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BINARY NATURE OF THE HADS STARS AN LYN & BE LYN[1]

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RESUMEN

A partir de los recién determinados tiempos de máximo en la fotometría CCD de las estrellas HADS AN Lyn & BE Lyn y de una recopilación de tiempos de máximo de la literatura, hemos sido capaces de determinar la naturaleza binaria de estas estrellas, así como los parámetros físicos, con la fotometría $uvby-\beta$.

ABSTRACT

From newly determined times of maxima from CCD photometry of the HADS stars AN Lyn & BE Lyn and a compilation of previous times of maxima, we are able to determine the binary nature of these stars. We determine their physical parameters by means of $uvby-\beta$ photometry.

Key Words: binaries — stars: variables: delta Scuti

1. MOTIVATION

HADS (High Amplitude Delta Scuti) stars have been a gold mine for small telescope observers: they are relatively bright, show large amplitudes of variation, and have short pulsational periods. These features make them easy targets. However, because some observers lack experience, not all their data are useful and, in some cases, erroneous data complicate the analysis. Among the HADS there are many indications of secular variability that have been interpreted as due to the nature of the stars.

A good example is AD CMi, discovered by (Hoffmeister 1934). (Fu & Jiang 1996) conclude in a study of O−C data accumulated for several thousands of cycles, that in contradiction to some other canonical possibilities, such as an increasing period change, the residuals fit a variation of trigonometric function type. The orbital period they obtain is about 30.0 yr overlapped by a rate of change of the period around 0.46×10^{-12} day/cycle. They suggest that to confirm the conclusions they reach, it would be necessary to obtain more observations, especially radial velocities. In a more recent study, (Hurta, Pocs & Szeidl 2007), confirm the previous conclusions but change the values to $(1/P)(dP/dt) = (9.32 \pm 0.11) \times 10^{-8}$ yr^{-1} with an orbiting period $P_{orb} = 42.88 \pm 0.83$ yr due to binary motion in an elliptical orbit.

Many other stars follow the same trend in their residuals. For example, SZ Lyn was found to follow a sinusoidal variation with a period of $P = 3.138 \pm 0.028$ yr (Barnes & Moffett 1975) and it was suggested that this could be due to a light travel time effect, because it is a member of a binary system.

For the two stars in the present study, general properties are presented in Table 1 and the following has been published:

BE Lyn. This star was discovered to be variable by (Oja 1987). In the study by (Boonyarak et al. 2011) it was concluded that, due to errors of times of maximum light, the linear and quadratic fits gave the same residuals. (Derekas et al. 2003) could not confirm or reject the previous findings by (Kiss & Szatmáry 1995) because they could not find a cyclic feature with 106 times of maximum light.

AN Lyn. (Hintz et al. 2005) found this star to be the most intriguing of the three they studied (GW UMa, BO Lyn, and AN Lyn). Over a time span of 5 yr, they obtained an unusual (O−C) diagram that would not fit a clear sinusoidal shape. Nevertheless, their spectroscopic data over a relatively short time span, in accordance with the photometric data,

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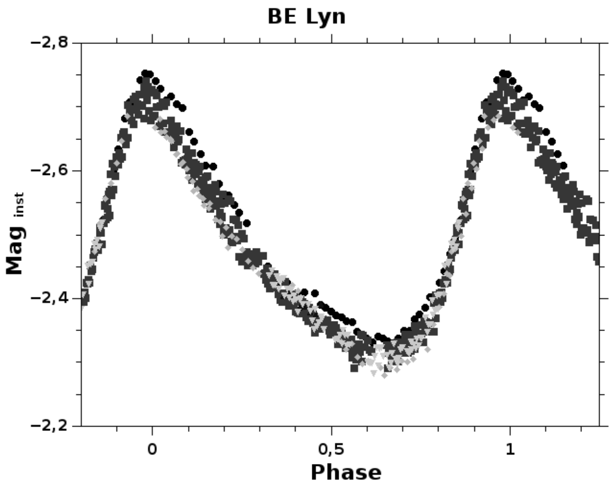

Fig. 1. Phased light curve for BE Lyn.

suggest that the velocity toward us has increased. The combination of the (O−C) with radial velocities clearly shows that AN Lyn is a binary system. They estimate an orbital period of approximately 22 yr.

With new data for these and other HADS we carried out an analysis of the newly determined compiled times of maximum light of AN Lyn and BE Lyn. Our analysis uses a least squares criterion to discriminate between the error points that, as in the case of BE Lyn, kept (Boonyarak et al. 2011) from reaching a final conclusion. Our results support the binary model.

2. OBSERVATIONS

These were all taken at the Observatorio Astronómico Nacional, Tonantzintla, México. The 1.0 meter telescope and a 10-inch Meade telescope were used. The two telescopes were provided with CCD cameras: SBIG STL-1001E, and SBIG ST-8XE for the 1 meter and the 10-inch telescope, respectively. Table 2 presents the log of observations.

2.1. *Data acquisition and reduction*

During all the observational nights the following procedure was utilized. Sequence strings in the V filter were obtained. The integration time at the 1-meter telescope was 3 min. The integration time at the 10-inch telescope was shorter, 1 min. It may seem contradictory to give a longer integration time to the larger aperture telescope. However, this is done since the mounting of the 10-inch telescope is of altazimuth type, which does not allow large integration times. Nevertheless for the 1-meter telescope there were around 40,000 counts and for the 10-inch telescope there were 11,000 counts, enough to secure high precision. The reduction work was done with AstroImageJ (Collins 2012). This software is relatively easy to use and has the advantage that it is free and works satisfactorily on the most common computing platforms.

2.2. *Data obtained*

Two reference stars were utilized whenever possible at the two telescopes in a differential photometry mode. The results were obtained from the difference $V_{\rm variable} - V_{\rm reference}$ and the scatter calculated from the difference $V_{\rm reference1} - V_{\rm reference2}$. Light curves were obtained and have been represented in a phase diagram as can be seen in Figure 1 for BE Lyn. No light curve for AN Lyn is presented because different reference stars were employed at the telescopes that were used. The ephemerides considered are indicated in Table 1.

Table 2 lists the times of maximum light for the observed stars. Each of these times was calculated to have an accuracy of 2×10^{-3} day. In this table, Column 1 reports the ID of the stars, Column 2 the filter employed, Column 3 the times of maximum light in HJD and the last column indicates the telescope utilized.

3. PHYSICAL PARAMETERS

To determine the physical parameters for each star the calibrations developed for $uvby-\beta$ photometry for different spectral types were utilized. Since AN Lyn has a spectral type of A7IV/V, whereas the spectral type of BE Lyn is A3, we considered two calibrations: that of (Shobbrook 1984) for O and early A types and that of (Nissen 1988) for late A and F stars. These allowed us to determine the reddening for each star, and hence the unreddened indexes, as well as the distance. These calibrations are described in detail in (Peña et al. 2005).

The photometric $uvby-\beta$ values reported by Simbad for AN Lyn and (Rodríguez et al. 1994) for BE Lyn stars were considered. For AN Lyn the corresponding photometric values were $(V,(b-y),m_1,c_1,\beta) = (10.70, 0.202, 0.191, 0.796, 2.762)$ whereas for BE Lyn they were $(8.82, 0.16, 0.16, 0.84, 2.78)$. Using the above mentioned calibration, we obtained the values presented in Table 3, in which Column 1 presents the star ID, Column 2 the reddening $E(b-y)$ and Columns three to five the unreddened indexes $(b-y)_0$, m_0 and c_0. Hβ is presented in Column six. V_0 and M_v

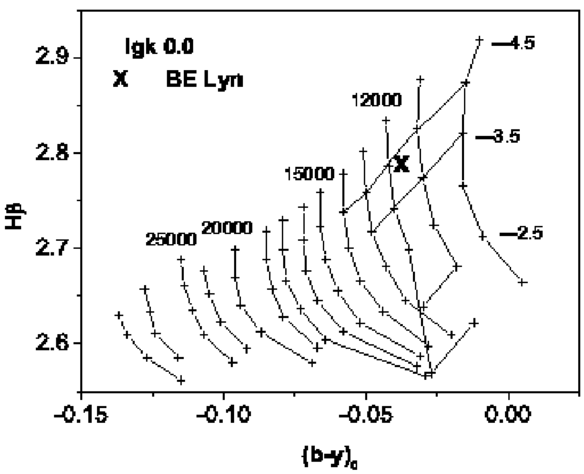

Fig. 2. Position of BE Lyn in the theoretical grids of LGK86.

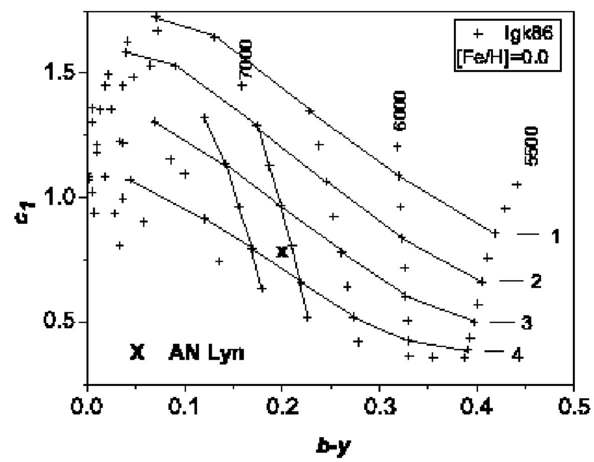

Fig. 3. Position of AN Lyn in the theoretical grids of LGK86.

TABLE 1

PROPERTIES OF THE STUDIED STARS

Star	R.A.$_{(2000)}$	Declination	V	δV	T_0-2400000	Period(d)
AN Lyn	09 14 28.69	+42 46 38.2	10.58	0.18	44291.0326	0.0983
BE Lyn	09 18 17.18	+46 09 11.3	8.80	0.39	49018.2681	0.0959

TABLE 2

TIMES OF MAXIMA OF THE OBSERVED HADS

Star	Filter	Time of Maximum	Telescope
AN Lyn	V	2456346.776	1 meter
	V	2456375.663	1 meter
	V	2456375.764	1 meter
BE Lyn	V	2456347.779	1 meter
	none	2456347.779	$10''$
	none	2456347.875	$10''$
	V	2456360.819	1 meter
	V	2456374.814	1 meter
	V	2456376.637	1 meter
	V	2456376.732	1 meter

are presented in Columns seven and eight. The distance modulus (DM) and the distance (in parsecs) are given in the subsequent columns.

Once the unreddened colors are known, it is possible to determine some physical parameters ($\log Te$ and $\log g$) for each star from a direct comparison with the models developed by (Lester, Gray & Kurucz 1986), LGK86. A metallicity has to be assumed since no metallicity is listed for these stars. It was decided to adopt the solar composition of SZ Lyn as reported in SIMBAD. The positions for each star in LGK86 grids are shown in Figures 2 and 3. The temperature of the stars was determined from their positions in the LGK86 grids to be 25000 K, and 7100 K for BE Lyn and AN Lyn, respectively, and it is listed in Table 4. The reddening $E(B-V)$ was calculated utilizing the well-known relation $E(b-y) = 0.7 \times E(B-V)$.

4. O−C ANALYSIS

Before calculating the coefficients of the ephemerides equation, we studied the existing literature related to BE Lyn and AN Lyn. Several authors have conducted studies of the O−C behavior of these particular objects, and in this preliminary stage we took the existing equation and reproduced the diagrams with our updated list of times of maxima taken from literature plus the data that we acquired.

The equations that best represented a continuum behavior were then selected by sight from the O−C diagrams. The best representation is not always the

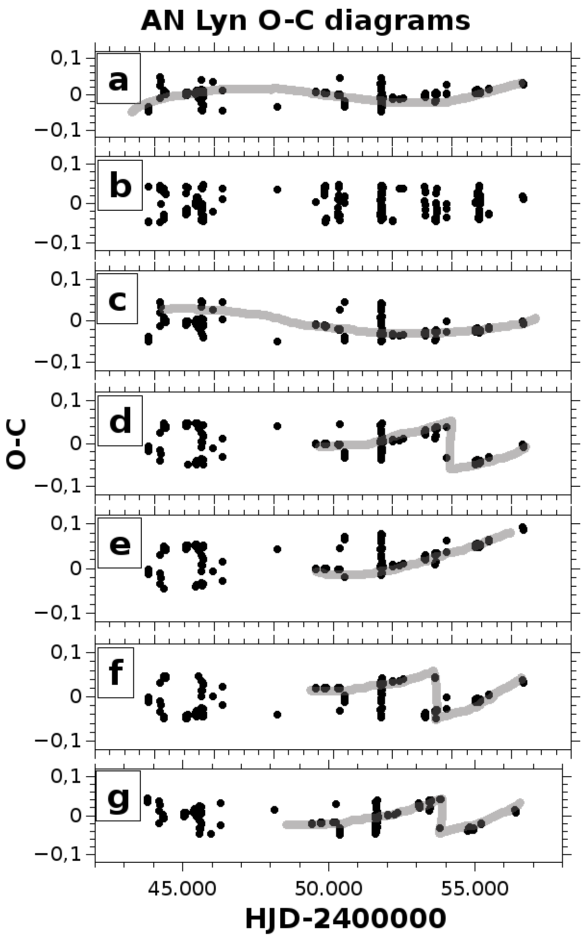

Fig. 4. AN Lyn O−C diagrams from the literature. (a) (Li & Qian 2010), (b) (Agerer et al. 1983), (c) (Yamasaki, Okazaki & Kitamura 1983), (d) (Rodríguez et al. 1997), (e) (Rodríguez et al. 1994), (f) (Zhou 2002), (g) (Hintz et al. 2005).

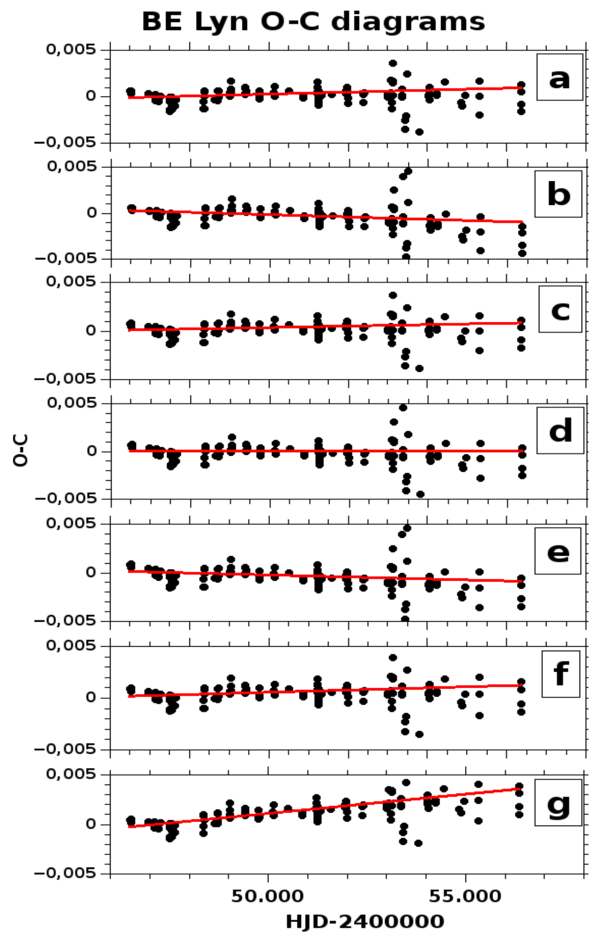

Fig. 5. BE Lyn O−C diagrams from literature. (a) (Boonyarak et al. 2011), (b) (Boonyarak et al. 2011), (c) (Fu & Jiang 2005), (d) (Szakats et al. 2008), (e) (Kiss & Szatmáry 1995), (f) (Tang, Yang & Jiang 1992), (g) (Wunder, Wieck & Garzanolli 1992).

TABLE 3

REDDENING AND UNREDDENED PARAMETERS OF THE STUDIED HADS

ID	$E(b-y)$	$(b-y)_0$	m_0	c_0	Hβ	V_0	M_V	DM	Dist
BE Lyn	0.198	-0.038	0.225	0.802	2.780	7.97	0.03	7.94	390
AN Lyn	0.024	0.200	0.197	0.795	2.760	10.60	1.98	8.62	530

one with the lowest standard deviation. For example, in Figure 4 there are three cases of ephemerides (Rodríguez et al. 1994), (Zhou 2002) & (Hintz et al. 2005) whose behavior shows abrupt jumps. We selected as best equation the one that has the smoothest curve, even if it had a larger dispersion. Once we chose the best model, we proceeded to use those coefficients to begin a new fitting process with the observational data, using a typical least squares regression fitting method in order to get a new set of coefficients that best represented the observational times of maxima.

Once the coefficients were chosen, we proceeded to make another fitting of the data using a statistical tool available on the web. The site, `http://statpages.org/` has a tool to perform nonlinear least squares regression (`http://statpages.org/nonlin.html`). This tool was used to acquire a new

TABLE 4

COMPILED CHARACTERISTICS FOR THE STUDIED HADS

	AN Lyn	BE Lyn
Spectral Type	A7IV/V	A3
Galactic longitude	178.5	173.7
Galactic latitude	+43.7	+44.2
Distance [pc]	529	388
Reddening [mag] $E(b-y)$	0.024	0.198
Reddening [mag] $E(B-V)$	0.03	0.3
Distance modulus [mag]	8.6	7.9
Log T_e	3.8	4.1
Log g	3.8	3.8

set of coefficients and RMS error values using as a starting point the values of the selected equation. The error was used to discriminate the data points that strongly differed from the model, in order to obtain the clean list of observational times of maxima, which were used to perform a new fitting process, from which we obtained the final values for our new ephemerides equation.

Using the new equation to calculate the theoretical times of maxima, we calculated the differences between the observed times and those we had calculated. These differences constitute the well-known O−C, values which are plotted on a graph on the Y axis and the time (HJD) on the X axis. Making use of the software Period04 (Lenz & Breger 2005) and `http://webda.physics.muni.cz` created for applications in asteroseismology, we were able to calculate the main frequencies of the apparent oscillatory behavior of the O−C data. However, for practical purposes in the current research we only used the main frequency, which helped us identify a likely period related to a hypothetical second component of a binary system.

4.1. *BE Lyn*

Following the above mentioned process, the coefficients of the ephemerides equation from (Fu & Jiang 2005) and (Boonyarak et al. 2011) were selected as initial data for the O−C analysis.

The different derived equations for this star are shown in Table 5 and the reconstruction of the O−C diagrams with the updated data is shown in Figure 5. The charts show that not all equations reach a good distribution around zero. For example, (Boonyarak et al. 2011) suggest a quadratic equation with an underestimated period, which is evident from the negative slope of the distribution on the O−C diagram. Therefore, we considered the equation proposed by (Wunder, Wieck & Garzanolli 1992). This equation shows an overestimated period, hence, a positively sloped distribution on the O−C diagram. The same criterion was followed in each of the previous analyses.

What was immediately seen was the exceedingly large spread in the O−C values. To diminish the scatter the following was done: a Gaussian fit was calculated and the mean value and the standard deviation were obtained from the Gaussian fit. From the graphical representation of the O−C differences, those values with a large spread from the mean stood out. The results from this histogram gave a mean value of 4.29×10^{-4} and a sigma of 0.0021. Those O−C points which were beyond the one sigma value were discarded. It should be mentioned that most of these came from two observers, Klingenberg & Poschinger as referred to in (Wunder, Wieck & Garzanolli 1992), making them appear to have a large systematic error. Their removal eliminated the large spread and made it possible to define a more logical behavior of the star.

Once the ephemerides equations were chosen, the process for the calculation of the new values was performed twice: the first time for a linear fitting and the second for a quadratic fitting. The iterative process gave the final values shown in Table 6 for the two proposed equations with their respective RMS errors.

As can be seen in Figure 6, the diagrams show a regular distribution around zero and the RMS errors are quite similar. However, a distribution with a slightly negative slope in the figure corresponding to the linear adjustment can be seen, while in the quadratic fit the distribution appears closer to a zero slope.

With a new ephemerides equation and a clean list of times of maxima, we carried out an analysis of the O−C diagram using Period04 in order to obtain the main frequency of the apparent oscillation in the difference of the times of maxima observed and the calculated ones. The result of this analysis is the equation and coefficients shown in Table 7. The period derived from the oscillation frequency is $P \approx 9.513$ years and the plot is shown in Figure 7.

4.2. *AN Lyn*

As with BE Lyn, two equations were chosen from the existing literature as the initial data values for our analysis.

TABLE 5

BE LYN EPHEMERIDES EQUATIONS

Author	T_0	P	β
Boonyarak et al. (2011)	49018.2680	0.095869513	0
Boonyarak et al. (2011)	49018.2682	0.09586952	6.26×10^{-13}
Fu et al. (2005)	49018.2680	0.095869513	0
Derekas (2003)	49018.2684	0.09586954	0
Szakats el al. (2008)	49749.4651	0.09586952	0
Kiss et al. (1995)	49018.2684	0.0958695	0
Tang el al. (1992)	46506.0073	0.09586951	0
Wunder et al. (1992)	48347.37-29	0.095869483	0

TABLE 6

NEW EPHEMERIDES EQUATIONS OF BE LYN

	T_0	P	dP	β	RMS error
PP Linear	49018.26828	0.09586952	2×10^{-8}	0	0.002075
PP Quadratic	49018.26836	0.09586952	2×10^{-8}	$-4.689776 \times 10^{-13}$	0.002094

TABLE 7

BE LYN **O−C** OSCILLATION ANALYSIS[a]

$Z = 0.00003404$	(*Zero-Point*)
$A = 0.0006785$	(*Amplitude*)
$\Omega = 0.000288$	(*Frequency*)
$\Phi = 0.9335$	(*Phase*)

[a] $Z + A\sin(2\pi(\Omega t + \Phi))$, harmonic wave equation.

TABLE 8

AN LYN EPHEMERIDES EQUATIONS

Author	T_0	P	β
Rodriguez et al. (1997)	49398.7489	0.09827342	0
Rodriguez et al. (1997)	49398.7489	0.0982739	0
Ai Ying Zhou (2002)	43776.718	0.09827315	0
Hintz et al. (2005)	44291.0326	0.09827292	0
Li Lin-Jia el al. (2010)	44291.0232	0.09827445	0
Yamasaki et al. (1983)	44291.12521	0.0982747	0
Agerer el al. (1983)	45342.3822	0.097949	0

Table 8 shows the equations considered for the study and Figure 4 shows the O−C reconstruction with the updated data. This figure shows an abnormal behavior. The differences of the distributions is caused by an incorrect estimation of the period of the star. Sometimes when fitting the equation, the system is forced to achieve a minimal deviation of the data until the distribution loses its continuity. This is visible in Figure 4. The figures derived from (Li & Qian 2010) and of (Yamasaki, Okazaki & Kitamura 1983) show a continuum pattern in the arrangement of the data, while in the other charts it

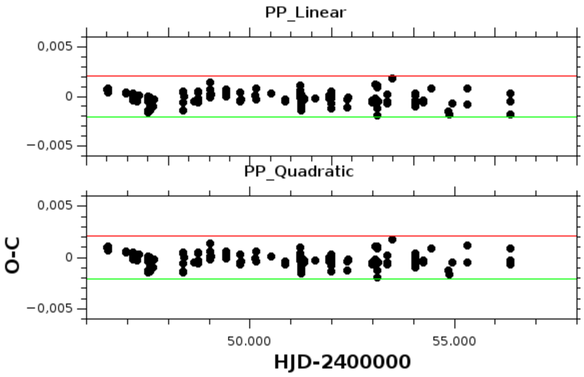

Fig. 6. BE Lyn new O−C diagrams.

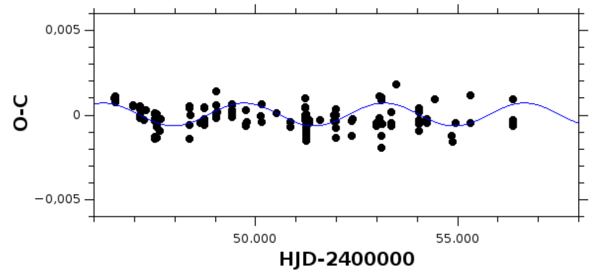

Fig. 7. BE Lyn O−C period analysis.

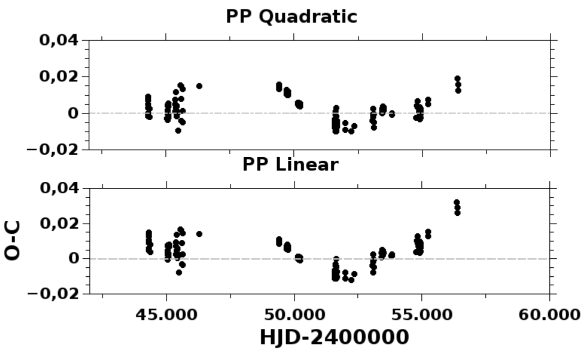

Fig. 8. AN Lyn, quadratic and linear O−C diagrams.

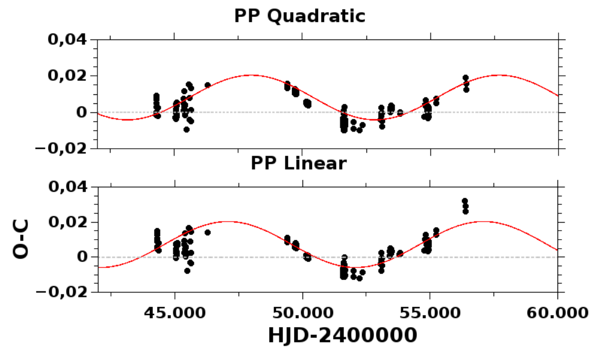

Fig. 9. AN Lyn O−C linear and quadratic fits of both residuals fitted by a sinusoidal curve. The newly determined times of maxima have a better behavior in the quadratic fit. The elements of this sinusoid are presented in the text.

TABLE 9

AN LYN NEW EPHEMERIDES EQUATIONS

	T_0	P	dP	β	RMS error
PP Linear	44291.02077	0.09827447	2.02×10^{-8}	0	0.01502
PP Quadratic	44291.02664	0.09827407	2.02×10^{-8}	7.556573×10^{-12}	0.01596

is difficult or impossible to find regular behavior in the data. After completing the analysis of the O−C diagrams, the equations of (Li & Qian 2010) and (Yamasaki, Okazaki & Kitamura 1983) were taken as initial data for the new analysis.

After performing the least squares regressions, cleaning the data, and performing a new regression, a new set of coefficients was obtained as in the case of BE Lyn.

Table 9 lists the coefficients for the new linear and quadratic fitting equations. Those equations

TABLE 10

AN LYN **O−C** OSCILLATION ANALYSIS[a]

$Z =$	0.00818990649	(*Zero-Point*)
$A =$	0.0122762717	(*Amplitude*)
$\Omega =$	0.000103321975	(*Frequency*)
$\Phi =$	0.289732	(*Phase*)

[a] $Z + A\sin(2\pi(\Omega t + \Phi))$, harmonic wave equation.

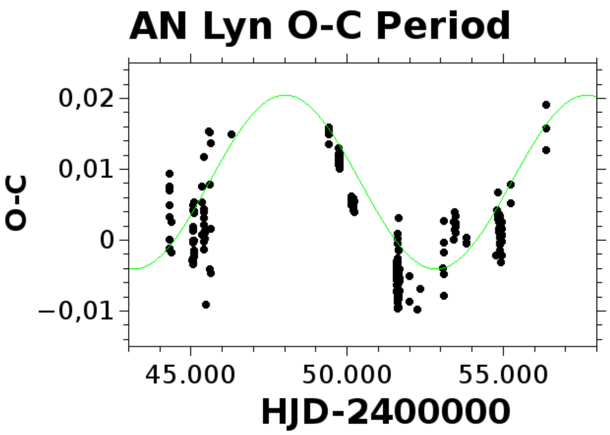

Fig. 10. AN Lyn O−C best fitting curve.

were used to plot the new O−C diagrams shown in Figure 8. The choice of the best chart was difficult after a simple visual inspection. We took both the new set of O−C data, linear and quadratic, in order to analyze their oscillatory behavior with Period04. The fitting functions are shown in Figure 9 and it is clearly noticeable that the quadratic equation is the one that best represents a sinusoidal function (Figure 10). Table 10 lists the derived elements. Then, according to the main frequency, the period of the probable second component of the binary system is $P \approx 26.5166$ years.

5. CONCLUSIONS

New times of maximum light have been gathered for two HADS, AN Lyn and BE Lyn, from CCD photometry at the Tonantzintla Observatory, Mexico. With the inclusion of these maxima and those gathered from the literature, new ephemerides were calculated. The binary nature of AN Lyn, indicated by other authors, has been tightened up with the new times of maxima determined. Hence, the solution for AN Lyn is valid since it is supported by a longer time string. In the case of BE Lyn, the scatter of the maxima has been polluted by possible carelessly determined maxima. Through a mathematical analysis some noisy maxima have been discarded. The residuals indicate that this star might have the same sinusoidal behavior as AN Lyn which would indicate a binary nature. The obvious recommendation is to gather more observations that, in the long run, would prove or disprove this binary assumption.

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