Draft version February 16, 2021
Typeset using LaTeX **twocolumn** style in AASTeX63

Testing models of accreting stars in massive binaries on ζ Ophiuchi

M. Renzo,[1,2] Y. Götberg,[3] 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*
[3] *The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, 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 Ophiuchi[1] (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). 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 ($v\sin(i) \gtrsim 400\,\mathrm{km\ s^{-1}}$, 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) suggested 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 $\sim 1.5\,\mathrm{Myr}$ ago. This argues strongly for a successful supernova explosion accompanied by a large $\sim 250\,\mathrm{km\ s^{-1}}$ 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

[1] also known as HD 149 757.

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?]** ■.

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. 6.

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

We describe here the evolution of a binary system with initial masses $M_1 = 25\,M_\odot$, $M_2 = 17\,M_\odot$ on

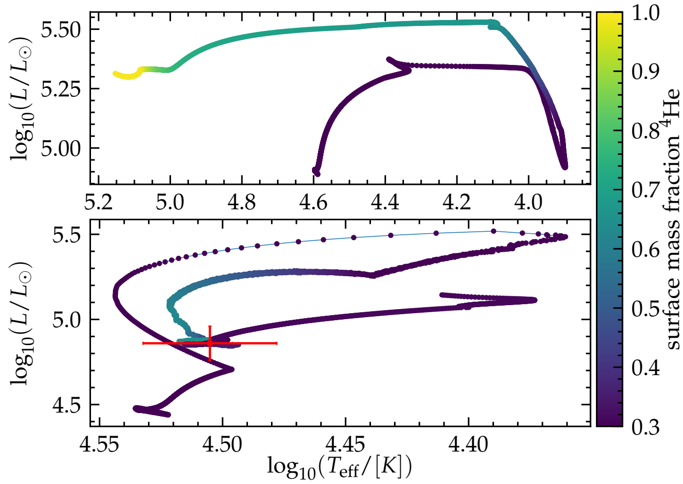

Figure 1. Hertzsprung-Russell diagram for the progenitor binary of ζ Oph. The bottom (top) panel shows the accretor (donor), with the color indicating the surface ^{4}He mass fraction. The red datapoint shows the position of ζ Oph according to Villamariz & Herrero (2005). Note the different scale on the two panels, and that the bottom panel shows a longer time, until the end of the accretor's main sequence.■ **[maybe color with something better]** ■ ■ **[maybe don't show stripped star?]** ■

a period of 100 days at $Z = 0.01$. Fig. 1 shows the Hertzsprung-Russell diagrams of both stars. The donor star (top panel) evolves off the main sequence and shortly ■ **[quantify?]** ■ after mass transfer ensue, resulting in a stable case B (Kippenhahn & Weigert 1967) Roche lobe overflow (RLOF) when the donor's effective temperature reaches about 10^4 K. We refer to Gotberg et al. (2017); Laplace et al. (2021) ■ **[more refs?]** ■ and references therein for a detailed description of the evolution of massive donor stars in binaries: although our models here are significantly more massive, the qualitative behavior is similar.

At this point, the accretor star (bottom panel) is still on the main sequence (effective temperature $T_{\rm eff} \simeq 10^{4.5}$ K), and because of the accretion of matter it quickly becomes over-luminous ($L \simeq 10^{5.4}\,L_\odot$), and its radius increases dramatically ■ **[quantify]** ■. Once the accretor reaches critical rotation, the star begins contracting and its $T_{\rm eff}$ increases. At $T_{\rm eff} \simeq 4.43$ K the material transferred from the companion star becomes progressively more He-rich, causing a "v-shaped" feature in the evolutionary track. This indicates that the outer layers of the donor core, which have been left behind by the core mass recession during the main sequence evolution, are uncovered by mass transfer. This also starts vigorous thermohaline mixing in the accreting star, which progressively dilutes the surface He mass fraction and causes well-known loops on the HR diagram (cf. Cantiello et al. 2007).

Right at the end of RLOF, the donor star briefly expands again ($T_{\rm eff} \simeq 10^{4.1}$ K, $L \simeq 10^{5.5}\,L_{\odot}$). This is due to the transient appearance of a surface convection layer due to partial recombination of the He rich material. This small feature was found to be the culprit of failing computations in older `MESA` releases, because although only a very small amount ■ **[quantify]** ■ of mass is involved, this would lead to large radial expansion much beyond the donor's Roche lobe, and cause numerical problems.

After RLOF, the donor star is a $9.4\,M_{\odot}$ core with surface He mass fraction of $\sim$0.8, and quickly contracts. Such a star would likely appear as a Wolf-Rayet ■ **[Ylva: want to comment on appearance with companion star next to it?]** ■. We keep evolving the binary until core-He exhaustion of the donor ■ **[defined how?]** ■. The evolutionary track of the top panel stops at this point. We then take the accretor, which has now a mass of $20.1\,M_{\odot}$ and an orbital velocity of $\sim$ 40km s^{-1} (corresponding to a period of $\sim$ 160 days) and continue it evolution as a single star with the same setup until its terminal age main sequence (shown in the bottom panel).

The orbital velocity would likely decrease a bit further due to wind-driven widening of the binary ■ **[estimate and ref]** ■, therefore one can expect this system to produce a runaway star of velocity comparable to ζ Oph if the stripped donor can successfully explode **??**.

4. ROBUSTNESS OF THE MODEL

In this section we investigate the sensitivity of our results to physical parameters.

■ **[How to present results? Table? Showing what? surface mass fractions, rotation, L, Teff]** ■

■ **[Binary parameters:**

- M_1
- M_2
- P
- **J-accretion**

] ■

■ **[Single star parameters:**

- **thermohaline mixing**
- **Eddington-Sweet circulations**
- **metallicity**

] ■

■ **[others?]** ■

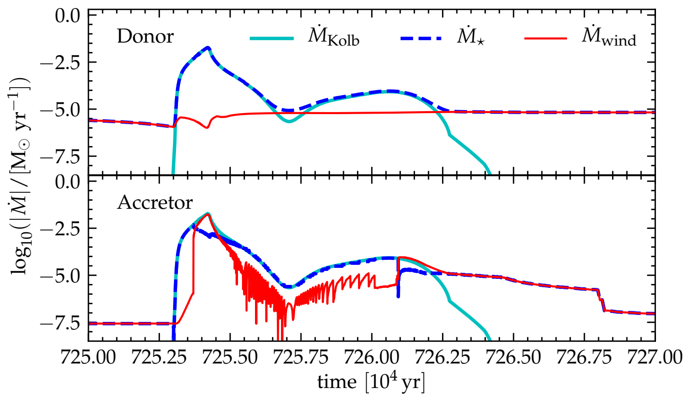

Figure 2. Mass transfer history during RLOF. The top (bottom) panel shows the donor (accretor) star. The cyan solid line shows the mass transfer rate between the two stars, the dashed blue line shows the actual change in the mass of the stars, and the thin red line shows the wind mass loss rates. During RLOF the accretor reaches critical rotation, which leads to oscillations in the rotationally-enhahnced wind mass loss. ■ **[better x-axis]** ■

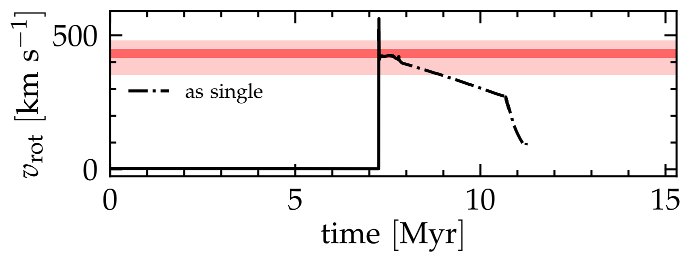

Figure 3. Surface averaged rotation rate for the accretor model. Shortly after $\sim$7 Myr the mass transfer quickly spins up the accretor at critical rotation. By the time the donor detaches from the RLOF the accretor is still spinning at $\sim$400 km s^{-1}. At this point (beginning of the dot-dashed line), we continue the evolution as a single star, and the accretor quickly spins down. Note however that we use a wind mass-loss rate from Vink et al. (2001), which is observed to be $\sim$2 orders of magnitude too high.

5. DISCUSSION

■ **[no SN pollution, but ? shows this is a small effect.]** ■

6. CONCLUSIONS

We have demonstrated that self-consistent one-dimensional calculations of coupled stellar models with masses $\gtrsim 20\,M_{\odot}$ are possible with the `MESA` software

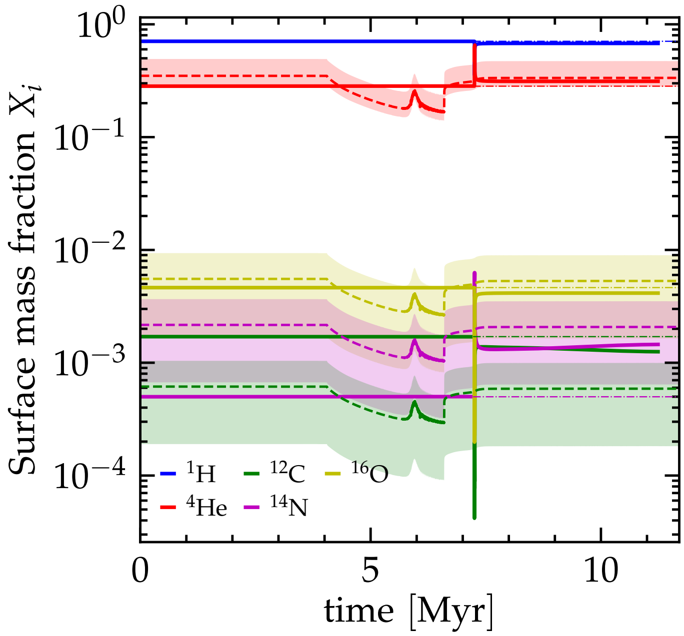

Figure 4. Evolution of the surface composition of the accretor. The thin dot-dashed lines show the initial mass fractions, the dashed line show the mass fractions from Villamariz & Herrero (2005) with the corresponding shaded area for the errorbars. These evolve in time since we use the surface mass fraction of hydrogen to convert the reported number fractions into mass fraction. The solid lines show the surface mass fractions of the accretor, which deviate from the initial values during RLOF because of accretion, and afterwards because of internal mixing.

instrument. As a first application, we focused on finding a model for ζ Oph, assuming its runaway nature is explained by the binary SN scenario.

We found that it is likely possible to explain its surface composition without assuming that the surface excess of He and N comes from within the star. Instead, this material comes from the receeding core of the donor star. Therefore, the present day abundances constrain the accretion efficiency and mixing in the accretor.

ζ Oph should therefore *not* be used to test models of rotational mixing in single star evolution, nor its more extreme version of chemically homogeneous evolution.

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 $\alpha_{\rm MLT} = 1.5$ 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

Brott, 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

Gotberg, Y., de Mink, S. E., & Groh, J. H. 2017. https://arxiv.org/abs/1701.07439

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, 209

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

Kippenhahn, R., & Weigert, A. 1967, ZA, 65, 251

Langanke, K., & Martínez-Pinedo, G. 2000, Nuclear Physics A, 673, 481, doi: 10.1016/S0375-9474(00)00131-7

Laplace, E., Justham, S., Renzo, M., et al. 2021, arXiv e-prints, arXiv:2102.05036. https://arxiv.org/abs/2102.05036

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., Gautschy, 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

Pols, O. R., Tout, C. A., Eggleton, P. P., & Han, Z. 1995, MNRAS, 274, 964, doi: 10.1093/mnras/274.3.964

Potekhin, A. Y., & Chabrier, G. 2010, Contributions to Plasma Physics, 50, 82, doi: 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

Rogers, F. J., & Nayfonov, A. 2002, ApJ, 576, 1064, doi: 10.1086/341894

Saumon, D., Chabrier, G., & van Horn, H. M. 1995, ApJS, 99, 713, doi: 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

Tauris, T. M., Kramer, M., Freire, P. C. C., et al. 2017, ApJ, 846, 170, doi: 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

Timmes, F. X., & Swesty, F. D. 2000, ApJS, 126, 501, doi: 10.1086/313304

Townsend, R. 2018, MESA SDK for Linux: 20180822, doi: 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

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

Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574, doi: 10.1051/0004-6361:20010127

Walker, G. A. H., Yang, S., & Fahlman, G. G. 1979, ApJ, 233, 199, doi: 10.1086/157381

Yoon, S.-C., Langer, N., & Norman, C. 2006, A&A, 460, 199, doi: 10.1051/0004-6361:20065912

Zehe, T., Mugrauer, M., Neuhäuser, R., et al. 2018, Astronomische Nachrichten, 339, 46, doi: 10.1002/asna.201713383