PERIOD VARIATIONS OF THE ECLIPSING SYSTEM EE AQUARII

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Abstract. The O–C diagrams of EE Aquarii have been presented for the first time, the period variations present in the system have been analysed, and tentative results have been presented. In all, four period decreases and three period increases are noted in the time interval 1940 to 1985. The strongest period change is noted in the time interval 1957 to 1959. Sufficiently strong period changes have also been noted in the time intervals, 1948 to 1950 and 1970 to 1976. Besides four period decreases and three period increases, eleven period fluctuations are also seen in the O–C diagram (II) of EE Aqr. The total period change in different portions of the O–C diagram (II) ranges from 1.7×10^{-7} d to 8.2×10^{-6} d. The period increases are stronger than the period decreases. An overall picture of the period variations suggests that weak period variations are present in the system EE Aqr.

1. Introduction

The light variations of the eclipsing binary system EE Aquarii (= BD − 20°6454 = HD 213863 = BV 320 = SAO 191236 = CPD − 20°8980) were reported by Strohmeier and Knigge (1960) from their photographic observations, who quoted the spectral type of the system as F0. Filatov (1961) reported photographic minima of the system. Strohmeier *et al.* (1962) presented the photographic light curve of EE Aqr, which showed the variation in the primary minimum from $8^{m}.35$ to $9^{m}.10$. They found no evidence of the secondary minimum, and declared the system to be of Algol-type. Photoelectric *UBV* observations of EE Aqr were reported by Williamon (1974) and Padalia (1979), who analysed the system and gave the orbital elements of the system. However, the two sets of elements differ in some aspects. They reported the spectral types of the components. Many observers reported times of minima of EE Aqr, which are detailed in Section 2.

2. Period

The times of primary minima of EE Aqr have been given by various investigators. Filatov (1961) and Strohmeier *et al.* (1962) presented photographic minima of the system. Locher (1971a, b, 1972a, b, c, d, e, 1973, 1974a, b, c, 1975a, b, 1976a, b, c, d, 1978a, b, 1980), Grough (1972), Diethelm (1974), Germann (1981a, b), and Paschke (1985) gave visual minima of EE Aqr. Williamon (1974) and Padalia (1979) presented photoelectric minima of the system.

Strohmeier *et al.* (1962) presented the first period of the system. The epochs and the periods of EE Aqr, given by various authors, alongwith the periods have been listed in

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TABLE I

Epochs and periods of EE Aqr

No.	Author	Epoch and period
1	Strohmeier *et al.* (1962)	J.D. 2429 881.310 + $0\overset{d}{.}5089951$
2	Williamon (1974)	J.D. 2440 828.7804 + $0\overset{d}{.}50899555$
3	Padalia (1979)	J.D. 2429 881.310 + $0\overset{d}{.}5089954$
		J.D. 2441 985.221 + $0\overset{d}{.}5089956$

Table I. The table shows that there has been no controversy about the orbital period of the system. The photoelectric observers have also indicated no significant change in the period of the system, however, none has gone in for a detailed period study of the system EE Aqr.

3. O–C Diagrams

All available times of the minima of EE Aqr have been collected from the literature, which have been observed in the time interval 1940 and 1985, and an O–C diagram has been constructed from the O–C values calculated from the ephemeris, viz.:

$$\text{Primary Minimum} = \underset{\text{(Filatov, 1961)}}{\text{J.D. } 2429881.297} + \underset{\text{(Williamon, 1974)}}{0\overset{d}{.}50899555E} .$$

The times of minima alongwith the O–C values and cycles have been listed in Table II. The O–C values versus cycles have been plotted in Figure 1 (O–C diagram I), wherein the open circles represent the individual minima, while the solid circles represent the mean values of minima.

Out of 82 minima available in the literature, 14 are photoelectric, 17 are photographic, and the remaining are visual. It is apparent from Table II that EE Aqr has remained neglected photoelectrically since its discovery. It was photoelectrically pursued only in two time intervals, 1970 to 1971 and 1973 to 1975. The errors of all the minima are not available in the literature. However, we feel O–C > $0\overset{d}{.}01$ are important for period discussions.

An inspection of the O–C diagram (I) reveals that the time interval (1940 to 1985) gets split-up into 21 (dashed and solid line) portions between the points A and S. A large scatter is present in the O–C diagram. In order to reduce the large scatter, and to search out the epochs of period changes, we have taken the mean of the O–C values and the cycles, which are listed in the fifth and the third column of Table II, respectively. The mean and few individual values have been joined by the solid and the dashed lines, respectively, in Figure 1. The dashed lines indicate the superposed fluctuations in the orbital period lying around the solid lines, while the solid lines represent the trend of period variations.

Since some of the portions, such as AE, GH, IK are scantily covered, our discussion of the period variations of EE Aqr is based on the assumption that the period of the system varies linearly in different portions of the O–C diagrams.

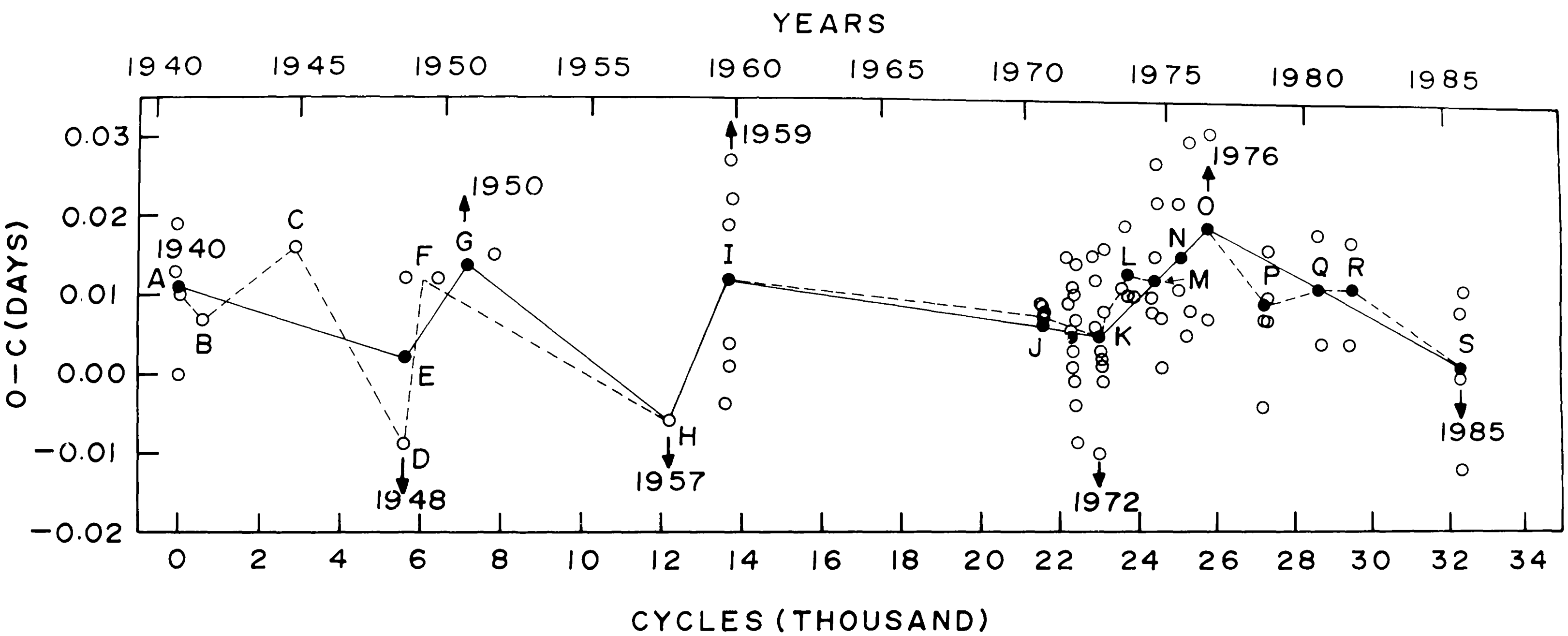

Fig. 1. O–C diagram (I) of EE Aquarii. The solid circles represent the mean values, while the open circles represent the individual observations. Solid lines represent the trend of period variation, while the dashed lines indicate superposed period changes or fluctuations.

TABLE II

Primary minima of EE Aqr

Minima ($JD_\odot$)	Cycle	Mean of cycles	O–C (days)	Mean of O–C (days)	Weighted mean of O–C values	Reference
2429881.297	0		0.000			Filatov (1961)
.310	0		+ 0.013			Filatov (1961)
902.185	41	22	+ 0.019	+ 0.011	+ 0^{d}0105	Filatov (1961)
4.212	45		+ 0.010		+ 0.007	Filatov (1961)
30200.426	625		+ 0.007			Filatov (1961)
1375.215	2935		+ 0.016		+ 0.016	Filatov (1961)
2744.388	5625	5652	− 0.009	+ 0.002	+ 0.0015	Filatov (1961)
71.383	5678		+ 0.012			Filatov (1961)
3187.235	6495	7193	+ 0.012	+ 0.014	+ 0.0135	Filatov (1961)
897.287	7890		+ 0.015			Filatov (1961)
6080.348	12179		− 0.006		− 0.006	Filatov (1961)
822.465	13637		− 0.004			Strohmeier *et al.* (1962)
44.375	13680		+ 0.019			Strohmeier *et al.* (1962)
5.375	13682	13698	+ 0.001	+ 0.012	+ 0.0115	Strohmeier *et al.* (1962)
6.396	13684		+ 0.004			Strohmeier *et al.* (1962)
68.306	13727		+ 0.027			Strohmeier *et al.* (1962)
93.242	13776		+ 0.022			Strohmeier *et al.* (1962)
40828.7799	21508		+ 0.0067			Williamon (1974)
30.8179	21512		+ 0.0087			Williamon (1974)
.8164	21512		+ 0.0072			Williamon (1974)
.8161	21512		+ 0.0069			Williamon (1974)
46.5949	21543		+ 0.0068			Williamon (1974)
.5943	21543	21533	+ 0.0072	+ 0.0074	+ 0.0075	Williamon (1974)
.5949	21543		+ 0.0068			Williamon (1974)
7.6146	21545		+ 0.0085			Williamon (1974)
8.6318	21547		+ 0.0077			Williamon (1974)
.6319	21547		+ 0.0078			Williamon (1974)
.6316	21547		+ 0.0075			Williamon (1974)
2441157.599	22154		+ 0.015			Locher (1971a)
81.516	22201		+ 0.009			Locher (1971a)
227.316	22291		+ 0.001			Locher (1971b)
30.382	22297		+ 0.011			Locher (1971b)
2.410	22301		+ 0.003			Locher (1971b)
52.268	22340	22321	+ 0.010	+ 0.005	+ 0.005	Locher (1972a)
3.275	22342		− 0.001			Locher (1972a)
63.462	22362		+ 0.007			Grough (1972)
80.248	22395		− 0.004			Locher (1972a)
2.302	22399		+ 0.014			Locher (1972a)
308.238	22450		− 0.009			Locher (1972b)
521.531	22869		+ 0.015			Locher (1972c)
2.540	22871		+ 0.006			Locher (1972c)
50.541	22926		+ 0.012			Locher (1972d)
94.293	23012		− 0.010			Locher (1972e)
5.323	23014	23008	+ 0.002	+ 0.005	+ 0.005	Locher (1972e)
6.340	23016		+ 0.001			Locher (1972e)

Table II (continued)

Minima ($JD_\odot$)	Cycle	Mean of cycles	O–C (days)	Mean of O–C (days)	Weighted mean of O–C values	Reference
2441621.282	23065		+ 0.003			Locher (1972e)
3.314	23069		− 0.001			Locher (1972e)
48.264	23118		+ 0.008			Locher (1972e)
9.290	23120		+ 0.016			Locher (1972e)
891.567	23596		+ 0.011			Locher (1973)
2.593	23598	23700	+ 0.019	+ 0.013	+ 0.0112	Locher (1973)
985.221	23780		+ 0.010			Padalia (1979)
2009.144	23827		+ 0.010			Padalia (1979)
255.496	24311		+ 0.008			Diethelm (1974)
8.552	24317		+ 0.010			Locher (1974a)
61.607	24323		+ 0.011			Locher (1974b)
304.378	24407	24426	+ 0.027	+ 0.012	+ 0.012	Locher (1974b)
5.384	24409		+ 0.015			Locher (1974b)
55.268	24507		+ 0.017			Locher (1974c)
84.271	24564		+ 0.007			Locher (1975a)
5.283	24566		+ 0.001			Locher (1975a)
596.526	24981		+ 0.011			Locher (1975b)
621.478	25030		+ 0.022			Locher (1975b)
4.525	25036	25151	+ 0.015	+ 0.015	+ 0.0126	Locher (1975b)
97.306	25179		+ 0.005			Padalia (1979)
777.216	25336		+ 0.008			Locher (1976a)
80.292	25342		+ 0.030			Locher (1976b)
2442990.484	25755	25804	+ 0.007	+ 0.019	+ 0.019	Locher (1976c)
3040.390	25853		+ 0.031			Locher (1976d)
725.471	27199		+ 0.004			Locher (1978a)
6.492	27201	27234	+ 0.007	+ 0.009	+ 0.009	Locher (1978a)
32.600	27213		+ 0.007			Locher (1978a)
55.508	27258		+ 0.010			Locher (1978b)
76.383	29299		+ 0.016			Locher (1978b)
4437.570	28598	28627	+ 0.018	+ 0.011	+ 0.011	Locher (1980)
66.568	28655		+ 0.004			Locher (1980)
878.346	29464	29465	+ 0.004	+ 0.011	+ 0.011	Germann (1981a)
9.377	29466		+ 0.017			Germann (1981b)
6325.424	32307		+ 0.008			Paschke (1985)
48.304	32352	532344	− 0.017	+ 0.005	+ 0.005	Paschke (1985)
50.357	32356		0.000			Paschke (1985)
2.404	32360		+ 0.011			Paschke (1985)

In order to differentiate the various observations, we have obtained the weighted means of the O–C values by giving arbitrary weights 1, 2, and 3 to the visual, the photographic, and the photoelectric observations, respectively. These are listed in Table II, and are plotted in Figure 2 (O–C diagram II). Then, the O–C diagram (II) clearly splits up into seven portions between points *B* to *N*. Our final results are based on this diagram.

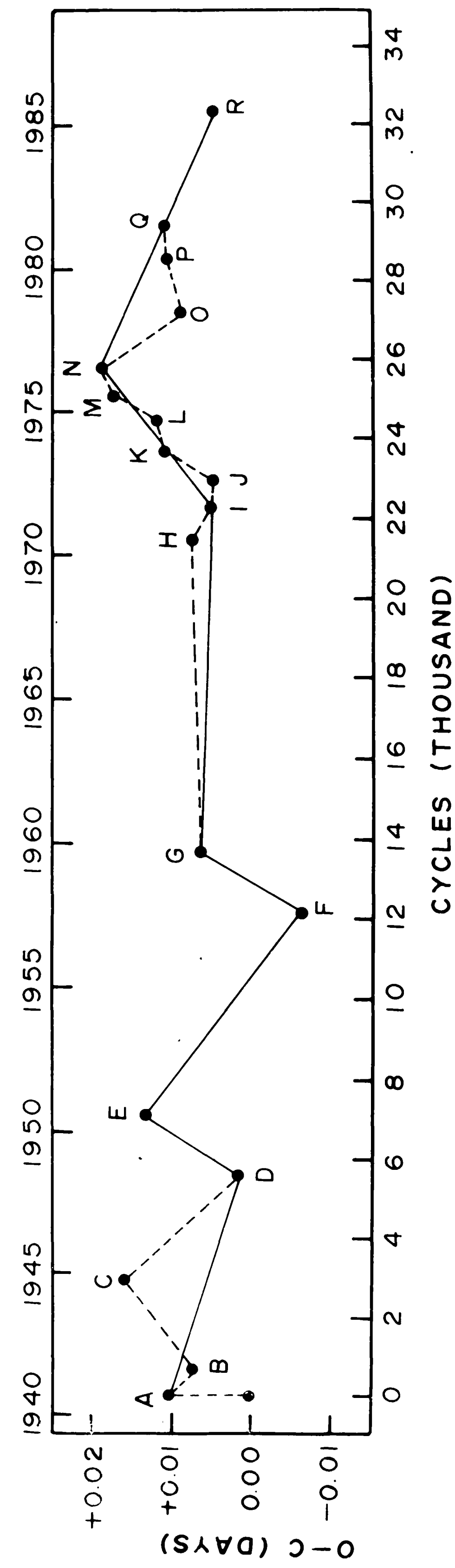

Fig. 2. O–C diagram (II) of EE Aquarii based on the weighted O–C values. Solid lines represent the trend of period variations, while the dashed lines indicate period fluctuations.

4. Light Curve Features and Colours of EE Aqr

Before discussing the period variations of EE Aqr, it is desirable to list the peculiarities of the system, which may throw some light on the period variations and fluctuations, and which deserve proper attention.

(i) Williamon (1974) has reported that there was no indication of any period change, although such a change would be difficult to detect over such a period of time. Padalia (1979) also could not detect any period change, as he compared only his observations with those of the Wiliamon (1974), whose time interval was too short.

(ii) Padalia (1979) has found the mean oblateness of the system to be 0.122 ± 0.004 as compared to that given by Williamon (1974), 0.170 ± 0.026. He stated that the tidal forces and the interaction effects between the components appear to be less dominant.

(iii) Both the authors found that the depth of the secondary minimum was too shallow and, thus, they used only the primary eclipse for deriving the orbital elements of EE Aqr.

From the visual inspection of the figures given by these authors, the depth of the secondary minimum appear to be around $0\overset{m}{.}2$. Padalia (1979) reported that he could not measure the depth of the secondary minimum in the U filter on rectification, while Williamon (1974) found a depth, $1 - l_0^{oc} = 0.04$. Strohmeier *et al.* (1962) also could not find the depth of the secondary minimum.

(iv) Padalia (1979) reported that the effects of ellipticity and reflection on the U light curve are much more than those reported by Williamon (1974).

(v) Visual inspection of the figures given by Williamon (1974) reveal that the points around $0\overset{p}{.}25$ are higher than those around $0\overset{p}{.}75$, and large scatter is present in the secondary minimum phase, particularly in the ascending branch of the secondary minimum, around phase 0.75. Padalia's (1979) figures also indicate large scatter in the secondary minimum around phase 0.8, but it appears from his figures that the points around $0\overset{p}{.}8$ are slightly higher than those around $0\overset{p}{.}3$, particularly in the U and B filters.

(vi) The colours of the components of EE Aqr derived by Williamon (1974) and Padalia (1979) are quoted here. Padalia (1979) derived the colours from the fractional luminosities of the components.

The colours are given as under:

Author	Primary component			Secondary component		
	$B - V$	$U - B$	Sp.	$B - V$	$U - B$	Sp.
Williamon (1974)	$+0\overset{m}{.}290$	$+0\overset{m}{.}072$	F0IV	$+1\overset{m}{.}124$	$-0\overset{m}{.}254$	K5
Padalia (1979)	$+0.410$	$+0.130$	F5V	$+0.070$	-0.294	A1.5I

The spectral types, given above, are based on the standard colour sequences given by Golay (1974). The colours of the secondary component given by Williamon (1974) are inconsistent with any standard colour sequence, and considering only the $B - V$ value, the spectral, class of the secondary component is given as K5. The colour of the secondary component, quoted by Padalia (1979), appears undesirable (or wrong), as the secondary components is shown to be of earlier spectral type.

(vii) The depths listed by Padalia (1979) in his Table VI show large differences, for which no attention has been paid. Padalia's (1979) Figure 3 shows that both the components are the Main-Sequence stars, while the Williamon's (1974) observations reveal that the secondary component is highly evolved.

(viii) None of these investigators have quoted the times of secondary minimum, which are important in understanding the cause of the period variations.

(ix) Strohmeier *et al.* (1962) declared the system EE Aqr to be of Algol type, while Williamon (1974) and Padalia (1979) found it to be of β-Lyrae type variable.

All these facts suggest that the system EE Aqr is a complicated system, and its light curve features are not stable. Hence, it is expected that there may be some unidentified causes, which may also be responsible for the period fluctuations and large scatter (O–C diagram I).

5. Period Variations

The O–C diagram I (Figure 1) shows seven portions (AE, EG, GH, HI, IK, KO, OS), where period variations seem to have occurred. Appreciable period changes are noted around the years 1948, 1950, 1957, 1972, and 1976. The extent of the period decrease and increase has been estimated in different portions of the O–C diagram (I).

A very strong period increase appears to have occurred in the portion HI (time interval 1957 to 1959). However, such a period change is unusual for EE Aqr. The reality of this period change is doubtful. It has occurred in a very short interval of time and only one point (or minimum) is situated around 1957. Sufficiently strong period decrease and period increase have occurred in the time intervals 1950 to 1957 and 1972 to 1976, respectively. The former time interval is also short and thus, former period change can be regarded as considerable. The later time interval is rich with the minima observations, and as such its reality is beyond doubt. Likewise, the portion OS is beyond question. However, the portions AE, GH, and IK are scantily covered, and their reality is open to question. At point H, all the photoelectric minima of Williamon (1974) are centered and thus, the position of this point is not questionable. Moreover, in this portion (IK), the period change is the smallest as compared to other portions.

From Figure 1, it is apparent that around the years 1959, 1971, 1972, 1973, 1974, 1975, 1976, and 1985, the scatter is large. In 1971, 1973, and 1975, few photoelectric minima are also available, but these are masked by the visual observations. In 1959, the minima are photographic. In the remaining years, the minima are visual, except the minima given by Williamon (1974) and Padalia (1979), which are photoelectric. The scatter may be partly due to the inaccuracies in determining the photographic and the visual times of minima.

We have derived the results from Figure 2 (O–C diagram II). This shows seven distinct portions between points B to N. The portion AB is centered between 0 and 22 cycles, and is not considered in the discussion. The portions BC, CD, DE, EF, FG are defined. Some fluctuations or variation (dashed lines) are seen around portions GJ and JN. The total change of period in different portions of the O–C diagram II (Figure 2)

TABLE III
Changes in period of EE Aqr

Portion	Interval of cycles	Total change in period (days)	Period trend
AD	$E = 0$ to $E = 5652$	1.60×10^{-6}	D
DE	$E = 5652$ to $E = 7193$	7.79×10^{-6}	I
EF	$E = 7193$ to $E = 12179$	3.71×10^{-6}	D
FG	$E = 12179$ to $E = 13698$	8.23×10^{-6}	I
GJ	$E = 13698$ to $E = 22321$	1.74×10^{-7}	D
JN	$E = 22321$ to $E = 25804$	3.64×10^{-6}	I
NR	$E = 25804$ to $E = 32344$	2.14×10^{-6}	D

D = decrease; I = increase.

have been estimated and are listed in Table III. The strongest period change appears to have occurred in the portion FG (1957 to 1959). Sufficiently strong period changes are noted in the portions DE (1948 to 1950) and JN (1970 to 1976). Besides four-period decreases and three-period increases period fluctuations (dashed lines) are seen in the O–C diagram II (Figure 2). The period also shows two small stand still in the portions (IJ and PQ). The period changes given in Table III are influenced by the complications, which are described in Section 4. Thus it appears that there exists no strong period variation in EE Aqr. However, it shows slight increasing trend since Strohmeier *et al.*'s (1962) epoch.

6. Discussion

The large scatter is present in the O–C diagram I. We have already mentioned that 14 minima are photoelectric, 17 minima are photographic, and 51 minima are visual. Eleven photoelectric minima of Williamon (1974) are centered in the time interval 1970–1971, while two photoelectric minima of Padalia (1979) are found around 1973 and 1975. Padalia's (1979) minima are masked by several visual observations. Since majority of minima are visual and photographic, hence, it is possible that the uncertainties in their time determinations are partly responsible for the scatter. However, we have tried to minimise the scatter by taking averages of the O–C values and cycles in several time intervals. We feel that undetected eccentricity, oblateness of the components, and some other unidentified physical and the orbital changes may also contribute to a part of scatter. Some spurious O–C residuals may also result from the light curve irregularities and peculiarities. However, by taking the mean values of the scattered points, we are to some extent safe in discussing the period variations. Weighted O–C values have further reduced the scatter and have helped in locating the epoch of period changes.

It is unfortunate that neither the spectroscopic study of this system nor the times of the secondary minimum are available in the literature. Therefore, many hidden peculiarities of the system EE Aqr cannot be discussed.

Williamon (1974) had stated that due to proximity of the components and their interactions, the observations of the times of primary minima over a number of years could possibly reveal period anomalies. Since this publication, we have added minima observed during the eleven years of time, and, thus, noted two period changes in the time intervals, 1970 to 1976 and 1976 to 1985.

In Section 4, we have listed some interesting features of EE Aqr, which have not been taken seriously into consideration. Most important are the colours and spectral types of the system. There is a vast difference between the spectral types of the secondary component derived from Williamon's (1974) and Padalia's (1979) observations. There is also difference in the spectral class of the primary component. The change in the colour indices, variation in depths of minima, difference in the oblateness and some other factors reveal that some physical phenomenon like mass transfer and others may be present in the system, and may be causing period changes, which remain undetected, as such, our period study is important.

Lastly, except the period change in the portions (DE, EF, and JN), the other period changes are small. The period change in the portions (GJ and JN) appears somewhat definite, as there are number of weighted points to define the slopes. Overall picture of O–C values suggests that the period changes are not stronger in the system EE Aqr. Many more photoelectric minima are required to confirm the existence of period variations in EE Aqr.

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