The use of Python in astrophysics for the post-processing and visualization of "star-in-a- box" simulations

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Abstract

Hydrodynamic and magnetohydrodynamic direct numerical simulations are very valuable tools for the study of a number of astrophysical problems. We present here our use of Python, Scipy and various scientific libraries to analyze "star-in-a-box" simulations, prototype post-processing functions and produce publication-quality plots.

The Pencil Code

The Pencil Code (PC) is a high-order finite-difference code for compressible hydrodynamic flows with magnetic fields and particles [1] developed by a core team of ∼ 30 researchers plus additional contributors, and distributed under the GPL. The code is designed with scalability and modularity in mind, and is successfully used to deal with a variety of astrophysical problems such as driven MHD turbulence in a periodic box, accretion disc turbulence in the shearing sheet approximation, self-gravity, non-local radiation transfer, dust particle evolution with feedback on the gas, etc.

Star-in-a-box simulations

Global numerical simulations of fluid motion in stellar interiors are generally carried out in spherical geometries using spectral codes (physical quantities are decomposed on a spherical harmonics basis in angular directions and on Chebishev polynomials in the radial direction) providing a high computational accuracy. During the past decade a complementary approach has emerged, called star-in-a-box, that consists in running global stellar simulations in Cartesian geometry by embedding the star in a cubic box [2].

Spherical harmonics

- Stellar surface = surface of coordinates
- Spectral precision

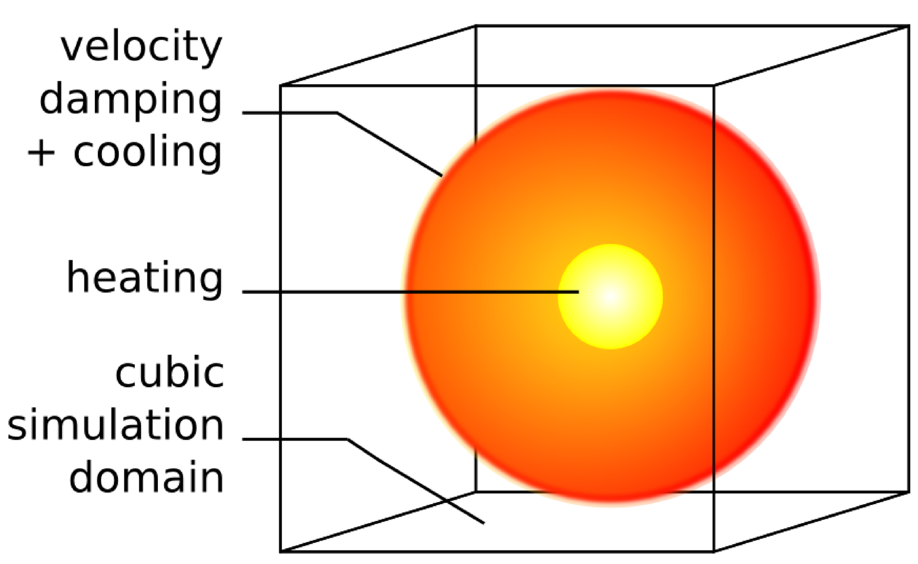
- Central singularity
- Computation of non-linear terms
- Complex parallelization

Star-in-a-box

- No singular point
- Non-linear terms are handled naturally
- Highly parallelizable

- ∼ half grid points lost
- Non-spectral precision
- Boundary conditions
- Heavier post-processing

This method is very well-suited to the study of fully-convective stars – young T Tauri stars, main sequence red dwarfs, or evolved cool giants – in particular the generation of magnetic fields by dynamo effect in these objects [3].



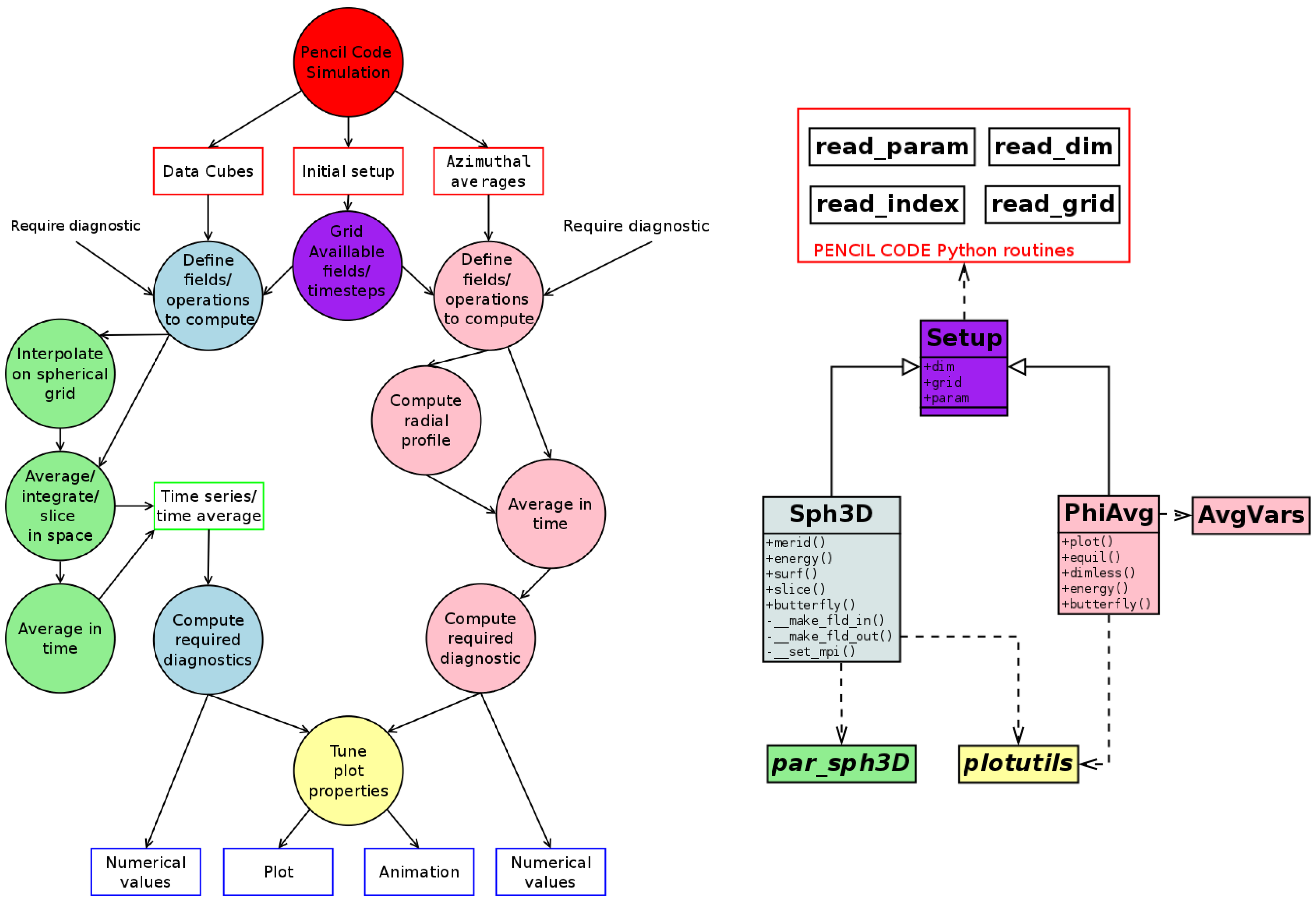
Developing post-processing routines in Python

The Pencil Code is provided with a number of post-processing and plotting routines mostly developed in IDL and for cartesian diagnostics. We focus here on the development of a set of routines dedicated to star-in-a-box simulations in Python, though since Python I/O routines to deal with PC data products are now provided Python-based post-processing is increasingly used in the PC community (*e.g.*, [4]). The crucial factors for the choice of Python are:

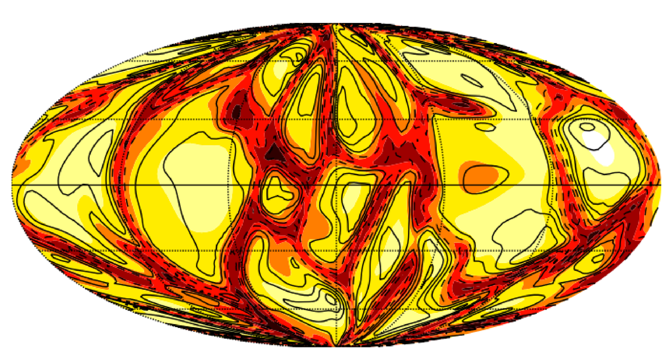
- Python and main libraries are free and libre software
- A number of high-quality libraries are available
  - Numpy/Scipy: array processing, interpolation, integration
  - Matplotlib + basemap toolkit: plots and spherical projections
  - PyPar: interface with MPI
- Performance is generally better than IDL

Data flow and software architecture

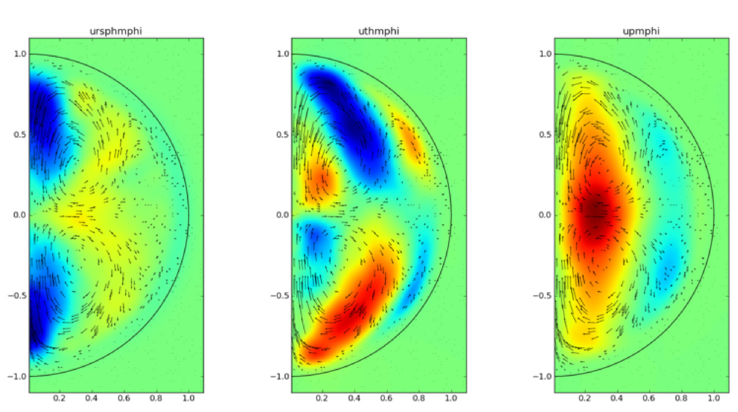
Two processing tools are available: directly from data cubes (`Sph3D`) or from azimuthal averages (`PhiAvg`) computed internally during PC runs. New diagnostics are prototyped with `Sph3D` on low-resolution runs and then implemented in the PC (computation part) and in (`PhiAvg`) (plotting part).



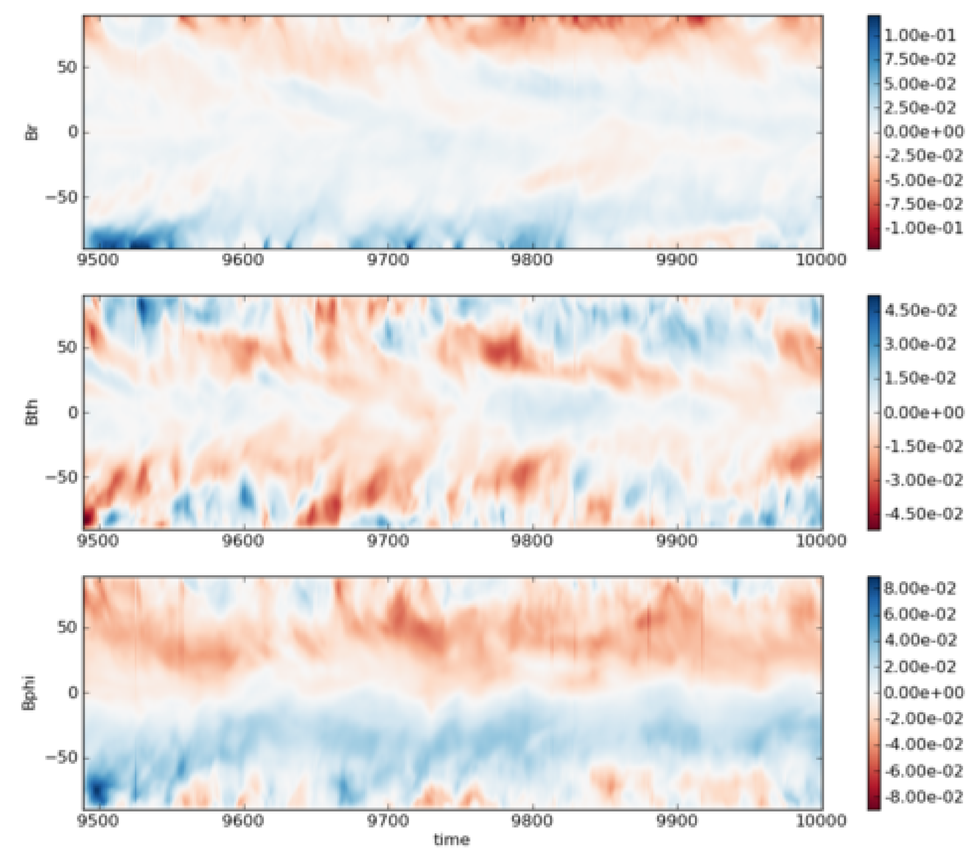
Examples of available plots



Interpolation on a spherical surface



Azimuthal and temporal averages



"Butterfly"-like diagram

See also [5] for additional examples.

Future plans

- Extend usage of PyPar to PhiAvg for high resolution runs.
- Implement spherical harmonics decomposition directly from Cartesian coordinates.
- Extend to 3-D visualization with Mayavi and Pencil Code vtk file converter.
- Release publicly.

Assessment of our Python experience

- Switching to Python/Numpy/SciPy is rather easy thanks to "natural" syntax.
- Array processing performance is good, provided appropriate syntax is used.
- PyPar allows simple data parallelization based on MPI.
- The weak typing of Python combined with optional arguments/default values makes the code very flexible.

References

[1] Brandenburg A., Dobler W., 2002, CoPhC, 147, 471
[2] Freytag B., Steffen M., Dorch B., 2002, AN, 323, 213
[3] Dobler W., Stix M., Brandenburg A., 2006, ApJ, 638, 336
[4] Gastine T., Dintrans B., 2008, A&A, 490, 743
[5] J. Morin, PhD thesis, http://tel.archives-ouvertes.fr/tel-00480428/

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Pencil Code resources

- Project homepage: http://code.google.com/p/pencil-code/
- SVN repository: http://pencil-code.googlecode.com/svn/trunk/
- Pencil Code user meeting: http://pencilcode11.obs-mip.fr/index.html