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A STUDY OF BO LYN, A NEGLECTED HADS STAR[1]

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RESUMEN

Fotometría $uvby-\beta$ de la estrella tipo HADS BO Lyn nos permitió determinar sus parámetros físicos. La variación secular se estableció mediante el análisis de los tiempos de máximo con el método de O-C recabados de la literatura y con los nuevos adquiridos con fotometría CCD. En este trabajo hemos demostrado que la estrella BO Lyn se encuentra pulsando con un periodo estable, cuyos residuos muestran un patrón sinusoidal compatible con el efecto del tiempo de viaje de la luz.

ABSTRACT

$uvby-\beta$ photometry of the high amplitude δ Scuti (HADS) star BO Lyn allowed us to determine its physical characteristics. A secular period variation was established through the O-C of all the available times of maximum light and those newly acquired through CCD photometry. In the present study we have demonstrated that BO Lyn is pulsating with one stable varying period whose O-C residuals show a sinusoidal pattern compatible with a light-travel time effect.

Key Words: stars: variables: delta Scuti — techniques: photometric

1. INTRODUCTION

Very little has been done on BO Lyn since its discovery by Kinman et al. (1994) (as reported by Kazarovets & Samus, 1997, star 73243 in their Table 1). Kinman (1998) analyzed the star and assigned to it a period of 0.0933584 days and a V-magnitude range of 11.85-12.05 with a slightly variable light curve. He further stated that "the location, space motion, and other properties of this star indicate that it is a higher amplitude δ Scuti star (or 'dwarf Cepheid') that is a member of the old disk population". The most recent study was done by Hintz et al. (2005) who examined the star both photometrically and spectroscopically and proposed that the period is decreasing at a constant rate.

2. OBSERVATIONS

This star was observed at both the Observatorio Astronómico Nacional of San Pedro Mártir, México with the 0.84 m telescope and a $uvby-\beta$ spectrophotometer and at Tonantzintla, México with 14-inch and 10-inch telescopes provided with SBIG ST 8300 and ST1001 CCD cameras, respectively. The log of the observations is given in Table 1. Column 1 reports the date (year month day), Column 2 the telescope and implicitly, the observatory; Columns 3 and 4 the number of points and the time span of the observations; Column 5 the uncertainty in each night; it should be kept in mind that in the first two rows we present the uncertainty in the absolute transformation to the standard system and in the remaining rows, the error of differential magnitudes; finally, the last column lists the observers.

2.1. *Data Acquisition and Reduction at Tonantzintla*

During all the observational nights the following procedure was utilized. Sequence strings were obtained in the V filter with an integration time of 30 sec. There were 551,111 counts for BO Lyn, 1,555,128 for the comparison star C_1 and 2,774,289 counts for the check star C_2, enough counts to secure high accuracy. The error in each measurement is, of course, a function of both the spectral type and the brightness of each star but they were observed long enough to secure sufficient photons to get a good S/N ratio and an observational error of 0.001 mag in all cases. The reduction work was done with AstroImageJ (Collins, 2012). This software is relatively

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easy to use and has the advantage that it is free and works satisfactorily on the most common computing platforms.

For the CCD photometry of BO Lyn (08:43:01.224, +40:59:51.79) two reference stars were utilized. A bright star TYC 2985-290-1 identified in the present paper as C_1 (08:42:39.883, +40:59:48.30, V = 10.91, SpT= N/A) was used as comparison star, and a brighter star, BD +41 1869, identified as C_2 (08:42:33.428, +41:05:59.97, V = 10.30, SpT=F8) as a check star to obtain the light curves in a differential photometry mode. The reason for using the less bright star C_1 as a comparison object instead of C_2 is that, during the observation, C_2 was out of the observed field near the time of maximum due to the rotation of the telescope caused by the alt-azimuthal mounting. The results were obtained from the difference V_{variable} - $V_{\mathrm{comparison}}$ and the scatter calculated from the difference $V_{\mathrm{comparison}} - V_{\mathrm{check}}$. Each of these times of maxima has an accuracy of 3×10^{-4} day. Figure 1 presents the light curves of BO Lyn.

3. O-C ANALYSIS

To investigate the secular behavior of the period of BO Lyn we studied the literature related to it. Besides Kinman (1998) only two groups of researchers have observed BO Lyn: Klingenberg et al. (2006) with few observations and, previously, Hintz et al. (2005) who performed studies of the O-C behavior of this star. A summary of their findings is presented in Table 2. In Column 1 the author is presented, Column 2, 3 and 4 the ephemerides determined by each author; T_0, P and β respectively. Columns 5 and 6 list the mean value of the (O-C) for all the times of maximum light and the standard deviation, respectively. Hubscher et al. (2013) published only one time of maximum light. All are presented schematically in Figure 2.

Table 3 lists the observed times of maximum light of BO Lyn and includes the new observations. In this table, Column 1 reports the time of maximum light (in HJD), Column 2, the source and Column 3 the epoch with the ephemerides parameters determined in this paper.

Since the study of Hintz et al. (2005), more observations have been carried out, some of them recently, and they are presented in this paper in Table 3. We tested the old proposed ephemerides equations with the complete set of times of maximum light which is constituted of a set of only 34 times of maximum light including those observed in 2016 (Figure 2). At the time of the Hintz et al. (2005)

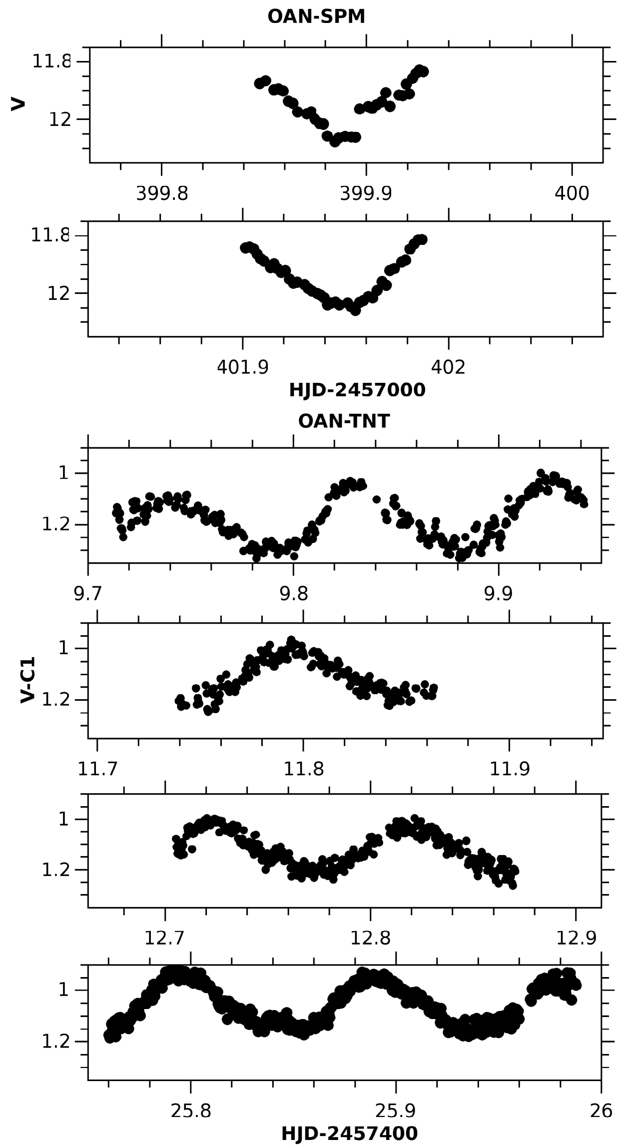

Fig. 1. Light curves of BO Lyn. Top: those obtained by $uvby - \beta$ absolute photometry, bottom: those observed at Tonatzintla with CCD detectors by differential photometry.

study, the time basis was only 5554 days or 15 years. In 2016 the time basis has been extended to 9492 days or 26 years, almost double that used for the calculations of Hintz et al (2005).

4. PERIOD DETERMINATION

To determine the period behavior of BO Lyn we followed three methods.

4.1. *Period04*

In this method all detailed photometry was used: Kinman (1998) which is presented in apparent magnitudes, and that of the present paper which includes

TABLE 1

LOG OF OBSERVING SEASONS

Date	Telescope	Npoints	ΔT (d)	ΔV	Observers*
16/01/1112	84 cm	37	0.079	0.054	aas, jg
16/01/1314	84 cm	41	0.086	0.054	aas, jg
16/01/2122	14 inch	297	0.228	0.020	ESAOBELA16
16/01/2324	14 inch	266	0.123	0.018	ESAOBELA16
16/01/2425	14 inch	356	0.165	0.020	ESAOBELA16
16/02/0607	10 inch	469	0.227	0.031	jg, ap

*aas, A.A. Soni; jg, J. Guillén; ap, A. Pani; ESAOBELA16: A. Rodríguez; V. Valera; A. Escobar; M. Agudelo; A. Osorto; J. Aguilar; R. Arango; C. Rojas; J. Gomez; J. Osorio; M. Chacon

TABLE 2

BO LYN EPHEMERIDES EQUATIONS

Author	T_0	P	β	(O-C)mean	(O-C)std dev
Kinman (1998)	2438788.0355	0.0933584		−0.021	0.028
Hintz et al. (2005) linear	2447933.8183	0.09335724		−0.007	0.014
Hintz et al. (2005) parabolic	2447933.7988	0.09335800	$-7.2(1.0)\times10^{-12}$	−0.001	0.009

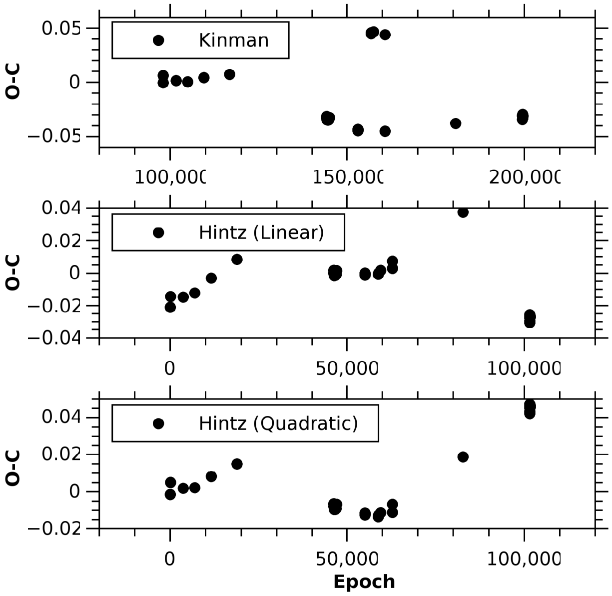

Fig. 2. (O-C) diagrams for the ephemerides proposed in the literature (Table 2).

that observed at the Tonantzintla and San Pedro Martir Observartories, Mexico and, as has been explained, consisted of two samples: absolute photometry in San Pedro Martir for two nights and differential photometry in Tonantzintla for four nights. Because of the amplitude difference between the instrumental and the apparent magnitudes and for a consistent analysis, all the light curves were normalized subtracting the average of each night from itself; in this way the amplitudes became similar and capable of giving more accurate results.

The whole time series was analyzed with Period04 (Lenz & Breger, 2005) to determine a representative period of the whole sample. Three data sets were created. The first one, the Kinman (1998) data, consisted of 142 data points over 17 nights separated by a time span of 2187 days. The second was the one currently presented, with 76 points over 2 nights for the absolute photometry and 1364 points over 4 nights for a time span of 27 days for the differential photometry; the third data set was the whole data set, for which, as has been said, amplitudes were normalized.

For the first data set (Kinman, 1998) Period04 gave the following frequency: 10.71140620 c/d, with an error of 5.12×10^{-6}. The 2016 data season gave a frequency of 10.710874 c/d with an error of 2.43×10^{-4}. Finally, the whole data set gave 10.711447500 c/d with an error of 7.42×10^{-7}. These final results are presented in Figure 3. The corresponding periods were 0.093358423, 0.093363062 and 0.093358064 d, respectively.

Once the whole time string was analyzed the period was utilized as a seed period, which was taken to calculate the number of cycles, E. A least squares fit of T_{max} vs. E was implemented giving as output

TABLE 3

TIMES OF MAXIMA OF BO LYN

Time of Maximum	Reference	Epoch
2447933.7964	Hintz-Kinman	0
2447938.7478	Hintz-Kinman	53
2448274.9308	Kinman	3654
2448577.9691	Hintz-Kinman	6900
2449010.7845	Kinman	11536
2449685.9520	Kinman	18768
2452252.8044	Hintz	46263
2452252.8993	Hintz	46264
2452264.7545	Hintz	46391
2452264.8459	Hintz	46392
2452266.7141	Hintz	46412
2452266.8091	Hintz	46413
2452288.6538	Hintz	46647
2452288.7455	Hintz	46648
2452288.8399	Hintz	46649
2452310.6849	Hintz	46883
2452331.7861	Hintz	47109
2453075.7484	Hintz	55078
2453075.8406	Hintz	55079
2453083.7767	Hintz	55164
2453427.7978	Hintz	58849
2453429.7592	Hintz	58870
2453487.7356	Hintz	59491
2453795.5356	Klingenberg	62788
2453795.6334	Klingenberg	62789
2455654.4061	Hubscher	82699
2457409.7380	Esaobela16	101501
2457409.8276	Esaobela16	101502
2457409.9249	Esaobela16	101503
2457411.7932	Esaobela16	101523
2457412.7228	Esaobela16	101533
2457412.8180	Esaobela16	101534
2457425.7953	jg, aas	101673
2457425.8890	jg, aas	101674

the refined period and the corrected initial epoch T_0 of the ephemerides equation, as well as the error parameters. The resultant equation is the following:

$$T_{max} = (2447933.7845 \pm 4.7 \times 10^{-3}) + (0.093358109 \pm 7.4 \times 10^{-8}) \times E$$

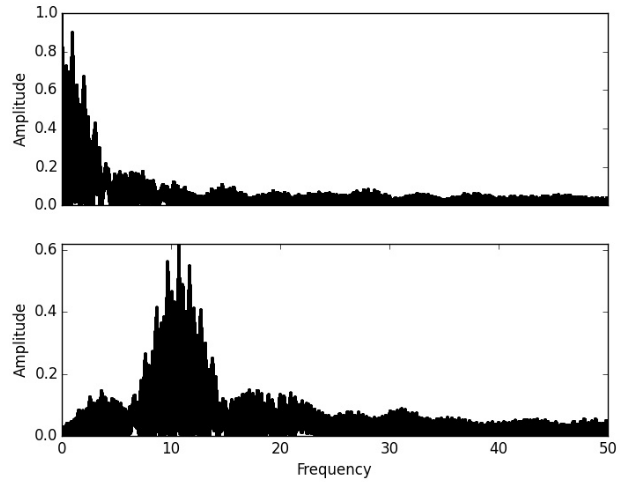

Fig. 3. Periodogram of all the available light curves of BO Lyn. Top: the window function. Bottom: the obtained periodogram,.

4.2. *Minimization of the Standard Deviation of the O-C Residuals (MSDR)*

The second method utilizes as criteria of goodness, the minimization of the standard deviation of the O-C residuals (MSDR).

We implemented a method based on the O-C standard deviation minimization analogous to the idea proposed by Stellingwerf (1978) for period determination by phase dispersion minimization. We considered the set of T_{max} listed in Table 3 in our analysis. The mean period was determined through the differences of two or three times of maxima that were observed on the same night and the associated standard deviation. Given the standard deviation and the period we determined, we swept between these limits calculating 5000 steps which gives the sufficient accuracy provided by the time span of the observations. The obtained precision of one millionth provides the new period and the limits for the iteration (Figure 4). In each iteration, the O-C standard deviation was calculated. We chose as the best period that which showed the minimum standard deviation. The resulting equation is:

$$T_{max} = (2447933.7845 \pm 4.7 \times 10^{-3}) + (0.093358109 \pm 7.4 \times 10^{-8}) \times E$$

The previous methods gave basically the same result. Therefore, it can be seen that the O-C residuals show a sinusoidal behavior. This pattern in the O-C diagram is usually related with the light-travel time effect (LTT). In view of this, the O-C residuals were analyzed in Period04 and fitted with an

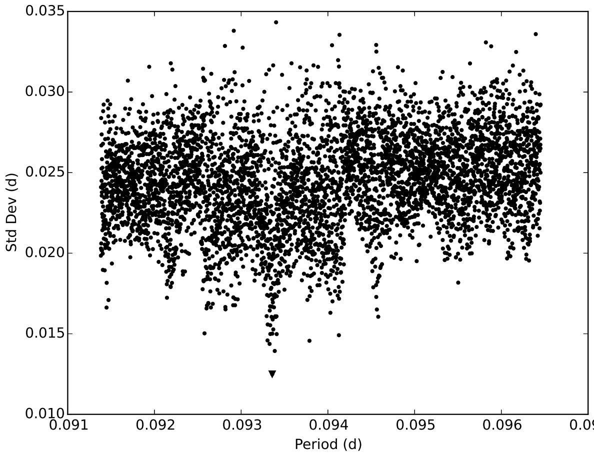

Fig. 4. Standard deviation vs. period. This diagram served to determine the best period.

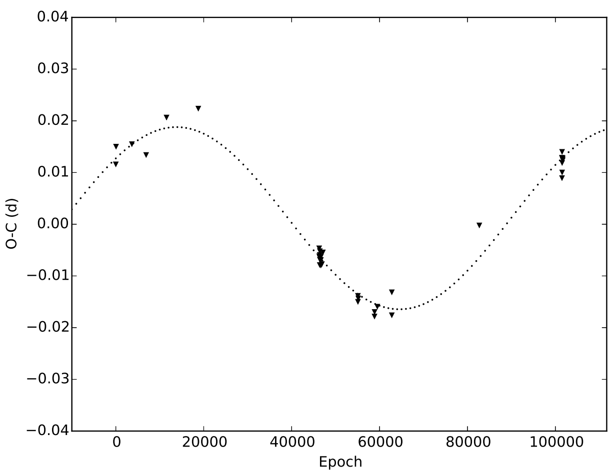

Fig. 5. O.C residuals by the minimization of the standard deviation.

equation of the following type:

$$(O-C) = Z + A \times \sin[2\pi(\Omega E + \Phi)] \quad (1)$$

The result is shown in Figure 5 and the elements of the fit are listed in Table 4.

4.3. *Period Determination Through an O-C Differences Minimization (PDDM)*

In the third procedure, we implemented a method based on the idea of searching the minimization of the chord length which links all the points in the O-C diagram for different values of the periods, looking for the best period which corresponds to the minimum chord length. With this idea in mind, we tried to obtain the smoothest curve. Since we were dealing with the classical O-C diagram, we plotted the time in the x-axis and the O-C values in the y-axis. Since in the x-axis distances are constant, we just concentrated on the change in the distance in the y-axis in each diagram, generated by one period. Once the difference was calculated for each period, the minimum one indicated, at this stage, the best period (period determination through an O-C differences minimization PDDM). We considered the set of T_{max} listed in Table 3 in our analysis. Given the mean period determined from the consecutive times of maxima and the associated standard deviation, (0.0936 days and 0.0027 days), we calculated values of epoch and O-C by sweeping the period in the range provided by the standard deviation limits, 0.091 to 0.096 days, calculating 5×10^6 steps, a number fixed by the the difference of the deviation limits and the desired precision of one billionth. This provided the new period for the minimum difference (Figure 6). The T_0 time used for the present analysis was the one of the 2016 observation run, 2457412.8196, because we are certain of its precision.

TABLE 4

EQUATION PARAMETERS FOR THE SINUSOIDAL FIT OF THE O-C RESIDUALS

Value	Period04 & MSDR	PDDM
Z	1.17×10^{-3}	-1.67×10^{-2}
Ω	9.85×10^{-6}	1.18×10^{-5}
A	1.76×10^{-2}	1.68×10^{-2}
Φ	1.14×10^{-1}	2.39×10^{-1}
Z_{Err}	4.25×10^{-4}	3.62×10^{-4}
Ω_{Err}	2.43×10^{-7}	2.31×10^{-7}
A_{Err}	5.82×10^{-4}	4.89×10^{-4}
Φ_{Err}	7.81×10^{-3}	1.65×10^{-2}
Residuals	2.00×10^{-3}	1.9×10^{-3}

As a result we determined the linear ephemerides equation as:

$$T_{max} = (2457412.8196) + (0.093358338 \times E$$

Figure 7 shows the O-C diagram for the ephemerides equation found by the above method (PDDM).

Assuming the wave behavior as a part of the physics in the system, we adjusted a sinusoidal function to the O-C, performing a fitting using Levenberg-Marquardt Algorithm for the best 1,000 O-C lengths. This would be, in this particular case, another way of finding the best period and, at the same time, the sinusoidal function which is similar

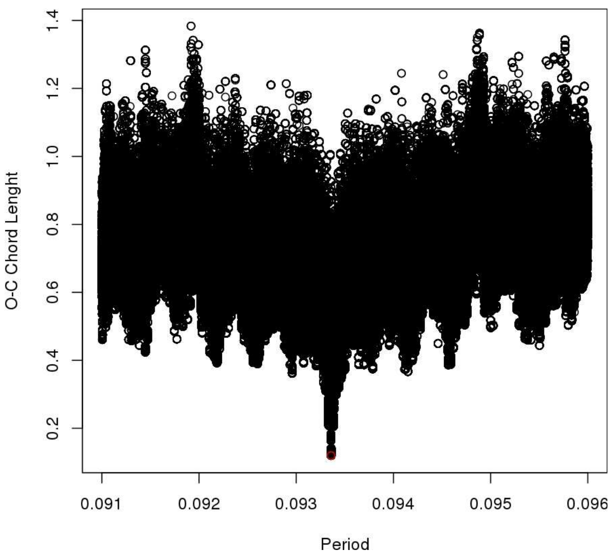

Fig. 6. Period determination through an O-C differences minimization, PDDM.

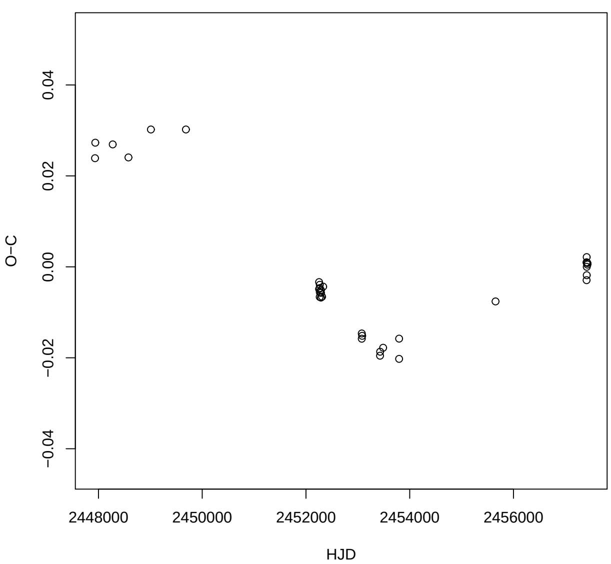

Fig. 7. (O-C) residuals after the adjustment to the obtained period.

to the one assumed in the second method. The parameters which best represents the system are listed in Table 4. The parameter used to prove the goodness of the adjustment is the residual sum of squares RSS. Then, we plotted the periods of the best O-C lengths vs. the RSS value of every fit, Figure 8.

After this, the ephemeris equation was set as:

$$T_{max} = (2457412.8196) + (0.093357995 \times E$$

As we can see, only one frequency explains this

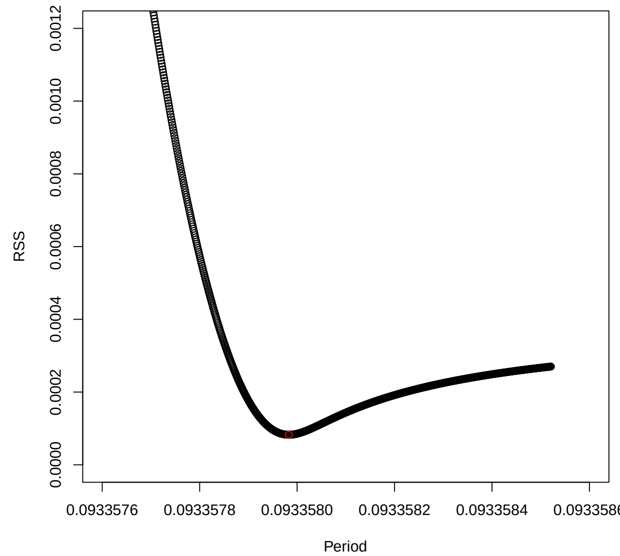

Fig. 8. Zoom RSS vs. Period.

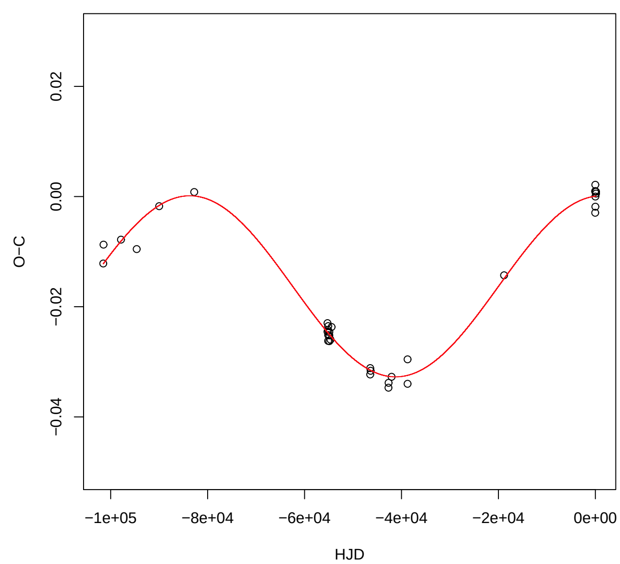

Fig. 9. Diagram of the O-C adjusted to a sinusoidal function.

sinusoidal behavior. The parameters are presented in Table 4 and are shown schematically in Figure 9. This frequency corresponds to a period of 7,779.83 days or 21.49 years.

4.4. *(O-C) Discussion*

BO Lyn was discovered relatively recently and has been scarcely observed. The whole sample of times of maximum light contains only 34 unevenly distributed entries.

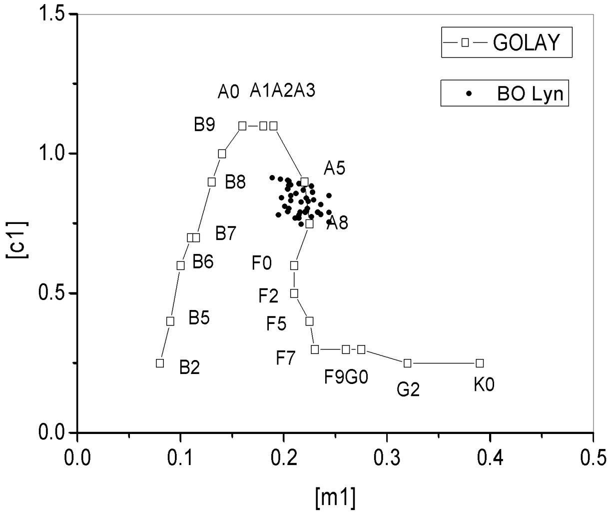

Fig. 10. Position of BO Lyn in the $[m_1] - [c_1]$ diagram.

As can be seen, the parameters of the equations obtained with the light curves analyses and the standard deviation minimization for the times of maxima give the same results. This confirms the results among themselves since both solutions converge to the same period. Then in both cases a sinusoidal behavior can be seen. The third method, PDDM, with a completely different approach, gives basically the same results.

After a quick review of the most conspicuous and well-studied HADS stars, the majority (nine) have increasing period changes and only a few (four), the opposite. What we have found in BO Lyn is that it is a star in a stable evolutionary stage.

With respect to its amplitude, a variation in the light curves was suggested by Kinman (1998), and later Hintz et al. (2005) suggested that this could be due to two probable secondary frequencies in the pulsation modes. In our analysis we can explain the behavior of the star with only one pulsational period and an orbital period .

Continued monitoring of times of maximum will be crucial, and such observations are encouraged.

5. PHYSICAL PARAMETERS

Physical parameters can be obtained using the advantages given by Strömgren photometry with calibrations made by Nissen (1988) for the A and F stars or by Shobbrook (1984), for earlier spectral types. These calibrations are described in detail in Peña et al. (2002).

The evaluation of the reddening was done by first establishing to which spectral class the stars belong. As a primary criterion the location of the stars in the $[m_1] - [c_1]$ diagram of the classical textbook of Golay (1974) (Figure 10) or the results derived for the open cluster α Per (Peña & Sareyan, 2006) were employed. As can be seen in this figure, the spectral type of BO Lyn varies between A5 and A8. There has been until now, no assignment of a spectral type for BO Lyn. Once a spectral class is assigned, we can choose the prescription for unreddening which, for the spectral type of BO Lyn, is that of Nissen (1988).

TABLE 5

TRANSFORMATION COEFFICIENTS OBTAINED FOR THE 2016 SEASON

Coefficient	B	D	F	J	H	I	L
value	0.031	1.008	1.031	−0.004	1.015	0.159	−1.362
σ	0.028	0.003	0.015	0.017	0.005	0.004	0.060

5.1. *Data Acquisition and Reduction at SPM*

The observational pattern as well as the reduction procedure have been employed at the SPM Observatory since 1986 and hence have been described many times. A detailed description of the methodology can be found in Peña et al. (2007). During the three nights of observations the following procedure was utilized: each measurement consisted of at least five ten-second integrations of each star and one ten-second integration of the sky for the *uvby* filters and the narrow and wide filters that define Hβ. It is important to emphasize here that the transformation coefficients for the observed season (Table 5) and the season errors were evaluated using the ninety-one observed standard stars. These uncertainties were calculated through the differences in magnitude and colors for (V, $b-y$, m_1, c_1 and β) which were (0.054, 0.012, 0.019, 0.025, 0.012), respectively. We emphasize the large range of the standard stars in the magnitude and color values: V:(5.62, 8.0); $(b-y)$:(-0.09, 0.88); m_1:(-0.09, 0.67); c_1:(-0.024, 1.32) and β:(2.495, 2.90).

Table 6 lists the photometric values of the observed star. In this table Column 1 contains the time of the observation in HJD, Columns 2 to 5 the Strömgren values V, $(b-y)$, m_1 and c_1, respectively; Column 6 lists β, whereas Columns 7 to 9 list the unreddened indexes $[m1]$, $[c1]$ and $[u\text{-}b]$ derived from the observations. Unfortunately in none of the SPM observations (two nights) a time of maximum light was reached, although the observations were almost long enough to completely cover the whole pulsation cycle.

TABLE 6

$uvby-\beta$ PHOTOELECTRIC PHOTOMETRY OF BO LYN

HJD	V	$(b-y)$	m_1	c_1	β	$[m1]$	$[c1]$	$[u-b]$
-2457000.00								
399.8477	11.875	0.130	0.195	0.928	2.706	0.237	0.902	1.375
399.8506	11.865	0.160	0.154	0.952	2.754	0.205	0.920	1.330
399.8546	11.897	0.149	0.186	0.872	2.743	0.234	0.842	1.310
399.8567	11.894	0.162	0.180	0.865	2.791	0.232	0.833	1.296
399.8591	11.901	0.172	0.169	0.881	2.774	0.224	0.847	1.295
399.8617	11.937	0.160	0.167	0.893	2.804	0.218	0.861	1.297
399.8638	11.944	0.166	0.177	0.881	2.751	0.230	0.848	1.308
399.8662	11.974	0.164	0.157	0.882	2.683	0.209	0.849	1.268
399.8706	11.980	0.193	0.139	0.877	2.730	0.201	0.838	1.240
399.8728	11.974	0.210	0.123	0.877	2.695	0.190	0.835	1.215
399.8747	11.999	0.195	0.157	0.833	2.682	0.219	0.794	1.233
399.8768	12.012	0.192	0.167	0.824	2.664	0.228	0.786	1.242
399.8790	12.015	0.206	0.135	0.856	2.731	0.201	0.815	1.217
399.8809	12.056	0.155	0.222	0.802	2.691	0.272	0.771	1.314
399.8846	12.076	0.157	0.215	0.784	2.675	0.265	0.753	1.283
399.8864	12.064	0.174	0.190	0.812	2.713	0.246	0.777	1.269
399.8895	12.057	0.188	0.178	0.791	2.698	0.238	0.753	1.230
399.8926	12.059	0.196	0.155	0.830	2.694	0.218	0.791	1.226
399.8946	12.061	0.181	0.171	0.823	2.715	0.229	0.787	1.245
399.8966	11.964	0.253	0.121	0.717	2.739	0.202	0.666	1.070
399.9008	11.956	0.247	0.118	0.739	2.730	0.197	0.690	1.084
399.9027	11.962	0.232	0.115	0.791	2.708	0.189	0.745	1.123
399.9049	11.950	0.224	0.139	0.751	2.719	0.211	0.706	1.128
399.9073	11.939	0.205	0.148	0.795	2.715	0.214	0.754	1.181
399.9093	11.907	0.221	0.124	0.792	2.717	0.195	0.748	1.137
399.9114	11.955	0.173	0.162	0.869	2.777	0.217	0.834	1.269
399.9157	11.916	0.167	0.159	0.878	2.731	0.212	0.845	1.269
399.9176	11.918	0.161	0.173	0.907	2.811	0.225	0.875	1.324
399.9193	11.878	0.168	0.151	0.913	2.792	0.205	0.879	1.289
399.9208	11.911	0.135	0.190	0.912	2.743	0.233	0.885	1.351
399.9224	11.857	0.163	0.163	0.891	2.757	0.215	0.858	1.289
399.9240	11.840	0.153	0.160	0.950	2.742	0.209	0.919	1.337
399.9257	11.828	0.151	0.163	0.925	2.777	0.211	0.895	1.317
399.9276	11.833	0.142	0.176	0.911	2.770	0.221	0.883	1.325
401.9013	11.842	0.155	0.171	0.918	2.764	0.221	0.887	1.328
401.9033	11.838	0.159	0.164	0.923	2.796	0.215	0.891	1.321
401.9052	11.845	0.180	0.146	0.939	2.799	0.204	0.903	1.310
401.9070	11.863	0.167	0.166	0.901	2.773	0.219	0.868	1.306
401.9086	11.879	0.157	0.177	0.913	2.789	0.227	0.882	1.336
401.9103	11.888	0.169	0.151	0.934	2.779	0.205	0.900	1.310
401.9135	11.909	0.152	0.195	0.878	2.730	0.244	0.848	1.335

TABLE 6 (CONTINUED)

HJD	V	$(b-y)$	m_1	c_1	β	$[m1]$	$[c1]$	$[u-b]$
-2457000.00								
401.9152	11.897	0.171	0.173	0.895	2.794	0.228	0.861	1.316
401.9168	11.914	0.187	0.144	0.909	2.774	0.204	0.872	1.279
401.9187	11.927	0.173	0.173	0.895	2.794	0.228	0.860	1.317
401.9207	11.921	0.189	0.164	0.866	2.783	0.224	0.828	1.277
401.9227	11.951	0.182	0.164	0.875	2.788	0.222	0.839	1.283
401.9245	11.964	0.185	0.153	0.893	2.806	0.212	0.856	1.280
401.9264	11.961	0.202	0.133	0.881	2.766	0.198	0.841	1.236
401.9301	11.969	0.195	0.174	0.855	2.746	0.236	0.816	1.289
401.9319	11.983	0.187	0.184	0.825	2.753	0.244	0.788	1.275
401.9337	11.992	0.199	0.169	0.829	2.802	0.233	0.789	1.255
401.9362	12.000	0.204	0.162	0.814	2.719	0.227	0.773	1.228
401.9378	12.005	0.217	0.146	0.822	2.753	0.215	0.779	1.209
401.9395	12.015	0.208	0.155	0.834	2.743	0.222	0.792	1.236
401.9411	12.039	0.195	0.159	0.827	2.728	0.221	0.788	1.231
401.9430	12.033	0.218	0.147	0.790	2.769	0.217	0.746	1.180
401.9450	12.030	0.231	0.121	0.825	2.769	0.195	0.779	1.169
401.9469	12.039	0.212	0.133	0.852	2.734	0.201	0.810	1.211
401.9509	12.033	0.231	0.130	0.837	2.672	0.204	0.791	1.199
401.9526	12.046	0.219	0.141	0.812	2.670	0.211	0.768	1.190
401.9547	12.058	0.193	0.159	0.829	2.784	0.221	0.790	1.232
401.9567	12.031	0.210	0.146	0.811	2.770	0.213	0.769	1.195
401.9586	12.025	0.203	0.151	0.830	2.773	0.216	0.789	1.221
401.9610	12.010	0.212	0.147	0.810	2.758	0.215	0.768	1.197
401.9631	12.015	0.183	0.185	0.791	2.770	0.244	0.754	1.242
401.9652	11.990	0.187	0.176	0.818	2.791	0.236	0.781	1.252
401.9677	11.959	0.213	0.137	0.845	2.779	0.205	0.802	1.213
401.9697	11.971	0.170	0.169	0.836	2.753	0.223	0.802	1.249
401.9714	11.921	0.190	0.156	0.863	2.747	0.217	0.825	1.259
401.9735	11.913	0.188	0.147	0.868	2.828	0.207	0.830	1.245
401.9772	11.891	0.185	0.148	0.885	2.779	0.207	0.848	1.262
401.9791	11.885	0.166	0.176	0.866	2.751	0.229	0.833	1.291
401.9812	11.846	0.166	0.154	0.920	2.781	0.207	0.887	1.301
401.9832	11.828	0.171	0.150	0.919	2.817	0.205	0.885	1.294
401.9852	11.814	0.179	0.132	0.948	2.810	0.189	0.912	1.291
401.9869	11.813	0.166	0.144	0.940	2.833	0.197	0.907	1.301

5.2. *Physical Parameter Determination*

The application of the above mentioned numerical unreddening packages gave the results listed in Table 7 for BO Lyn. This table lists, in the first column, the HJD. Subsequent columns present the reddening, the unreddened indexes, the unreddened magnitude, the absolute magnitude, the distance modulus, and the distance. Mean values were calculated for $E(b-y)$, the distance modulus (DM) and the distance for two cases: (i) the whole data sample and (ii) in phase limits between 0.3 and 0.8, which is customary for pulsating stars to avoid the maximum. We obtained, for the whole cycle, values of 0.020 ± 0.021; 10.7 ± 0.9 and 1497 ± 756 for $E(b-y)$, DM and distance (in pc), respectively, whereas for the mentioned phase limits we obtained,

TABLE 7

REDDENING AND UNREDDENED PARAMETERS OF BO LYN

HJD	$E(b-y)$	$(b-y)_0$	m_0	c_0	Hβ	V_0	M_V	DM	d(pc)
-2457000.00									
401.9832	.052	.119	.166	.909	2.817	11.60	1.76	9.84	928
399.9176	.036	.125	.184	.900	2.811	11.76	1.78	9.98	990
401.9852	.058	.121	.149	.936	2.810	11.57	1.40	10.17	1080
401.9245	.055	.130	.170	.882	2.806	11.73	1.83	9.89	952
399.8617	.028	.132	.176	.887	2.804	11.81	1.80	10.01	1005
401.9337	.059	.140	.187	.817	2.802	11.74	2.35	9.39	754
401.9052	.049	.131	.161	.929	2.799	11.63	1.31	10.32	1159
401.9033	.024	.135	.171	.918	2.796	11.73	1.41	10.32	1160
401.9152	.032	.139	.183	.889	2.794	11.76	1.63	10.13	1060
401.9187	.034	.139	.183	.888	2.794	11.78	1.63	10.15	1070
399.9193	.029	.139	.160	.907	2.792	11.75	1.44	10.31	1154
399.8567	.017	.145	.185	.862	2.791	11.82	1.86	9.96	982
401.9652	.038	.149	.187	.810	2.791	11.83	2.28	9.55	811
401.9086	.015	.142	.182	.910	2.789	11.81	1.40	10.41	1210
401.9227	.036	.146	.175	.868	2.788	11.80	1.73	10.07	1034
401.9547	.039	.154	.171	.821	2.784	11.89	2.08	9.81	917
401.9207	.038	.151	.175	.858	2.783	11.76	1.73	10.03	1012
401.9812	.019	.147	.160	.916	2.781	11.77	1.21	10.55	1288
401.9103	.022	.147	.157	.930	2.779	11.80	1.06	10.74	1404
401.9677	.057	.156	.154	.834	2.779	11.72	1.86	9.86	935
401.9772	.033	.152	.158	.878	2.779	11.75	1.50	10.25	1122
399.9114	.017	.156	.167	.866	2.777	11.88	1.61	10.27	1130
399.9257	.001	.150	.163	.925	2.777	11.82	1.11	10.71	1389
399.8591	.015	.157	.174	.878	2.774	11.84	1.46	10.37	1188
401.9168	.033	.154	.154	.902	2.774	11.77	1.21	10.56	1296
401.9070	.011	.156	.169	.899	2.773	11.81	1.27	10.55	1287
401.9586	.040	.163	.163	.822	2.773	11.85	1.91	9.95	976
399.9276	.000	.142	.176	.911	2.770	11.83	1.13	10.70	1382
401.9567	.043	.167	.159	.802	2.770	11.85	2.03	9.81	918
401.9631	.014	.169	.189	.788	2.770	11.95	2.21	9.74	889
401.9430	.048	.170	.161	.780	2.769	11.83	2.21	9.62	840
401.9450	.065	.166	.140	.812	2.769	11.75	1.89	9.86	938
401.9264	.039	.163	.145	.873	2.766	11.79	1.34	10.45	1232
401.9013	.000	.155	.171	.918	2.764	11.84	.98	10.86	1489
401.9610	.035	.177	.158	.803	2.758	11.86	1.86	10.00	998
399.9224	.000	.163	.163	.891	2.757	11.86	1.12	10.74	1405
399.8506	.000	.160	.154	.952	2.754	11.86	.53	11.34	1851
401.9319	.008	.179	.186	.823	2.753	11.95	1.66	10.29	1144
401.9378	.038	.179	.157	.814	2.753	11.84	1.68	10.16	1076
401.9697	.000	.170	.169	.836	2.753	11.97	1.56	10.41	1209
399.8638	.000	.166	.177	.881	2.751	11.94	1.12	10.82	1458

TABLE 7 (CONTINUED)

HJD	E($b-y$)	$(b-y)_0$	m_0	c_0	Hβ	V_0	M_V	DM	d(pc)
-2457000.00									
401.9791	.000	.166	.176	.866	2.751	11.89	1.26	10.63	1334
401.9714	.010	.180	.159	.861	2.747	11.88	1.23	10.65	1347
401.9301	.013	.182	.178	.852	2.746	11.91	1.29	10.62	1332
399.8546	.000	.149	.186	.872	2.743	11.90	1.09	10.80	1447
399.9208	.000	.135	.190	.912	2.743	11.91	.73	11.18	1719
401.9395	.022	.186	.162	.830	2.743	11.92	1.44	10.49	1250
399.9240	.000	.153	.160	.950	2.742	11.84	.38	11.46	1961
399.8966	.052	.201	.137	.707	2.739	11.74	2.42	9.32	730
401.9469	.021	.191	.139	.848	2.734	11.95	1.09	10.86	1483
399.8790	.014	.192	.139	.853	2.731	11.96	.98	10.97	1564
399.9157	.000	.167	.159	.878	2.731	11.92	.79	11.13	1682
399.8706	.002	.191	.140	.877	2.730	11.97	.77	11.20	1737
399.9008	.042	.205	.131	.731	2.730	11.77	2.01	9.76	895
401.9135	.000	.152	.195	.878	2.730	11.91	.76	11.15	1695
401.9411	.000	.195	.159	.827	2.728	12.04	1.17	10.86	1489
399.9049	.016	.208	.144	.748	2.719	11.88	1.64	10.23	1114
401.9362	.000	.204	.162	.814	2.719	12.00	1.07	10.93	1531
399.9093	.015	.206	.129	.789	2.717	11.84	1.22	10.62	1333
399.8946	.000	.181	.171	.823	2.715	12.06	.87	11.19	1730
399.9073	.000	.205	.148	.795	2.715	11.94	1.13	10.81	1451
399.8864	.000	.174	.190	.812	2.713	12.06	.91	11.15	1701
399.9027	.020	.212	.121	.787	2.708	11.88	.95	10.93	1532
399.8477	.000	.130	.195	.928	2.706	11.88	-.44	12.32	2909
399.8895	.000	.188	.178	.791	2.698	12.06	.60	11.46	1955
399.8728	.000	.210	.123	.877	2.695	11.97	-.40	12.38	2986
399.8926	.000	.196	.155	.830	2.694	12.06	.04	12.02	2537
399.8809	.000	.155	.222	.802	2.691	12.06	.20	11.86	2351
399.8662	.000	.164	.157	.882	2.683	11.97	-.98	12.95	3892
399.8747	.000	.195	.157	.833	2.682	12.00	-.49	12.48	3140
399.8846	.000	.157	.215	.784	2.675	12.08	-.19	12.27	2838
401.9509	.000	.231	.130	.837	2.672	12.03	-.89	12.93	3847
401.9526	.000	.219	.141	.812	2.670	12.05	-.68	12.72	3506
399.8768	.000	.192	.167	.824	2.664	12.01	-1.02	13.04	4048

0.022 ± 0.022; 10.5 ± 0.8 and 1383 ± 702 respectively. The uncertainty is merely the standard deviation. In the case of the reddening, most of the values for the spectral type F of BO Lyn produced negative values which is unphysical. In those cases we forced the reddening to be zero in which case the $(b-y)$ index is the same. If the negative values are included, the mean $E(b-y)$ is 0.009 ± 0.038.

If the photometric system is well-defined and calibrated, it provides an efficient way to investigate physical conditions such as effective temperature and surface gravity via a direct comparison of the unreddened indexes with the theoretical models. These calibrations have already been described and used in previous analyses (Peña & Peniche; 1994; Peña & Sareyan, 2006).

A comparison between theoretical models, such as those of Lester, Gray & Kurucz (1986), hereinafter LGK86 and intermediate or wide band photometry obtained for the stars allows a direct comparison.

TABLE 8

EFFECTIVE TEMPERATURE OF BO LYN

Phase	T_e	T_e	Mean	OP&J	$\log g$
[Fe/H]	0.0	-0.5		-0.5	-0.5
0.05	7300	7100	7200	7251	3.4
0.15	7400	7200	7300	7235	3.8
0.25	7300	7200	7250	7259	3.8
0.35	7200	7000	7100	7234	3.6
0.45	7400	7500	7450	7494	3.7
0.55	7800	7500	7650	7582	3.8
0.65	8000	7700	7850	7781	3.9
0.75	7800	7500	7650	7469	3.7
0.85	7700	7400	7550	7642	3.7
0.95	7700	7400	7500	7569	3.5

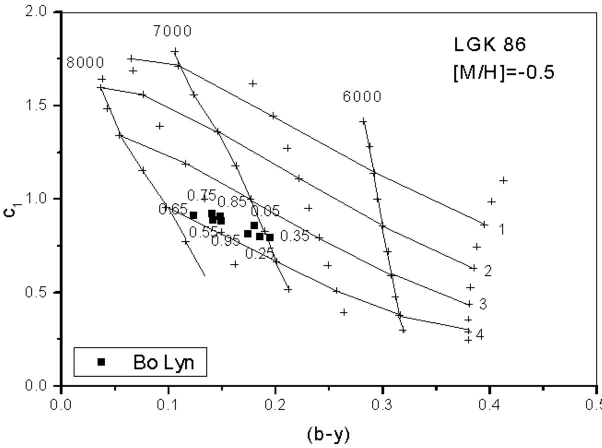

Fig. 11. Location of the unreddened points of BO Lyn (dots) in the LGK86 grids. The numbers indicate the phase.

LGK86 calculated grids for stellar atmospheres for G, F, A, B and O stars with different values of [Fe/H] in a temperature range from 5500 up to 50 000 K. The surface gravities vary approximately from the main sequence values to the limit of the radiation pressure in 0.5 intervals in $\log g$. A comparison between the photometric unreddened indexes $(b-y)_0$ and c_0 obtained for each star with the models allowed us to determine the effective temperature T_e and surface gravity $\log g$.

In order to locate our unreddened points in the theoretical grids of LGK86, a metallicity had to be assumed. LGK86 calculated their outputs for several metallicities. Particularly in the case of BO Lyn, for which we determined a mean metallicity of $[Fe/H] = -0.39 \pm 0.31$, there are two applicable models, either $[Fe/H] = 0.0$ or -0.5. We tested both since our determined mean metallicity of $[Fe/H] = -0.39 \pm 0.31$ lies in between. To diminish the noise and to see the variation of the star in phase, mean values of the unreddened colors were calculated in phase bins of 0.1 starting at 0.05. As can be seen in Figure 11, for the case of $[Fe/H] = -0.5$, the effective temperature varies between 7000 K and 7700 K; the surface gravity varies between 3.4 and 3.9. Table 8 lists these values. Column 1 shows the phase, Columns 2 and 3 list the temperature obtained from the plot for each [Fe/H] value; Column 4, the mean value and Column 5, the standard deviation for a $[Fe/H] = -0.5$ metallicity. Column 6 lists the effective temperature obtained from the theoretical relation reported by Rodriguez (1989) based on a relation of Petersen & Jorgensen (1972, hereinafter P&J) $T_e = 6850 + 1250 \times (\beta - 2.684)/0.144$ for each value and averaged in the corresponding phase bin. The last column lists the surface gravity $\log g$ from the plot.

5.3. *Physical Parameter Discussion*

New observations in $uvby-\beta$ photoelectric photometry were carried out on the HADS star BO Lyn. From this $uvby-\beta$ photoelectric photometry we determined first its spectral type, varying between A5V and A8V. From Nissen's (1988) calibrations the reddening was determined as well as the unreddened indexes. These served to obtain the physical characteristics of this star, $\log T_e$, in the range from 7000 K to 7700 K and $\log g$ from 3.2 to 3.6, using two methods: (1) from the location of the unreddened indexes in the LGK86 grids and (2) through the theoretical relation (Petersen et al., 1972). They are similar within the error bars, and give a good idea of the star's behavior. Furthermore, when mean values are obtained from the two closest metallicity values, the result is closer to the obtained theoretical value.

6. DISCUSSION

According to Rodriguez & Breger (2001) "only 14 % of the known δ Scuti stars are part of binary or multiple stellar systems Only five variables are fainter than $V = 10.0$.... Hence, multiplicity is catalogued for 22 of all the δ Scuti known up $10\overset{m}{.}0$. This percentage is very low because more than 50% of the stars are expected to be members of multiple systems". They later state that "pulsating stars in eclipsing binaries are important for accurate determinations of fundamental stellar parameters and the study of tidal effects on the pulsations.... During the last two decades, unusual changes in the light curves have been detected, leading to a number of different interpretations..."

They later say that "pulsation provides an additional method to detect multiplicity through a study of the light-time effects in a binary system. This method generally favors high-amplitude variables with only one or two pulsation periods (which tend to be radial). Several decades of measurements are usually required to study these (O-C) residuals in the times of maxima".

At that time they listed, in their Table 4, only six stars with known orbital periods. Since then, with a longer time basis for those stars, and for an increased number of measured times of maximum, a better definition of their orbital elements is available. There have been numerous studies of HADS stars with this purpose. For example, Boonyarak et al. (2011) carried out a study devoted to the analysis of the stability of fourteen stars of this type. Many other authors carried out analyses on a star-by-star basis. Some of the HADS stars show a behavior of the O-C residuals compatible with the light-travel time effect that is expected for the binaries AD CMi, KZ Hya, AN Lyn, BE Lyn, SZ Lyn, BP Peg, BS Aqr, CY Aqr, among others; whereas there are some stars that, on the contrary, are varying with one period and its harmonics and do not show a light-travel time effect. To this category, according to Boonyarak et al., (2011) belong GP And, AZ CMi, AE UMa, RV Ari, DY Her, DH Peg.

In the present study we have demonstrated that BO Lyn is pulsating with one stable varying period whose O-C residuals show a sinusoidal pattern compatible with a light-travel time effect. In relation to this topic, it is interesting to mention that in the excellent discussion of Templeton (2005), he states that: "In all cases except SZ Lyn, the period of the purported binarity is close to that of the duration of the (O-C) measurements, making it difficult to prove that the signal is truly sinusoidal. A sinusoidal interpretation is only reliable when multiple cycles are recorded, as in SZ Lyn. While the binary hypothesis is certainly possible in most of these cases, conclusive proof will not be available for years or even decades to come. Continued monitoring of times of maximum will be crucial, and such observations are encouraged. In the meantime, however, other possible interpretations of their behavior must also be explored".

We feel that the results presented in this paper fulfill Templeton's (2005) requirement that "a sinusoidal interpretation is only reliable when multiple cycles are recorded".

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REFERENCES

Boonyarak, C., Fu, J., et al. 2011, ApSpSc, 333,125
Collins, K. 2012, AstroImageJ
Golay, M. 1974, Introduction to astronomical photometry, (Durdrecht: Reidl)
Hintz, E., Bush, T. C. & Rose, M. B. 2005, AJ, 130, 2876
Hubscher, J., Braune, W. Lehman, P. B. 2013, IBVS, 6048
Kazarovets, E. V. & Samus, N. N. 1997, IBVS, 4471
Kinman, T. D., Suntzeff, N. B. & Kraft, R. P. 1994, AJ, 108, 1722
Kinman, T. D. 1998, PASP, 110, 1277
Klingenberg, G., Dvorak, S. W. & Robertson, C. W. 2006, IBVS, 5701
Lenz, P. & Breger, M. 2005, CoAst, 146, 53
Lester, J. B., Gray, R. O., & Kurucz, R. I. 1986, ApJS, 61, 509
Nissen, P. 1988, A&A, 199, 146
Peña, J. H., et al. 2002, RMxAA, 38, 31
Peña, J. H. & Peniche, R. 1994, RMxAA, 28, 139
Peña, J. H. & Sareyan, J. P. 2006, RMxAA 42, 179
Peña, J. H., Sareyan, J. P., Cervantes-Sodi, B., et al. 2007, RMxAA, 43, 217
Petersen, J. O. & Jorgenesen, H. E. 1972, A&A 17, 367
Rodriguez, E., 1989 Tesis Doctoral, Universidad de Granada, Spain
Rodriguez, E. & Breger, M. 2001, A&A 366, 178
Shobbrook, R. R. 1984, MNRAS, 211, 659
Stellingwerf, R.F. 1978, ApJ, 224, 953
Templeton, M. R. 2005, JAAVSO, 34

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