\bar{f}_{\mathrm{W}, \mathrm{SSW}}$ from the WIND satellite. On the other hand, in the case of FSW flows, the maximum flux deviation is recorded for the calendar year 2018. Then, the $\bar{f}_{\mathrm{S}, \mathrm{FSW}}$ from the SOHO satellite is approx. $200 \%$ smaller than $\bar{f}_{\mathrm{W}, \mathrm{FSW}}$ from the WIND satellite. Hypothetically, higher flux magnitude deviation between all four satellite data sets for SSW flows, rather than FSW flows, may be related to higher uncertainty of proton current measurements performed by satellite FC subsystem for proton energies $\lesssim 1.3 \mathrm{keV}$. Differences in computational procedures could also explain the deviation when the proton number density and velocity are estimated out of SSW proton current measurements.

Also, one has to keep in mind that all four satellites were built within a time span of two decades. There is a comprehensive technology spread between all their subsystems responsible for SW proton current measurements. Hence, proton currents that are measured and processed vary between all four satellites. Therefore, it is of most interest, not only to the RHA community but more widely to the space science community, to report a study that would indicate differences in proton flux magnitudes calculated based on data from multiple solar observatories.

Integral average proton flux magnitudes manifest similar behavior as the average proton flux spectra, i.e., there is a higher flux magnitude deviation for SSW flows rather than FSW flows, see bottom right plot on Fig. 4. The proton flux is calculated based on Eq. 2. The plot has one flux value for SSW and FSW flows and a selected calendar year.

The SSW and FSW flows are quantified here as omnidirectional -differential, -average, and -integral fluxes. They are commonly used in the RHA community, e.g., while calculating radiation loads within satellite components in the low Earth orbit space environment, e.g., by use of the AP-8 or AE-8 models (ECSS, 2020). However, a transformation of omni-directional to the directional flux of SW protons can be simply performed by dividing flux magnitudes by a factor of $2 \pi$. This, truly not an ideal transformation, would only average omnidirectional fluxes by a solid angle of a hemisphere. A $2 \pi$ factor shall be used since a satellite SW proton current is measured from a hemisphere with a set of the so-called azimuth angles defined between the center direction to the Sun and a normal of a satellite measuring subsystem, e.g. a FC of a WIND satellite, see B. Such a value is used to calculate the proton number density $n$. Hence, $n$ encapsulates information about proton currents coming from all azimuth angles. This procedure is well explained, e.g., by Kasper et al. (2006).

A huge deviation between SW proton fluxes has a direct impact on the RHA study process. When calculating radiation loads within satellite components, one must always consider a worst-case scenario. Hence, having in hand proton flux magnitudes from four different satellites, one has to choose the one with the highest value. Here, that would be the highest average differential flux spectrum chosen from all four satellites. The minimum, as well as the maximum differential fluxes, can be treated by RHA scientists as a minimum and maximum boundary needed for estimating radiation loads margins. Moreover, in the C, a simple study case for determining the proton fluence spectra of a reflector material is presented. It can be treated as an exemplary use case of differential proton spectra presented here.

Average and integral flux magnitudes presented here are calculated for two separate proton energy ranges, i.e., for SSW and FSW flows, that is for proton speeds lower as well as higher-equal than $500 \mathrm{~km} \mathrm{~s}^{-1}(1.3 \mathrm{keV})$. As it was already pointed out in the Section 3 , this classification was chosen after Abbo et al. (2016) and Bale et al. (2019). However, tables given in the D can be


Figure 5: Mesh grid differential flux spectra from the SOHO, the WIND, the ACE, and the DSCOVR satellites for the first 7 days of the calendar year 2017. Color-coded scale is chosen accordingly, i.e., for a time period of 7 days is set from 1 to 7 .
used to calculate integral proton fluxes with any preferable energy range. For example, assuming that the SSW flow is classified for proton speeds smaller than $440 \mathrm{~km} \mathrm{~s}^{-1}(\approx 1 \mathrm{keV})$, then the FSW integral flux can be simply read out from the table row where integration was made from 1.0 keV till the end of the energy range. Then SSW integral flux is a product of subtraction of an integral value from the whole energy range and the value from FSW flow, e.g., an integral average FSW proton flux from DSCOVR satellite in the calendar year 2018 is $1.97 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$. Now integral average SSW proton flux is $(5.02-1.97) \times 10^{8}=3.05 \times 10^{8}$ $\mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$, see Table 15 . Such a procedure can be applied to any value listed in tables given in the $D$. That makes the tables flexible and generic tools for estimating a magnitude of an integral proton flux within any energy range. Additionally, the differential minimum, the average, and the maximum proton fluxes for all calendar years of the SC 23 and the SC 24, as presented in Fig. 2 bottom plots, are stored as CSV data files and released on a publicly available GitHub repository (Sznajder, 2022). With such files in hand, one can estimate integral flux spectra within any preferable energy range.
As already mentioned in the introduction, a bi-modal nature of the SW flow at 1 AU distance from the Sun was proven by, e.g., Larrodera \& Cid (2020). The authors used all historical SW data from the ACE satellite. In fact, two separate groups of SW flows, i.e., the SSW and the FSW can be seen in the mesh grid differential flux spectra when a small portion of data is analyzed. Here, the first 7 days of the calendar year 2017 were taken and the flux spectra were plotted from four considered satellite data sets, see Fig. 5. Clearly, one can distinguish two flux populations, i.e., one between $\sim 2 \mathrm{keV}$ and $\sim 3 \mathrm{keV}$ and a second one below that range. Those correspond to the FSW and the SSW flow, respectively. The color-coded scale was set from 1 to 7 . Hence, one can indicate two hot spots in these two groups of flows. Hence, a mesh grid representation of the SW differential flux makes it a flexible tool to, at least qualitatively, analyze the appearance of any grouped populations within the SW flow. A detailed data analysis from the SOHO, the WIND, and the DSCOVR satellite would be required to compare it with the Larrodera \& Cid 2020) findings which are
based on the ACE satellite data.
Differential proton flux spectra as well as proton speed and number density histograms can be used to qualitatively indicate the time evolution of the SSW and the FSW flows as well as protons originating from the CME events, see A. Flux spectra and the histograms are derived out of the SOHO, the WIND, the ACE, and the DSCOVR satellite data for four calendar years from 2016 till 2019. Spectra and the histograms give an impression of how the SSW and the FSW evolved while the Sun approached its minimum activity state in 2019. Histograms reveal that satellites record protons within slightly different energy ranges for a given calendar year. This finding indicates the importance of comparing SW data from multiple satellites when any SW plasma parameter needs to be derived. On the other hand, quantitative SW evolution is represented by average and integral fluxes given in Tables 1, 2, 3, and 4. Clearly, the energy range of the FSW flow decreases while the Sun approaches its minimum state, e.g., from DSCOVR, from $E_{\max }=3.86$ keV in 2017 down to $E_{\max }=2.2 \mathrm{keV}$ in 2019. Consequently, the integral proton flux magnitude for the FSW flow is smaller for Sun minimum activity as opposed to its maximum activity state. It is related due to the fact that during the solar maximum activity state the coronal holes (Karna et al., 2020) and the CME events (Lamy et al., 2019 Gour et al., 2021) appear more frequently nearby the Sun's equator. They are both responsible for generating protons with a wider energy range in the SW stream.

Integral proton flux magnitudes for the FSW flow listed in Tables 1, 2, 3, and 4 are given for two proton energy ranges. This separation was made since some authors set the upper energy limit for the FSW flux, e.g., Schwenn (2000), to $\sim 3.3 \mathrm{keV}\left(800 \mathrm{~km} \mathrm{~s}^{-1}\right)$. The FSW energy range can be freely chosen after any author, and hence, proton integral flux magnitudes can be calculated by use of the tables published here, see D. and differential proton fluxes stored as CSV files within the GitHub repository (Sznajder, 2022). Lastly, it must be emphasized that differential flux spectra available as CSV files as well as calculated integral proton flux magnitudes given in all tables are based on the assumption that the Sun emits plasma into the interplanetary space in a quasi-static way. Here it means that fluxes
are calculated for a calendar year time frame, which corresponds to $\sim 10 \%$ of an SC period. More representative flux values would be gained when such a period is reduced to a month, which would correspond to $\sim 1 \%$ of an SC period. Such calculation activity is planned in the next phase of the study. Spectra will be successively added to the GitHub repository (Sznajder, 2022).

Here, for the first time, the RHA community is provided with the SW proton flux spectra and flux magnitude values for every calendar year for the last two solar cycles. Hence, RHA scientists are able to precisely calculate proton fluence values for any space mission dedicated to the IS radiation environment. Up to now, the data was available as flux plots or as single flux values calculated for a given time interval and from a selected satellite, see, e.g., the work of Gloeckler (1984); Yu \& Zhang (1990); Lin et al. (1995); Minow et al. (2007), or Gloeckler et al. (2008). Therefore, comparing fluxes from two or more study sources was impossible. Moreover, further calculations, e.g., of fluence magnitude, were accompanied by high uncertainty.

The results presented here indirectly contribute to radiation damage to satellite materials and components. Proton differential flux spectra and integral proton flux magnitudes are used as the basis to calculate proton fluence. Fluence is then used to estimate the degree of material degradation planned for satellite manufacturing. It provides information on how much particles hit a target material per unit surface area within a given period of time. A material degradation prediction can be made in two ways. First, by reviewing the literature and trying to find a material under study that was exposed to a particular set of radiation test conditions (particle type, energy, flux, fluence, etc.) that match the space environment under study. Then, one can estimate how fast and how 'strongly' a material under study will degrade. Another way of making a prediction is to perform a dedicated radiation test. Here, radiation analysis (using proton spectra provided here) will allow the proper selection of radiation test parameters. Then, a test can be carefully performed, and conclusions can be drawn.

## 5 Conclusions

The average proton flux magnitudes calculated for calendar years for SC 23 and SC 24 vary up to a maximum of $240 \%$. Such a high spread in proton flux values recorded by different satellites (higher during SC 24) may be caused by performance degradation of satellite subsystems responsible for proton current measurements. Degradation may be caused by years of operation (e.g. SOHO since 1996) under the harsh radiation environment of the IS. However, it must be emphasized that it is a speculative hypothesis. Further studies on this topic are highly required and will be performed in the next study campaign. The average flux $\bar{f}$ for the whole cycle 23 is $2.44 \times 10^{8}, 2.53 \times 10^{8}$, and $2.64 \times 10^{8}$ $\mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ based on data analyzed from the SOHO, the WIND, and the ACE satellites, respectively. In the case of the SC 24, the average flux $\bar{f}$ is smaller than the
one for the SC 23 , i.e., $1.64 \times 10^{8}, 2.51 \times 10^{8}, 2.03 \times 10^{8}$, and $2.66 \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ based on the data taken from the SOHO, the WIND, the ACE, and the DSCOVR satellites, respectively. The calculated SSW and the FSW flux values compare favorably with proton flux magnitudes reported, e.g., by Schwenn (2000), Gloeckler et al. (2008), or Larrodera \& Cid (2020). Smaller flux magnitudes for SC 24 to SC 23 are related to the Sun's activity, which was higher for SC 23 than for SC 24. Solar activity is associated with the number of NSS (ECSS, 2020, Clette et al. 2014). During SC 23 the NSS was higher than for SC 24 , see Fig. 4 . Hence, the Sun was more active in SC 23 than in SC 24 . Also, it was found that there is a strong correlation (with coefficient of determination $\sim 0.7$ ) between the NSS and the average proton flux, i.e., the larger the NSS, the larger the flux. Huge flux deviations based on data taken from different satellites and individual calendar years have a direct impact on an RHA study phase. One shall choose an average differential flux with the highest magnitude, reflecting a worst-case scenario when a satellite RHA analysis is foreseen for the IS environment.

Studies of the SW plasma population, see A, revealed that for a selected calendar year, the four considered satellites record the SW protons with slightly different velocity and number density ranges. Consequently, the obtained SW proton fluxes differ between the satellites. The difference may be caused, as already speculated, by degradation of satellite subsystems responsible for measuring the SW proton current. It may also be caused because the considered satellites were built at different times, i.e., with different technologies applied for their construction. This problem will be deeply investigated in the next study campaign. However, for now, it is strongly recommended to compare data from multiple satellites when the SW proton population properties are intended to be used and analyzed.

It was observed that the energy range of the SW protons varies with the Sun's activity. At the solar maximum of the SC 23 (the calendar year 2002), the maximum proton energy is roughly 2 -times larger than at the solar minimum (the calendar year 2009). Similar behavior on behalf of the SW proton energy range is confirmed for SC 24. There, maximum proton energy at the maximum solar activity level (the calendar year 2014) is roughly 2 -times larger than at the minimum activity (the calendar year 2019).

It must be strongly emphasized that the results presented here are applicable for the protons recorded at the ecliptic plane where the radiation environment is mainly driven by the SSW, see, e.g., McComas et al. (2003) or Manoharan (2012). More precisely, the SSW dictates a radiation environment in approx. $\pm 30^{\circ}$ stripe above and below the ecliptic plane. Hence, a space mission whose objective is to explore the north or the southern hemisphere of the IS shall take into account that the radiation environment there is driven by the FSW. Such an environment is not analyzed in the study presented here.

Future work will be focused on five aspects. First,
another SW data source will be explored and processed to calculate differential and integral SW proton fluxes, and will be compared with the results presented here. Those are data sets, e.g., from the Voyager, the StereoA and -B, as well as the Parker Solar Probe satellites. Second, data from Helios will be analyzed to estimate the proton differential and integral fluxes above the ecliptic plane. Third, as mentioned in the discussion section, proton flux spectra and proton integral flux values will be derived from the SW data based on month sets. Fourth, proton data sources will be explored and analyzed to estimate proton fluxes in the energy range of $10 \mathrm{keV} \lesssim E \lesssim 100 \mathrm{keV}$. This is a range where nmand $\mu \mathrm{m}$ - depth materials are aged by the electrons, protons, and ions with $\mathrm{Z}>1$. Finally, a cause for the difference between average proton fluxes from multiple solar observatories will be studied and explained.

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## Data Availability

Data used to calculate the SW differential and integral fluxes are publicly available. The SOHO satellite SW data were downloaded from the SOHO CELIAS MTOF proton monitor web page (ESA/NASA, 2021). The WIND satellite SW data were downloaded from the OMNIWeb Plus web page (NASA, 2021). The ACE satellite SW data were downloaded from the Caltech web page (Caltech, 2021). The DSCOVR satellite SW data were downloaded from the OMNIWeb Plus web page (NASA, 2021). The sunspot numbers were obtained from the SILSO webpage (SILSO, 2021). The differential proton fluxes computed here are available as CSV format data files from the (Sznajder, 2022) GitHub repository. The repository also contains plots of mesh differential proton flux spectra as shown on the top row in Fig. 2.

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## A Time evolution of differential proton flux spectra

Distributions of proton speed, density as well as differential flux spectra can be used to visually and qualitatively examine a time evolution of the solar wind flow. Here, as an example, four calendar years from SOHO, ACE, WIND, and DSCOVR satellite data sets were used, i.e., from 2016 till 2019. These are years when data from all four satellites can be compared, since DSCOVR data are available only from 2016. Two collections of histogram plots are shown in the Figs. 6 and 7 The former depicts a normalized number of records as a function of the proton speed, while the latter shows a normalized number of records as a function of proton number density. On the other hand, the third figure, Fig. 8, shows a collection of proton differential flux spectra in a mesh grid representation. Comparing proton speed histograms, it can be noticed that, e.g., ACE
and DSCOVR (the year 2019) have no records with proton speeds larger than approx. $600 \mathrm{~km} \mathrm{~s}^{-1}$, while WIND recorded protons with a speed of up to approx. $800 \mathrm{~km} \mathrm{~s}^{-1}$ and SOHO of up to approx. $900 \mathrm{~km} \mathrm{~s}^{-1}$. A similar situation can be recognized when histograms with proton number densities are compared, see Fig. 7 For example, for the year 2017, SOHO and ACE satellites recorded protons only up to approx. $60 \mathrm{~cm}^{-3}$, while WIND and DSCOVR recorded up to $90 \mathrm{~cm}^{-3}$. Histograms can be used to reveal population structure within the SW plasma flow. There, one can distinguish the SSW and the FSW flows. Also, the CME tail can be noticed, i.e., seen in the proton speed histograms $\gtrsim 800 \mathrm{~km} \mathrm{~s}^{-1}$. The energy range and the flux magnitude in the mesh grid representation of the differential flux differ between satellites for a given calendar year, see Fig. 8. This is caused by the fact that it is a product of the proton velocity and the number density. Populations of both quantities are slightly different when being measured by the satellites. Therefore, this qualitative analysis shows that complete information about the SW proton plasma population recorded within a year can be obtained only when data from multiple satellites are compared.
As already explained in the discussion section, the FSW flow decreases in magnitude while the Sun approaches its minimum activity state. This can be observed by reviewing the spectra visually as well as reading out their values, i.e., the average and the integral proton flux magnitudes given in Tables 1, 2, 3, and 4.

## B SW particle current measurement system and a scaling factor used during transformation from omni-directional to directional SW proton flux

All satellites considered here measure an incident SW particle current in order to estimate the plasma parameters. Here, the measuring principle is explained by using the WIND satellite subsystem equipped with a Faraday cup Ogilvie et al., 1995). The current is recorded with two parameters being changed. The first of these is an angle between the line of sight to the Sun and a normal vector of a collector plate of the cup, the so-called azimuth angle $\phi$. Hence, the particle stream can be measured from different incidence angles. The second one is a set of energy windows. Here, particles with a given energy range pass a set of grids having a specific voltage applied. A detector records a particle current coming from different angles and having different energies within one measuring period of 92 seconds. Such a current snapshot can be seen in Fig. 9 The picture is taken from the OMNIWeb Plus database (NASA, 2021). Measurements were made on the $1^{\text {st }}$ of September 2016. The Y-axis denotes the $\phi$ angle, while the X-axis holds the energy per charge $E / Q$ of the incident particles. The angle changes from $-\frac{\pi}{2}$ to $\frac{\pi}{2}$. The highest proton current signal is measured when a FC di-


Figure 6: A normalized number of protons recorded within a calendar year is given as a function of the velocity. Records are provided for the four considered satellites and calendar years from 2016 to 2019.


Figure 7: A normalized number of protons recorded within a calendar year is given as a function of the number density. Records are provided for the four considered satellites and calendar years from 2016 to 2019.


Figure 8: Differential proton flux spectra in a mesh grid representation calculated for calendar years from 2016 to 2019. Records are provided for the four considered satellites.


Figure 9: A snapshot from a FC current measurements made by the WIND satellite. It is taken within 92 seconds. The current is plotted as a function of the $\mathrm{E} / \mathrm{Q}$ values (X-axis) and the angle between the normal of a FC collector plate and the line of sight to the Sun (Y-axis). A snapshot is taken from the OMNIWeb Plus database NASA (2021).
rectly points to the Sun (when the angle has 0 radians). On the other hand, the lowest FC current signal (almost 0 pA ) is measured when the FC is orientated perpendicular to the SW stream. Different $E / Q$ windows are achieved by rapidly changing voltages to a set of grids placed in front of a collector plate. The figure presents a snapshot of a full scan of SW particle current, so all angles and all energies are measured. A $\phi \neq 0$ proton currents are coming from two effects. First, there are non-radial SW streams, see, e.g., the work of Richardson et al. (1996); Owens \& Cargill (2004) or Němeček et al. (2020). Second, a radial SW particle stream measured at an angle $\phi$ has a value of $I_{\phi}=I_{\text {radial }} \cdot \cos (\phi)$. Both effects result in a 'cumulative' current recorded by the FC. Now, having a particle current measured for all angles and energy windows, one can apply procedures to calculate the moments $(v, n)$. They are described in detail, e.g., by Verscharen et al. (2019) or Case et al. (2020).

The SW particle current measurement principle dictates how a transformation of a proton omni-directional to a directional flux shall be made. When such a transformation is applied, one shall divide an omnidirectional flux by a factor of $2 \pi$ (a hemisphere). However, it must be kept in mind that for SEPs, a $4 \pi$ scaling factor shall be used. This is due to the fact that SEPs are recorded for much higher grazing angles than the SW particles, i.e., higher than $\pm \frac{\pi}{2}$ measured from the line of sight to the Sun, see, e.g., Reames et al. (2001). A similar situation is found for the GCRs, which penetrate the heliosphere from all directions.

## C Proton fluence spectra for an exemplary study case

In this appendix, a simple study case is considered to calculate the so-called proton fluence spectra. Proton fluence is defined as a flux integrated over a given period of time (ECSS, 2020).

Here, for simplicity, one can consider a study case where a solar reflector, a thin membrane material, is made of a flexible polyimide (PI) film that is coated on one side with an Aluminum layer. The reflector is placed in a fixed location in space at a 1 AU distance from the Sun in an ecliptic plane. Its surface is orientated perpendicular to the stream of SW ions. The metallic side of the film is faced to the Sun. Also, it is assumed that the Aluminum layer has a thickness of $0.1 \mu \mathrm{~m}$ while the polyimide substrate has a thickness of $10 \mu \mathrm{~m}$. The membrane is exposed to radiation for a period of the SC 24. Here, fluence spectra for protons stuck within Aluminum and PI are provided.

The upper plot in Fig. 10 shows a relative number of incident protons which are stuck within the Aluminum and PI layers after the membrane is exposed to the SW protons. For example, for the kinetic energy of 4.5 keV , approx. $87 \%$ of protons will be deposited within the Aluminum, while the remaining $13 \%$ will be implanted in the PI substrate. The analysis was performed using the SRIM software (Ziegler et al., 2010). The light red background represents the range of proton kinetic energies recorded by the four satellites during the SC 24. The lowest energy of 0.28 keV was recorded by the WIND satellite, see Table 2, while the highest energy of 5.13 keV was recorded by the SOHO satellite, see Table 1. A proton with the energy of 5.13 keV travels through the Aluminum layer and is stuck within the PI substrate at a depth of approx. 100 nm measured from the interface between the two layers (Ziegler et al. 2010). Hence, all SW protons produced by the Sun during the SC 24 would be implanted within the membrane material.

The lower plot in the Fig. 10 depicts SW proton fluence spectra. Two curves are presented, i.e., the first, for the protons deposited in the Aluminum layer (black line), and the second, for the protons stuck within the PI substrate (blue line). Here, the fluence was calculated by use of the average differential flux spectra from the WIND satellite. The choice was dictated by the fact that WIND satellite average differential flux has the highest magnitude among all four considered satellites, and it would represent a worst-case scenario, i.e., a situation when a membrane would accumulate the highest number of protons during the SC 24 . The maximum WIND flux magnitude can be verified by looking into Tables from 1 to 4 . The fluence spectra reveal that the membrane would accumulate approx. $2 \times 10^{17} \mathrm{p}^{+} \mathrm{cm}^{-2}$ and $2.3 \times 10^{15} \mathrm{p}^{+} \mathrm{cm}^{-2}$ within the Aluminum and PI at the end of the SC 24 , respectively. However, it must be strongly emphasized that fluence magnitude depends on many constituents, such as: time of exposure to the particle stream, the distance of the test object to the Sun, the grazing angle of the studied surface to the SW
proton stream or solar activity state at which the studied material was deployed in space. Values calculated here correspond to a very simplistic study case. It is intended to show how the differential proton spectra presented here can be used.

## D Integral proton flux

Integral proton fluxes are calculated based on the minimum, the average, and the maximum differential proton fluxes, which are integrated in a descending set of energy ranges with a step of 0.1 keV , e.g. from 0.2 keV ... 5.0 keV , from 0.3 keV ... 5.0 keV , and so on, down to 4.9 keV ... 5.0 keV . Integral fluxes are calculated and tabulated for each calendar year of the SC 23 and the SC 24 and, for those satellites which have available data, also for the calendar year 2020.

The integral SW proton fluxes calculated from the minimum, the average, and the maximum differential proton fluxes based on data taken from the SOHO satellite are provided in Table 6, Table 7, and Table 8. respectively.

Then, the integral SW proton fluxes calculated from the minimum, the average, and the maximum differential proton fluxes based on data taken from the WIND satellite are provided in Table 9, Table 10, and Table 11. respectively.

Next, the integral SW proton fluxes calculated from the minimum, the average, and the maximum differential proton fluxes based on data taken from the ACE satellite are provided in Table 12, Table 13, and Table 14. respectively.

Finally, the integral SW proton fluxes calculated from the minimum, the average, and the maximum differential proton fluxes based on data taken from the DSCOVR satellite are provided in Table 15.



Figure 10: The top plot shows a relative number of SW protons stuck within a membrane material as a function of the proton kinetic energy. The membrane is built up from a $0.1 \mu \mathrm{~m}$ Aluminum and a $100 \mu \mathrm{~m}$ polyimide substrate film. The bottom plot depicts proton fluence spectra deposited within the Aluminum and polyimide layers.


|  | Table 7: Integral SW proton flux $f_{\mathrm{S}}^{\mathrm{I}, \mathrm{A}}$ |  |  |  |  |  | $\times 10^{8}$2002 | $\mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ |  | based 2005 | $\begin{aligned} & \text { on an } \\ & 2006 \end{aligned}$ | avera2007 | 2008 | rential | ${ }_{2010}^{\text {proto }}$ | 2011 | $\begin{aligned} & \text { spectr } \\ & 2012 \end{aligned}$ | $\begin{gathered} \text { a calcu } \\ 2013 \end{gathered}$ |  | $\begin{gathered} \text { rom } \\ 2015 \end{gathered}$ | $\begin{array}{r} \mathrm{OHO} \\ 2016 \\ \hline \end{array}$ | satellite data. |  | 2019 | 2020 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| E [ keV$]$ |  |  |  |  |  |  |  |  | 2017 |  |  |  |  |  |  |  |  |  |  |  |  | 2018 |  |  |
| 0.3-5.3 | 6.04 | 5.90 | 9.22 |  | 7.69 | 10.88 |  |  |  | 5.69 | 6.32 | 5.91 | 4.26 | 3.56 | 2.64 | 4.35 | 4.39 | 5.98 | 4.08 | 4.99 | 5.51 | 4.73 | 4.12 | 2.84 | 3.77 | 2.58 |
| 0.4-5.3 | 5.80 | 5.80 | 9.10 | 6.14 | 7.53 | 10.77 | 6.58 | 6.69 | 5.63 | 6.25 | 5.84 | 4.20 | 3.49 | 2.56 | 4.25 | 4.30 | 5.88 | 3.99 | 4.91 | 5.43 | 4.64 | 4.07 | 2.77 | 3.73 | 2.52 |
| 0.5-5.3 | 4.85 | 4.99 | 8.24 | 5.27 | 6.64 | 10.01 | 5.88 | 6.13 | 5.23 | 5.76 | 5.46 | 3.89 | 3.16 | 2.27 | 3.89 | 3.88 | 5.51 | 3.63 | 4.55 | 5.03 | 4.33 | 3.80 | 2.53 | 3.49 | 2.30 |
| 0.6-5.3 | 4.16 | 4.41 | 7.67 | 4.67 | 6.13 | 9.51 | 5.35 | 5.73 | 4.90 | 5.37 | 5.10 | 3.57 | 2.91 | 2.03 | 3.61 | 3.59 | 5.23 | 3.33 | 4.21 | 4.72 | 4.02 | 3.59 | 2.29 | 3.29 | 2.11 |
| 0.7-5.3 | 3.57 | 3.91 | 7.19 | 4.15 | 5.71 | 9.09 | 4.90 | 5.36 | 4.58 | 5.03 | 4.82 | 3.33 | 2.68 | 1.81 | 3.36 | 3.34 | 4.97 | 3.11 | 3.95 | 4.42 | 3.73 | 3.34 | 2.07 | 3.09 | 1.94 |
| 0.8-5.3 | 3.14 | 3.50 | 6.78 | 3.77 | 5.36 | 8.76 | 4.52 | 5.01 | 4.29 | 4.72 | 4.56 | 3.10 | 2.48 | 1.61 | 3.13 | 3.11 | 4.71 | 2.87 | 3.70 | 4.11 | 3.46 | 3.09 | 1.86 | 2.93 | 1.80 |
| 0.9-5.3 | 2.81 | 3.16 | 6.44 | 3.44 | 5.06 | 8.47 | 4.19 | 4.69 | 4.04 | 4.48 | 4.32 | 2.89 | 2.31 | 1.46 | 2.92 | 2.93 | 4.48 | 2.65 | 3.48 | 3.84 | 3.24 | 2.90 | 1.69 | 2.80 | 1.69 |
| 1.0-5.3 | 2.52 | 2.86 | 6.15 | 3.15 | 4.78 | 8.21 | 3.88 | 4.39 | 3.82 | 4.28 | 4.14 | 2.71 | 2.13 | 1.30 | 2.76 | 2.78 | 4.29 | 2.47 | 3.28 | 3.62 | 3.04 | 2.74 | 1.54 | 2.69 | 1.59 |
| 1.1-5.3 | 2.27 | 2.55 | 5.89 | 2.90 | 4.50 | 7.98 | 3.61 | 4.13 | 3.61 | 4.09 | 3.96 | 2.57 | 1.98 | 1.18 | 2.62 | 2.63 | 4.14 | 2.31 | 3.11 | 3.40 | 2.86 | 2.58 | 1.41 | 2.56 | 1.48 |
| 1.2-5.3 | 2.06 | 2.30 | 5.67 | 2.68 | 4.27 | 7.78 | 3.37 | 3.91 | 3.43 | 3.91 | 3.80 | 2.42 | 1.84 | 1.06 | 2.48 | 2.46 | 3.99 | 2.15 | 2.93 | 3.18 | 2.68 | 2.43 | 1.27 | 2.44 | 1.36 |
| 1.3-5.3 | 1.84 | 2.09 | 5.46 | 2.52 | 4.07 | 7.58 | 3.13 | 3.68 | 3.25 | 3.75 | 3.62 | 2.27 | 1.70 | 0.94 | 2.36 | 2.30 | 3.85 | 2.01 | 2.76 | 2.98 | 2.51 | 2.28 | 1.14 | 2.33 | 1.24 |
| 1.4-5.3 | 1.66 | 1.90 | 5.27 | 2.37 | 3.90 | 7.39 | 2.90 | 3.48 | 3.08 | 3.61 | 3.45 | 2.13 | 1.57 | 0.84 | 2.26 | 2.16 | 3.72 | 1.87 | 2.60 | 2.81 | 2.36 | 2.14 | 1.03 | 2.22 | 1.14 |
| 1.5-5.3 | 1.49 | 1.73 | 5.09 | 2.22 | 3.75 | 7.21 | 2.69 | 3.28 | 2.94 | 3.47 | 3.31 | 2.00 | 1.46 | 0.75 | 2.16 | 2.03 | 3.59 | 1.75 | 2.47 | 2.66 | 2.24 | 2.00 | 0.93 | 2.14 | 1.05 |
| 1.6-5.3 | 1.33 | 1.56 | 4.92 | 2.09 | 3.61 | 7.03 | 2.50 | 3.11 | 2.81 | 3.35 | 3.20 | 1.90 | 1.37 | 0.68 | 2.08 | 1.92 | 3.49 | 1.66 | 2.36 | 2.55 | 2.14 | 1.90 | 0.84 | 2.06 | 0.95 |
| 1.7-5.3 | 1.19 | 1.43 | 4.77 | 1.97 | 3.46 | 6.86 | 2.33 | 2.96 | 2.68 | 3.24 | 3.10 | 1.79 | 1.28 | 0.61 | 2.00 | 1.82 | 3.40 | 1.57 | 2.26 | 2.43 | 2.03 | 1.80 | 0.75 | 1.95 | 0.87 |
| 1.8-5.3 | 1.06 | 1.25 | 4.62 | 1.85 | 3.29 | 6.72 | 2.15 | 2.81 | 2.56 | 3.13 | 3.00 | 1.68 | 1.18 | 0.50 | 1.91 | 1.70 | 3.29 | 1.46 | 2.17 | 2.29 | 1.89 | 1.68 | 0.66 | 1.83 | 0.78 |
| 1.9-5.3 | 0.94 | 1.09 | 4.46 | 1.73 | 3.15 | 6.59 | 2.00 | 2.66 | 2.42 | 3.01 | 2.89 | 1.57 | 1.08 | 0.39 | 1.82 | 1.57 | 3.19 | 1.35 | 2.07 | 2.15 | 1.77 | 1.57 | 0.56 | 1.71 | 0.68 |
| 2.0-5.3 | 0.83 | 0.94 | 4.31 | 1.62 | 3.00 | 6.45 | 1.86 | 2.50 | 2.30 | 2.89 | 2.79 | 1.47 | 0.99 | 0.30 | 1.72 | 1.47 | 3.08 | 1.23 | 1.94 | 2.01 | 1.65 | 1.45 | 0.47 | 1.59 | 0.60 |
| 2.1-5.3 | 0.70 | 0.77 | 4.16 | 1.50 | 2.87 | 6.32 | 1.72 | 2.35 | 2.18 | 2.78 | 2.70 | 1.37 | 0.90 | 0.22 | 1.61 | 1.37 | 2.96 | 1.13 | 1.78 | 1.88 | 1.55 | 1.35 | 0.39 | 1.49 | 0.53 |
| 2.2-5.3 | 0.58 | 0.63 | 4.00 | 1.39 | 2.74 | 6.18 | 1.58 | 2.21 | 2.05 | 2.67 | 2.61 | 1.29 | 0.82 | 0.15 | 1.51 | 1.29 | 2.84 | 1.02 | 1.63 | 1.74 | 1.45 | 1.25 | 0.32 | 1.40 | 0.48 |
| 2.3-5.3 | 0.46 | 0.52 | 3.87 | 1.29 | 2.61 | 6.03 | 1.45 | 2.07 | 1.90 | 2.56 | 2.53 | 1.21 | 0.75 | 0.09 | 1.42 | 1.22 | 2.72 | 0.94 | 1.52 | 1.60 | 1.37 | 1.16 | 0.27 | 1.32 | 0.43 |
| 2.4-5.3 | 0.34 | 0.43 | 3.74 | 1.20 | 2.50 | 5.88 | 1.33 | 1.94 | 1.77 | 2.44 | 2.46 | 1.14 | 0.68 | 0.03 | 1.33 | 1.16 | 2.61 | 0.86 | 1.43 | 1.49 | 1.30 | 1.09 | 0.22 | 1.25 | 0.38 |
| 2.5-5.3 | 0.24 | 0.34 | 3.65 | 1.12 | 2.40 | 5.71 | 1.22 | 1.83 | 1.65 | 2.35 | 2.39 | 1.07 | 0.63 |  | 1.23 | 1.11 | 2.50 | 0.79 | 1.36 | 1.40 | 1.23 | 1.02 | 0.17 | 1.19 | 0.34 |
| 2.6-5.3 | 0.17 | 0.26 | 3.55 | 1.05 | 2.28 | 5.51 | 1.13 | 1.72 | 1.55 | 2.27 | 2.33 | 1.01 | 0.58 | - | 1.11 | 1.06 | 2.40 | 0.73 | 1.28 | 1.29 | 1.17 | 0.96 | 0.13 | 1.13 | 0.30 |
| 2.7-5.3 | 0.10 | 0.18 | 3.40 | 0.99 | 2.16 | 5.26 | 1.04 | 1.61 | 1.47 | 2.19 | 2.27 | 0.95 | 0.52 | - | 1.04 | 1.02 | 2.31 | 0.66 | 1.21 | 1.21 | 1.11 | 0.90 | 0.09 | 1.08 | 0.26 |
| 2.8-5.3 | 0.02 | 0.10 | 3.19 | 0.94 | 2.07 | 5.03 | 0.97 | 1.50 | 1.41 | 2.11 | 2.21 | 0.89 | 0.47 | - | 0.93 | 0.97 | 2.23 | 0.60 | 1.12 | 1.15 | 1.05 | 0.84 | 0.06 | 1.02 | 0.21 |
| 2.9-5.3 |  | 0.02 | 2.89 | 0.87 | 1.97 | 4.84 | 0.90 | 1.40 | 1.32 | 2.03 | 2.14 | 0.83 | 0.41 | - | 0.82 | 0.93 | 2.16 | 0.57 | 1.03 | 1.09 | 0.99 | 0.77 | 0.03 | 0.96 | 0.16 |
| 3.0-5.3 | - | - | 2.56 | 0.80 | 1.87 | 4.69 | 0.84 | 1.30 | 1.21 | 1.95 | 2.07 | 0.76 | 0.35 | - | 0.72 | 0.88 | 2.10 | 0.52 | 0.95 | 1.01 | 0.92 | 0.69 | - | 0.89 | 0.11 |
| 3.1-5.3 |  | - | 2.20 | 0.74 | 1.75 | 4.53 | 0.77 | 1.21 | 1.10 | 1.87 | 2.00 | 0.70 | 0.29 |  | 0.60 | 0.84 | 2.02 | 0.48 | 0.86 | 0.94 | 0.84 | 0.60 |  | 0.82 | 0.06 |
| 3.2-5.3 | - | - | 1.98 | 0.67 | 1.64 | 4.36 | 0.71 | 1.12 | 1.01 | 1.75 | 1.90 | 0.62 | 0.22 | - | 0.49 | 0.78 | 1.89 | 0.44 | 0.77 | 0.87 | 0.76 | 0.52 | - | 0.75 | 0.02 |
| 3.3-5.3 |  |  | 1.81 | 0.60 | 1.48 | 4.20 | 0.68 | 1.03 | 0.91 | 1.64 | 1.81 | 0.52 | 0.16 |  | 0.41 | 0.72 | 1.80 | 0.39 | 0.65 | 0.80 | 0.66 | 0.44 |  | 0.67 |  |
| 3.4-5.3 | - | - | 1.64 | 0.52 | 1.35 | 4.07 | 0.64 | 0.95 | 0.83 | 1.54 | 1.71 | 0.42 | 0.09 | - | 0.32 | 0.67 | 1.69 | 0.34 | 0.57 | 0.74 | 0.58 | 0.38 | - | 0.61 |  |
| 3.5-5.3 |  | - | 1.50 | 0.47 | 1.20 | 3.92 | 0.60 | 0.88 | 0.73 | 1.44 | 1.62 | 0.34 | 0.04 | - | 0.25 | 0.61 | 1.56 | 0.31 | 0.50 | 0.68 | 0.48 | 0.32 | - | 0.54 | - |
| 3.6-5.3 | - | - | 1.34 | 0.39 | 1.10 | 3.80 | 0.57 | 0.81 | 0.65 | 1.35 | 1.56 | 0.24 |  | - | 0.17 | 0.56 | 1.44 | 0.27 | 0.43 | 0.62 | 0.39 | 0.25 |  | 0.48 |  |
| 3.7-5.3 |  | - | 1.16 | 0.35 | 1.03 | 3.64 | 0.53 | 0.75 | 0.58 | 1.27 | 1.50 | 0.15 | - | - | 0.10 | 0.51 | 1.34 | 0.25 | 0.38 | 0.56 | 0.32 | 0.18 | - | 0.43 | - |
| 3.8-5.3 | - | - | 1.03 | 0.31 | 0.95 | 3.55 | 0.49 | 0.68 | 0.51 | 1.17 | 1.43 | 0.06 |  |  | 0.02 | 0.46 | 1.23 | 0.23 | 0.33 | 0.51 | 0.24 | 0.12 |  | 0.37 |  |
| 3.9-5.3 | - | - | 0.91 | 0.28 | 0.86 | 3.38 | 0.46 | 0.62 | 0.45 | 1.08 | 1.36 |  | - | - | - | 0.42 | 1.13 | 0.21 | 0.29 | 0.46 | 0.16 | 0.06 | - | 0.32 | - |
| 4.0-5.3 |  |  | 0.80 | 0.25 | 0.81 | 3.16 | 0.42 | 0.56 | 0.40 | 1.00 | 1.32 |  |  |  | - | 0.37 | 0.96 | 0.18 | 0.24 | 0.41 | 0.09 |  |  | 0.27 |  |
| 4.1-5.3 | - | - | 0.70 | 0.23 | 0.75 | 2.93 | 0.38 | 0.51 | 0.36 | 0.94 | 1.24 | - | - | - | - | 0.33 | 0.87 | 0.16 | 0.22 | 0.37 | 0.01 | - | - | 0.23 | - |
| 4.2-5.3 |  |  | 0.62 | 0.21 | 0.69 | 2.64 | 0.35 | 0.45 | 0.32 | 0.86 | 1.18 |  |  |  |  | 0.28 | 0.80 | 0.14 | 0.19 | 0.32 |  |  |  | 0.17 |  |
| 4.3-5.3 | - | - | 0.55 | 0.18 | 0.63 | 2.26 | 0.31 | 0.40 | 0.29 | 0.80 | 1.05 | - | - | - | - | 0.24 | 0.72 | 0.12 | 0.16 | 0.27 | - | - | - | 0.14 | - |
| 4.4-5.3 |  |  | 0.48 | 0.16 | 0.56 | 1.94 | 0.28 | 0.36 | 0.26 | 0.72 | 1.00 | - |  |  | - | 0.20 | 0.63 | 0.09 | 0.14 | 0.23 |  |  | - | 0.10 |  |
| 4.5-5.3 |  | - | 0.41 | 0.14 | 0.51 | 1.46 | 0.24 | 0.31 | 0.23 | 0.64 | 0.95 | - |  | - | - | 0.16 | 0.56 | 0.07 | 0.11 | 0.19 | - | - | - | 0.07 | - |
| 4.6-5.3 | - | - | 0.33 | 0.12 | 0.45 | 1.16 | 0.20 | 0.28 | 0.20 | 0.58 | 0.85 | - | - | - | - | 0.12 | 0.41 | 0.05 | 0.10 | 0.15 | - |  | - | 0.04 |  |
| 4.7-5.3 |  | - | 0.25 | 0.09 | 0.39 | 0.95 | 0.16 | 0.24 | 0.17 | 0.51 | 0.69 | - |  | - | - | 0.07 | 0.33 | 0.03 | 0.08 | 0.12 | - |  | - | 0.01 |  |
| 4.8-5.3 |  | - | 0.17 | 0.07 | 0.32 | 0.88 | 0.13 | 0.20 | 0.15 | 0.45 | 0.53 | - | - | - | - | 0.03 | 0.25 | 0.02 | 0.04 | 0.08 |  |  |  | - | - |
| 4.9-5.3 | - | - | 0.10 | 0.04 | 0.19 | 0.67 | 0.09 | 0.17 | 0.12 | 0.39 | 0.38 | - | - | - | - |  | 0.17 | 0.01 | 0.02 | 0.04 | - | - | - | - | - |
| 5.0-5.3 | - | - | - | 0.01 | 0.10 | 0.31 | 0.07 | 0.13 | 0.10 | 0.31 | 0.20 | - | - | - | - | - | 0.09 | - | - | - | - | - | - | - | - |
| 5.1-5.3 |  |  |  |  | 0.05 | 0.13 | 0.03 | 0.10 | 0.06 | 0.20 | 0.06 |  |  | - | - | - | 0.02 | - | - | - | - |  |  |  |  |
| 5.2-5.3 | - | - | - | - | 0.03 | 0.08 |  | 0.05 | 0.02 | 0.10 |  | - | - | - | - | - |  | - | - | - | - | - | - | - | - |



















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Table 9: Integral SW proton flux $f_{\mathrm{W}}^{\mathrm{I}, \mathrm{MIN}} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ based on a minimum differential proton flux spectra calculated from WIND satellite data.


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Table 12: Integral SW proton flux $f_{\mathrm{A}}^{\mathrm{I}, \mathrm{MIN}} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ based on a minimum differential proton flux spectra calculated from ACE satellite data.









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Table 14: Integral SW proton flux $f_{\mathrm{A}}^{1, M A X} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ based on a maximum differential proton flux spectra calculated from ACE satellite data.












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Table 15: Integral SW proton fluxes $f_{\mathrm{A}}^{\mathrm{I}, \mathrm{MIN}}, f_{\mathrm{A}}^{\mathrm{I}, \mathrm{A}}$, and $f_{\mathrm{A}}^{\mathrm{I}, \mathrm{MAX}} \times 10^{8} \mathrm{p}^{+} \mathrm{cm}^{-2} s^{-1}$ based on a minimum, an average, and a maximum differential proton flux spectra calculated from DSCOVR satellite data.

| E [keV] | 2016 | 2017 | 2018 | 2019 | 2016 | 2017 | 2018 | 2019 | 2016 | 2017 | 2018 | 2019 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.3-3.9 | 2.83 | 3.15 | 2.15 | 1.98 | 6.39 | 6.91 | 5.02 | 4.32 | 18.98 | 23.09 | 13.64 | 10.70 |
| 0.4-3.9 | 2.48 | 2.91 | 2.05 | 1.74 | 5.96 | 6.61 | 4.91 | 3.99 | 18.48 | 22.73 | 13.53 | 10.29 |
| 0.5-3.9 | 2.17 | 2.57 | 1.63 | 1.34 | 5.19 | 5.75 | 4.15 | 3.32 | 16.82 | 20.23 | 12.20 | 9.11 |
| 0.6-3.9 | 2.02 | 2.44 | 1.49 | 1.18 | 4.45 | 5.12 | 3.42 | 2.76 | 14.21 | 17.50 | 9.53 | 7.07 |
| 0.7-3.9 | 1.94 | 2.35 | 1.39 | 1.08 | 3.92 | 4.60 | 2.91 | 2.29 | 11.63 | 14.49 | 7.32 | 5.03 |
| 0.8-3.9 | 1.87 | 2.29 | 1.31 | 1.00 | 3.57 | 4.17 | 2.51 | 1.95 | 9.61 | 11.72 | 5.38 | 3.83 |
| 0.9-3.9 | 1.83 | 2.23 | 1.24 | 0.94 | 3.25 | 3.84 | 2.22 | 1.70 | 8.30 | 9.73 | 4.29 | 3.17 |
| 1.0-3.9 | 1.77 | 2.18 | 1.17 | 0.86 | 2.95 | 3.55 | 1.97 | 1.50 | 7.07 | 7.87 | 3.57 | 2.60 |
| 1.1-3.9 | 1.70 | 2.11 | 1.09 | 0.81 | 2.70 | 3.33 | 1.75 | 1.32 | 5.79 | 6.94 | 3.06 | 2.16 |
| 1.2-3.9 | 1.62 | 2.04 | 1.01 | 0.77 | 2.49 | 3.13 | 1.56 | 1.17 | 5.03 | 6.30 | 2.62 | 1.84 |
| 1.3-3.9 | 1.54 | 1.98 | 0.92 | 0.72 | 2.32 | 2.96 | 1.39 | 1.03 | 4.48 | 5.73 | 2.27 | 1.56 |
| 1.4-3.9 | 1.46 | 1.92 | 0.84 | 0.65 | 2.17 | 2.82 | 1.25 | 0.89 | 4.02 | 5.26 | 2.00 | 1.29 |
| 1.5-3.9 | 1.40 | 1.86 | 0.76 | 0.59 | 2.03 | 2.68 | 1.13 | 0.76 | 3.59 | 4.82 | 1.79 | 1.03 |
| 1.6-3.9 | 1.33 | 1.80 | 0.67 | 0.50 | 1.90 | 2.54 | 0.99 | 0.63 | 3.22 | 4.40 | 1.57 | 0.82 |
| 1.7-3.9 | 1.27 | 1.75 | 0.60 | 0.41 | 1.78 | 2.42 | 0.87 | 0.48 | 2.88 | 4.03 | 1.32 | 0.57 |
| 1.8-3.9 | 1.22 | 1.70 | 0.52 | 0.31 | 1.67 | 2.30 | 0.74 | 0.35 | 2.60 | 3.66 | 1.09 | 0.40 |
| 1.9-3.9 | 1.16 | 1.65 | 0.44 | 0.22 | 1.57 | 2.19 | 0.61 | 0.23 | 2.36 | 3.33 | 0.90 | 0.25 |
| 2.0-3.9 | 1.11 | 1.61 | 0.36 | 0.13 | 1.48 | 2.08 | 0.50 | 0.13 | 2.15 | 3.05 | 0.71 | 0.14 |
| 2.1-3.9 | 1.06 | 1.57 | 0.29 | 0.05 | 1.39 | 1.98 | 0.40 | 0.05 | 1.96 | 2.78 | 0.56 | 0.06 |
| 2.2-3.9 | 1.02 | 1.53 | 0.24 | - | 1.31 | 1.89 | 0.32 | - | 1.79 | 2.54 | 0.43 | - |
| 2.3-3.9 | 0.98 | 1.50 | 0.20 | - | 1.22 | 1.81 | 0.24 | - | 1.63 | 2.32 | 0.30 | - |
| 2.4-3.9 | 0.93 | 1.46 | 0.15 | - | 1.14 | 1.72 | 0.17 | - | 1.47 | 2.12 | 0.20 | - |
| 2.5-3.9 | 0.89 | 1.43 | 0.10 | - | 1.05 | 1.64 | 0.11 | - | 1.31 | 1.93 | 0.12 | - |
| 2.6-3.9 | 0.84 | 1.39 | 0.06 | - | 0.96 | 1.55 | 0.06 | - | 1.15 | 1.75 | 0.07 | - |
| 2.7-3.9 | 0.79 | 1.34 | 0.03 | - | 0.88 | 1.47 | 0.03 | - | 1.00 | 1.60 | 0.03 | - |
| 2.8-3.9 | 0.74 | 1.29 | 0.01 | - | 0.79 | 1.38 | 0.01 | - | 0.85 | 1.48 | 0.01 | - |
| 2.9-3.9 | 0.67 | 1.24 | - | - | 0.69 | 1.30 | - | - | 0.72 | 1.36 | - | - |
| 3.0-3.9 | 0.56 | 1.16 | - | - | 0.57 | 1.20 | - | - | 0.59 | 1.24 | - | - |
| 3.1-3.9 | 0.42 | 1.06 | - | - | 0.42 | 1.08 | - | - | 0.43 | 1.11 | - | - |
| 3.2-3.9 | 0.33 | 0.94 | - | - | 0.33 | 0.96 | - | - | 0.33 | 0.98 | - | - |
| 3.3-3.9 | 0.23 | 0.83 | - | - | 0.23 | 0.83 | - | - | 0.23 | 0.84 | - | - |
| 3.4-3.9 | 0.14 | 0.69 | - | - | 0.14 | 0.69 | - | - | 0.14 | 0.70 | - | - |
| 3.5-3.9 | 0.09 | 0.55 | - | - | 0.09 | 0.55 | - | - | 0.09 | 0.55 | - | - |
| 3.6-3.9 | 0.04 | 0.40 | - | - | 0.04 | 0.41 | - | - | 0.04 | 0.41 | - | - |
| 3.7-3.9 | - | 0.15 | - | - | - | 0.15 | - | - | - | 0.15 | - | - |
| 3.8-3.9 | - | 0.05 | - | - | - | 0.05 | - | - | - | 0.05 | - | - |


[^0]:    *Maciej.Sznajder@p3run.com

