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pfsspy: A Python package for potential field source surface modelling

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Software

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Summary

Magnetic fields play a crucial role in the dynamics and evolution of our Sun and other stars. A common method used to model the magnetic fields in solar and stellar atmospheres is the potential field source surface (PFSS) model (Altschuler & Newkirk, 1969; Schatten, Wilcox, & Ness, 1969). The PFSS equations assume that there is zero electrical current in the domain of interest, leading to the equations

$$\nabla \cdot \mathbf{B} = 0; \quad \nabla \times \mathbf{B} = 0 \tag{1}$$

These are solved in a spherical shell between the surface of the star and a configurable outer radius called the 'source surface'. Boundary conditions are given by the user specified radial component of $\mathbf{B}$ on the inner boundary and the imposed condition of a purely radial field on the source surface, which mimics the effect of the escaping stellar wind.

Historically, either custom implementations or the `pfsspack`[1] IDL library have been used to perform PFSS extrapolations. As Python has become a major programming language within the solar physics and wider astronomy community (Bobra et al., 2020), there is a need to provide well documented and tested functionality to perform PFSS extrapolations within the Python ecosystem, a niche that `pfsspy` fills.

pfsspy

`pfsspy` is a Python package for solving the PFSS equations, and carrying out other common related tasks such as tracing magnetic field lines through the solution, importing various magnetic field data sources, and visualising all of this data.

The PFSS code implements a finite difference solver, based on the method of Ballegooijen, Priest, & Mackay (2000). Given a 2D map of the radial magnetic field on the inner boundary, the magnetic vector potential is calculated on a 3D grid equally spaced in $\sin(\text{latitude})$, longitude, and $\ln(\text{radius})$. This method is tailored in order to achieve $\nabla \times \mathbf{B} = 0$ to machine precision. More details on the exact numerical scheme are given in the online documentation[2].

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[1] https://www.lmsal.com/~derosa/pfsspack/, which forms part of the larger `SolarSoft` library for solar physics (Freeland & Handy, 1998), written in Interactive Data Language (IDL).

[2] https://pfsspy.readthedocs.io

Integration

`pfsspy` is designed to closely integrate with other packages in the astronomical and solar physics Python ecosystems. Coordinate aware input and output maps are created with the sunpy package (Mumford et al., 2020; The SunPy Community et al., 2020), and `pfsspy` is fully integrated with the coordinate and unit framework present in astropy (The Astropy Collaboration et al., 2018). This makes it easy to combine magnetic fields and field lines calculated in `pfsspy` with other data sources. As an example, Figure 1 shows magnetic field lines overplotted on an extreme-ultraviolet image of a large active region on the Sun.

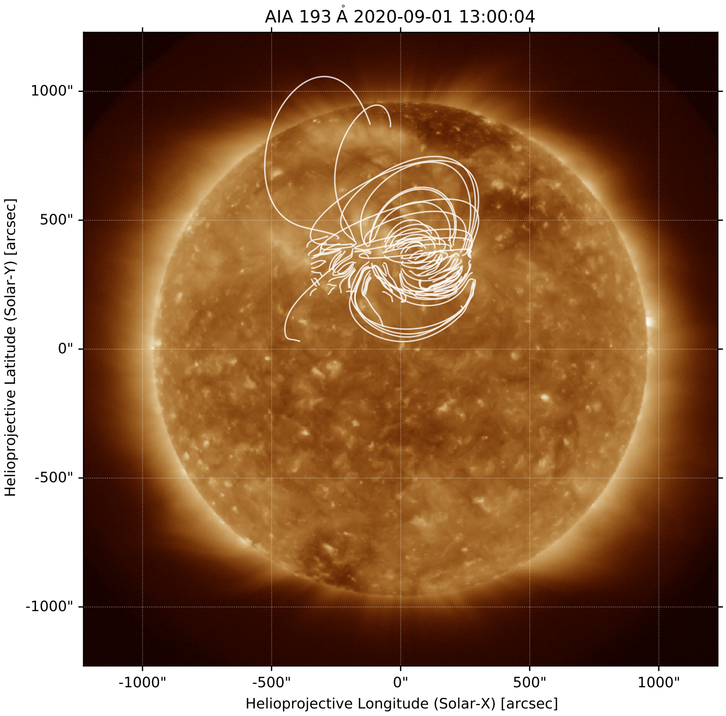

Figure 1: An image of the Sun taken by SDO/AIA at 193 angstroms, with selected magnetic field lines traced through a PFSS solution overplotted in white. The PFSS solution and field line tracing were done with `pfsspy`, with a Global Oscillations Network Group (GONG) photospheric magnetogram as input and a source surface at 2.5 solar radii. Although only selected field lines are shown, the magnetic field is solved over the whole Sun.

The solar physics community has already made use of `pfsspy` in a number of works, from interpreting observations from Parker Solar Probe (Badman et al., 2020; Bale et al., 2019), investigating the structure of coronal mass ejections (Maguire, Carley, McCauley, & Gallagher, 2020), and drawing links between the Sun and the solar wind (Stansby, Baker, Brooks, & Owen, 2020). We hope that it continues to provide a useful resource for the community in the future.

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