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planetMagFields: A Python package for analyzing and plotting planetary magnetic field data

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Software

- Review
- Repository
- Archive

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Summary

Long term observations and space missions have generated a wealth of data on the magnetic fields of the Earth and other solar system planets (Alken et al., 2021; Anderson et al., 2012; Cao et al., 2020; Connerney et al., 1987, 1991, 2022; Kivelson et al., 2002). `planetMagfields` is a Python package designed to have all the planetary magnetic field data currently available in one place and to provide an easy interface to access the data. `planetMagfields` focuses on planetary bodies that generate their own magnetic field, namely Mercury, Earth, Jupiter, Saturn, Uranus, Neptune and Ganymede. `planetMagfields` provides functions to compute as well as plot the magnetic field on the planetary surface or at a distance above or under the surface. It also provides functions to filter out the field to large or small scales as well as to produce `.vts` files to visualize the field in 3D using Paraview (Ahrens et al., 2005; Ayachit, 2015), VisIt (Childs et al., 2012) or similar rendering software. Lastly, the `planetMagfields` repository also provides a Jupyter notebook for easy interactive visualizations.

Statement of need

Planetary scientists studying the magnetic field of planets need to constantly access, visualize, analyze and extrapolate magnetic field data. In addition, with technological advancements in space exploration and planetary missions, we are constantly getting new data for planetary magnetic fields and hence, better field models. Though reviews of these field models are often written (Schubert & Soderlund, 2011; Stanley, 2014), there is very little software available that provides easy access to these models with a high level language and a way to easily visualize and analyze them. To the knowledge of the authors, there are a few publicly available repositories that are capable of providing access to planetary magnetic field data and tools to analyze them such as `JupiterMag` (James et al., 2024; Wilson et al., 2023),`KMAG` (Khurana, 2020), `ChaosMagPy` (Kloss, 2024) and `libinteralfield` (https://github.com/mattkjames7/libinternalfield). The first two of these are dedicated towards Jupiter and Saturn, respectively. `ChaosMagPy` is a python interface for the CHAOS model of the Earth's magnetic field (Finlay et al., 2020). Out of these, only `libinteralfield` provides software to analyze and access magnetic fields of all planets. However, it is a `C++` library which needs to be interfaced with something at a higher level to enable fast analyses and visualization. Thus, a software package that has different magnetic field models for all different planets of the solar system in one place, as well as provides a high level API to access, analyze and visualize them is not available. `planetMagfields` is intended not only to currently fill this gap, but also to provide a central repository, to be constantly updated, as more magnetic field models become available.

In addition to the research aspect of our software, the interactive Jupyter notebook provided exemplifies the potential of computational tools in enhancing the understanding of planetary sciences. By offering an intuitive platform for the exploration of magnetic fields, it serves as a valuable educational resource, fostering a deeper appreciation for the complexities of planetary magnetic environments. The integration of code, data visualization, and structured documentation within the Jupyter notebook environment presents a novel approach to scientific exploration, making complex astrophysical concepts accessible to a broader audience. This approach not only democratizes access to complex astrophysical data but also encourages interactive learning by allowing users to manipulate data and visualize the outcomes in real-time.

Mathematics

Magnetic fields in planets are generated by electric currents in a fluid region inside them through a process called dynamo action (Jones, 2011; Schubert & Soderlund, 2011; Stanley, 2014). Outside this region, in the absence of current sources, the magnetic field $\vec{B}$ can be written as the gradient of a scalar potential V. The potential V is usually written as an expansion in orthogonal functions in spherical coordinates,

$$V = R_p \sum_{l,m} \left(\frac{R_p}{r}\right)^{l+1} \left[g_l^m \cos(m\phi) + h_l^m \sin(m\phi)\right] P_l^m(\cos\theta)\,, \tag{1}$$

where, g_l^m and h_l^m are called the Gauss coefficients. Here, (r, θ, ϕ) are spherical coordinates representing radial distance from the center of a planet, co-latitude and longitude, respectively. R_p represents the radius of the planet and P_l^m are associated Legendre functions of order l and degree m, where l and m are integers. The above equation can be recast in terms of spherical harmonics, which is what the code uses,

$$V = R_p \sum_{l,m} \left(\frac{R_p}{r}\right)^{l+1} \left[g_l^m \mathrm{Re}(Y_l^m(\theta,\phi)) + h_l^m \mathrm{Im}(Y_l^m(\theta,\phi))\right], \tag{2}$$

where, Re and Im represent real and imaginary parts of the spherical harmonic $Y_l^m(\theta, \phi)$ of order l and degree m. The radial magnetic field is easily obtained using

$$B_r(r,\theta,\phi) = -\frac{\partial V}{\partial r} = \sum_{l,m} (l+1) \left(\frac{R_p}{r}\right)^{l+2} \left[g_l^m \cos(m\phi) + h_l^m \sin(m\phi)\right] P_l^m(\cos\theta)\,. \tag{3}$$

This is the most commonly visualized component of the magnetic field of a planet, since the angular representation of the potential is unaffected and thus, it readily provides a representation of the field geometry (e.g: dipole vs quadrupole). Equation (2) provides a way to extrapolate the field to any desired altitude with respect to the planetary surface, both above and below, as long as the region is outside the field generating region. For the radial part, this is done through equation (3). However, to obtain all three components, we have to extrapolate the potential to a desired height (or depth) with (1) and perform a spherical harmonic transform. We use the SHTns library (Schaeffer, 2013) for this purpose.

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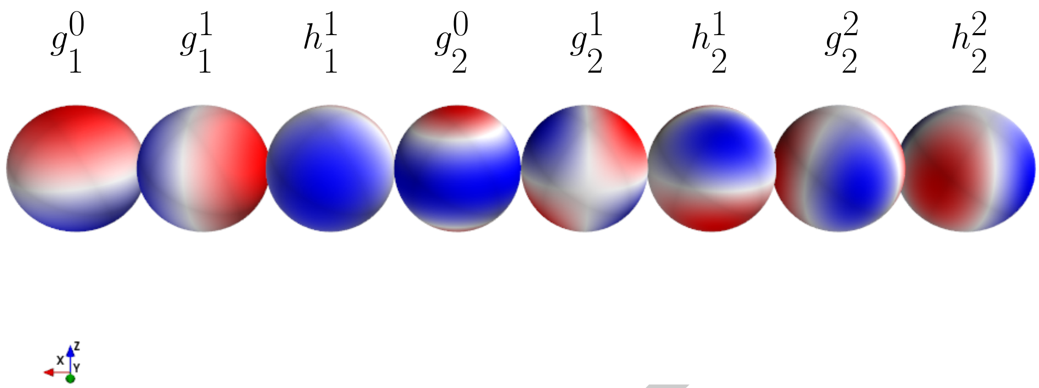

Figure 1: Illustration of the potential/radial field patterns of the first eight Gauss coefficients.

The Gauss coefficients represent the multipole modes of a planet's magnetic field, as illustrated in figure 1. For example, g_1^0 represents the axial dipole (along the rotation axis) while g_1^1 and h_1^1 represent orthogonal components of the equatorial dipole. Thus, the dipole tilt of a planet, or the angle between the dipole and the rotation axis is given by:

$$\theta_{dip} = \tan^{-1} \frac{\sqrt{(g_1^1)^2 + (h_1^1)^2}}{g_1^0}$$

while the longitude of the dipole is given by:

$$\phi_{dip} = \tan^{-1} h_1^1 / g_1^1$$

The raw data obtained from satellites or space missions are usually inverted to obtain these Gauss coefficients. These coefficients are the key to describing the surface magnetic field of a planet as well as how that magnetic field looks like at a certain altitude from the surface. The magnetic energy content on the surface in a certain degree l is given by the Lowes spectrum:

$$R_l = (l+1) \sum_m \left((g_l^m)^2 + (h_l^m)^2 \right),$$

l plays the role of a wavenumber. Low degrees represent large spatial features in the field while high degrees represent small scale features. The maximum available degree l_{max} of data for a particular planet depends on the quality of observations. For example, for Earth $l_{max} = 13$ because beyond that the magnetic field of magnetized rocks on the crust obscures any signal coming from the self generated field. Similarly, Jupiter's field was known only well constrained till $l_{max} = 4$ (Connerney et al., 1998) before the Juno mission provided excellent observations of finer scale structure to extend the well constrained l_{max} to 18 (Connerney et al., 2022).

Benchmarking

We benchmarked our software against two publicly available repositories : `JupiterMag` (James et al., 2024; Wilson et al., 2023) for Jupiter and the `CHAOS-7` (Finlay et al., 2020; Kloss, 2024) for Earth. For Jupiter, we compare the field at a depth of 85% of planetary radius, thus testing our extrapolation capability while for Earth, we compare the field on the surface in 2016, testing our implementation of taking into account changes in the Earth's field in a linear fashion (as is done for the IGRF model, Alken et al. (2021)) The comparisons are shown in figure 2. We also use these cases in our unit testing.

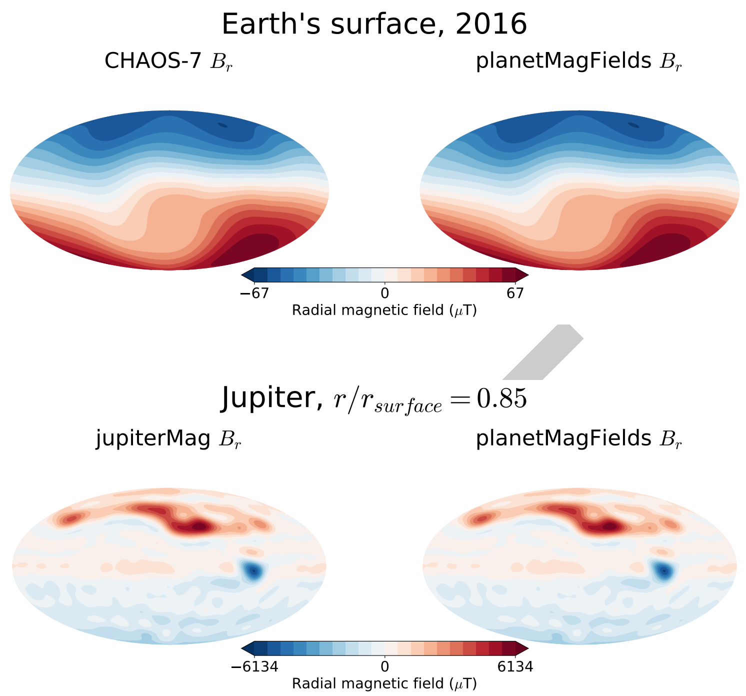

Figure 2: Benchmarking the code against publicly available repositories.

Description of the software

The software package

`planetMagfields` has data files containing Gauss coefficients from various inversion studies of planetary magnetic models for different planets. These coefficients are then used to obtain the magnetic field on a grid of latitude and longitude using equations (1) and (3). The main way of accessing the data is through the `Planet` class. An example is provided below using IPython (Pérez & Granger, 2007),

```
In [1]: from planetmagfields import *

In [2]: p = Planet(name='jupiter',model='jrm09')
Planet: Jupiter
Model: jrm09
l_max = 10
Dipole tilt (degrees) = 10.307870

In [3]: p.glm[p.idx[2,0]]      # g20
Out[3]: 11670.4

In [4]: p.hlm[p.idx[4,2]]      # h42
Out[4]: 27811.2

In [5]: p.plot(r=0.85,proj='Mollweide')
```

Jupiter $r/r_{\mathrm{surface}} = 0.85$

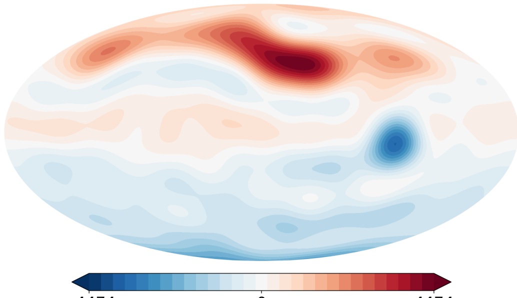

Figure 3: Plotting example of Jupiter's radial magnetic field at a depth of 85% of the planetary radius.

The last plot statement produces figure 3 which is the radial magnetic field at 85% of the planetary radius. This can be compared against figure 1h of Moore et al. (2018). `planetMagfields` primarily uses `NumPy` (Harris et al., 2020), `Matplotlib` (Hunter, 2007) and `SciPy` (Virtanen et al., 2020) for most of its analyses. Further support for various map projections is added through Cartopy (Met Office, 2010 - 2015). `planetMagfields` also provides functions to extrapolate and obtain all components of the magnetic field at a certain depth or height through spherical harmonic transforms using the SHTns library (Schaeffer, 2013). Finally, this extrapolation also allows one to visualize the field in 3D. To enable that, `planetMagfields` uses the `PyEVTK` library (https://github.com/paulo-herrera/PyEVTK) to write `.vts` files which can be visualized using software like Paraview or VisIt. An example for Jupiter is provided below in figure 4. A full list of available features is provided in the documentation.

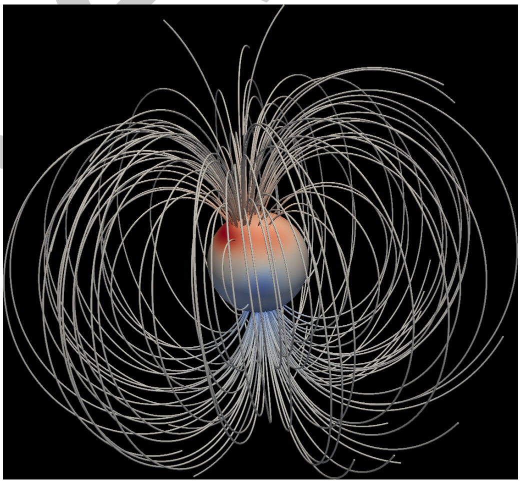

Figure 4: 3D rendering of Jupiter's magnetic field using Paraview, using a vts file produced by planet-Magfields.

Magnetic field models used

`planetMagfields` currently supports the following magnetic field models:

- *Mercury* : Anderson et al. (2012) , Thébault et al. (2018), Wardinski et al. (2019)
- *Earth* : The International Geomagnetic Reference Field (IGRF) (Alken et al., 2021)
- *Jupiter* : The VIP-4 model (Connerney et al., 1998), JRM09 (Connerney et al., 2018), JRM33 (Connerney et al., 2022)

- *Saturn* : Cassini Saturn orbit insertion (SOI) (Burton et al., 2009), Cassini11 (Dougherty et al., 2018), Cassini11+ (Cao et al., 2020)
- *Uranus* : Connerney et al. (1987)
- *Neptune* : Connerney et al. (1991)
- *Ganymede* : Kivelson et al. (2002)

When new magnetic field models become available, either through newly available data or through reanalysis of existing observations, we will add them to the current repository, either ourselves or through a community effort of pull requests.

Jupyter frontend

We provide a Jupyter notebook that gives interactive access for visualizing the radial magnetic fields and the corresponding Lowes spectra at various depths, with different background color options. The utilization of an interactive Jupyter notebook for the exploration of planetary magnetic fields represents a significant advancement in the pedagogical and research approach to planetary magnetic fields. This notebook, leveraging the computational capabilities of the `planetMagFields` package, facilitates a hands-on, dynamic exploration of magnetic field models across various planets with present day dynamo activity in our solar system. By integrating Python code with informative markdown, the notebook offers a structured, user-friendly interface that enhances learning and exploration.

The notebook is designed to guide users through the process of installing necessary dependencies, extracting available planetary data from the planetMagFields package, selecting specific planets and magnetic field models, and visualizing the radial magnetic field morphology and spectrum. Key features of the notebook include the dynamic extraction of planet names for which magnetic field models are available, the selection of specific models for detailed examination, and the interactive plotting of magnetic fields. Figure 5 shows the list of planets and models - as new models become available and are imported into the software package, this interactive portion will be able to summarize all available models.

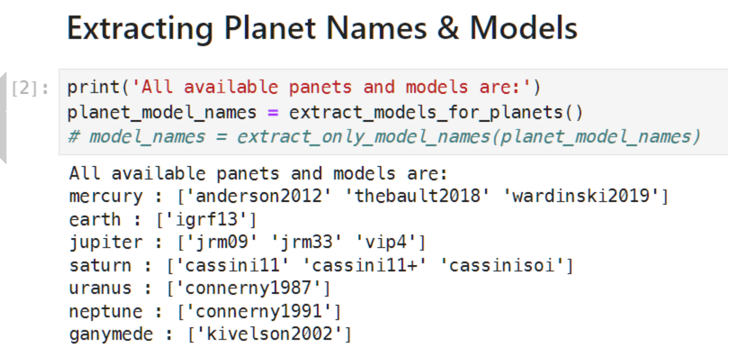

Figure 5: Screenshot of the Jupyter notebook listing all available models.

The use of Jupyter widgets (https://ipywidgets.readthedocs.io/) and `Matplotlib` for data manipulation and visualization provides a seamless experience with dropdown lists and a slider bar for visualizing the radial magnetic field and Lowes spectra for different planets, models and altitudes (figure 6).

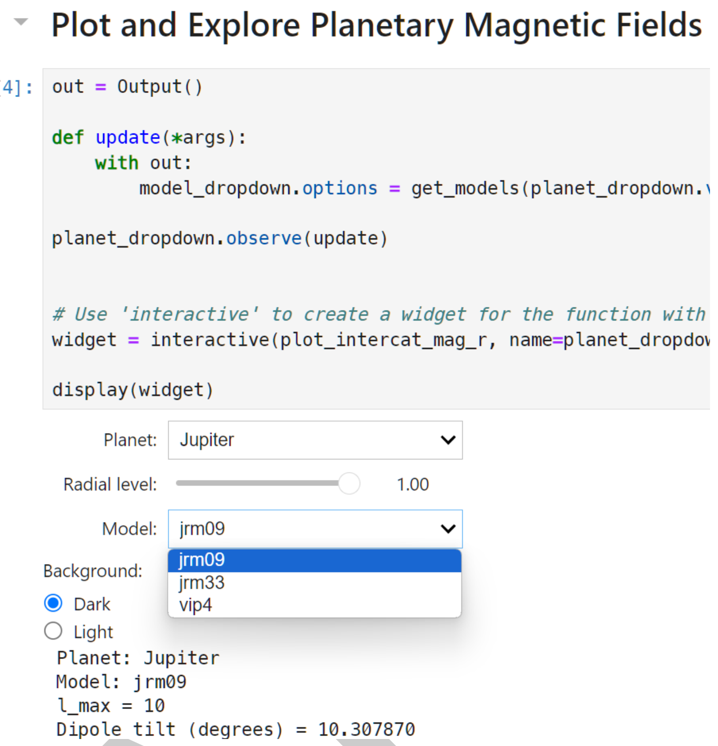

Figure 6: Screenshot of the interactive functions of the Jupyter notebook.

Documentation

The software has been documented using Sphinx (https://www.sphinx-doc.org/) and the documentation is available here: https://ankitbarik.github.io/planetMagFields/.

References

Ahrens, J., Geveci, B., & Law, C. (2005). 36 - ParaView: An end-user tool for large-data visualization. In C. D. Hansen & C. R. Johnson (Eds.), *Visualization handbook* (pp. 717–731). Butterworth-Heinemann. https://doi.org/https://doi.org/10.1016/B978-012387582-2/50038-1

Alken, P., Thébault, E., Beggan, C. D., Amit, H., Aubert, J., Baerenzung, J., Bondar, T. N., Brown, W. J., Califf, S., Chambodut, A., Chulliat, A., Cox, G. A., Finlay, C. C., Fournier, A., Gillet, N., Grayver, A., Hammer, M. D., Holschneider, M., Huder, L., … Zhou, B. (2021). International Geomagnetic Reference Field: the thirteenth generation. *Earth, Planets and Space*, *73*(1), 49. https://doi.org/10.1186/s40623-020-01288-x

Anderson, B. J., Johnson, C. L., Korth, H., Winslow, R. M., Borovsky, J. E., Purucker, M. E., Slavin, J. A., Solomon, S. C., Zuber, M. T., & McNutt, Jr., Ralph L. (2012). Low-degree structure in Mercury's planetary magnetic field. *Journal of Geophysical Research (Planets)*, *117*, E00L12. https://doi.org/10.1029/2012JE004159

Ayachit, U. (2015). *The ParaView guide: A parallel visualization application*. Kitware, Inc. ISBN: 1930934300

Burton, M. E., Dougherty, M. K., & Russell, C. T. (2009). Model of saturn's internal planetary magnetic field based on cassini observations. *Planetary and Space Science*, *57*(14), 1706–1713. https://doi.org/https://doi.org/10.1016/j.pss.2009.04.008

Cao, H., Dougherty, M. K., Hunt, G. J., Provan, G., Cowley, S. W. H., Bunce, E. J., Kellock, S., & Stevenson, D. J. (2020). The landscape of saturn's internal magnetic field from the cassini grand finale. *Icarus*, *344*, 113541. https://doi.org/https://doi.org/10.1016/j.icarus.2019.113541

Childs, H., Brugger, E., Whitlock, B., Meredith, J., Ahern, S., Pugmire, D., Biagas, K., Miller, M. C., Harrison, C., Weber, G. H., Krishnan, H., Fogal, T., Sanderson, A., Garth, C., Bethel, E. W., Camp, D., Rubel, O., Durant, M., Favre, J. M., & Navratil, P. (2012). *High Performance Visualization–Enabling Extreme-Scale Scientific Insight*. https://doi.org/10.1201/b12985

Connerney, J. E. P., Acuna, M. H., & Ness, N. F. (1987). The magnetic field of Uranus. *Journal of Geophysical Research*, *92*(A13), 15329–15336. https://doi.org/10.1029/JA092iA13p15329

Connerney, J. E. P., Acuna, M. H., & Ness, N. F. (1991). The magnetic field of Neptune. *Journal of Geophysical Research*, *96*, 19023–19042. https://doi.org/10.1029/91JA01165

Connerney, J. E. P., Acuña, M. H., Ness, N. F., & Satoh, T. (1998). New models of Jupiter's magnetic field constrained by the Io flux tube footprint. *Journal of Geophysical Research*, *103*(A6), 11929–11940. https://doi.org/10.1029/97JA03726

Connerney, J. E. P., Kotsiaros, S., Oliversen, R. J., Espley, J. R., Joergensen, J. L., Joergensen, P. S., Merayo, J. M. G., Herceg, M., Bloxham, J., Moore, K. M., Bolton, S. J., & Levin, S. M. (2018). A New Model of Jupiter's Magnetic Field From Juno's First Nine Orbits. *Geophysical Research Letters*, *45*(6), 2590–2596. https://doi.org/10.1002/2018GL077312

Connerney, J. E. P., Timmins, S., Oliversen, R. J., Espley, J. R., Joergensen, J. L., Kotsiaros, S., Joergensen, P. S., Merayo, J. M. G., Herceg, M., Bloxham, J., Moore, K. M., Mura, A., Moirano, A., Bolton, S. J., & Levin, S. M. (2022). A New Model of Jupiter's Magnetic Field at the Completion of Juno's Prime Mission. *Journal of Geophysical Research (Planets)*, *127*(2), e07055. https://doi.org/10.1029/2021JE007055

Dougherty, M. K., Cao, H., Khurana, K. K., Hunt, G. J., Provan, G., Kellock, S., Burton, M. E., Burk, T. A., Bunce, E. J., Cowley, S. W. H., Kivelson, M. G., Russell, C. T., & Southwood, D. J. (2018). Saturn's magnetic field revealed by the Cassini Grand Finale. *Science*, *362*(6410), aat5434. https://doi.org/10.1126/science.aat5434

Finlay, C. C., Kloss, C., Olsen, N., Hammer, M. D., Tøffner-Clausen, L., Grayver, A., & Kuvshinov, A. (2020). The CHAOS-7 geomagnetic field model and observed changes in the South Atlantic Anomaly. *Earth, Planets and Space*, *72*(1), 156. https://doi.org/10.1186/s40623-020-01252-9

Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk, M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science & Engineering*, *9*(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

James, M. K., Provan, G., Kamran, A., Wilson, R. J., Vogt, M. F., Brennan, M. J., & Cowley, S. W. H. (2024). *JupiterMag* (Version v1.3.1). Zenodo. https://doi.org/10.5281/zenodo.10602418

Jones, C. A. (2011). Planetary Magnetic Fields and Fluid Dynamos. *Annual Review of Fluid Mechanics*, *43*(1), 583–614. https://doi.org/10.1146/annurev-fluid-122109-160727

Khurana, K. K. (2020). *KMAG - kronian magnetic field model* (Version 1.0). Zenodo. https://doi.org/10.5281/zenodo.4080294

Kivelson, M. G., Khurana, K. K., & Volwerk, M. (2002). The Permanent and Inductive Magnetic Moments of Ganymede. *Icarus*, *157*(2), 507–522. https://doi.org/10.1006/icar.2002.6834

Kloss, C. (2024). *Ancklo/ChaosMagPy: ChaosMagPy v0.13* (Version v0.13). Zenodo. https://doi.org/10.5281/zenodo.10598528

Met Office. (2010 - 2015). *Cartopy: A cartographic python library with a matplotlib interface*. https://scitools.org.uk/cartopy

Moore, K. M., Yadav, R. K., Kulowski, L., Cao, H., Bloxham, J., Connerney, J. E. P., Kotsiaros, S., Jørgensen, J. L., Merayo, J. M. G., Stevenson, D. J., Bolton, S. J., & Levin, S. M. (2018). A complex dynamo inferred from the hemispheric dichotomy of Jupiter's magnetic field. *Nature*, *561*(7721), 76–78. https://doi.org/10.1038/s41586-018-0468-5

Pérez, F., & Granger, B. E. (2007). IPython: A system for interactive scientific computing. *Computing in Science and Engineering*, *9*(3), 21–29. https://doi.org/10.1109/MCSE.2007.53

Schaeffer, N. (2013). Efficient spherical harmonic transforms aimed at pseudospectral numerical simulations. *Geochemistry, Geophysics, Geosystems*, *14*(3), 751–758. https://doi.org/10.1002/ggge.20071

Schubert, G., & Soderlund, K. M. (2011). Planetary magnetic fields: Observations and models. *Physics of the Earth and Planetary Interiors*, *187*(3), 92–108. https://doi.org/10.1016/j.pepi.2011.05.013

Stanley, S. (2014). Chapter 6 - magnetic field generation in planets. In T. Spohn, D. Breuer, & T. V. Johnson (Eds.), *Encyclopedia of the solar system (third edition)* (Third Edition, pp. 121–136). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-415845-0.00006-2

Thébault, E., Langlais, B., Oliveira, J. S., Amit, H., & Leclercq, L. (2018). A time-averaged regional model of the hermean magnetic field. *Physics of the Earth and Planetary Interiors*, *276*, 93–105. https://doi.org/https://doi.org/10.1016/j.pepi.2017.07.001

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Wardinski, I., Langlais, B., & Thébault, E. (2019). Correlated Time-Varying Magnetic Fields and the Core Size of Mercury. *Journal of Geophysical Research (Planets)*, *124*(8), 2178–2197. https://doi.org/10.1029/2018JE005835

Wilson, R. J., Vogt, M. F., Provan, G., Kamran, A., James, M. K., Brennan, M., & Cowley, S. W. H. (2023). Internal and External Jovian Magnetic Fields: Community Code to Serve the Magnetospheres of the Outer Planets Community. *Space Science Reviews*, *219*(1), 15. https://doi.org/10.1007/s11214-023-00961-3