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NEW INTERPRETATIONS ON THE VARIATIONS OF V 651 MON

J.H. Peña

Instituto de Astronomía
Universidad Nacional Autónoma de México

and

M.A. Hobart

Facultad de Física
Universidad Veracruzana

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RESUMEN

Se realizó un análisis de frecuencias de los datos fotométricos reportados en la literatura sobre la nebulosa planetaria NGC 2346 encontrándose que las frecuencias 0.06259, 0.067415 y 0.00608 c/d ajustan las observaciones fotométricas separadas en 2867 días, aunque su existencia no las explica ningún modelo de pulsación en estrellas tempranas. Se demuestra que el modelo previamente propuesto para este sistema no describe correctamente las observables y en su lugar se postula un modelo de un sistema triple que, mediante pulsación y rotación describe todos los parámetros observados.

ABSTRACT

This paper carries out a frequency analysis of the photometric data available in the literature pertaining to the planetary nebula NGC 2346. The frequencies 0.06259, 0.067415 and 0.00608 c/d were found from these data that cover a time span of 2867 days, although their very existence is unexplained by any model of an early type star. A careful analysis of the data shows that the previously proposed model does not adequately describe the observations and that the observations are more easily explained by pulsation and eclipses in a triple system.

Key words: **BINARIES - CLOSE — BINARIES - ECLIPSING — PLANETARY NEBULAE - INDIVIDUAL (NGC 2346) — STARS - INDIVIDUAL — STARS - OSCILLATIONS**

I. INTRODUCTION

NGC 2346 is a planetary nebula whose central ar, V651 Mon, is a well-known spectroscopic ınary consisting of an A type star and a hot ›mpanion and having an orbital period of nearly 5 days. The spectral type of the A star has been ›ted as A2V by Méndez (1978) and as an A0III y Calvet & Cohen (1973). A compilation of its ıaracteristics, as well as new photoelectric and CD photometry have been secured by Costero al. (1993). They reported that the large optical ıd infrared variations detected with a modulation milar to the orbital period (Kohoutek 1982, 1983; éndez, Gathier, & Niemela 1982; Roth et al.)84), were interpreted as being caused by a dust oud passing in front of the orbit of the central nary star. Costero et al. (1993) reported that ese occultations were periodic and developed a condary minimum when the primary one faded and that, for several years it remained constant or nearly constant until the star was reported to vary again.

The ephemeris of this star was determined by Méndez & Niemela (1981) from 46 spectrograms of NGC 2346. The stellar velocity was determined by averaging the results from six absorption lines, whereas the nebular velocity was determined using the spectral lines [Ne III] $\lambda 3868$, Hγ and He II $\lambda 4686$. The standard deviation of one plate was of 3 km s^{-1}.

Using the method of Lafter & Kinman (1965) and the above values, Méndez & Niemela (1981) deduced an orbital period of 15.995 $\pm$ 0.025 d closely followed by two periods in the neighborhood of one day, 0.93874 and 1.06358 d. They reported that all significant periods between 0.25 and 50 d were tested.

The observations reported by Costero et al.

(1993) were mostly made with the multi channel *uvby* photometer attached to the 1.5-m telescope at San Pedro Mártir, México and were carried out in two observing seasons in 1992 during the months of April 29 – May 10 and November 13 – 27. A few CCD observations were done on the nights of April 19 – 22, 1992. The results presented in their Table 1, are shown schematically in a phase diagram in their Figure 1 for which the ephemeris reported by Méndez & Niemela (1981) and not, as they stated, by Méndez et al. (1982) was used. The ephemeris employed was: JD = 2,443,126.0 + 15.991 E.

The estimated errors of the photometric data presented by Costero et al. (1993) are less that 0.01 mag in both magnitude and color.

2. ANALYSIS

Upon examining the phase diagrams of the observations by Costero et al. (1993) separated by observational seasons into two separate diagrams, it became evident that they do not correspond to any periodic phenomena. Several possibilities emerge: the first is that although variable the phenomenon is not periodic; second, that the period is not correctly determined; third, that more than one period is acting simultaneously and last, that another physical mechanism exists that fits the observations. An analogous situation also occurred before at the dawn of the development of knowledge about the periods of δ Scuti type stars (see the review by Breger 1979): long and continuous strings of data were lacking that could unequivocally throw light on the determination of the pulsational periods.

In order to determine the periods, if stable and if they exist, the spectroscopic data of Méndez & Niemela (1981) were analyzed, as a first step, by the authors of the present paper with an alternative method of period determination, MUFRAN, (MUltiple FRequency ANalysis) developed by Kollath (1990). The sweeping was done in a frequency interval between 0 and 0.1 c/d in 500 frequency intervals and the same result, as Méndez & Niemela (1981), was obtained. However, the data string by Méndez & Niemela (1981) consisted of six groups containing only a few data each and of a time span shorter, except for one, than the reported period and covering an elapsed time of almost three and a half years.

Despite the complexities due to the window function of the spectroscopic data of Méndez & Niemela (1981) thereafter, a single period analysis was assumed and small modifications to the ephemeris were subsequently used to adjust the data. For example, this ephemeris led to the phase diagrams of the data of Costero et al. (1993) in which the data were presented, with the putative period, in the original paper as a double diagram with no periodic phenomenon discernible. Since the photometric data of Costero et al. (1993) covered a much longer time span than the spectroscopic data of Méndez & Niemela (1981) the analysis of this photometric data could throw light on the periodic content of the variations. In this paper light curves of the high quality photometric data presented by Costero et al. (1993) were constructed. This light curve can be fitted at first sight by a period of 32 d. The data of Costero et al. (1993) have been plotted in phase diagrams using both periods (see Figures 1*a* and 1*b*). It is immediately evident that the apparent unperiodic events of Figure 1 (period of 15.991 d) in Costero et al. (1993) become a periodic phenomenon if a period of 32.0 d is assumed. This period also describes a periodic phenomenon with the photometric data secured by Kohoutek (1982) and the radial velocities from the spectroscopic data obtained by Méndez et al. (1982).

It is desirable to understand how these frequencies are related to each other. From the studies of periodic phenomena it is known that if the period of vibration is P, the fundamental angular frequency $\omega = 2\pi/P$ and the harmonics are 2ω, 3ω etc. In this particular case, if the period determined in the present paper (P = 32.0 d) is assumed, a corresponding frequency of 0.0313 c/d is found. The first harmonic is 0.0625 c/d which corresponds to 15.991 d, the period determined by Méndez & Niemela (1981), and by us from the analysis of the same spectroscopic data.

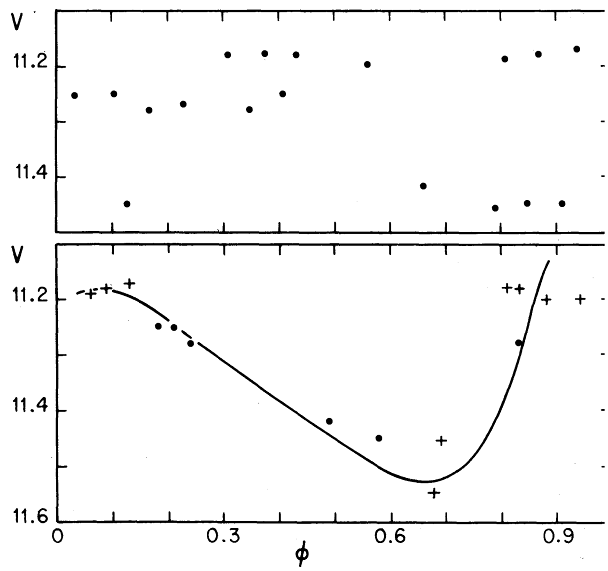

Fig. 1. *a*) Phase diagram of the photometric data of Costero et al. (1993) using the ephemeris proposed by Méndez & Niemela (1981). No periodic pattern can be distinguished from this diagram. *b*) Phase diagram of the same data but considering a period of 32 d.

We propose, then, that the spectroscopic data :ring considered produced a peak in the power ›ectrum diagram which corresponds to the first armonic. When better data are analyzed (the hotometric data presented by Costero et al. 1993), different periodic content of the phenomenon is nveiled.

Is this interpretation valid or is lacking a more xtensive period analysis of longer and better data :rings? To answer this question, we decided to arry out an extensive study of all the observational ata available since, if the derived frequencies exist nd are stable, they should describe the whole et of observations of this object. Table 1 lists compilation of the observations of NGC 2346: olumn 1 lists the initial time of the observations ı each season; column 2, the time span of the bservations and column 3, the number of nights bserved in this time interval. Mention of the nethods employed for the data acquisition are listed ı column 4 and 5. Columns 6, 7 and 8 list the mplitude of the variation, the mean value of the ariation and the mean color index $\langle B - V \rangle$ in each eason, respectively. The source from which the ata were obtained is listed in column 9 and, finally, here is a brief comment in column 10.

From this Table 1, the following can be deterıined: First, with respect to the spectroscopic bservations, the whole sample covers a time span f 1239 d (3.39 yr) lumped into six groups of which nly one is longer in time than the derived period. lowever, as has already been stated, both Méndez : Niemela (1981) and the analysis carried out of ıeir data in the present paper give a period of 5.99 d, a single period interpretation which has een accepted yielding only slight modifications ı the period and no multi periodic analysis of ıese data has ever been done. The reported ifferent periods around the determined value btained by Méndez & Niemela (1981) have been ımmarized in Table 1 and have been deterıined by Kohoutek (1982, 1991), and Kohoutek, lantegazza, & Hainaut (1992). Second, although ıe period correctly describes all the data except the ıost recent observations of Costero et al. (1993), does not explain the huge amplitude variations hich range from 3.19 mag in JD 2444995.0 as reorted by Kohoutek (1982) to the smallest observed alue of 0.11 mag in JD 2448264.0 also reported y Kohoutek (1991), with a wide range of values in etween.

In view of these unexplained amplitude variaons it was decided to analyze the photometric data rst. To do this the following was carried out:

As a first step, the mean photometric value as subtracted from the data for each season to liminate the long term variation, the nature of hich will be faced later.

Then, an analysis of the longest data string was made by means of a method previously employed by the authors in period analysis of other objects (W UMa: Peña, Hobart, & Rodríguez 1993; RR Lyrae: Peniche et al. 1989; δ Scuti: Hobart, Peña, & Peniche 1989). This method consists of a first guess of the frequency by a standard Fast Fourier Transform. Then, this frequency is refined by adjusting the data to periodic functions and sweeping in a frequency interval to decide, through numerical evaluation of the goodness of fit, which frequency best describes the data. Prewhitening this frequency from the original data is done and the method is repeated iteratively until the noise level in the power spectrum is reached. The MFF method is capable of managing up to five frequencies simultaneously.

3. RESULTS

As can be seen from Table 1, the longest data string is that of Costero et al. (1986), carried out during two seasons separated from one another by almost one year. First, our analysis was done independently for each season obtaining a period of similar value as that obtained by Méndez & Niemela (1981) and the present analysis on the Méndez & Niemela's (1981) data.

However, with only one frequency it is impossible to describe such a large amplitude variation of 2.56 and 0.43 mag for each season, respectively.

Hence, both seasons, taken simultaneously, were analyzed. In the first step, a frequency of 0.06264 c/d, very similar to the reported ephemeris of Méndez & Niemela (1981) was obtained but, after prewhitening this frequency from the data, a frequency very close to it was derived.

In order to determine a unequivocal set of frequencies that could describe a larger observational basis, the data of Costero et al. (1993) was added to the Costero et al. (1986) data. This was done since to our knowledge, it consists of the same observing team and hence indicates homogeneous reduction.

The analysis of the above mentioned data set of Costero et al. (1986, 1993) together gave, as a first frequency, a value of 0.06259 c/d. After prewhitening, the residuals indicated the presence of another frequency of 0.067415 c/d very close to the first one determined. A third frequency of 0.00608 c/d was also obtained. The results of this period analysis are presented in Table 2; they are also shown schematically in Figure 2. Emphasis should be put on the fact that the prediction (continuous line) was done with the whole data set and that the time separation is of 2867 days (7.86 yr).

This set of frequencies (0.6259, 0.67415, and 0.00608 c/d) was tested on each of the NGC 2346 data sets that have been listed in Table 1. The results

TABLE 1

COMPILATION OF THE OBSERVATIONS OF NGC 2364

HJD 2440000+	ΔT days	N	Technique	Type	Amplitude km s^{-1}	Amplitude mag	⟨Vel⟩ km s^{-1}	⟨V⟩ mag	⟨B – V⟩ mag	Source[a]	Notes[b]
3138	63	9	spectr	rad vel	...	...	...	...	...	MN	1
3878	17	15	spectr	rad vel	38	...	27.44	...	...	MN	1
3914	7	3	spectr	rad vel	38	...	27.44	...	...	MN	1
4137	9	7	spectr	rad vel	30	...	28.00	...	...	MN	...
4265	13	12	spectr	rad vel	31	...	23.71	...	...	MN	...
4377	1	1	spectr	rad vel	45	...	22.45	...	...	L83	...
4628	75	15	photogr	*V*	...	0.50	...	11.18	...	L83	...
4984	116	13	photogr	*V*	...	1.90	...	11.954	...	L83	...
4995	21	19	photomtr	*UBV*	...	3.19	...	12.02	0.373	K82	2
5090	344	55	photogr	*V*	...	3.5	...	13.13	...	MMC	...
5090	41	20	photogr	*V*	...	2.6	...	11.91	...	MW	...
5288	55	18	photomtr	*UBV*	...	3.57	...	13.73	0.577	MMC	3
5384	170	1	photogr	*V*	...	...	12.9	...	L83	...	...
5719	37	12	photomtr	*UBV*	...	0.60	...	13.47	0.780	KC	...
6084	68	30	photomtr	*V*	...	2.56	...	12.73	...	CTM	...
6400	54	23	photomtr	*V uvby*	...	0.43	...	11.34	...	CTM	...
8264	12	12	photomtr	*UBV*	...	0.11	...	11.29	0.275	K91	4
8281	12	12	photomtr	Δ*V*	...	0.13	...	...	...	KMH	5
8731	23	10	photomtr	*V*	...	0.21	...	11.34	0.280	CST	...
8939	15	10	photomtr	*UBV*	...	0.38	...	11.26	0.287	CST	...

[a] Source: CTM = Costero et al. 1986; CST = Costero et al. 1993; K82 = Kohoutek 1982; K91 = Kohoutek 1991; KC = Kohoutek & Celnik 1985; KMH = Kohoutek, Mantegazza, & Hainaut 1992; L83 = Luthardt 1983; MW = Marino & Williams 1983; MMC = Méndez et al. 1985; MN = Méndez, & Niemela 1981.
[b] Notes: 1) First period deduced; 2) P = 17.2d; 3) Max. amplitude; 4) Min. amplitude; 5) P = 13.65d.

TABLE 2

CORRELATION COEFFICIENTS FOR SEVERAL SEASONS USING THE SET OF FREQUENCIES DETERMINED IN THE PERIOD ANALYSIS

HJD 2440000+	ΔT	R^2
3138	1239	0.90
4995	...	0.97
5090	345	0.63
5288	55	0.97
6084	68	0.95
6417	54	0.89
8264	...	0.81
8281	...	0.96
8731	224	0.86
8939	16	0.99
6084	2870	0.89[a]

[a] Photometric data from CTM and CST. See text.

are presented in Table 2. As can be seen, judgin from the high correlation coefficient for each one the determined frequencies adjust significantly bet ter the photometric observations. With the same se of determined frequencies, the spectroscopic dat of Méndez & Niemela (1981) were tested. The nu merical results are also presented in Table 2 and th comparison of the observations with the prediction are presented in Figure 3.

Up to now a careful time series analysis of th available photometric data have yielded a set c frequencies that adjust well to the observation: However, what kind of objects fit these findings?

In order to answer this question we must revie the knowledge acquired from the observations an that have been summarized in Table 1. As alread mentioned, the most important parameter to de scribe is the large variation in the amplitude, as we as the variation of the mean value of the apparen magnitude and the ⟨*B* – *V*⟩ index of each seasor In fact, they seem to be correlated as is shown i

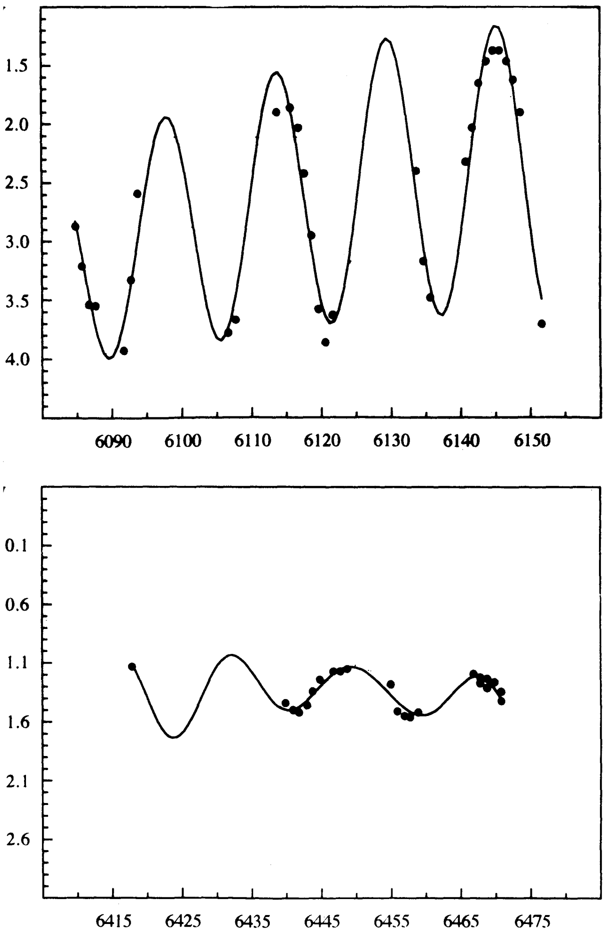

Fig. 2. Observations versus predictions (continuous line) for the observations by Costero et al. (1986) and Costero et al. (1993) taken simultaneously. The frequencies employed are those described in the text.

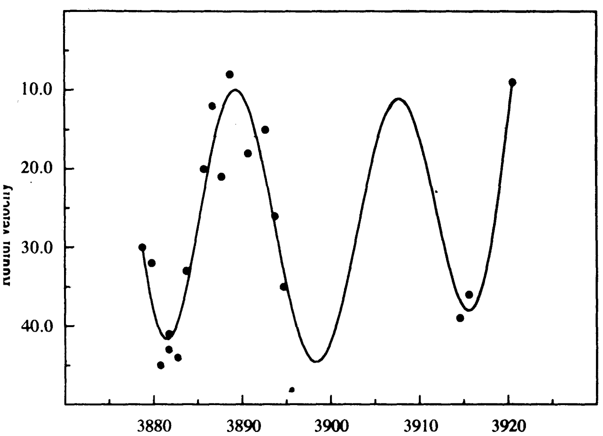

Fig. 3. Observations versus predictions (continuous line) for the spectroscopic data of Méndez & Niemela (1981). The prediction has been done using the frequencies determined from the photometric data.

Figure 4. Also the fact that it is a well known planetary nebula and that there is a star of an early A spectral type must be taken into consideration.

If the one period binary model were correct, no modulation would be possible and, hence, from the point of view of the variations due to eclipses in this binary system, no variation of amplitude could be explained and consequently, this model has to be discarded.

It is also impossible to consider that the light variations originate from the nucleus of the planetary nebula since it is much fainter than the A type star.

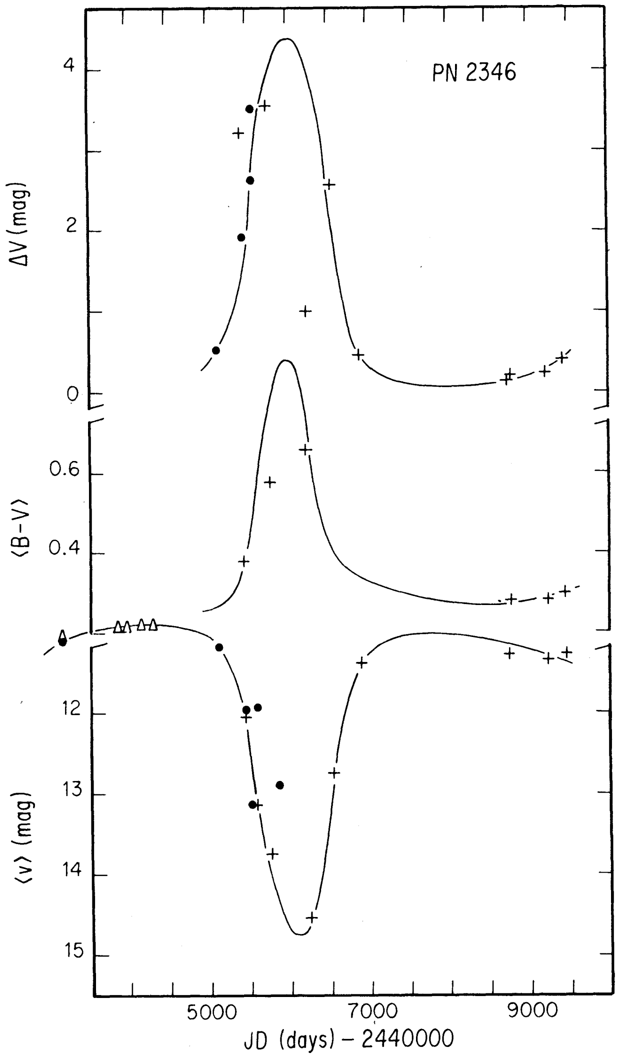

Fig. 4. Correlation of the amplitude of variation, the mean value of the color index $B - V$ and the mean apparent magnitude versus time for the photometric data presented in Table 1. Dots are photographic data, crosses, photometric and triangles spectroscopic measurements. Solid line is a freehand trace to the data.

3.1. *Multi Periodic Interpretation*

On the other hand, if the findings of the present analysis are correct, i.e., that the amplitude of variation is due to the simultaneous interaction of three modes of pulsation, one would have to explain such large amplitude variations and periods for an early A star. These types of stars are known to pulsate with more than one mode present and, for such a close pair of frequencies such that P_1/P_0 = 0.98 they would be interpreted as stars pulsating in non-radial modes. However, the periods for these stars are in the range of a few hours at the most and hardly present amplitudes of variation greater than 1 mag. The long period variation could be due, as already has been stated by Costero et al. (1993) to dust clouds.

However, although the period analysis of the data carried out in the present paper gives satisfactory results from a mathematical point of view, doubts still remain with respect to a possible physical scenario. A verification of this pulsation of several modes acting simultaneously could be carried out by monitoring the variations of this object since, if this interpretation is correct, it will eventually have a larger amplitude variation.

3.2. *Multiple System Model*

Another plausible explanation is provided by a simple triple system model. If we consider the sketches of Figure 4, the following is implied: When at its brightest, V around 11 mag, the $B - V$ index is that of an A star and the amplitude of variation at minimum, around $\Delta V = 0.4$ mag. Whereas at minimum light, $\langle V \rangle = 14.6$ mag, the color index $\langle B - V \rangle$ is around 0.88 and the amplitude of variation at maximum value around $\Delta V \geq 3.5$ mag.

From that, the following can be inferred: At maximum light we are seeing an A star, whereas at minimum light we are looking at a fainter star with $\langle B - V \rangle$ around 0.77 which corresponds to a G6 star at either class V or III. Hence we would be looking at a three star system constituted by an A, the hot companion, and a G star. The brightest one, the A star is of magnitude 11 whereas the G star has a magnitude equal to or fainter than 14.5 mag. This latter star would be pulsating with a period of 16 days. The photometric period deduced from the photometric data and the variation of the amplitude is due to a partial eclipse of the G star by the brightest star. At minimum, when only the G star is visible, the amplitude of the variation reaches its normal value of $\Delta V \geq 3.5$ mag.

The existence of the hot companion is unquestionable since neither of the two stars, the A or the G, is hot enough to ionize the gas. Furthermore, the A star and the hot companion model would constitute a system revolving synchronously with the period of pulsation of the G star. This conclusion is reached from the period analysis of the spectroscopic data from Méndez & Niemela (1981) who have shown that the central star of NGC 2346 is a single-lined spectroscopic binary and have also shown that the nebular velocity coincides with the γ velocity of the system. Since the analysis of the data implied that the period is of P = 15.995 $\pm$ 0.003 days, the same as the period deduced from the photometric data, the only plausible explanation would be that the orbital rotation of the A star and the hot companion around their center of mass is synchronous with the pulsation of the G star.

If the pattern presented in Figure 4 is repeated, assuming that there are indications of a beginning of the next eclipse, then it is clear that at the time of the determination of the spectroscopic observations of Méndez & Niemela (1981) and Méndez et al. (1982) the system was uneclipsed (Mendez et al. 1982; Schafer 1983) and the spectrum shows the features of the brightest component, the A star. Unfortunately, no spectrum was obtained at JD between 2445300 and 2445800, i.e., when the system was at minimum light and the G star eclipsed the brightest one. A spectrum taken at that time would have shown the characteristics of a G star and the spectral lines corresponding to an object with the $\langle B - V \rangle$ observed index.

If this simple model is correct then it will be periodic, and if the slight curvature at the right side of Figure 4 is an indication of the beginning of a new eclipse, then the system will be at minimum light in the near future when we will be looking at the G star.

In view of the discrepancies of the plausible physical explanations that describe the available observations we strongly encourage the community to secure new continuous observations both spectroscopically and photometrically to determine the true nature of this interesting and puzzling object since, if this simple model is correct and if the slight curvature at the right side of Figure 4 is an indication of the beginning of a new eclipse the the system will soon be at minimum light, mid 1994 to mid 1995; then we will be looking at the G star.

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Marco A. Hobart: Facultad de Física, Universidad Veracruzana, Apartado Postal 270, 91190 Xalapa, Ver., México.
José H. Peña: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., México. E-mail: jhpena@astroscu.unam.mx.