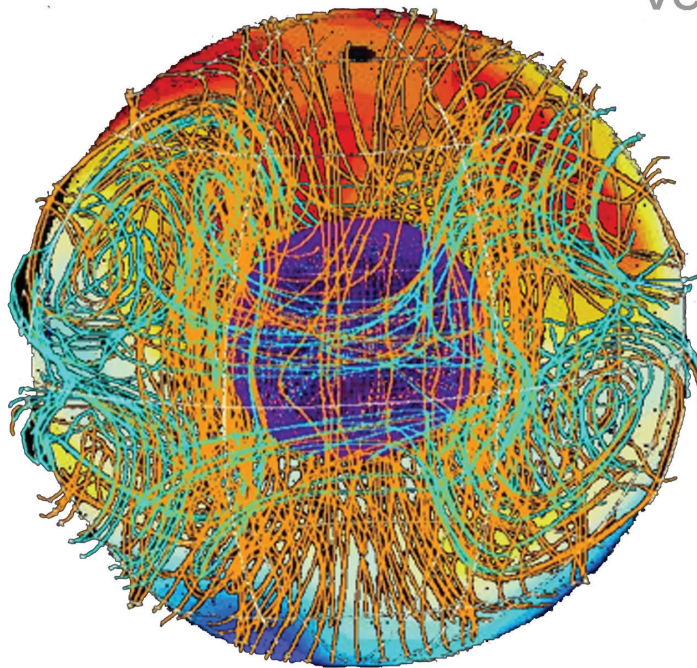


COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)

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# MAG

User Manual  
Version 1.0.2



[www.geodynamics.org](http://www.geodynamics.org)

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# MAG

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Peter Olson and Wei Mi  
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# Part I

## Preface



# Preface

## About This Document

This document is organized into three parts. Part I consists of traditional book front matter, including this preface. Part II begins with an introduction to MAG version 1.0.2 and its capabilities and proceeds to the details of implementation. Part III provides appendices and references.

The style of this publication is based on the Apple Publications Style Guide ([developer.apple.com/documentation/UserExperience/Conceptual/APStyleGuide/AppleStyleGuide2003.pdf](http://developer.apple.com/documentation/UserExperience/Conceptual/APStyleGuide/AppleStyleGuide2003.pdf)), as recommended by Python.org ([www.python.org](http://www.python.org)). The documentation was produced using LyX ([www.lyx.org](http://www.lyx.org)) to facilitate the transformation of files from one format to another. LyX is a document processor that encourages an approach to writing based on the structure of your documents, not their appearance. It is released under a Free Software/Open Source license.

Errors and bug fixes in this manual should be directed to the CIG Geodynamo Mailing List ([cig-geodyn@geodynamics.org](mailto:cig-geodyn@geodynamics.org)).

## Who Will Use This Document

This documentation is aimed at scientists who prefer to use prepackaged and specialized analysis tools. Users are likely to be experienced computational Earth scientists and have familiarity with basic scripting, software installation, and programming; but are not likely to be professional programmers. Of those, there are likely to be two classes of users: those who just run models and those who modify the source code.

## Citation

Computational Infrastructure for Geodynamics (CIG) is making this source code available to you in the hope that the software will enhance your research in geophysics. The underlying Fortran code was donated to CIG in July of 2006. A number of individuals have contributed a significant portion of their careers toward the development of MAG. It is essential that you recognize these individuals in the normal scientific practice by citing the appropriate peer reviewed papers and making appropriate acknowledgements.

The MAG development team asks that you cite the following:

- Olson, P., G.A. Glatzmaier (1993), Highly supercritical thermal convection in a rotating spherical shell: centrifugal vs. radial gravity. *Geophys. Astrophys. Fluid Dyn.*, *70*, 113-136.
- Olson, P., G.A. Glatzmaier (1995), Magnetoconvection in a rotating spherical shell: structure of flow in the outer core. *Phys. Earth Planet Int.*, *92*, 109-118.
- Olson, P., G.A. Glatzmaier (1996), Magnetoconvection and Thermal Coupling of the Earth's Core and Mantle. *Phil. Trans. R. Soc. Lond.*, *A354*, 1413-1424.
- Christensen, U.R., J. Aubert (2006), Scaling properties of convection-driven dynamos in rotating spherical shells and application to planetary magnetic fields. *Geophys J. Int.* *166*, 97-114.
- Olson, P., U. Christensen, G.A. Glatzmaier (1999), Numerical Modeling of the Geodynamo: Mechanisms of Field Generation and Equilibration. *J. Geophys. Res.*, *104*, 10,383-10,404.

- Christensen, U., P. Olson, G.A. Glatzmaier (1999), Numerical modelling of the geodynamo: a systematic parameter study. *Geophys. J. Int.*, 138, 393-409.
- Christensen, et al. (2001), A numerical dynamo benchmark. *Phys. Earth Planet Int.*, 128, 25-34 (benchmark cases).

[Note: there are more recent papers by the same authors.] The developers also request that in your oral presentations and in your paper acknowledgements that you indicate your use of this code, the authors of this code (G. Glatzmaier, U. Christensen, P. Olson), and CIG ([geodynamics.org](http://geodynamics.org)).

## Support

MAG development was funded by grants from NASA HPC and NSF Geophysics. Continued support of MAG is made possible under NSF EAR-0406751.

# Part II

## Chapters



# Chapter 1

## Introduction

Dynamo codes represent a powerful new tool for the quantitative study of a broad range of geophysical processes, ranging from short time-scale phenomena such as magnetic variations, rotational variations, and flow in the core, to long-term phenomena such as magnetic excursions, reversals, superchrons, and the evolution of the core and its thermal and chemical interaction with the mantle. The primary objective of CIG in this area is to provide the Earth Science community with robust, reliable, efficient, flexible, state-of-the-art numerical codes for modeling dynamo processes in the Earth's core and in the interiors of other planets. Another CIG objective is to support graphical- and user-interfaces for these codes that allow Earth scientists to analyze, display, and interpret dynamo code results, and to compare results from the various codes that we support, as well as with geomagnetic, space magnetic, and paleomagnetic data.

### 1.1 About MAG

MAG is a serial version of Gary Glatzmaier's rotating spherical convection/magnetoconvection/dynamo code, modified by Uli Christensen and Peter Olson. The code solves the non-dimensional Boussinesq equations for time-dependent thermal convection in a rotating spherical shell filled with an electrically conducting fluid. The equations of motion are: the Navier-Stokes equation including Coriolis, Lorentz, Buoyancy, pressure, viscous, and inertial terms; the heat equation including advection, diffusion, and uniform-density heat sources; the continuity equation for velocity and Gauss' law for magnetic field; and the induction equation for the magnetic field.

All variables are non-dimensional (see Appendix A); time scale is viscous diffusion, length scale is shell thickness, temperature scale is boundary temperature difference, magnetic field and electric currents use Elsasser number scaling. A variety of boundary and initial conditions has been selected as options.

Mag uses toroidal-poloidal decomposition for velocity and magnetic field with explicit time steps. Linear terms are evaluated spectrally (spherical harmonics plus Chebyshev polynomials in radius) and nonlinear terms are evaluated on a spherical grid.

Additional technical information is found in [1]-[8].

### 1.2 Governing Equations

MAG solves the following non-dimensional Boussinesq magnetohydrodynamics equations for dynamo action due to thermal convection of an electrically conducting fluid in a rotating spherical shell (e.g., Olson et al. 1999)[5].

$$E \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - \nabla^2 \mathbf{u} \right) + 2\hat{\mathbf{z}} \times \mathbf{u} + \nabla P = Ra \frac{r}{r_o} T + \frac{1}{Pm} (\nabla \times \mathbf{B}) \times \mathbf{B} \quad (1.1)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{Pm} \nabla^2 \mathbf{B} \quad (1.2)$$

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \frac{1}{Pr} \nabla^2 T + \epsilon \quad (1.3)$$

$$\nabla \cdot \mathbf{u} = 0, \quad \nabla \cdot \mathbf{B} = 0 \quad (1.4)$$

where  $\mathbf{u}$  is the velocity,  $\mathbf{B}$  is the magnetic field,  $T$  is temperature,  $t$  is time,  $\hat{z}$  is a unit vector in the direction of the rotation axis,  $P$  is pressure, and  $r$  is the position vector in the spherical coordinates  $r\theta\phi$ .

Four basic non-dimensional parameters in 1.1 - 1.4 control the dynamo action. The Rayleigh number represents the strength of buoyancy force driving the convection

$$Ra = \frac{\alpha g_0 \Delta T D^3}{\nu \kappa} \quad (1.5)$$

where  $\alpha$  is thermal expansivity,  $g_0$  is gravitational acceleration on the outer boundary at radius  $R$ ,  $\Delta T$  is the temperature difference between the inner and outer boundaries,  $D$  is shell thickness,  $\nu$  is kinematic viscosity, and  $\kappa$  is thermal diffusivity. The Ekman number represents the ratio of viscous and Coriolis forces

$$E = \frac{\nu}{\Omega D^2} \quad (1.6)$$

Here  $\Omega$  is rotation rate. The Prandtl number is the ratio of kinematic viscosity to thermal diffusivity

$$Pr = \frac{\nu}{\kappa} \quad (1.7)$$

and the magnetic Prandtl number is the ratio of kinematic viscosity to magnetic diffusivity  $\lambda$

$$P_m = \frac{\nu}{\lambda} \quad (1.8)$$

An additional (optional) control parameter is the non-dimensional volumetric heat source (or heat sink) strength  $\epsilon$ .



## Chapter 2

# Installation and Getting Help

### 2.1 Introduction

To test run MAG, download the source package (in the form of a compressed `tar` file) from the Geodynamics Software Packages web page ([geodynamics.org/cig/software/packages](http://geodynamics.org/cig/software/packages)). After unpacking the source, use the `make` utility to build MAG from source, and background execute MAG with the provided benchmark input file.

Advanced users and software developers may be interested in downloading the latest MAG source code directly from the CIG source code repository, instead of using the prepared source package. See Section 2.6 later in this chapter. MAG has been tested on Linux, Mac OS X, and Windows.

### 2.2 Getting Help

For help, send e-mail to the CIG Geodynamo Mailing List ([cig-geodyn@geodynamics.org](mailto:cig-geodyn@geodynamics.org)). You can subscribe to the Mailing List and view archived discussion at Geodynamics Mail Lists ([geodynamics.org/cig/lists](http://geodynamics.org/cig/lists)).

### 2.3 System Requirements

MAG requires the following:

- A Fortran compiler, `g77` or `gFortran`.
- For Windows you need to install `cygwin` ([cygwin.com](http://cygwin.com)).

### 2.4 Downloading and Unpacking Source

Download MAG from the Geodynamics website ([geodynamics.org](http://geodynamics.org)). Click the “software” tab at the top of the page. Then click “Software Packages” and then “Geodynamo.” Once you click the MAG link, download the source archive and unpack it using the `tar` command:

```
$ tar xzf MAG-1.0.2.tar.gz
```

If you don’t have GNU Tar, try the following command instead:

```
$ gunzip -c MAG-1.0.2.tar.gz | tar xf -
```

## 2.5 Installation Procedure

### 2.5.1 MAG File Structure

After unpacking the source, you will find the following directories:

`~/src` Contains the set of FORTRAN source code files with suffix “.f.” This includes sample grid parameter value files with names like `param32s4.f` for a coarse grid (up to 32 spherical harmonics, 24 radial grid intervals, and 4-fold symmetry in  $\phi$ ). A makefile named `makefile`. Sample files with input parameters, `par.XXX`. The case `par.bnch0` is for rotating convection at an Ekman number of 1E-3, starting from a conductive temperature perturbation with imposed perturbation with  $l=4$ ,  $m=4$ , and running for a short time. This is the “benchmark0” test case in Christensen et al., 2001[6]. Another input file is `par.bnch1`, the dynamo “benchmark1” case in Christensen et al. [6].

`~/doc` The directory where you will find this manual and other documentation files.

`~/bench-data` Contains output files `ls.benchX`, `l.benchX`, `g.benchx`, and `d.benchx` obtained with short runs of benchmark0 and benchmark1 on a Linux workstation. Explanations of the contents of these files are found in Appendix C. These data files can be used for comparison with the result obtained by your local run of MAG.

`~/rev-data` Contains output files from runs of the reversal dynamo case; movie files are also included.

`~/idl` This is where the postprocessing IDL (Interactive Data Language) routines reside.

### 2.5.2 Prepare MAG for Running

1. First you need to create a path for execution of `magx` (below is an example; use your path):

```
printenv PATH $ PATH=$PATH:/your_mag_dir_path $ export PATH
```

2. Compile the program using `make` in the source directory, which by default uses the existing `param.f` grid and symmetry

```
$ make
```

Note that makefile uses -g77 or other Fortran compiler, and creates executables, either `magx` (default) or `magxYYsZ`, where `YY`=spherical harmonic truncation and `Z`=longitudinal symmetry.

3. To delete all the object files and executables, type:

```
$ make clean
```

## 2.6 Installing from the Software Repository

The MAG source code is available via a Subversion server at the Geodynamics website ([geodynamics.org](http://geodynamics.org)). This allows users to view the revision history of the code, and check out the most recent development version of the software.

**NOTE:** If you are content with the prepared source package, you may skip this section.

### 2.6.1 Tools You Will Need

In addition to the usual system requirements, you must have a Subversion client installed in order to work with the source from the CIG software repository. To check whether you have a subversion client installed on your machine, type:

```
$ svn help
```

It should return a usage message. For more information on Subversion, visit the Subversion website ([subversion.tigris.org](http://subversion.tigris.org)).

### 2.6.2 Download Source from Subversion

To check out the latest version of the software, use the `svn checkout` command:

```
$ svn checkout http://geodynamics.org/svn/cig/geodyn/3D/MAG/trunk MAG
```

where "MAG" is the directory created with the file structure mentioned in 2.5.1.



# Chapter 3

## Running MAG

### 3.1 Using MAG

For test-running the code, perform the following steps:

1. Uncompress all files, and create a path (see 2.5.2)
2. Link the grid parameter file to `param.f`,<sup>1</sup> which enters into most subroutines through “include” statements. For example, a grid parameter file named `param32f4.f` (32 spherical harmonics truncation degree, longitude symmetry is 4) is linked using

```
$ ln -sf param32s4.f param.f
```

3. Compile the program with:

```
$ make
$ mv magx magx32s4 (Renaming is optional)
```

4. MAG uses a standard input file. Background execute using `par.XXX` as the input file and `.YYY` as the output file’s extension:

```
$ magx32s4 <par.XXX >p.YYY &
```

For running with the benchmark input files (`par.bnch0` or `par.bnch1`) , the execution statement should be:

```
$ magx32s4 <par.bnch0 >p.bench0 &
```

5. If there is a problem with the input file list, it is often the final three lines; with some systems, a “\$” may be required at the end.
6. MAG produces a series of output files. For example, when using input file `par.bnch0` (the example in step 4) MAG generates: `1.bench0`, `1s.bench0`, `g[i].bench0` and `d[i].bench0`, where `i=0,1,2...9`. See Appendix C for details on MAG’s output files. Compare your output files with the data provided in the directory `~/bench-data/data_bench0`.

**Warning:** You must delete, move, or rename all of the output files in the current directory before re-running with the same “output” filename. **Retaining same-named output files in the current directory causes MAG to crash.**

---

<sup>1</sup>To change grids or symmetry (in `param.f`), MAG needs to be recompiled. The code looks for `param.f`, which needs to be changed for remaking. Examples of `param.f` are `param32s6.f` and `param32s4.f`.

## 3.2 Changing Parameters

Physical and time-step parameters can be changed in the par-file namelist without re-compiling MAG. See Appendix B for a list of the input parameter names and definitions. Grid parameters must be changed in `param.f` and MAG must be then re-compiled. There are some numerical restrictions on the grid parameter combinations, which are given in Appendix A.

## Chapter 4

# Postprocessing and Graphics

### 4.1 Introduction

Once you finish running MAG, you should have a series of output data files. To visualize your results, the MAG software package provides a set of IDL routines found in the directory called `PREFIX/idl`, where `PREFIX` is the directory under which you installed MAG. We should mention here that IDL is a commercial visualization tool by ITT Visual Information Solutions ([www.ittvis.com/idl](http://www.ittvis.com/idl)). A free IDL compatible program called GDL ([gnudatalanguage.sourceforge.net](http://gnudatalanguage.sourceforge.net)) works with MAG's line plot IDL procedure `MAGTS.pro`, but not with the interactive IDL procedures in MAG.

### 4.2 Time Series and Spectra Plots

Procedures `MAGTS.pro` and `MAGXY.pro` take data from l-files generated by MAG and create time series plots and statistics. This version reads an l-file consisting of 17 time series, the first record being dimensionless time (see Appendix C for details on output file format). Energies and rms magnetic field and velocity are scaled as in MAG; tilt is dipole vector colatitude; pole longitude is dipole vector longitude. Figures 4.1 and 4.2 show the energy time series plot and spectra plot from a time-dependent dynamo.

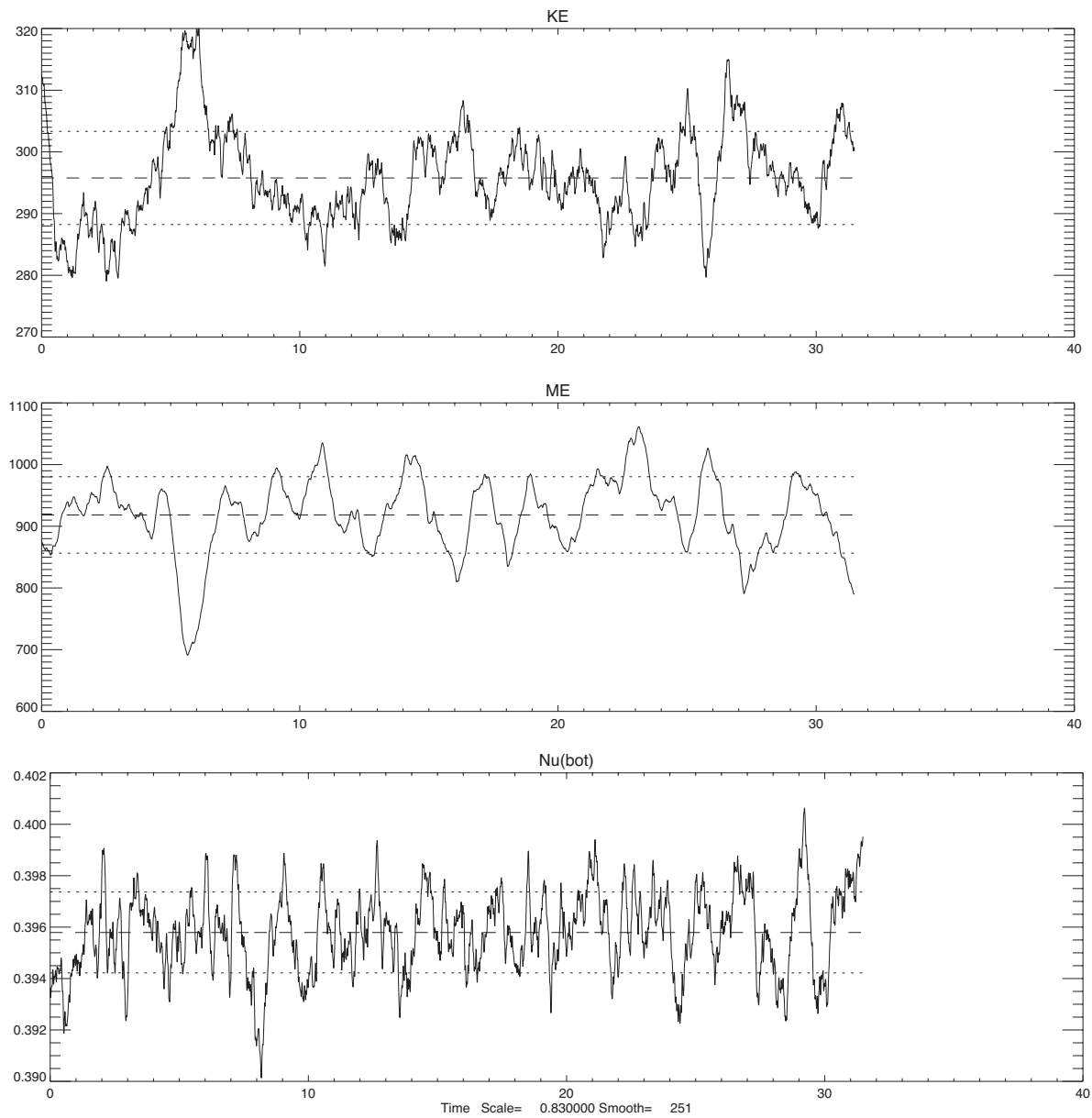


Figure 4.1: Time series plot of energy



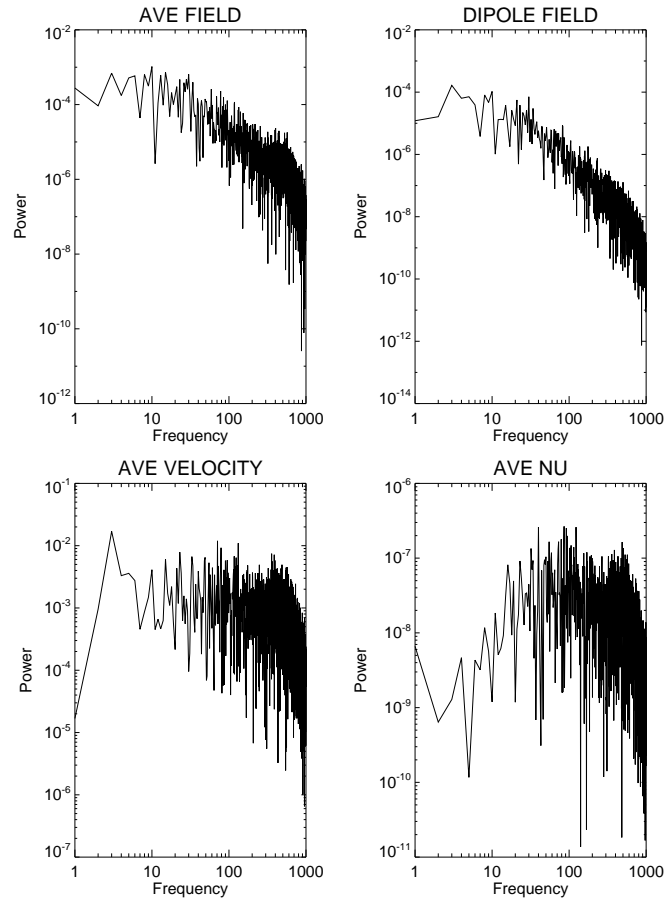


Figure 4.2: Spectra plot of a time dependent dynamo

### 4.3 Interactive IDL Procedures

`MAGSYM.pro` is an interactive procedure display which results from a `g`-file produced by `MAG`. This version uses modified IDL color tables and assumes formatted input. It creates either postscript `.ps` or `.gif` files. If other output file formats are required, you must modify “`LABELOUT.`” `MAGSYM` has many plot options: `map`, `closeup`, `equator`, `slice`, etc. Producing each plot is straightforward and accomplished by choosing from the option menu. Figure 4.3 is plotted with the `map` option.

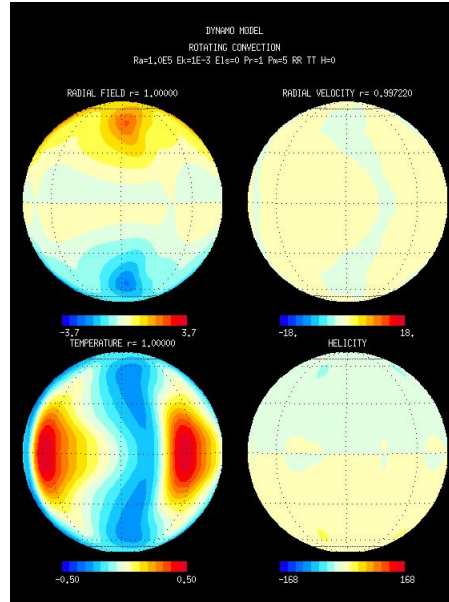


Figure 4.3: IDL figure with Map option

MAGVOL.pro is another interactive IDL procedure to display volume results from rotating convection, magnetoconvection and dynamo calculations (written by P. Olson). It uses g-files produced by MAG (some longitudinal symmetry may be assumed in the g-file). This version uses modified IDL color tables and assumes formatted or unformatted input (it asks for .gif but creates .jpg files); if other output file formats are required, modifications of “labelout” are required. This version assumes x-window screen graphics; for other graphics devices, change the `set_plot,'x'` and `tvrd()` commands accordingly. MAGVOL procedure creates volume-rendered images of temperature, helicity, the z-component of vorticity, kinetic and magnetic energy, joule heating, work by Lorentz forces and buoyancy forces. Figure 4.4 shows a plot of kinetic energy and magnetic energy obtained from a numerical dynamo model.

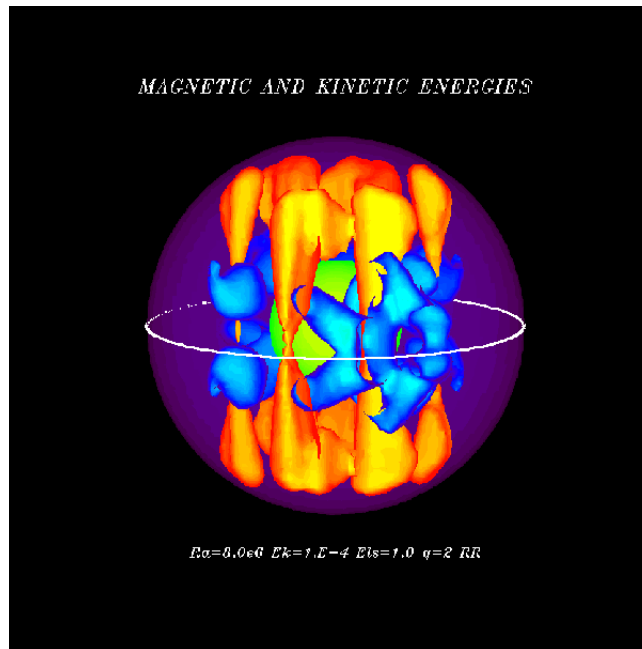


Figure 4.4: Kinetic energy (yellow) and Magnetic energy (blue) plot by the MAGVOL procedure



# Chapter 5

## Examples

Included in this chapter are two benchmark cases and a reversal dynamo case. We will present the cases with their input parameters and a typical run of the case with output data analysis.

### 5.1 Benchmark Cases

Historically, these are the cases defined in the benchmark study published in the 2001 paper by Gary Glatzmaier et al. [6]. Case 0 is a benchmark of rotating non-magnetic convection. Case 1 is a dynamo with an insulating inner core co-rotating with the outer boundary. The regions outside the fluid shell are electrical insulators and the magnetic field on the boundaries matches with appropriate potential fields in the exterior that imply no external sources of the field.

In both cases the Ekman number is  $E = 10^{-3}$  and the Prandtl number is  $Pr = 1$ . The Rayleigh number is set to  $Ra = 100000$ . Note that the definition of the Rayleigh number differs from the one in the published cases [6] by a factor of Ekman number  $E$ , i.e.,  $Ra = \frac{Ra}{E}$ . [6] The magnetic Prandtl number is zero in the non-magnetic convection case 0, and is  $Pm = 5$  in case 1. The spherical harmonic expansion is truncated at degree  $lmax = 32$  and a four-fold symmetry is assumed in the longitudinal direction (`param.f` should be linked to `param32s4.f` when you compile MAG). The input parameter files are `par.bench0` for case 0 and `par.bench1` in case 1; both files reside in the `~/src` directory.

The output files of the benchmark cases are stored in the directory `~/bench-data/data_bench0` and `~/bench-data/data-bench1` respectively. In the following table we see the solutions from MAG agree with the benchmark suggested value with a small difference margin. In both case 0 and case 1, the values listed were obtained with low resolution and a relatively short run of MAG.

	Case 0 Suggested Value	Mag Case 0	Case 1 Suggested Value	Mag Case 1
$E_{kin}$	$58.348 \pm 0.050$	58.35	$30.733 \pm 0.020$	30.72
$E_{mag}$			$626.41 \pm 0.40$	627.15
$T$	$0.42812 \pm 0.00012$		$0.37338 \pm 0.00040$	
$\mu_\phi$	$-10.1571 \pm 0.0020$	-10.80	$-7.6250 \pm 0.0060$	-7.84
$B_\theta$			$-4.9289 \pm 0.0060$	
$\omega$	$0.1824 \pm 0.0050$		$-3.1017 \pm 0.0040$	

### 5.2 Reversal Dynamo Case

In this example, we produce a magnetic field reversal using MAG. The input parameter in the source directory for this case is `~/src/par.Rev`. There is no longitudinal symmetry in this case, so when you compile MAG,

use `param32s1.f` linking to `param.f`. The Ekman number is  $E = 0.02$ , the Prandtl number is  $Pr = 1$  and the magnetic Prandtl number is  $Pm = 10$ . The Rayleigh number is  $Ra = 12000$ .

### 5.2.1 Results and Discussions

This case has run on 32-bit and 64-bit Intel processors. Figure 5.1 shows a plot of mean velocity  $V_{rms}$ , mean magnetic field  $B_{rms}$ , the axial dipole and the dipole tilt on the outer boundary. It indicated a magnetic field reversal between time steps 25 and 30. Figure 5.2 shows a longer run of MAG, where we see the magnetic field reversed again. At this time, the magnetic field had weakened substantially. In Figure 5.3, the top is the pole plot before the second field reversal and the bottom is the pole plot after the second field reversal.

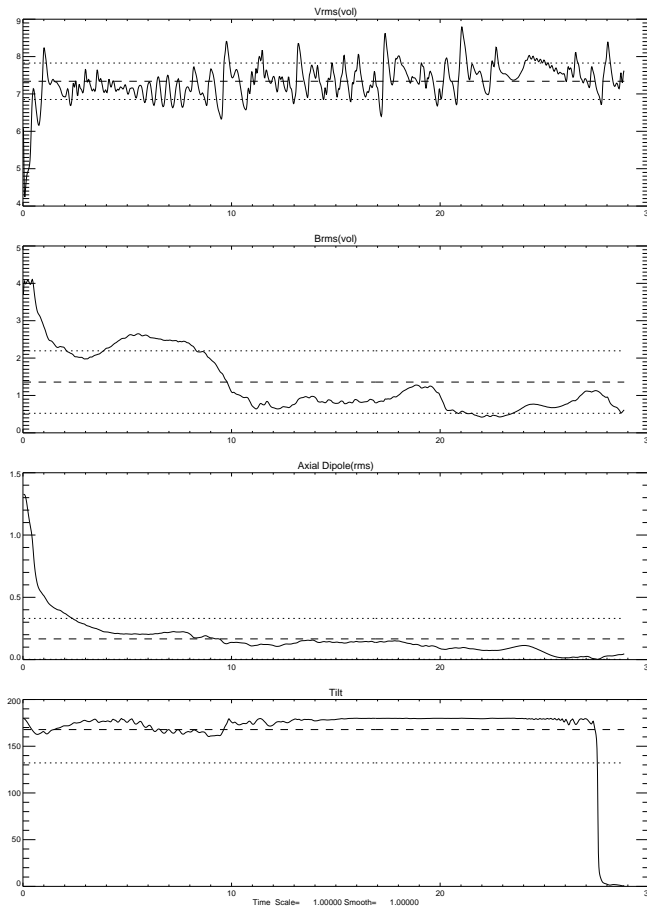


Figure 5.1: Field Plot for Reversal Dynamo Case

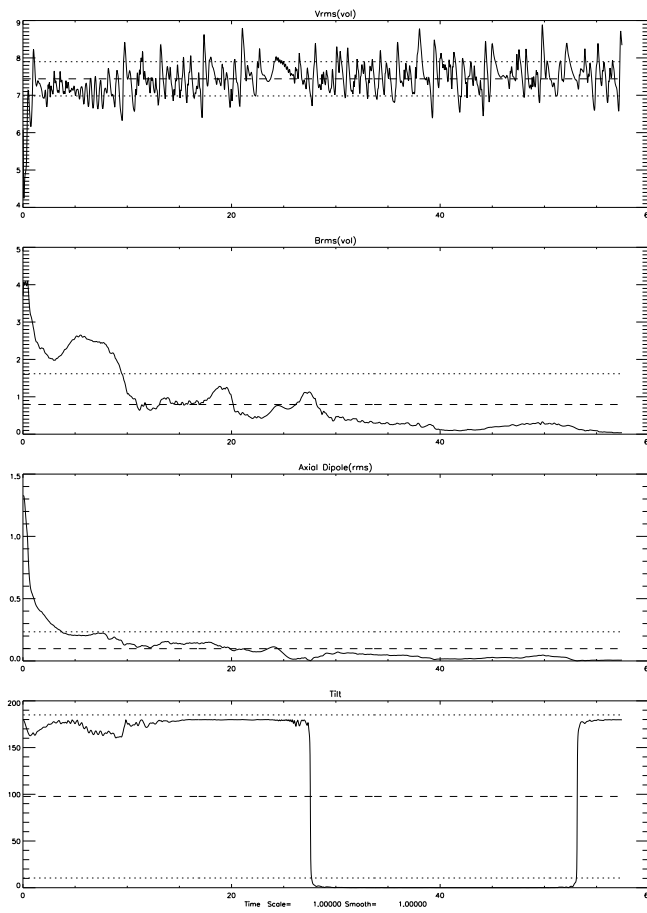


Figure 5.2: Field Plot for Reversal Dynamo Case (longer run)

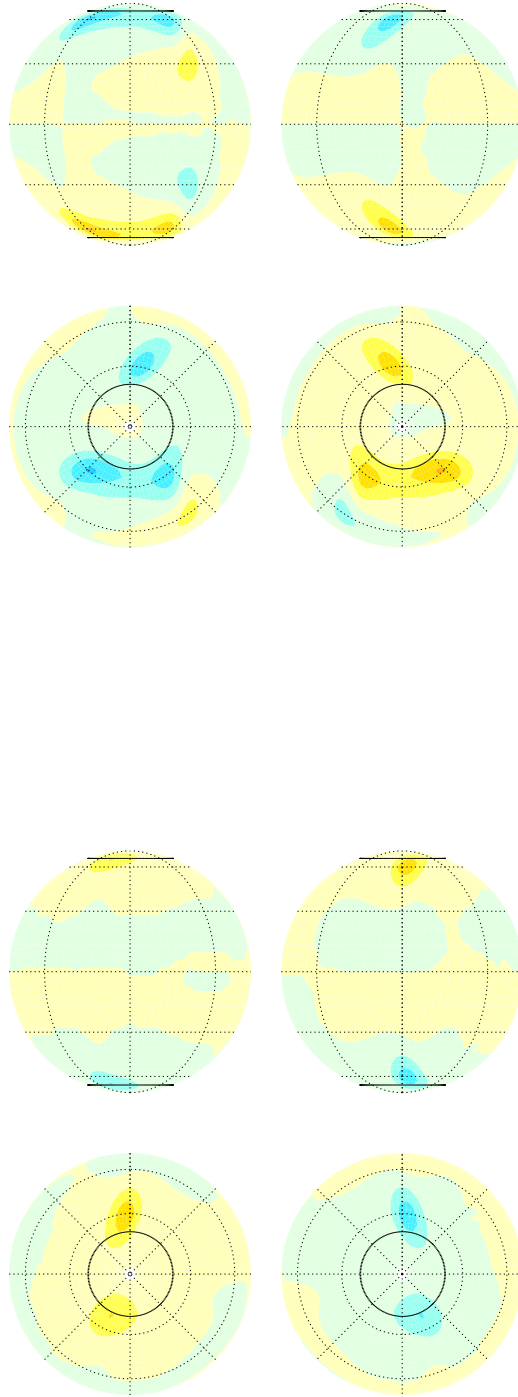


Figure 5.3: Magnetic Field Pole Plot. The top is the pole plot at the beginning of the second field reversal; the bottom is the pole plot at the end of the second field reversal.



## 5.2.2 Creating a Reversal Dynamo Movie

### 5.2.2.1 Generating Movie Files

MAG has the function to record a movie. The input parameter `imovopt` gives the option to write  $B_r$  at the outer surface, the output file is produced with prefix “mm.” when `imovopt=100` or the digit at the hundreds is larger than zero. For our reversal dynamo case we examine the field plot and decide to record the first field reversal. As shown the figure 5.4, we pick the time interval to generate the movie file. The input parameter for movie recording is in `~/src/par.revRmv`. We choose restart file d5 as our starting point, and set to record the movie at time  $t = 22$ . This records 400 frames over an 8 time unit. The sample output files are in `~/rev-data`.

This version of MAG provides an IDL routine `magmovieCIG.pro` (`~/idl/magmovieCIG.pro`), it reads in the movie file `mm.` and displays the magnetic field at the outer surface. This procedure can also create JPG files of the movie-frame images. Figure 5.5 shows the first and the last frames of the reversal dynamo movie.

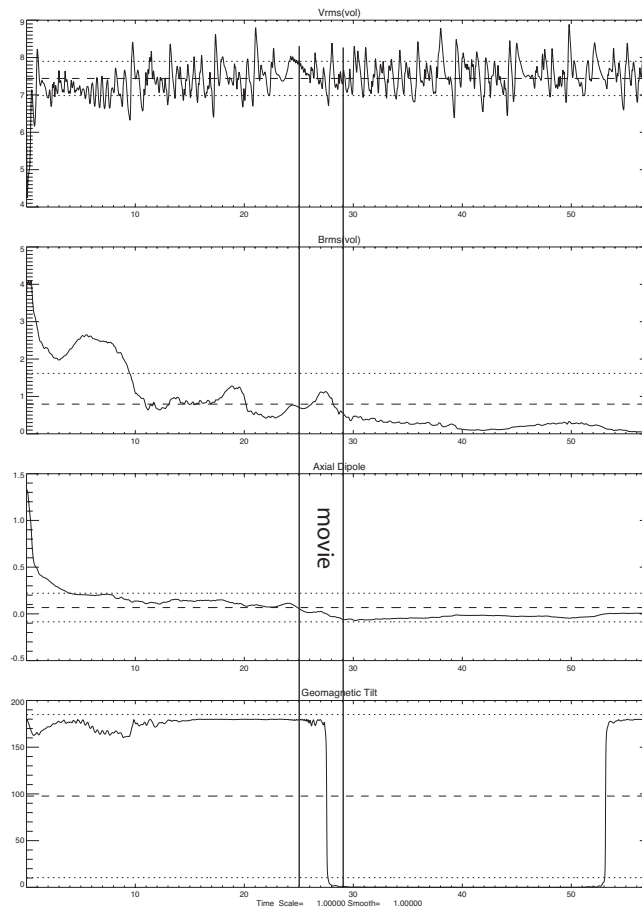


Figure 5.4: Interval to record movie

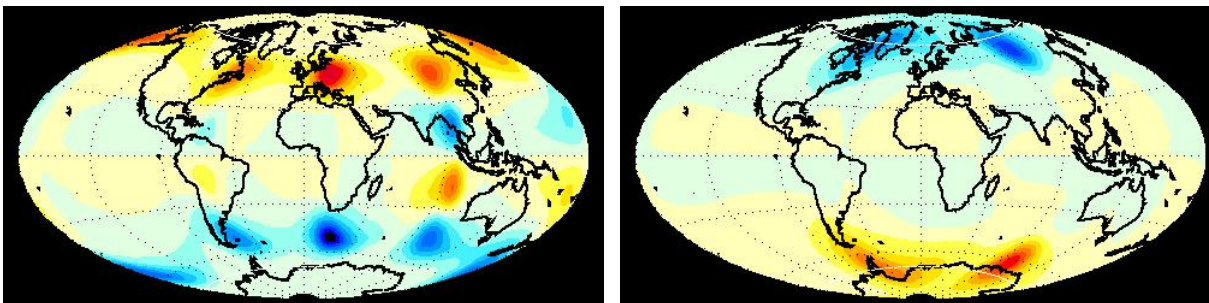


Figure 5.5: Reversal Dynamo Movie. Left: first frame of movie; right: last frame of movie

### 5.2.2.2 Creating MPEGs with IDL

IDL provides an `IDLgrMPEG` class that allows the user to save an array of image frames as an MPEG movie. See the IDL Reference Guide ([www.rsinc.com/idl/pdfs/refguide.pdf](http://www.rsinc.com/idl/pdfs/refguide.pdf)).

The `MPEG_PUT` procedure stores the specified image array at a specified frame index in an MPEG sequence. The `MPEG_SAVE` procedure encodes and saves an open MPEG sequence. The images can be read using the `READ_IMAGE` function.

The module `mpg.pro` reads a sequence of images (named `prefix00001.suffix`) and produces an MPEG1 or MPEG2 movie. Supported formats are BMP, GIF, JPEG, PNG, PPM, SRF, TIFF, and DICOM. `mpg.pro` runs with the following parameters:

**prefix** string (required). A string specifying the prefix of the images to read included the path, e.g.,  
`"/home/data/images/Image"`

**suffix** string (required). A string specifying the suffix of the images to read, e.g., `"jpg"`

**n\_start** integer (required). An integer specifying the first image in the sequence

**n\_end** integer (required). An integer specifying the last image in the sequence

**digits** integer (required). An integer specifying the number of digits of the number field in the sequence, e.g., `image00001.jpg` would require `digits=5`

**dims** integer (optional). An integer array specifying the size of the output image; if not specified the size of the first image is used

**format** integer (optional). An integer with values 0 for MPEG1 and 1 for MPEG2 (default is MPEG1)

**frame\_rate** integer (optional). An integer with values

- 1 = 23.976 frames/sec: NTSC encapsulated film rate
- 2 = 24 frames/sec: standard film rate
- 3 = 25 frames/sec: PAL video frame rate
- 4 = 29.97 frames/sec: NTSC video frame rate
- 5 = 30 frames/sec: NTSC drop frame video rate (the default)
- 6 = 50 frames/sec: double frame rate/progressive PAL
- 7 = 59.94 frames/sec: double frame rate NTSC
- 8 = 60 frames/sec: double frame rate NTSC

**mpeg\_file** string (optional). A string specifying the output MPEG file (default `outfile.mpg`)

**tmp\_dir** string (optional). A string specifying the temporary directory to use for the temporary image files

To run the IDL movie generator, type in a shell:

```
$ idl
> .compile mpg.pro
> make_mpg, prefix='image', suffix='JPG', n_start=0, n_end=100, digits=3,
    dims=[512,512], frame_rate=2, mpeg_file='mympeg.mpg'
```

A movie file (`magrev#.mpg`) produced by `magmovieCIG.pro` and `mpg.pro` is also included in the `~/rev-data` directory.

## 5.3 Gauss Coefficients Conversion

Making the MAG output useful to the broader geomagnetism community is one of CIG's top priorities. In this release, we have added the option of output files consisting of the Gauss coefficients of the external magnetic field computed as a function of time.

Here is some background: The standard procedure for extrapolating the main geomagnetic field from the core to the Earth's surface and nearby space assumes the mantle, crust, and atmosphere can be treated as current-free regions. In these regions the geomagnetic potential of the core field satisfies Laplace's equation and can be expressed as a series of spherical harmonics. MAG uses fully-normalized, complex-valued spherical harmonics for its magnetic field and other internal variables, and in addition, the MAG spherical harmonics are packed into one-dimensional arrays for optimal computation and they have non-dimensional coefficients. In contrast, the geomagnetism scientific community uses real-valued Schmidt-type spherical harmonics for representing the main field, with dimensional coefficients called the Gauss coefficients (see [8, 1] for their exact definitions). Gauss coefficients are denoted by  $g(l,m)$  and  $h(l,m)$  respectively, where  $(l,m)$  are harmonic degree and order, respectively, and are usually expressed in nanoTesla units. For example, the present-day axial dipole field has a Gauss coefficient near  $g(1,0) = -29,500$  nT, the minus sign indicating the field points radially inward in the northern hemisphere.

MAG now provides the option for converting its fully-normalized, complex harmonics of the field to the standard geomagnetic format, by requesting an output file (prefix `cg.`) that consists of the model Gauss coefficients in nanoTesla at the same times as the output for the movie files (prefixes `me` and `mm`). The conversion from non-dimensional to dimensional coefficients is based on Elsasser number magnetic field scaling and assumes nominal values of the Earth's core radius, rotation rate, and electrical conductivity. This option is invoked with the `IMOVOPT` command in the MAG par-file list.



## Part III

# Appendices



# Appendix A

## Variables Used in MAG

This is a list of variables and names used in the program set in MAG. The list is in alphabetical order for ease of reference.

**adrke** axisymmetric toroidal kinetic energy (diagnostic)

**ai** imaginary unit =  $\text{complex}(0,1)$

**aj** (**nlma,nn+1**) poloidal magnetic field potential (spectral form); the second index is either the Chebyshev degree (n) or the radial grid point (kc)

**ajmat** (**nn,nn,lmax**) LU-decomposed matrix from Chebyshev collocation of toroidal induction equation. Built in ludc, used in amhd.

**aleg1** (**nlma,ni**) Value of associated Legendre function at grid points

**aleg2** (**nlma,ni**) Value of associated Legendre function, multiplied with Gaussian weight, at grid points

**aleg3** (**nlma,ni**) Value of derivative of associated Legendre function multiplied with  $\sin(\theta)$  at grid points

**alfilt** [INPUT] Filter parameter for  $B_r$  in graphics output, see nfil

**alfac** [INPUT] Controls the contribution of the (modified) Alfvén velocity to the Courant time step limit (see under “courfac”). The modified Alfvén velocity is given by  $v_{\text{alfven}}' = (v_a)^2 / \{(v_a)^2 + [\pi(\eta + \nu)/\Delta x]^2\}$  where  $v_a = B/\sqrt{\mu\rho}$  and  $\Delta x$  is the Courant length (either  $\Delta x_r$  or  $\Delta x_h$ )

**alpha** [INPUT] =0 linear terms in the equations are treated fully explicit, =1 linear terms are treated fully implicit, =0.5: Crank-N.

**alumn0** Factor for scaling heat flow in output amcke: axisymmetric poloidal kinetic energy

**amhd** [SUBROUTINE] The “workhorse” of the program: advance solution by nstep time steps

**amps** [INPUT] can be used to re-scale entropy

**ampj** [INPUT] can be used to re-scale toroidal magnetic field

**ampb** [INPUT] can be used to re-scale poloidal magnetic field

**ampw** [INPUT] can be used to re-scale poloidal velocity

**ampz** [INPUT] can be used to re-scale toroidal velocity

**anorm** =  $\sqrt{2/(nn+1)}$

**apome** axisymmetric poloidal magnetic field energy

**atome** axisymmetric toroidal magnetic field energy

**b (nlma,nn+1)** poloidal magnetic field potential (spectral form, see aj)

**bleg1 (lmax)** auxiliary array for calculation of aleg1

**bleg2 (lmax)** auxiliary array for calculation of aleg2

**bleg3 (lmax)** auxiliary array for calculation of aleg3

**bmat(nn,nn,lmax)** LU-decomposed matrix from Chebyshev collocation of poloidal induction equation.  
Built in ludc, used in amhd.

**bnlc1 (nja/2,ni)** bnlr1 stored in complex form

**bnlc2 (nja/2,ni)** bnlr2 stored in complex form

**bnlc3 (nja/2,ni)** bnlr3 stored in complex form

**bnlr1 (nja,ni)** nonlinear products for updating b (on grid points)

**bnlr2 (nja,ni)** nonlinear products for updating aj (on grid points)

**bnlr3 (nja,ni)** nonlinear products for updating aj (on grid points)

**bots(0:lmax,0:mmax)** [INPUT] harmonic coefficients of prescribed temperature (entropy) on inner boundary

**br (nja,ni)**  $= r^2 * B_r$  on gridpoints

**brc** br stored as complex array

**bscl**  $= dt * radtop^2$

**bt (nja,ni)**  $= r * \sin(\theta) * b_\theta$

**btrdt (ni)** used in movmout to calculate j\_phi

**bts (ni,3)** used in movmout to calculate j\_phi

**btc** bt stored as complex array

**bp (nja,ni)**  $= r * \sin(\theta) * b_\phi$

**bpc** bp stored as complex array

**bpeak** [INPUT] maximum value of imposed field on boundaries

**bpeakbot** maximum value of imposed field on inner boundary

**bpeaktop** maximum value of imposed field on outer boundary

**cbr (nja,ni)**  $= r^2 * \text{curl}(B) * e_r$

**cbrc** cbr stored as complex array

**cbt (nja,ni)**  $= r * \sin(\theta) * \text{curl}(B) * e_\theta$

**cbtc** ctr stored as complex array

**cbp (nja,ni)**  $= r * \sin(\theta) * \text{curl}(B) * e_\phi$

**cbpc** cbp stored as complex array



**cheb (nn,nn)** cheb(i,j) = value of Chebyshev polynomial i at grid point j

**chebi** [SUBROUTINE] initialize subroutine chebtf

**chebtf** [SUBROUTINE] multiple fast Chebyshev transform

**clm (lmax,mmax)** normalization factors of spherical harmonics

**cmb** [INPUT] integrated conductivity of thin D"-layer

**colat (ni)** vector of colatitudes (Gauss points), local array in subroutine prep

**courfac** [INPUT] factor controlling the time step as fraction of courant advection length. The time step is limited to  $dt < \min( dx/[ courfac * v + alffac * v\_alfven' ] )$

**cvr (nja,ni)**  $= r^2 * \text{curl}(v) * e\_r$

**cvrc** cvr stored as complex array

**db (nlma,nn+1)** radial derivative of poloidal magnetic potential (spectral form, see aj)

**dbdt (nlma,nn,2)** time derivative of poloidal magnetic potential b

**dcheb (nn,nn)** dcheb(i,j) = 1st derivative of Chebyshev polynomial i at grid point j

**d2cheb (nn,nn)** d2cheb(i,j) = 2nd derivative of Chebyshev polynomial i at grid point j

**d3cheb (nn,nn)** d3cheb(i,j) = 3rd derivative of Chebyshev polynomial i at grid point j

**ddb (nlma,nn+1)** 2nd radial derivative of poloidal magnetic potential b

**ddj (nlma,nn+1)** 2nd radial derivative of toroidal magnetic potential aj

**ddw (nlma,nn+1)** 0.25 \* 2nd radial derivative of poloidal velocity potential w

**ddz (nlma,nn+1)** 0.25 \* 2nd radial derivative of toroidal velocity potential z

**djdt (nlma,nn,2)** time derivative of toroidal magnetic potential z

**dpdt (nlma,nn,2)** time derivative of pressure

**dsdt nlma,nn,2)** time derivative of temperature (entropy)

**dw (nlma,nn+1)** 0.50 \* radial derivative of poloidal velocity potential w

**dwdt (nlma,nn,2)** time derivative of poloidal velocity potential w

**dz (nlma,nn+1)** 0.50 \* radial derivative of toroidal velocity potential z

**dzdt (nlma,nn,2)** time derivative of toroidal velocity potential z

**delxh (nn)** horizontal Courant length squared

**delxr (nn)** radial Courant length

**difamp** [INPUT] amplitude of hyperdiffusivity  $D=D*(1 + difamp * [(1+1-ldif)/(lmax+1-ldif)]^{ldifexp})$  when  $l > ldif$

**dipfilt** [INPUT] If nfilt>0 multiply axial dipole component of B\_r on outer surface by dipfilt in graphics file

**dj (nlma,nn+1)** radial derivative of toroidal magnetic potential (spectral form, see aj)

**dt** current time step

**dtchck** [SUBROUTINE] controls time step

**dth** Courant time based on horizontal velocity + Alfven velocity

**dtmax** [INPUT] Upper limit on time step (and initial step)

**dtmin** Lower limit on time step (stop when  $dt < dtmin$ )

**dtold** Time step of previous iterative step

**dtr** Courant time based on radial velocity + Alfven velocity

**dtstart** [INPUT] Initial time step. If =0, dtmax, or when beginning from restart file, the old dt is taken

**dvpdr (nja,ni)** =  $d [r * \sin(\theta) * v_{\phi}] / dr$  on gridpoints

**dvpdrc** dvpdr stored as complex array

**dvpdp (nja,ni)** =  $d [r * \sin(\theta) * v_{\phi}] / d\phi$  on gridpoints

**dvpdpc** dvpdp stored as complex array

**dvrdr (nja,ni)** =  $d [r^2 * v_r] / d\phi$  on gridpoints

**dvrdrpc** dvrdr stored as complex array

**dvrdr (nja,ni)** =  $d [r^2 * v_r] / dr$  on gridpoints

**dvrdrpc** dvrdr stored as complex array

**dvrdrdt (nja,ni)** =  $\sin(\theta) * d [r^2 * v_r] / d\theta$  on gridpoints

**dvrdrdtc** dvrdrdt stored as complex array

**dvtddp (nja,ni)** =  $d [r * \sin(\theta) * v_{\theta}] / d\phi$  on gridpoints

**dvtddpc** dvtddp stored as complex array

**dvtddr (nja,ni)** =  $d [r * \sin(\theta) * v_{\theta}] / dr$  on gridpoints

**dvtddrc** dvtddr stored as complex array

**dw (nlma,nn+1)** 0.5 \* radial derivative of poloidal velocity potential w

**dz (nlma,nn+1)** 0.5 \* radial derivative of toroidal velocity potential z

**escale** scaling factor for energies in output

**ek** [INPUT] Ekman number

**enb** [OUTPUT] magnetic energy

**ens** [OUTPUT] thermal energy

**enscale** [INPUT] in output listing, energies are multiplied by enscale

**ent** [OUTPUT] total energy

**env** [OUTPUT] kinetic energy

**epsc0** [INPUT] internal heating rate

**flmb1 (nlma+..)** r-component of  $(v \times B)$  term

**flmb2 (nlma+..)** theta-component of  $(v \times B)$  term

**flmb3 (nlma+..)** phi-component of  $(\mathbf{v} \times \mathbf{B})$  term  
**flms1 (nlma+..)** r-component of entropy advection term  
**flms2 (nlma+..)** theta-component of entropy advection term  
**flms3 (nlma+..)** phi-component of entropy advection term  
**flmw1 (nlma+..)** r-component of  $\mathbf{v} \cdot \text{grad}(\mathbf{v}) + \text{Lorentz force}$  term  
**flmw2 (nlma+..)** theta-component of  $\mathbf{v} \cdot \text{grad}(\mathbf{v}) + \text{Lorentz force}$  term  
**flmw3 (nlma+..)** phi-component of  $\mathbf{v} \cdot \text{grad}(\mathbf{v}) + \text{Lorentz force}$  term  
**gauss (ni)** vector with Gaussian weighting factors, local array in subroutine prep  
**gquad** [SUBROUTINE] finds zeros and Gaussian weight of associated Legendre function  
**graffle** [CHARACTER] file name for data on spatial grid for graphics with prefix “g.”; added to outfile set  
**grav (nn)** gravity at radial levels  
**ib (nn,lmax)** pivot array for LU-decomposition of matrix bmat created in sgefa, used in sgesl  
**ic** stepping variable commonly used for steps in colatitude  
**icour** [INPUT] Courant criterion is checked each ICOUR'th time step  
**idiftyp** [INPUT] controls radial variation of diffusivity; =0, no variation  
**ifaxc** [13] auxiliary array (factorization) for Chebyshev transform  
**ifaxf** [13] auxiliary array (factorization) for Fourier transform  
**ifbfrz** [INPUT] logical; if .TRUE., do not update magnetic field  
**ifirst** =1 before first call of time-step checking routine, =0 thereafter  
**iframes** [INPUT] write altogether iframes frames on the movie files (see description under imovopt)  
**ifsfrz** [INPUT] logical; if .TRUE., do not update temperature (entropy)  
**ifvfrz** [INPUT] logical; if .TRUE., do not update velocity  
**ij (nn,lmax)** pivot array for LU-decomposition of matrix ajmat created in sgefa, used in sgesl  
**imagcon** [INPUT] <0 imposed poloidal field ( $l=1, m=0$ ) at ICB >=0 imposed toroidal field ( $l=2, m=0$ ) at ICB >=10 additionally imposed field at CMB, field is of same sign and amplitude if imagcon=10 and of opposite sign if imagcon=11  
**imovopt** [INPUT] four-digit integer number, controls options for generating movie files.

**Last digit > 0** write  $B_z$ ,  $W_z$  (vorticity) and  $T$  in the equatorial plane on file with prefix “me.”, imovopt=0001  
**2nd last digit > 0** write longitudinally averaged  $B_\phi$ ,  $j_\phi$  and  $v_\phi$  on file with prefix “ma.”, imovopt=0010  
**3rd last digit > 0** write  $B_r$  at outer surface on file with prefix “mm.”, imovopt=0100  
**4th last digit > 0** write spherical harmonic coefficients for poloidal field at outer boundary and for velocity potentials at radial level on file with prefix “cc.”. (This option works only when any or all of the movie options are turned on, i.e., any of the “m?” files are also produced. imovopt=1000 will not produce a “cc.” file.)

**imovct** counter variable for movie frames

**infile** [CHARACT INPUT] name of input file for initial values (restart)

**init** [INPUT] =0 start from dat-file, =1: random initial cond., =-1: hydro. condition from dat-file, magnetic random >=100: initial temperature perturbation in a single mode l,m. Here m is given by the last two digits of init and l by the preceding digits.

**ip0 (nn)** pivot array for LU-decomposition of matrix p0mat created in sgefa, used in sgesl

**iprnt** counting blocks in time iteration sequence with printed output created at completion of block

**is (nn,lmax)** pivot array for LU-decomposition of matrix smat created in sgefa, used in sgesl

**is0 (nn)** pivot array for LU-decomposition of matrix s0mat created in sgefa, used in sgesl

**iscale** [INPUT] determines which diffusivity is used for scaling of time, velocity, energy. 1=viscous, 2=thermal, 3=magnetic

**istep** time step counter (routine amh)

**istor** counting superblocks in time iteration sequence, upon completion of superblock disk file with data saved

**ivflt** [INPUT] Apply filter to v\_r at radial level ivflt and right into first radial position in graphics file; see nflt

**iwp (nn,lmax)** pivot array for LU-decomposition of matrix wpmat created in sgefa, used in sgesl

**iz (nn,lmax)** pivot array for LU-decomposition of matrix zmat created in sgefa, used in sgesl

**k2k (nn1)** auxiliary array for Chebyshev transform

**kc** stepping variable commonly used for steps in radius

**kcour** auxiliary variable for time step checking procedure

**kbotb** [INPUT] magnetic bottom condition; =1 insulating, =2 perfect condition

**kbotv** [INPUT] mechanical bottom condition; =1 free, =2 rigid

**kbots** [INPUT] thermal bottom condition; =1 fixed entropy, =2 flux

**kei** [SUBROUTINE] calculates kinetic energy

**kstep** global time step counter

**ktops** [INPUT] thermal top condition; =1 fixed entropy, =2 flux

**ktopb** [INPUT] magnetic top condition; =1 insulating, =2 perfect condition

**ktopv** [INPUT] mechanical top condition; =1 free, =2 rigid

**ldif** [INPUT] control parameter for hyperdiffusivity, see difamp

**ldifexp** [INPUT] control parameter for hyperdiffusivity, see difamp

**lm** stepping variable used to cover all l and m  $lm = m*(lmax+1)/mnc - m*(m-mnc)/(2*mnc) + l-m+1$

**lmax** maximum harmonic degree, calculated as  $(nj-1)/3$

**logfile** [CHARACT] file name for continuous log of energies and other data prefix "l."; added to outfile set

**lot** [PARAM] = 2 \* nlma (twice the number of harmonic modes)

**lpfile** [CHARACT] file name for continuous log of specified values with prefix “lp.”; added to outfile set

**lsfile:** [CHARACT] file name for power spectra of magnetic and kinetic as function of l and m with prefix “ls.”; added to outfile set

**ludc:** [SUBROUTINE] Chebyshev collocation

**mclm (nlma)** used to unscramble harmonic order m from variable lm

**mclma (nlma)** =  $m/\text{minc}+1$  for given lm (storage order of m)

**kei** [SUBROUTINE] calculates magnetic energy

**minc** [PARAM] if >1, minc-fold symmetry in longitude assumed

**mmax** maximum harmonic order, is the largest integer  $\leq l_{\text{max}}$  divisible by minc

**movafle** [CHARACT] file name for movie data (longitudinal averages) with prefix “ma.”; added to outfile set

**movefile** [CHARACT] file name for movie data in equatorial plane with prefix “me.” ; added to outfile set

**movmfile** [CHARACT] file name for movie data in map views with prefix “mm.” ; added to outfile set

**n, nc** stepping variables commonly used for steps over Chebyshev polynomial

**ncp** [PARAM] =  $n_{\text{ja}}/2$  used for storage of points in phi in complex array

**nfilt** [INPUT] Apply filter  $F(l)=\exp(-|l|/l_{\text{filt}})^{\text{nfilt}}$  to  $B_r$  on outer surface in graphics output file (if  $\text{nfilt}>0$  and  $\text{alfilt}>0$ ) When  $\text{nfilt}>0$ ,  $\text{alfilt}<0$ , apply cos-tapered filtered with cutoff at  $\text{nfilt}$  and taper width  $|\text{alfilt}|$

**ngcolat** [INPUT] graphics output on each  $\text{ngcolat}$ ’th point in latitude

**ngform** [INPUT] if .ne. 0, graphics output is written each time a restart file is (finally) written.  $\text{ngform}=1$  or -1: formatted graphics file,  $\text{ngform}=2$ : unformatted for  $\text{ngform}=-1$  additional comment lines are inserted (this is to look at the file, not for graphics)

**nglon** [INPUT] graphics output for each  $\text{nglon}$ ’th point in longitude

**ngrad** [INPUT] graphics output on each  $\text{ngrad}$ ’th radial level

**ni** [PARAM] # of grid points in colatide; must be even

**nip1** [PARAM] =  $\text{ni}+1$

**nj** [PARAM] # of grid points in longitude;  $\text{nj}/\text{minc}$  must be multiple of four

**nja** =  $\text{nj}/\text{minc}$ , # of actually needed grid points in phi

**njp1** [PARAM] =  $\text{nj}+1$

**nlaf** [PARAM] =  $\text{lmax}+1$

**nlafp1** [PARAM] =  $\text{lmax}+2$

**nlm** [PARAM] =  $(\text{mmax}+1)*(\text{mmax}+2)/2$

**nlma** [PARAM] # of angular modes employed  $\text{nlma} = \text{mmax}*(\text{lmax}+1)/\text{minc} - \text{mmax}*(\text{mmax}-\text{minc})/(2*\text{minc}) + \text{lmax}-\text{mmax}+1$ .

**nlmpa** [PARAM] =  $\text{nlma} + \text{mmax}/\text{minc} + 1$

**nlogstep** [INPUT] write data on logfile (prefix l.) after each  $\text{nlogstep}$  steps.

**nmaf** [PARAM] = mmax+1

**nmafa** [PARAM] = mmax/minc+1

**nn** [PARAM] # of radial grid points, nn-1 must be multiple of 4, and contain no prime factors larger than 5

**nn1** [PARAM] = nn-1

**nn2** [PARAM] = nn-2

**nn3** [PARAM] = nn-3

**nnp1** [PARAM] = nn+1

**nnp2** [PARAM] = nn+2

**nnaf** [PARAM] # of radial Chebyshev modes, must be  $\leq$  nn

**nnx2** [PARAM] = 2\*nn

**nplog** [INPUT] if >0 write velocity values at specific points of the grid on separate logfile (prefix "lp.") after every nplog steps (for arrays, see vrpoint, vppoint, vtpoint in subroutine amhd for details)

**nprnt** [INPUT] # of printed output blocks created until next data storage for restart

**nps2** [PARAM] = (nn+1)/2

**nrp** [PARAM] = nja+2 (# of points in phi +2)

**ns2** [PARAM] = (nn-1)/2

**nstep** [INPUT] # of time steps done until next printed output (total # of time steps is nstep\*nprnt\*nstor)

**nstor** [INPUT] # of data storages before program termination

**ntf** [PARAM] = 3\*nja/2+1, used for Fourier transform array trigsf

**ocorevol** volume of spherical shell (outer core)

**oek** = 1. / Ekman number

**oekpm** = 1. / (Ekman number \* Magnetic Prandtl number)

**oodt** = 1. / dt (inverse time step)

**oosscl** = 1. / dt

**opr** = 1. / Prandtl number

**outfile** [CHARACT INPUT] Name of output files (pre-fixes d.,l.,ls.,g.,me.,ma.,mm., lp. added)

**p0mat** (**nn,nn**) LU-decomposed matrix from Chebyshev collocation of pol. equation of motion, l=0-term for pressure. Constructed in ludc, used in amhd

**pbar** [SUBROUTINE] Calculates value of associated Legendre function

**pscale** scaling pressure in output

**pr** [INPUT] Prandtl number

**prmag** [INPUT] Magnetic Prandtl number

**prnt** [SUBROUTINE] print diagnostic data

**pscl** =  $\text{radtop}^2$

**qi** (**ni,5**) array with various coefficients depending on colatitude (look in subroutine prep, loop “do 32” for details)

**qk** (**nn,16**) array with various coefficients depending on radius (look in subroutine prep for details)

**ql** (**nlma,10**) various expressions depending on l and m (look in subroutine prep, loop “do 35” for details)

**qn** (**nn,6**) Chebyshev integrals

**r** (**nn**) vector with radial levels,  $r(1)=\text{radtop}$ ,  $r(\text{nn})=\text{radbot}$

**ra** [INPUT] Rayleigh number

**rapr** = Rayleigh number / Prandtl number

**radbot** radius of inner boundary

**radratio** [INPUT] ratio of inner radius to outer radius

**radtop** radius of outer boundary

**rderiv** [SUBROUTINE] radial derivative

**rftti** [SUBROUTINE] subroutine called in chebi

**rstfile** [CHARACTER] file name for data in spectral form (‘restart data’) with prefix “d.” or “d0.”, “d1.” ...; added to outfile set

**runid** [CHAR\*64] text identifying the run

**rva** (**nn**) auxiliary array used in prep

**rvap** (**nn**) auxiliary array used in kei, mei

**rvat** (**nn**) auxiliary array used in kei, mei

**rvb** (**nn**) auxiliary array used in prep, kei, mei

**rvc** (**nn**) auxiliary array used in kei, mei

**p** (**nlma,nn+1**) pressure (spectral form)

**p00co** =  $4/\sqrt{3}$

**prep** [SUBROUTINE] parameter input, set up auxiliary arrays, set initial conditions, etc.

**s** (**nlma,nn+1**) entropy perturbation (spectral form)

**sc** (**nep,ni**) sr stored in complex form

**snlc1** (**nep,ni**) slnr1 stored in complex form

**snlc2** (**nep,ni**) slnr2 stored in complex form

**snlc3** (**nep,ni**) slnr3 stored in complex form

**snlr1** (**nep,ni**) nonlinear term (radial advection) for updating temperature

**snlr2** (**nep,ni**) nonlinear term (theta advection) for updating temperature

**snlr3** (**nep,ni**) nonlinear term (phi advection) for updating temperature

**sr** (**nep,ni**) temperature (entropy) on grid points

**s0mat (nn,nn)** LU-decomposed matrix from Chebyshev collocation of temperature equation,  $l=0$ -term.  
Constructed in ludc, used in amhd

**samp** [INPUT] amplitude of initial entropy perturbation

**smat (nn,nn,lmax)** LU-decomposed matrix from Chebyshev collocation of temperature equation. Built  
in ludc, used in amhd

**sr (nja,ni)** entropy on gridpoints

**src** sr stored as complex array

**sscl** = dt

**stor** [SUBROUTINE] store data in restart file

**tei** [SUBROUTINE] calculates thermal energy

**time** time

**timediff** time

**tipdipole** [INPUT] rotate poloidal dipole term when beginning from restart file

**tmovnext** auxiliary variable (next output time) for movie file generation

**tmovstart** [INPUT] time at which to start writing movie-frames on m.\*-file

**tmovstep** [INPUT] time increments for writing movie-frames on m.\*-file

**tops (0:lmax,0:mmax)** [INPUT] harmonic coefficients of prescribed temperature (entropy) on outer bound-  
ary

**treset** [INPUT; LOGICAL] if true reset time and step counter to zero when starting from a stored dataset

**trigsc (nn)** auxiliary array for Chebyshev transform routine created in chebi, used in chebtf

**trigsf (ntf)** auxiliary array for Fourier transform routine created in fftsig, used in fourtf

**tscale** scaling of time in output

**up (nja,3)** phi-component of velocity in equatorial plane for three consecutive radial levels; used in moveout  
to calculate vorticity

**urdp (nja)** derivative  $dv_r/d\phi$  in equatorial plane; used in moveout to calculate vorticity

**vr (nja,ni)** =  $r^2 * v_r$  on grid points

**vrc** vr stored as complex array

**vp (nja,ni)** =  $c * \sin(\theta) * v_\phi$  on grid points

**vpc** vp stored as complex array

**vscale** scaling of velocity in output

**vt (nja,ni)** =  $r * \sin(\theta) * v_\theta$  on grid points

**vtc** vt stored as complex array

**w (nlma,nn+1)** poloidal velocity potential (spectral form)

**wpmat (nn,nn,lmax)** LU-decomposed matrix from Chebyshev collocation of poloidal equation of motion;  
built in ludc, used in amhd



**wnlc1 (nja/2,ni)** wnlr1 stored in complex form  
**wnlc2 (nja/2,ni)** wnlr2 stored in complex form  
**wnlc3 (nja/2,ni)** wnlr3 stored in complex form  
**wnlr1 (nja,ni)** nonlinear products for updating w (on grid points)  
**wnlr2 (nja,ni)** nonlinear products for updating z (on grid points)  
**wnlr3 (nja,ni)** nonlinear products for updating z (on grid points)  
**work (lot,nnp2)** work array used in Fourier and Chebyshev transforms  
**wsave (nn)** auxiliary array used for Chebyshev transform  
**wscl** =  $dt * radtop^2$   
**y00** =  $1/\sqrt{4*\pi}$   
**z (nlma,nn+1)** toroidal velocity potential (spectral form)  
**zscl** =  $dt * radtop^2$   
**zmat (nn,nn,lmax)** LU-decomposed matrix from Chebyshev collocation of toroidal equation of motion;  
 built in ludc, used in amhd



## Appendix B

# MAG Input File Format

### Introduction

This is an overview of the components of the code, input parameters, structure of output files, etc. MAG expects Unix-styled ASCII files (i.e., no carriage-return character following new line character) for all input files. This can be a nuisance in DOS/Windows systems. You may want to find a text editor that can write Unix-style ASCII files. All parameters are in non-dimensional units unless specified.

### Input Parameters

Parameters have pre-defined (default) values. They are read through a namelist in the subroutine “prep.”

#### INPUT, OUTPUT, STEPPING CONTROL, INITIALIZATION OF THE RUN

**outfile** Name of output files (prefixes **d.**, **g.**, **l.**, **ls.**, **me.**, **ma.**, **mm.**, are added)

**infile** Complete name of file from which initial values are read (restart file)

**runid** Arbitrary text of up to 64 characters to describe the model

**init** Set 1 to start from scratch (random noise initial condition); set 0 to start from a previous result obtained on the same grid which has been written into a file named `d[0-9].<name>` set to a value  $\geq 100$  to start from an initial temperature perturbation of one given mode `l,m`. Here, `m` is given by the two last digits of `init` and `l` by the preceding digits; for example `init=606` means that a temperature perturbation of `l=6` and `m=6` is imposed.

**samp** Amplitude of initial perturbation (whether random or single mode)

**nstep** Do one block of `nstep` time steps before producing a summary printout of some diagnostics standard output; `nstep` should be an even number

**nprnt** Do one “superblock” consisting of `nprnt` blocks of `nstep` time steps each, before saving all data in file `'d[0-9].name'`. If `nstor=1`, there is no number added after the `'d'`; if `nstor>1` the number is incremented by one for each new superblock, starting with zero.

**nstor** Do `nstor` “superblocks” consisting of `nstep*nprnt` time steps before terminating the process. The total number of time steps is `nstep*nprnt*nstor`; `nstor` must be  $\leq 10$ .

**ngform** Write data at grid points for graphics processing and other post-processing (programs `column.f` `diagnos.f`) into file `'g[0-9].<name>'` each time a superblock is written.

**ngform=2** unformatted file

**ngform=1** formatted file  
**ngform=0** nothing written  
**ngform=-1** comment lines are included into file for easier reading (cannot be used for graphics processing in this form)

**ngrad** Output on graphics file for each ngrad'th radial point

**ngcolat** Output on graphics file every ngcolat'th point in colatitude

**nlon** Output on graphics file every nlon'th point in longitude

**nfilt** If  $>0$  apply filter of type  $F(l) = \exp[-(l/\text{alfilt})^{\text{nfil}}]$  to the radial component of the magnetic field on the outer radius ( $kc=1$ ) before writing data into graphics file (for  $\text{alfilt} > 0$ ). When  $\text{alfilt} < 0$  then apply filter  $F(l) = (1 + \sin(\pi * (l - \text{nfil}) / \text{alfilt}))$  as long as  $|l - \text{nfil}| < 0.5 * \text{alfilt}$ , and  $F=1$  and  $F=0$  respectively for small/large  $l$ .

**alfilt** See under **nfil**

**ivfilt** If  $>0$  apply the same filter as above to the radial velocity at radial level **ivfilt** and write the result into graphics file at the first radial location ( $kc=1$ )

**dipfilt** If **nfil** $>0$  multiply axial dipole component of  $B_r$  on outer surface by **dipfilt** in graphics output

**nlogstep** Writes data on logfile (prefix **l**.) after each **nlogstep** step

**nplog** If  $>0$ , writes velocity values at specific points of the grid on separate logfile (prefix "lp.") after every **nplog** step (for arrays, see **vrpoint**, **vpptpoint**, **vtpoint** in subroutine **amhd** for details)

**iscale** Determines which diffusivity is used for scaling of time, velocity and energy. 1=viscous, 2=thermal, 3=magnetic

**enscale** In output listings, energies are multiplied by **enscale**

**treset** [LOGICAL] If true, reset time and step counter to zero when starting from a stored dataset

**tipdipole** When starting calculation without imposed symmetry (**minc**=1) from a data file with symmetry (**minc** $>1$ ), add an equatorial dipole component with **tipdipole** times the magnitude of the polar dipole

**amps** Option for rescaling temperature perturbation (from restart file) by factor **amps** (if not equal to 1)

**ampw** Same for poloidal velocity

**ampz** Same for toroidal velocity

**ampb** Same for poloidal magnetic field

**ampj** Same for toroidal magnetic field

**ifvfrz** [LOGICAL] If true, do not update velocity during iteration

**ifbfrz** [LOGICAL] If true, do not update magnetic field during iteration

**ifsfrz** [LOGICAL] If true, do not update temperature during iteration

## TIME STEP CONTROL

**dtmin** Minimum time step (in seconds). If the dynamically determined time step becomes less, the program terminates.

**dtmax** Maximum (and usually initial) time step. This must be less than  $0.25 \cdot \text{ek}$ . Between dtmax and dtmin the actual time step is controlled by a Courant criterion (see below).

**dtstart** Initial time step. If dtmax=0, dtmax is used for the initial time step when init>0 and the last time step used in the previous run (stored in the restart file) is used when init=0.

**courfac** Controls the contribution of the fluid velocity to the Courant time step limit (a larger value leads to smaller dt)

**alfac** Controls the contribution of the (modified) Alfven velocity to the Courant time step limit (a larger value leads to smaller dt)

**icour** Check Courant criterion after each icour time step (even numbers)

## PHYSICAL CONTROL PARAMETERS

**ra** Rayleigh number (defined with gravity on outer boundary)

**ek** Ekman number

**pr** Prandtl number

**prmag** Magnetic Prandtl number

**radratio** Ratio of inner to outer radius

**bpeak** Peak value of magnetic field imposed by boundary conditions at ICB (also when imagcon=0, bpeak controls the initial magnetic field: toroidal when bpeak>0, poloidal dipole when bpeak<0!)

**epsc0** Volumetric rate of internal heating

## BOUNDARY CONDITIONS AT INNER AND OUTER RADII

**ktops** thermal boundary condition at CMB. 1-fixed temp, 2-fixed radial heat flow. (ktops=2 not tested!).

**kbots** thermal boundary condition at ICB. As above.

**ktopv** velocity condition at CMB. 1-free, 2-rigid.

**kbotv** velocity condition at ICB. As above.

**kbotb** =1 for insulating inner core =2: ideally conducting inner core

**ktopb** =1 for insulating mantle =2: not implemented! imagcon: <0 imposed poloidal field (l=1,m=0) at ICB >=0 imposed toroidal field (l=2,m=0) at ICB >=10 imposed toroidal field (l=2,m=0) at both CMB and ICB (same amplitude and same sign if =10, opposite sign if =11)

**cmb** If >0, thin conducting layer at bottom of mantle (not tested!)

## HYPERDIFFUSIVITIES

**difamp** Amplitude of hyperdiffusivities

**ldif** Hyperdiffusivities applied for harmonic degrees  $l \geq \text{ldif}$

**ldifexp** Exponent for increase of hyperdiffusivities with  $l$  (analytical details see definition of ql(lm,11) in prep.f)

**PARAMETERS FOR GENERATING MOVIE FILES**

**imovopt** Three-digit integer number, options for generating movie files

**Last digit > 0** Write  $B_z$ ,  $W_z$  (vorticity) and  $T$  in the equatorial plane on file with prefix “me.”

**2nd last digit > 0** Write longitudinally averaged  $B_\phi$ ,  $j_\phi$  and  $v_\phi$  on file with prefix “ma.”

**3rd last digit > 0** Write  $B_r$  at outer surface and  $B_r$  and  $v_r$  at mid- depth on file with prefix “mm.”

**4th last digit > 0** Write spherical harmonic coefficients for poloidal field at outer boundary and for velocity potentials at radial level on file with prefix “cc.”

**iframes** Write altogether iframes frames on the movie files

**tmovstart** Time at which to start writing movie-frames

**tmovstep** Time increments for writing movie-frames

## Appendix C

# MAG Output File Format

MAG produces a set of output files for further processing. All outputs are in non-dimensional units unless specified.

**l.[outfile]** Lists a set of diagnostic values each nlogstep time-steps.

**ls.[outfile]** Spectra of kinetic energy and magnetic field every nprint time steps, sorted for modes with equal  $l$ , and additionally sorted for modes with equal  $m$ .

**g.[outfile] or g[i].[outfile]** where  $i=0,1,2,..9$  (optional, written when  $ngstep>0$ ). Contains temperature, velocity and magnetic field components for graphics processing (idl-program magts).

**d.[outfile] or d[i].outfile** Restart files with the complete set of variables (stored as spectral values  $l,m$  in the angular coordinates for radial grid-levels).

**lp.[outfile]** Written when  $nplog>0$ . Velocity at specific points written every  $nplog$ 'th time step.

**me.[outfile]** Written when first digit of  $imovopt>0$ , i.e.,  $imovopt=0001$ . Values in the equatorial plane for producing movie (idl-program: magmov EQ3.pro).

**ma.[outfile]** Written when second digit of  $imovopt>0$ , i.e.,  $imovopt=0010$ . Longitudinal averages for producing movie (idl-program, not provided).

**mm.[outfile]** Written when third digit of  $imovopt>0$ , i.e.,  $imovopt=0100$ . Values on spherical surfaces for producing movie (idl-program: magmovieCIG.pro, magmovCMB.pro).

**cc.[outfile]** Written when the last (fourth) digit and any of  $imovopt>0$  and any of the other three digits is larger than zero, i.e.  $imovopt>1000$ . Record the spherical harmonic coefficients for poloidal field at outer boundary and their converted Gauss coefficients.

**Note:** If one of the above files already exists, the program will not run.

The standard output file contains summaries of grid parameters and all process control and physical parameters that occur in the namelist statements. It lists the values of non-dimensional parameters and of the various diffusive time-scales. Then, at the end of each block, it lists a number of diagnostic values:

Parameters	Definitions
dt	actual time step
dtrmin	Courant time calculated with radial velocities
dthmin	Courant time calculated with horizontal velocities
cour	maximum inverse Courant time based on radial fluid velocity
couh	maximum inverse Courant time based on horizontal fluid velocity
alfr	maximum inverse Courant time based on radial modified Alfven velocity
alfh	maximum inverse Courant time based on horizontal modified Alfven velocity (in addition, the radial level at which the maximum is reached is indicated)
ent	total energy
env	kinetic energy
enb	magnetic energy

The meaning of other quantities is obvious.

For the primary variables, the modes for which they assume their absolute maximum and the maximum are printed. Maxima are determined for the toroidal potential multiplied by  $1/r$ , and for poloidal potentials multiplied by  $l(l+1)/r^2$ , in order to find the modes which exhibit the maximum longitudinal toroidal velocity (field strength) and the maximum radial velocity (field strength), respectively.

**l.[outfile]** printed every nlogstep time step, one record is printed that contains 17 output fields:

- 1) time
- 2) mean kinetic energy density
- 3) mean poloidal kinetic energy density
- 4) mean magnetic energy density
- 5) mean poloidal magnetic energy density
- 6) mean axisymmetric toroidal kinetic energy density
- 7) mean axisymmetric poloidal kinetic energy density
- 8) mean axisymmetric poloidal magnetic energy density
- 9) mean axisymmetric toroidal magnetic energy density
- 10) mean top heatflow (nusselt number)
- 11) mean bottom heatflow (nusselt number)
- 12) mean magnetic field strength
- 13) rms dipole, outer boundary
- 14) rms axial dipole, outer boundary
- 15) dipole tilt, outer boundary
- 16) dipole longitude, outer boundary
- 17) mean velocity

**ls.[outfile]** Printed each nprint time step are four records with time being the first variable followed by the spectral power of kinetic and magnetic energy, respectively, as a function of harmonic degree  $l$ , from  $l=0$  to  $l_{\max}$  (first two records in a block), and spectral power as a function of harmonic order  $m$  in the last two records of a block.



# Appendix D

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