Revisiting the Period Change and Frequency Analysis of a Variable Star SZ Lyncis

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Abstract

This study aims to investigate the period change of the variable star SZ Lyncis. The observations were conducted at the Regional Observatory for the Public, Nakhon Ratchasima (ROP-NMA), operated by the National Astronomical Research Institute of Thailand (NARIT), on January 8th-9th and February 19th-20th 2024. The data was acquired using the CCD camera with a *B*-filter mount on the 0.7-m reflecting telescope. We report the period change of $1.37(\pm0.08)\times10^{-12}$ day cycle^{-1}. Analysis of the O-C diagram revealed the presence of a binary companion with a semi-amplitude of 0.0052(±0.0002) days, the projected semi-major axis of 0.90(±0.04) AU, the eccentricity of 0.25(±0.09), and the orbital period of 1184.1(±1.5) days and the mass function of 0.07(±0.01) M⊙. We also identified the time-series light curve data using the Discrete Fourier transform (DFT) in the Period04 package and obtained results of four frequencies. The main frequency of 8.29630(±0.00002) cycle day^{-1} corresponds to a period of 0.1205357(±0.0000003) days. These results contribute to our understanding of the pulsation properties of SZ Lyncis and its binary system.

Keywords: Variable star, Period change, SZ Lyncis

Introduction

The variable star is a sky object that demonstrates variable brightness over time. It is classified into two types: intrinsic variable stars and extrinsic variable stars. A variable star is very important for studying the evolution of stars. Many different types of variable stars play a crucial role in the understanding of stellar structure and evolution. Among these, pulsating stars hold particular significance. The oscillation frequencies observed in these stars, a method known as asteroseismology, act as a probe into their internal structure. Asteroseismology provides detailed insights into the star's internal layers, allowing astronomers to determine properties such as density, temperature, and chemical composition, which deepens our understanding of stellar evolution. One of the most prominent groups of pulsating stars is the Delta Scuti variables (Kahraman 2023).

SZ Lyncis (R.A. = $8^h\ 9^m\ 35.75^s$, Dec. = +44° 28′ 17.60″, V = 9.08) is a Delta Scuti type pulsating variable star (Li & Qian, 2013). The investigation of pulsation frequencies and period change among Delta Scuti-type pulsating variable stars is crucial for estimating their pulsation modes and evolutionary paths.

Van Genderen (1967) discovered a period variation of SZ Lyncis of 1129 days for SZ Lyncis using the O-C diagram when O defines the observation time and C is the calculation time of light maximum. Barnes and Moffett (1975) suggested that SZ Lyncis is a single- lined spectroscopic binary with a period of 1146±10 days, a semi-amplitude of 494±16 seconds, and a total velocity of 19 km s^{-1}. Moffett et al. (1988) reported the SZ Lyncis's pulsation period of 0.12052115 days, a secular period change of 3×10^{-12} days cycle^{-1}, a period variation of the binary at 118.1 days, and an orbital eccentricity of 0.188. Recently, Li and Qian (2013) analyzed the O-C diagram of SZ Lyncis, showing that the variation of the O-C diagram can be attributed to a close binary system, indicating that the component of SZ Lyncis is a binary system. Expanding on their findings, our study not only confirms the observed period changes but also identifies a previously unreported fourth frequency. This discovery offers new insights into the star's pulsation behavior and provides refined orbital parameters, contributing to a deeper understanding of the system's evolution.

The interest in SZ Lyncis lies in its period variation caused by the component binary. Therefore, we will analyze the O-C diagram to confirm the period variation due to the component of SZ Lyncis. This analysis aims to address the specific research question of whether the period changes observed in SZ Lyncis are consistent with the effects of its binary component, thereby providing a clear direction for our study.

Materials and Methods

1. Observation and data reduction

The observation of SZ Lyncis was conducted at the Regional Observatory for the Public, Nakhon Ratchasima (ROP-NMA) operated by the National Astronomical Research Institute of Thailand (NARIT), using a CCD camera (model ProLine PL16803) equipped with a *B*-filter attached to the 0.7-m reflecting telescope during 8,9 January and 19,20 February 2024. The ROP-NMA is located at a latitude of 14° 52′ 25″ N, and longitude 102° 1′ 44″ E, and an elevation of 250 m above sea level. The exposure time for each image was set to 10 seconds. All images were reduced and subjected to using the AstroImageJ software program (Collins et al., 2017). Detailed information about SZ Lyncis, regarding the reference star and the check star, is listed in Table 1, while the image captured during our observation is presented in Fig. 1.

Table 1 The details of SZ Lyncis, a referenced star, and the checked star (The SIMBAD astronomical database)

Star	R.A.(J2000)	Dec.(J2000)	*B* magnitude
SZ Lyncis	$8^h\ 9^m\ 35.75^s$	+44° 28′ 17.60″	9.73
TYC2979-1329-1 (Referenced star)	$8^h\ 9^m\ 55.82^s$	+44° 25′ 48.67″	11.83
TYC2979-657-1 (Checked star)	$8^h\ 9^m\ 46.68^s$	+44° 19′ 30.90″	12.27

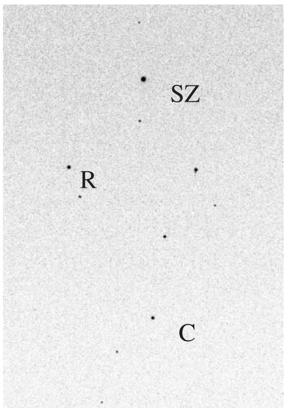

Figure 1 The image of SZ Lyncis, the referenced star (R) and the checked star (C) from our observation

2. Data analysis

The light curve obtained from our observation is shown in Figure 2. We determined the time of maximum light using the Kwee and van Woerden fitting method (Kwee & van Woerden 1956; Deeg, 2020). This analysis yielded seven new light maxima times, which are presented in Table 2. Additionally, we included the light maxima times reported by Li and Qian (2013) in our analysis.

Table 2 The result of computed light maxima times for SZ Lyncis

HJD	Epoch	O-C
2460318.17137(±0.00001)	62570	0.0024
2460318.29208(±0.00001)	62571	0.0025
2460318.41210(±0.00001)	62572	0.0020
2460319.25656(±0.00001)	62579	0.0027
2460319.37699(±0.00001)	62580	0.0026
2460360.11759(±0.00001)	62918	0.0023
2460361.08094(±0.00001)	62926	0.0014

To analyze the O- C diagram, we adopted the linear ephemeris from Li and Qian (2013) to calculate the O-C value. The equation is defined as:

$$HJD_{\max} = 2452776.28105(\pm 0.00021) + 0.120535208(\pm 0.000000023) \times E. \quad (1)$$

This equation determines the times of the light maximum (HJD_{max}) based on the epoch number (E). Our modifications include refined parameters for the epoch and the pulsation period, improving the accuracy of the O-C values derived from the light curve data. The resulting O-C diagram for SZ Lyncis is shown in Fig. 2, showing the period changes that indicate the presence of a binary companion.

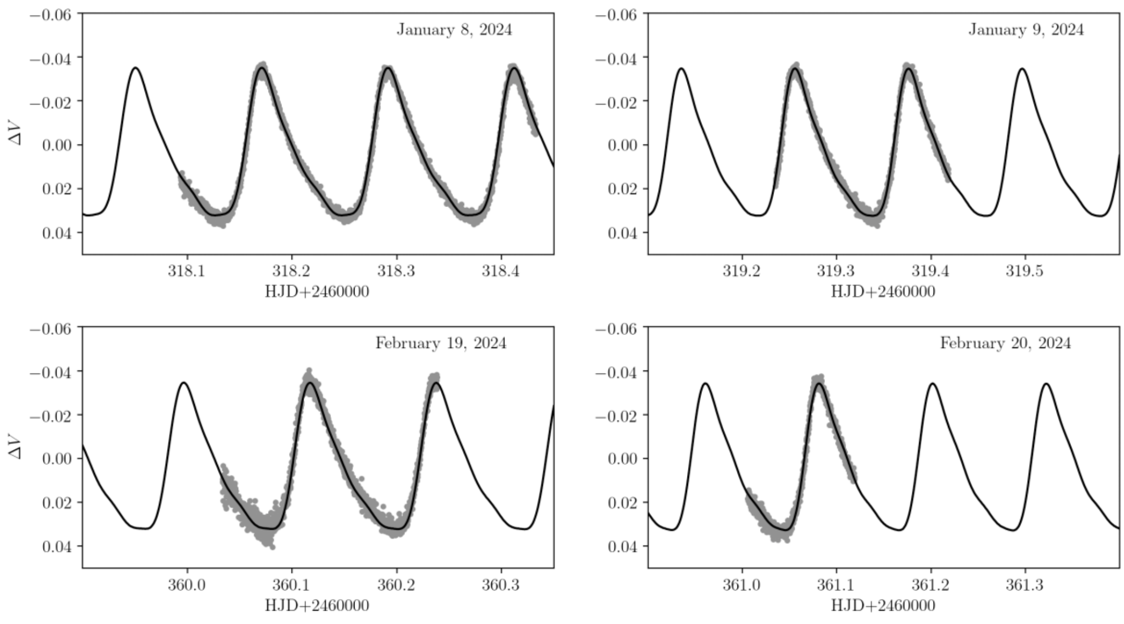

Figure 2 The resulting light curve of SZ Lyncis

Results

1. Period variation

The O- C diagram of SZ Lyncis shows an upward parabolic trend, indicating the period change of $1.37(\pm 0.08)\times 10^{-12}$ day cycle^{-1}. This period variation of the O-C diagram was analyzed using the light travel-time effect (LTT) described by Equation (2), which was proposed by Irwin (1952) as follows:

$$O - C = \Delta T_0 + \Delta P_0 E + \frac{1}{2}\beta E^2 + \tau, \quad (2)$$

$$\tau = K\left[(1-e^2)\frac{\sin(\nu+\omega)}{1+e\cos\nu} + e\sin\omega\right],$$
$$= K\left[\sqrt{(1-e^2)}\sin E^*\cos\omega + \cos E^*\sin\omega\right], \quad (3)$$

where τ is the sinusoidal term for light travel-time (LTT) effect, ΔT_0 is the revised epoch, ΔP_0 is the revised orbital period, β is the rate of period change, e is the orbital eccentricity, ν is the true anomaly, and ω is the longitude of the periastron passage. While the K represent the semi- amplitude of the light travel time effect, which can be expressed as:

$$K = \frac{a\sin i}{c}, \quad (4)$$

where $a\sin i$ represents the projected semi-major axis and c is the speed of light. The parameter E^* can be solved by the equation as follows:

$$N = E^* - e\sin E^* = \frac{2\pi}{P}(t - T), \quad (5)$$

where N represent the mean anomaly, t is the time of maximum, and T is the periastron passage. We can also estimate the mass function $f(m)$ of SZ Lyncis according to the third Kepler law, which is given by:

$$f(m) = \frac{(a\sin i)^3}{P^2}, \quad (6)$$

where $f(m)$ is the mass function ($M_\odot$). The results of the orbital elements of SZ Lyncis are presented in Table 3 and the O-C diagram for this system is shown in Figure 3.

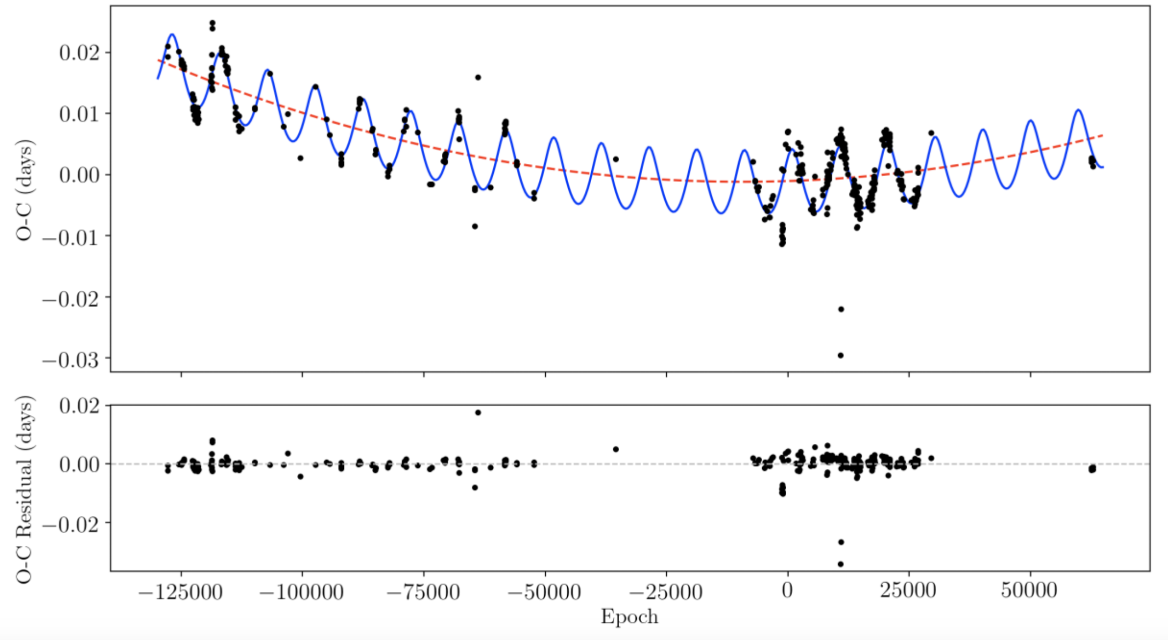

Figure 3 The O-C diagram of SZ Lyncis. The upper panel shows the observed data points. The red dashed line represents the quadratic fit derived from Equation (2), while the blue solid line represents the linear ephemeris from Equation (1). The lower panel displays the O-C residual diagram of SZ Lyncis

Table 3 The orbital element of SZ Lyncis

Parameters	Results
ΔT_0	-0.0011(±0.0003)
ΔP_0	2.6(±0.8)×10^{-9}
β (day cycle^{-1})	1.37(±0.08)×10^{-12}
K (day)	0.0052(±0.0002)
e	0.25(±0.09)
$a\sin i$ (AU)	0.90(±0.04)
ω(degree)	83(±22)
P(day)	1184.1(±1.5)
T(day)	2445762(±69)
$f(m)$ ($M_\odot$)	0.07(±0.01)

Additionally, the O-C diagram of SZ Lyncis shows that the data is not continuous. However, our results of the O-C diagram analysis are closely Li and Qian (2013). For the O-C diagram analysis to be clear, more continuous observation is needed.

2. Frequency analysis

We used the Period04 software package (Lenz & Breger 2005) to analyze the frequency of SZ Lyncis. This software utilizes discrete Fourier analysis and pre-whitening techniques to extract periodic signals from astronomical time series data, by following the formula:

$$m(t) = Z + \sum_{i=1}^{n} A_i sin[2\pi(\omega_i t + \phi_i)],$$

where m is the magnitude at a time, Z is the zero point, A_i is the amplitude, ω_i is the frequency, and ϕ_i is the phase.

The result shows a fundamental frequency (f_0) of 8.29630 (±0.00002) cycle day^{-1} that corresponds to a main pulsation period of 0.1205357 (±0.0000003) days. The light curve of SZ Lyncis obtained from the Period04 software package is presented in Figure 4. Additionally, we obtained the three harmonic frequencies: $2f_0$, $3f_0$, $4f_0$, which are presented in Table 4. The results satisfy the signal-to-noise ratio (S/N), which is greater than the four established by Breger et al. (1993). The power spectrum of the high-amplitude light curve is shown in Figure 5.

Table 4 The results obtained from the Period04 software package

Mode	Frequency (cycle day^{-1})	Amplitude(mmag)	Phase(rad)	S/N
f_0	8.29630(±0.00002)	29.69(±0.04)	0.8379(±0.0002)	79.75
$2f_0$	16.59260(±0.00005)	10.18(±0.04)	0.0720(±0.0006)	49.56
$3f_0$	24.91330(±0.00014)	3.87(±0.05)	0.9647(±0.0018)	25.86
$4f_0$	33.18590(±0.00031)	1.72(±0.03)	0.8380(±0.0034)	17.92

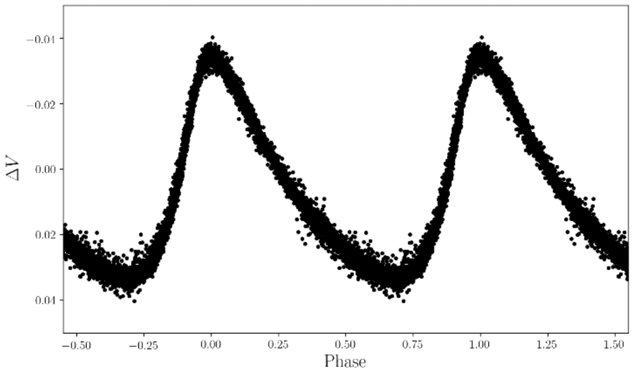

Figure 4 The light curve of SZ Lyncis with the main pulsation period obtained from Period04 software package

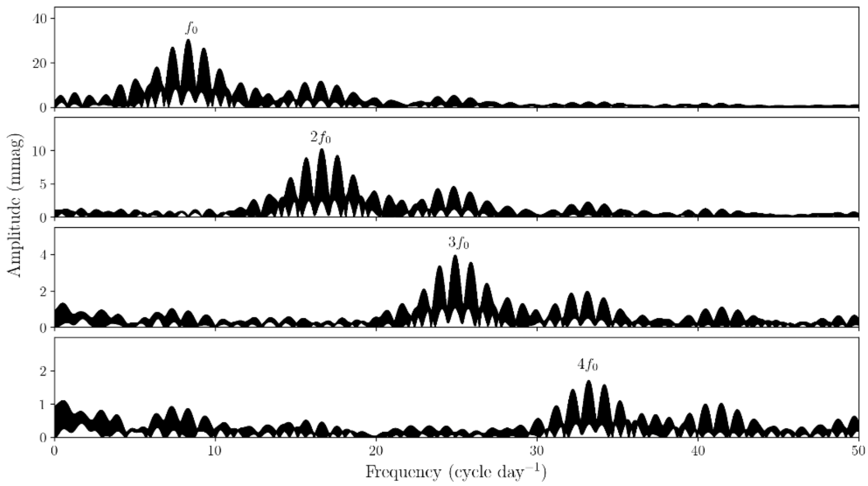

Figure 5 The power spectrum of the high amplitude of SZ Lyncis in each frequency obtained from Period04 software package

Discussion

Our analysis of the O- C diagram shows a long- term period increase of 1.37(±0.08)×10^{-12} day $cycle^{-1}$. This value aligns with the observed period changes in many delta Scuti stars, including V2455 Cyg (Ostadnezhad et al., 2020) and is comparable to theoretical predictions (Breger & Pamyatmyk 1998). For the evolutionally with a period increasing might be the T_{eff} and M_{bol} decrease (Wang et al., 2014). While Li and Qian (2013) suggested a binary component as a possible explanation for the period variation, our orbital element determination yielded results similar to theirs. The derived orbital parameters include a semi-amplitude of 0.0052(±0.0002) days, a projected semi-major axis of 0.90(±0.04) AU, an eccentricity of 0.25(±0.09), and an orbital period of 1184.1(±1.5) days. The calculated mass function of the system is 0.07(±0.01) $M_\odot$. These findings suggest that the system may be undergoing evolutionary changes, likely linked to mass transfer or angular momentum loss within the binary system. This contributes to our understanding of the evolutionary paths of Delta Scuti stars, as period variations can indicate changes in stellar structure. Furthermore, these findings enhance our knowledge of pulsation characteristics in such stars, showing how binary interactions may influence pulsation modes and periods in multi-frequency radial pulsators like SZ Lyncis.

The frequency analysis of SZ Lyncis using the Period04 software (Lenz & Breger 2005) identified four frequencies in the data (refer to Table 4). The main frequency of 8.29630(±0.00002) cycles day^{-1} corresponds to a pulsation period of 0.1205357(±0.0000003) days (Fig. 4). This confirms SZ Lyncis as a multi-frequency radial pulsation variable star, consistent with the findings of Adassuriya et al. (2021), who reported a fundamental mode of 8.296 cycles per day, a value very close to our result. In addition, when comparing the derived orbital parameters from our O-C diagram analysis with those from previous studies, such as Li and Qian (2013) Adassuriya et al. (2021), we observe similar trends in the period variations and binary companion characteristics. This comparison provides a more comprehensive view of the binary system and its potential evolution. Radial pulsations cause the star's radius to rhythmically increase and decrease, explaining the observed light curve variations.

Some limitations may include the gaps in long- term observational data, which could affect the precision of the derived O-C values and orbital parameters. Additionally, uncertainties in the fitting methods and measurement errors can also impact the results. These limitations increase the credibility of our research and provide important directions for future studies, such as the need for more continuous monitoring of SZ Lyncis to confirm our findings and further investigations. Future research could focus on exploring the nature of the binary companion to better understand its impact on the system's evolution.

Conclusion and Suggestions

Our analysis of SZ Lyncis, a Delta Scuti variable star, confirms its multi- frequency radial pulsations and reveals the presence of a binary companion. The long-term period increase observed in the O-C diagram suggests the presence of a binary companion, consistent with previous propositions (Li & Qian, 2013). Our analysis derived the following orbital elements: a semi-amplitude of 0.0052(±0.0002) days, a projected semi-major axis of 0.90(±0.04) AU, an eccentricity of 0.25(±0.09), and an orbital period of 1184.1(±1.5) days. The mass function of the system is estimated to be 0.07(±0.01) $M_\odot$. Additionally, the frequency analysis using

Period04 software identified four frequencies in the light curve. The main frequency is 8.29630(±0.00002) day^{-1}, corresponding to a pulsation period of 0.1205357(±0.0000003) days. This confirms SZ Lyncis as a multi-frequency radial pulsator, where the star's radius rhythmically expands and contracts, causing the observed light variations. Understanding these pulsation modes provides further insight into the internal structure of Delta Scuti stars.

Additional observations are crucial to confirm the presence and track the evolution of the binary companion. High-precision photometric and spectroscopic data will be valuable in refining the orbital parameters and providing a clearer understanding of the companion's characteristics. Long-term monitoring of SZ Lyncis is also necessary to detect any variations in its pulsation frequencies or period, shedding light on the interaction between the binary components. Furthermore, in-depth mode identification studies could offer further insights into the star's pulsation behavior, contributing valuable information to asteroseismology models of Delta Scuti stars.

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Author Contributions

Ronnakrit Rattanamala: Conceptualization, Methodology, Software, Data curation, Supervision, Writing — Original draft preparation, Observation

Pornapa Artsang: Supervision, Writing — original draft preparation, Writing — reviewing & editing

Chanruangrit Channok: Writing — original draft preparation

Thaweechai Chonsungnoen: Observation

Nutchanat Krinsungnoen: Observation

Pimmada Ngiabking: Observation

Phiyada Phumnok: Observation

Conflict of Interests

All authors declare that there are no conflicts of interest regarding the publication of this paper.

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