Recently Determined Light Elements for the δ Scuti Star ZZ Microscopii

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Abstract The δ Scuti star ZZ Microscopii (HD 199757) was studied by photoelectric photometry (PEP) on three nights in 2008 and by DSLR photometry on three nights in 2014. PEP yielded 51 magnitude measurements in V, including 4 peaks of the light curve, and DSLR photometry yielded 622 measurements, including 14 peaks of the light curve. Fourier analysis of the DSLR photometric data found a principle frequency F1 of 14.8853 (0.0001) c/d, and a harmonic frequency 2F1 of 29.7706 (0.0007) c/d, similar to the results of others. Another frequency F2 of 22.2049 (0.0025) c/d, of much lower amplitude than F1, was identified. F2 is higher than the frequency (19.15 c/d) previously reported in the literature, and its accuracy is regarded as uncertain as the semi-amplitude of F2 is low. Regression analysis of an O–C diagram, plotted from 33 historical times of maximum from 1960 to 2003, 4 times of maximum from our PEP in 2008, and 14 times of maximum light from our DSLR photometry in 2014 indicated that a cubic regression provided the best fit. The fitted curve confirms conclusions of others that the period of ZZ Mic was increasing at a constant rate during the years 1960 to 2003, and indicates that the period has decreased during more recent years. The following cubic ephemeris was derived, with zero epoch defined as the first peak of the DSLR photometry light curve on 19 July 2014: T_{max} (HJD) = 2456858.0131 (0.0002) – 7.644 (2.532) × 10^{-19} E^3 – 2.646 (0.973) × 10^{-13} E^2 + 0.06717917 (0.00000001) E.

1. Introduction

ZZ Mic (HD 699757) is a δ Scuti star whose variability was first reported by Churms and Evans (1961). It has a very short principal period of 0.0672 d (Churms and Evans 1961; Leung 1968; Chambliss 1971; Derekas *et al.* 2009; Kim and Moon 2009). The amplitude of this pulsation is approximately 0.35 mag (Chambliss 1971; Balona and Martin 1978; Derekas *et al.* 2009). Percy (1976, as quoted by Kim and Moon 2009) analyzed the data published by Leung (1968), and reported two periods of 0.0654 d and 0.0513 d. Derekas (2009) determined the second period to be 0.0522 d, but with a much smaller amplitude (approximately 0.03 mag) than that of the principal period.

Kim and Moon (2009) published a study which dealt mainly with astrophysical properties of ZZ Mic, but included analysis of an O–C diagram of their own data and data by others collected between September 1960 and July 2003, a span of nearly 43 years. These authors fitted a second order polynomial expression to the O–C data. The fitted curve was concave up, indicating that the period of the star was increasing at a constant rate.

Since more than 11 years have elapsed since the time of the most recent (2003) data in Kim and Moon's (2009) publication, it is considered timely to report further studies of the periods of ZZ Mic, incorporating data from photoelectric and DSLR photometry.

2. Data and analysis

Photoelectric photometry was performed in 2008 using an SSP-5 photometer from Optec Inc, Lowell, Michigan. The instrument was fitted with a Hamamatsu R6358 multialkali photomultiplier tube, and Johnson V and B photometric filters. Measurements were taken through a Celestron C9.25 Schmidt-Cassegrain telescope, on a Losmandy GM-8 German equatorial mount. The comparison and check stars were HD 200027 and HD 200320, respectively. Non-transformed magnitudes in V were calculated, since the color indices of the variable and comparison stars are relatively close. Photometry was performed on three nights in 2008, namely, 31 July, 9 August, and 28 October. A total of 51 magnitude determinations were made over a period of 5 hours 20 minutes.

DSLR photometry was performed on RAW images taken with a Canon EOS 500D DSLR camera through a refracting telescope with an aperture of 80 mm at f/7.5, mounted on a Losmandy GM-8 German equatorial mount. Images were obtained on three nights in 2014, namely, 19, 27, and 28 July. A total of 622 magnitude determinations were made over a total observing period (including meridian flips) of 25 hours 35 minutes.

Photometric data reduction from DSLR instrumental magnitudes utilized the software package AIP4WIN (Berry and Burnel 2011). The comparison and check stars were the same as those chosen for photoelectric photometry. Transformed magnitudes in V were calculated using transformation coefficients for the blue and green channels of the DSLR sensor, calculated from images of standard stars in the E regions (Menzies *et al.* 1989).

The time of each magnitude measurement (the mid point of each set of three PEP measurements, and the mid point of each DSLR exposure) was recorded initially in Julian Days (JD), and subsequently converted to Heliocentric Julian Days (HJD). The heliocentric correction was calculated for the mid point in time of the observation set for each night, and that correction was applied to each time in JD for the corresponding night.

Fourier analysis used the software package PERIOD04. The software package PERANSO was used to determine the time of maximum light for each peak in the light curve, calculated as the maximum value of a 6th order polynomial expression fitted to each peak.

3. Results

Examples of light curves of ZZ Mic from photoelectric and DSLR photometry are shown in Figures 1 and 2, respectively.

The results of Fourier analysis (Table 1 and Figure 3) identified a principal frequency F1 14.8853 (0.0001) c/d which corresponds to a period of 0.0672 d, confirming the results of others (Churms and Evans 1961; Leung 1968; Chambliss 1971; Derekas *et al.* 2009; Kim and Moon 2009). The harmonic frequency 2F1, 29.7706 (0.0007) c/d is close to that in the

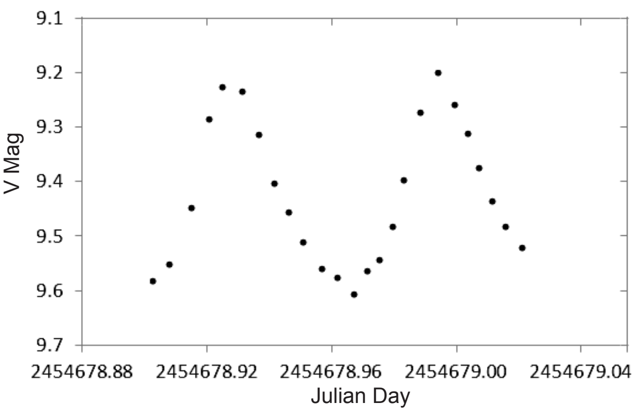

Figure 1. Light curve of ZZ Mic obtained by photoelectric photometry from observations taken on one night over 2 hours 51 minutes.

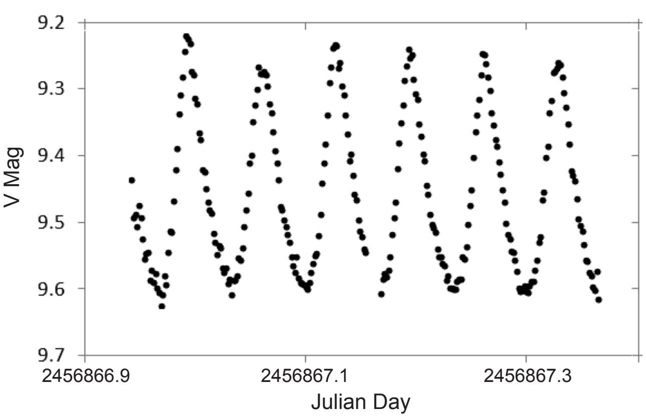

Figure 2. Light curve of ZZ Mic obtained by DSLR photometry from observations taken on one night over 10 hours 10 minutes.

Table 1. Results of Fourier analysis by the software package PERIOD04. The second frequency (2F1, 19.7706 c/d) is almost exactly twice the principal frequency (F1), and is therefore a harmonic of F1. The values of sigma were calculated in PERIOD04 using a Monte Carlo simulation with 100 processes, in which frequency and phase uncertainties were not uncoupled. Note that the semi amplitude of F2 is substantially less than that of F1.

F	*Frequency (c/d)*	*Frequency Sigma*	*Semi-Amplitude*	*Semi-Amplitude Sigma*
F1	14.8853	0.0001	0.164	0.001
2F1	29.7706	0.0007	0.038	0.001
F2	22.2049	0.0025	0.009	0.001

literature, but the other identified frequency, 22.2049 (0.0025) c/d, is higher than the frequency of 19.15 c/d previously identified (Derekas *et al.* 2009).

An O–C diagram was drawn from the data in Table 3 of Kim and Moon (2009), combined with our own data. Kim and Moon stated that 34 times of maximum were utilized, but only 33 are tabulated in their paper, comprising their own observations, as well as those of Churms and Evans (1961), Leung (1968), Chambliss (1971), and Balona and Martin (1978). The publications representing the sources of the times of maximum are quoted by Kim and Moon, but are not referenced to each individual data point. Therefore, an attempt has been made to do this retrospectively. Table 2 lists the times of maximum for the O–C calculations from Kim and Moon's (2009) paper (rows 1 to 33 of Table 2), and includes the references to the sources of the data as interpreted by us from information in that paper. Table 2 also includes our own data (rows 34 to 51), comprising 4 times of maximum from photoelectric photometry in 2008 and 14 times of maximum from DSLR photometry in 2014. Figure 4 illustrates the O–C diagram, and the cubic (third order polynomial) model fitted to the data. The cubic regression for the O–C data is given by the equation:

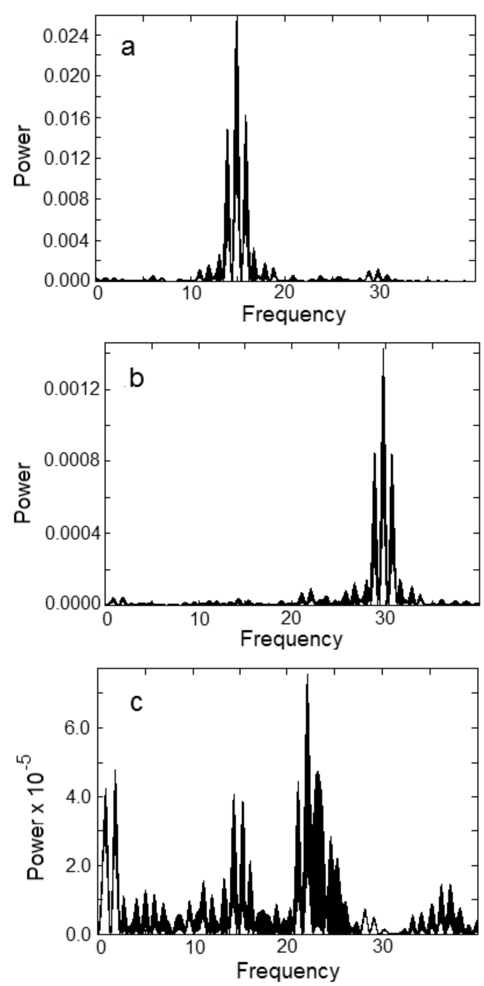

Figure 3. Fourier analysis by PERIOD04 of DSLR photometric data of ZZ Mic. Power spectra show: (a) the principal frequency F1 at 14.8853 c/d, (b) a harmonic frequency 2F1 at 29.7706 c/d, and (c) another frequency F2 at 22.2049 c/d, with the latter having a substantially lower amplitude than F1.

Table 2. Data for ZZ Mic from which the O–C diagram in Figure 2 was drawn.

Maximum	*TOM (HJD)*	*Epoch*	*O–C*	*Source**
1	2437192.31400	0	0.001000	1
2	2437249.28190	848	0.000955	1
3	2439320.21610	31675	0.002573	2
4	2439321.22350	31690	0.002286	2
5	2439330.15630	31823	0.000255	2
6	2439330.22340	31824	0.000176	2
7	2439331.22870	31839	–0.002212	2
8	2440449.56250	48486	–0.000221	3
9	2440449.63030	48487	0.000399	3
10	2440450.50300	48500	–0.000230	3
11	2440450.57040	48501	–0.000009	3
12	2440450.63730	48502	–0.000288	3
13	2440451.51050	48515	–0.000418	3
14	2440451.57790	48516	–0.000197	3
15	2440451.64630	48517	0.001024	3
16	2443356.33840	91755	–0.000261	4
17	2443356.40640	91756	0.000560	4
18	2449996.66450	190600	–0.000208	5
19	2449997.60620	190614	0.000983	5
20	2449997.60670	190614	0.001483	5
21	2449997.67360	190615	0.001204	5
22	2449997.67370	190615	0.001304	5
23	2449998.61390	190629	0.000996	5
24	2450405.58600	196687	0.001623	5
25	2450406.59410	196702	0.002036	5
26	2452237.29430	223953	0.002401	5
27	2452474.57070	227485	0.001938	5
28	2452477.52550	227529	0.000854	5
29	2452493.51640	227767	0.003109	5
30	2452495.53240	227797	0.003734	5
31	2452496.40690	227810	0.004904	5
32	2452496.47110	227811	0.001925	5
33	2452842.51120	232962	0.002069	5
34	2454678.92288	260298	0.003681	6
35	2454678.98960	260299	0.003229	6
36	2454687.99196	260433	0.003575	6
37	2454767.93562	261623	0.004012	6
38	2456858.01271	292735	0.002457	7
39	2456858.08010	292736	0.002663	7
40	2456865.94133	292853	0.003925	7
41	2456866.00668	292854	0.002104	7
42	2456866.07460	292855	0.002837	7
43	2456866.14110	292856	0.002163	7
44	2456866.20880	292857	0.002680	7
45	2456866.27554	292858	0.002244	7
46	2456866.94769	292868	0.002597	7
47	2456867.01531	292869	0.003043	7
48	2456867.08185	292870	0.002402	7
49	2456867.14919	292871	0.002568	7
50	2456867.21692	292872	0.003116	7
51	2456867.28342	292873	0.002434	7

**Notes: Rows 1 to 33 represent the data in Table 3 of Kim and Moon (2009). The sources of the data, in the last column on the right (as interpreted by us, from information in Kim and Moon's paper), are (1) Churms and Evans 1961; (2) Leung 1968; (3) Chambliss 1971; (4) Balona and Martin 1978; (5) Kim and Moon 2009; (6) photoelectric photometric data of the present authors; (7) DSLR photometric data of the present authors. Calculation of the O-C values is based on the ephemeris used by Kim and Moon (2009) for their own calculations, namely, T_0 (HJD) 2437192.313 and period 0.0671786 d.*

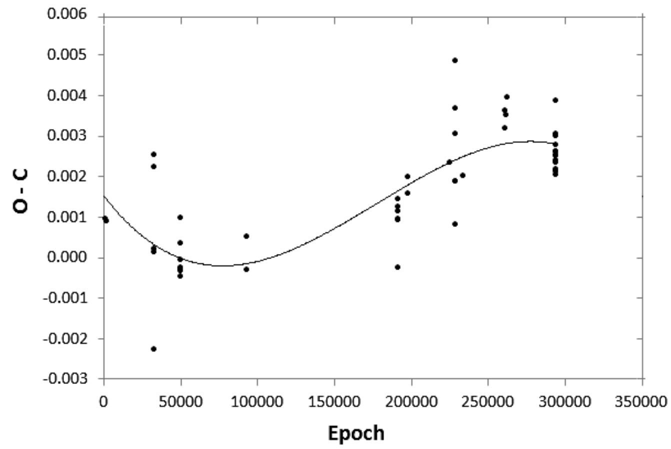

Figure 4. O–C diagram of ZZ Mic incorporating data from the literature and the authors' PEP and DSLR photometry. The diagram spans the years 1960 to 2014. The fitted curve represents a cubic (third order polynomial) expression. The earlier part of the curve, which is concave up, confirms that the period was increasing until 2003 approximately. In more recent years, the period has decreased.

$$O\text{–}C = 0.0015\ (0.0006) - 7.64\ (2.53) \times 10^{-19}\ E^3 + 4.07\ (1.28) \times 10^{-13}\ E^2 - 4.91\ (1.82) \times 10^{-8}\ E \qquad (1)$$

The fit was found to be superior to those of linear or second order polynomial models (see discussion in section 4 below). A cubic ephemeris was therefore calculated for the behavior of ZZ Mic, and represents new light elements for the star:

$$T_{max}\ (HJD) = 2456858.0131\ (0.0002) - 7.644\ (2.532) \times 10^{-19}\ E^3 - 2.646\ (0.973) \times 10^{-13}\ E^2 + 0.06717917\ (0.00000001)\ E \quad (2)$$

The zero epoch in this ephemeris is the time of the first maximum in the set of DSLR observations from 19 July 2014. The period of the star on that date is given in the last term in Equation 2, 0.06717917 (0.00000001) d.

4. Discussion

The principal frequency from Fourier analysis of the present DSLR photometric observations, 14.8853 c/d, corresponds to a period of 0.0672 d, a result similar to that reported in several previous publications (Churms and Evans 1961; Leung 1968; Chambliss 1971; Derekas *et al.* 2006; Kim and Moon 2009), and essentially identical to the more precise value of 0.06717917 d in a cubic ephemeris calculated by us from times of maximum light published by others and combined with our own data.

The Fourier harmonic 2F1 reported herein is mentioned in the literature only by Derekas *et al.* (2009). The additional frequency F2 of 22.2049 c/d corresponds to a period of 0.04505 d, which is shorter than the period of 0.0513 d reported by Percy (1976, as quoted by Kim and Moon 2009) and the period of 0.0522 d found by Derekas (2006). The period ratio of 0.78 was reported by both Percy (1976, as quoted by Kim and Moon 2009) and Derekas (2009) and falls within the range (0.74–0.78) accepted for the ratio of the first overtone to the fundamental frequency for a δ Scuti star pulsating in the radial mode (Breger 1979). In contrast, the ratio obtained by us is only 0.67, which falls outside the accepted range for such stars. It is therefore considered that the accuracy of this ratio is uncertain, as the semi-amplitude of F2 is low (0.009 magnitude in V) and substantially less than that of F1 at 0.164 magnitude (Table 1).

Analysis of the O–C diagram was undertaken by performing linear, second order, and third order polynomial regression analysis of the 51 data points available. The three models were compared by "extra sum of squares" analysis to determined whether each polynomial provided any statistically significant improvement in fit to its predecessor, based on the residual sum of squares of the fit. It was found that the linear and quadratic models were not statistically different from each other (P = 0.26). However, the cubic model was superior to both the linear and quadratic models ($P < 0.01$). All its four coefficients, including the intercept, were statistically significant ($P < 0.01$) and the adjusted coefficient of determination, R^2_{adj}, was greater than that of the other two (0.593 compared with 0.524 and 0.521); as the models are nested the values of R^2_{adj} are directly comparable. We therefore believe that the cubic model of the O–C data is superior to the others and is the model of choice in this case.

Weighted regression was attempted using the reciprocal of the variance of O–C values obtained at similar epochs as weights. Interesting results were obtained, including modestly different coefficients and improved residuals. This approach is promising but requires more analysis and has not been pursued further in the present work.

Therefore, the behavior of ZZ Mic, for the data available, is best described by a cubic ephemeris. The most recent previous O–C analysis of ZZ Mic in the literature is the paper by Kim and Moon (2009) who analyzed observations made across nearly 43 years, between 1960 and 2003. Those authors found that the period of the star was increasing at a constant rate across the time covered by that data set. The conclusion from the more recent data obtained by us is that the period of the star has decreased since the last 2003 data obtained by Kim and Moon.

5. Acknowledgements

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