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Unveiling the atmospheric evolution of exoplanets: the PASTA tool

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The reference paper

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Constraining stellar rotation and planetary atmospheric evolution of a dozen systems hosting sub-Neptunes and super-Earths

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ABSTRACT

Context. Planetary atmospheric evolution modelling is a prime tool for understanding the observed exoplanet population and constraining formation and migration mechanisms, but it can also be used to study the evolution of the activity level of planet hosts.
Aims. We constrain the planetary atmospheric mass fraction at the time of the dispersal of the protoplanetary disk and the evolution of the stellar rotation rate for a dozen multi-planet systems that host sub-Neptunes and/or super-Earths.
Methods. We employ a custom-developed PYTHON code that we have dubbed PASTA (*P*lanetary *A*tmospheres and *S*tellar Ro*T*ation R*A*tes), which runs within a Bayesian framework to model the atmospheric evolution of exoplanets. The code combines MESA stellar evolutionary tracks, a model describing planetary structures, a model relating stellar rotation and activity level, and a model predicting planetary atmospheric mass-loss rates based on the results of hydrodynamic simulations.
Results. Through a Markov chain Monte Carlo scheme, we retrieved the posterior probability density functions of all considered parameters. For ages older than about 2 Gyr, we find a median spin-down (i.e. $P(t) \propto t^{y}$) of $\bar{y} = 0.38^{+0.38}_{-0.27}$, indicating a rotation decay slightly slower than classical literature values ($\approx$0.5), though still within 1σ. At younger ages, we find a median spin-down (i.e. $P(t) \propto t^{x}$) of $\bar{x} = 0.26^{+0.42}_{-0.19}$, which is below what is observed in young open clusters, though within 1σ. Furthermore, we find that the x probability distribution we derived is skewed towards lower spin-down rates. However, these two results are likely due to a selection bias as the systems suitable to be analysed by PASTA contain at least one planet with a hydrogen-dominated atmosphere, implying that the host star has more likely evolved as a slow rotator. We further look for correlations between the initial atmospheric mass fraction of the considered planets and system parameters (i.e. semi-major axis, stellar mass, and planetary mass) that would constrain planetary atmospheric accretion models, but without finding any.
Conclusions. PASTA has the potential to provide constraints to planetary atmospheric accretion models, particularly when considering warm sub-Neptunes that are less susceptible to mass loss compared to hotter and/or lower-mass planets. The TESS, CHEOPS, and PLATO missions are going to be instrumental in identifying and precisely measuring systems amenable to PASTA's analysis and can thus potentially constrain planet formation and stellar evolution.

- Bonfanti et al. 2021b
- Available at: https://ui.adsabs.harvard.edu/abs/2021A%26A...656A.157B/abstract

Main goals

Unveil the atmospheric evolution of exoplanets by modelling the evolutionary history of:

- The rotation rate of the stellar host → to measure stellar activity and model the induced photo-evaporation of the planetary envelope
- The exoplanetary atmospheres → to retrieve the atmospheric content at the time of proto-planetary disk dispersal

Atmospheric evolution. Why?

- Shed light on the observed exoplanet population
- Constrain formation and migration mechanisms of exoplanets
- Possibly justify the sub-Jovian desert and sub-Neptune radius gap
- Track the activity level (P_{rot}, XUV flux, …) of the stellar hosts

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Atmospheric evolution. How?

PASTA (*P*lanetary *A*tmospheres and *S*tellar Ro*T*ation R*A*tes) algorithm, based upon:

- MESA stellar evolutionary tracks;
- A model of planetary structure: planetary observables $\leftrightarrow$ atmospheric mass;
- A model of the stellar XUV flux evolution;
- A model for computing the atmospheric escape

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PASTA algorithm. Overview

- Bayesian framework working in a MCMC fashion
- At each chain step, for each exoplanet, it computes a whole $f_{\mathrm{atm}}(t)$ track, $t \in [t_{\mathrm{disk}}, t_\star]$

Required input parameters:

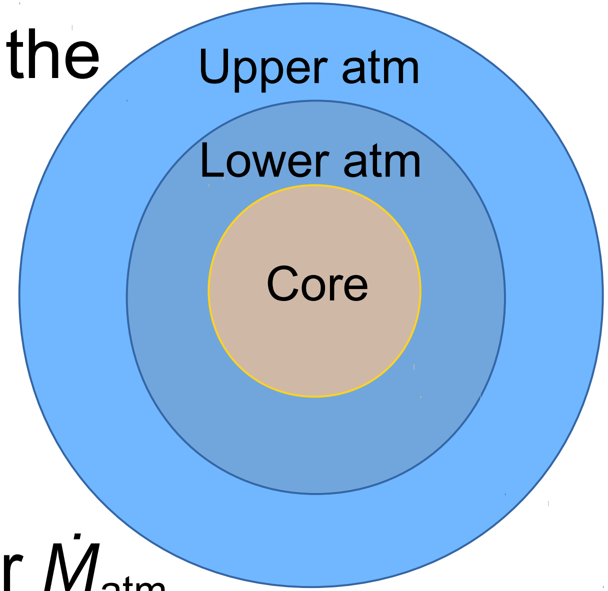
- Stellar $M_\star$, $t_\star$, $P_{\mathrm{rot},\star}$
- Planetary a, M_{p}, R_{p}

Stellar models

MESA: Modules for Experiments in Stellar Astrophysics (Paxton et al., 2018)

- MIST: MESA Isochrones and Stellar Tracks (Choi et al., 2016)
- Mass range $M_\star$ from 0.4 $M_\odot$ to 1.3 $M_\odot$
- At any given epoch t, each track lists L_{bol}, T_{eff}, $R_\star$

Planetary models

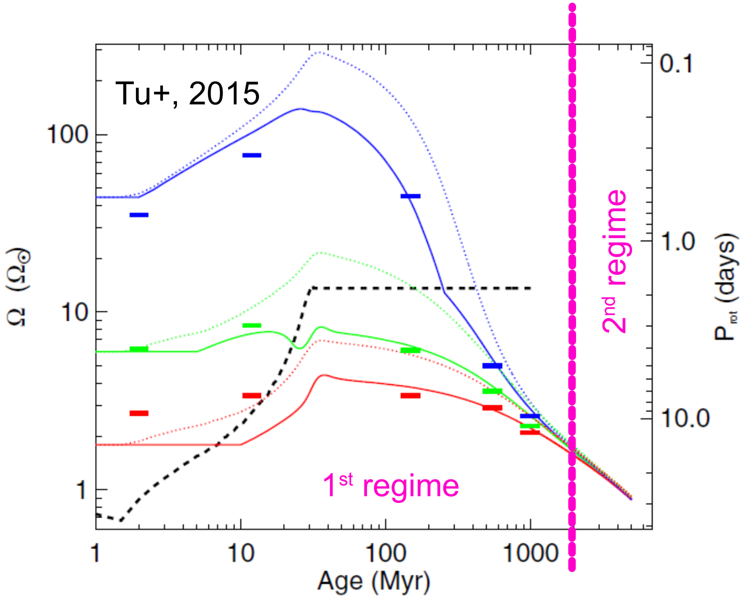


- *Core* + *Lower atmosphere* models based on the work of Johnstone et al. 2015
- *Upper Atmospheres* model developed by Kubyshkina et al. 2018
- Mass M_p from 1 $M_\oplus$ to 40 $M_\oplus$
- Models list M_p, R_p, T_{eq}, and M_{atm} to finally infer $\dot{M}_{atm}$

P_{rot}: a proxy for stellar activity

$$P_{\rm rot}(t) = P_{\rm rot,\star}\left(\frac{t}{t_\star}\right)^x \qquad t_\star < 2\ \rm Gyr$$

$$P_{\rm rot}(t) = \begin{cases} P_{\rm rot,\star}\left(\frac{t}{2}\right)^x\left(\frac{2}{t_\star}\right)^y & t < 2\ \rm Gyr \\ P_{\rm rot,\star}\left(\frac{t}{t_\star}\right)^y & t \geq 2\ \rm Gyr \end{cases} \qquad t_\star \geq 2\ \rm Gyr$$



Modelled through a broken power-law, splitted into two regimes, which are governed by two different exponents:

$x \in [0, 2]$ for $t < 2$ Gyr

$y \in [0.01, 1]$ for $t > 2$ Gyr

Why?

Many gyrochronological relations available in the literature (Barnes, 2003; Mamajek&Hillenbrand, 2008; Collier Cameron+, 2009; Barnes, 2010), but:

- Calibration is based on OCs
- Doubts when applying gyro ages to field stars (Barnes, 2009; Brown, 2014; Kovács, 2015; van Saders, 2016): isochronal ages greater than gyro ages

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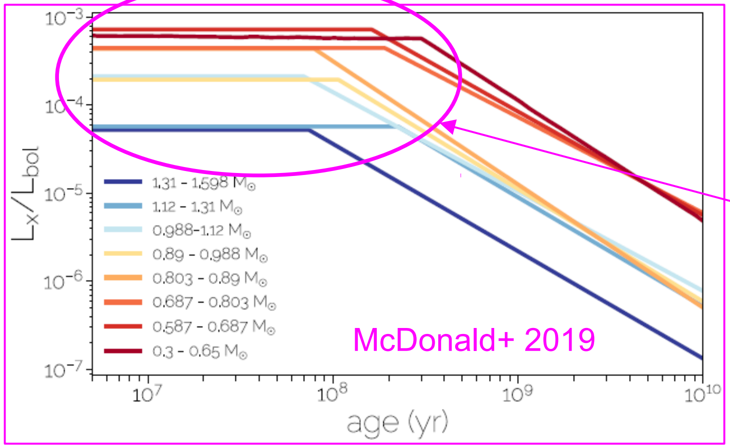
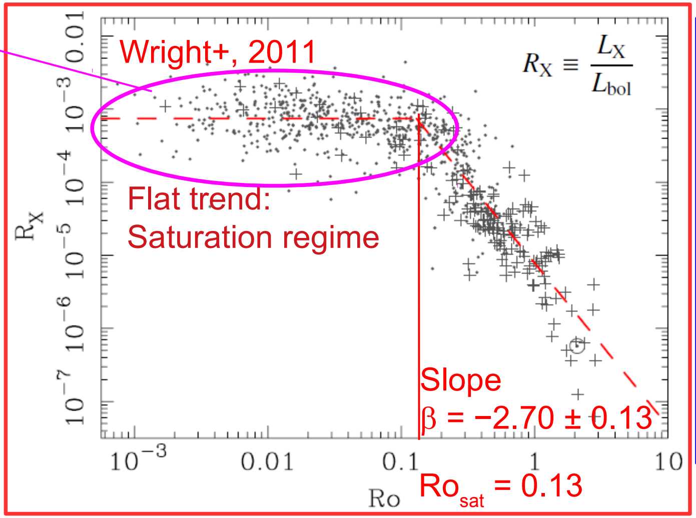
From P_{rot} to L_{EUV}

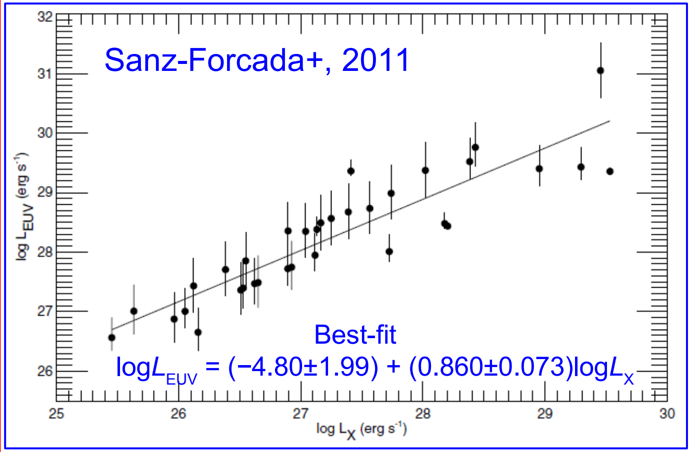
Convective turn-over time (Wright+, 2011) $\log \tau = 1.16 - 1.49 \log \frac{M}{M_\odot} - 0.54 \log^2 \frac{M}{M_\odot} \Rightarrow Ro = \frac{P_{rot}}{\tau}$ Rossby number

$P_{rot} \rightarrow \boxed{Ro \rightarrow L_X} \rightarrow L_{EUV}$



Saturated L_X is mass-dependent





Atmospheric loss model

- Within evolutionary studies of atmospheres the energy limited formula
  - is attractive for its simplicity
  - BUT can be inaccurate in many cases

$$\cancel{\dot{M}_{\rm en} = \frac{\pi\eta R_{\rm pl} R_{\rm eff}^2 F_{\rm XUV}}{G M_{\rm pl} K}}$$

- We used grids of ~7000 1D **upper-atmosphere hydrodynamic models** developed by Kubyshkina+, 2018
- Fitting within the grids, we derived analytical expressions for the atmospheric mass-loss rates: $\dot{M}_{\rm atm} = \dot{M}_{\rm atm}(M_{\rm p}, R_{\rm p}, a, T_{\rm eq}, L_{\rm EUV})$
- Accurate planetary evolution estimates w/o increasing computational time

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PASTA. The chain step

$M_{\star,\mathrm{step}}$ → Interpolation within MESA evolutionary tracks → $\forall t$: $L_{\mathrm{bol}}(t)$, $T_{\mathrm{eff}}(t)$, $R_\star(t)$

a_{step}

$$T_{\mathrm{eq}} = T_{\mathrm{eff}} \sqrt{\frac{R_\star}{2a}}$$

$T_{\mathrm{eq}}(t)$

$M_{\mathrm{p,step}}$

$f_{\mathrm{atm}}(t)$

$P_{\mathrm{rot},\star}(t) \Rightarrow F_{\mathrm{EUV}}(t)$

Atmospheric mass loss models

Planetary structure models

The Metropolis-Hastings rule decides whether to accept the atmospheric evolutionary track after comparing $R_p(t_\star)$ with R_p, hence the initial $R_p(t_{\mathrm{disk}}) \leftrightarrow f_{\mathrm{atm}}(t_{\mathrm{disk}})$ is found! → $P_{\mathrm{rot,young}}$

PASTA. The caveats

- Dealing with planets with hydrogen-dominated atmospheres
- No migration mechanisms after proto-planetary disk dispersal
- Planetary density $\rho_{\mathrm{p}} < 1\ \rho_{\oplus}$

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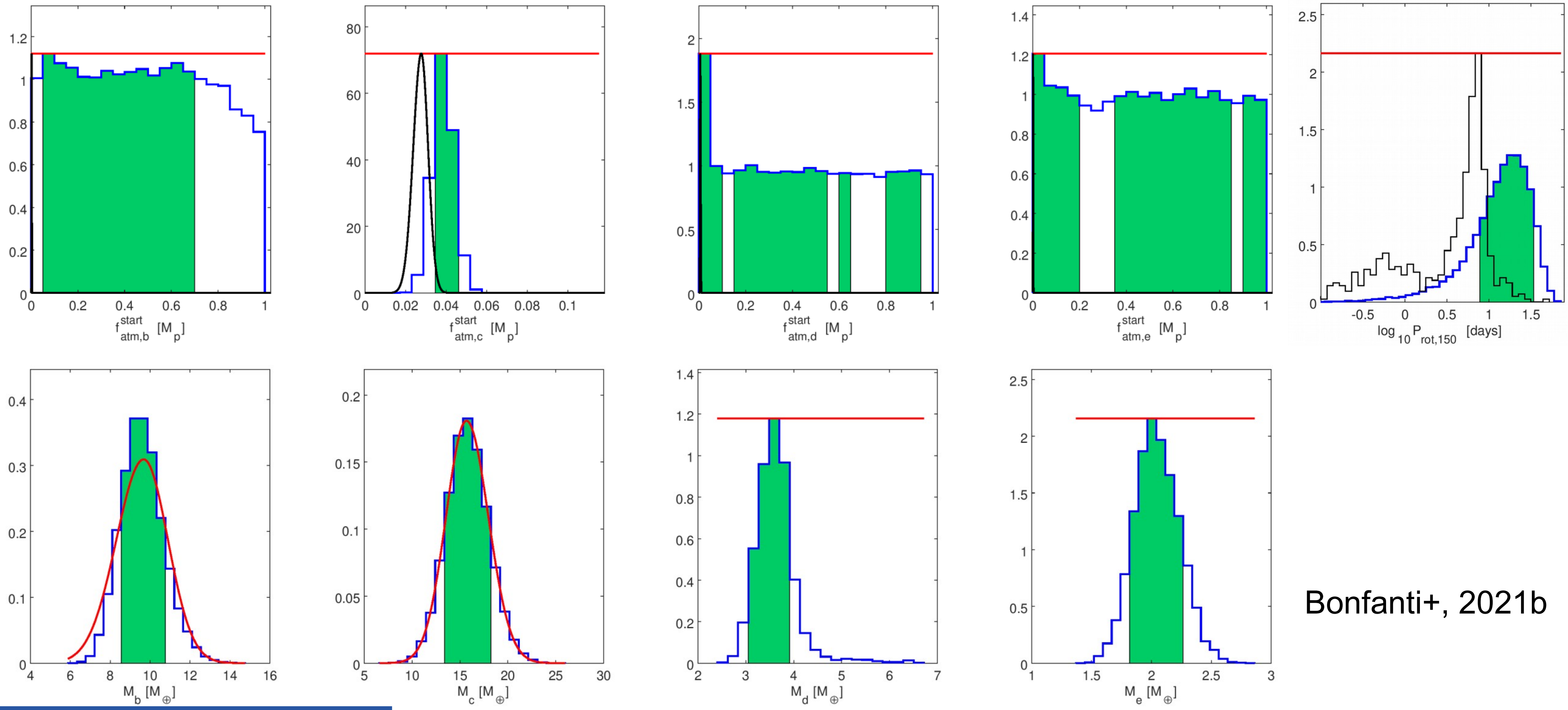
PASTA. The results

- Posterior PDFs of $P_{\mathrm{rot,150}}$ and $f_{\mathrm{atm}}(t_{\mathrm{disk}})$

The constraining power of the code increases with increasing number of planets in the system

- Different planets in the system provide multiple fitting points and simultaneously constrain the properties of the shared host
- Those fitting points may help in constraining some of the planetary masses M_{p}

An attractive example: K2-285

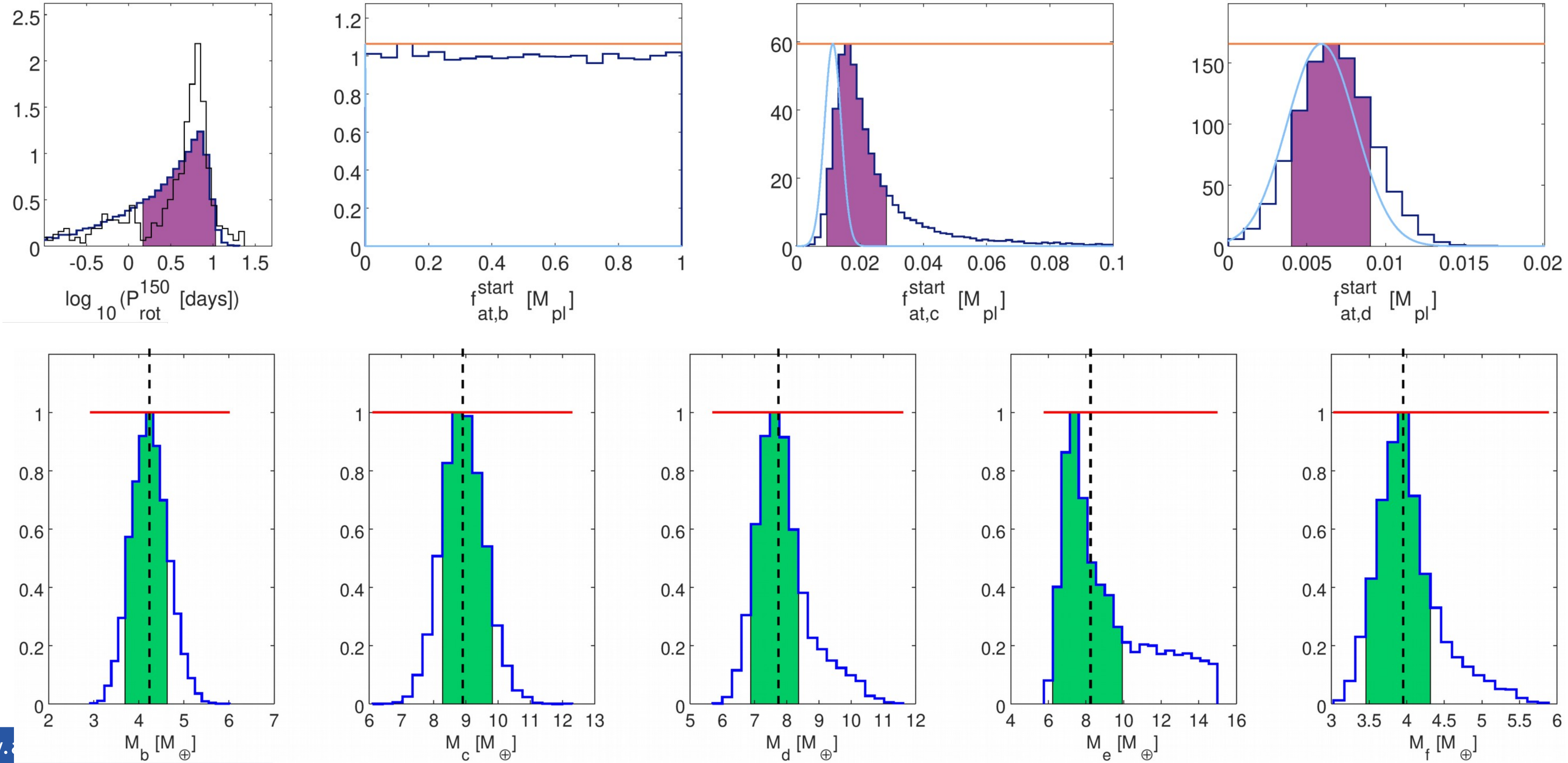


Bonfanti+, 2021b

Application to CHEOPS targets

ν^2 Lupi
Delrez+, 2021

TOI-1233
Bonfanti+, 2021



Conclusions

- PASTA unveils the first stages of evolution of exoplanetary systems
- TESS, CHEOPS + RV spectrographs already provide systems amenable for PASTA analyses
- PASTA has already been applied to 7 CHEOPS targets hence papers (from the “in prep.” status up to the “published” one)

Future developments

Improving the models behind PASTA, by e.g.

- Including elements in addition to H
- Providing a self-consistent calculation of the heating efficiency
- Accounting for orbital migration

Thanks for your attention!