Model S with full set of eigenmodes

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1 Introduction

This text contains some information on the complete set of eigenmodes (all solar p- and f-modes below the acoustic cutoff-frequency) I computed from Model S [4] using the *Aarhus adiabatic pulsation package* (Adipack, [2]) and a description of the content of the resulting files.

To obtain a well-defined result, I used the official Model S from Christensen-Dalsgaards website (`L5BI.D.15C.PRES.960126.AARHUS`[1]). The computation was performed using the (unofficial) 2010 release of Adipack (`adipack.c`, [3]), which seems to be commonly in use now (e.g. by MESA and ASTEC). The eigenmodes were computed using a p-mode grid containing 4800 grid points (`p3` grid). The set includes p-modes with n up to 36 ($l = 0$ and 1) and l up to 1669 ($n = 1$), aswell as f-modes with $l = 2$ to 2716. In total the set consists of 10993 modes.

For the computation a gravitational constant of $G = 6.67232 \cdot 10^{-8}\,\mathrm{cm^3 g^{-1} s^{-2}}$ was used. This value differs significantly from the currently recommended CODATA or IAU values, but it seems to match well with Model S, as the gravitational parameter GM, calculated from this value of G and the solar mass M from the model, comes very close to the observational value of GM. I, therefore, recommend to use this value for further calculations based on Model S.

The results are available as HDF5 files[2]: `mods_p3.h5` and `mods_p3_eigfcn.h5` (see section 2), where both files contain the same model and mode parameters except for the eigenfunctions, which are only included in the latter file.

[1] `http://astro.phys.au.dk/~jcd/solar_models/`
[2] Available at KIS under `/docs/seismo/mods/`

2 Model files

2.1 The Hierarchical Data Format

The *Hierarchical Data Format*[3] (HDF, HDF4, HDF5) is a set of standardized file formats, designed to store and manage large amounts of numerical data. Libraries to read and write HDF5 files are available for almost any commonly used programming language. HDF5 files have a tree-like structure, similar to that of a file system. The nodes (which are comparable to the directories of a file system) are called *Groups*, the leaves are called *Datasets* and can contain all kind of data (similar to files). In addition to this, all elements (nodes and datasets) can also have attributes assigned to them, which can be used to store metadata.

There are many command-line tools for HDF5 files available (e.g. `h5ls`, `h5dump`, `h5copy`, ...), which are useful to get information about the content of a HDF5 file, extract data and copy or move datasets inside the tree structure of a file and even between different HDF5 files. As a simple example, the command

```
h5ls -r mods_p3.h5
```

recursively lists all groups and datasets of the file `mods_p3.h5`. In addition to the command-line tools, a graphical Java application, HDFView, is available, which can be started on KIS machines using the command `hdfview`.

2.2 File structure

The model files `mods_p3.h5` and `mods_p3_eigfcn.h5` have the following root groups:

```
/                        Group
/agsm                    Group
/amdl                    Group
/fgong                   Group
/model                   Group
/modes                   Group
```

The `agsm` group contains the so-called *grand summary* output of the final `adipls.c.d` run, the `amdl` group contains the pulsation model, which was interpolated to a p-mode grid using the `redistrb.d` program from Adipack. For a description of all quantities in the `agsm` and `amdl` groups, see `adiab.prg.c.pdf` in [3]. The `fgong` group contains an extensive set of variables from Model S, converted from the provided GONG model file, which is documented in [1].

[3] `http://www.hdfgroup.org/`

The remainig `model` and `modes` groups contain the pulsation model (from `amdl`) and some derived quantities (e.g. pressure, density and sound speed), aswell as the most commonly used mode parameters and the eigenfunctions (`mods_p3_eigfcn.h5` only). The model grid here is slightly modified to match the eigenfunction grid, which has one grid point fewer than the original pulsation model. See tables 1 and 2 for a description of the contained quantities. All values in the `model` and `modes` groups are given in cgs units, if not specified differently.

Name	**Symbol/Definition**	**Description**
`R`	$R = 6.959894677 \cdot 10^{10}\,\mathrm{cm}$	photospheric radius
`M`	$M = 1.989 \cdot 10^{33}\,\mathrm{g}$	solar mass
`G`	$G = 6.67232 \cdot 10^{-8}\,\mathrm{cm^3 g^{-1} s^{-2}}$	gravitational constant
`r`	r	distance to the center
`m`	m	interior mass
`p`	p	pressure
`rho`	ρ	density
`T`	T	temperature
`c`	c	sound speed
`dp_dr`	$\mathrm{d}p/\mathrm{d}r$	pressure gradient
`g`	g	gravitational acceleration
`x`	$x \equiv r/R$	distance to the center in solar radii
`q_x3`	$A_1 \equiv q/x^3 \quad \text{with } q = m/M$	A_1 in [2], c_1^{-1} in [5]
`Vg`	$A_2 = V_g \equiv -\frac{1}{\Gamma_1}\frac{\mathrm{d}\ln p}{\mathrm{d}\ln r} = \frac{Gm\rho}{\Gamma_1 p r}$	A_2 in [2], V_g in [5]
`Gamma1`	$A_3 = \Gamma_1 \equiv \left(\frac{\partial \ln p}{\partial \ln \rho}\right)_{\mathrm{ad}}$	A_3 in [2], Γ_1 in [5]
`A`	$A_4 = A \equiv \frac{1}{\Gamma_1}\frac{\mathrm{d}\ln p}{\mathrm{d}\ln r} - \frac{\mathrm{d}\ln \rho}{\mathrm{d}\ln r}$	A_4 in [2], A^* in [5]
`U`	$A_5 = U \equiv \frac{\mathrm{d}\ln m}{\mathrm{d}\ln r} = \frac{4\pi\rho r^3}{m}$	A_5 in [2], U in [5]

Table 1: Datasets contained in the `model` group. The first part of the table contains global constants, stored as scalars. The second and third part contains commonly used physical quantities and the dimensionless numerical variables used in [2, 5], respectively, stored as one-dimensional arrays with 4800 grid points.

Name	Symbol/Definition	Description
`n`	n	radial order
`l`	l	harmonic degree
`nu`	$\nu \equiv \dfrac{\omega}{2\pi}$	frequency
`sigma2`	$\sigma^2 \equiv \dfrac{R^3}{GM}\omega^2$	squared dimensionless frequency
`E`	$E \equiv \dfrac{\int_{r_1}^{R_\mathrm{s}} \left[\xi_\mathrm{r}^2 + l(l+1)\xi_\mathrm{h}^2\right] \rho r^2 \mathrm{d}r}{M\left[\lvert\xi_\mathrm{r}(R)\rvert^2 + l(l+1)\lvert\xi_\mathrm{h}(R)\rvert^2\right]}$	dimensionless kinetic energy[4]
`y1`	$y_1 \equiv \xi_\mathrm{r}/R$	radial eigenfunctions[5]
`y2`	$y_2 \equiv \dfrac{l(l+1)}{R}\xi_\mathrm{h}$	horizontal eigenfunctions[5]

Table 2: Datasets contained in the `modes` group. All quantities in this group are stored as one-dimensional arrays, except for the eigenfunctions `y1` and `y2`, which depend on the radius and are therefore stored as two-dimensional arrays.

References

[1] J. Christensen-Dalsgaard. File format for GONG solar model project, Nov. 2005. URL `http://astro.phys.au.dk/~jcd/solar_models/file-format.pdf`.

[2] J. Christensen-Dalsgaard. ADIPLS – the Aarhus adiabatic oscillation package. Ap&SS, 316:113–120, Aug. 2008. doi:10.1007/s10509-007-9689-z.

[3] J. Christensen-Dalsgaard. Aarhus adiabatic pulsation package, May 2010. URL `http://astro.phys.au.dk/~jcd/adipack.c/`.

[4] J. Christensen-Dalsgaard, W. Dappen, S. V. Ajukov, E. R. Anderson, H. M. Antia, S. Basu, V. A. Baturin, G. Berthomieu, B. Chaboyer, S. M. Chitre, A. N. Cox, P. Demarque, J. Donatowicz, W. A. Dziembowski, M. Gabriel, D. O. Gough, D. B. Guenther, J. A. Guzik, J. W. Harvey, F. Hill, G. Houdek, C. A. Iglesias, A. G. Kosovichev, J. W. Leibacher, P. Morel, C. R. Proffitt, J. Provost, J. Reiter, E. J. Rhodes, Jr., F. J. Rogers, I. W. Roxburgh, M. J. Thompson, and R. K. Ulrich. The Current State of Solar Modeling. *Science*, 272:1286–1292, May 1996. doi:10.1126/science.272.5266.1286.

[5] W. Unno, Y. Osaki, H. Ando, H. Saio, and H. Shibahashi. *Nonradial oscillations of stars*, chapter 18. University of Tokyo Press, 2nd edition, 1989.

[4] normalized with total photospheric displacement (`iekinr = 1`)
[5] only available in `mods_p3_eigfcn.h5`

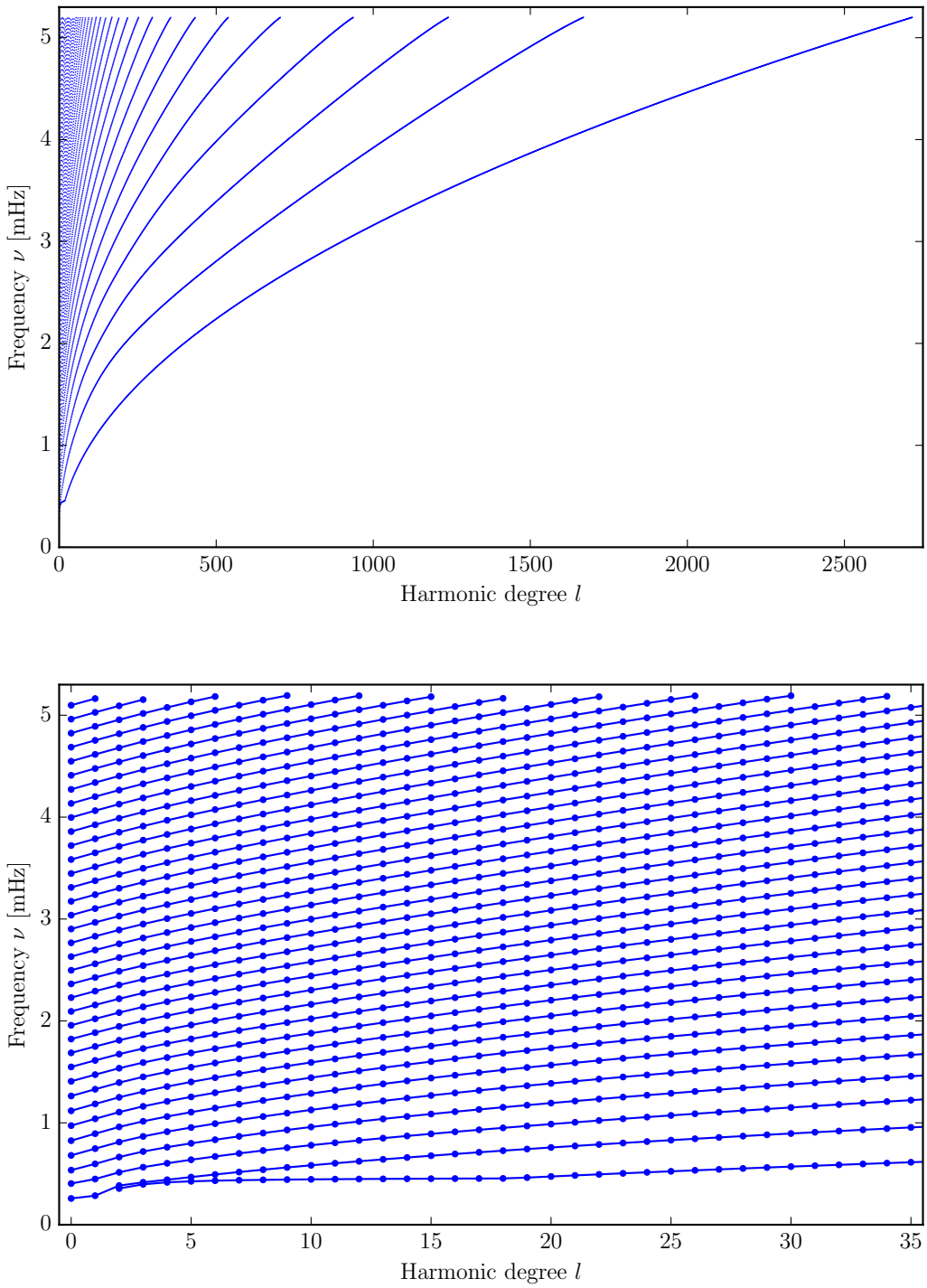

Figure 1: Frequencies of the full set of f- and p-modes (top panel), mode frequencies for modes with $l \leq 35$ (bottom panel).

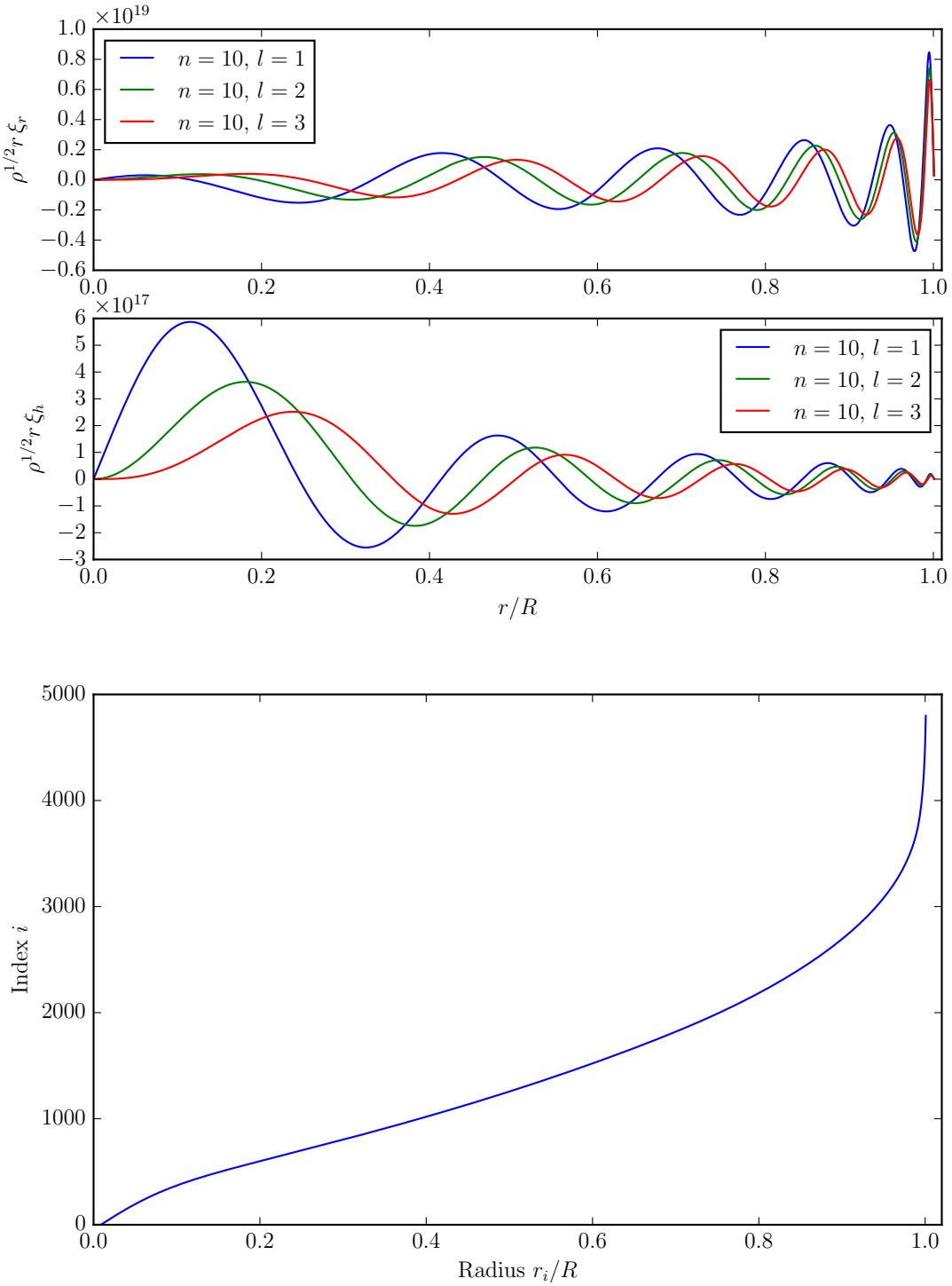

Figure 2: A selection of radial and horizontal eigenfunctions (top panels), p-mode grid (4800 grid points) used for the computation of the modes (bottom panel).