Dwarf nova EZ Lyncis second visit to instability strip

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Abstract

The analysis of 14 periodograms of EZ Lyn for data spaced over 565 d in 2012–2014 (2–3.5 yr after the 2010 outburst) yielded the existence of a stable signal around 100 cycles/day (c/d) and three signals around 310 c/d, 338 c/d, and 368 c/d (the corresponding periods are 864 s, 279 s, 256 s, and 235 s). We interpret them as independent nonradial pulsations of the white dwarf in EZ Lyn, but the possibility that a linear combination of a frequency of 100 c/d and a harmonic of the orbital period might produce a frequency of 368 c/d also cannot be excluded. The signal at 100 c/d was detected as a transient during the first stay in the instability strip. The period at 338 c/d has been a known nonradial pulsation since EZ Lyn entered the instability strip after the 2010 outburst. We detected the signals around 310 c/d and 368 c/d for the first time. We applied the two-dimensional least absolute shrinkage and selection operator (Lasso) analysis for the first time to explore the behavior of these signals on a time scale of hours in nightly runs of observations having a duration of 6–12 hr. The Lasso analysis revealed the simultaneous existence of all three frequencies (310 c/d, 338 c/d, and 368 c/d) on a majority of nights of observations, but with variable amplitudes and variable drifts of frequencies by 2%–6% on a time scale of ~5–7 hr. The largest drift we detected corresponded to 17.5 s in period in ~5 hr.

Key words: accretion, accretion disks — novae, cataclysmic variables — stars: dwarf novae — stars: individual (EZ Lyncis) — stars: oscillations

1 Introduction

A cataclysmic variable (CV) is a close binary system containing a late-type component transferring matter via the inner Lagrangian point onto the primary component, which is a white dwarf. Due to angular momentum loss, a CV with the hydrogen-dominant atmosphere evolves to an orbital period minimum of 76.2 min (Knigge 2006) with a decrease in the mass transfer rate of up to $10^{-11} M_{\odot} \text{yr}^{-1}$.
(Howell et al. 1995; Kolb & Baraffe 1999). The last circumstance enables the dominance of the white dwarf in the total radiation of the CV, and such short-period systems are attractive for studies of the white dwarf, in particular for the search for white dwarf pulsations. Indeed, since 1998 nonradial pulsations of 13 accreting white dwarfs have been found in cataclysmic variables. They are GW Lib (Warner & van Zyl 1998), PQ And (Vanlandingham et al. 2005), V455 And (Araujo-Betancor et al. 2005), SDSS J133941.11+484727.5 = V355 UMa (Gänsicke et al. 2006), SDSS J091945.11+085710.1 (Mukadam et al. 2007), SDSS J151413.72+454911.9 = PP Boo (Nilsson et al. 2006), SDSS J074531.91+453829.5 = EQ Lyn (Mukadam et al. 2007), RE J1255+266 (Patterson et al. 2005), SDSS J150722.33+523039.8 = OV Boo (Patterson et al. 2008; Szkody et al. 2010), SDSS J080434.20+510349.2 = EZ Lyn (Pavlenko 2009), SDSS J161033.64−010223.3 = V386 Ser (Woudt & Warner 2004), SDSS J145758.21+514807.9 (Uthas et al. 2012), and BW Cen (Uthas et al. 2012). With the exception of two (OV Boo and RE J1255+266), their orbital periods are within a range of 80–90 min.

Knowledge of white dwarf pulsations is important for measuring their stellar mass, core composition, age, rotation rate, magnetic field strength, and distance (Winget & Kepler 2008; Fontaine & Brassard 2008).

EZ Lyn was discovered by Szkody et al. (2006) to be a short-period (0.059 d) quiescent dwarf nova with an underlying white dwarf. Pavlenko et al. (2007) first found it at the superoutburst. The large amplitude and series of 11 rebrightenings implied that this star belongs to the WZ Sge-type subclass of dwarf novae. After the outburst, Zharkov et al. (2008) found a series of minioutbursts with an amplitude of about 0.5 mag.

In 2010, EZ Lyn had experienced the next superoutburst, which was discovered by H. Maehara (Kato et al. 2012). Contrary to the 2006 superoutburst, the 2010 superoutburst had six rebrightenings that are almost twice less numerous than in the 2006 superoutburst. One month after the end of the main outburst, EZ Lyn was ~1 mag fainter in the 2010 outburst than in the 2006 one.

The superhump period of EZ Lyn is 0.060 d (Shears et al. 2007; Pavlenko et al. 2007; Kato et al. 2009), and its orbital period is 0.059005 d (Kato et al. 2009). Kato et al. (2009) first clarified the grazing eclipse of EZ Lyn during the 2006 superoutburst.

Eight months after the 2006 outburst, Pavlenko (2009) discovered the 756 s (12.6 min) brightness modulation that was interpreted as nonradial pulsation of the white dwarf. This pulsation has been regularly detected and has displayed a drift from 732 s to 768 s on a scale of ~900 s (Pavlenko et al. 2012), and this wandering did not depend on the time. Besides this stable dominant period, other periodic signals have appeared from time to time between 846 s and 1302 s (Pavlenko et al. 2012).

Seven months after the 2010 outburst, EZ Lyn entered the instability strip for the second time, but with a new 256–257 s pulsation (Pavlenko et al. 2012; Szkody et al. 2013). The drift of the pulsation period as well as the change of pulsation amplitudes appears to be a common feature of accreting pulsators (Mukadam et al. 2010; Uthas et al. 2012). However, we are not clear what could be the shortest time scale of pulsation drift and change in amplitude.

Here, during the second stay of EZ Lyn in the instability strip, we present a detailed study of its periodic signals that are shorter than its orbital period. We used least absolute shrinkage and selection operator (Lasso) analysis (Tibshirani 1996; Kato & Uemura 2012) for the first time for studying the behavior of such signals on a time scale of hours.

### 2 Observations and data reduction

Observations of EZ Lyn have been carried out at the Crimean Astrophysical Observatory, the Terskol Observatory, and at TUBITAK National Observatory (Turkey) with the Russian-Turkish 1.5 m telescope (RTT150) in 2012–2014 over 14 nights. Standard aperture photometry (de-biasing, dark subtraction, and flat-fielding) was used for measuring EZ Lyn and comparison stars. We used the same comparison stars as Zharkov et al. (2008). The observations have been carried out without the use of filters. Typical accuracy of the Crimean and Terskol observations was 0.005–0.017 mag and that of the TUBITAK observations was 0.005–0.017 mag.

| Time BJD 2456000+ | Telescope/CCD* | Exposure (s) | N† |
|-------------------|----------------|--------------|----|
| 236.360−236.619   | A              | 60           | 242|
| 237.341−237.488   | A              | 45           | 181|
| 244.518−244.626   | A              | 60           | 120|
| 245.336−245.623   | A              | 45           | 415|
| 247.340−247.627   | A              | 60           | 304|
| 248.388−248.627   | A              | 90           | 202|
| 249.333−249.488   | B              | 30           | 246|
| 250.427−250.661   | B              | 20           | 716|
| 306.238−306.579   | B              | 30           | 579|
| 307.156−307.672   | B              | 20           | 1785|
| 385.208−385.259   | B              | 15           | 259|
| 697.184−697.676   | B              | 30           | 738|
| 711.407−711.547   | C              | 60           | 200|
| 801.298−801.370   | B              | 30           | 159|

* A: 2 m Terskol/FLI PL430; B: 2.6 m ZTSh/Apogee E47; C: 1.5 m RTT-150/TFOSC.
† N: Number of images.
data was \( \sim 0.025 \) mag. The observation log is given in table 1. Before the analysis we subtracted a smooth long-time trend for each night by using locally weighted polynomial regression (LOWESS: Cleveland 1979). The times of observations are expressed in barycentric Julian Date (BJD). We used a phase dispersion minimization (PDM: Stellingwerf 1978), whose 1\( \sigma \) error was estimated by the methods of Fernie (1989) and Kato et al. (2010), and fast Fourier transform (FFT: the ISDA package, Pel’t 1980). The false alarm probability (FAP) was estimated according to Scargle (1982).

Lasso was introduced to the period analysis of variable stars for the first time by Kato and Uemura (2012), and yielded very sharp signals. A two-dimensional Lasso power spectrum was found to be very effective in detecting varying multiple signals in Kepler observations of CVs (Kato & Maehara 2013; Osaki & Kato 2013; Kato & Osaki 2013). This method has been applied to unevenly sampled ground-based data (Kato et al. 2014; Ohshima et al. 2014), and the resultant two-dimensional Lasso power spectra have been proven to have a high resolution of frequency and are less affected by aliasing in unevenly sampled data than the result through the conventional Fourier analysis.

### 3 Periods

The complexity in the analysis of potential pulsations of the white dwarf in EZ Lyn is that they are contaminated by the orbital modulation. Both signals may
Fig. 2. FFT for the nightly data of EZ Lyn in 2012–2014. The number in each frame denotes the last three digits of JD. The positions of dominant pulsation at 756 s and 235 s are shown by the solid line, and those at 864 s, 279 s, and 256 s are shown by the dotted line. The horizontal dotted line denotes the 0.1% FAP level.
be variable amplitudes (Szkody et al. 2006; Pavlenko 2009), but the orbital signal is a typically dominant one. The PDM spectrum and the phase-averaged profile folded on the mean orbital period (affected by the lower-amplitude pulsations) for the data of 2013 January 14 are presented in figure 1. The strong first harmonic of the orbital signal is caused by the two-humped profile of the light curve. Its average amplitude is 0.08 mag; a grazing eclipse at the phase 0.7 is clearly seen. For this pattern the two humps are slightly unequal in height; the smaller amplitude hump precedent to the eclipse has a small depression. This “splitting” of one or two humps could sometimes be more prominent, and the periodograms of EZ Lyn often show the peak at 1/4 of the orbital period (Pavlenko 2009; Kato et al. 2009).

For each night’s data we subtracted the orbital modulation with its first harmonic (that is consistent with the two-humped curve) and calculated the power spectrum. The result is shown in figure 2.

All the spectra show indications of the periodic signals in both the low- and high-frequency regions. The signal at around the frequency 100 cycles/day (c/d) (864 s) is certainly seen every night (the exception is BJD 2456237, when the significance of this signal was much lower compared with other nights). The signal at around 1/4 of the orbital period is visible on all nights. The signal at 756 s, the dominant pulsation after the 2006 outburst, was apparently a transient one, and it is definitely detected only on BJD 2456306, 2456307, and 2456697.

Meanwhile, the behavior of the high-frequency signals is more complex and needs detailed analysis.

The first power spectrum in this figure corresponds to observations obtained ∼2 yr after the 2010 outburst of EZ Lyn (BJD 2456236). The 256 s pulsation, detected by Pavlenko et al. (2012) seven months after the 2010 outburst and Szkody et al. (2013) five months later, is the prominent and dominant one in the high-frequency part of the periodogram. But on the next night the spectrum changed dramatically. The 256 s pulsation disappeared (or at least its amplitude was reduced to the noise level). Instead, one can see the marginal signals at 279 s and 235 s.

One week later (BJD 2456244) the strong 235 s signal was detected. It remained the dominant one at least during the following week (BJD 2456244–2456250). At the same time, the signal at 279 s became prominent from BJD 2456248 and its amplitude increased till BJD 2456250. Again this signal practically fell below the noise level on BJD 2456306 and recovered on BJD 2456307. Since this date, the 279 s signal has been registered as the
dominant one in the high-frequency region. The signal at 256 s was detected close to the 0.1% FAP only on BJD 2456245 and BJD 2456250.

We suggest that all pulsations at the frequencies 100 c/d, 310 c/d, 338 c/d, and 368 c/d (the corresponding periods are 864 s, 279 s, 256 s, and 235 s) could be independent modes. However, there is an apparent linear combination of frequencies at 100 c/d ($F_{100}$), 368 c/d ($F_{368}$), and a harmonic of the orbital period ($F_{\text{orb}}$): $F_{368} = 3F_{100} + 4F_{\text{orb}}$. So this interpretation also cannot be excluded.

There was a similar problem to the identification of several pulsations in V386 Ser. While Woudt and Warner (2004) identified some pulsations as independent ones, Mukadam et al. (2010) argued that they could be caused by a linear combination of the orbital frequency and the frequency of another known pulsation.

### 4 Two-dimensional Lasso analysis

We calculated the two-dimensional Lasso analysis for each of 14 nights separately in the region of frequencies around 100 c/d and in the region around the high frequencies 275–400 c/d.

In figure 3 the Lasso spectra are shown for five closely spaced nights in 2012 November. It seems that these frequencies form a drift from night to night and even within a night.

More detailed behavior of this frequency is shown for the longest nightly data on BJD 2456307 (figure 4). This frequency displays a smooth quasi-periodic wandering within 98–100 c/d (or within ∼17 s) with a typical time of ∼4 hr.

To study the periods in the high frequency region, we selected the patterns for the longest time series (6–12 hr) on BJD 2456236, 2456245, 2456247, 2456248, 2456250, 2456307, and 2456697 and present them in figures 5, 6, 7, 8, 9, 10, and 11. After consideration of the two-dimensional power spectra, it became evident that they give information on the behavior of detected periods over several hours. First, there are indications of the simultaneous coexistence of all three periods around 279 s, 256 s, and 235 s (corresponding to frequencies of 310 c/d, 338 c/d, and 368 c/d) for a majority of the observations.

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**Fig. 4.** Above: Light curve on BJD 2456307. Below: Lasso analysis (log $\lambda = -2.8$). The width of sliding window and the time step used are 0.15 d and 0.005 d, respectively.
Fig. 5. Above: Light curve on BJD 2456236. Below: Lasso analysis ($\log \lambda = -2.8$). The width of sliding window and the time step used are 0.15 d and 0.005 d, respectively.

Fig. 6. Above: Light curve on BJD 2456245. Below: Lasso analysis ($\log \lambda = -2.8$). The width of sliding window and the time step used are 0.15 d and 0.005 d, respectively.
Fig. 7. Above: Light curve on BJD 2456247. Below: Lasso analysis (log $\lambda = -2.8$). The width of sliding window and the time step used are 0.15 d and 0.005 d, respectively.

Fig. 8. Above: Light curve on BJD 2456248. Below: Lasso analysis (log $\lambda = -2.8$). The width of sliding window and the time step used are 0.15 d and 0.005 d, respectively.
Fig. 9. Above: Light curve on BJD 2456250. Below: Lasso analysis (log $\lambda = -2.8$). The width of sliding window and the time step used are 0.15 d and 0.005 d, respectively.

Fig. 10. Above: Light curve on BJD 2456307. Below: Lasso analysis (log $\lambda = -2.8$). The width of sliding window and the time step used are 0.15 d and 0.005 d, respectively.
nights. Secondly, the domination of these periods could change within several hours due to the nonsynchronous increase or decrease of their amplitudes and to some drift of period.

The data on BJD 2456236 show that the amplitude of the signal at the dominant frequency around 338 c/d was higher for the initial several hours. There is no clear indication of a signal at 368 c/d and there is some indication of a weak signal at 310 c/d of variable amplitude and phase. The signal at the dominant frequency around 368 c/d looks stable in its amplitude and period on BJD 2456245. There is a weaker but prominent signal at 338 c/d, which is stronger during the first hours of the observation. The frequency of this signal shows some decrease with time. The signal at frequency around 368 c/d on BJD 2456247, 2456248, and 2456250 remains the dominant one. The signal at frequency 338 c/d is rather marginal on BJD 2456247 and BJD 2456248, but is strong on BJD 2456250. The signal at frequency 310 c/d is strong on all these nights.

The longest 12 hr data set on BJD 2456307 revealed the signal at 310 c/d of variable amplitude and near-constant period that produces the dominant peak on the FFT periodogram. The most unusual thing is the behavior of a rather strong signal that varies in frequency between 340 c/d and 352 c/d (this variation corresponds to 9 s in period) quasi-periodically on a typical time scale of ~7 hr. This causes a “smeared” peak on the FFT periodogram. We believe this signal is related to that at frequency 338 c/d. Using all the data set, this signal varied by more than 9 s in period. There was no strong indication of the signal at 368 c/d.

The two-dimensional power spectrum on BJD 2456697 only shows a signal at 310 c/d with a highly variable amplitude and increasing frequency from ~305 c/d to ~325 c/d that corresponds to the drift of 17.5 s in period in ~5 hr.

5 Summary

The analysis of 14 periodograms of EZ Lyn for data spaced over 565 d in 2012–2014 (2–3.5 yr after the 2010 outburst) yielded the existence of several signals and their evolution. These are signals at frequencies 100 c/d, 310 c/d, 338 c/d, and 368 c/d (the corresponding periods are 864 s, 279 s, 256 s, and 235 s). We believe that these signals arise from nonradial pulsations in the accreting white dwarf.

The transient appearance of pulsation at 846 s was detected during the first stay of EZ Lyn in the instability
strip (Pavlenko 2009; Pavlenko et al. 2012), and the pulsation at 256 s was the pulsation when EZ Lyn entered the instability strip for the second time. We detected the pulsations at 279 s and 235 s for the first time. We suggest that all pulsations could be independent modes, although a linear combination of frequencies at 100 c/d, 368 c/d, and a harmonic of the orbital period also cannot be excluded.

Our knowledge of a fast change in pulsation period and amplitude before this work had been rather limited. Recently, Uthas et al. (2012) reported that pulsations in accreting white dwarfs, BW Scl and SDSS J145758.21+514807.9, change in frequency by a few percent on a time scale of weeks or less; Chote and Sullivan (2013) found that in GW Lib a strong nonsinusoidal pulsation with a 19 min period varied slightly in frequency over the six nights of observations.

Here we showed that the pulsations of EZ Lyn change in frequency by 2%–6% on a time scale of hours and their amplitude may change on the same time scale. We found that Lasso is very powerful in detecting multiple frequencies and their variations in pulsating white dwarfs.

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