pfsspy Documentation

pfsspy contributors

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Contents

pfsspy is a python package for carrying out Potential Field Source Surface modelling. For more information on the actually PFSS calculation see this document.

Note: pfsspy is a very new package, so elements of the API are liable to change with the first few releases. If you find any bugs or have any suggestions for improvement, please raise an issue here: https://github.com/dstansby/pfsspy/issues

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pfsspy can be installed from PyPi using

```
pip install pfsspy
```

CHAPTER 1

Improving performance

pfsspy automatically detects an installation of numba, which compiles some of the numerical code to speed up pfss calculations. To enable this simply install numba and use pfsspy as normal.

CHAPTER 2

Citing

If you use pfsspy in work that results in publication, please cite the archived code at *both*

- https://zenodo.org/record/2566462
- https://zenodo.org/record/1472183

Citation details can be found at the lower right hand of each web page.

CHAPTER 3

Code reference

For the main user-facing code and a changelog see

3.1 pfsspy Package

3.1.1 Functions

load_output(file)	Load a saved output file.
pfss(input)	Compute PFSS model.

load_output

pfsspy.**load_output**(*file*)

Load a saved output file.

Loads a file saved using *Output.save()*.

Parameters

file [str, file, Path] File to load.

Returns

:class:'Output'

pfss

pfsspy.**pfss**(*input*)

Compute PFSS model.

Extrapolates a 3D PFSS using an eigenfunction method in r, s, p coordinates, on the dumfric grid (equally spaced in $\rho = \ln(r/r_{sun})$, $s = \cos(\theta)$, and $p = \phi$).

The output should have zero current to machine precision, when computed with the DuMFriC staggered discretization.

Parameters

input [*Input*] Input parameters.

Returns

out [*Output*]

3.1.2 Classes

FieldLine(x, y, z, output)	A single magnetic field line.
Grid(ns, nphi, nr, rss)	Grid on which the solution is calculated.
Input(br, nr, rss)	Input to PFSS modelling.
Output(alr, als, alp, grid)	Output of PFSS modelling.

FieldLine

class pfsspy.**FieldLine**(*x*, *y*, *z*, *output*)

Bases: `astropy.coordinates.sky_coordinate.SkyCoord`

A single magnetic field line.

This is a sub-class of *astropy.coordinates.SkyCoord*. For more details on

Parameters

x : Field line x coordinates as a fraction of solar radius

y : Field line y coordinates as a fraction of solar radius

z : Field line z coordinates as a fraction of solar radius

output [*Output*]

Attributes

representation_type [str] Coordinate system representation. By default is `'cartesian'`, but can also be manually set to `'spherical'`.

x, y, z : Field line cartesian coordinates. Can only be accessed if *representation_type* is `'cartesian'`.

r, theta, phi : field line spherical coordinates. Can only be accessed if *representation_type* is `'spherical'`.

Attributes Summary

expansion_factor	Magnetic field expansion factor.
is_open	Returns `True` if one of the field line is connected to the solar surface and one to the outer boundary, `False` otherwise.
polarity	Magnetic field line polarity.

Attributes Documentation

expansion_factor
Magnetic field expansion factor.

The expansion factor is defnied as $(r_\odot^2 B_\odot)/(r_{ss}^2 B_{ss}))$

Returns

exp_fact [float] Field line expansion factor. If field line is closed, returns `None`.

is_open
Returns `True` if one of the field line is connected to the solar surface and one to the outer boundary, `False` otherwise.

polarity
Magnetic field line polarity.

Returns

pol [int] 0 if the field line is closed, otherwise sign(Br) of the magnetic field on the solar surface.

Grid

class pfsspy.**Grid**(*ns*, *nphi*, *nr*, *rss*)
Bases: `object`

Grid on which the solution is calculated.

The grid is evenly spaced in (cos(theta), phi, log(r)). See *pfsspy.coords* for more information.

Attributes Summary

dp	Cell size in phi.
dr	Cell size in log(r).
ds	Cell size in cos(theta).
pc	Location of the centre of cells in phi.
pg	Location of the edges of grid cells in phi.
rc	Location of the centre of cells in log(r).
rg	Location of the edges of grid cells in log(r).
sc	Location of the centre of cells in cos(theta).
sg	Location of the edges of grid cells in cos(theta).

Attributes Documentation

dp
Cell size in phi.

dr
Cell size in log(r).

ds
Cell size in cos(theta).

pc
Location of the centre of cells in phi.

pg
Location of the edges of grid cells in phi.

rc
Location of the centre of cells in log(r).

rg
Location of the edges of grid cells in log(r).

sc
Location of the centre of cells in cos(theta).

sg
Location of the edges of grid cells in cos(theta).

Input

class pfsspy.**Input**(*br*, *nr*, *rss*)
Bases: object

Input to PFSS modelling.

> **Warning:** The input must be on a regularly spaced grid in ϕ and $s = \cos(\theta)$. See *pfsspy.coords* for more information on the coordinate system.

Parameters

br [2D array, sunpy.map.Map] Boundary condition of radial magnetic field at the inner surface. If a SunPy map is automatically extracted as map.data with *no* processing.

nr [int] Number of cells in the radial direction to calculate the PFSS solution on.

rss [float] Radius of the source surface, as a fraction of the solar radius.

Methods Summary

plot_input([ax])	Plot a 2D image of the magnetic field boundary condition.

Methods Documentation

plot_input(*ax=None*)
Plot a 2D image of the magnetic field boundary condition.

Parameters

ax [Axes] Axes to plot to. If None, creates a new figure.

Output

class pfsspy.**Output**(*alr*, *als*, *alp*, *grid*)
Bases: object

Output of PFSS modelling.

Parameters

alr : Vector potential * grid spacing in radial direction.

als : Vector potential * grid spacing in elevation direction.

alp : Vector potential * grid spacing in azimuth direction.

grid [Grid] Grid that the output was caclulated on.

Attributes Summary

al	Vector potential times cell edge lenghts.
bc	B on the centres of the cell faces.
bg	B as a (weighted) averaged on grid points.
source_surface_br	Br on the source surface.

Methods Summary

plot_pil([ax])	Plot the polarity inversion line on the source surface.
plot_source_surface([ax])	Plot a 2D image of the magnetic field at the source surface.
save(file)	Save the output to file.
trace(x0[, atol, rtol])	Traces a field-line from *x0*.

Attributes Documentation

al

Vector potential times cell edge lenghts.

Returns ar*Lr, as*Ls, ap*Lp on cell edges.

bc

B on the centres of the cell faces.

bg

B as a (weighted) averaged on grid points.

Returns

br [array]

bs [array]

bp [array]

source_surface_br

Br on the source surface.

Methods Documentation

plot_pil(*ax=None*, ***kwargs*)

Plot the polarity inversion line on the source surface.

The PIL is where Br = 0.

Parameters

ax [Axes] Axes to plot to. If `None`, creates a new figure.

****kwargs :** Keyword arguments are handed to *ax.contour*.

plot_source_surface(*ax=None*)
Plot a 2D image of the magnetic field at the source surface.

Parameters

ax [Axes] Axes to plot to. If `None`, creates a new figure.

save(*file*)
Save the output to file.

This saves the required information to reconstruct an Output object in a compressed binary numpy file (see `numpy.savez_compressed()` for more information). The file extension is `.npz`, and is automatically added if not present.

Parameters

file [str, file, `Path`] File to save to. If `.npz` extension isn't present it is added when saving the file.

trace(*x0*, *atol=0.0001*, *rtol=0.0001*)
Traces a field-line from *x0*. *x0* **must** be a cartesian coordinate. See *pfsspy.coords* for more information on coordinate transforms, and helper functions for transforming between coordinate systems.

Uses *scipy.integrate.solve_ivp*, with an LSODA method.

Parameters

x0 [array] Starting coordinate, in cartesian coordinates. *pfsspy.coords* can be used to convert from spherical coordinates to cartesian coordinates and vice versa.

dtf [float, optional] Absolute tolerance of the tracing.

rtol [float, optional] Relative tolerance of the tracing.

Returns

fl [*FieldLine*]

3.2 Changelog

3.2.1 0.1.4

- Added more explanatory comments to the examples
- Corrected the dipole solution calculation
- Added *pfsspy.coords.sph2cart()* to transform from spherical to cartesian coordinates.

3.2.2 0.1.3

- *pfsspy.Output.plot_pil()* now accepts keyword arguments that are given to Matplotlib to control the style of the contour.
- *pfsspy.FieldLine.expansion_factor* is now cached, and is only calculated once if accessed multiple times.

for usage examples see

3.3 pfsspy examples

Note: Click *here* to download the full example code

3.3.1 Dipole source solution

A simple example showing how to use pfsspy to compute the solution to a dipole source field.

First, import required modules

```
import astropy.constants as const
import matplotlib.pyplot as plt
import matplotlib.patches as mpatch
import numpy as np
import pfsspy
import pfsspy.coords as coords
```

To start with we need to construct an input for the PFSS model. To do this, first set up a regular 2D grid in (phi, s), where s = cos(theta) and (phi, theta) are the standard spherical coordinate system angular coordinates. In this case the resolution is (360 x 180).

```
nphi = 360
ns = 180

phi = np.linspace(0, 2 * np.pi, nphi)
s = np.linspace(-1, 1, ns)
s, phi = np.meshgrid(s, phi)
```

Now we can take the grid and calculate the boundary condition magnetic field.

```
def dipole_Br(r, s):
    return 2 * s / r**3


br = dipole_Br(1, s).T
```

The PFSS solution is calculated on a regular 3D grid in (phi, s, rho), where rho = ln(r), and r is the standard spherical radial coordinate. We need to define the number of rho grid points, and the source surface radius.

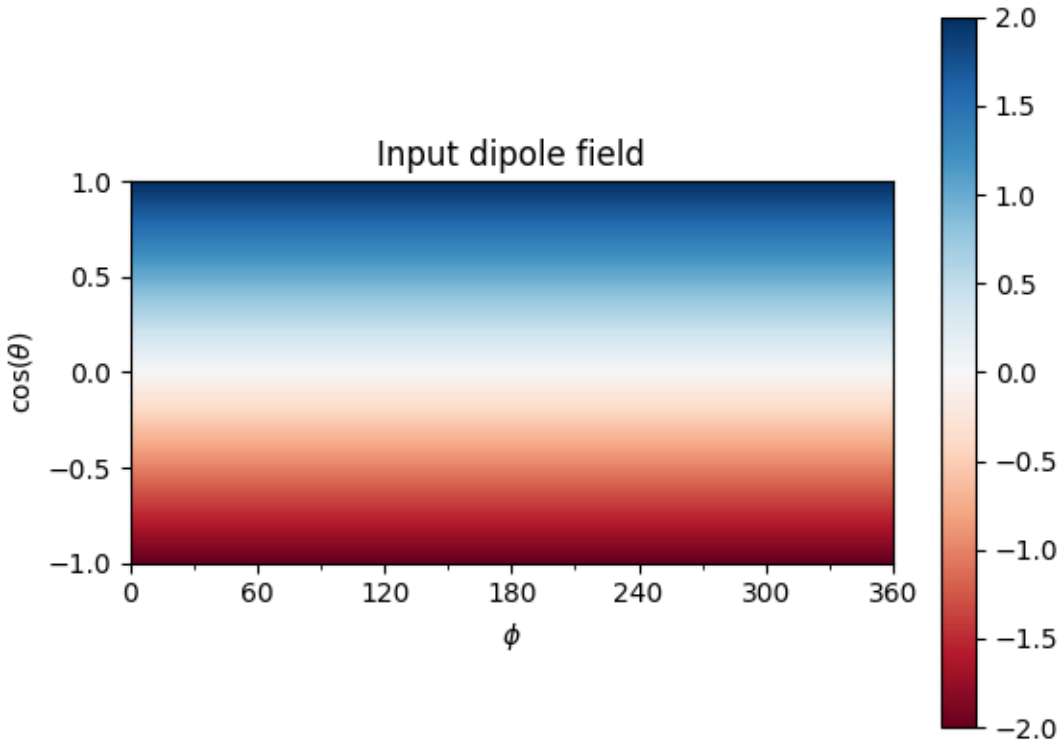
```
nrho = 50
rss = 2.5
```

From the boundary condition, number of radial grid points, and source surface, we now construct an Input object that stores this information

```
input = pfsspy.Input(br, nrho, rss)
```

Using the Input object, plot the input field

```
fig, ax = plt.subplots()
mesh = input.plot_input(ax)
fig.colorbar(mesh)
ax.set_title('Input dipole field')
```

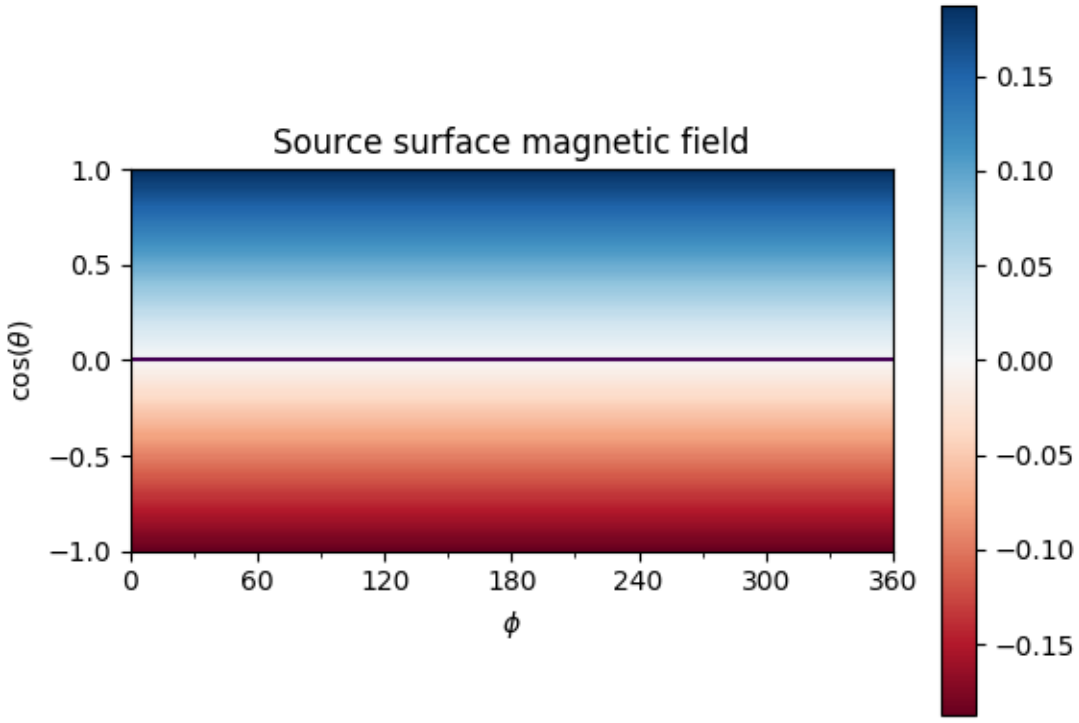


Now calculate the PFSS solution.

```
output = pfsspy.pfss(input)
```

Using the Output object we can plot the source surface field, and the polarity inversion line.

```
fig, ax = plt.subplots()
mesh = output.plot_source_surface(ax)
fig.colorbar(mesh)
output.plot_pil(ax)
ax.set_title('Source surface magnetic field')
```

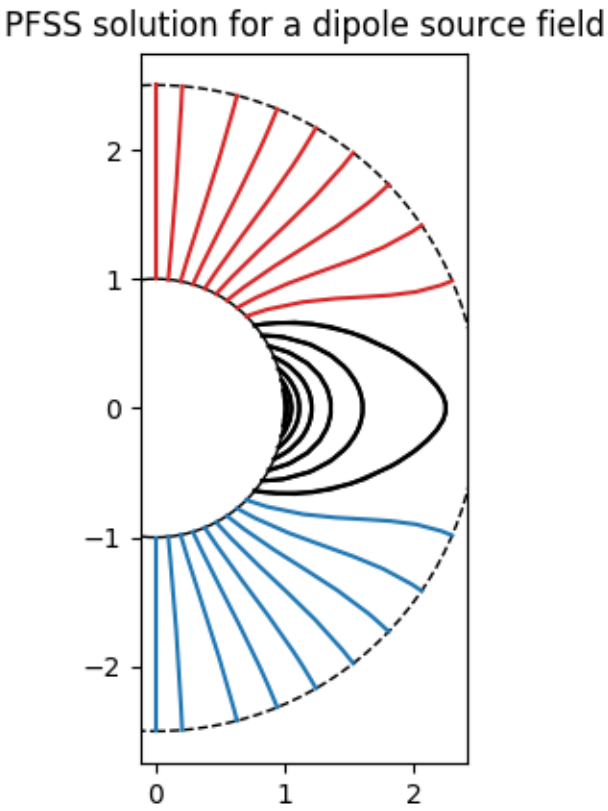


Finally, using the 3D magnetic field solution we can trace some field lines. In this case 32 points equally spaced in theta are chosen and traced from the source surface outwards.

```
fig, ax = plt.subplots()
ax.set_aspect('equal')

# Take 32 start points spaced equally in theta
r = 1.01
phi = np.pi / 2
for theta in np.linspace(0, np.pi, 33):
    x0 = coords.sph2cart(r, theta, phi)
    field_line = output.trace(np.array(x0))
    color = {0: 'black', -1: 'tab:blue', 1: 'tab:red'}.get(field_line.polarity)
    ax.plot(field_line.y / const.R_sun,
            field_line.z / const.R_sun, color=color)

# Add inner and outer boundary circles
ax.add_patch(mpatch.Circle((0, 0), 1, color='k', fill=False))
ax.add_patch(mpatch.Circle((0, 0), input.grid.rss, color='k', linestyle='--',
                           fill=False))
ax.set_title('PFSS solution for a dipole source field')
plt.show()
```



Total running time of the script: (0 minutes 9.620 seconds)

Note: Click *here* to download the full example code

3.3.2 GONG PFSS extrapolation

Calculating PFSS solution for a GONG synoptic magnetic field map.

First, import required modules

```
import os
import astropy.constants as const
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D
import numpy as np
import sunpy.map

import pfsspy
import pfsspy.coords as coords
```

Load a GONG magnetic field map. If 'gong.fits' is present in the current directory, just use that, otherwise download a sample GONG map.

```
if not os.path.exists('gong.fits') and not os.path.exists('gong.fits.gz'):
    import urllib.request
    urllib.request.urlretrieve(
        'https://gong2.nso.edu/oQR/zqs/201901/mrzqs190108/mrzqs190108t1114c2212_050.
↪fits.gz',
        'gong.fits.gz')

if not os.path.exists('gong.fits'):
    import gzip
    with gzip.open('gong.fits.gz', 'rb') as f:
        with open('gong.fits', 'wb') as g:
            g.write(f.read())
```

We can now use SunPy to load the .fits file, and extract the magnetic field data.

The mean is subtracted to enforce div(B) = 0 on the solar surface: n.b. it is not obvious this is the correct way to do this, so use the following lines at your own risk!

```
map = sunpy.map.Map('gong.fits')
br = map.data
br = br - np.mean(br)
```

The PFSS solution is calculated on a regular 3D grid in (phi, s, rho), where rho = ln(r), and r is the standard spherical radial coordinate. We need to define the number of rho grid points, and the source surface radius.

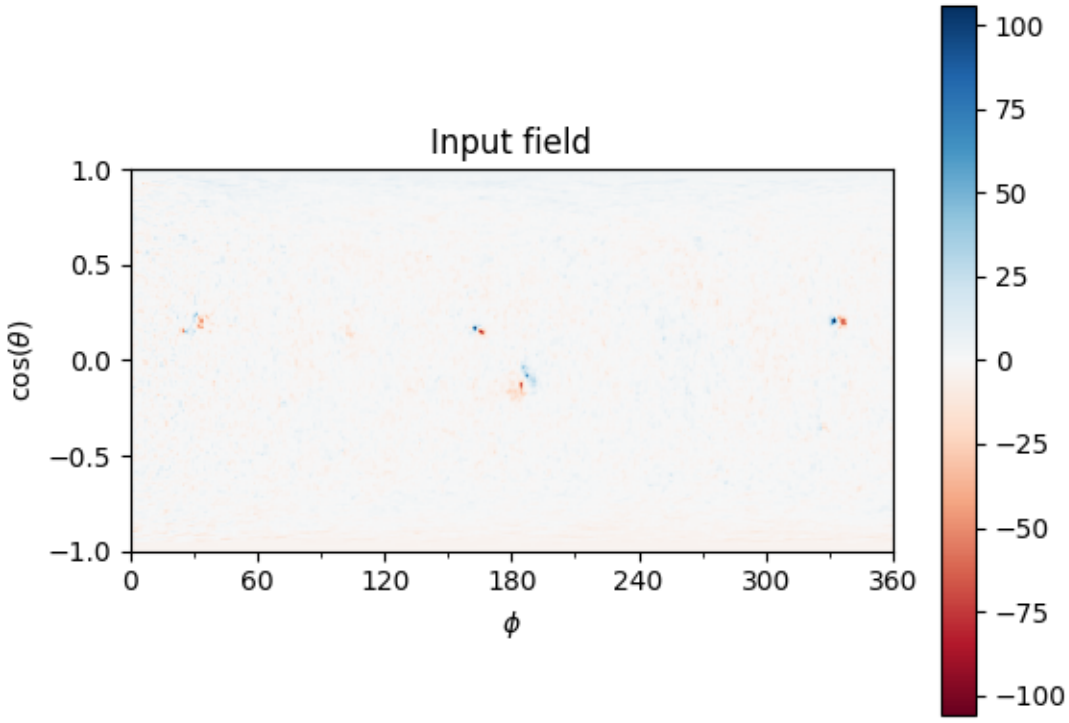
```
nrho = 60
rss = 2.5
```

From the boundary condition, number of radial grid points, and source surface, we now construct an Input object that stores this information

```
input = pfsspy.Input(br, nrho, rss)
```

Using the Input object, plot the input field

```
fig, ax = plt.subplots()
mesh = input.plot_input(ax)
fig.colorbar(mesh)
ax.set_title('Input field')
```

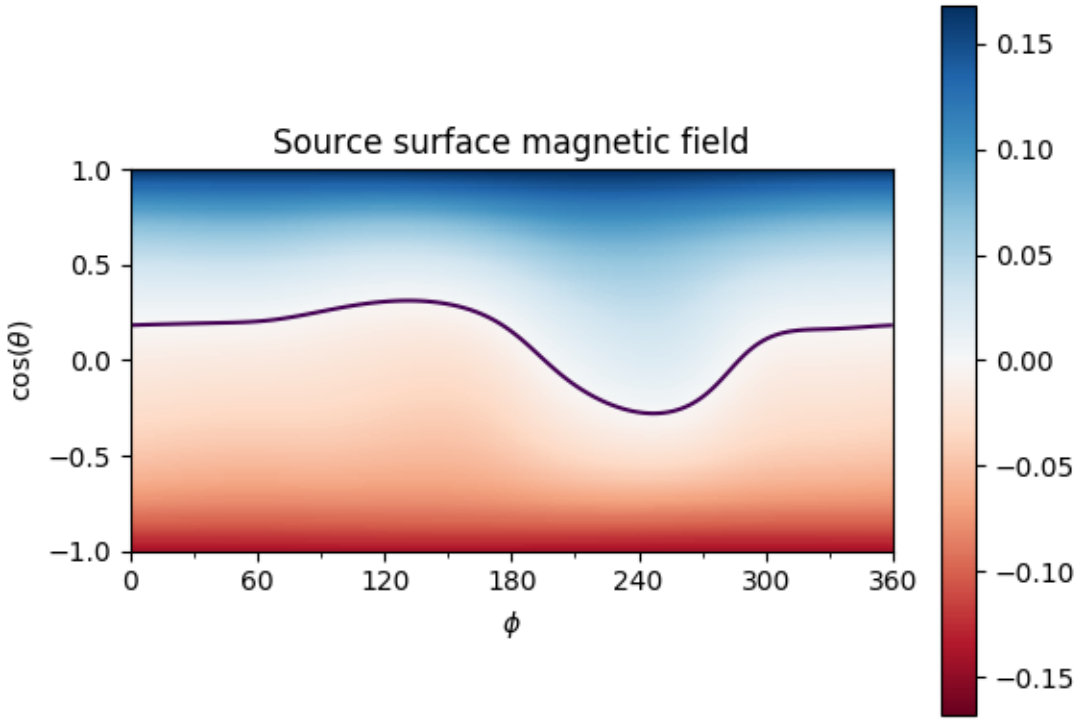


Now calculate the PFSS solution, and plot the polarity inversion line.

```
output = pfsspy.pfss(input)
output.plot_pil(ax)
```

Using the Output object we can plot the source surface field, and the polarity inversion line.

```
fig, ax = plt.subplots()
mesh = output.plot_source_surface(ax)
fig.colorbar(mesh)
output.plot_pil(ax)
ax.set_title('Source surface magnetic field')
```



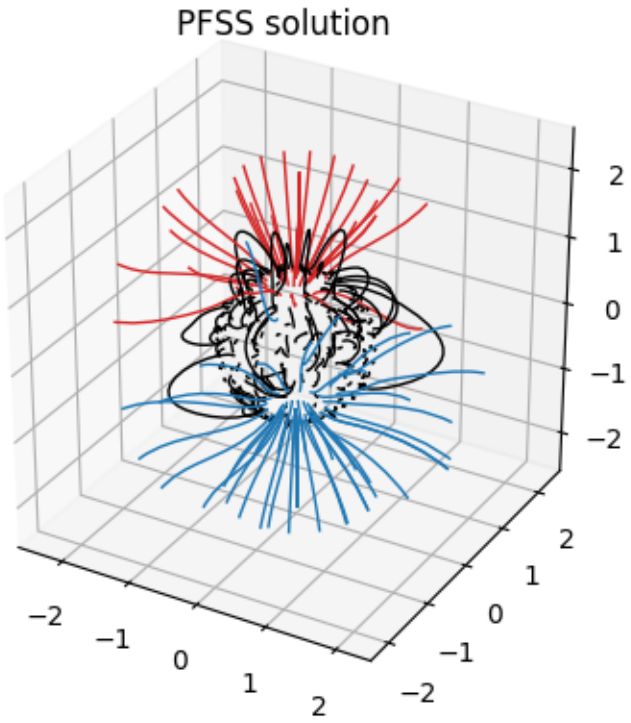
Finally, using the 3D magnetic field solution we can trace some field lines. In this case 256 points equally gridded in theta and phi are chosen and traced from the source surface outwards.

```
fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')
ax.set_aspect('equal')

# Loop through 16 values in theta and 16 values in phi
r = 1.01
for theta in np.linspace(0, np.pi, 17):
    for phi in np.linspace(0, 2 * np.pi, 17):
        x0 = np.array(coords.sph2cart(r, theta, phi))
        field_line = output.trace(x0)
        color = {0: 'black', -1: 'tab:blue', 1: 'tab:red'}.get(field_line.polarity)
        ax.plot(field_line.x / const.R_sun,
                field_line.y / const.R_sun,
                field_line.z / const.R_sun,
                color=color, linewidth=1)

ax.set_title('PFSS solution')
plt.show()

# sphinx_gallery_thumbnail_number = 3
```



Total running time of the script: (0 minutes 20.886 seconds)

and for the helper modules (behind the scense!) see

3.4 Helper modules

3.4.1 pfsspy.plot Module

Functions

contour(phi, costheta, field, levels[, ax])	**Parameters**
radial_cut(phi, costheta, field[, ax])	

contour

pfsspy.plot.**contour**(*phi*, *costheta*, *field*, *levels*, *ax=None*, ***kwargs*)

Parameters

phi :

costheta :

field :

levels :

ax [Axes, optional] Axes to plot to. If `None` a new figure is created.

****kwargs :** Keyword arguments are handed to *ax.contour*.

radial_cut

`pfsspy.plot.`**`radial_cut`**(*phi*, *costheta*, *field*, *ax=None*)

3.4.2 pfsspy.coords Module

Helper functions for coordinate transformations used in the PFSS domain.

The PFSS solution is calculated on a "strumfric" grid defined by

- $\rho = \log(r)$
- $s = \cos(\theta)$
- ϕ

where r, θ, ϕ are spherical cooridnates that have ranges

- $1 < r < r_{ss}$
- $0 < \theta < \pi$
- $0 < \phi < 2\pi$

The transformation between cartesian coordinates used by the tracer and the above coordinates is given by

- $x = r \sin(\theta) \cos(\phi)$
- $y = r \sin(\theta) \sin(\phi)$
- $z = r \cos(\theta)$

Functions

cart2strum(x, y, z)	Convert cartesian coordinates to strumfric coordinates.
sph2cart(r, theta, phi)	Convert spherical coordinates to cartesian coordinates.
strum2cart(rho, s, phi)	Convert strumfric coordinates to cartesian coordinates.

cart2strum

`pfsspy.coords.`**`cart2strum`**(*x*, *y*, *z*)

Convert cartesian coordinates to strumfric coordinates.

sph2cart

`pfsspy.coords.`**`sph2cart`**(*r*, *theta*, *phi*)

Convert spherical coordinates to cartesian coordinates.

strum2cart

pfsspy.coords.**strum2cart**(*rho*, *s*, *phi*)
Convert strumfric coordinates to cartesian coordinates.

3.5 Indices and tables

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