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SPECTROSCOPIC STUDIES OF POLARIS: GETTING BACK TO NORMAL LIFE OF A CEPHEID?

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ABSTRACT. Based on 583 radial velocity (RV) measurements we obtained at the Three College Observatory (TCO, North Carolina, USA) in 2015–2024, (including 396 not previously analyzed from 2020–2024) as well as on 236 RV data from the German amateur R. Bücke (2011–2022), we calculated the pulsation period and amplitude of the Cepheid Polaris Aa system (α UMi). The analysis showed that the pulsation period was stable within a few minutes in 2020–2024. During this time, the pulsation amplitude was increasing and reached the 1960s level (4–6 km s^{-1}), when its sharp decline began. Since its new growth began after Polaris Ab, the system secondary component, passed a periastron, we concluded that the observed amplitude changes were due to its orbital motion. It is clear that Polaris Aa is returning to normal pulsating activity.

Key words: α UMi (Polaris Aa and Polaris Ab) system: radial velocities; Polaris Aa pulsation period and amplitude.

АНОТАЦІЯ. За десятирічний період спостережень системи Полярної (α UMi) в Обсерваторії трьох коледжів (Three College Observatory, Північна Кароліна, США) з 2015 по 2024 роки було отримано 583 оцінки радіальної швидкості (RV). Серед них маємо 396 нових, раніше не проаналізованих оцінок, отриманих у період 2020–2024 років. Цей набір RV, разом з додатковими 236 оцінками, що був отриманй німецьким аматором Р. Бюке у період 2011–2022 років, склав велику базу даних для розрахунку значень пульсаційного періоду та амплітуди радіальної швидкості цефеїди Полярної Аа. Як показав аналіз, період пульсації цефеїди виявився досить стабільним протягом кількох хвилин у 2020–2024 роках, але були деякі помітні зміни у 2015 та 2019 роках. Хоча з 2011 по 2019 рік амплітуда пульсації була нестабільною на рівні 3–4 км $с^{-1}$, але з 2020 року вона почала стабільно зростати і досягала вже 4–6 км $с^{-1}$. Такі значення амплітуди спостерігалися у 60-х роках минулого сторіччя, перед тим, як почалося її різке зниження. Оскільки це нове зростання почалося після того, як вторинний компонент системи Полярна Ab пройшов периастр орбіти, то ми дійшли до висновку, що ці спостережувані зміни амплітуди пульсації головного компонента були пов'язані з орбітальним рухом вторинного компонента. Цілком зрозуміло, що таким чином первинний компонент системи Полярна Аа повертається до нормальної цефеїдної пульсуючої активності, яка була майже 60 років потому.

Ключові слова: α UMi: Polaris Aa і Polaris Ab; радіальні швидкості; період пульсації Polaris Aa; амплітуда.

1. Introduction

In our previous paper (Usenko et al. 2020), we used 187 measurements of the Polaris radial velocity (RV), obtained between September 2015 and April 2020 at the TCO observatory, together with a number of observations from Anderson (2019), to study variations of the pulsation period and amplitude of the Cepheid Polaris Aa. In fact, all these 351 measurements turned out to be a unique set of data (excluding amateur observations) taken between 2011 and 2020. This time interval is interesting and important as it covers a fragment of the orbit of the Polaris Ab companion that contains passages through periastron and ascending node. Analysis of the RV data showed that the average pulsation period in 2015–2020 demonstrates a certain stability, and the amplitude of Polaris Aa pulsations demonstrates very strong changes showing an increase to HJD 2457350 followed by a decrease, which began even before the periastron passage. As can be seen in Fig. 7 from Usenko et al. (2020) and Fig. 7 from Torres (2023), the pulsation amplitude changes over these 9 years followed a sinusoidal curve, which gave a reason to make a forecast of the future decrease of the amplitude beyond 2020. These amplitude changes were explained by the influence of the orbital motion of the secondary component, Polaris Ab. Such amplitude changes suggested further careful observations of the Polaris system RVs.

However Torres (2023) added RV measurements from low-resolution spectra obtained by the German amateur Roland Bücke in 2011–2022. It is noticeable In Fig. 7 from his paper that the pulsation amplitude between Spring 2020 and Spring 2023 suddenly increased by ≈ 0.75 km s^{-1}, which is the opposite to our predictions. To test this important fact, we decided to use data from our observations carried out at TCO from July 2020 to April 2024. Additionally, our new RV measurements can be used for refining the orbit of Polaris Ab.

2. Observations and development of spectra

We use 396 spectra in the current data set: 74 were taken in July–December 2020, 106 in January–December 2021, 50 in January–May 2022, 24 in September–November 2022, 14 in January–May 2022, 87 in July–December 2023, and 41 in January–April 2024. All the observations were obtained with the 0.81 m telescope of the Three College Observatory (TCO) in North Carolina. This telescope is equipped with an échelle spectrograph manufactured by Shelyak Instruments [1]. The instrument operates in a spectral range from 3850 to 7900 Å with a spectral resolving power of $R \approx 12{,}000$ and no gaps the between 31 spectral orders. The average S/N ratio in the continuum was 150–200, while most spectral lines used in our analysis were taken from the range 4900–6800 Å. The data were reduced with the *échelle* package in IRAF. Additionally, we use 236 spectra provided to us by Roland Bücke, who used a 0.2 m and a 0.45 m telescopes and a self-built long-slit spectrograph ($R = 3,500$) in 2011–2022[2]. Some results of the latter program were published in Bücke (2021).

To measure the RVs, cross-correlation was used in the wavelength ranges of 5045–5388 Å of the TCO spectra and 6035–6425 Å of the Bücke spectra. Since the total number of derived RV (396 and 236) does not allow for their publication here, they will be published separately.

3. Pulsation, amplitudes and orbital period analysis

In our previous studies, the spectral line positions were measured using the DECH 30 software package[3] by matching original and mirrored profiles for over 100 lines. Typical RV measurement errors with this procedure were 1.0–1.8 km s^{-1}. In this study we used the IRAF package *rvsao* to calculate RVs from continuum-normalized several spectral orders connected together with removal the order parts, which have the lowest signal-to-noise ratios (edges). The relative RVs were calculated with cross-correlation with respect to the spectrum, which was taken chronologically first (2013/07/28 in the TCO data and 2011/02/21 in Bücke's data).

TCO spectra were taken in 10-20 individual 10–20 second-long exposures and summed up, while Bücke's spectra consisted of 4–6 individual 4–5 minute-long exposures. Typical RV measurement errors were 0.05–0.10 km s^{-1} for the TCO data and 0.4–0.5 km s^{-1} for Búcke's data.

The measurement results were then grouped into yearly (TCO) or 2/3–year (Bücke) data sets that are larger than in our previous studies. The data sets were analyzed using a *python* code that calculates best sinusoidal fits to the data as well as uncertainties of the fit parameters (semi-amplitude, period, mean RV, and zero-point of the pulsation phase). The fitting procedure was implemented using the Monte Carlo method on Markov chains which produces many subsamples of each fitting parameter and allows deriving their most probable value and statistical uncertainty (Foreman-Mackey et al. 2013). The fitting results are shown in Tables 1 and 2, while examples of the fits are shown in Figs. 1 and 2.

[1] http://www.shelyak.com

[2] https://www.astro.buecke.de

[3] http://gazinur.com/DECH-software.html

Table 1: Pulsational periods and amplitudes of Polaris Aa in 2015–2024. TCO data.

Year	HJD 2400000+	N	Rej	Period days	σ days	Ampl km s^{-1}	σ km s^{-1}
2015	57283–57376	20	1	3.9781	0.0014	3.42	0.08
2016	57623–57744	36	0	3.9659	0.0062	3.96	0.14
2017	57772–58109	37	3	3.9713	0.0023	3.70	0.06
2018	58120–58479	46	3	3.9711	0.0004	4.04	0.04
2019	58489–58837	28	2	3.9802	0.0036	3.84	0.20
2020	58907–59213	44	1	3.9713	0.0012	3.76	0.04
2021	59219–59575	124	3	3.9750	0.0005	4.34	0.16
2022	59583–59892	76	0	3.9721	0.0004	4.27	0.08
2023	59950–60310	97	0	3.9713	0.0005	5.02	0.04
2024	60314–60416	44	0	3.9715	0.0009	4.24	0.02

N – number of RV measurements, Rej – number of data points rejected from fitting, Period – pulsation period, Ampl – pulsation amplitude, σ – standard deviation of the corresponding parameter from the best-fit

Table 2: Pulsational periods and amplitudes of Polaris Aa in 2011–2022. Bücke data.

Year	HJD 2400000+	N	Rej	Period days	σ days	Ampl km s^{-1}	σ km s^{-1}
2011/02–2014/05	55624–56780	43	0	3.9734	0.0004	3.72	0.11
2014/08–2016/09	56895–57639	44	0	3.9722	0.0004	4.25	0.02
2016/09–2017/09	57657–58001	41	0	3.9720	0.0016	3.28	0.39
2017/10–2019/04	58033–58595	45	0	3.9717	0.0009	3.49	0.45
2019/07–2022/12	58688–59905	63	0	3.9730	0.0003	4.02	0.03

Column information is the same as in Table 1

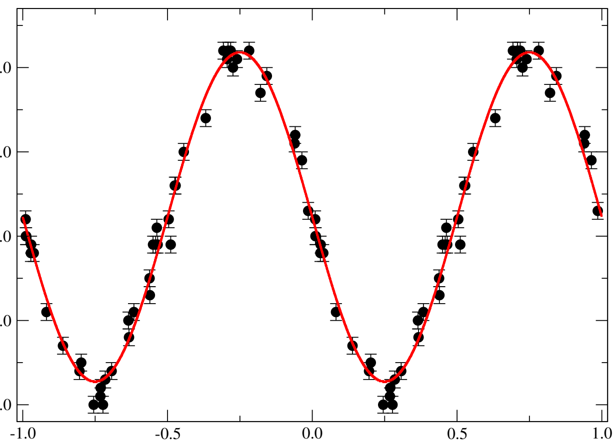

Figure 1: RVs measured from the 2024 TCO data and the best fitting sinusoidal approximation.

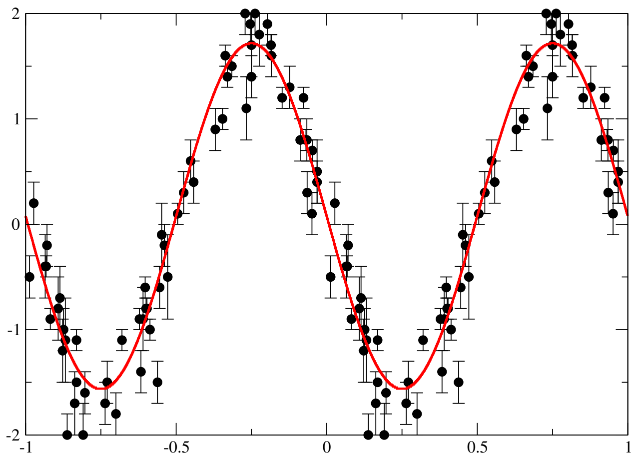

Figure 2: RVs measured from the 2019–2022 Búcke's data and the best fitting sinusoidal approximation.

The data sets analysis shows that the pulsation period of Polaris Aa was stable within 4.7 minutes (3.9733±0.0033 days), while the amplitude has been rising from ≈3.5 km s^{-1} to ≈3.5 km s^{-1} in 2011–2024. The average period is very close to that derived by Torres (2023), but a slight decrease predicted in this paper (see Fig. 6 there) is not obvious given the measurement uncertainties. The amplitude increase is consistent with the data shown in Fig. 9 from Torres (2023) and Fig. 4 from Bücke (2021). Our results are shown in Fig. 3.

Another result from our current study is the extension of the Polaris Aa/Ab binary orbit to the middle of 2024 (see Fig. 4). The relative TCO and Bücke's RVs were shifted to the heliocentric values

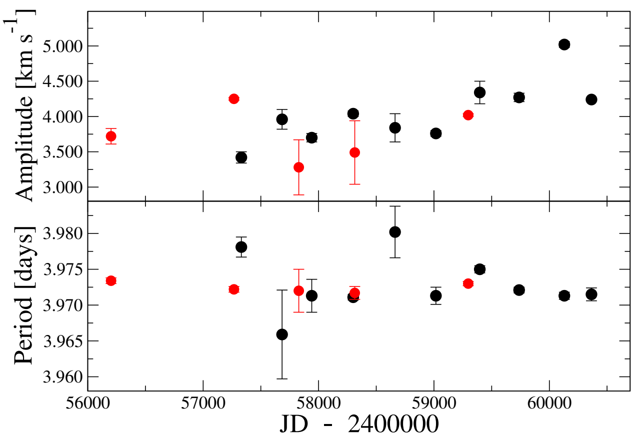

Figure 3: Variations of the pulsational amplitude (top panel) and period (bottom panel) of Polaris Aa. Symbols: black circles – TCO data, red circles – Bücke's data.

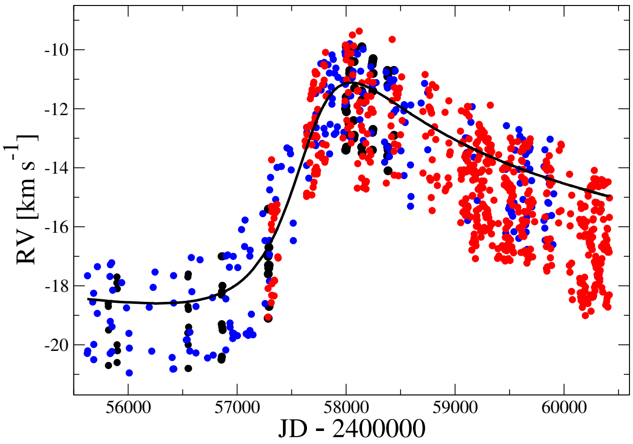

Figure 4: Updated orbit of the Polaros Aa/Ab binary system. Black circles represent data from Anderson (2019), blue circles show Bücke's data, and red circles show TCO data. Black solid line shows the orbital solution derived by Torres (2023), while the violet solid line shows the solution from Usenko et al. (2020).

from Anderson (2019) and compared to the orbital solution derived by Usenko et al. (2020) and Torres (2023). The comparison shows the RVs obtained after the last maximum achieved in 2017 decline faster than predicted. Since this orbital cycle is getting better and more accurately covered, it is important to continue monitoring the system to further improve the orbit and thus the system physical parameters.

5. Conclusions

The 583 RV observations obtained at TCO during the last ten years along with 164 RV data points published by Anderson (2019) and 236 ones obtained by Bücke (overall 983 measurements) covered a fragment of the Polaris Ab orbit, which contained passages through a periastron and an ascending node led us to the following conclusions.

1. The mean pulsational period during last four years has been stable within several minutes.

2. As mentioned earlier, the pulsation amplitude of Polaris Aa shows strong changes, which contain a growth before JD 2457350 with a subsequent decline. This decline has begun before the periastron passage, but the amplitude began increasing since 2021.

3. Our prediction (Usenko et al. 2020) that the pulsation amplitude would decrease after 2020 was wrong probably due to a different method of the data analysis. Apparently, after Polaris Ab passed the last periastron, the pulsation amplitude of the Polaris Aa Cepheid returns back to the pre-1960's level of 4 to 6 km s^{-1} (see Fig. 7 from Torres 2023).

4. Thus, we can assume that Polaris Aa is returning to the normal pulsating life of Cepheids. Therefore further Polaris Aa RV observations are essential during next coming years.

5. Orbital motion of Polaris Ab most likely influences the Polaris Aa pulsational amplitude.

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