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THE PERIOD AND LIGHT CURVE OF THE 71-SECOND VARIATION IN DQ HERCULIS

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ABSTRACT

The 71^{s} signal in the old nova DQ Herculis has been observed during the 1974 season. The period at the present epoch allows more accurate estimates of the secular decrease in period. The period decrease appears to be nonlinear. Evidence is also presented to show that the true period of the signal is 142^{s}.

Subject headings: binaries — pulsation

I. INTRODUCTION

The old nova DQ Herculis exhibits a 71^{s} sinusoidal variation which has been attributed to rotation or pulsation of a degenerate dwarf within the system. Recently Lamb (1974) has suggested that if the variations result from a hot spot caused by accretion onto a magnetic pole, then the true rotation period of the star may be 142^{s}, the near symmetry of the north and south magnetic poles with respect to our line of sight producing an apparent 71^{s} light curve. On the suggestion of Lamb, we began a series of observations to determine whether there might exist some small difference between even and odd 71^{s} pulses. While the observations were in progress, Swedlund, Kemp, and Wolstencroft and Kemp, Swedlund, and Wolstencroft (1974) reported the detection of circular and linear polarization from DQ Herculis. The Stokes parameters varied synchronously with the periodic light variations, and the fundamental period was 142^{s}.

II. OBSERVATIONS

A log of the observations is set out in table 1. Sixteen time series of varying lengths were taken at the University of Illinois 1-m telescope with an EMI 6256SA photomultiplier. No optical filter was employed. The data are analyzed under the assumption that the time of arrival of the 71^{s} pulses at the telescope is color independent. We therefore disregard differential atmospheric extinction which would shift the effective wavelength of the detector as a function of air mass. The light intensity was typically recorded at $0^{s}.01$ intervals, although for later runs integration times of 3^{s} were standard. Two additional data sets (A1 and A2), kindly provided by Roger Angel, were obtained with C31034A tubes behind *U* filters on the Steward Observatory 2.3-m telescope. Table 1 gives the UT date of each run, the heliocentric Julian date at the beginning of the run, and the duration of the run in seconds.

III. DATA ANALYSIS AND RESULTS

Each observation was signal averaged at $142^{s}.13$. The duration of the runs is long enough such that the phase shifts near binary phase 0.0 reported by Warner *et al.* (1972) can be ignored, although for reference the binary phase at the beginning of each run is given in table 1, column (5). The resulting light curves were

TABLE 1

LOG OF OBSERVATIONS

Run Number (1)	UT Date (1974) (2)	Start Time [JD$_{\odot}$ − 2442048.5] (3)	Duration [seconds] (4)	Binary Phase at Run Start (5)
1.......	JUN 18	168.14658	1848	0.7505
2.......	JUN 23	173.29901	4264	0.3616
3.......	JUN 23	173.35173	2132	0.6339
4.......	JUN 25	175.15856	5970	0.9657
A1......	JUN 26	176.34212	1138	0.0785
A2......	JUN 26	176.36951	1138	0.2744
5.......	JUL 17	197.24882	10376	0.0560
6.......	AUG 4	215.11969	14355	0.3544
7.......	SEP 17	259.08992	5543	0.4491
8.......	SEP 17	259.23159	2558	0.1807
9.......	OCT 1	273.05541	2700	0.5771
10.......	OCT 8	280.02114	5686	0.5533
11.......	OCT 8	280.10169	5686	0.9692
12.......	OCT 9	281.05027	5686	0.8685
13.......	OCT 11	283.10367	5686	0.4738
14.......	OCT 17	289.01875	10092	0.0236
15.......	OCT 19	291.06242	5686	0.5786
16.......	OCT 22	294.00817	5686	0.7926

fitted by a least-squares technique to

$$A_4 + A_5 t + \sum_{m=1}^{3} A_m \cos(m\omega t + \varphi_m)\,,$$

$$\omega = \frac{2\pi}{142.13}\ \mathrm{Hz}\,,$$

where A_1 through A_5 and φ_1 through φ_3 are the eight parameters simultaneously fitted and t is time. In table 2 we give A_1 and A_2 in arbitrary units and φ_1 and φ_2 in seconds. A power spectrum was also constructed for each run. The error in arrival time appearing in table 2, column (7), is estimated from Δt[seconds] = 71.06 Arctan x/y, where x^2 is the average local power in the neighborhood of 71^{s} and y^2 is the power at $71\overset{\mathrm{s}}{.}06$.

The phase of the 71^{s} component, φ_2, was added to the known starting time of each run to compute heliocentric arrival times for the 71^{s} maxima. We then extracted the best period P and phase for the 1974 seasons by least-squares fitting to runs 1–16. The χ^2 for the 14 degrees of freedom is 21, with run 2 contributing 7 units. Possibly an error occurred in recording the starting time of run 2, but, in any case, eliminating run 2 from the fitting procedure would increase P by only one-half of the standard deviation. We obtain a period

$$P = 71\overset{\mathrm{s}}{.}065445 \pm 0\overset{\mathrm{s}}{.}000021\,,$$

with a light maximum occurring at $\mathrm{JD}_\odot = 2{,}442{,}223.658568 \pm 70$.

Adding the phases of the 142^{s} components, φ_1, to the heliocentric run start times, we obtained the 142^{s} heliocentric arrival times. These arrival times were divided by $2P$ to obtain the dimensionless 142^{s} residuals, θ_1, listed in table 2. Contrary to what one would expect in the presence of random noise, the residuals are not uniformly distributed. This point is illustrated in figure 1, in which we plot the residuals θ_1 and their respective amplitudes as vectors. The sum of the vectors for the individual runs has amplitude 14.05 and phase $-54°$. It is the vector that one would obtain by folding all the data sets at $2P$ to obtain a single light curve, and then fitting to obtain a phase and amplitude. For comparison we also show in figure 1 the equivalent vector sum for the 71^{s} component, drawn to the same scale. Since 360° in figure 1 corresponds to 142 seconds, there is a second (unplotted) 71^{s} vector rotated by 180°.

For a set of vectors with polar coordinates $(a_\alpha, \theta_\alpha)$, with θ_α drawn from a uniform random population, the expectation value of the amplitude A of the sum vector is given by

$$\bar{A}^2 = \sum_\alpha a_\alpha{}^2\,.$$

For a large number of vectors a_α, the distribution of A is given by $(dA/\bar{A}) \exp(-A/\bar{A})$. The probability for a chance occurrence of the measured sum vector is 0.077. The validity of an exponential distribution for the particular 18 vectors a_α was checked by a Monte Carlo program which yielded the same probability. We use the tables of Groth (1975) to estimate the amplitude of the signal present, A_{SIG}:

$$A_{\mathrm{SIG}}/\bar{A} = 1.4 \pm 0.8\,.$$

This yields a ratio between 142^{s} and 71^{s} component amplitudes of $A_1/A_2 = 0.35 \pm 0.20$. The phase of the signal, a light maximum, is $\mathrm{JD}_\odot = 2{,}442{,}223.65800 \pm 13$.

No statistically significant signal was observed for the second harmonic described by A_3 and φ_3.

IV. DISCUSSION

a) *Period and Period Change*

The period and phase we have observed for the 71^{s} variation during 1974 is in agreement with the 1974

TABLE 2

Run Number (1)	A_1 [arbitrary units] (2)	φ_1 [seconds] (3)	θ_1, 142^{s} Residual [dimensionless] (4)	A_2 [arbitrary units] (5)	φ_2 [seconds] (6)	$\Delta\varphi_2$ Error [seconds] (7)
1...........	0.04	125.1	0.56	0.21	16.3	12.5
2...........	1.88	53.3	0.17	1.92	9.4	8.3
3...........	1.14	35.9	0.09	0.17	0.3	14.8
4...........	3.45	95.4	0.87	3.40	0.5	3.0
A1..........	0.73	45.6	0.99	1.15	13.3	...
A2..........	0.77	69.8	0.81	1.31	57.6	...
5...........	3.43	52.2	0.02	5.15	4.8	3.6
6...........	3.30	89.7	0.81	3.72	66.8	5.3
7...........	0.45	110.5	0.04	1.68	54.2	4.1
8...........	1.26	8.7	0.44	1.23	39.3	6.5
9...........	2.14	111.3	0.53	0.47	15.8	15.0
10...........	2.56	127.5	0.04	2.21	9.0	6.8
11...........	1.91	95.7	0.78	0.80	12.5	11.9
12...........	1.61	137.9	0.71	0.99	64.6	10.2
13...........	1.01	133.4	0.92	1.93	30.4	3.9
14...........	2.26	5.9	0.75	7.23	1.6	2.4
15...........	3.25	79.5	0.59	1.13	15.9	11.8
16...........	0.81	29.3	0.93	1.56	61.4	12.3

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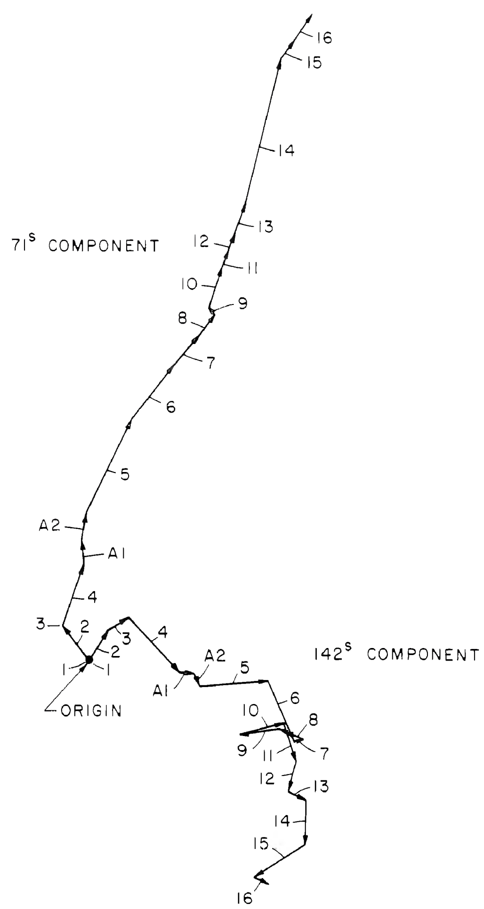

FIG. 1.—Each vector labeled by a run number represents the heliocentric phase and amplitude of 71^{s} and 142^{s} components for that run. The vectors are summed to show the presence of a phase-coherent signal.

value $71\overset{\mathrm{s}}{.}06542 \pm 0\overset{\mathrm{s}}{.}00004$ given by Swedlund *et al.* (1974), but does not agree with the elements reported by Herbst, Hesser, and Ostriker (1974) derived from all data through 1969,

$$P = 71\overset{\mathrm{s}}{.}065461 \pm 0\overset{\mathrm{s}}{.}000002 \quad \text{(1969 April)}\,,$$

$$\dot{P} = -26.9 \pm 0.8\ \mu\mathrm{s\ yr}^{-1}\,.$$

In view of the difficulties of extrapolating the 1969 value of P into 1974, it is worthwhile to make a new determination of $\dot{P}$.

We treat each observer and season as a separate determination of P for that epoch. Values of P and ΔP, the error in P, are derived by a least-squares fit to the published times of maximum light under the assumption that $\dot{P}$ may be neglected for observations spanning a single season. The errors, ΔP, are the formal errors of the fit. The results are presented in table 3. $\dot{P}$ is determined by a least-squares fit through the tabulated values of P, yielding

$$P = 71\overset{\mathrm{s}}{.}065417 \pm 0\overset{\mathrm{s}}{.}000018 \text{ (1974 August)}\,,$$

$$\dot{P} = -20.8 \pm 1.5\ \mu\mathrm{s\ yr}^{-1}\,.$$

The χ^2 for this fit is 10.5 for 6 degrees of freedom, whereas the χ^2 for the former elements is 60.3. Figure 2 displays the time behavior of the period, with the solid line the least-squares fit and the dashed line the elements obtained by Herbst *et al.* (1974) with their shorter baseline.

We have omitted from consideration the times of maximum light given by Warner *et al.* (1972) for 1970 and 1971. If these two data points are taken as a measurement of P, one obtains $P = 71\overset{\mathrm{s}}{.}065443 \pm 0\overset{\mathrm{s}}{.}000006$ for JD = 2,441,041, where a 10-μs correction in P has been applied to account for $\dot{P}$. This value for P lies several standard deviations from the fit curve, and this fact considered in conjunction with the rather marginal χ^2 (probability 0.2) for a straight-line fit leads us to suggest that $\dot{P}$ is not a constant. Rather

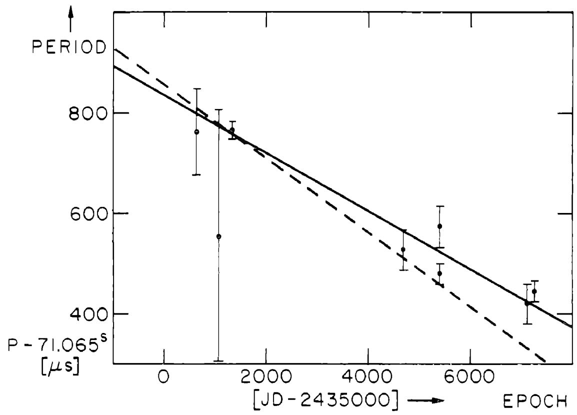

FIG. 2.—Period of DQ Her at various epochs, 1956–1974, computed from data of several observers.

TABLE 3

71^{s} PERIODS AT VARIOUS EPOCHS

Observer	Date	Epoch [JD − 2435000]	Period [s]	Error for Period [μs]
Walker..............	1956	678	71.065762	86
Walker..............	1957	1107	71.065555	251
Walker..............	1958	1364	71.065766	17
Herbst *et al.*..........	1967	4702	71.065527	41
Herbst *et al.*..........	1969	5410	71.065480	20
Warner *et al.*..........	1969	5431	71.065574	38
Swedlund *et al.*........	1974	7162	71.065420	40
Nelson..............	1974	7280	71.065445	21

than introducing $\ddot{P}$ at this time, it appears more reasonable to await future measurements of P to elucidate the temporal behavior of the period.

b) *Possible 142^s Component*

The 142^s component is weak: random fluctuations would produce our observed signal one time in 13. However, in view of the aforementioned large residual of the 71^s phase obtained in run 2, we now examine the consequence of discarding these data. Furthermore, although run 9 in figure 1 has a 71^s phase which is not inconsistent with its error, run 9 was taken during full moon with signal to background of 1/8. Difficulties in guiding may account for the large 142^s component. We also discard run 9. The resulting vector sum of 16 remaining runs has a random occurrence probability of only 0.028. The phase of the vector is unchanged. We consequently believe that a true signal has been detected. Observations with the same statistical weight as those presented here should suffice to settle the question.

The phase of the observed 142^s component is of some interest in that it lags the 71^s component by 60° ± 30°. From a model in which the 71^s maxima originate at hot spots on the north and south magnetic poles, one would predict 142^s maxima in phase with alternate 71^s maxima. We suggest the following picture, more in agreement with our results. Assume the 71^s maxima are associated with optically thick accretion columns at the magnetic poles. Light maxima occur when one views the accretion columns broadside. The sinusoidal character of the variations results from a geometric projection factor. If our line of sight favors one rotation pole, one 71^s minimum will be deeper than the other. Thus, the 142^s maximum would lag the 71^s maximum by 90° (142^s/4). A model with optically thick accretion columns also accounts for the phase relation of the observed circular polarization with respect to the 71^s maxima. Swedlund *et al.* (1974) find maximum circular polarization at 71^s light minima. This is to be expected with optically thick columns because light minima occur when the magnetic poles are viewed most directly.

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