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Nova Herculi 2021 as an intermediate polar

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Abstract. We report the results of observations of Nova Herculi 2021 - V1674 Her. The object is characterized by several exceptional properties. The progenitor was identified as an intermediate polar. The speed of the outflow reached 10000 km s^{-1}. The brightness decline was exceptionally rapid: $t_2 \cong 1.2\,d$, $t_3 \cong 3\,d$. The pulse spin signal was detected in photometry soon after the nova eruption. Extremely fast spin-up of the white dwarf rotation was measured. Despite challenges in cycle counting, we successfully constructed the O - C diagram of spin pulse maxima based on three seasons of observations. The result suggests a stable spin acceleration, with an anticipated gradual decline over the next decades. Additionally, we investigated the evolution of the orbital period.

Key words: cataclysmic variables – novae

1. Introduction

In recent years, the northern hemisphere has witnessed an elevated occurrence of nova eruptions. One of them is V1674 Her = Nova Herculi 2021. The nova outburst was discovered on 2021 June 12.537 UT by Seiji Ueda. Chandra satellite observed a strong X-ray signal with a period of 503.9 *s* (Maccarone et al., 2021). A similar period of 501.42 *s* was found by Mroz et al. (2021) in the Zwicky Transient Facility (ZTF) data obtained before the nova outburst. Another modulation with a period 0.15302(2) *days* was reported by Shugarov & Afonina (2021). A substantial set of fast photometry optical data collected within the Center for Backyard Astrophysics (CBA) network was analyzed by Patterson et al. (2022). They concluded that the progenitor of the nova is an intermediate polar. The short period was linked to the spin of the white dwarf, and the longer one with the orbital motion. They also reported the exceptionally rapid spin period change. We know several novae with intermediate polar as the progenitor. GK Per, V4745 Sgr, and V2487 Oph, among them. But this is the first case when we know the pre-outburst spin period.

We regularly make intermediate polar observations within the "Inter - Longitude Astronomy" project (Andronov et al., 2003). The primary objective is to monitor the spin period changes. The theory predicts oscillations between spin-up and spin-down. Most intermediate polars are observed spinning up (Patterson et al., 2020), possibly due to a selection effect associated with higher accretion rates linked to higher brightness. Our observational approach involves fast photometry runs lasting 3 - 4 hours, with the typical cadence of 1 run per month per target. This way, we can construct an O - C diagram of spin pulse maxima. Following the report of the pre-outburst spin period, we added V1674 Her to our list of observation targets.

2. Observations

In this work, we analyze data from two sites. On the Astronomical Observatory on Kolonica Saddle, the Vihorlat National Telescope VNT 1000/9000 mm and FLI PL1001E camera were used. The second site was M.R. Štefánik Observatory in Hlohovec, where Csere Telescope 600/2500 mm equipped with Atik 383L CCD Camera was employed. Both instruments work with B, V, Rc, Ic filters. However, the focus of our observing program primarily involved integral light without filters. The reason is the higher importance of a good signal-to-noise ratio for period analysis rather than color information. To effectively capture variations in the $\sim 8\,min$ spin period, we set the maximum exposure time at 120 s. The fast period change in this particular object requires a higher cadence of observations than in regular intermediate polar. So we made observations every suitable night. We were trying to accumulate observations on several consecutive nights to provide data for orbital period investigation. Ensemble differential photometry was employed for data reduction using CoLiTecVS (Kudzej et al., 2019) and MCV (Kim et al., 2004; Andronov & Baklanov, 2004) software packages.

In addition to our self-consistent dataset, we have used observations from the database of The American Association of Variable Star Observers (AAVSO), particularly focusing on the beginning of the 3^{rd} observing season. These observing runs were acquired just after the solar conjunction, resulting in short runs with a relatively large error in the mean time of spin maxima. Nonetheless, these data were crucial for correct cycle counting between 2^{nd} and 3^{rd} season of observations.

3. Analysis

We used the trigonometric polynomial approximation of the light curve implemented in MCV to determine spin maxima and orbital minima timings. We choose a 2 - periodic model in the form:

$$m(t) = m_0 + r_1 cos(\omega_1(t - T_{01})) + r_2 cos(\omega_2(t - T_{02})), \quad (1)$$

where $m(t)$ is the smoothed value of brightness at time t, m_0 is the average brightness of theoretical curve, $\omega_j = 2\pi/P_j$, r_j is the semi-amplitude, and T_{0j}

is the epoch for maxima of brightness of photometric wave with number j and period P_j. In our case, $j = 1$ corresponds to the spin modulation and $j = 2$ to the orbital wave. This method has been previously widely used for approximation of observations of intermediate polars (see Kim et al. (2005); Breus, Petrík, & Zola (2019)).

4. Results

4.1. Spin period

The O - C diagram of mean spin maxima for each observing night was generated based on the following ephemeris:

$$T_{max}[HJD] = 59392.4526 + 0.00580320E. \tag{2}$$

We take special care to keep correct cycle counting. However, the period change between 1^{st} (2021) and 2^{nd} (2022) season was large. There are several possible solutions for how to deal with it. We prefer the solution depicted in Fig. 1, as it can be reasonably approximated by a 3^{rd} order polynomial. But we can not exclude abrupt period change, for instance, in the seasonal gap between 2021 and 2022. So we plot only 2^{nd} order polynomial approximation for the data from 2^{nd} and 3^{rd} season. Such an approximation has a clear physical background. It is an acceleration of the white dwarf rotation, most likely due to the stable accretion of the mass with higher angular momentum. The following formula describes the approximation:

$$T_{max}[HJD] = 59392.447(2) + 0.00580349(5)E - 4.4(3) \times 10^{-12}E^2. \tag{3}$$

Equation (3) can be employed for future monitoring of the spin evolution.

O - C diagram is our main contribution to the investigation of V1674 Her. Patterson et al. (2022) analyzed a large dataset collected by CBA network citizen observers (our data from 2021 and 2022 included). But they didn't construct one O - C diagram for all data. Instead, they generated distinct plots for each season based on different spin periods. Using their method, we can list the mean spin period values in Tab. 1. Looking at the 3^{rd} column, one can compare it with other "normal" intermediate polars. The typical value of the spin-up period rate is $1 - 2$ milliseconds per year.

4.2. Orbital period

To investigate orbital period evolution, we constructed O - C diagram of times of minima of the orbital wave. Patterson *et al.* (2022) previously established that the orbital modulation displays two minima. It was difficult to distinguish between primary and secondary minima, especially in noisy data during low brightness of the target. However, precise TESS observations (Luna et al., 2023)

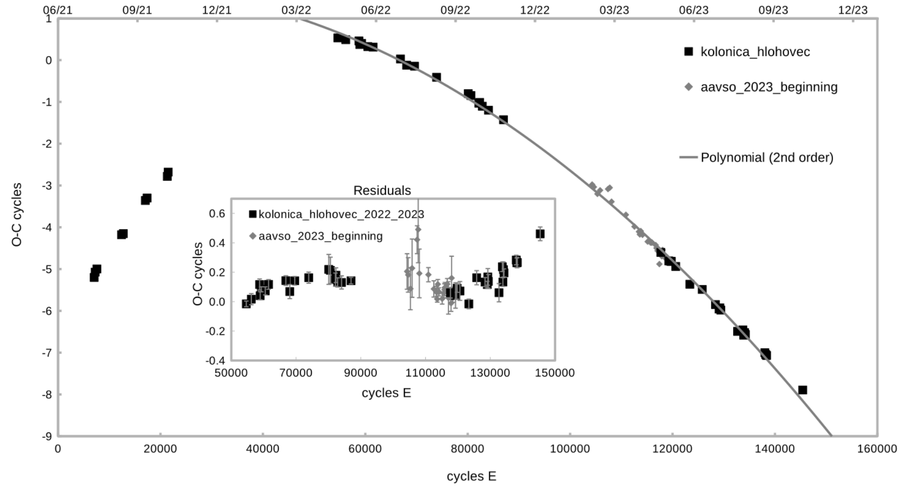

Figure 1. O-C diagram of spin pulse maxima.

Table 1. Mean spin period values for each observing season. Relative difference means the increase compared to the previous line. Absolute is the difference compared to the pre-outburst value.

Season	**Period**	**Difference** (relative)	**Difference** (absolute)
WD spin before nova event	$P_{spin} = 0.00580356\,d$		
WD spin in 2021	$P_{spin} = 0.00580417\,d$	$+53\,ms$	$+53\,ms$
WD spin in 2022	$P_{spin} = 0.00580315\,d$	$-88\,ms$	$-35\,ms$
WD spin in 2023	$P_{spin} = 0.00580260\,d$	$-47\,ms$	$-82\,ms$
Orbital motion	$P_{orb} = 0.152921d$		

revealed that secondary minima are exactly distant at $\Delta\,\phi\, =\, 0.5$ from the primary minimum. Therefore, we used half of the orbital period to plot the O - C diagram, employing the following ephemeris:

$$T_{min}[HJD] = 59400.636 + 0.0764605E. \tag{4}$$

The approximation plotted in the Fig. 2 is described by the following formula:

$$T_{min}[HJD] = 59873.817(5) + 0.0764574(9)E - 1.5(3) \times 10^{-9}E^2. \tag{5}$$

The approximation is far from perfect. It is evident that between 2021 and 2022, the orbital period was on the rise, consistent with expectations for super-

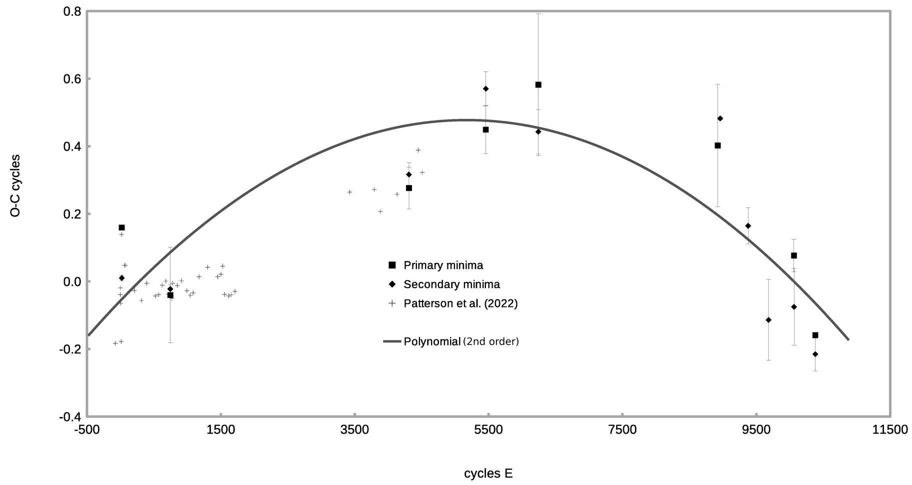

Figure 2. O-C diagram of orbital minima.

soft X-ray sources. The period shortening observed in 2023 is unexpected. It can be a short-term event or a long-term trend. In any case, if confirmed, it will require a theoretical explanation.

5. Conclusions

– We confirm an extremely fast spin-up after the nova eruption.

– Based on recent spin maxima measurements, we can conclude that following the turbulent period associated with the nova eruption, the system is now in a stable spin-up phase. The future evolution is expected to follow the provided ephemeris.

– The brightness is also stable, still 3 mag above the pre-eruption level. The difference could be attributed to the intermediate polar being in a low accretion, the spin-down phase just before the eruption.

– Evaluation of the orbital period evolution requires a more extended time baseline.

– For future research we provide calculated times of pulse maxima from our observations. They are listed in the Tab. 2. Orbital minima are provided in the Tab. 3.

Table 2. Spin pulse maxima timings in BJD - 2400000. BJD based on UTC.

59392.4526	59403.4640	59516.2187	59796.4009
59394.5963	59404.4282	59517.2523	59821.3880
59394.5787	59409.3899	59709.4903	59860.2959
59393.3941	59410.4580	59718.4792	59857.3133
59393.3892	59413.4425	59733.3991	59869.2898
59395.4433	59433.3640	59734.4200	59870.2706
59395.4436	59434.4267	59736.4570	59873.2646
59397.4402	59436.4351	59743.4669	59880.2801
59397.4407	59464.3474	59749.4731	59897.2125
59401.4382	59466.3671	59758.3849	60075.4916
59401.4385	59491.3081	59780.4547	
59402.4539	59493.2873	59787.4409	

Table 3. Orbital minima timings in BJD - 2400000. Values featuring a colon symbol represent what, in our opinion, are secondary minima.

59402.166 :	59730.205 :	60083.000	60170.052 :
59402.177	59817.992	60085.759 :	60194.356 :
59457.597 :	59818.077 :	60117.619 :	60194.360
59457.672	59878.013 :	60140.994 :	
59730.202	59878.100	60169.987	

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