Kepler-93: a benchmark target for accurate asteroseismic characterization in preparation for the PLATO era

J. Bétrisey[†], C. Pezzotti, G. Buldgen, S. Khan, P. Eggenberger, S. J. A. J. Salmon, and A. Miglio

[†] Observatoire de Genève, Université de Genève, Chemin Pegasi 51, 1290 Versoix, Suisse.
E-mail: Jerome.Betrisey@unige.ch

Abstract

The advent of space-based photometry missions, such as CoRoT, Kepler and TESS, has favoured a rapid development of asteroseismology and its synergies with exoplanetology. Such multi-disciplinary studies will further develop in the future with the PLATO mission.

A detailed characterization of the host star can significantly improve our understanding of exoplanetary systems. In this context, we focused on Kepler-93, whose high-quality data and stellar properties make it a PLATO benchmark target. We carried out a detailed stellar modelling using global and local minimization techniques, also considering various changes of the physical ingredients. Our analysis was completed by inversion techniques to provide a more robust mean density estimate and test the impact of surface effects.

The revised stellar parameters allowed us to update the planetary parameters of Kepler-93b and simulate its orbital evolution under the effects of tides and atmospheric evaporation. We found that a detailed asteroseismic modelling will be able to meet the PLATO standards for such a solar-like star (Bétrisey et al. 2022).

Context: Kepler-93 as PLATO benchmark

The Kepler-93 system is composed of a host star, Kepler-93, and an exoplanet, Kepler-93b.

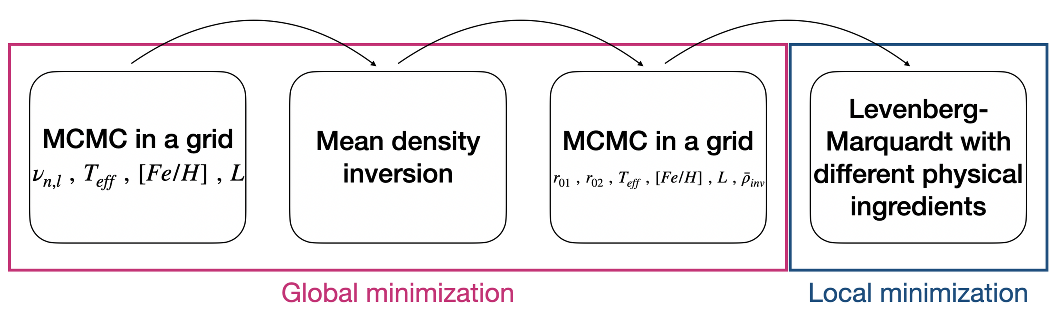
PLATO requirements
Benchmark target: G spectral type, $\sim 6000K$, $\sim 1M_\odot$, and $\sim 1R_\odot$
Precision requirements: 15% in mass, 1-2% in radius, and 10% in age

Kepler-93
Solar-type star with p-modes precisions similar to expectations for PLATO (Huber et al. 2013, Marcy et al. 2014, Ballard et al. 2014, Silva-Aguirre et al. 2015, Bellinger et al. 2016, 2019)
⇒ benchmark target to test how far we can go with PLATO

Kepler-93b
Rocky world laying in the lower part of the radius valley, that probably lost its atmosphere during its evolution (Borucki et al. 2011, Marcy et al. 2014, Dressing et al. 2015)
⇒ good candidate to study the impact of stellar tides and evaporation of the planetary atmosphere

Stellar modelling strategy

Modelling strategy: We use a two-step procedure. First, we conduct a global minimization to restrict the parameter space. Here, we fit the asteroseismic and spectroscopic data, and perform a mean density inversion to use it as additional the constraint for a second MCMC. Then, we conduct a local minimization with a Levenberg-Marquardt algorithm to test the impact of the physical ingredients.



Observation: The addition of the inverted mean density in the constraints of the MCMC, thanks to the mean density inversion, greatly improves the precision on the stellar mass and radius (Figs. 1 and 2).

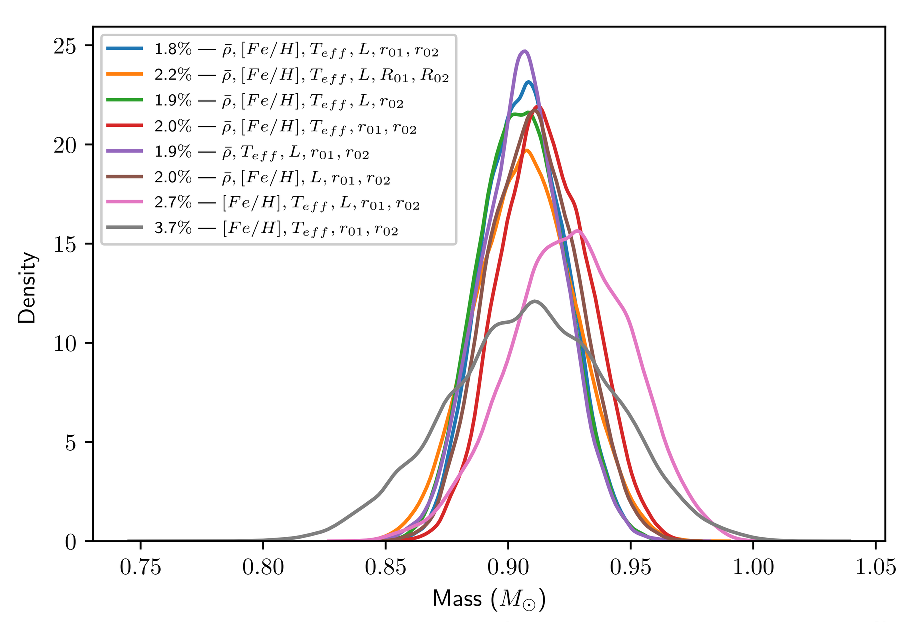


Fig. 1: Kernel density estimate of the stellar mass using different sets of constraints in the MCMC.

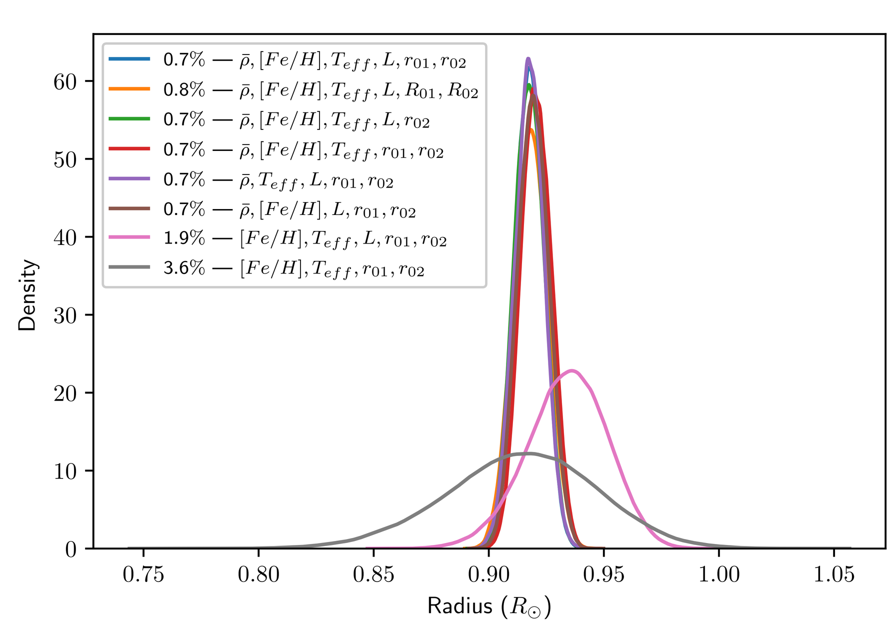


Fig. 2: Kernel density estimate of the stellar radius using different sets of constraints in the MCMC.

Revised stellar parameters

Result 1: We obtain the following revised stellar parameters:

$$M/M_\odot = 0.907 \pm 0.023 \quad (2.5\%)$$
$$R/R_\odot = 0.918 \pm 0.008 \quad (0.9\%)$$
$$\text{Age [Gyr]} = 6.78 \pm 0.32 \quad (4.7\%)$$
$$\bar{\rho}\ [\text{g/cm}^3] = 1.654 \pm 0.004 \quad (0.2\%)$$

Observation 1: The revised parameters include the systematics for the choice of the physical ingredients.

Observation 2: We show in Fig. 3 the mean density inversions of the models from the local minimization, including the impact of the surface effects.

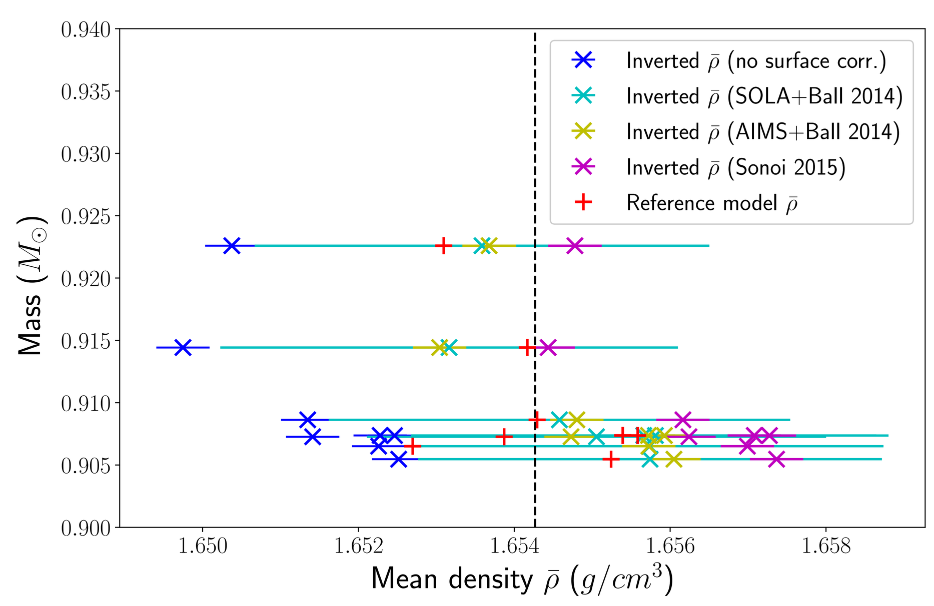


Fig. 3: Mean density inversions considering different prescriptions for the surface effects.

Result 2: We tested the survival of a convective core coming from out-of-equilibrium ^{3}He burning at the beginning of the evolution (Roxburgh 1985). The models with high overshooting efficiencies ($\alpha > 0.10$) were in worse agreement with the seismic data. Hence, it is unlikely that a convective core survived for 3 Gyr or more.

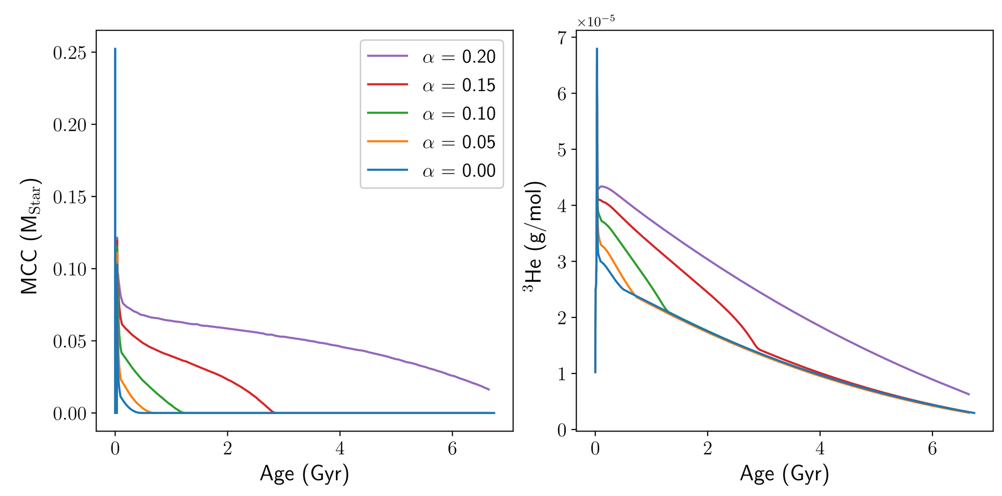
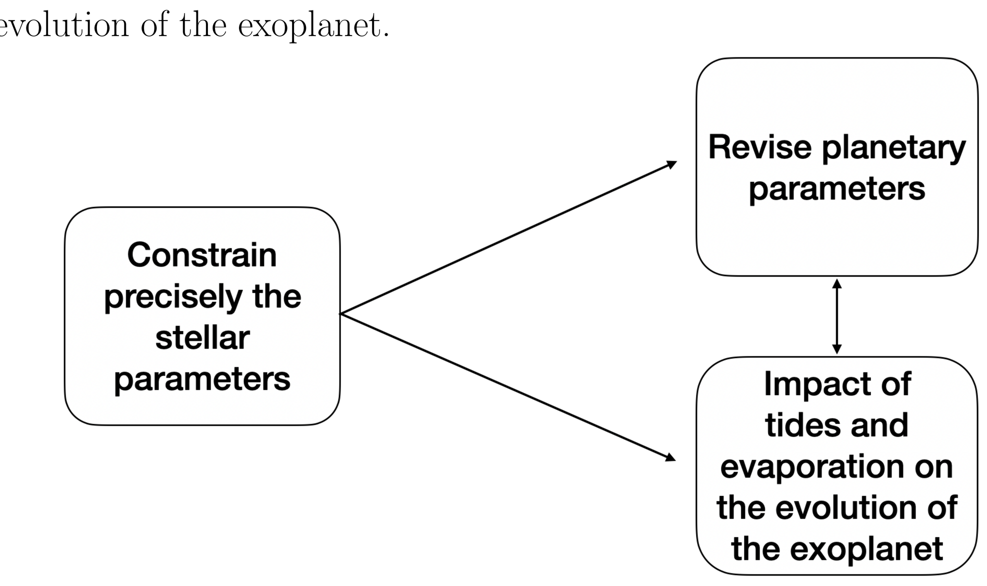


Fig. 4: Evolution of the mass of the convective core (MCC, left) and of the central ^{3}He abundance (right) for different overshooting efficiencies.

Revised planetary parameters

Modelling synergies: With the precisely determined stellar parameters, we can revise the planetary parameters and constrain the past evolution of the exoplanet.



Result 1: We obtain the following revised planetary parameters:

$$M_p/M_\oplus = 4.01 \pm 0.67 \quad (16.7\%)$$
$$R_p/R_\oplus = 1.478 \pm 0.014 \quad (0.9\%)$$
$$a_p\ [\text{AU}] = 0.0533 \pm 0.0005 \quad (0.9\%)$$
$$\bar{\rho}_p\ [\text{g/cm}^3] = 6.84 \pm 1.16 \quad (17.0\%)$$

Observation: Great precision improvement for the planetary radius and orbital distance. The mass and mean density were limited by the radial velocity follow-up, not asteroseismology.

Result 2: We found that it is unlikely that Kepler-93b formed with a mass high enough ($M_{\text{p,initial}} > 100M_\oplus$) to be impacted on its orbit by stellar tides (Fig. 5).

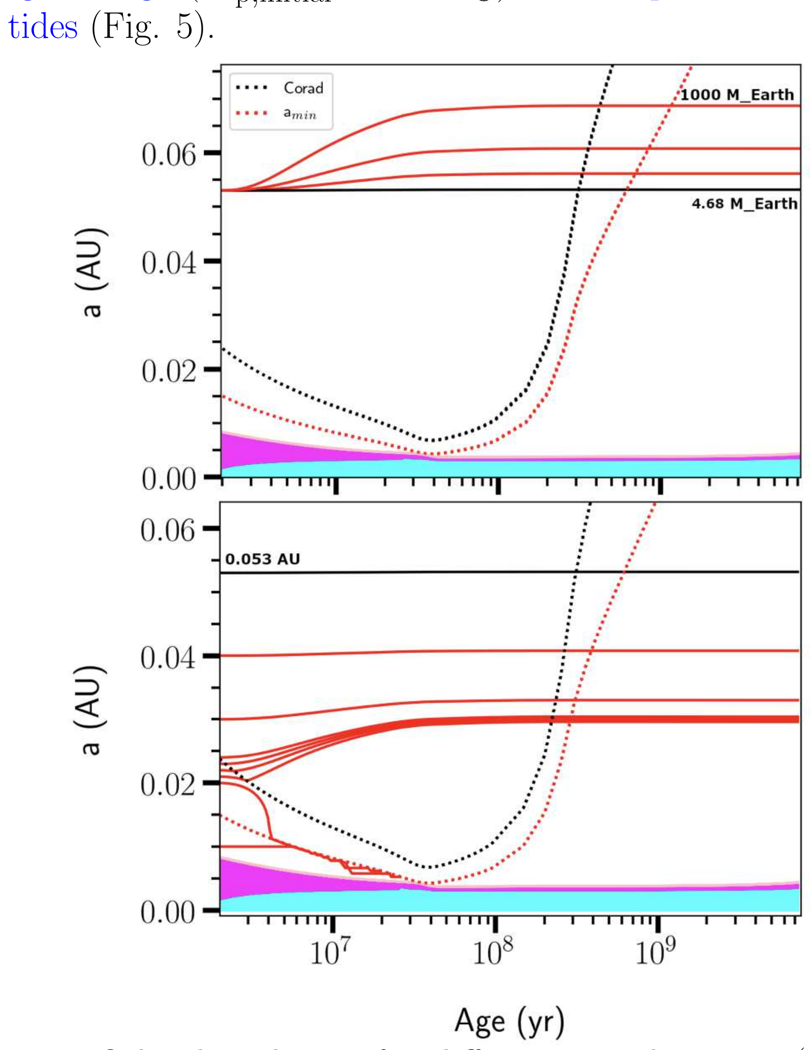


Fig. 5: Orbital evolution for different initial masses (top) and orbital distances (bottom).

Conclusions

We meet the PLATO requirements

- Data quality of Kepler-93 similar to expectations of PLATO
  → we can reach the PLATO precision requirements (15% in mass, 1-2% in radius and 10% in age)
- Mean density inversions can help to get more precise stellar masses and radii

Going further with PLATO

- Mean density inversions are applicable for the majority of the PLATO sample
- Asteroseismology helps to better understand the evolution of exoplanets
  → limiting factor is the radial velocities follow-up for Kepler-93, not asteroseismology

References

- Ballard, S. et al. 2014, ApJ, 790, 12
- Bellinger, E. P. et al. 2016, ApJ, 830, 31
- Bellinger, E. P. et al. 2019, A&A, 622, A130
- Bétrisey, J. et al. 2022, A&A, 659, A56
- Borucki, W. J. et al. 2011, ApJ, 736, 19
- Dressing, C. D. et al. 2015, ApJ, 800, 135
- Huber, D. et al. 2013, ApJ, 767, 127
- Marcy, G. W. et al. 2014, ApJS, 210, 20
- Silva Aguirre, V. et al. 2015, MNRAS, 452, 2127
- Roxburgh, I. W. 1985, Sol. Phys., 100, 21