D3.13 First version of the database of models and basic stellar properties for Kepler

Scientific purpose and requirements of the database contribution

The primary purpose of the KASOC (for Kepler Asteroseismic Science Operations Centre) database was to distribute observational data from the *Kepler* mission, at various levels of processing. In addition, it serves for the collaboration on and distribution of scientific publications based on these data (see D3.12), and access to other types of observational data on the stars observed by *Kepler* has been included (see D3.11). However, as the detailed analysis of the *Kepler* data develops, an additional very useful tool, within the *Kepler* community and beyond, is access to the results of the analysis, in terms of inferred stellar properties and the resulting stellar models.

It should be kept in mind that these results depend on the analysis procedures and the stellar modelling tools used, not least the specific stellar evolution code and the assumed physics of the calculations. Thus it cannot be a goal to provide a unique 'best model' of a given star. Rather, the database will need to support a variety of model results, which should be fully characterized, for a given set of observed data. These models will give a good indication of the properties of the star and a starting point for further even more penetrating analysis, and comparisons of the different results for the same star provide a measure of the sensitivity of the results to the systematics of the modelling.

The database has been extended to include model data and other results of the analysis of the Kepler data. In addition, procedures will be set up to allow user upload of the relevant model results, in standardized formats. As an example results are provided for the *Kepler* target (Kepler 10) which yielded the first definite *Kepler* detection of a rocky planet, around a star that must have been formed very early in the life of the Galaxy.

Properties of the model database contribution

For a given stellar model fit, the database contains results both for the best-fitting stellar model and suitably statistically characterized parameters of the stars based on the model fitting. The database is set up based on the following input files:

1. A description of the evolution track containing the best-fitting model
2. The detailed properties of the best-fitting model.
3. Frequencies for the best-fitting model
4. (Possibly modified) frequencies fitted to the observations
5. Average stellar parameters and their standard deviations resulting from the fit.

On 1. This should provide basic properties of the full evolution track extending at least to the best-fitting model and possibly beyond, to provide a graphical presentation of the evolution stage of the star.

On 2. This should provide a detailed description of the overall properties of the best-fitting model, including the variation of relevant quantities with position in the model. This is based on the so-called `fgong`–format which has become a de-facto standard in model distribution and comparison.

On 3. This should provide adiabatic oscillation frequencies for the best-fitting model, in a standardized format (degree, radial order, frequency in µHz, mode inertia).

On 4. In the fitting to the observations, some techniques include modifications to the frequencies to correct for known inadequacies in the modelling. This set of frequencies should be those on which the measure of the quality of the fit is based.

On 5. This should provide inferred stellar global parameters, based on the fit, with standard deviations. This set still needs to be fully standardized, but can easily be expanded and modified. Obvious quantities are stellar mass, radius, mean density, age, surface gravity and composition.

In addition to these results, the upload must include a full description of the modelling and fitting procedures, or at least references (in the form of bibcodes) where such complete descriptions can be found.

The above defines the properties included at present, and reflecting the present stage of the efforts towards model fitting. Future updates could include nonadiabatic oscillation results, including line widths for comparison with observations. Also, the statistical treatment of the model fitting is under development, and hence simple standard deviations may become replaced by fully characterized probability distribution functions for the parameters.

On user input of these results the database automatically generates quick-look tables and a plot of the evolution track in a Hertzsprung-Russell diagram (see also below) and sets up links to produce output files in standardized form.

For the models themselves, the files available for download by the users are the same as were initially uploaded for the result, which means the `fgong`-file containing the stellar structure and a file containing the stellar evolutionary track. For the latter the `bcsum`-file format produced by ASTEC is currently used, but can in principle be extended to other formats as well. This file is a simple ASCII-file listing important global properties of the stellar evolution.

Frequency tables are currently available for download in the following formats:

- *ASCII* – Plain text format where each line corresponds to a mode of oscillation and each column corresponds to a particular parameter. A header is provided that fully explains the contents of the different columns.
- *XML* – "Extensible Markup Language" format which is fully machine- and human-readable and fully describes the oscillation parameters including units and errors. The long-term goal is that

this format can be extended and used as the standard-format used when exchanging results in between researchers in the working groups.

- *AMP* – Input format used by the Asteroseismic Modelling Portal (AMP; Metcalfe et al. 2009, Woitaszek et al. 2009) for easy collaboration between these systems. This format is only available for peakbagging results.
- *OBS* – ASCII based format which contains relevant columns for comparing the output of different stellar models and pulsation codes, like oscillation frequencies and mode inertias. This format is only available for model frequencies.

Short description how to access and use the data base

The KASOC Analysis Results Repository is available on the KASOC website (http://kasoc.phys.au.dk) by clicking the "Results" tab at the top of the page (see Figure 1). The system is integrated into the existing KASOC database and website, which is running on dedicated servers at Aarhus University.
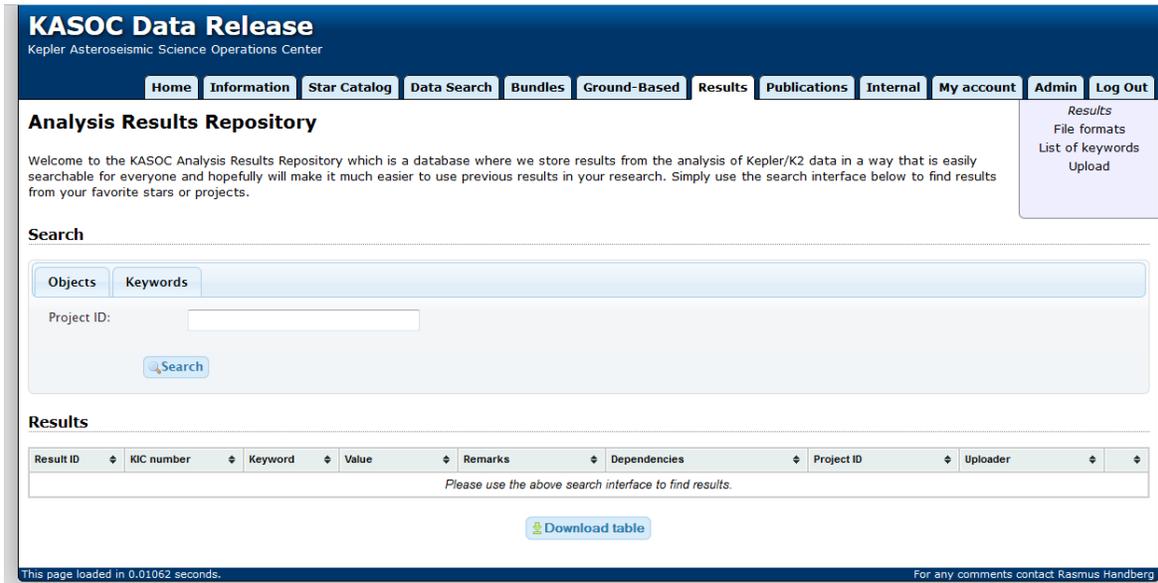

Figure 1: The KASOC Analysis Results Repository front page.

The user can use the search-interface to search for results associated to a particular set of stars, to a specific project and which keywords/properties of the stars he is interested in. A full list of available keywords and a description of them can be found on the page "List of keywords" shown in the top menu. After the user clicks the "Search" button, any available results will be rendered in a table like the one shown in Figure 2.

Result ID	KIC number	Keyword	Value	Remarks	Dependencies	Project ID	Uploader	
416	11904151	model	SHOW MODEL	Stellar Structure of Kepler-10	Results: • 459 • 460	KASOC/model_test	Jørgen Christensen-Dalsgaard	
417	11904151	modelfreq	OPEN TABLE	Adiabatic oscillation frequencies from best-fitting model of Kepler-10	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	
418	11904151	$\langle \rho \rangle$	1.0682 ± 0.0012	No diffusion.	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	
419	11904151	$R/R_\odot$	1.0571 ± 0.0065	No diffusion.	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	
420	11904151	$M/M_\odot$	0.896 ± 0.017	No diffusion.	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	
421	11904151	$L/L_\odot$	1.059 ± 0.035	No diffusion.	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	
422	11904151	$\tau_\star$	12.2 ± 1.0	No diffusion.	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	
423	11904151	X_0	0.7194 ± 0.0038	No diffusion.	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	
425	11904151	Y_0	0.2667 ± 0.0032	No diffusion.	Results: • 416	KASOC/model_test	Jørgen Christensen-Dalsgaard	

Figure 2: Example of results from searching for Kepler-10 (KIC 11904151). Not all available results are shown.

The system renders the list of available results in a nice human-readable format on screen which contains all the relevant information about each result, including any dependencies of other results in the database or original Kepler data. In the example shown in Figure 2, it can for example be seen that the stellar properties and oscillation frequencies depends on the stellar model with Result ID = 416. In this way, all results can be placed into a stringent hierarchy where results can be traced all the way back to the original measurements by the spacecraft.

If the user clicks the "Download Table" button at the bottom of the page (see Figure 1), he will be presented with an ASCII file containing the content of the table in a way that is easily read by a computer program. This can for instance be used to compare results on many stars or between different analysis teams in a coherent and easy way.

There are a few special keywords available in the results tables that do not have a "simple" numerical value like most of the other results. These are:

1. Stellar models.
2. Stellar model frequencies.
3. Peakbagging results (measured individual frequencies).
4. Auxiliary files.

For all these results, instead of a numerical value, the user is presented with a link that can be clicked to show the full details of the given result. When clicked, the link will open a dialog box that will look different depending on the type of result clicked.

On 1. For stellar models, the dialog will contain details of the given stellar model as shown in Figure 3. All information is automatically extracted from the uploaded `fgong` and `bcsum` files and presented as a description of the model, a table of extracted properties and plot of Hertzsprung-Russell diagram of the stellar evolution. Below these, the original files are available for download. Next, any results that are derived from the particular model will be listed, in much the same way as they are on the main results

4

page. At the end, any auxiliary files associated with this model are listed. These could typically contain further documentation on the procedures used to generate the model and additional data used to obtain the best-fit model.
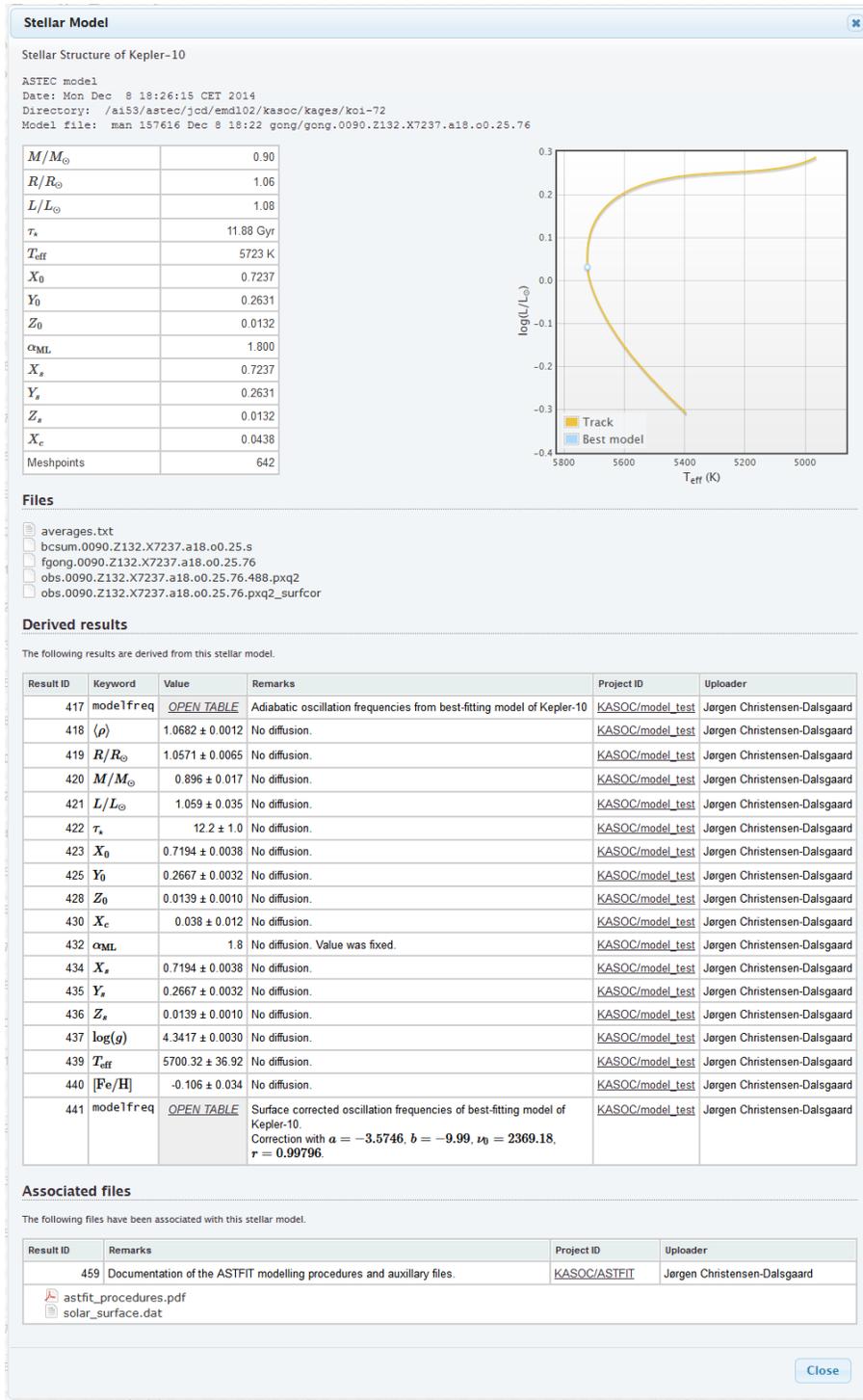
Stellar Model

Stellar Structure of Kepler-10

```
ASTEC model
Date: Mon Dec  8 18:26:15 CET 2014
Directory:  /ai53/astec/jcd/emd102/kasoc/kages/koi-72
Model file:  man 157616 Dec 8 18:22 gong/gong.0090.Z132.X7237.a18.o0.25.76
```

$M/M_\odot$	0.90
$R/R_\odot$	1.06
$L/L_\odot$	1.08
τ_*	11.88 Gyr
T_{eff}	5723 K
X_0	0.7237
Y_0	0.2631
Z_0	0.0132
α_{ML}	1.800
X_s	0.7237
Y_s	0.2631
Z_s	0.0132
X_c	0.0438
Meshpoints	642

Files

- averages.txt
- bcsum.0090.Z132.X7237.a18.o0.25.s
- fgong.0090.Z132.X7237.a18.o0.25.76
- obs.0090.Z132.X7237.a18.o0.25.76.488.pxq2
- obs.0090.Z132.X7237.a18.o0.25.76.pxq2_surfcor

Derived results

The following results are derived from this stellar model.

Result ID	Keyword	Value	Remarks	Project ID	Uploader
417	modelfreq	*OPEN TABLE*	Adiabatic oscillation frequencies from best-fitting model of Kepler-10	KASOC/model_test	Jørgen Christensen-Dalsgaard
418	$\langle \rho \rangle$	1.0682 ± 0.0012	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
419	$R/R_\odot$	1.0571 ± 0.0065	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
420	$M/M_\odot$	0.896 ± 0.017	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
421	$L/L_\odot$	1.059 ± 0.035	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
422	τ_*	12.2 ± 1.0	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
423	X_0	0.7194 ± 0.0038	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
425	Y_0	0.2667 ± 0.0032	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
428	Z_0	0.0139 ± 0.0010	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
430	X_c	0.038 ± 0.012	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
432	α_{ML}	1.8	No diffusion. Value was fixed.	KASOC/model_test	Jørgen Christensen-Dalsgaard
434	X_s	0.7194 ± 0.0038	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
435	Y_s	0.2667 ± 0.0032	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
436	Z_s	0.0139 ± 0.0010	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
437	$\log(g)$	4.3417 ± 0.0030	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
439	T_{eff}	5700.32 ± 36.92	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
440	$[\text{Fe}/\text{H}]$	-0.106 ± 0.034	No diffusion.	KASOC/model_test	Jørgen Christensen-Dalsgaard
441	modelfreq	*OPEN TABLE*	Surface corrected oscillation frequencies of best-fitting model of Kepler-10. Correction with $a = -3.5746$, $b = -9.99$, $\nu_0 = 2369.18$, $r = 0.99796$.	KASOC/model_test	Jørgen Christensen-Dalsgaard

Associated files

The following files have been associated with this stellar model.

Result ID	Remarks	Project ID	Uploader
459	Documentation of the ASTFIT modelling procedures and auxillary files.	KASOC/ASTFIT	Jørgen Christensen-Dalsgaard

- astfit_procedures.pdf
- solar_surface.dat

Close

Figure 3: Example of Stellar Model dialog for Kepler-10.

On 2 and 3. For stellar model frequencies and peakbagging results, clicking on the "Open Table" link provided as the listed value for these results will open a dialog (see Figure 4) with a table listing all the available quantities per oscillation mode and plotting an Echelle-diagram used to visualize the oscillation pattern. The table can in principle contain all available properties of the modes (including linewidths, heights, amplitudes, rotational splittings and so on), but will for stellar models in most cases only contain radial order (n), degree (l), frequency and mode inertia.
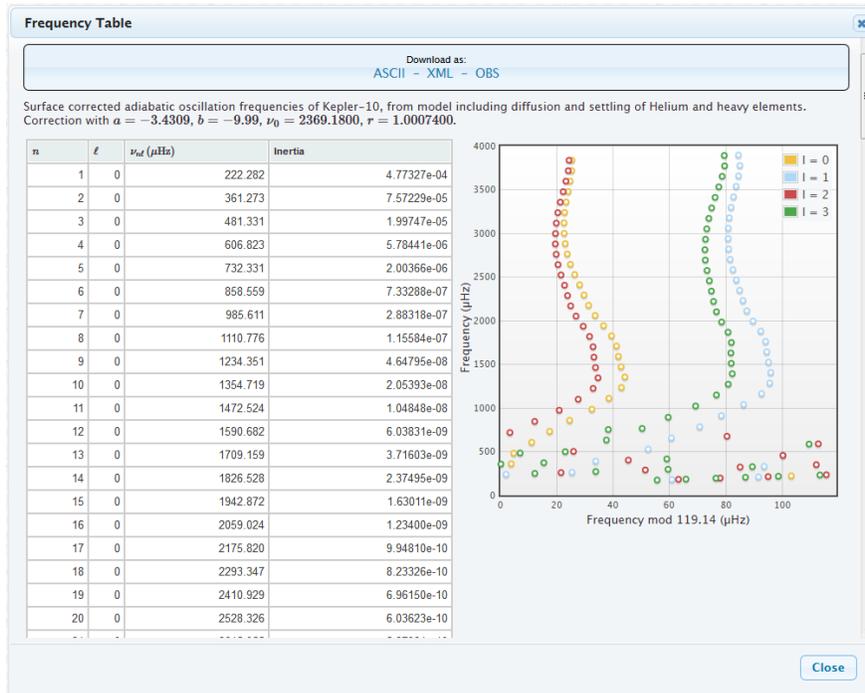
Figure 4: Example of frequency table for Kepler-10 stellar model.

At the top of the dialog links are provided to download the tables in ASCII, XML or AMP-format (see previous section). Clicking these links will result in the user being prompted with a download-box to download the table to their own computer.

On 4. For auxiliary files, clicking the link will simply open a dialog box listing the uploaded files. Clicking the files will prompt the user with a download box to download or open the files on their own computer. The purpose of these records is to keep any files or results that cannot directly be listed as a numerical result or a table. This can for example include documentation about a particular result or plots or data relating to other results.

6

Figure 5: Example of the KASOC Star Catalog of Kepler-10, showing peakbagging and stellar model results listed together with all other known information about the star.

In addition to being listed on the Analysis Results Repository, peakbagging and model results are also listed on the KASOC Star Catalog (see Figure 5) when searching for information on a specific star. This allows the users easily to look up all available information about individual stars.

Short description how to upload new results to the database

In the menu at the top of the Analysis Results Repository pages (see Figure 1) there is a link named "Upload" which when clicked will take the user to a new page. Here the user can choose which type of result he wishes to upload (stellar model, frequency table, auxiliary files or another observable). The user should then specify the target to which this result is related (KIC/EPIC number), a project this result is related to, a description of the result and any other relevant information and possibly a reference to a publication. Relevant files are then uploaded and the result is immediately available for download by all users in the database.

These features are still under final development, but will be available shortly.

Models and stellar properties currently included

As a pilot project illustrating the procedures for model inclusion we have considered the star Kepler 10 which hosts a two-planet system, including a planet definitely demonstrated to be rocky, with a mass of around 1.5 Earth masses. This has been subject to extensive modelling, demonstrating that the star has an age of around 10.6 Gyr, which makes it amongst the oldest stars in the Galaxy. The full set of *Kepler* data for this star has been analysed by Davies et al. (in preparation), resulting in the frequencies that have been used for the analysis. The full list of measured oscillation frequencies is also available in the system.

The fit to the observations was carried out using the Aarhus stellar evolution and pulsation codes (ASTEC and ADIPLS) in the ASTFIT fitting procedure. This is based on optimizing the fit of model frequencies to the observations along evolution tracks in an extensive model grid, including also the observed effective temperature and metallicity. On this basis the overall best-fitting model is identified, and averages and standard deviations are determined with weights given by the likelihood of the identified best-fitting models for each track. The model frequencies are corrected for the inadequacy of the modelling of the near-surface layers by applying a correction scaled from the near-surface frequency error determined in the solar case. Notes providing a more detailed description of the modelling and the fitting procedures are provided as part of the database.

Two sets of models are considered: one neglecting diffusion and settling and one where diffusion and settling of helium and heavy elements are included.

This analysis is part of the so-called *Kages project* to provide detailed analysis of all *Kepler* exoplanet hosts for which extensive asteroseismic data are available. Full details for all the more than 30 stars considered in the project will be uploaded to the database, as part of the publication of the results (Silva Aguirre et al., in preparation).

Human efforts and costs

Many researchers have contributed to the work. Human resources allocated directly to the present work correspond to 0.35 FTE.

The related costs to travels and meetings are 11 kEUR.