# THE (O-C) DIAGRAMS OF ECLIPSING BINARIES: TRADITIONAL AND NEW WAYS OF TREATMENT

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ABSTRACT. In this review, the traditional and the new ways of treatment of the orbital period changes of close eclipsing binaries are presented. Moreover, a comparison is made, and a general discussion is given. All methods are described, in a more or less detail way, and examples are given to prove the inadequacy of the traditional methods. The latter are not only very simple and extremely restrict, but they violate the uniqueness of the solutions. Moreover, it is shown that, although sometimes traditional methods give results close to that found by the continuous methods, and because of this some could conclude that the results coming out from the classic methods and the new ones are equivalent (within observat

ional errors), this is not the case. The big and important difference between traditional and new ways of the (O-C) diagrams' analysis, is their physical interpretation, which in the new ways of treatment is consistent with the physics of close eclipsing binaries and with the physical mechanisms which could produce the observed orbital period variations.

**Key words**: Stars: eclipsing binaries: orbital period changes

## 1. Introduction

A basic characteristic of an eclipsing binary, is its orbital period, $P_{orb}$. If $P_{orb}$ is constact, the time that a primary minimum occures (an **observed** minimum, hereafter referred as **O**), will coincide with this its appropriate ephemeris formula predicts, (the **calculated** minimum, hereafter referred as **C**); see, for example, Tsesevich (1973).

If, for any reason $P_{orb}$ changes, the observed minimum will be different than the calculated one, and thus the difference (O-C) will not be equal to zero. In such a way an (O-C) diagram is builted up.

The appereance of an (O-C) diagram, is strongly depended on the ephemeris formula used to construct it. See for example the (O-C) diagrams of *AM Leo* (Demircan and Derman 1992), of *V566 Oph* (Rovithis-Livaniou et al. 1993); of *ST Per* (Demircan and Selam 1993); of *AB And* (Kalimeris et al. 1994b, or Demircan et al. 1994). For this reason, some investigators are using different ephemeris formulae, as well as different ways of approach to describe an (O-C) diagram.

Traditional analysis ways of an (O-C) diagram, use a *linear*, or a *quadratic* least square fitting, which is sometimes combined with a *sinusoidal* periodic term (Batten 1973, Tsessevich 1973).

On the other hand, three new ways of treatment developed during the last seven years. The new proposed methods are:
1) the higher order polynomial method, (HOP), or the first continuous method, (Kalimeris et al. 1994a);
2) the state-space model, (SSM), (Koen, 1996), and
3) a second continuous method (Jetsu et al. 1997).
The later is considered as a method, although it has been applied to one system only, namely to the *AR Lac*, so far. It is considered so, because it fulfils the basic condition of the new methods; that is, to treat and subsequently analyze an (O-C) diagram as a whole. Actually, the most important difference between traditional and new methods is that the new ones face an (O-C) diagram as a whole. They describe and analyze it in the same continuous way, without deviding it to linear segments, that yield to abrupt period variations which although have been proven to be inconsistent (e.g. Hall 1990, Kalimeris et al., 2001), are still in use (e.g. Qian 2001ab).

Thus, in this review, and after the short description of all methods, (presented in Sections 2 and 3), a general discussion will be given, and a comparison will be made, which will prove the inadequancy of traditional methods of (O-C) diagrams analysis.

## 2. Traditional Methods

### *2.1. Linear and Piecewise Approximation*

Orbital period, $P_{orb}$, is not only a basic characteristic of an eclipsing binary, but is also one of its elements caclulated with great accuracy. If $P_{orb}$ is known, the time of minimum light (*primary minimum*, or *MinI*), is given by a linear relation of the form:

$$MinI = t_0 + P_{orb} \times E$$

where $t_0$ stands for the time of the first observed minimum, (*zero epoch*), and E -known as the epoch- is an integer number that denotes the number of the cycles elapsed from $t_0$.

The forgoing linear formula is very simple, and predicts the time a primary minimum is expected; thus, is widely used by observers. Especially by those who are mainly interested to minimum times only, and not for the whole light curve of an eclipsing binary.

If the orbital period of an eclipsing binary is constant, let us say: $P_{orb} = P_e$, where $P_e$ will be hereafter used to denote the constant orbital period of an eclipsing binary given by its ephemeris formula (ephemeris period), its (O-C) diagram will be appeared as a straight line. More specifically: if the (O-C) residuals from some assumed ephemeris are plotted versus the number of cycles elapsed, they should be clustered around the line (O-C)=0, if the period is chosen correctly. This line will be parallel to the time-axis, if the period is accurately determined; while a positive or a negative slope indicates that the real orbital period is longer or shorter than $P_e$, respectively (Batten 1973).

In reality things are not thus simple. The (O-C) diagrams of many systems appeared to be quite complicated. A simple glance to the (O-C) diagrams of some eclipsing binaries (e.g. Hall and Kreiner 1980, Kreiner et al. 1994, Kalimeris et al. 1994ab, 1995, Simon 1996, Kim et al. 1997, Mayer 1997, Chochol et al. 1998, Qian 2000), is enough to recognize this fact, which is not due to scatter. (Scatter is expected, since individual points, used for the construction of an (O-C) diagram, usually exhibit small or large discrepancies).

In cases where an (O-C) diagram is impossible to be described by a linear relation -similar to that previously described- the usual way of treatment is to devide it in a number of small linear segments, each one of which is interpreted by a different linear ephemeris. This procedure is known as the *step variation technique*, (e.g. Hall 1975, Yamasaki 1975, Kreiner 1977). Both the **number of segments**, as well as the **choice of time** is not objective and is subject to high-handed acts, according to the investigator wish. In spite of all these, the method is still in use, (e.g. Chambliss 1976, Bakos 1977, Demircan et al. 1990, Kim 1991, Herczeg 1993, Berrington and Hall 1994, Simon 1996, 1997, Kim et al. 1997, Pribulla et al., 1997, Qian et al. 1999a, Qian 2000, Qian and Liu 2000, Qian et al. 2000, Qian 2001ab, Qian and Ma 2001).

### *2.2. Quadratic Approximation*

When the orbital period of an eclipsing binary is variable, and this variation is made at a constant rate, then the quadratic least squares approximation is used to describe an (O-C) diagram. This is the case of the well-known *parabola fitting*. In such a case, the (O-C) differences can be calculated by the relation:

$$(O-C) = 1/2(dP_{orb}/dt)\bar{P}E^2$$

where $\bar{P}$ is the average period over the elapsed time interval.

Many (O-C) diagrams of eclipsing binaries have been treated using the parabola fitting. In some of the cases, this quadratic approximation is enough; but, it is not always the case. Two good examples to explain and present this fact, are the *RT And*, and *AH Vir* systems.

In the *RT And* case (Rovithis-Livaniou et al. 1994), parabola fitting as well as third and fourth order polynomials were used to describe its (O-C) diagram. A comparison of the polynomials coefficients, their RMS errors and the fitting in these three different cases, did not show significant differences. Thus, a second order approximation is good enough for the (O-C) description of *RT And*, yielding to the conclusion that its period varies with a constant rate. (See also Rovithis-Livaniou et al. 1996).

On the other hand, the case of *AH Vir* (Kalimeris et al. 1994a, Rovithis-Livaniou et al. 1996a), shows that quadratic approximation -except the restriction it puts- is not always enough. Indeed, neither a piecewise linear approximation, presented by Demircan et al. (1990), who devided the (O-C) diagram of *AH Vir* in 3 segments, nor the quadratic approximation they used, is good to describe the (O-C) diagram of the system. This is more than obvious from a glance to Figs. 1 and 2 of the foregoing mentioned paper. The division in 3 linear segments, yields to the previously described *step-variation technique*, and the parabola fitting to a continuous variation, with a constant rate. It's not only that none of them is good enough for the description of the (O-C) diagram of *AH Vir*. This is not a simlpe description's matter. It is very important, because description is related to results concerning the way the system's orbital period varies. Thus, a roughly or not accurate description yields to inaccurate or even to erroneous results.

### *2.3. Sinusoidal Variation*

In some cases the appereance of an (O-C) diagram, yield investigators to include for its description a sinusoidal term, too. In such a case, the time of minimum light is given by an equation of the form:

$$MinI = t_0 + PE + 1/2(dP/dt)PE^2 + \alpha \sin(2\pi E/P_* + \phi)$$

where $\alpha$ is the amplitude of the sinusoidal variation, $P_*$ its periodicity, and $\phi$ stands for the phase.

See for example the cases of *XX Cep* (Mayer 1984), of *TX Her* (Kreiner and Zola 1989), of *TW Dra* (Abhyankar and Panchatsaram 1984), of *R CMa* (Radhakrishnan et al. 1984), of *AK Her* and *ER Ori* (Abhyankar and Panchatsaram 1982), of *CM Lac*, *AB And*, and *YY*

*Eri* (Panchatsaram and Abhyankar 1981) and many-many others, analyzed by various investigators.

In all of the cases mentioned above the presence of a third body in the system was assumed. But, in more recently published papers, another mechanism is also considered; namely, that of magnetic activity cycles (Applegate 1992).

*2.4 Combined Methods*

In cases of (O-C) diagrams, that have a more or less strange appereance, and since is well known that this is strongly depended on the ephemeris formula used to construct the diagram, all three previously described methods might be used.

See for a example the case of *ST Per* in the analysis made by Demircan and Selam (1993), where the (O-C) diagram of the system was treated using:

a) a linear ephemeris
b) using **8** linear segments
c) by the combined effect of two sinusoidal variations.

## 3. New Methods

*3.1. The First Continuous Method*

According to this new method, the orbital period $P_{orb}$ and its rate of change $dP_{orb}/dt$ are assumed to be **continuous functions of time**, of a **non-prescribed** form. It is also supposed that the calculated time of conjuction is given, at any cycle E, by the usual linear ephemeris:

$T_c(E) = t_0 + P_e E$

where E has been used as the time variable, $t_0$ is a time of conjuction (in Hel.JD), and $P_e$ is the ephemeris period, (which is always constant, as has been already mentioned).

In absence of photometric perturbations (such as spots, flares etc) conjuctions should coincide with primary eclipses. Expressing the T(E) function piecewise, e.g. by least squares, using orthogonal polynomials over a weighting sequence (Kalimeris et al. 1994a), it is found that:

$\Delta T(E) = \sum_{j=0}^{n} c_j E_N^j$,

where the best order of approximation, **n**, can be chosen by inspection of the error diagram, and $E_N^j$ is defined as: $E_N^j = E/c$, where **c** is a constant, (*scale constant*), such that: $\mid maxE_{N,min}, E_{N,max} \mid < 1$

Then, the period of the system at cycle E is equal to the duration of the corresponding cycle E, that is:

$P(E) = T_{ob}(E) - T_{ob}(E-1) = P_e + \Delta T(E) - \Delta T(E-1)$

So, the orbital period variations of the system, are calculated with a simple and accurate mathematical way. More details can be found in Kalimeris et al. (1994a) paper. Moreover, the P(E) function shape, -being independent of the ephemeris formula used to construct the (O-C) diagram- can be used to search for periodicities, if any (Kalimeris et al. 1994b).

*3.2. A Statistical Method*

Koen (1996) used a statistical method to find the orbital period changes from the (O-C) diagrams of some stars. He applied this method to the following **18** variables:

**4** Cepheids, the: *S Sge*, *BW Vul*, *Y Oph*, *ζ Gem*,
**3** δ Scuti stars, the: *CY Aqu*, *DY Peg*, *YZ Boo*,
**3** RS CVn's, the: *RS CVn*, *RT Lac*, *RT And*,
**5** eclipsing binaries, the: *V471 Tau, SV Cam, U Cep, X Tri and ST Per*, to the dwarf nova *V1159 Ori*, to the X-ray source *Cygnus X-3*, and to the RR Lyrae-type system *AR Per*.

The method is the second one that appear to treat an (O-C) diagram as a whole. Koen is continuously working in time series analysis methods. His methods are statistical, and the last one (Koen 2001), was used for the analysis either of the maximum or minimum light of monoperiodic pulsating stars.

*3.3. Another Continuous Method*

Another continuous method was proposed to describe and analyze the (O-C) diagram of the RS CVn-type system *AR Lac*, and has not been used to any other eclipsing binary. We considered it as one of the new methods proposed so far for the (O-C) diagrams treatment of eclipsing systems, as has been already mentioned, since it was shown that it is possible to explain the period variations of *AR Lac* without abrupt changes. This is very important, for the reasons explain below, in the next Section.

According to this method, the models for the (O-C) data are given by equation:

$$(O-C)f(T,P_0) = \sum C_i(P_0)T^i$$

where the standard least squares fit method is applied to solve the best value for the free parameters $C_0(P_0), ..., C_k(P_0)$. Time scale is $T = (t - t'')/T_{scale}$, where $t''$ is the mid point of the time interval of the data, and the choice of **k** can be settled by setting all weights to unity, modeling the foregoing equation to different orders, and find where the mean residuals stop decreasing.

## 4. Mechanisms causing Period Changes

If the (O-C) diagram of an eclipsing binary, is such that it can be described by a linear least squares approximation, the orbital period of the system is constant.

If, on the other hand, it is curved, the orbital period changes. In this case, the main aim of an investigator, is not only to make a good description of the (O-C) diagram, and find the way the orbital period of the system changes; but, to find also the physical mechanisms that might cause it.

As was mentioned before, quadratic approximation is widely used. This is so, because the following three physical mechanisms support such period changes:
1) Mass transfer from one star to the other.
2) Mass loss through $L_2$, or via enhanged stellar wind.
3) Tidal interaction of the two members of the binary star.

The description of an (O-C) diagram of an eclipsing binary using a sinusoidal term can be physically supported, too. In such a case, the existence of a third body, the well known *light-time effect*, could be responsible for a sinusoidal variation, (Borkovits and Hegedus 1996).

Another possible explanation for a sinusoidal or any other periodic variation could be the development of magnetic activity cycles, in one or both of the components (Applegate 1992). Applications have been made to many systems (e.g. Lanza and Rodono 1999)

On the other hand, the orbital period changes of many eclipsing systems have been explained as coming from one or the other of these two mechanisms, idependently of the way used to describe their (O-C) diagram. More specifically, the systems: *AM Leo* (Demircan and Derman 1992), *AB And* (Kalimeris et al. 1994b, Demircan et al., 1994), *RZ Psc* (Kalimeris et al. 1995), *V505 Sgr* (Rovithis-Livaniou et al. 1996b, Qian et al. 1998a), *UV Psc, ER Vul, and AR Lac* (Qian et al. 1998b, 1998c, and 1999b, respectively).

Only the abrupt period changes seems to be poorly supported, as is explained below.

Sudden period changes are not suitable for the description of an (O-C) diagram of an eclipsing binary for the following reasons:
1) they introduce arbitrary restrictions, since it is suggested to describe a random time-series, as an (O-C) diagram is, with an arbitrary and pre-chosen way.
2) the whole procedure is arbitrary, since both the **place** and the **number** of the suspected (or supposed) sudden changes are strongly depended on the **personal choice** of the investigator.
3) the mathematical description and the analysis of the observational material, based to a number of small linear parts, is not either self-consistent, nor unique depedent.
4) there is not any physical mechanism to produce such sudden period changes. Most of the earlier models proposed (e.g. the rocket effect, the sudden mass transfer, or coronal mass ejections), yielding to abrupt orbital period changes, have been proven to be inconsistent (Hall 1990).
5) they require immediately cutting in of the dynamical and thermal perturbations, although there is not any binary that could be back to a totally stable situation just after a sudden change of its orbital period, (e.g. Van't Veer 1972, 1991).

In spite of the foregoing referred reasons, sudden period variations are still in use (e.g. Kim 1991, Demircan and Derman 1992, Demircan and Selam 1993, Simon 1996 and 1997, Qian 2000, Qian et al. 2000ab, 2001ab, and many others).

A possible explanation is that in some cases, the orbital period variation is made in a very short interval of time. Thus, although there are not abrupt orbital period variations, but continuous changes made very rapidly, this rapid change gives the inpression of an abrupt period variation. A very good example to see this very clearly is the *X Tri* case. In an analysis of this system, presented by Rovithis-Livaniou et al. (2000a), is shown -(their Fig. 3)- that a big period change occured in a rather s
mall time interval.

It seems that some of the pioneers in the binary stars field, agree with these statement. For example, Batten (1973), on page 86 of his book, writes for the period variations of *RW Tau*: *the change in period of RW Tau appears to have been abrupt, but there is always sufficient observational error to obscure the distiction between an abrupt change and a very rapid change that was continuous.*

## 5. Summary Discussion and Conclusions

In this review the traditional as well as the new methods used to analyze an (O-C) diagram of an eclipsing binary were outlined. It was shown that:
Linear approximation is easy in use; moreover, it is very useful, mainly to observers, and especially to some amateurs, who are dealing with observations of minima times only. Linear fitting, on the other hand, can not be used to most of the systems, since it corresponds to constant orbital period, which is usually an exceptional case.

On the other hand, linear approximation can be applied to a small interval of time, if one wants to compute and propose a new ephemeris formula; but, we should keep in mind that this formula might not be valid for long (depending on the rate of period change).

The step variation technique, is absolutely inconsistent with the physics of eclipsing binaries, since there is no any mechanism that could produce abrupt period changes. Those proposed so far, are not valid any more, (Hall 1990), and in general, in most of the cases, there is **plenty of freedom** in choosing the intervals for fitting. Sterken (2000) refers to this subject as: "*the piecewise linear segments can point out the* **occurance** *of a period jump, but cannot reveal exactly* **when** *such events do occur*". Moreover, one must be very carefull and special attention has to be paid during their construction. In many cases, period jumps may not real, and might come from erronious computation of the value of epoch E, especially in cases of very short period eclipsing binaries.

Second order approximation, (the classical parabola fitting), corresponds to a continuous period variation, at a constant rate. There is physical support for such a change, but as was shown, it is not suitable in all cases. This seems to be more and more clear, as much more observational material is added. A good example to recognize this is the *XX Cep* case. In this, when newer data were used (Mayer 1984), it was found that the classical parabola fitting that had been earlier applied (Rafert 1982), was not good enough any more.

It is also worthwhile to mention, Wood and Forbes (1963) work, where some (O-C) diagrams of eclipsing binaries were described using a third order approximation. They did so, in cases where this was impossible with any other of the known methods, at that time.

A sinusoidal fitting, although has been satisfactorily used in many cases, is restricted, and this might yield to erroneous results. A good example to present this is the *AK Her* case. In this, when newer times of minimum light were used (Rovithis-Livaniou et al. 1999), it was shown that they did not follow the previously proposed sinusoidal variation (Tunca et al., 1987).

Moreover, sinusoidal variation, in some cases, is not consistent with the presence of a third body (Kreiner et al. 1994). In such cases, magnetic activity cycles can be also used (e.g. Demircan and Derman 1992, Qian et al. 1999b, Rovithis-Livaniou et al. 2000).

Much more cases is expected to be added in the examples previously referred for quadratic approximation, as well as for sinusoidal variations.

These as regards the traditional methods of an (O-C) diagram analysis. Concerning the new ones: this of Koen (1996) is statistical and has been applied so far to a rather small number of eclipsing binaries; that of Jetsu et al. (1997) to one system only.

On the other hand, the first continuous method, has been applied to a large number of eclipsing binaries of every kind. In Kalimeris et al. (1994a), the orbital period variations of four contact binaries were examined; namely of: *GK Cep, V502 Oph, V566 Oph and AH Vir.* The *AB And* system in (Kalimeris et al. 1994b); the *RZ Psc* in (Kalimeris et al. 1995); the *V505 Sgr* by Rovithis-Livaniou et al. (1996b), as well as by Qian et al. (1998a); the *UV Psc, ER Vul, and AR Lac* by Qian et al. 1998b, 1998c, 1999b, respectively; the *X Tri* (Rovithis-Livaniou et al. 2000); the *AK Her* (Rovithis-Livaniou et al. 2001a), and some semi-detached systems (Rovithis-Livaniou et al. 2001b).

Moreover, this method does not put any restriction, (as quadratic or sinusoidal approximations do), and is well supported by physical mechanisms (Kalimeris et al. 1994b, 1995; Qian et al. 1998a,b,c, 1999b).

Besides, it is worthwhile to mention that the classical way of (O-C) curves analysis emerges as a specific application of Kalimeris et al. (1994a) method. This is obvious from the following:

Suppose that T(E) is given by: $\Delta T(E) = c_1 E_N + c_o$.

Then, $\dot{P}(E) = 0$ and $\Delta P(E) = 0$

That is, the well known fact: *whenever an (O-C) diagram exhibits linear sections, the period remains constant.*

Moreover, suppose that T(E) is given by:

$\Delta T(E) = c_2 E_N^2 + c_1 E_N + c_o$

Then:

$\dot{P}(E) = 2c_2$ and $\Delta P(E) = 2c_2$

which is another well known result: *whenever an (O-C) diagram exhibits parabolic arcs, the period is changing at a constant rate.*

For the above mentioned reasons, it is clear that the first continuous method proposed and developed by Kalimeris et al. (1994a) is a remarkable and reliable method.

The appereance of an (O-C) diagram, is strongly depended on the ephemeris formula used to construct it. For this reason, some investigators are using different ephemeris formulae, as well as different approaching ways to describe an (O-C) diagram. See for example the *AM Leo* case in the paper by Demircan and Derman (1992), where 1) a linear least square fitting, 2) three linear segments, and 3) a fifth degree polynomial were used for its (O-C) diagram description. Doing so, and because of the strong depedence of the appereance of an (O-C) diagram on the ephemeris formula used, they are hoping that another look will help them to get an idea for a possible hinden periodicity. But this is not a proper way to search for periodicities. Kalimeris et al. (1994b) have shown, (see Appendix I, of their paper), that: *The orbital period P(E), as well as its spectrum, remain invariable -within the errors of least squares description of an (O-C) diagram- irrespective of the ephemeris used to calculate the (O-C) differences.* It is thus suggested that searching for periodicities, one has to analyse the $P(E) - P_e$ function which remains **invariant** and is independed of the ephemeris used, and not the (O-C) diagram which varies according to the ephemeris.

Finally, dealing with (O-C) diagrams of eclipsing binaries, one has to be patient, and do not come to conclusions that may be proven wrong afterwards. Especially when the results are covering a small time interval, and if there is an undetected third companion in the system. Many years of observational material is needed to get reliable results.

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