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ζ Ophiuchi as a test for models of accreting stars in massive binaries

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ABSTRACT

■ [write abstract] ■

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1. INTRODUCTION

The nearest O-type star to Earth is ζ Ophiuchi (spectral type O9.5IVnn, Sota et al. 2014), at a distance of $\sim$110 pc (e.g., Neuhäuser et al. 2020, and references therein). It was originally identified as a runaway star through its large proper motion by Blaauw (1952), who identified the Scorpio-Centaurus group as its parent association. Unfortunately, the *Gaia* data for this object are not of sufficient quality to improve previous astrometric results, but estimates of the peculiar velocity range in $30-50\,\mathrm{km\ s^{-1}}$ (e.g., Zehe et al. 2018; Neuhäuser et al. 2020). The large velocity with respect the surrounding interstellar material is also confirmed by the presence of a prominent bow-shock (e.g., Bodensteiner et al. 2018).

Because of its young apparent age, extremely fast rotation ($v\sin(i) \sim 400\,\mathrm{km\ s^{-1}}$, e.g., Zehe et al. 2018), and nitrogen (N) and helium (He) rich surface (e.g., Blaauw 1993; Villamariz & Herrero 2005; Marcolino et al. 2009), ζ Oph is considered a prime candidate for the binary supernova scenario (Blaauw 1961; Renzo et al. 2019). In this scenario, after a phase of mass transfer in a massive binary, the core collapse of the donor star disrupts the binary, and the former accretor is ejected with its pre-explosion orbital velocity. Many studies have suggested ζ Oph might have accreted mass from a companion before acquiring its large velocity, both from spectroscopic and kinematic considerations (e.g., Blaauw 1993; Hoogerwerf et al. 2000, 2001; Tetzlaff et al. 2010; Neuhäuser et al. 2020) and using stellar modeling arguments (e.g., van Rensbergen et al. 1996). More specifically, Neuhäuser et al. (2020) suggested that the supernova that ejected ζ Oph produced PSR B1706-16 and also injected the short-lived radioactive isotope ^{60}Fe on Earth about ~ 1.5 Myr ago. This argues strongly for a successful supernova explosion accompanied by a large $\sim 250\,\mathrm{km\ s^{-1}}$ natal kick, which would suffice to disrupt the binary.

Although the nature of ζ Oph as a binary product is well established, its large rotation rate has lead most attempts to explain the surface composition to rely on rotational mixing (e.g., Maeder & Meynet 2000). Even the binary models of van Rensbergen et al. (1996) assumed spin-up due to mass accretion (e.g., Packet 1981) to drive rotational mixing from the interior of the accreting star (see also Cantiello et al. 2007). However, Villamariz & Herrero (2005) were unable to find good fit for the stellar spectra using the rotating models from Meynet & Maeder (2000).

This may not be surprising, since rotational mixing has lower efficiency for metal-rich and relatively low mass stars because of the increased importance of mean molecular weight gradients and longer thermal timescales compared to more massive stars (e.g., Yoon et al. 2006; Perna et al. 2014). The parent association of ζ Oph has $Z = 0.01 - 0.02 \simeq Z_\odot$ (e.g., Murphy et al. 2021), and mass estimates for the star range from $13-25\,M_\odot$, i.e. on the lower end of the range where efficient mixing might bring He and CNO-processed material to the surface (chemically homogeneous evolution).

On top of the surface abundances, its extreme rotation rate, and the peculiar space velocity, ζ Oph poses a number of still open puzzles. Its wind mass loss rate appears lower than commonly assumed (weak wind problem, Marcolino et al. 2009), it exhibits spectral variability with occasional appearance of Hα in emission (e.g., Walker et al. 1979).

■ [In the intro:

- **weak wind problem**

Methods:

- **self-consistent modeling of the evolution (see also van Rensbergen et al. 1996)**

- **depends on many free parameters governing the intricate and coupled physics of mass transfer, mixing, rotation**

Aim:

- **since observations are not always agreeing with each other, we aim at finding a model in the right ballpark and explore how physical variations move such model around**

- **in this way we find a set of recommended parameters for the evolution of massive binary system going through stable mass transfer**

] ■

■ **[vanrensbergen:96 already excluded single star solutions based on the age of the parent association and the surface composition, but invoked large scale (rotational) mixing during binary evolution for the surface abundances]** ■

2. MODELING MASS TRANSFER WITH MESA

3. INITIAL GRID OF MODELS

3.1. *Favorite model*

4. PHYSICAL VARIATIONS

5. DISCUSSION

6. CONCLUSIONS

Software: mesaPlot (?), mesaSDK (?), ipython/jupyter (?), matplotlib (?), NumPy (?), MESA(?????)

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APPENDIX

A. MESA SETUP

■ [MLT–?] ■

■ [possibly move to methods] ■ We use MESA version 15140 to compute our models. The MESA equation of state (EOS) is a blend of the OPAL ?, SCVH ?, PTEH ?, HELM ?, and PC ? EOSes. ■ [update EOS] ■

Radiative opacities are primarily from OPAL (??), with low-temperature data from ? and the high-temperature, Compton-scattering dominated regime by ?. Electron conduction opacities are from ?.

Nuclear reaction rates are a combination of rates from NACRE (?), JINA REACLIB (?), plus additional tabulated weak reaction rates ???. Screening is included via the prescription of ?. Thermal neutrino loss rates are from ?. We compute the pre-merger evolution using an 8-isotope α-chain nuclear reaction network and switch to a 22-isotope nuclear network for the post-merger evolution.

We evolve our models from the pre-main sequence to the terminal age main sequence of the most massive $58\,M_\odot$ star, defined as the time when the central hydrogen abundance $X(^1\mathrm{H}) \leq 10^{-4}$. We treat convection using the Ledoux criterion, and include thermohaline mixing (until the central temperature $\log_{10}(T_c/[\mathrm{K}]) > 9.45$, ?) and semiconvection, both with an efficiency factor of 1. We assume $\alpha_{\mathrm{MLT}} = 2.0$ and use ? overshooting for the convective core burning. We have tested that varying core overshooting does not impact significantly the post-merger evolution, however, when including shell overshooting and/or undershooting we were unable to find solutions to the stellar structure equations. Moreover, we employ the MLT++ artificial enhancement of the convective flux (e.g., ??). Stellar winds are included using the algorithms from ? with an efficiency factor of 1.

The inlists, processing scripts, and model output will be made available at link.

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