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Solar-MACH: An open-source tool to analyze solar magnetic connection configurations

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The Solar MAgnetic Connection HAUS[1] tool (Solar-MACH) is an open-source tool completely written in Python that derives and visualizes the spatial configuration and solar magnetic connection of different observers (i.e., spacecraft or planets) in the heliosphere at different times. For doing this, the magnetic connection in the interplanetary space is obtained by the classic Parker Heliospheric Magnetic Field (HMF). In close vicinity of the Sun, a Potential Field Source Surface (PFSS) model can be applied to connect the HMF to the solar photosphere. Solar-MACH is especially aimed at providing publication-ready figures for the analyses of Solar Energetic Particle events (SEPs) or solar transients such as Coronal Mass Ejections (CMEs). It is provided as an installable Python package (listed on PyPI and conda-forge), but also as a web tool at solar-mach.github.io that completely runs in any web browser and requires neither Python knowledge nor installation. The development of Solar-MACH is open to everyone and takes place on GitHub, where the source code is publicly available under the BSD 3-Clause License. Established Python libraries like `sunpy` and `pfsspy` are utilized to obtain functionalities when possible. In this article, the Python code of Solar-MACH is explained, and its functionality is demonstrated using real science examples. In addition, we introduce the overarching SERPENTINE project, the umbrella under which the recent development took place.

[1] Heliophysics Archives USer group at ESA.

KEYWORDS

Python (programming language), software package, solar energetic particle (SEP), corona, coronal mass ejection (CME), spacecraft, heliosphere, PFSS

1 Introduction

The *Solar energetic particle analysis platform for the inner heliosphere* (SERPENTINE, 2021–2024) is a 42-month long project funded through the H2020-SPACE-2020 call of the European Union's Horizon 2020 framework programme. The project addresses several outstanding questions on the origin of solar energetic particle (SEP) events and provides an advanced data analysis and visualization platform that will benefit the whole heliophysics community. It utilizes the most recent European and US missions, i.e., Solar Orbiter (Müller et al., 2020), Parker Solar Probe (Fox et al., 2016) and BepiColombo (Benkhoff et al., 2021). These observations are complemented with supporting data from several current missions near Earth's orbit as well as ground-based radio imaging and spectroscopic observations by the European Low Frequency Array (LOFAR; van Haarlem et al., 2013).

SEP events are large and sporadic outbursts of charged particle radiation from the solar corona that are related to solar eruptions such as flares and coronal mass ejections (CMEs; e.g., Reames, 1999). They can be classified as impulsive and gradual events, based on their duration and the duration of the related solar X-ray flare. Impulsive SEP events are associated with impulsive flares and narrow CMEs, and they are enriched in electrons, ^{3}He isotope and heavy ions. Gradual SEP events are associated with gradual solar X-ray flares and fast and wide CMEs, and their abundances resemble nominal coronal abundances (Reames, 2013; Desai and Giacalone, 2016). Gradual events are usually broader in their helio-longitudinal extent than impulsive events and their intensities are also typically larger, making them the main concern of spacecraft operations and crews (Vainio et al., 2009).

The primary reason for the broad spatial extent of some gradual events is still unresolved. It could be due to a broad source, like a global coronal shock driven by a CME (e.g., Lario et al., 2016), due to efficient particle transport processes across the heliospheric magnetic field, or as a result of both mechanisms (e.g., Dresing et al., 2012; Rodríguez-García et al., 2021). The main objective of SERPENTINE is to pinpoint the primary causes of large gradual and widespread SEP events. To address this objective, SERPENTINE will answer the following open science questions:

Q1: What are the primary causes for widespread SEP events observed in the heliosphere?

Q2: What are the shock acceleration mechanisms responsible for accelerating ions from thermal/suprathermal energies to near-relativistic energies in the corona and in the interplanetary medium?

Q3: What is the role of shocks in electron acceleration in large gradual and widespread events? How does it relate to ion acceleration and what is its importance relative to flare acceleration?

To reach these goals and also to broaden the impact of the project, SERPENTINE will develop and release to the community a platform of tools for analyzing SEP events. Furthermore, the tools may also be useful for the broader heliospheric community looking at different aspects of solar activity or solar wind phenomena. Part of this platform will be a JupyterHub server that provides free access to the tools developed by the SERPENTINE project as Jupyter Notebooks, without requiring any installations beyond a web browser. This manuscript and the accompanying papers (Kouloumvakos et al., 2022; Palmroos et al., 2022; Trotta et al., 2022) will present the first batch of these tools to the heliophysics community.

Because SEPs are measured *in situ* as enhancements of the energetic particle fluxes, the presence of multiple, well-separated observers is indispensable to study widespread SEP events (e.g., Dresing et al., 2014; Richardson et al., 2014). The new space missions in combination with established spacecraft form a fleet that is ideal for this purpose, as it covers varying heliocentric distances and large longitudinal ranges around the Sun. The different orbits of the multiple spacecraft, in combination with varying source regions at the Sun, constantly form new constellations, building the baseline for in-depth SEP event analyses. The first released tool of SERPENTINE, Solar-MACH, provides the user with a quick overview of these specific constellations for a selected time, as shown in the example of **Figure 1**. "Solar-MACH" is an abbreviation for *Solar MAgnetic Connection HAUS*, with HAUS standing for the Heliophysics Archives USer group at ESA. "MACH" is intended to be pronounced like the *Mach* number.

2 Method

The main functionality of Solar-MACH is to provide the user with a polar plot showing a Sun-centered top view of the heliographic equatorial plane with the constellation of different observers for a given time, as shown in **Figure 1**. Additional information can be added, such as indicating the magnetic connection of each observer to the Sun as given by an idealized

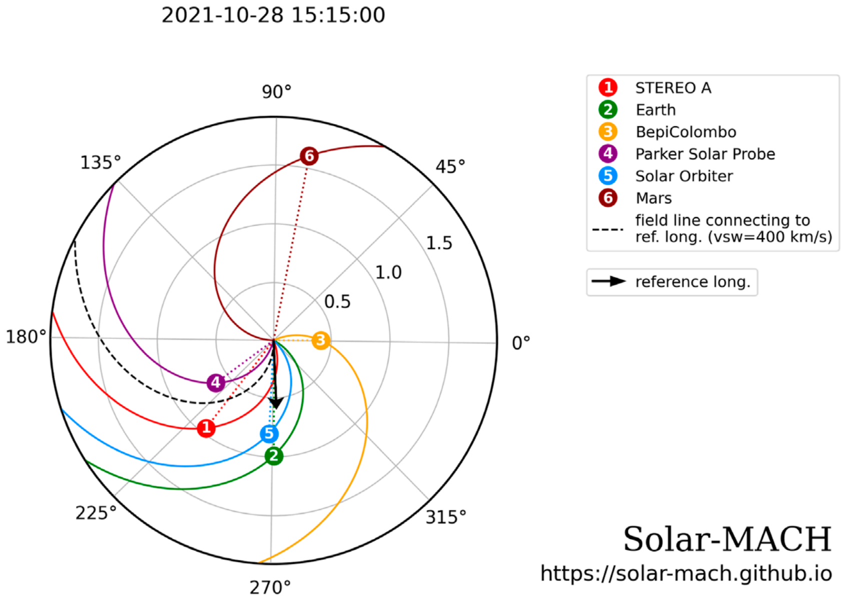


FIGURE 1
Solar-MACH plot for the time of the ground-level enhancement (GLE) event on 28 October 2021. Numbered symbols indicate the observers' locations and the spiral lines corresponding HMF lines connecting them to the Sun. Radial distance is provided in astronomical units (AU), and the angular information is given in Carrington longitude. The arrow points out the freely choosable location of a "reference" (e.g., a solar flare) at the Sun, and the dashed spiral line indicates a corresponding HMF line originating at that position.

classic Parker heliospheric magnetic field line, whose curvature is dependent on the radial solar wind speed. This and other options are described in **Section 2.1**.

All software operations are performed within Python 3 (e.g., Van Rossum and Drake, 2009); the corresponding package `solarmach` is described in **Section 2.2**. In addition, a web tool is provided that requires neither Python knowledge nor installation. This web tool and its technical background are presented in **Section 2.4**.

2.1 General functionality

2.1.1 Ephemeris

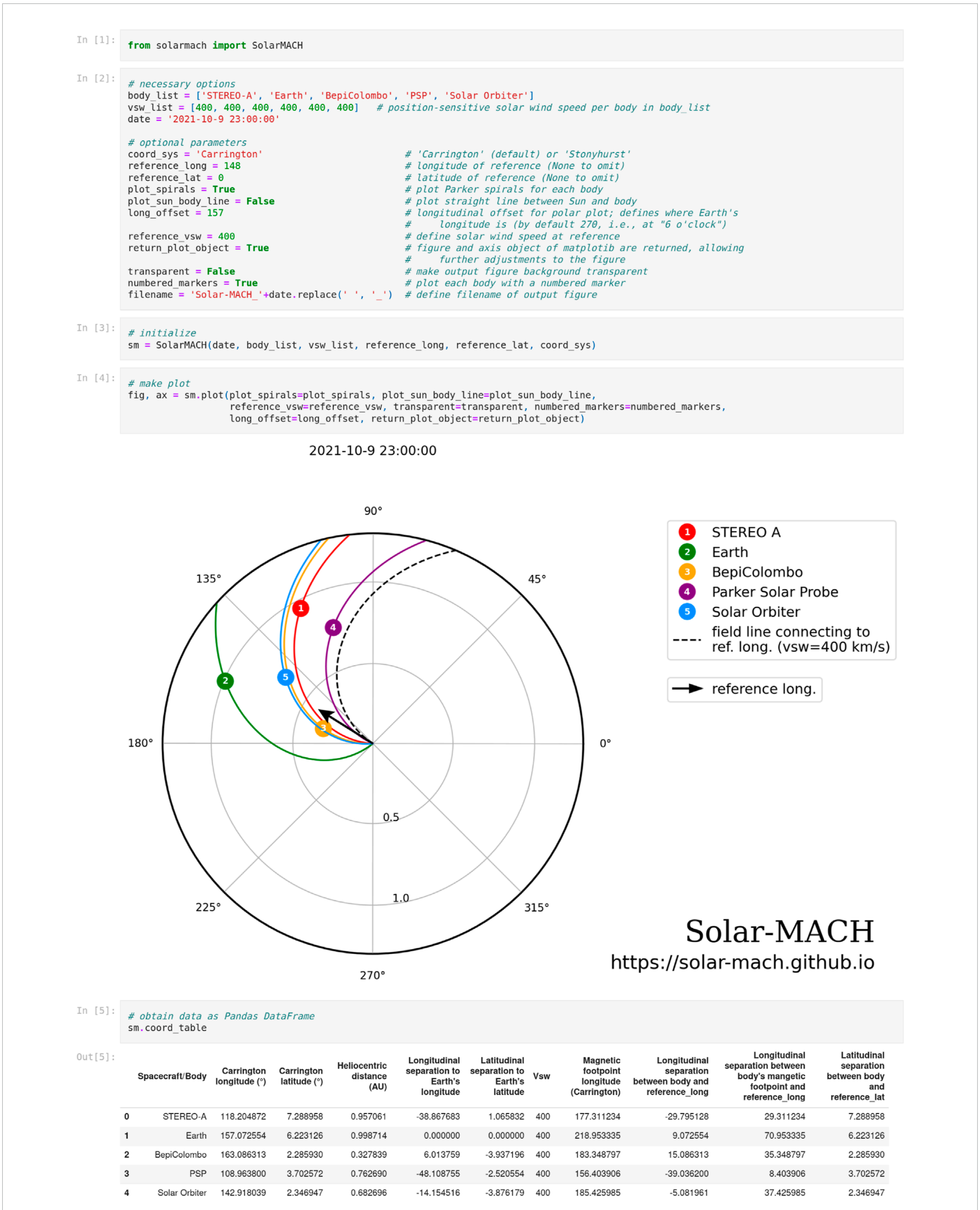
After the user provides a specific date and time, the spatial coordinates of all requested observers are obtained dynamically from JPL Horizons, an online Solar System data and ephemeris computation service that is maintained by the Solar System Dynamics Group of the Jet Propulsion Laboratory (JPL). In addition to the web interface, JPL Horizons provides an API for programmatic control. This API is utilized through version 4.0.5 (Mumford et al., 2022) of the `sunpy` open-source software package (The SunPy Community et al., 2020), which itself uses Astropy's (Astropy Collaboration et al., 2013; Astropy Collaboration et al., 2018; Astropy Collaboration et al., 2022) affiliated package astroquery (Ginsburg et al., 2021) for this functionality. The ephemeris information is returned per observer within Python as a SkyCoord object, which inherently provides coordinate system transformations. This allows easily supporting different heliographic coordinate systems. At the moment, the user can decide whether all operations should be carried out in Stonyhurst or Carrington coordinates (e.g., Thompson, 2006), with the latter being the default setting.

2.1.2 Magnetic connectivity

One important property for analyzing SEP events is the magnetic connection of each observer to the Sun. A simple approximation for this connection can be obtained by assuming an ideal Archimedean spiral configuration for the heliospheric magnetic field (Parker, 1958), which is defined in spherical coordinates by:

$$\varphi(r) = \varphi_0 + \frac{\omega(\vartheta)}{v_{sw}} \cdot (R - r) \cdot \cos\vartheta, \tag{1}$$

with heliographic longitude φ as a function of radial distance r, heliographic latitude ϑ, differential solar rotation frequency $\omega(\vartheta)$, radial solar wind speed v_{sw}, as well as radial distance R and longitude φ_0 of the observer. The differential solar rotation frequency $\omega(\vartheta)$ takes into account that the Sun's rotation speed varies with latitude. Here, we apply an empirical model by Poljančić Beljan et al. (2017) that describes $\omega(\vartheta)$ by $14.50 - 2.87\sin^2\vartheta$ (deg/day), which corresponds to



In [1]:
```
from solarmach import SolarMACH
```

In [2]:
```
# necessary options
body_list = ['STEREO-A', 'Earth', 'BepiColombo', 'PSP', 'Solar Orbiter']
vsw_list = [400, 400, 400, 400, 400, 400]   # position-sensitive solar wind speed per body in body_list
date = '2021-10-9 23:00:00'

# optional parameters
coord_sys = 'Carrington'                        # 'Carrington' (default) or 'Stonyhurst'
reference_long = 148                            # longitude of reference (None to omit)
reference_lat = 0                               # latitude of reference (None to omit)
plot_spirals = True                             # plot Parker spirals for each body
plot_sun_body_line = False                      # plot straight line between Sun and body
long_offset = 157                               # longitudinal offset for polar plot; defines where Earth's
                                                #     longitude is (by default 270, i.e., at "6 o'clock")
reference_vsw = 400                             # define solar wind speed at reference
return_plot_object = True                       # figure and axis object of matplotib are returned, allowing
                                                #     further adjustments to the figure
transparent = False                             # make output figure background transparent
numbered_markers = True                         # plot each body with a numbered marker
filename = 'Solar-MACH_'+date.replace(' ', '_') # define filename of output figure
```

In [3]:
```
# initialize
sm = SolarMACH(date, body_list, vsw_list, reference_long, reference_lat, coord_sys)
```

In [4]:
```
# make plot
fig, ax = sm.plot(plot_spirals=plot_spirals, plot_sun_body_line=plot_sun_body_line,
                  reference_vsw=reference_vsw, transparent=transparent, numbered_markers=numbered_markers,
                  long_offset=long_offset, return_plot_object=return_plot_object)
```

In [5]:
```
# obtain data as Pandas DataFrame
sm.coord_table
```

Out[5]:

	Spacecraft/Body	Carrington longitude (°)	Carrington latitude (°)	Heliocentric distance (AU)	Longitudinal separation to Earth's longitude	Latitudinal separation to Earth's latitude	Vsw	Magnetic footpoint longitude (Carrington)	Longitudinal separation between body and reference_long	Longitudinal separation between body's mangetic footpoint and reference_long	Latitudinal separation between body and reference_lat
0	STEREO-A	118.204872	7.288958	0.957061	-38.867683	1.065832	400	177.311234	-29.795128	29.311234	7.288958
1	Earth	157.072554	6.223126	0.998714	0.000000	0.000000	400	218.953335	9.072554	70.953335	6.223126
2	BepiColombo	163.086313	2.285930	0.327839	6.013759	-3.937196	400	183.348797	15.086313	35.348797	2.285930
3	PSP	108.963800	3.702572	0.762690	-48.108755	-2.520554	400	156.403906	-39.036200	8.403906	3.702572
4	Solar Orbiter	142.918039	2.346947	0.682696	-14.154516	-3.876179	400	185.425985	-5.081961	37.425985	2.346947

FIGURE 2
Example of using the Python package solarmach in a Jupyter Notebook for the SEP event on 9 October 2021.

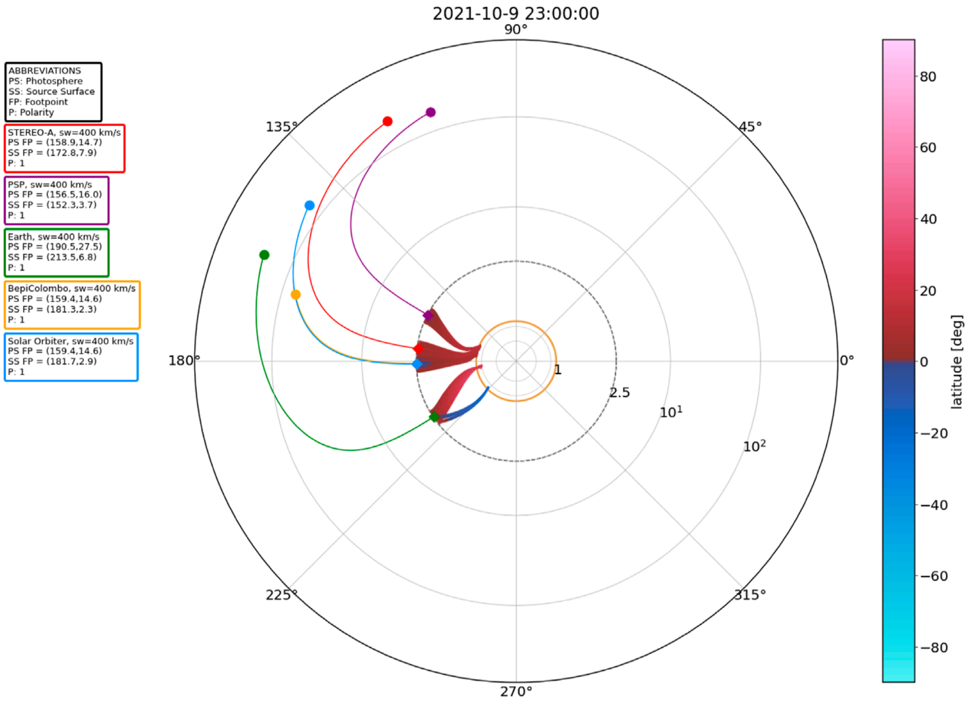


FIGURE 3
PFSS backmapping output of Solar-MACH for the SEP event on 9 October 2021. Note the different scaling of the radial axis compared to Figure 2 (see text for details). The yellow circle represents the photosphere at one solar radius.

14.50 (deg/day) $= 1.678241 \cdot 10^{-4}$ (deg/s) at the heliographic equator. For the two-dimensional visualization, all spherical coordinates are projected to the heliographic equatorial plane. The resulting field lines are shown in Figure 1 as solid spiral lines, with color-coding of the respective spacecraft. As the spatial coordinates are dynamically obtained for each spacecraft, the solar wind speed v_{sw} is the only free parameter that needs to be provided for each observer in units of km/s. By default, this is assumed to be 400 km/s. Automatically obtaining real measurements of the solar wind speed is planned as an option for the future. Applying Eq. 1 for $r = R_\odot$ provides the magnetic footpoint coordinate for each spacecraft, that is, the heliographic longitude where the assumed magnetic field line originates at the Sun. This information is especially important in order to connect *in situ* measurements of SEPs with remote-sensing observations of the associated source regions at the Sun. We must point out, though, that this analysis is just an estimation that may deviate significantly from reality. Employing this tool for magnetic backmapping purposes comes with the known caveats of the simple assumptions of ballistic backmapping, which are a constant and totally radial solar wind speed as well as the absence of interplanetary structures (e.g., interplanetary CMEs) that could deform the ideal Parker field.

2.1.3 Reference location

To further assist this analysis, the location of a so-called "reference" at the Sun (and a corresponding v_{sw}) can be provided to the tool, for example, the position of a flare that is assumed to be related with the SEP event. This information is then used on the one hand to visually indicate the position of the reference (i.e., flare) in the plot with a black arrow (cf. Figure 1) and its corresponding heliospheric magnetic field line, which helps to quickly estimate which spacecraft are possible observers of particles originating at this flare. On the other hand, the separation angles between the position of the reference and the magnetic footpoints of the different spacecraft are calculated. This information can then be obtained for further use in a table that also contains all other coordinate parameters provided by JPL Horizons, as demonstrated in the bottom of Figure 2.

2.1.4 Plotting options

In addition to the functional options described so far, Solar-MACH provides some plotting settings that enable users to have several options of visualization customization:

- Deactivate plotting of the heliospheric magnetic field lines.
- Add a straight line from the Sun to each observer, indicating the line of sight.

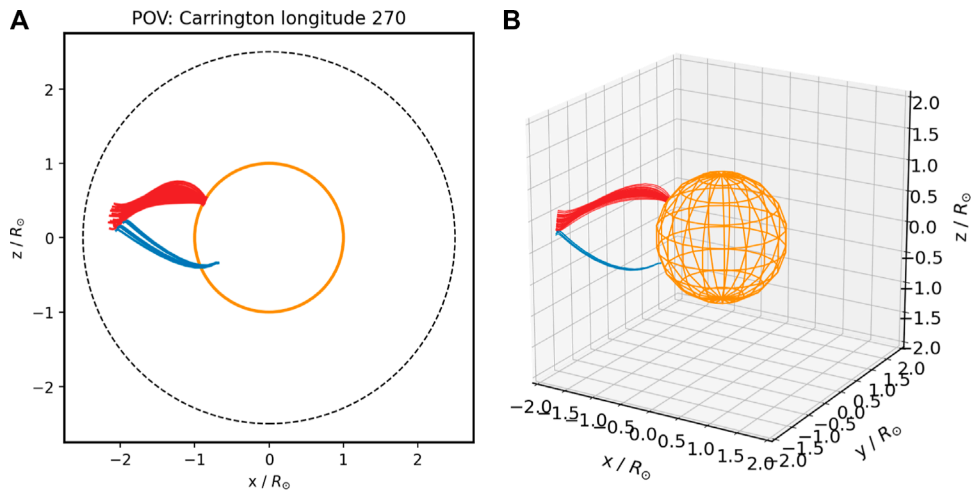


FIGURE 4
Detailed view of Earth's magnetic connection from the PFSS backmapping example shown in **Figure 3**. **(A)** Two-dimensional side view with the point of view (POV) at Carrington longitude 270° (i.e., the observer is located at *six o'clock* in **Figure 3**), **(B)** freely rotatable three-dimensional view. The two colors of the field lines indicate the corresponding magnetic polarity.

- Use numbered markers for the spacecraft to help with color vision deficiency issues or if the plot needs to be converted to grayscale.
- Provide a longitudinal offset for the polar plot to define where the Earth is located (by default 270°, i.e., at *six o'clock*).
- Make the background of the plot transparent.

2.2 Python package solarmach

The Solar-MACH Python code is made available as an installable Python package called `solarmach` (Gieseler et al., 2022b) that is listed on PyPI and conda-forge, i.e., it can be installed using either the `pip` or the `conda` command line tool, which are by far the most widely used means of installing Python packages. Installing the package in this way ensures that all other required packages are also installed.

An example of the standard workflow for the package is shown in a Jupyter Notebook in **Figure 2**. This specific Notebook is also available from the subfolder `examples` in the corresponding GitHub repository. The workflow consists of the following steps (each step is represented by one code cell in the example Notebook in **Figure 2**):

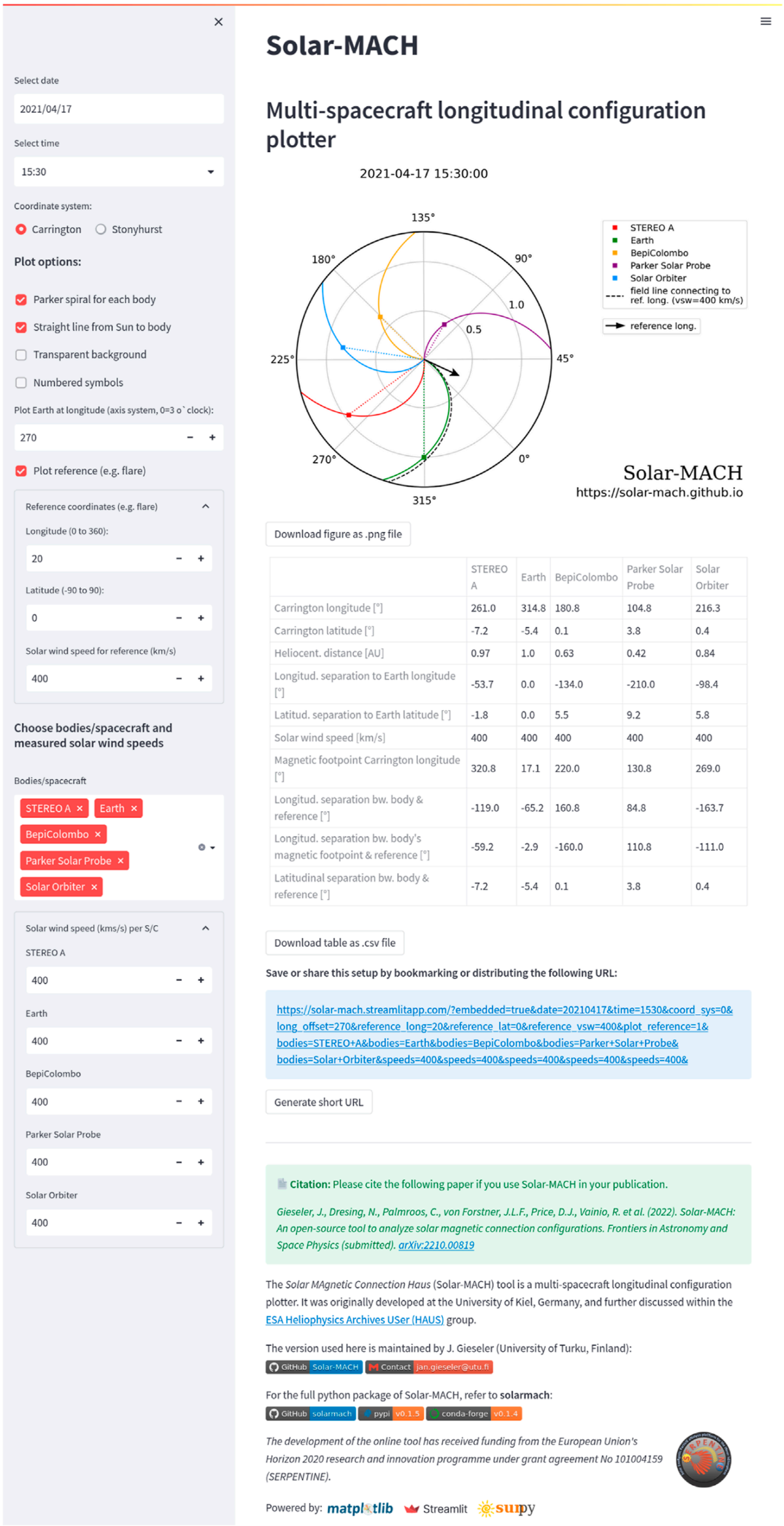
1. Import the `SolarMACH` class
2. Provide necessary options and optional parameters
3. Initialize the `SolarMACH` object with these settings
4. Generate a plot from the `SolarMACH` object (optionally)
5. Obtain the data as a Pandas DataFrame from the `SolarMACH` object (optionally)

The Pandas DataFrame obtained in the last step does not only display the dataset in a tabular form, but also provides the user with a ready-to-use dataset for further analyses, ultimately enabling fast diagnostic pipelines (McKinney, 2010). Furthermore, through the optional settings in step 2, it is possible to either provide a file name and ending under which the plot will then be saved (where the file type is automatically determined, e.g., "file.png" or "file.pdf"), or to return the matplotlib (Hunter, 2007) plot object in order to further manipulate it.

A Jupyter Notebook with more detailed descriptions and various use cases is available in the SERPENTINE software repository (Gieseler et al., 2022c). This Notebook contains examples on how to connect the Solar-MACH outputs with other Python functionalities. One example is the creation of an animated GIF file that shows a time-lapse of the spacecraft constellation over a given time period (see here for an example). In addition, this extended Notebook provides the functionality to continue the interplanetary magnetic connections to the solar corona with a PFSS model, which is described in more detail in **Section 2.3**.

2.3 Further backmapping with PFSS

The magnetic field configuration close to the Sun in the corona differs drastically from the heliospheric magnetic field (HMF) and cannot be described using the simple Parker spiral approach given by **Eq. 1**. In order to further extend the magnetic connectivity from an observer towards the solar surface, a



Select date

2021/04/17

Select time

15:30

Coordinate system:

● Carrington ○ Stonyhurst

Plot options:

☑ Parker spiral for each body

☑ Straight line from Sun to body

□ Transparent background

□ Numbered symbols

Plot Earth at longitude (axis system, 0=3 o`clock):

270

☑ Plot reference (e.g. flare)

Reference coordinates (e.g. flare)

Longitude (0 to 360):

20

Latitude (-90 to 90):

0

Solar wind speed for reference (km/s)

400

Choose bodies/spacecraft and measured solar wind speeds

Bodies/spacecraft

STEREO A × Earth × BepiColombo × Parker Solar Probe × Solar Orbiter ×

Solar wind speed (kms/s) per S/C

STEREO A

400

Earth

400

BepiColombo

400

Parker Solar Probe

400

Solar Orbiter

400

Solar-MACH

Multi-spacecraft longitudinal configuration plotter

Download figure as .png file

	STEREO A	Earth	BepiColombo	Parker Solar Probe	Solar Orbiter
Carrington longitude [°]	261.0	314.8	180.8	104.8	216.3
Carrington latitude [°]	-7.2	-5.4	0.1	3.8	0.4
Heliocent. distance [AU]	0.97	1.0	0.63	0.42	0.84
Longitud. separation to Earth longitude [°]	-53.7	0.0	-134.0	-210.0	-98.4
Latitud. separation to Earth latitude [°]	-1.8	0.0	5.5	9.2	5.8
Solar wind speed [km/s]	400	400	400	400	400
Magnetic footpoint Carrington longitude [°]	320.8	17.1	220.0	130.8	269.0
Longitud. separation bw. body & reference [°]	-119.0	-65.2	160.8	84.8	-163.7
Longitud. separation bw. body's magnetic footpoint & reference [°]	-59.2	-2.9	-160.0	110.8	-111.0
Latitudinal separation bw. body & reference [°]	-7.2	-5.4	0.1	3.8	0.4

Download table as .csv file

Save or share this setup by bookmarking or distributing the following URL:

https://solar-mach.streamlitapp.com/?embedded=true&date=20210417&time=1530&coord_sys=0&long_offset=270&reference_long=20&reference_lat=0&reference_vsw=400&plot_reference=1&bodies=STEREO+A&bodies=Earth&bodies=BepiColombo&bodies=Parker+Solar+Probe&bodies=Solar+Orbiter&speeds=400&speeds=400&speeds=400&speeds=400&speeds=400&

Generate short URL

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The *Solar MAgnetic Connection Haus* (Solar-MACH) tool is a multi-spacecraft longitudinal configuration plotter. It was originally developed at the University of Kiel, Germany, and further discussed within the ESA Heliophysics Archives USer (HAUS) group.

The version used here is maintained by J. Gieseler (University of Turku, Finland):

GitHub Solar-MACH Contact jan.gieseler@utu.fi

For the full python package of Solar-MACH, refer to **solarmach**:

GitHub solarmach pypi v0.1.5 conda-forge v0.1.4

The development of the online tool has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004159 (SERPENTINE).

Powered by: matplotlib Streamlit sunpy

FIGURE 5
The Streamlit web version at solar-mach.github.io.

Potential Field Source Surface (PFSS) model (e.g., Mackay and Yeates, 2012, and references therein) is applied by using version 1.1.2 (Stansby et al., 2022) of the `pfsspy` open-source software package (Stansby et al., 2020). The main purpose is to calculate a set of open magnetic field lines in a defined circular area around the point where an idealized HMF line connects an interplanetary observer to the source surface, at which the field lines are forced by the PFSS model to be radial. This is illustrated in **Figure 3** for the situation on 9 October 2021. The outer colored field lines correspond to those of **Figure 2**, only that the radial distance is now plotted in a semilogarithmic scale, so that the situation close to the Sun can be depicted in more detail. The radial axis is given in units of solar radii, with a linear scale up to where the source surface is assumed (this is a free parameter, by default set to 2.5 solar radii). Further out, a logarithmic scale is used, which explains the slightly different shape of the HMF lines compared to **Figure 2**. Below the source surface, for each HMF line a set of open field lines is calculated and traced back to the photosphere. Color-coding gives additional information about the corresponding latitudes, as depicted by the color bar on the right. **Figure 4** presents alternative ways to illustrate the results, where the set of coronal field lines obtained for the HMF line connecting to the Earth is shown in a two-dimensional side view (**Figure 4A**) or in a freely rotatable three-dimensional view (**Figure 4B**). These figures illustrate a situation in which the magnetic connection below the source surface is ambiguous as the bundle of field lines splits, each leading to a different region at the photosphere. Although the tool cannot provide an unambiguous backmapped magnetic footpoint location, such a result contains important information for the user, which are valuable for further analyses.

At the moment, the PFSS functionality of Solar-MACH is only provided through the Jupyter Notebook in the SERPENTINE software repository (Gieseler et al., 2022c) that has already been mentioned in **Section 2.2**. This part has not yet been added to the `solarmach` package, but this is planned for the near future, subsequently making it available through the Streamlit web tool (cf. **Section 2.4**), too. In order to be able to obtain Helioseismic and Magnetic Imager (HMI) synoptic maps through the Joint Science Operations Center (JSOC) at Stanford University, which are needed as input for the PFSS model in the current version, the user needs to register once at http://jsoc.stanford.edu/ajax/register_email.html. For the future, especially for the integration into the Streamlit web tool, we aim at removing this requirement.

2.4 Streamlit web tool

While all the functionality of Solar-MACH depends fully on Python, a web tool is provided online at solar-mach.github.io that completely runs in the web browser, features a fully graphical user interface (GUI), and requires neither Python knowledge nor installation. It is implemented using the open-source Python package streamlit. This package provides an easy way to set up a GUI to Python functions that is made available through a web server. It is possible to run it locally on a computer (if Python and all other requirements are installed), offering a full GUI to the user instead of running the code in a Jupyter Notebook or terminal. But the main purpose is to deploy the Streamlit application to a web hosting service, because only then it provides all the underlying Python functionalities without the need to install any kind of (Python) software. A screenshot of the web tool is shown in **Figure 5**. We emphasize that the possibility to use the web tool is invaluable for getting started quickly in a non-code environment, which is especially important for new users.

In addition to quickly obtaining an overview of the observer constellation when a SEP event just took place, another important functionality of the web tool is to bookmark or share a given combination of options that has been set through the GUI. After all settings have been done, a specific URL for this configuration is shown at the bottom of the web page (blue box in **Figure 5**). An option is provided next to it to generate a short link of this URL because it contains all settings and is thus rather long. An advantage of this configuration is that almost all settings can be provided through the URL, which thus can be used as a simple API. This API is not documented yet, but should be self-explanatory using a given example.

For further use of the Solar-MACH results, the user can save the plot by clicking with the right mouse button on it and using the web browser functionality, exactly like in the Jupyter Notebook version mentioned in **Section 2.2** and **Section 2.3**. In addition, the web tool provides a download button for the plot that might be helpful, especially when using mobile devices like smartphones or tablets. The web tool also automatically displays a table with all ephemeris, magnetic footpoint, and separation information, which can be downloaded as a comma-separated values (CSV) file.

The Streamlit application itself consists of a rather small code base that is open source (Gieseler et al., 2022a). It collects all necessary parameters from the user through the GUI, hands them over to the `solarmach` package described in **Section 2.2**, and presents the returned results. The online version provided at solar-mach.github.io is automatically redeployed whenever the corresponding GitHub repository is updated. In this process, the latest `solarmach` version available at PyPI is installed. Because the GUI needs to be adjusted manually to any new functionality, the Streamlit version may not always offer the latest additions to the `solarmach` package.

3 Discussion

This paper introduces the Solar-MACH tool to the scientific community. Solar-MACH automatically obtains and visualizes the constellation of the heliospheric spacecraft fleet for a given time and provides a first estimation of the magnetic connectivity of all observers. Here, we illustrated the general workflow of the tool, presented the corresponding Python package `solarmach` and its PFSS extension, and described the important web version of it provided through the `streamlit` library. While the tool is intended to have a very simple interface, it is important to point out that for the magnetic backmapping several assumptions are made in the background. Those results should therefore only be interpreted by users with sufficient knowledge of the topic.

The development process of Solar-MACH started at the University of Kiel, Germany, and further discussion took place within the ESA Heliophysics Archives USer (HAUS) group. Now, the main development continues within the SERPENTINE EU Horizon 2020 project, which has been presented in the beginning of this paper. It is important to note that the project is, and remains, fully open source (under the BSD 3-Clause License) and very much encourages everyone to contribute, either by actual code or by any other kind of feedback.

The software is completely developed in Python and uses established open-source Python libraries such as `pfsspy`, `streamlit`, and `sunpy`. The development takes place continuously in public GitHub repositories (separated for the Python package `solarmach` and the web application), which are also the main entry point for any kind of participation. We encourage users to give feedback on bugs or possible new features by submitting GitHub issues. This should also be the starting point for code contributions. But of course we are also open to feedback through direct communication. All code versions released on GitHub are automatically archived at Zenodo with a DOI, so that each version (or the latest) can be cited independently.

Solar-MACH is already used widely in the scientific community (e.g., Badman et al., 2022; Hu et al., 2022; Mierla et al., 2022; Papaioannou et al., 2022; Rodríguez-García et al., 2022), but the development is still ongoing with the introduction of additional functionalities. Some important future plans have already been mentioned in this paper, such as fully integrating the PFSS extension into Solar-MACH. Further ideas are listed in the GitHub repository's issues section and contain, among others, using dynamically obtained solar wind speeds for the HMF lines, adding trajectories of spacecraft, or introducing features related to CME analyses, such as providing a reference cone instead of an arrow. Furthermore, it is planned to incorporate functions that have already been demonstrated in the Jupyter Notebooks into the core `solarmach` package, for example, the creation of animated GIF files with time-lapses of the spacecraft constellation. For this, like for all other Solar-MACH functions, one important aspect is to provide them in a way such that they remain accessible to all levels of Python users.

Data availability statement

The source code used in this study can be found online:

- Python package code in GitHub repository solarmach, archived at https://doi.org/10.5281/zenodo.7311178
- Streamlit code in GitHub repository Solar-MACH, archived at https://doi.org/10.5281/zenodo.7311215
- Extended example Jupyter Notebook in GitHub repository serpentine, archived at https://zenodo.org/record/7104866.

Author contributions

ND proposed the initial idea of Solar-MACH and discussed it with VG, AM, MR, and AV. Based on code by ND, the initial software version was designed by ND and JvF. JG continued the development. JG developed the Python package and the Streamlit version. JG, ND, CP, and RV designed further functionalities. CP and ND developed the pfsspy integration. AK, DP, LR-G, and DT tested the software and provided critical comments for the development. JG and RV prepared the first paper draft, and all authors were involved in the preparation of the final manuscript. All authors revised the manuscript before submission.

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Conflict of interest

Author JvF was employed by the company Paradox Cat GmbH since 2021. This article is based on his research conducted prior to that at the University of Kiel and unrelated to his current commercial affiliation.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., Earl, N., Starkman, N., Bradley, L., et al. (2022). The Astropy Project: Sustaining and growing a community-oriented open-source project and the latest major release (v5.0) of the core package. *ApJ.* 935, 167. doi:10.3847/1538-4357/ac7c74

Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., Günther, H. M., Lim, P. L., Crawford, S. M., et al. (2018). The Astropy Project: Building an open-science project and status of the v2.0 core package. *AJ* 156, 123. doi:10.3847/1538-3881/aabc4f

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., et al. (2013). Astropy: A community Python package for astronomy. *A&A* 558, A33. doi:10.1051/0004-6361/201322068

Badman, S. T., Carley, E. P., Cañizares, L. A., Dresing, N., Jian, L. K., Lario, D., et al. (2022). Tracking a beam of electrons from the low solar corona into interplanetary space with the Low Frequency Array, Parker Solar Probe and 1 au spacecraft. doi:10.3847/1538-4357/ac90c2

Benkhoff, J., Murakami, G., Baumjohann, W., Besse, S., Bunce, E., Casale, M., et al. (2021). BepiColombo - mission overview and science goals. *Space Sci. Rev.* 217, 90. doi:10.1007/s11214-021-00861-4

Desai, M., and Giacalone, J. (2016). Large gradual solar energetic particle events. *Living Rev. Sol. Phys.* 13, 3. doi:10.1007/s41116-016-0002-5

Dresing, N., Gómez-Herrero, R., Heber, B., Klassen, A., Malandraki, O., Dröge, W., et al. (2014). Statistical survey of widely spread out solar electron events observed with STEREO and ACE with special attention to anisotropies. *A&A* 567, A27. doi:10.1051/0004-6361/201423789

Dresing, N., Gómez-Herrero, R., Klassen, A., Heber, B., Kartavykh, Y., and Dröge, W. (2012). The large longitudinal spread of solar energetic particles during the 17 January 2010 solar event. *Sol. Phys.* 281, 281–300. doi:10.1007/s11207-012-0049-y

Fox, N. J., Velli, M. C., Bale, S. D., Decker, R., Driesman, A., Howard, R. A., et al. (2016). The Solar Probe Plus Mission: Humanity's first visit to our star. *Space Sci. Rev.* 204, 7–48. doi:10.1007/s11214-015-0211-6

Gieseler, J., Dresing, N., and Freiherr von Forstner, J. L. (2022a). jgieseler/Solar-MACH: 0.1.5. doi:10.5281/zenodo.7311215

Gieseler, J., Dresing, N., Freiherr von Forstner, J. L., Palmroos, C., and Vainio, R. (2022b). jgieseler/solarmach: 0.1.5. doi:10.5281/zenodo.7311178

Gieseler, J., Palmroos, C., Dresing, N., Morosan, D., Asvestari, E., Yli-Laurila, A., et al. (2022c). serpentine-h2020/serpentine: v1.1. doi:10.5281/zenodo.7139716

Ginsburg, A., Sipcz, B., Parikh, M., Brasseur, C. E., jcsegovia, Groener, A., et al. (2021). Astropy/astroquery: v0.4.5. doi:10.5281/zenodo.5804082

Hu, Q., He, W., and Chen, Y. (2022). A magnetic flux rope configuration derived by optimization of two-spacecraft *in-situ* measurements. *Front. Phys.* 10, 960315. doi:10.3389/fphy.2022.960315

Hunter, J. D. (2007). Matplotlib: A 2d graphics environment. *Comput. Sci. Eng.* 9, 90–95. doi:10.1109/MCSE.2007.55

Kouloumvakos, A., Rodríguez-García, L., Gieseler, J., Price, D., Vourlidas, A., and Vainio, R. (2022). PyThea: An open-source software package to perform 3d reconstruction of coronal mass ejections and shock waves. *Front. Astronomy Space Sci.* 9. doi:10.3389/fspas.2022.974137

Lario, D., Kwon, R.-Y., Vourlidas, A., Raouafi, N. E., Haggerty, D. K., Ho, G. C., et al. (2016). Longitudinal properties of a widespread solar energetic particle event on 2014 February 25: Evolution of the associated CME shock. *ApJ.* 819, 72. doi:10.3847/0004-637X/819/1/72

Mackay, D. H., and Yeates, A. R. (2012). The Sun's global photospheric and coronal magnetic fields: Observations and models. *Living Rev. Sol. Phys.* 9, 6. doi:10.12942/lrsp-2012-6

McKinney, W. (2010). "Data structures for statistical computing in Python," in *Proceedings of the 9th Python in science conference*. Editors Stéfan van der Walt, and Jarrod Millman, 56–61. doi:10.25080/Majora-92bf1922-00a

Mierla, M., Zhukov, A. N., Berghmans, D., Parenti, S., Auchère, F., Heinzel, P., et al. (2022). Prominence eruption observed in He II 304 Å up to >6 $R_\odot$ by EUI/FSI aboard Solar Orbiter. *A&A* 662, L5. doi:10.1051/0004-6361/202244020

Müller, D., Cyr, O. C., Zouganelis, I., Gilbert, H. R., Marsden, R., Nieves-Chinchilla, T., et al. (2020). The Solar Orbiter Mission. Science overview. *A&A* 642, A1. doi:10.1051/0004-6361/202038467

Mumford, S. J., Freij, N., Stansby, D., Christe, S., Ireland, J., Mayer, F., et al. (2022). SunPy. doi:10.5281/zenodo.7074315

Palmroos, C., Gieseler, J., Dresing, N., Mororsan, D. E., Asvestari, E., Valkila, S., et al. (2022). Solar energetic particle time series analysis with Python. *Front. Astronomy Space Phys.* doi:10.3389/fspas.2022.1073578

Papaioannou, A., Kouloumvakos, A., Mishev, A., Vainio, R., Usoskin, I., Herbst, K., et al. (2022). The first ground-level enhancement of solar cycle 25 on 28 October 2021. *A&A* 660, L5. doi:10.1051/0004-6361/202142855

Parker, E. N. (1958). Dynamics of the interplanetary gas and magnetic fields. *ApJ.* 128, 664. doi:10.1086/146579

Poljančić Beljan, I., Jurdana-Šepić, R., Brajša, R., Sudar, D., Ruždjak, D., Hržina, D., et al. (2017). Solar differential rotation in the period 1964-2016 determined by the Kanzelhöhe data set. *A&A* 606, A72. doi:10.1051/0004-6361/201731047

Reames, D. V. (1999). Particle acceleration at the Sun and in the heliosphere. *Space Sci. Rev.* 90, 413–491. doi:10.1023/A1005105831781

Reames, D. V. (2013). The two sources of solar energetic particles. *Space Sci. Rev.* 175, 53–92. doi:10.1007/s11214-013-9958-9

Richardson, I. G., von Rosenvinge, T. T., Cane, H. V., Christian, E. R., Cohen, C. M. S., Labrador, A. W., et al. (2014). >25 MeV proton events observed by the high energy telescopes on the STEREO A and B spacecraft and/or at Earth during the first ∼ seven years of the STEREO mission. *Sol. Phys.* 289, 3059–3107. doi:10.1007/s11207-014-0524-8

Rodríguez-García, L., Gómez-Herrero, R., Zouganelis, I., Balmaceda, L., Nieves-Chinchilla, T., Dresing, N., et al. (2021). The unusual widespread solar energetic particle event on 2013 August 19. Solar origin and particle longitudinal distribution. *A&A* 653, A137. doi:10.1051/0004-6361/202039960

Rodríguez-García, L., Gómez-Herrero, R., Dresing, N., Lario, D., Zouganelis, I., Balmaceda, L. A., et al. (2022). Solar energetic electron events measured by MESSENGER and Solar Orbiter. Peak intensity and energy spectrum radial dependences: Statistical analysis. *A&A*. (in press). doi:10.1051/0004-6361/202244553

Stansby, D., Badman, S., Ancellin, M., and Barnes, W. (2022). dstansby/pfsspy: pfsspy 1.1.2. doi:10.5281/zenodo.7025396

Stansby, D., Yeates, A., and Badman, S. T. (2020). pfsspy: A python package for potential field source surface modelling. *J. Open Source Softw.* 5, 2732. doi:10.21105/joss.02732

The SunPy Community Barnes, W. T., Bobra, M. G., Christe, S. D., Freij, N., Hayes, L. A., et al. (2020). The SunPy project: Open source development and status of the version 1.0 core package. *ApJ.* 890, 68. doi:10.3847/1538-4357/ab4f7a

Thompson, W. T. (2006). Coordinate systems for solar image data. *A&A* 449, 791–803. doi:10.1051/0004-6361:20054262

Trotta, D., Vuorinen, L., Hietala, H., Horbury, T. S., Dresing, N., Gieseler, J., et al. (2022). Single-spacecraft techniques for shock parameters estimation: A systematic approach. *Front. Astronomy Space Phys.* (accepted). doi:10.3389/fspas.2022.1005672

Vainio, R., Desorgher, L., Heynderickx, D., Storini, M., Flückiger, E., Horne, R. B., et al. (2009). Dynamics of the Earth's particle radiation environment. *Space Sci. Rev.* 147, 187–231. doi:10.1007/s11214-009-9496-7

van Haarlem, M. P., Wise, M. W., Gunst, A. W., Heald, G., McKean, J. P., Hessels, J. W. T., et al. (2013). Lofar: The LOw-Frequency ARray. *A&A* 556, A2. doi:10.1051/0004-6361/201220873

Van Rossum, G., and Drake, F. L. (2009). *Python 3 reference manual*. Scotts Valley, CA: CreateSpace.