

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

M. RENZO<sup>1,2</sup> AND ■ [TBD] ■

<sup>1</sup>*Department of Physics, Columbia University, New York, NY 10027, USA*

<sup>2</sup>*Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*

### ABSTRACT

■ [TBD] ■

*Keywords:* stars: individual: ζ Ophiuchi – stars: massive – stars: binaries

### 1. INTRODUCTION

The nearest O-type star to Earth is ζ Ophiuchi (spectral type O9.5IVnn, Sota et al. 2014), at a distance of ∼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 km s<sup>−1</sup> (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 ( $v \sin(i) \sim 400$  km s<sup>−1</sup>, 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 <sup>60</sup>Fe on Earth about ∼1.5 Myr ago. This argues strongly for a successful supernova explosion accompanied by a large ∼250 km s<sup>−1</sup> 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 other puzzles: its wind mass-loss rate is about two orders of magnitude lower than theoretical predictions (weak wind problem, Marcolino et al. 2009), the star exhibits spectral variability with occasional appearance of Hα in emission (e.g., Walker et al. 1979), and is potentially magnetic ■ [true?ref?] ■.

### ■ [ Aim:

- importance of binary products and opportunity to understand binary physics with ζ Oph
- 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

] ■

Here, we present the first self-consistent binary evolution model for  $\zeta$  Oph computing simultaneously the coupled evolution of donor and accretor star. After presenting our calculations in Sec. 2, we show our best model which reproduces the majority of the salient features of this star in Sec. 3, and discuss the sensitivity of our results to the admittedly many free parameters required for this kind of computations in Sec. 4. Finally, we conclude in Sec. 5.

## 2. MODELING MASS TRANSFER WITH MESA

■ [ **Methods:**

### 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 Rogers & Nayfonov (2002), SCVH Saumon et al. (1995), PTEH Pols et al. (1995), HELM Timmes & Swesty (2000), and PC Potekhin & Chabrier (2010) EOSes. ■ [ **check if updated EOS?** ] ■

Radiative opacities are primarily from OPAL (Iglesias & Rogers 1993, 1996), with low-temperature data from Ferguson et al. (2005) and the high-temperature, Compton-scattering dominated regime by Buchler & Yueh (1976). Electron conduction opacities are from Cassisi et al. (2007).

Nuclear reaction rates are a combination of rates from NACRE (Angulo et al. 1999), JINA REACLIB (Cyburt

- self-consistent modeling of the evolution

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

] ■

### 3. BEST MODEL

### 4. PHYSICAL VARIATIONS

### 5. CONCLUSIONS

*Software:* mesaPlot (Farmer 2018), mesaSDK (Townsend 2018), ipython/jupyter (Pérez & Granger 2007), matplotlib (Hunter 2007), NumPy (van der Walt et al. 2011), MESA (Paxton et al. 2011, 2013, 2015, 2018, 2019)

### ACKNOWLEDGEMENTS

## APPENDIX

et al. 2010), plus additional tabulated weak reaction rates Fuller et al. (1985); Oda et al. (1994); Langanke & Martínez-Pinedo (2000). Screening is included via the prescription of Chugunov et al. (2007). Thermal neutrino loss rates are from Itoh et al. (1996). We use a 22-isotope nuclear network (approx\_21\_plus\_cr56).

We treat convection using the Ledoux criterion, and include thermohaline mixing and semiconvection, both with an efficiency factor of 1. We assume  $\alpha_{\text{MLT}} = 1.5$  and use ■ [ **fix** ] ■ Brott et al. (2011) overshooting for the convective core burning. ■ [ **fix** ] ■ Moreover, we employ the MLT++ artificial enhancement of the convective flux (e.g., Paxton et al. 2015). Stellar winds are included using the algorithms from Vink et al. (2001) with an efficiency factor of 1.

The inlists, processing scripts, and model output will be made available at [link](#).

## REFERENCES

- Angulo, C., Arnould, M., Rayet, M., et al. 1999, Nuclear Physics A, 656, 3, doi: [10.1016/S0375-9474\(99\)00030-5](#)
- Blaauw, A. 1952, BAN, 11, 414
- . 1961, BAN, 15, 265
- Blaauw, A. 1993, in Astronomical Society of the Pacific Conference Series, Vol. 35, Massive Stars: Their Lives in the Interstellar Medium, ed. J. P. Cassinelli & E. B. Churchwell, 207
- Bodensteiner, J., Baade, D., Greiner, J., & Langer, N. 2018, A&A, 618, A110, doi: [10.1051/0004-6361/201832722](#)

- Brott, I., de Mink, S. E., Cantiello, M., et al. 2011, *A&A*, 530, A115, doi: [10.1051/0004-6361/201016113](https://doi.org/10.1051/0004-6361/201016113)
- Buchler, J. R., & Yueh, W. R. 1976, *ApJ*, 210, 440, doi: [10.1086/154847](https://doi.org/10.1086/154847)
- Cantiello, M., Yoon, S., Langer, N., & Livio, M. 2007, *A&A*, 465, L29
- Cassisi, S., Potekhin, A. Y., Pietrinferni, A., Catelan, M., & Salaris, M. 2007, *ApJ*, 661, 1094, doi: [10.1086/516819](https://doi.org/10.1086/516819)
- Chugunov, A. I., Dewitt, H. E., & Yakovlev, D. G. 2007, *PhRvD*, 76, 025028, doi: [10.1103/PhysRevD.76.025028](https://doi.org/10.1103/PhysRevD.76.025028)
- Cyburt, R. H., Amthor, A. M., Ferguson, R., et al. 2010, *ApJS*, 189, 240, doi: [10.1088/0067-0049/189/1/240](https://doi.org/10.1088/0067-0049/189/1/240)
- Farmer, R. 2018, *rjfarmer/mesaplot*, doi: [10.5281/zenodo.1441329](https://doi.org/10.5281/zenodo.1441329)
- Ferguson, J. W., Alexander, D. R., Allard, F., et al. 2005, *ApJ*, 623, 585, doi: [10.1086/428642](https://doi.org/10.1086/428642)
- Fuller, G. M., Fowler, W. A., & Newman, M. J. 1985, *ApJ*, 293, 1, doi: [10.1086/163208](https://doi.org/10.1086/163208)
- Hoogerwerf, R., de Bruijne, J. H. J., & de Zeeuw, P. T. 2000, *ApJL*, 544, L133, doi: [10.1086/317315](https://doi.org/10.1086/317315)
- . 2001, *A&A*, 365, 49, doi: [10.1051/0004-6361:20000014](https://doi.org/10.1051/0004-6361:20000014)
- Hunter, J. D. 2007, *Computing In Science & Engineering*, 9, 90
- Iglesias, C. A., & Rogers, F. J. 1993, *ApJ*, 412, 752, doi: [10.1086/172958](https://doi.org/10.1086/172958)
- . 1996, *ApJ*, 464, 943, doi: [10.1086/177381](https://doi.org/10.1086/177381)
- Itoh, N., Hayashi, H., Nishikawa, A., & Kohyama, Y. 1996, *ApJS*, 102, 411, doi: [10.1086/192264](https://doi.org/10.1086/192264)
- Langanke, K., & Martínez-Pinedo, G. 2000, *Nuclear Physics A*, 673, 481, doi: [10.1016/S0375-9474\(00\)00131-7](https://doi.org/10.1016/S0375-9474(00)00131-7)
- Maeder, A., & Meynet, G. 2000, *ARA&A*, 38, 143, doi: [10.1146/annurev.astro.38.1.143](https://doi.org/10.1146/annurev.astro.38.1.143)
- Marcolino, W. L. F., Bouret, J. C., Martins, F., et al. 2009, *A&A*, 498, 837, doi: [10.1051/0004-6361/200811289](https://doi.org/10.1051/0004-6361/200811289)
- Meynet, G., & Maeder, A. 2000, *A&A*, 361, 101
- Murphy, S. J., Joyce, M., Bedding, T. R., White, T. R., & Kama, M. 2021, *MNRAS*, 502, 1633, doi: [10.1093/mnras/stab144](https://doi.org/10.1093/mnras/stab144)
- Neuhäuser, R., Gießler, F., & Hambaryan, V. V. 2020, *MNRAS*, 498, 899, doi: [10.1093/mnras/stz2629](https://doi.org/10.1093/mnras/stz2629)
- Oda, T., Hino, M., Muto, K., Takahara, M., & Sato, K. 1994, *Atomic Data and Nuclear Data Tables*, 56, 231, doi: [10.1006/adnd.1994.1007](https://doi.org/10.1006/adnd.1994.1007)
- Packet, W. 1981, *A&A*, 102, 17
- Paxton, B., Bildsten, L., Dotter, A., et al. 2011, *ApJS*, 192, 3, doi: [10.1088/0067-0049/192/1/3](https://doi.org/10.1088/0067-0049/192/1/3)
- Paxton, B., Cantiello, M., Arras, P., et al. 2013, *ApJS*, 208, 4, doi: [10.1088/0067-0049/208/1/4](https://doi.org/10.1088/0067-0049/208/1/4)
- Paxton, B., Marchant, P., Schwab, J., et al. 2015, *ApJS*, 220, 15, doi: [10.1088/0067-0049/220/1/15](https://doi.org/10.1088/0067-0049/220/1/15)
- Paxton, B., Schwab, J., Bauer, E. B., et al. 2018, *ApJS*, 234, 34, doi: [10.3847/1538-4365/aaa5a8](https://doi.org/10.3847/1538-4365/aaa5a8)
- Paxton, B., Smolec, R., Gaudy, A., et al. 2019, <https://arxiv.org/abs/1903.01426>
- Pérez, F., & Granger, B. E. 2007, *Computing in Science & Engineering*, 9, 21
- Perna, R., Duffell, P., Cantiello, M., & MacFadyen, A. I. 2014, *ApJ*, 781, 119, doi: [10.1088/0004-637X/781/2/119](https://doi.org/10.1088/0004-637X/781/2/119)
- Pols, O. R., Tout, C. A., Eggleton, P. P., & Han, Z. 1995, *MNRAS*, 274, 964, doi: [10.1093/mnras/274.3.964](https://doi.org/10.1093/mnras/274.3.964)
- Potekhin, A. Y., & Chabrier, G. 2010, *Contributions to Plasma Physics*, 50, 82, doi: [10.1002/ctpp.201010017](https://doi.org/10.1002/ctpp.201010017)
- Renzo, M., Zapartas, E., de Mink, S. E., et al. 2019, *A&A*, 624, A66, doi: [10.1051/0004-6361/201833297](https://doi.org/10.1051/0004-6361/201833297)
- Rogers, F. J., & Nayfonov, A. 2002, *ApJ*, 576, 1064, doi: [10.1086/341894](https://doi.org/10.1086/341894)
- Saumon, D., Chabrier, G., & van Horn, H. M. 1995, *ApJS*, 99, 713, doi: [10.1086/192204](https://doi.org/10.1086/192204)
- Sota, A., Maíz Apellániz, J., Morrell, N. I., et al. 2014, *ApJS*, 211, 10, doi: [10.1088/0067-0049/211/1/10](https://doi.org/10.1088/0067-0049/211/1/10)
- Tetzlaff, N., Neuhäuser, R., Hohle, M. M., & Maciejewski, G. 2010, *MNRAS*, 402, 2369, doi: [10.1111/j.1365-2966.2009.16093.x](https://doi.org/10.1111/j.1365-2966.2009.16093.x)
- Timmes, F. X., & Swesty, F. D. 2000, *ApJS*, 126, 501, doi: [10.1086/313304](https://doi.org/10.1086/313304)
- Townsend, R. 2018, *MESA SDK for Linux: 20180822*, doi: [10.5281/zenodo.2603170](https://doi.org/10.5281/zenodo.2603170)
- van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, *Computing in Science Engineering*, 13, 22, doi: [10.1109/MCSE.2011.37](https://doi.org/10.1109/MCSE.2011.37)
- van Rensbergen, W., Vanbeveren, D., & De Loore, C. 1996, *A&A*, 305, 825
- Villamariz, M. R., & Herrero, A. 2005, *A&A*, 442, 263, doi: [10.1051/0004-6361:20052848](https://doi.org/10.1051/0004-6361:20052848)
- Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, *A&A*, 369, 574, doi: [10.1051/0004-6361:20010127](https://doi.org/10.1051/0004-6361:20010127)
- Walker, G. A. H., Yang, S., & Fahlman, G. G. 1979, *ApJ*, 233, 199, doi: [10.1086/157381](https://doi.org/10.1086/157381)
- Yoon, S.-C., Langer, N., & Norman, C. 2006, *A&A*, 460, 199, doi: [10.1051/0004-6361:20065912](https://doi.org/10.1051/0004-6361:20065912)
- Zehe, T., Mugrauer, M., Neuhäuser, R., et al. 2018, *Astronomische Nachrichten*, 339, 46, doi: [10.1002/asna.201713383](https://doi.org/10.1002/asna.201713383)