Anomalously low-mass core-He-burning star in NGC 6819 as a post-common-envelope phase product

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ABSTRACT

Precise masses of **red-giant** stars enable a robust inference of their ages, but there are **cases where** these estimates can be highly precise yet **very inaccurate**. Examples are core-He-burning (**CHeB**) stars **that have lost more mass** than predicted by standard evolutionary models. Members of star clusters in the *Kepler* database represent a unique opportunity to find such stars, because they combine exquisite asteroseismic constraints with age information (members of a star cluster share similar age and chemical composition).

In our study we focus on the single metal-rich ($Z \approx Z_{\odot}$) Li-rich anomalously low-mass CHeB star KIC 4937011, which is a member of the well-known old cluster NGC 6819 (turn-off mass of $\approx 1.6\,M_{\odot}$, i.e. age of ≈ 2.4 Gyr). This star has $\approx 1\,M_{\odot}$ less mass than expected for its age and metallicity, thus, it could be the result of a binary interaction or of the poorly understood mass-loss mechanism along the red-giant branch. To infer formation scenarios, a Bayesian approach is needed on an evolutionary code that includes the physics of binary stars and is as fast as possible. We used the **binary_c v2.2.3** code coupled with the Dynamic Nested Sampling approach contained in the **dynesty v2.1.1** package.

We found that this star is the **result of a common-envelope-evolution phase in which the companion does not survive**. Photometric and spectroscopic **predictions are consistent with observations**, although **some systematic effects need to be included in the models**.

INTRODUCTION

There are cases where mass-based age estimates are much higher than the age of the Universe or the age of the star cluster to which they belong. Therefore, the current mass of these stars is incompatible with the cosmological constraints on the age of the Universe or the constraints based on the age of the cluster to which they belong. They have **lost more mass than expected**, most likely via interaction with a companion star (see e.g. Li et al., 2022; Bobrick et al., 2022, Matteuzzi et al., to be submitted) or because of the poorly understood mass-loss mechanism along the RGB. **Examples are observed in open star clusters and in the field** (see e.g. Handberg et al., 2017; Matteuzzi et al., 2023), and some of them are found in the colour-magnitude diagram (CMD) between the RR Lyrae red edge and the RC; consequently, their position suggests that they have a Helium core similar to that of RC stars ($\approx 0.48\,M_{\odot}$), but with a smaller Hydrogen-rich envelope ($\approx 0.2\,M_{\odot}$).

I studied possible **formation scenarios for such stars** (Matteuzzi et al., to be submitted).

- Open cluster **NGC 6819** (see Figure 1): $Z \approx Z_{\odot}$, $t_{age} = 2.38 \pm 0.05 \pm 0.22$ Gyr, $< M_{RC} > = 1.64 \pm 0.02\,M_{\odot}$, $\eta_{RGB} = 0.1$ (e.g. Burkhead, 1971; Brewer et al., 2016; Handberg et al., 2017);
- **KIC 4937011** is a **RC star member** of the cluster (see Figure 1): $M = 0.71 \pm 0.08\,M_{\odot}$, **Li-rich, O unusually high,** $v_{rot} \sin i = 8.3 \pm 0.3$ km/s (e.g. Anthony-Twarog et al., 2013; Carlberg et al., 2015; Lee-Brown et al., 2015; Handberg et al., 2017).
- **No evidence of a companion**: it could be the result of a binary interaction with a merger, as suggested for other metal-rich "stripped" CHeB stars (e.g. Li et al., 2022; Matteuzzi et al., 2023).

This star is in the *Kepler* database, thus, it combines exquisite asteroseismic constraints with age information (members of a star cluster share similar age and chemical composition).

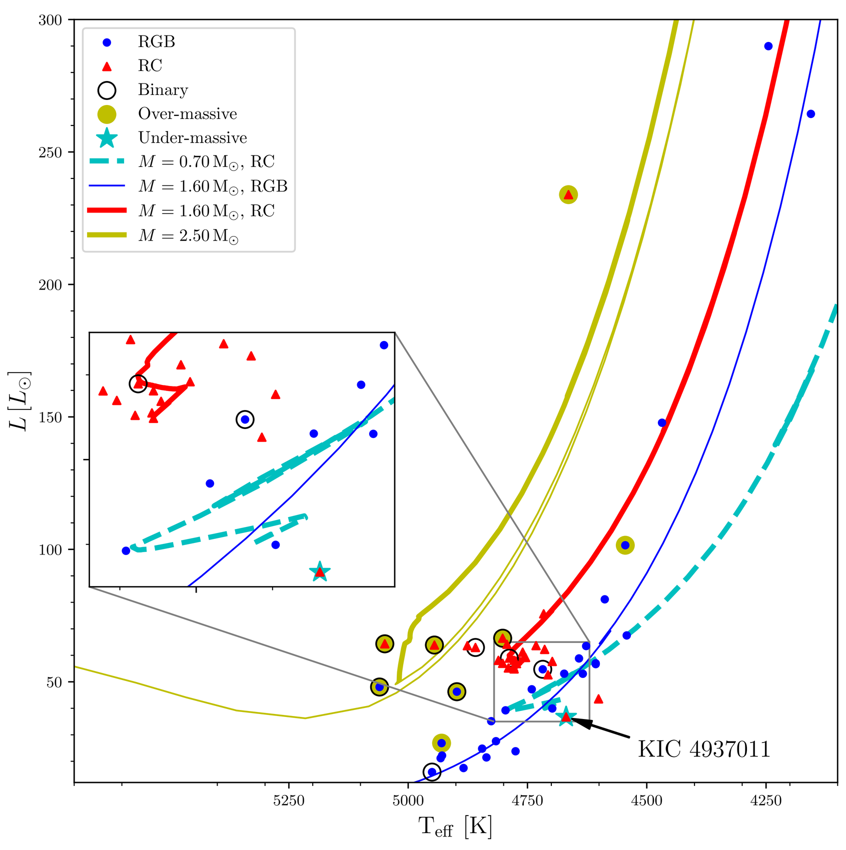

Figure 1. HRD of red-giant stars in NGC 6819.

In Equation 1 the α-formalism for the common-envelope-evolution (CEE; e.g., Paczyński 1976; Webbink 1984; Röpke & De Marco 2023). To summarise (see also Figure 3):

- **Unstable** Roche lobe overflow (**RLOF**) with the **engulfment of the companion**;
- **Dragging forces in action**: angular momentum transfer to the envelope;
- The orbit shrinks and a **merger can occur**.

$$\underbrace{\frac{G m_1 m_{1,\mathrm{env}}}{\lambda_{ce} R_1}}_{E_{\mathrm{bind,env}}} = \alpha_{ce} \underbrace{\left(-\frac{G m_1 m_2}{2 a_i} + \frac{G m_{1,c} m_2}{2 a_f} \right)}_{\Delta E_{\mathrm{orb}}}$$

Equation 1. α-formalism energy equation for the CEE.

METHODS

Bayesian approach to **understand formation scenarios** (see Figure 2):

- Fast evolutionary codes for binary stars **binary_c v2.2.3** (Izzard et al., 2004; Izzard & Jermyn, 2023) and **binary_c-python v0.9.6** (Hendriks & Izzard, 2023);
- **Monte Carlo (MC) simulations using** the code **dynesty v2.1.1** (Speagle, 2020) to find the density distribution of initial parameters;
- **Starting point** for all MC simulations are two ZAMS stars with circular orbits;
- $Z = 0.02$ and $\eta_{RGB} = 0.1$ from observations **for all MC simulations** (we tried also different values);
- Uniform priors for $\alpha_{ce} \cdot \lambda_{ce}$, $\log P_0$ and q_{ZAMS};
- Chabrier et al. 2003 probability density distribution for $M_{1,ZAMS}$;
- Gaussian likelihood based on the current evolutionary phase, $t_{age} = 2.38 \pm 0.27$ Gyr, $M_{1,CHeB} = 0.71 \pm 0.08\,M_{\odot}$ and $\log\left(T_{eff,1,CHeB}/K\right) \leq 3.78$.

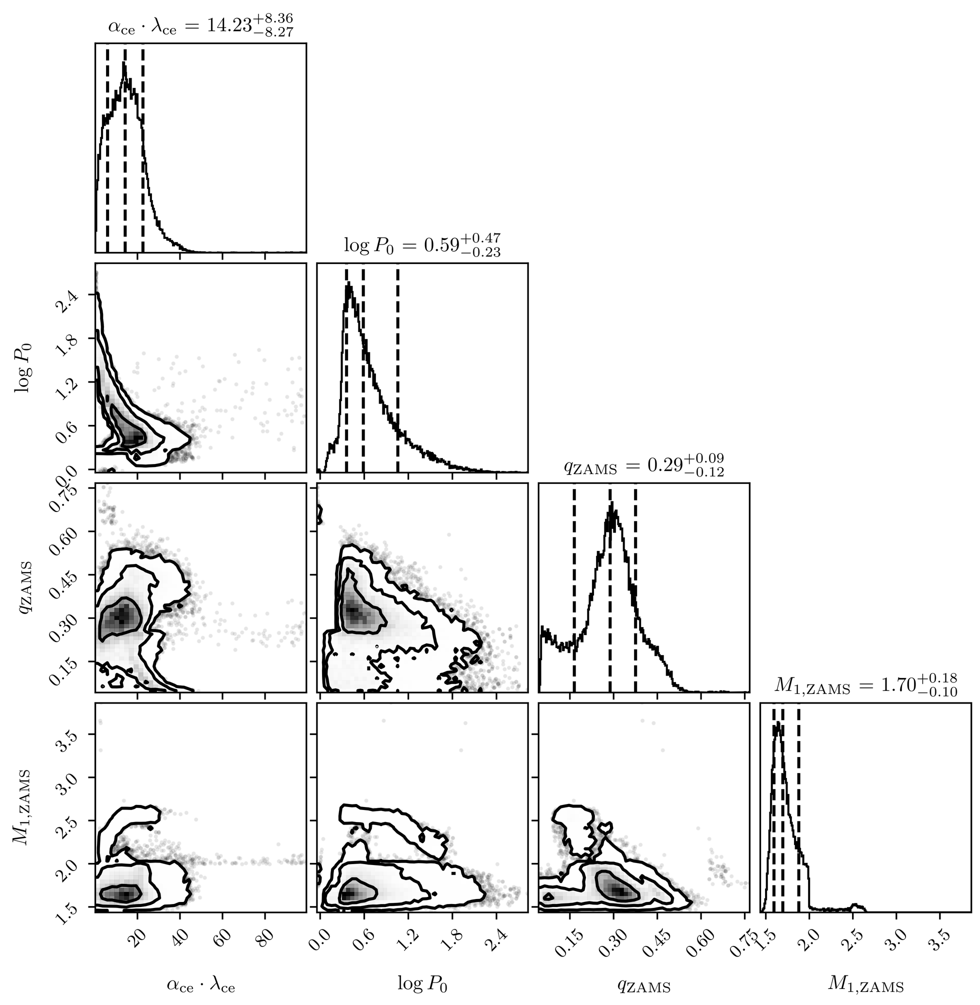

Figure 2. Corner plot showing the posterior density distributions of the MC models. The contours are referred to 1, 2, and 3-σ, respectively.

MAIN RESULTS

- Result of a **post-CE phase** in which the **companion** does **not survive** and $\approx 1\,M_{\odot}$ of material is ejected from the system;
- **Dichotomy appears**: two C/N peaks in the full sample with two different main formation channels (see Figure 3);
- **Subsample selection**: CHeB primary stars with $C/N \lesssim 2.5$ and $L \lesssim 100\,L_{\odot}$ (from observations);
- The **most credible formation scenario** for the subsample is in Figure 3.
- Within the errors this **scenario has predictions consistent with the observations** (see Figure 4): however, **some systematics** must be included.

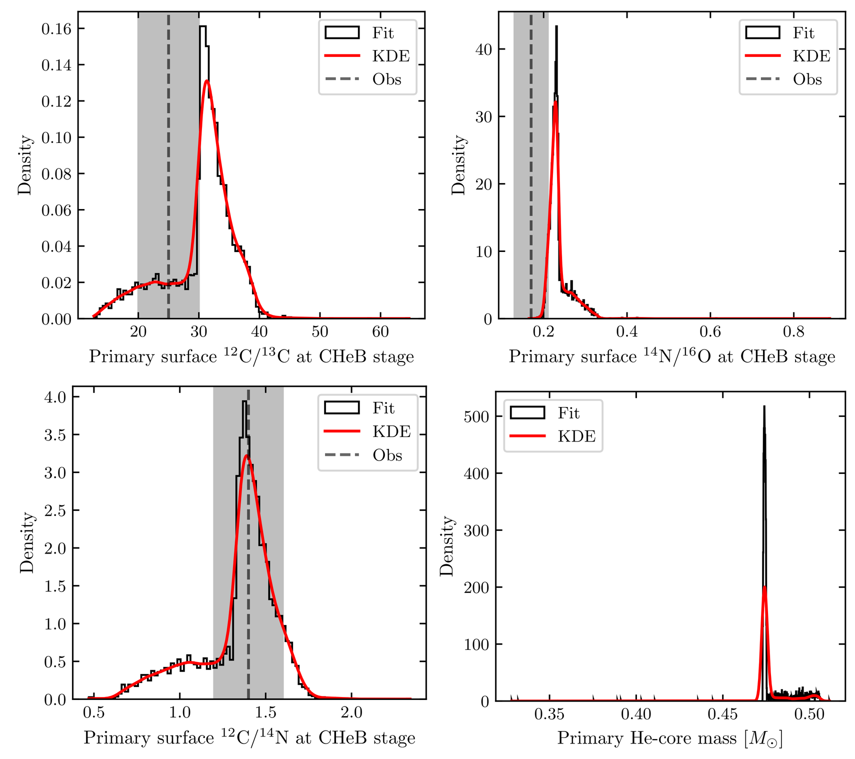

Figure 4. Posterior density distributions for the subsample.

CONCLUSIONS

Figure 3 and 4 show that:

- We have a CHeB star with an evolved Helium core of $\approx 0.48\,M_{\odot}$ and a small envelope of the order of $\approx 0.23\,M_{\odot}$ **(consistent with observations,** see e.g. Matteuzzi et al., 2023);
- Predictions are consistent with observations, but **some systematics has to be included** in the models;
- These stars are **excellent astrophysical laboratory** for improving current models (for example, transition between sdBs, metal-rich RR Lyrae, and RC stars);
- KIC 4937011 is a **post-common-envelope phase product with no surviving companion**;
- In future we **could analyse and identify other metal-rich rHBs** with such models.

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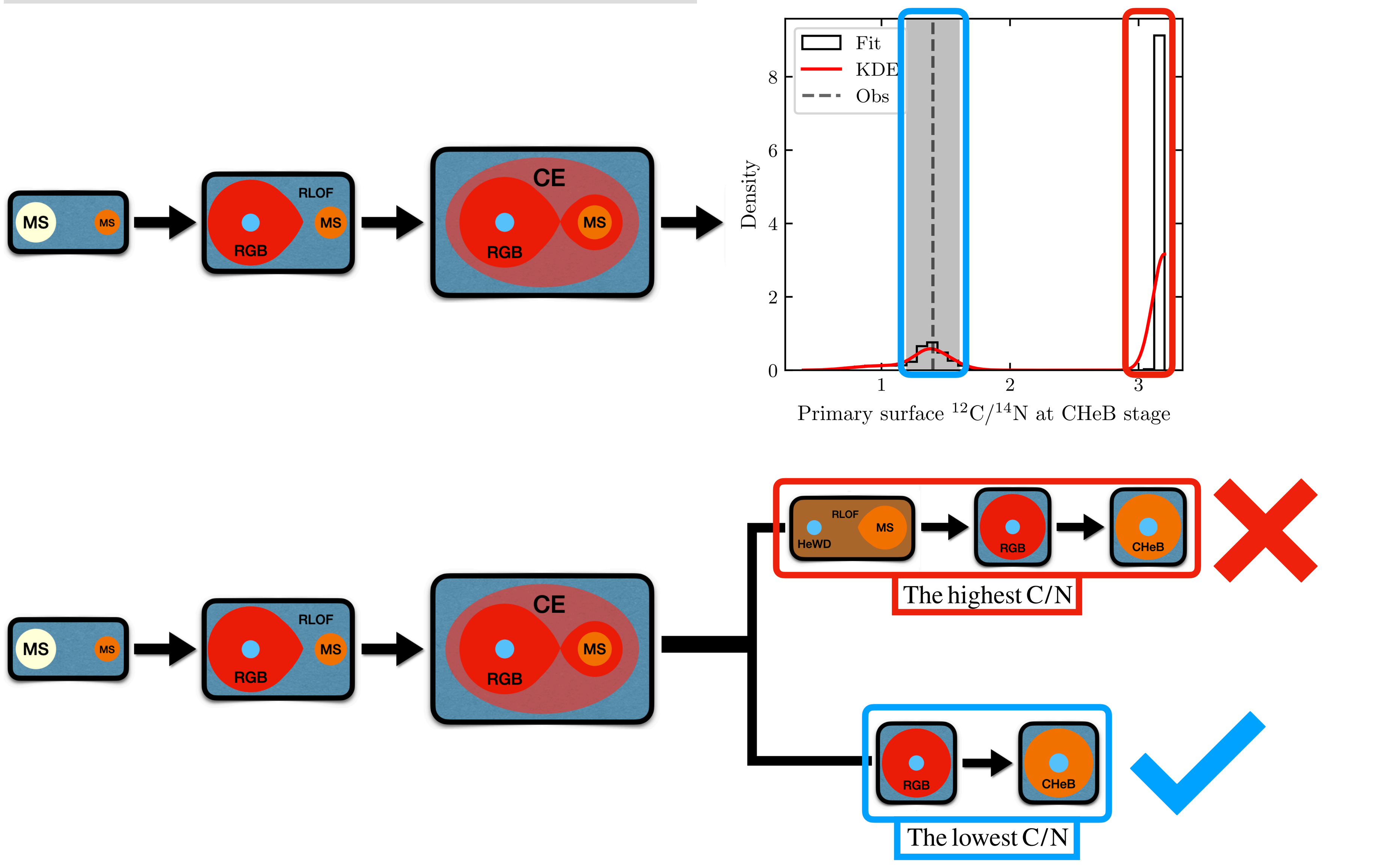

Figure 3. The two main formation channels in the full sample. In blue the most credible one.

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