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ORIGINAL ARTICLE

The period variation of DY Hercules

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Abstract In this paper the researchers collected 28 times of maximum light including 4 times of those observed at the Xinglong station, the National Astronomical Observation of China between May 27, 2004 and June 1, 2004 and 1 time of maximum light from a 60 cm telescope on May 4, 1984. It found that the O-C point distribution was more completely compared than in any papers published before. The period is decreasing at the rate of about $(1.4 \pm 0.1) \times 10^{-8}$ per year, which should not be caused by stellar evolution. It might be only part of a binary orbital light-time variation or other unknown reason. The time scale is longer than Pocs and Szeidl's suggestion; the star needs more observations before we can be certain of the exact light-time variation.

Keywords DY Her · Delta Scuti · HADS · Period variation · Variable star

1 Introduction

DY Hercules was discovered as a variable star by Hoffmeiser (1935) in 1935. It is a high amplitude delta Scuti variable with a period of about 0.14863 days. McNamara (1978) and Breger et al. (1978) suggested a radius of 2.7 $R_\odot$. McNamara (1997) re-determined its radius as 3.42 $R_\odot$ and gave its mass as 2 $M_\odot$. Szeidl and Mahdy (1981) provided the first study about its long-term period variations; they revealed a slow period decrease. Rodriguez (1989), Lopes de Coca et al. (1990), and Antonello (1990) also described this star in their papers. Yang et al. (1993) added some new times of maximum light and got almost the same results. Milone et al. (1994) derived a mean radius of 2.77 $R_\odot$ and a bolometric visual magnitude of 1.41. That means DY Hercules is a population I post main sequence star. Pena et al. (1999) made some new observations and summarized DY's main characteristics. Jiang and Boonyarak (1999) included its period variation in their summary table of the period variation of delta Scuti variables. Pocs and Szeidl (2000) used the averaged O-C data and interpreted DY's long-term O-C diagram in terms of the light-time effect caused by a hypothetical low-mass component. Jiang (2002) also mentioned its period variation and suggested that it was binary. Jiang (2003) even guessed the unseen companion might be a brown dwarf. Recently, Derekas et al. (2003) gave out 4 new times of maximum light. In total, from the literature, there were 70 times of maximum light non-homogeneously distributed within 63 years. They got $\text{O-C} = -0.0001(2) + 3.9(1) \times 10^{-7} E - 8.3(1.1) \times 10^{-13} E^2$ with the rms of 0.00115 days. They did not confirm the hypothetical binary nature supposed by Pocs and Szeidl. They did not use averaged (O-C) as Pocs and Szeidl did. To check the binary nature once again, we observed it between May 27, 2004 and June 1, 2004 at the Xinglong station of the NAOC of the Chinese Academy of Sciences. Here, we are publishing our results plus one time of maximum light which was recorded on May 4, 1984 at the Xinglong station by Jiang. We have also added 11 times of maximum light determined from the data of Milone et al. (1994). We also used 7 times of maximum light from Agerer and Huebscher published in IBVS No. 5296 (2002), Huebscher published in IBVS No. 5643 (2005),

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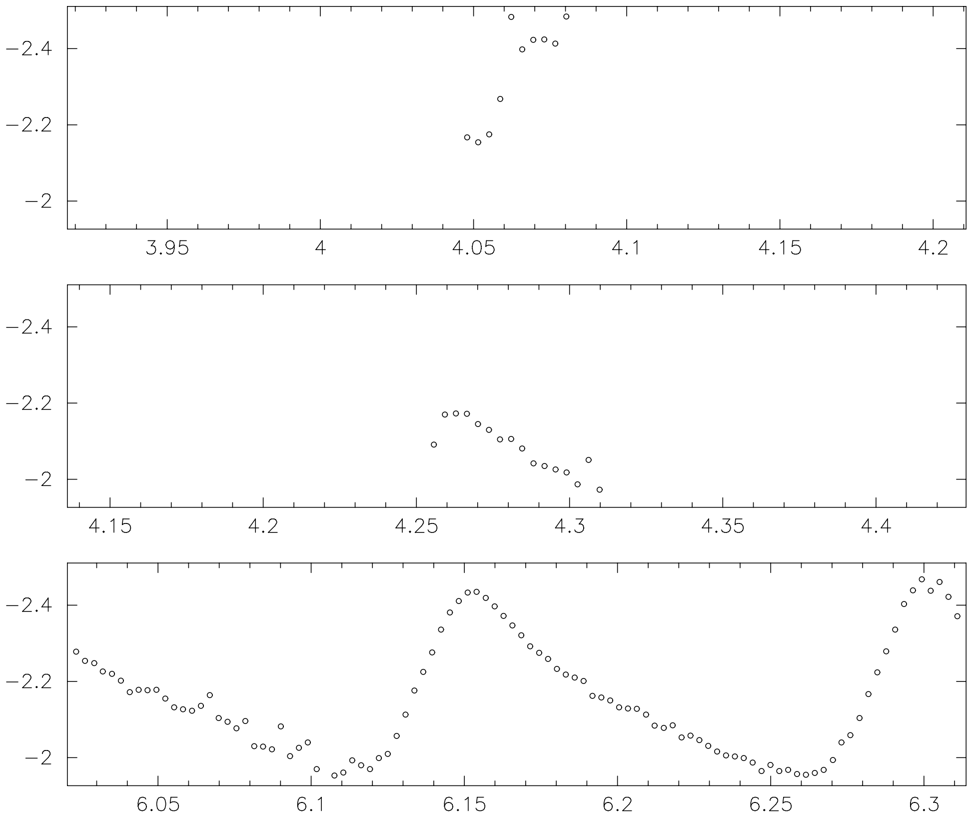

Fig. 1 The light curve of DY Her at HJD 2453154.0479 to 2453156.3109, the *X-axis* is time in HJD, need to add 2453150.0 to get the real observation time, the *Y-axis* is the differential magnitude with the comparison star

Huebscher et al. (2005) published in IBVS No. 5657 as follows: HJD 2451672.5222, 2452075.4608, 2452085.4183, 2452151.4102, 2453094.6223, 2453145.4558, and 2453164.4832. Recently, Klingenberg et al. (2006) published 5 times of maximum light in IBVS No. 5701.

2 Observations

We observed DY Hercules (TASS Mark 1478147) from May 27, 2004 to June 1, 2004 at the Xinglong station of the National Astronomical Observatory of China from a reflecting telescope with a diameter of 85 cm. The CCD is Ap7p with 512 square pixels of 24 square microns. The field of view is about 7 square arc-minutes of the sky. We used TASS Mark 1478118 as a comparison star with coordinate 2004.4 RA = 16:31:11.49, DEC = +11:59:03. We used TASS Mark 1478151 as a check star with coordinate 2004.4 RA = 16:31:34.02, DEC = 12:02:37.4. As the weather was not very good, we only got data on the 27th, 28th, and 30th of May and on the 1st of June. In total we got 4 times of maximum light: HJD 2453154.0725, 2453156.1539, 2453156.3022, and 2453158.0853. Jiang used an old observation from the Xinglong Station of NAOC which used a 60 cm telescope and a photoelectric photometer and got a time of maximum light of HJD 2445796.2407. Some light curves of DY Hercules which were observed from the Xinglong station are shown in Fig. 1.

3 The O-C results

The times of maximum light HJD_{max} are collected in Table 1. In Table 1 we also give out the time sequence, the cycle number $E(I)$, the linear fit residual L(O-C), the quadratic fit residual LQ(O-C), the weight and biographic references. For the weight, we used 0.1 for all photographic observations; we used 0.2 for uvbybeta photoelectric observations; we used 0.5 for photoelectric observations or CCD photometry using a small telescope with moderate accuracy; we used 1.0 for photoelectric photometry or CCD photometry for greater accuracy. Our results include 98 times of maximum light HJD_{max}. We set the equations for linear and quadratic fits as follows:

$$HJD_{max} = \mathrm{T01} + \mathrm{P01}E \tag{1}$$

$$HJD_{max} = \mathrm{T02} + \mathrm{P02}E + 0.5\mathrm{Beta}E^2. \tag{2}$$

Here HJD_{max} is the time of maximum light for each cycle number E that we collected. We used

$$HJD_{max} = 2433439.4871 + 0.1486309 \tag{3}$$

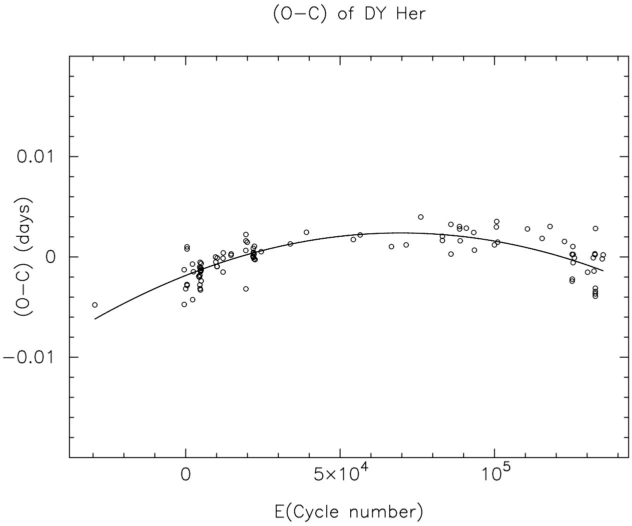

Fig. 2 The quadratic fit of (O-C) of DY Her, the *X-axis* is in cycle number E, the *Y-axis* is the linear (O-C), the *curve* is the quadratic fit curve

to calculate the cycle number E for each HJD_{max} which are listed in Table 1. Then, we used the OMC01 software compiled by Fu and Jiang in 1996 to get the linear and quadratic solutions for the calculated times of maximum light: T01 = 2433439.4889 ± 0.0002, is the calculated time of the maximum light with $E = 0$ under a linear fit. P01 = 0.14863117212 ± 0.000000002 days, is the period for a linear fit. T02 = 2433439.4871 ± 0.0002 is the calculated time of the maximum light with $E = 0$ under a quadratic fit. P02 = 0.148631294 ± 0.000000009 days, is the period for a quadratic fit. Beta $= -8.76 \times 10^{-13}$ day/cycle is the period variation rate. The negative means the pulsation period of DY Hercules is decreasing. DBeta $= 6.4 \times 10^{-14}$ day/cycle is the error of Beta. It is much smaller than Beta itself. This means the period-decreasing rate of DY Hercules is reliable. The final rms of the quadratic fit is 0.0013 days. This is much better than the rms of the linear fit of 0.0023 days. That means that the period is decreasing at the rate of $(-1.4 \pm 0.1) \times 10^{-8}$ year^{-1}. This rate is smaller and more reliable than $(-2.8 \pm 0.4) \times 10^{-8}$ year^{-1} given by Derekas et al. (2003). Figure 2 is the quadratic fit of (O-C) of DY Her.

4 The yearly average of LQ(O-C)

In Table 1 we get the weighted yearly average of LQ (O-C). We listed them in Table 2. We also listed the semi-amplitude of the scatter, the total weight, the total number of times of maximum light and the year. From these data we can see the yearly distribution is not homogeneous. Many years there have been no observations. From 1938 to 1950 there were only low weight photographic observations and there were no observations for 11 years. During 68 years, only 30 years were observed. There were no observations for the 38 years: 1939–1949, 1953, 1957, 1961, 1962, 1963, 1965, 1967–1971, 1974–1976, 1978, 1980, 1982, 1983, 1989, 1990, 1992–1994, 1996, 1999, and 2002. For 12 years there was only 1 observation. For 4 years there were only 2 observations. Non-homogeneous observation is not good for studying the light time effect. Figure 3 shows Table 2 in graph form. From Fig. 3 we can see there is a kind of variation which looks similar to a binary orbital light time effect. The period is about 58.9 years, which is 20 years longer than that given by Pocs and Szeidl in 2000. Because the first group had only one point and a low quality of observation, the real scatter may be as large as ±0.002 days, and the real shape of this variation is still not clear.

5 Discussion

As DY Her is a post main sequence population I delta Scuti type variable, the negative direction means its period variation is not really caused by stellar evolution although it is not much different from the evolutionary calculation in absolute size. This period variation may be just some parts of the sine wave of a long period binary orbital light time effect. The period in this research is not the same as what Pocs and Szeidl suspected. Here the period is much longer. As we mentioned, the weighted yearly averaged (O-C)'s time variation curve in Fig. 3, shows some long time scale variations with a period of about 58.9 years. Due to uncompleted (each year needs at least more than 4 times of maximum light and it is better to get more than 10) and non-homogeneous (some years have no observations), we can't get a reasonable periodical solution. The conclusion of Pocs and Szeidl looks reasonable, but it can't be really proved at this moment. When we compare Fig. 2 with Derekas et al. (2003), we collected more data (4 years) and the data points are more homogeneously distributed. We found and used data published by Milone et al. (1994) and analyzed his 11 times of maximum light. Their accuracy is not very good but should be more reliable than photographic observations.

Suppose DY Her is really a binary(see Fig. 3) we can calculate its orbital period $P_{orb} \approx (115413 + 29409) \times 0.1486312$ days = 21525 days or 58.9 years. Its projection of semi-major axis $a_1 \sin i \approx 0.5 \times (0.002 + 0.0005) \times 86400 \times 300000$ km = 32400000 km ≈ 0.22 au. We use the formula of mass function:

$$\begin{aligned} f(M) &= [M_2^3/(M_1+M_2)^2](\sin i)^3 = (a_1 \sin i)^3/P_{orb}^2 \\ &= 0.000003 M_\odot \end{aligned} \tag{4}$$

Here M_1 is the mass of DY Her $= 2.0 M_\odot$ which is given by McNamara (1997); M_2 is the mass of its unseen companion

Table 1 The times of maximum light from the researchers and references

No.	$T_{max}(I)$	$E(I)$	L(O-C)	LQ(O-C)	Weight	Reference
1	29068.390000	−29409.0	−0.004788	0.001404	0.1	Szeidl and Mahdy (1981)
2	33366.807000	−489.0	−0.001277	0.000635	0.1	Ashbrook (1954)
3	33371.857000	−455.0	−0.004737	−0.002829	0.1	Ashbrook (1954)
4	33442.607000	21.0	−0.003174	−0.001325	0.1	Ashbrook (1954)
5	33501.614000	418.0	−0.002750	−0.000949	0.1	Ashbrook (1954)
6	33506.671000	452.0	0.000791	0.002587	0.1	Ashbrook (1954)
7	33507.563000	458.0	0.001004	0.002800	0.1	Ashbrook (1954)
8	33509.640000	472.0	−0.002833	−0.001038	0.1	Ashbrook (1954)
9	33767.517200	2207.0	−0.000716	0.000871	0.5	Broglia and Masani (1955)
10	33775.837000	2263.0	−0.004262	−0.002681	0.1	Smith (1954)
11	33815.524300	2530.0	−0.001484	0.000065	0.5	Smith (1954)
12	34068.940000	4235.0	−0.001932	−0.000581	0.1	Smith (1954)
13	34097.923000	4430.0	−0.002011	−0.000682	0.1	Smith (1954)
14	34118.881000	4571.0	−0.001006	0.000307	0.1	Smith (1954)
15	34119.771000	4577.0	−0.002793	−0.001481	0.1	Smith (1954)
16	34123.785000	4604.0	−0.001835	−0.000525	0.1	Smith (1954)
17	34133.744000	4671.0	−0.001123	0.000178	0.1	Smith (1954)
18	34134.785000	4678.0	−0.000542	0.000759	0.1	Smith (1954)
19	34137.755000	4698.0	−0.003165	−0.001866	0.1	Smith (1954)
20	34139.689000	4711.0	−0.001370	−0.000073	0.1	Smith (1954)
21	34149.794000	4779.0	−0.003290	−0.002000	0.1	Smith (1954)
22	34159.457000	4844.0	−0.001316	−0.000034	0.5	Lenouvel and Daguillon (1954)
23	34162.429500	4864.0	−0.001439	−0.000160	0.5	Lenouvel and Daguillon (1954)
24	34178.481800	4972.0	−0.001306	−0.000038	0.5	Lenouvel and Daguillon (1954)
25	34180.414000	4985.0	−0.001311	−0.000045	0.5	Lenouvel and Daguillon (1954)
26	34182.495000	4999.0	−0.001148	0.000117	0.5	Lenouvel and Daguillon (1954)
27	34184.427700	5012.0	−0.000653	0.000610	0.5	Lenouvel and Daguillon (1954)
28	34188.439000	5039.0	−0.002395	−0.001135	0.5	Lenouvel and Daguillon (1954)
29	34875.563300	9662.0	−0.000002	0.000754	0.5	Broglia and Masani (1955)
30	34888.493700	9749.0	−0.000514	0.000233	0.5	Broglia and Masani (1955)
31	34945.419000	10132.0	−0.000953	−0.000245	0.5	Broglia and Masani (1955)
32	34956.417700	10206.0	−0.000959	−0.000260	0.5	Broglia and Masani (1955)
33	34960.431600	10233.0	−0.000101	0.000596	0.5	Broglia and Masani (1955)
34	35241.789000	12126.0	−0.001509	−0.001006	0.5	Fitch (1957)
35	35241.939000	12127.0	−0.000140	0.000363	0.5	Fitch (1957)
36	35249.817000	12180.0	0.000408	0.000905	0.5	Fitch (1957)
37	35622.881000	14690.0	0.000166	0.000417	0.5	Fitch (1957)
38	35631.799000	14750.0	0.000296	0.000541	0.5	Fitch (1957)
39	36336.757000	19493.0	0.000648	0.000457	0.1	Spinrad (1959)
40	36337.799000	19500.0	0.002230	0.002039	0.1	Spinrad (1959)
41	36337.947000	19501.0	0.001599	0.001407	0.1	Spinrad (1959)
42	36338.834000	19507.0	−0.003188	−0.003380	0.1	Spinrad (1959)
43	36404.385000	19948.0	0.001465	0.001234	0.5	Broglia (1961)
44	36681.878000	21815.0	0.000067	−0.000322	0.5	Hardie and Lott (1961)
45	36694.809700	21902.0	0.000855	0.000458	0.5	Hardie and Lott (1961)
46	36695.701000	21908.0	0.000368	−0.000029	0.5	Hardie and Lott (1961)
47	36696.741000	21915.0	−0.000050	−0.000448	0.5	Hardie and Lott (1961)

Table 1 (*Continued*)

No.	$T_{max}(I)$	$E(I)$	L(O-C)	LQ(O-C)	Weight	Reference
48	36703.726700	21962.0	−0.000015	−0.000417	0.5	Hardie and Lott (1961)
49	36704.767600	21969.0	0.000467	0.000064	0.5	Hardie and Lott (1961)
50	36730.480600	22142.0	0.000274	−0.000143	0.5	Broglia (1961)
51	36733.750000	22164.0	−0.000212	−0.000631	0.5	Hardie and Lott (1961)
52	36747.722600	22258.0	0.001058	0.000632	0.5	Hardie and Lott (1961)
53	36782.649600	22493.0	−0.000267	−0.000713	0.5	Hardie and Lott (1961)
54	37075.453800	24463.0	0.000524	−0.000081	1.0	Broglia (1961)
55	38476.006100	33886.0	0.001292	0.000020	0.5	Fitch et al. (1966)
56	39252.902400	39113.0	0.002457	0.000883	0.5	Epstein (1969)
57	41508.379700	54288.0	0.001725	−0.000458	1.0	Szeidl and Mahdy (1981)
58	41840.422200	56522.0	0.002187	−0.000051	1.0	Geyer and Hoffmann (1974)
59	43341.744500	66623.0	0.001020	−0.001359	1.0	Breger et al. (1978)
60	44050.418100	71391.0	0.001193	−0.001191	1.0	Szeidl and Mahdy (1981)
61	44755.229900	76133.0	0.003976	0.001627	0.5	Yang et al. (1993)
62	45795.348500	83131.0	0.001636	−0.000590	1.0	Yang et al. (1993)
63	45796.240700	83137.0	0.002049	−0.000177	0.5	Xinglong Observatory
64	46205.869400	85893.0	0.003239	0.001085	0.2	Milone et al. (1994)
65	46210.919900	85927.0	0.000280	−0.001874	0.2	Milone et al. (1994)
66	46619.807000	88678.0	0.003026	0.000958	0.2	Milone et al. (1994)
67	46625.752000	88718.0	0.002779	0.000712	0.2	Milone et al. (1994)
68	46652.801700	88900.0	0.001606	−0.000455	0.2	Milone et al. (1994)
69	46945.755000	90871.0	0.002866	0.000876	0.2	Milone et al. (1994)
70	47305.887900	93294.0	0.002437	0.000542	0.2	Milone et al. (1994)
71	47335.761000	93495.0	0.000671	−0.001215	0.2	Milone et al. (1994)
72	48302.607300	100000.0	0.001199	−0.000378	1.0	Pocs and Szeidl (2000)
73	48392.828200	100607.0	0.002977	0.001433	0.2	Milone et al. (1994)
74	48407.840500	100708.0	0.003529	0.001990	0.2	Milone et al. (1994)
75	48456.738100	101037.0	0.001473	−0.000047	0.2	Milone et al. (1994)
76	49890.435700	110683.0	0.002790	0.001882	1.0	Agerer and Huebscher (1996)
77	50593.460200	115413.0	0.001847	0.001299	1.0	Agerer and Huebscher (1998)
78	50975.443500	117983.0	0.003036	0.002700	1.0	Agerer et al. (1999)
79	51672.522200	122673.0	0.001540	0.001621	0.5	Agerer and Huebscher (2002)
80	52040.380400	125148.0	−0.002410	−0.002094	1.0	Derekas et al. (2003)
81	52040.531700	125149.0	0.000259	0.000575	1.0	Derekas et al. (2003)
82	52049.447100	125209.0	−0.002212	−0.001890	1.0	Derekas et al. (2003)
83	52075.460800	125384.0	0.001033	0.001372	0.5	Agerer and Huebscher (2002)
84	52085.418300	125451.0	0.000245	0.000590	0.5	Agerer and Huebscher (2002)
85	52086.457900	125458.0	−0.000574	−0.000227	1.0	Derekas et al. (2003)
86	52151.410200	125895.0	−0.000096	0.000294	1.0	Agerer and Huebscher (2002)
87	52786.658400	130169.0	−0.001524	−0.000697	0.5	Klingenberg et al. (2006)
88	53054.939100	131974.0	−0.000089	0.000932	1.0	Klingenberg et al. (2006)
89	53094.622300	132241.0	−0.001412	−0.000362	0.5	Huebscher et al. (2005)
90	53132.673600	132497.0	0.000308	0.001387	1.0	Klingenberg et al. (2006)
91	53145.455800	132583.0	0.000227	0.001315	0.5	Huebscher (2005)
92	53154.072500	132641.0	−0.003681	−0.002586	1.0	Present Paper
93	53156.153900	132655.0	−0.003117	−0.002021	1.0	Present Paper
94	53156.302200	132656.0	−0.003448	−0.002352	1.0	Present Paper
95	53158.085300	132668.0	−0.003922	−0.002825	1.0	Present Paper

Table 1 (*Continued*)

No.	$T_{max}(I)$	$E(I)$	L(O-C)	LQ(O-C)	Weight	Reference
96	53164.483200	132711.0	0.002837	0.003939	0.5	Huebscher et al. (2005)
97	53489.833800	134900.0	−0.000198	0.001151	1.0	Klingenberg et al. (2006)
98	53535.612600	135208.0	0.000201	0.001585	1.0	Klingenberg et al. (2006)

Table 2 The yearly averaged LQ(O-C) of DY Her from 1938 to 2006

Year	E	LQ(O-C)	Scatter ±	W	Numbers
1938	−29409.0	0.0019	0.0000	0.1	1
1950	125.3	0.0001	0.0028	0.7	7
1951	2333.3	0.0003	0.0013	1.1	3
1952	4745.2	−0.0002	0.0014	4.5	17
1954	9948.0	0.0003	0.0005	2.5	5
1955	12144.3	0.0001	0.0010	1.5	3
1956	14720.0	0.0004	0.0001	1.0	2
1958	19589.8	0.0007	0.0027	0.9	5
1959	22052.8	−0.0002	0.0007	5.0	10
1960	24463.0	−0.0002	0.0000	1.0	1
1964	33886.0	−0.0001	0.0000	0.5	1
1966	39113.0	0.0007	0.0000	0.5	1
1972	54288.0	−0.0006	0.0000	1.0	1
1973	56522.0	−0.0002	0.0000	1.0	1
1977	66623.0	−0.0015	0.0000	1.0	1
1979	71391.0	−0.0013	0.0000	1.0	1
1981	76133.0	0.0015	0.0000	0.5	1
1984	83134.0	−0.0005	0.0003	1.5	2
1985	85910.0	−0.0005	0.0005	0.4	2
1986	88765.3	0.0003	0.0007	0.6	3
1988	93394.5	−0.0004	0.0004	0.4	2
1991	100588.0	0.0003	0.0012	1.6	4
1995	110683.0	0.0020	0.0000	1.0	1
1997	115413.0	0.0015	0.0000	1.0	1
1998	117983.0	0.0030	0.0000	1.0	1
2000	122673.0	0.0019	0.0000	0.5	1
2001	125384.9	−0.0001	0.0017	6.0	7
2003	130169.0	−0.0007	0.0000	0.5	1
2004	132514.0	−0.0001	0.0034	6.5	9
2005	135054.0	0.0014	0.0002	2.0	2

and the angle i is an inclination angle of its orbit related to our line of sight. Because M_2 is much smaller than M_1, we can ignore it and by substituting M_1 the equation (4) will be:

$$[M_2^3/(2)^2](\sin i)^3 = 0.25[(M_2 \sin i)^3] = 0.000003 M_\odot \quad (5)$$

So

$$M_2 \sin i \approx 0.023 M_\odot \quad (6)$$

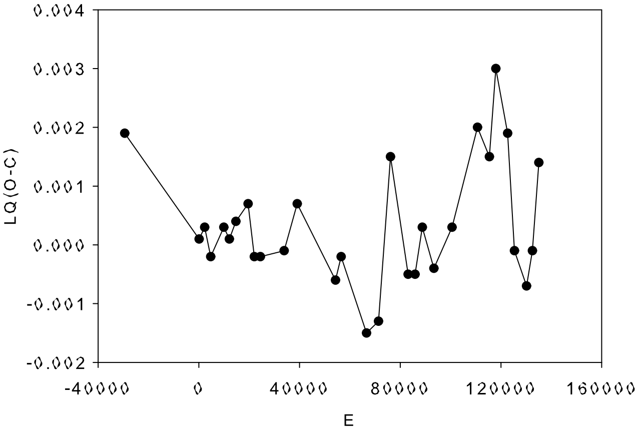

Fig. 3 The averaged LQ(O-C) of DY Her from 1938 to 2006

In general, the inclination angle i set to be 45 degrees then $M_2 = 0.032 M_\odot$, and the unseen companion of DY Her should be a brown dwarf.

To solve this interesting star, it is good to encourage all those people who have small telescopes and cheap CCDs to observe it between April and June, so that every year we can have more observation times of maximum light and then the average of LQ(O-C) will be much more reliable.

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