

## Research Article

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# Orbital Period Variations in the NY Vir System, Revisited in the Light of New Data

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**Abstract:** NY Virginis is an eclipsing binary system with a subdwarf B primary and an M type dwarf secondary. Recent studies (Qian et al. 2012; Lee et al. 2014) suggested the presence of two circumbinary planets with a few Jovian masses within the system. Lee et al. (2014) examined the orbital stabilities of the suggested planets, using the best-fit parameters derived from their eclipse timing variation analysis. They found that the outer companion should be ejected from the system in about 800 000 years. An observational report from Pulley et al. (2016) pointed out that the recent mid-eclipse times of the binary deviate significantly from the models suggested by Lee et al. (2014). In fact, variations in the orbital period of the system had already been recognized by many authors, but the parameters of these variations vary significantly as new data accumulate. Here, we analyze the eclipse timing variations of the NY Vir system, using new mid-eclipse times that we have obtained together with earlier published measurements in order to understand the nature of the system and constrain its parameters.

**Keywords:** stars: subdwarfs, eclipsing binaries, O-C variations, planets: circumbinary planets, NY Vir

## 1 Introduction

NY Virginis was noted in the Palomar-Green Survey for the first time from its ultraviolet excess (Green et al. 1986), and later classified by Kilkenney et al. (1998) as an HW Vir-type eclipsing binary with an sdB primary. The pulsation properties of the sdB component were studied by many authors from photometry (Kilkenney et al. 1998; Charpinet et al. 2008) and spectroscopy (Reed et al. 2000; Vučković et al. 2009; van Grootel et al. 2013).

Orbital solutions for the eclipsing binary have been sought in several studies (Kilkenney et al. 1998; Zola 2000; Vučković et al. 2007; Çamurdan et al. 2012). All orbital solutions for the eclipsing binary and asteroseismic analyses of the pulsation frequencies from the sdB primary, using photometric and spectroscopic observations of the system, resulted in an sdB primary (with an effective temperature between 30000 and 33000 K, a mass value in the range 0.39 - 0.50  $M_{\odot}$ , and a surface gravity of 5.70 - 5.77), and an M-dwarf secondary ( $T_{\text{eff}}$  between 3000 and 3150 K,  $M_2$  in the range 0.11 - 0.15  $M_{\odot}$ ). The orbital period of the sys-

tem varies, the reasons for which have been discussed by Kilkenney et al. (2000), Kilkenney (2011), Çamurdan et al. (2012), and Kilkenney (2014), based on the recorded timings of minima in the literature. Only very recently, two studies (Qian et al. 2012; Lee et al. 2014) attributed the cyclic changes observed in the orbital period of the system to unseen third and fourth bodies in the planetary mass regime, potentially in resonant orbits (Lee et al. 2014).

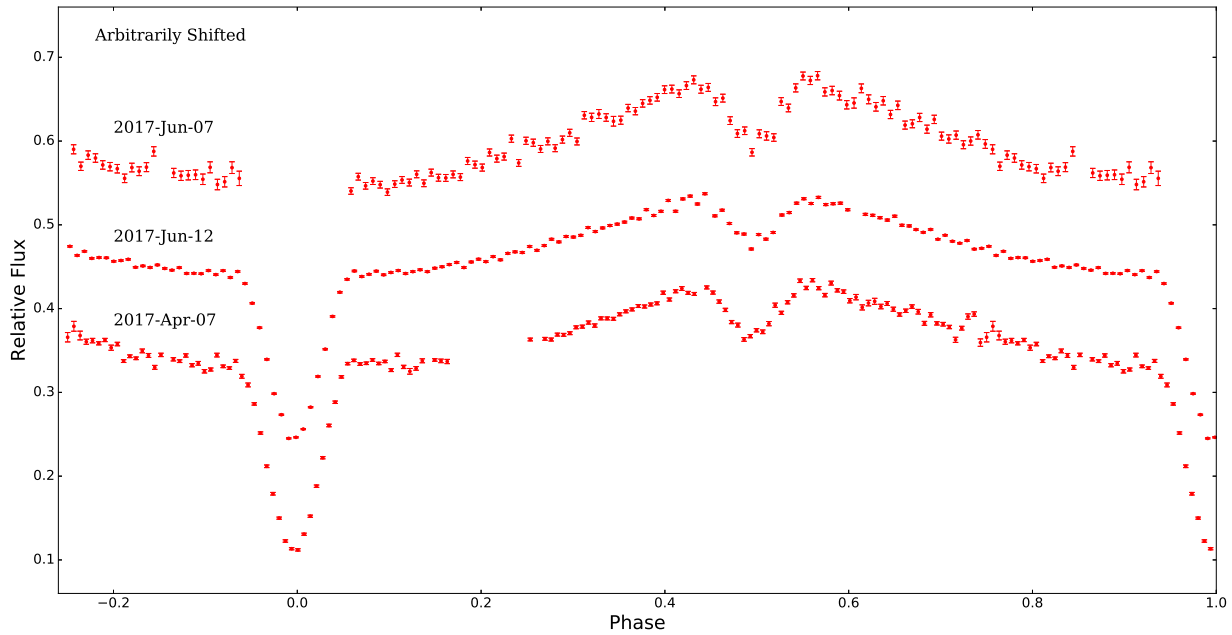
We analyzed the system's orbital period behaviour in the light of new photometric data, collected both from the literature and calculated from our own observations. We have seen that new minima timings deviate significantly from the models proposed by both Qian et al. (2012), and Lee et al. (2014). We suggest a new model for the variations observed in the orbital period of the binary. We also briefly discuss potential problems in the measurements of eclipse timings and their consequences.

## 2 Observations

We observed the system photometrically 3 different nights with the 1 meter Turkish telescope, T100, in TÜBİTAK National Observatory of Turkey (TUG). The telescope is located in the campus of the observatory in Bakırlitepe, Antalya at an altitude of 2500 m above sea level. We reduced the raw images and corrected them for the instrumental ef-

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**Figure 1.** T100 Light Curves of NY Vir (in  $R_c$  band) with respect to orbital phase, shifted arbitrarily in the relative flux.

fects in the standard manner (header manipulations and bias-dark-flat corrections), aligned them and performed ensemble, differential aperture photometry using the AstroImageJ software. In differential photometry we made use of several comparison stars, weighted according to the amount of the scatter around their nightly mean, forming an average synthetic comparison star with respect to which we determined and normalized the brightness of our target. Finally, we removed the overall parabolic trend due to the airmass effect from our measurements. We computed the orbital phase of each observation point based on the light elements corrected by us using recently published minima timings ( $T_0$  [BJD-TDB] = 2454195.411394, and  $P = 0.101016$  d). We present our light curves, acquired in the Johnson-Cousins  $R_c$  band, in Figure 1.

### 3 Analysis

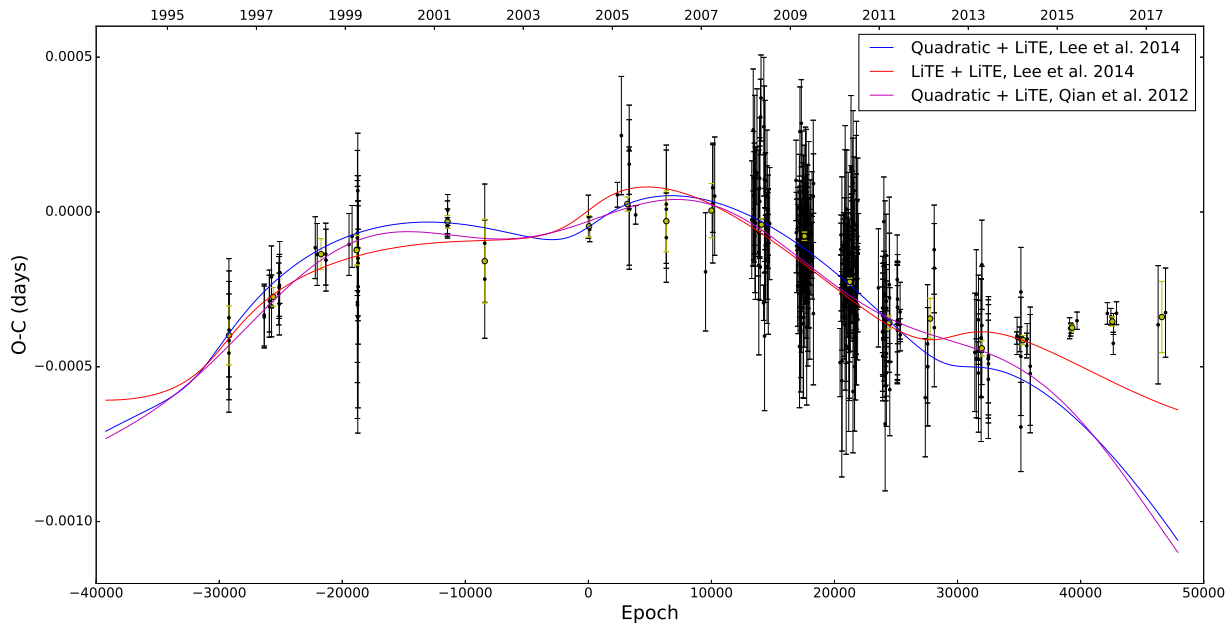
We derived the timings of the eclipses of both the primary and secondary components in our own T100 observations (Table 1) with the well-established Kwee-van Woerden method (Kwee & van Woerden 1956). We have collected all the eclipse timings from the literature, calculated the corresponding Dynamical Barycentric Time (BJD-TDB) and the epoch (E) for all the points that we have used, then plotted the so-called O-C diagram (Figure 2), displaying the differences between the observed eclipse timings

**Table 1.** Times of The Primary and Secondary Minima Derived From T100 Light Curves.

Eclipse Timing (BJD-TDB) [days]	Error [days]	Filter	Type
2457851.53215	0.00011	$R_c$	secondary
2457851.58296	0.00001	$R_c$	primary
2457912.34334	0.00021	$R_c$	secondary
2457917.34439	0.00004	$R_c$	primary
2457917.39487	0.00020	$R_c$	secondary

(O) and the timings calculated (C) with respect to the elements that we had also used in the computation of the orbital phases of our own light curves. We then plotted the models proposed by both Qian et al. (2012), and Lee et al. (2014) on the O-C diagram for comparison.

The recently acquired times of minimum light levels deviate from the proposed models significantly. We attempted to calculate seasonal averages for the minima timings as given by (Lohr et al. 2014) based on the WASP archive data (Butters et al. 2010). We have divided the minima (74 data points in total) they gave to small chunks, and calculated the average eclipse timing in each chunk in order to mitigate the disruptive effects of the tightly packed data points around the epoch 20000 in Figure 2, with relatively larger errors due to poor photometric precision propagated to the computation of eclipse timings. We also used the entire data set in our analysis without seasonal averages to have an alternative solution. We eliminated the



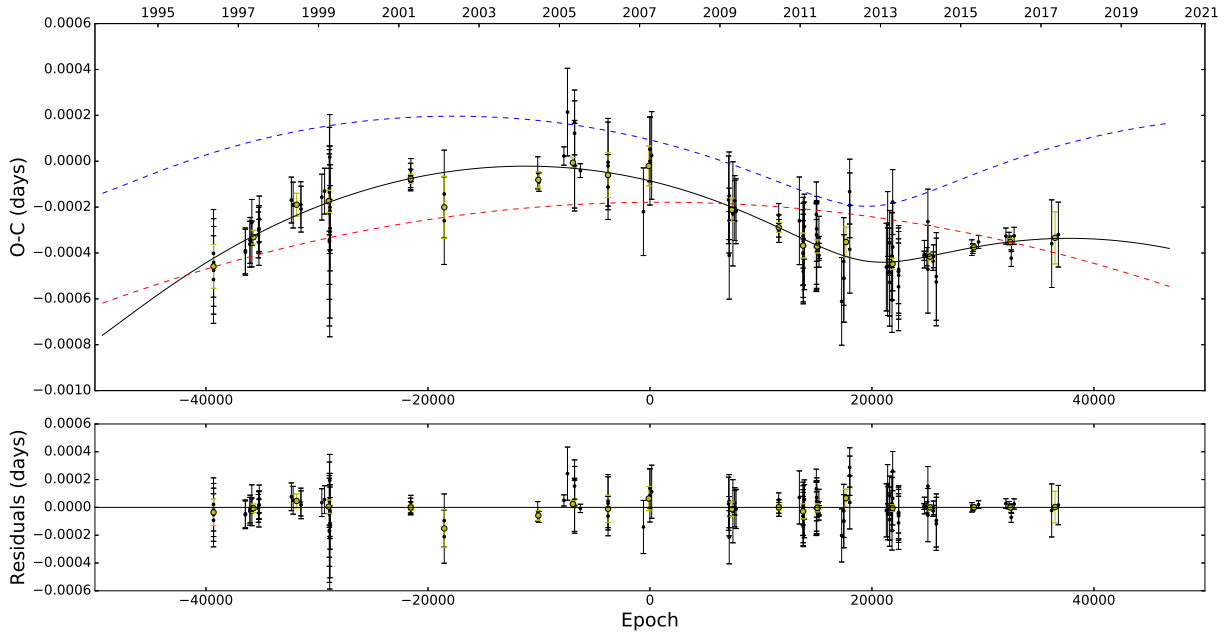
**Figure 2.** Eclipse Timing Variation (O-C) of NY Vir. The graph contains all the minima times that we collected from the literature and our own observations. Models are from Lee et al. (2014) (blue & red) and Qian et al. (2012) (magenta). Data points with large error bars around the epoch 20000 are from WASP Public Archive as calculated by Lohr et al. (2014).

data points with error bars larger than 0.0005 days (about 43 seconds) before the fitting procedure.

We have made use of a Python code written by us to model the observed variation in the O-C diagram, simultaneously by more than one model when needed. Parabola fitting is being handled in the standard manner, and periodic function fitting is based on Irwin's formalism (Irwin 1959) of the so-called Light Time Travel Effect (LiTE in short), both aiming at the least squares minimization. We have attempted solutions involving two periodic functions, only one quadratic, and one quadratic + one periodic functions when the residuals of the solution with only one quadratic function seemed to follow a somewhat sinusoidal trend. In fact, the solution with a periodic function, having an eccentricity of 0.49, superimposed on a downward parabola resulted in the best fit with the least scatter, reflected in the root-mean square ( $\text{RMS} = 3.88$  seconds), and the reduced  $\chi^2$  values (0.69). The fitting procedure ended in very similar results, when we made use of the entire data set as it is and when we used the seasonal average timings instead, the latter giving a slightly larger error. The resultant model curves looked almost identical on the O-C diagram. Therefore, we decided to adopt henceforth the data set including the seasonal average timings.

## 4 Results

As a result, we found that an eccentric periodic function superimposed on a downward parabolic trend best explains the observed orbital period variation on the O-C diagram in Figure 3. The significant eccentricity value we have found ( $e = 0.49$ ) for the periodic trend can only be attributed to the so-called Light-Time Effect (LiTE), caused by the reflex motion of the system around the common center of mass with an unseen third body, and the finite speed of light. Such periodic variations in the orbital period of a binary system can also be explained by the changes in the quadruple moment of the system due to magnetic activity in one of its components (Applegate 1992). But the orbital period variations of this sort is known to cause cyclic changes, with changing lengths and amplitudes from one cycle to another. The magnetic activity cycle due to solar dynamo is one good example of such cyclic changes. In addition, such variations can not follow a periodic trend with some eccentricity, which we observe in the variation in the orbital period of NY Vir system. Therefore, we attribute this variation to an unseen third body, minimum mass for which we calculated a value  $3.4(2) M_{\text{jup}}$  based on the formalism given by Irwin (1959). We give the parameters of the best fit and basic properties of the unseen third body in Table 2 together with that of the downward parabolic



**Figure 3.** Eclipse Timing Variation (O-C) of the NY Vir and our own models, parabolic variation (in red) and periodic variation (in blue), sum of both variations (in black). Parameters of our fits are given on the upper right corner of the plot.

fit that is superimposed on it. The parabolic trends are explained by either mass transfer between the components of the binary system, gravitational radiation, and / or magnetic braking in the cool secondary. The magnetic braking of the cool M-dwarf secondary might have been causing it to rotate more slowly (Rappaport et al. 1983), and decrease the size of its orbit due to the conservation of angular momentum. As a result of the shrinkage of the orbit, the orbital period decreases, and a negatively-sloped parabolic trend is observed in the minima timings, that are calculated with respect to a reference minimum and a reference orbital period. As explained by Lee et al. (2014), this is the most likely explanation why a secular decreasing trend is observed in the orbital variation of the system because a mass transfer between the components is not expected in such systems, components of which are not in contact. Gravitational radiation would cause a sinusoidal variation (a periodic variation without an eccentricity) (Paczynski 1967) with an amplitude much smaller compared to the one observed in the case of NY Vir (Lee et al. 2014).

## 5 Discussion

Quality of any analysis heavily depends on the accuracy and precision of the observational data and the employed measurement technique. Although NY Vir is a relatively

**Table 2.** Results from the O-C analysis.

Parameter	Value	Error
$T_0$ [BJD-TDB]	2454195.411215	0.000230
$P$ [days]	0.101016	0.000001
$dP/dt$	$-3.5 \times 10^{-13}$	$4 \times 10^{-14}$
$P_3$ [years]	20.63	2.03
$A$ [sec]	17.25	2.60
$\omega$ [°]	271	23
$e$	0.49	0.06
$M_{3,min}$ [ $M_{Jup}$ ]	3.4	0.9

faint system ( $m_V \sim 13^m.30$ ), its recent photometric and spectroscopic observations have better quality thanks to the improvements in instrumentation. Many researchers were able to study the pulsations of the sdB component of the binary using precise spectroscopic and photometric data. But the pulsations also have detrimental effects on the minima profiles from which we compute the eclipse timings without accounting for such modulations. We also have to make use of the measurements reported in the literature to be able to study variations like orbital periods of binaries, requiring longer time baselines. Those measurements are naturally from different instruments and were made by employing different techniques. Even when the measurement method is mentioned, which is not the case especially for the historical photometric data, either it's

not documented well in terms of its details, or inadequate for the data in hand.

It is challenging to derive minima times from asymmetric profiles of eclipsing binary systems with pulsating components. With poor photometric precision and / or timing resolution, pulsations can also reveal themselves as noise. Therefore, the eclipse timings are subject to errors both from the observational noise, which is documented well at least by formal error computations, and systematic errors arising from the measurement technique, which is ignored most of the time. In addition, there are many studies in the literature, that are based on minima timings reported in different reference time frames. Deducing important results from such data and improper handling of it can be problematic, leading to much debate. Instead of collecting minima times from the literature, greater accuracy might be achieved by collecting their sources (light curves), and making the measurements on them with an appropriate technique would lead to a homogenous analysis. Then we would be more certain about the sources of the variations, and our discussion on the consequences of finding different planets with different parameters each time we analyze the accumulated data of the same system would make real sense.

From this perspective, we plan to collect the available light curves of NY Vir system, with as much information as possible, and build a consistent set of eclipse timing measurements. We also plan to experiment with different measurement techniques, and try to determine the most convenient way of measuring eclipse timings from wavy minima profiles of eclipsing binaries with pulsating components. We also plan to make use of statistical inference techniques in our analysis, such as Bayesian inference, popularly used in other fields of astronomy. We are aware that such a thorough, and homogenous analysis will require significant amount of time, therefore we leave it aside for a future study, for which this work will constitute a very good starting point. We also plan to perform a light curve analysis of the system, making use of the latest results coming from the spectroscopic and asteroseismic analyses (van Grootel et al. 2013) and our own data. We suggest observers to make multicolor photometric observations of this interesting system in particular, and hope to shed more light on its orbital behaviour in a near-future study.

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