

Testing models of accreting stars in massive binaries on ζ Ophiuchi

M. RENZO^{1,2} AND ■ [TBD] ■

¹*Department of Physics, Columbia University, New York, NY 10027, USA*

²*Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*

ABSTRACT

Binarity dominates the evolution of massive stars, and the nearest O-type star to Earth, ζ Ophiuchi, has long been proposed to be a product of binary evolution. Despite this, most stellar models have tried unsuccessfully to reproduce its observable properties relying on single-star rotating models. ■ [Here we do better] ■

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

1. INTRODUCTION

The nearest O-type star to Earth is ζ Ophiuchi¹ (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). 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 $30 - 50 \text{ km s}^{-1}$ (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 ($v \sin(i) \gtrsim 400 \text{ km s}^{-1}$, e.g., Zehe et al. 2018), and nitrogen (N) and helium (He) rich surface (e.g., Herrero et al. 1992; Blaauw 1993; Villamariz & Herrero 2005; Marcolino et al. 2009), ζ Oph is 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 which can spin up the accreting star (e.g., Packet 1981), the core-collapse of the donor star disrupts the binary. This results in the ejection of the former accretor as a fast rotator and with its pre-explosion orbital velocity as peculiar 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). Recently, Neuhäuser et al. (2020) sug-

gested that a supernova in Upper-Centaurus-Lupus produced the pulsar PSR B1706-16, ejected ζ Oph, 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 $\sim 250 \text{ km s}^{-1}$ natal kick, which in most cases would be sufficient 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: 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 $13 - 25 M_{\odot}$, at the lower end of the range where efficient mixing might bring He and CNO-processed material to the surface (chemically homogeneous evolution).

■ [maybe paragraph below goes in discussion] ■ 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.

¹ also known as HD149757.

2009), the star exhibits spectral variability with occasional appearance of H α in emission (e.g., Walker et al. 1979), and is potentially magnetic ■ [true?ref?] ■.

Given the challenges in explaining the surface composition of ζ Oph with rotational mixing from the stellar interior and the strong evidence for its past as a member of a binary system, this star offers a unique opportunity to constrain the evolution of accreting stars in massive binary systems, which is hard to model because of the interplay of rotation, mixing, and accretion (e.g. Hellings 1983, 1984; Braun & Langer 1995).

While we focus here on this particular star, we emphasize that understanding the evolution of accretors in massive binaries has wider and crucial implications. Observed stellar populations might contain $\sim 10\%$ of presently single O-type that accreted mass previously (Renzo et al. 2019), gravitational-wave progenitors in isolated binary formation scenarios go through a common envelope phase initiated by the originally less massive accretor after the formation of the first compact object (e.g., Belczynski et al. 2016; Tauris et al. 2017; Law-Smith et al. 2020), ■ [more reasons?] ■

Here, we present the first self-consistent binary evolution model for ζ Oph computing simultaneously the coupled evolution of *both* 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. In this model, the surface abundances of ζ Oph are explained by pollution from the former companion, rather than upward mixing from the interior of ζ Oph itself. We 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:

- 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

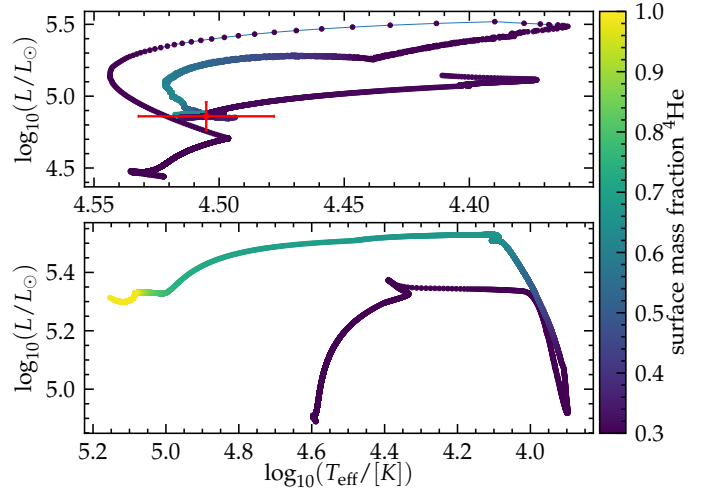


Figure 1. Hertzsprung-Russell diagram for the progenitor binary of ζ Oph. The top panel shows the accretor, the bottom panel show the donor, with the color indicating the surface ^4He mass fraction. The red datapoint shows the position of ζ Oph according to Villamariz & Herrero (2005). Note the different scale on the two panels.

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

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 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](#)
- Belczynski, K., Holz, D. E., Bulik, T., & O’Shaughnessy, R. 2016, *Nature*, 534, 512, doi: [10.1038/nature18322](#)
- 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](#)
- Braun, H., & Langer, N. 1995, *A&A*, 297, 483
- Brodt, I., de Mink, S. E., Cantiello, M., et al. 2011, *A&A*, 530, A115, doi: [10.1051/0004-6361/201016113](#)
- Buchler, J. R., & Yueh, W. R. 1976, *ApJ*, 210, 440, doi: [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](#)
- Chugunov, A. I., Dewitt, H. E., & Yakovlev, D. G. 2007, *PhRvD*, 76, 025028, doi: [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](#)
- Farmer, R. 2018, *rjfarmer/mesaplot*, doi: [10.5281/zenodo.1441329](#)
- Ferguson, J. W., Alexander, D. R., Allard, F., et al. 2005, *ApJ*, 623, 585, doi: [10.1086/428642](#)
- Fuller, G. M., Fowler, W. A., & Newman, M. J. 1985, *ApJ*, 293, 1, doi: [10.1086/163208](#)
- Hellings, P. 1983, *Ap&SS*, 96, 37, doi: [10.1007/BF00661941](#)
- . 1984, *Ap&SS*, 104, 83, doi: [10.1007/BF00653994](#)
- Herrero, A., Kudritzki, R. P., Vilchez, J. M., et al. 1992, *A&A*, 261, 109
- Hoogerwerf, R., de Bruijne, J. H. J., & de Zeeuw, P. T. 2000, *ApJL*, 544, L133, doi: [10.1086/317315](#)
- . 2001, *A&A*, 365, 49, doi: [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](#)
- . 1996, *ApJ*, 464, 943, doi: [10.1086/177381](#)
- Itoh, N., Hayashi, H., Nishikawa, A., & Kohyama, Y. 1996, *ApJS*, 102, 411, doi: [10.1086/192264](#)
- Langanke, K., & Martínez-Pinedo, G. 2000, *Nuclear Physics A*, 673, 481, doi: [10.1016/S0375-9474\(00\)00131-7](#)
- Law-Smith, J. A. P., Everson, R. W., Ramirez-Ruiz, E., et al. 2020, *arXiv e-prints*, arXiv:2011.06630, <https://arxiv.org/abs/2011.06630>
- Maeder, A., & Meynet, G. 2000, *ARA&A*, 38, 143, doi: [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](#)
- 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](#)
- Neuhäuser, R., Gießler, F., & Hambaryan, V. V. 2020, *MNRAS*, 498, 899, doi: [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](#)
- 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](#)
- Paxton, B., Cantiello, M., Arras, P., et al. 2013, *ApJS*, 208, 4, doi: [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](#)
- Paxton, B., Schwab, J., Bauer, E. B., et al. 2018, *ApJS*, 234, 34, doi: [10.3847/1538-4365/aaa5a8](#)
- Paxton, B., Smolec, R., Gaudoch, 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)
- Tauris, T. M., Kramer, M., Freire, P. C. C., et al. 2017, *ApJ*, 846, 170, doi: [10.3847/1538-4357/aa7e89](https://doi.org/10.3847/1538-4357/aa7e89)
- 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)