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"WHY Y OPH IS OFF ?" PULSATION MODELING OF THE CEPHEID Y OPHIUCHI WITH MESA/RSP

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Abstract. Y Ophiuchi (Y Oph) is a classical Cepheid having a quasi-sinusoidal and small amplitude light-curve, with a pulsation period of 17.12 days. The distance of Y Oph as derived from the Baade-Wesselink (BW) method indicates that Y Oph is much fainter than derived from the Period-Luminosity relation. On the other hand, BW distance is discrepant with Gaia DR3 parallax. To investigate the origin of this difference we used hydrodynamical pulsation and evolution modeling to explore Y Oph's properties and understand its low amplitude and luminosity, using a comprehensive set of observations. Our models show that Y Oph is not a first-overtone pulsator, but a fundamental one for which the small amplitude is likely due to its proximity to the blue edge of the instability strip. A pulsation mass of 7-8 $M_\odot$ agrees with non-canonical evolutionary models and *Gaia* parallax, but a mass below 5 $M_\odot$ is required to match BW distances. We suggest that the BW distance is likely affected by the CSE's impact on photometry and an unusually high projection factor. We also discuss the reasons why Y Oph cannot be a first-overtone mode pulsator.

The SF2A conference is a great opportunity to honor the dedication of French astronomer and variable star observer Michel Luizet from the Observatory of Lyon, who observed Y Oph with binoculars an impressive 309 times over the span of 1898-1904. He published over 100 articles on variable star observation and was acknowledged as a reference in the history of variable star astronomy (Shapley 1919).

Keywords: Cepheids, distance scale, modeling

1 Introduction

Y Ophiuchi (Y Oph) is a fascinating Cepheid variable star, first discovered over 130 years ago with a pulsation period of about 17 days (Sawyer 1890; Luizet 1905). While it shares characteristics with other Cepheids, Y Oph is not included in calibrating the period-luminosity (PL) relation, which has been fundamental to distance measurement in astronomy since its discovery in the early 1900s (Leavitt 1908). Early studies using the BW method found that Y Oph is about one magnitude fainter than expected, suggesting a luminosity more typical of a Cepheid with a much shorter pulsation period of around 10 days as shown by Abt (1954). Over the years, astronomers have tried to determine the distance to Y Oph using various methods, with results ranging from 400 to 650 parsecs aligning with Abt's result (see Fig. 1). Many of these estimates relied on surface brightness-color relations (SBCR), which can be tricky because Y Oph is close to the galactic plane and has a significant color excess, making its unreddened color $V-K$ uncertain. However, the interferometric version of the BW method (Mérand et al. 2007), independent of the reddening, allowed to determine a very short distance of about 490 pc, therefore increasing the tension with the brightness inferred from the PL relation and also with the *Gaia* parallax which complicates the puzzle about this star. Indeed, according to Gaia DR3 and DR2, Y Oph is much farther away—around 742±21 parsecs (see Fig. 1). The parallax of Y Oph from Gaia is (in principle) considered reliable, with a RUWE of 1.04. However the star slightly saturates Gaia's detectors, which could introduce some error (Lindegren et al. 2018). Still, this does not seem enough to explain the significant difference in distance estimates. Additionally, Y Oph's relatively small amplitude in brightness variation suggests that any chromaticity effects on the Gaia detectors should be minimal. Several studies have provided evidence that Y Oph is part of a spectroscopic binary system (Szabados 1989). Although its influence on photometric and radial velocity measurements appears to be weak, the question remains open for its true influence on the *Gaia* parallax measurement. Despite this, no companion was detected in *IUE* spectra Evans (1992), and NACO

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lucky imaging showed a magnitude difference of at least 2.5 mag in the K_s band, making the companion faint or elusive (Gallenne et al. 2014). More recently, a third, distant companion with an orbital period of around 28,000 days has been suspected, based on light-travel time effects observed in the $O-C$ diagram (Csörnyei et al. 2022). By coincidence, assuming *Gaia* parallax is accurate, the luminosity of Y Oph would naturally align with PL calculation of fundamental Cepheids. It is therefore legimitate to investigate whether BW of *Gaia* distance is correct, and what is the fundamental reason explaining this difference. To gain a deeper understanding of Y Oph, especially regarding its unusually low amplitude, and the discrepancies in its brightness and distance, we explored the star's properties using hydrodynamical pulsation models. Non-linear pulsation modeling has long been a powerful tool for unraveling the physics behind variable stars, first demonstrated by Christy in the 1960s (Christy 1966) thanks to progress of radiative transfer theory developped at Los Alamos. Here, we aim to apply this approach to Y Oph, using an extensive dataset of observational data to constrain the models.

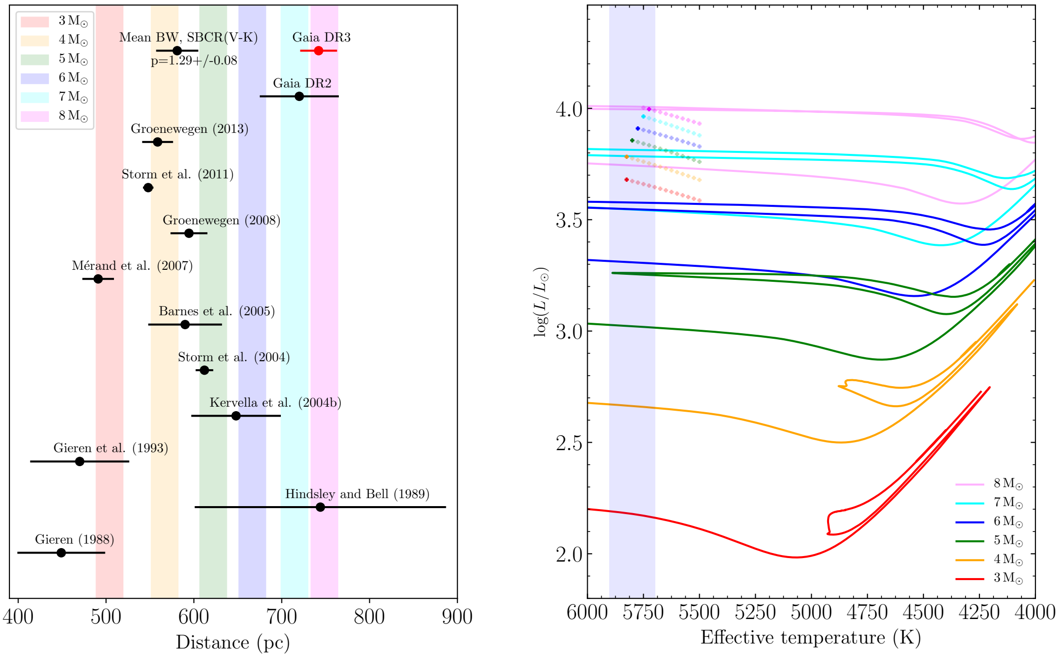

Fig. 1. Left: Comparison of distances obtained using variant of Baade-Wesselink methods (Gieren et al. 1993; Kervella et al. 2004; Mérand et al. 2007; Groenewegen 2008; Storm et al. 2011; Groenewegen 2013) with *Gaia*. **Right:** HR diagram comparing parameters of `MESA-RSP` models of Y Oph (colored points) with evolutionary tracks computed with MESA for different stellar masses (Ziółkowska et al. 2024). The vertical strip is the average effective temperature measured by Luck (2018).

2 Linear non-adiabatic and non-linear analysis with Radial Stellar Pulsation/MESA

On the modeling side, we used Radial Stellar Pulsation (RSP) tool from the Modules for Experiments in Stellar Astrophysics (MESA, Smolec & Moskalik 2008; Paxton et al. 2019; Jermyn et al. 2023). This one-dimensional Lagrangian convective code, which has already been successfully used to model RR Lyrae, BL Her, and classical Cepheids, is perfect for studying Y Oph's non-linear pulsation. Our method consists first of computing a linear non-adiabatic (LNA) stability analysis of a grid of models with `MESA-RSP` as described, for instance, in Smolec (2016) and Paxton et al. (2019). For this study, we used `MESA` version `r15140` and OPAL opacity tables from Iglesias & Rogers (1996) and Ferguson et al. (2005), using the solar abundance mixture from Asplund et al. (2009). `MESA-RSP` uses the time-dependent model of turbulent convection described in Kuhfuss (1986) and follows the implementation of Smolec & Moskalik (2008). Details on the input parameters (convection, metallicity) are provided in (Hocdé et al. 2024b). We chose to perform LNA analysis for six different stellar masses: 3, 4, 5, 6, 7, and 8 $M_\odot$. Our grid is also evenly spaced for the effective temperature by 50 K between 5500 and 6000 K and for the luminosity by 250 $L_\odot$ between 3000 and 10000 $L_\odot$. We computed the linear periods of the fundamental mode, the first-overtone and the 11 consecutive radial overtones together with the corresponding linear growth rates.

3 Results

As a first result of the linear computation, we can rule out the possibility that Y Oph is a first-overtone (FO) pulsator because we do not find any positive growth for linear pulsation period above about 10 days, and, thus these modes are linearly damped in our grid. We then computed non-linear models for combination of effective temperature and luminosity involving linear pulsation period of about 17 days. Comparing RSP models with a complete set of observations we find remarkable agreement between the measurements along the pulsation cycle. Specifically, the best RSP models closely follow the variations in angular diameter measured by interferometry, the radial velocity, and the effective temperature from high-resolution spectroscopy, as well as light curves in the $VJHK_sLM$ bands. For all stellar masses, we find the best agreement at the highest effective temperature. This is illustrated in Fig. 2, where the variations of the total χ^2 are plotted against the effective temperature. Our key conclusion is that the quasi-symmetric, low-amplitude behavior of these different curves can be attributed to Y Oph's extreme proximity to the blue edge of the instability strip (IS), regardless of the stellar mass assumed. For each mass, we also computed color excess and the distance (see Fig. 1-left) . We find that *Gaia* distance is in agreement with stellar mass of 7-8 $M_\odot$ while a low mass of about 4-5 $M_\odot$ is necessary to explain BW distance. We emphasize here that evolutionary models *cannot* match pulsation properties of Y Oph for masses below 7 $M_\odot$ (see Fig.1-right). Inspecting closely all the BW method variants applied to Y Oph shows that the assumed p-factor of 1.29 ± 0.08 in average is the major source of systematic error. We thus suggest that the p-factor of Y Oph is necessarily much higher close to 1.5 although we are not able to explain why. On the other hand, the presence of a circumstellar envelope also affects the photometry of the star which can lead to underestimate the BW distance (Nardetto et al. 2023; Hocdé et al. 2024b).

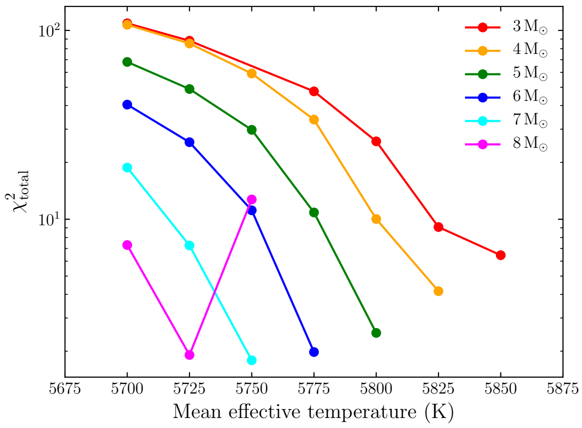

Fig. 2. Mean χ^2_r *vs.* the mean effective temperature for models of different pulsational masses, showing the best agreement of the pulsation models at higher temperature, close to the blue edge of the instability strip.

4 Conclusion : Why Y Oph is not a first-overtone pulsator, theoretical and empirical point of views

Y Oph is often assumed to be pulsating in the FO mode because of its low amplitude. If Y Oph is a FO then the absolute brightness must be higher than for fundamental (FU) Cepheids (fundamentalized pulsation period of ≈24 days). In this case, the discrepancy with the short BW distance for this star is even larger. On the modeling side, our grid of linear models with RSP/MESA does not produce positive growth rates of FO at such long-period which means that FO is not linearly unstable at high luminosity. Empirically, low amplitude is not a good way to identify the pulsation mode, simply because the FU Cepheids can have low amplitudes as well, see for example V340 Nor, HW Car and others. Quasi-sinusoidal and low-amplitude light curve is also possible among FU Cepheids, see for example YZ Car and OGLE-LMC-CEP-3396. In the case of Y Oph, the quasi-sinusoidal and low amplitude is well explained by the star proximity with the blue edge of the instability strip. We emphasize that Y Oph follows perfectly the trend of Fourier parameters ϕ_{21} of both the light-curve and the radial velocity curves of FU Cepheids (Hocdé et al. 2024a) which follows a tight progression with the pulsation period. It is not excluded that hypothetical very long-period FO Cepheids can have such ϕ_{21}. However, this remains unlikely since the longest pulsation period for a securely identified FO Cepheid is 7.57 days in the case of V440 Per (Baranowski et al. 2009) and the longest overtone period claimed is 9.437 days (Udalski et al. 2018; Pietrukowicz et al. 2021). Last but not least, we derived the phase lag $\Delta\phi_1 = \phi_1^{RV} - \phi_1^{LC}$ between the radial velocity and light curve in the V-band such as $\Delta\phi_1 = -0.422 \pm 0.011$ rad which places Y Oph firmly among FU Cepheids and far away from the FO sequence (Ogłoza et al. 2000).

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