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The Period Changes of the Cepheid RT Aurigae

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ABSTRACT. Observations of the light curve for the 3.7 day Cepheid RT Aur both before and since 1980 indicate that the variable is undergoing an overall period increase, amounting to $+0.082 \pm 0.012$ s yr^{-1}, rather than a period decrease, as implied by all observations prior to 1980. Superposed on the star's $O - C$ variations is a sinusoidal trend that cannot be attributed to random fluctuations in pulsation period. Rather, it appears to arise from light travel time effects in a binary system. The derived orbital period for the system is $P =$ 26,429 $\pm$ 89 days (72.36 $\pm$ 0.24 yr). The inferred orbital parameters from the $O - C$ residuals differ from those indicated by existing radial velocity data. The latter imply the most reasonable results, namely $a_1 \sin i =$ $9.09(\pm 1.81) \times 10^8$ km and a minimum secondary mass of $M_2 = 1.15 \pm 0.25\ M_\odot$. Continued monitoring of the brightness and radial velocity changes in the Cepheid are necessary to confirm the long-term trend and to provide data for a proper spectroscopic solution to the orbit.

1. INTRODUCTION

Every well-studied Cepheid undergoes changes in pulsation period: some rapidly, others extremely slowly, and ~10% in irregular fashion, attributable to random fluctuations in pulsation period, generally superposed on parabolic evolutionary trends, e.g., SV Vul (Turner & Berdnikov 2004). For the large majority, the effect can be attributed directly to gradual changes in mean radius as post–main-sequence stars of 3–20 $M_\odot$ evolve through the instability strip in the H-R diagram (Turner et al. 2006). Parabolic trends in Cepheid $O - C$ diagrams—temporal plots of the differences between observed and computed times of light maxima—are diagnostic features of stars undergoing slow changes in mean radius (Parenago 1958; Struve 1959).

The case for the 3.7 day Cepheid RT Aur is most unusual. Summaries by Szabados (1977, 1991) and Fernie (1993) of observed times of maximum light between 1897 and 1980 provide a strong case for a regular period decrease in the Cepheid (Turner 1998), although Szabados (1977) preferred to interpret the $O - C$ data as evidence for a discontinuous period change, contrary to the arguments for evolution (Szabados 1983; Turner et al. 2006). The available $O - C$ data to 1980, from Szabados (1977, 1991), Fernie (1993), Wunder (1992), and an unpublished list of observed times of maximum light by V. Goransky of the Sternberg Astronomical Institute, cited by A. Kosinsky et al. (2006, unpublished),[1] are shown in Figure 1 (*top*). The weighting scheme for the data used throughout this paper is that employed by Szabados (1977), with weights assigned to sources not cited by Szabados (1977, 1991) on the basis of the perceived quality of the result. The negative parabolic trend is the signature of a regular period decrease (Struve 1959), and the inferred rate of -0.123 ± 0.018 s yr^{-1} is close to what is predicted from stellar evolutionary models for a star in the second crossing of the Cepheid instability strip (Turner et al. 2006).

Regular photoelectric monitoring of the brightness variations of RT Aur by professional observers ceased over a decade ago, with the exception of Berdnikov et al. (1997), Barnes et al. (1997), Kiss (1998), and observations by the *Hipparcos* satellite (ESA 1997). A variety of other observations of the star, primarily by amateur astronomers, has generated additional times of light maximum that are listed by Wunder (1992), A. Ko-

[1] A. S. Kosinsky, V. G. Tamello, I. J. Kushmar, I. S. Bryukhanov, A. S. Semenyuta, & I. I. Balyuk 2006, Belarussian Correspondence Astronomical Club (http://www.astroclub.belastro.net/rt_aur_period_eng.php).

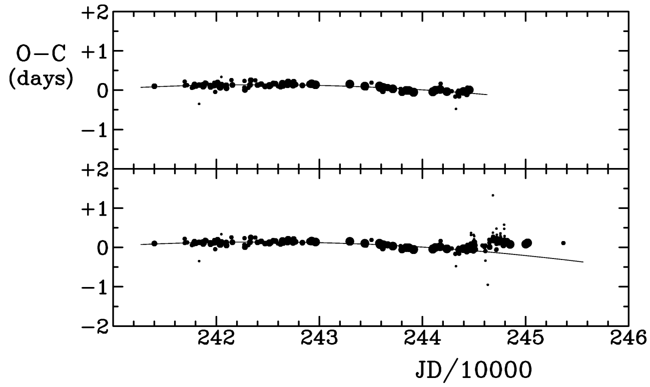

FIG. 1.—$O-C$ data for RT Aur as available by 1980 (*top*), and with more recently published observations (*bottom*), with symbol size proportional to the weight assigned to each datum. The negative parabolic trend in both cases is a least-squares fit to the pre-1980 data, indicative of a regular period decrease for the Cepheid.

sinsky et al. (2006, see footnote 1), and Meyer (2004, 2006). They are plotted in Figure 1 (*bottom*), using the weighting scheme described above, but are generally of lower quality than most observations by professional observers, as indicated by the larger scatter in the more recent times of light maxima. Nevertheless, it is clear that current $O-C$ data do not confirm the regular period decrease evident prior to 1980. A similar trend is indicated in an $O-C$ plot for RT Aur generated by Berdnikov et al. (2003) using low-quality observations by members of the American Association of Variable Star Observers (AAVSO), who, in conjunction with European observers, have been the primary observers of the Cepheid in the current era.

Here we present additional data that confirm the more recent observations of the curious change in pulsation period for RT Aur, and argue that the long-term brightness changes of the Cepheid are actually more consistent with a period *increase* than a period decrease. There is, in fact, convincing evidence for a superposed sinusoidal trend that hints at more complex behavior generally consistent with orbital motion in a binary system. The main point to be made, however, is that the true situation will only be established by further monitoring of the star. The last few decades of observation merely hint at the interesting changes occurring in the system.

2. OBSERVATIONAL DATA

We obtained a selection of new $O-C$ data points for RT Aur through analysis of a variety of unpublished observations for the Cepheid, which include observations by members of AAVSO from A. Henden (Observations from the AAVSO International Database; 2006, private communication, hereafter AH06) and data from Group Betelgeuse. The latter include individual observations of RT Aur by group members, as well as data obtained from visual inspection of photographic images in the plate archives at Minsk and Odessa.

All data listed only by Julian Date were converted into heliocentric equivalents and were phased using a new ephemeris given by

$$\mathrm{HJD}_{\max} = 2{,}441{,}723.6925 + 3.72824\,E, \qquad (1)$$

where E is the number of elapsed cycles. We also made use of a standard light curve for RT Aur, in B and V, constructed from the detailed photometry of Winzer (1973), supplemented by data from Moffett & Barnes (1984) that were matched in both phase and magnitude to the observations of Winzer (1973).

Since RT Aur is a fifth-magnitude Cepheid, its brightness is typically monitored optically by means of binoculars or low-power oculars, although magnitude estimates without optical aid would likely be more accurate, given the eye's increasing precision for estimating brightness levels when functioning near the visibility limit (Turner 2000). Stellar brightness is more difficult to establish optically when it falls well above the eye limit, which may partly explain the large scatter in the AAVSO estimates for RT Aur (AH06), as indicated in Figure 2. The large number of individual AAVSO estimates compensates for the large scatter, however, and results in very precise $O-C$ estimates. The AAVSO database for RT Aur is relatively sparse prior to 1969 (cf., Berdnikov et al. 2003), which restricts its usefulness mainly to the last four decades.

The Group Betelgeuse brightness estimates for RT Aur are a mix of different sources: individual eye estimates obtained between 1989 and 2000, as well as from 2005 to 2007, by individual group members, using low-power oculars and wide-field telescopes, and eye estimates from photographs in the plate archives of Odessa and Minsk. The archival photographic material dates from 1988 to 1996 and consists of panchromatic GZS-2 film with a magnitude limit of $V = 9.0$, and A500 film exposed through a UV filter with a magnitude limit of $B = 9.0$–9.5. Typically, two to four reference stars differing in brightness by ~0.5 mag were used for comparison purposes, with individual estimates made using the step method. Some typical light curves are illustrated in Figure 3, where the superior quality of eye estimates from single observers over those of inhomogeneous groups is evident.

We also obtained new V-band photometry for RT Aur during 2007 January, February, and March using a ST9 CCD camera equipped with Bessel filters on the 0.28 m C11 Schmidt-Cassegrain telescope at Dave Lane's automated Abbey Ridge Observatory. The data were normalized using the previously constructed standard light curve. The observations are listed in Table 1, along with phases computed as indicated previously.

For reference purposes, we list in Table 2 the times for light maximum compiled by Goransky and not compiled elsewhere in the literature. Some of the cited values are of indeterminate authorship.

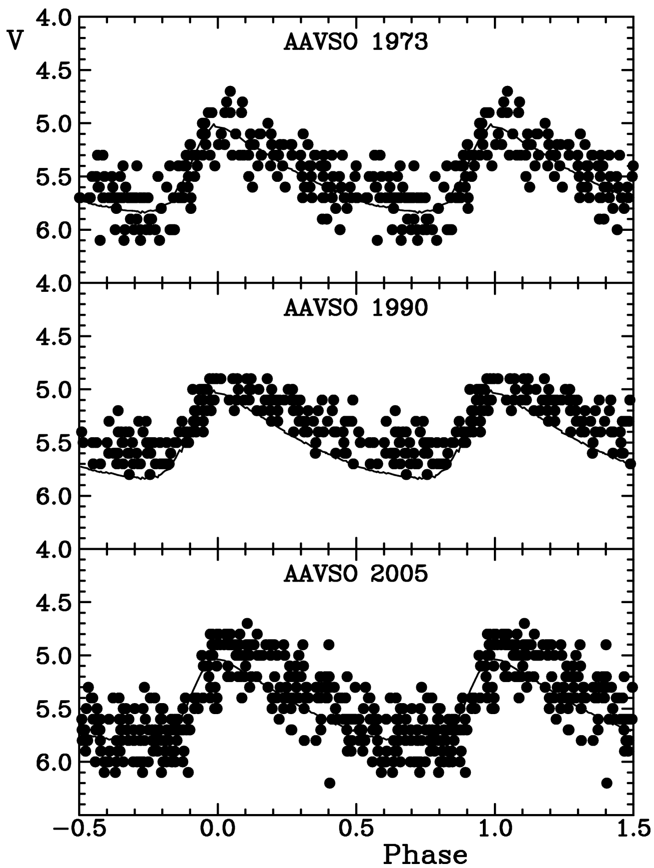

FIG. 2.—Sample of yearly compilations of observations for RT Aur taken from the AAVSO database. The plotted relation in each case is the adopted standard light curve.

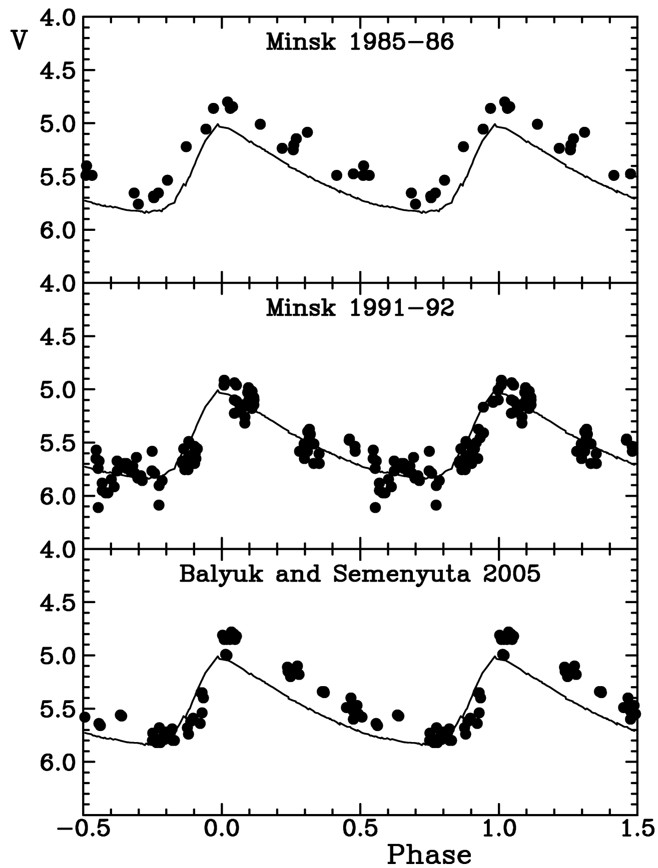

FIG. 3.—Sample of observations for RT Aur obtained from Group Betelgeuse. The upper two sections contain data obtained from eye estimates off plates in the Minsk collection; the lower section shows individual observations by Group observers I. Balyuk and A. Semenyuta. The plotted relation in each case is the adopted standard light curve.

3. ANALYSIS

Seasonal light curves for RT Aur were constructed from the observational data and were matched to the standard *B* and *V* light curves using the robust software described previously (Turner 1998). Despite the large amount of scatter in the AAVSO observations, the large number of individual estimates results in relatively precise $O - C$ estimates, as indicated by the small scatter for the AAVSO values in Figure 4 (*top*). The individual light curves from the Group Betelgeuse data exhibit slightly smaller scatter, but generally result in less accurate $O - C$ values, because of the smaller number of individual estimates, according to Figure 4 (*bottom*). Both sets of observations confirm the trend indicated by the $O - C$ data derived by other observers, primarily amateur astronomers (Fig. 1, *bottom*). It is not clear from the $O - C$ estimates cited by Wunder (1992), A. Kosinsky et al. (2006, see footnote 1), and Meyer (2004, 2006) how the times of light maximum were derived, but the techniques are apparently less robust than the variant of Hertzsprung's method employed here.

The new photometry obtained here (Table 1), as well as visual observations of the Cepheid by Bryukhanov between 2006 December and 2007 April, also display a phase shift relative to the standard light curve, as evident from Figure 5,

TABLE 1
CCD OBSERVATIONS OF RT AURIGAE

HJD	Phase	*V*
2,454,114.4960	0.504	5.601
2,454,122.5157	0.655	5.766
2,454,122.6002	0.678	5.791
2,454,123.4933	0.917	5.707
2,454,124.5660	0.205	5.231
2,454,124.8261	0.275	5.300
2,454,128.5226	0.266	5.318
2,454,128.6473	0.300	5.360
2,454,135.5390	0.148	5.184
2,454,135.6977	0.191	5.228
2,454,136.6442	0.445	5.554
2,454,167.5417	0.732	5.778
2,454,183.6046	0.041	5.051

TABLE 2
ARCHIVAL $O-C$ DATA FOR RT AURIGAE

HJD_{max}	Cycles E	$O-C$ (days)	Weight	Source
2,417,173.360	−6585	+0.128	0.5	Williams (1905)
2,418,347.279	−6270	−0.348	0.0	Mergentaler (1941)
2,420,957.478	−5570	+0.082	1.0	Kukarkin (1935)
2,422,784.241	−5080	+0.008	1.0	Soloviev (1922)
2,436,146.219	−1496	−0.027	1.0	Schaltenbrand & Tammann (1971)
2,442,838.410	+299	−0.026	0.5	Boninsegna (1982)
2,443,181.270	+391	−0.164	0.5	Budquest (1981)
2,443,490.870	+474	−0.008	0.5	Budquest (1981)
2,443,535.540	+486	−0.077	0.5	Budquest (1981)
2,443,550.370	+490	−0.160	0.5	Budquest (1981)
2,443,990.420	+608	−0.042	1.0	Harris (1980)
2,446,488.580	+1278	+0.197	0.5	Goldman et al. (1988)
2,446,518.405	+1286	+0.196	0.5	Goldman et al. (1988)
2,446,824.299	+1368	+0.374	0.0	Goldman et al. (1988)
2,446,827.900	+1369	+0.247	0.5	Goldman et al. (1988)
2,446,850.298	+1375	+0.276	0.5	Goldman et al. (1988)
2,446,917.304	+1393	+0.173	1.0	Anonymous (1987)
2,447,148.220	+1455	−0.062	0.5	Ratz & Schille (1988)
2,447,152.230	+1456	+0.220	1.0	Anonymous (1987)
2,447,234.249	+1478	+0.218	1.0	Anonymous (1987)

that confirms the $O-C$ trend of the other observations. A compilation of all $O-C$ estimates from the present study is given in Table 3, including, where possible, reworkings of older data sets available in the literature.

The complete set of $O-C$ data, including the values compiled by Szabados (1977, 1991), that of Kelsall (1971) cited by Fernie (1993), Wunder (1992), A. Kosinsky et al. (2006, see footnote 1) as given in Table 2, and Meyer (2004, 2006) is illustrated in Figure 6 (*bottom*) relative to the situation that existed prior to 1980 (Fig. 6, *top*). A weighted least-squares fit of a parabola to the full data set indicates that RT Aur is undergoing an overall period *increase* rather than a period decrease, at a calculated rate of $+0.082 \pm 0.012$ s yr^{-1}. The value is consistent with the 3.7 day pulsation period of RT Aur, as indicated by its location in the period change diagram of Figure 7, which is adapted from Figure 5 of Turner et al. (2006). RT Aur has a pulsational amplitude near the maximum value displayed by Cepheids with periods of ~4 days, so it must lie

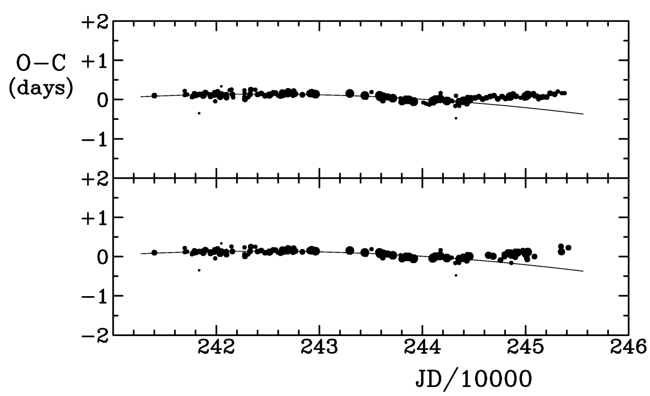

FIG. 4.—Newly derived $O-C$ data for RT Aur, plotted relative to existing pre-1980 data for the AAVSO sample (*top*) and the Group Betelgeuse sample (*bottom*). The plotted relation in each case is the least-squares fit to the pre-1980 data, and symbol size is proportional to the weight assigned to the $O-C$ datum.

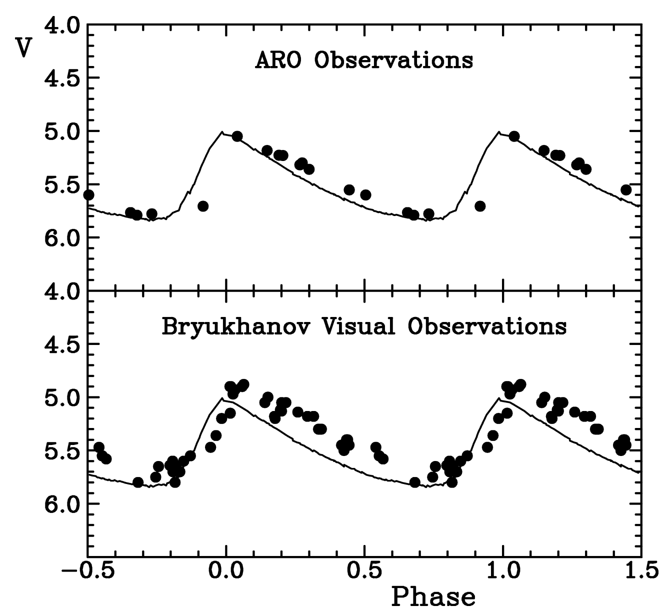

FIG. 5.—New CCD observations of RT Aur obtained from the Abbey Ridge Observatory (*top*) and from visual observations by I. Bryukhanov with a 7 × 50 monocular (*bottom*). The plotted relations are the adopted standard light curve.

TABLE 3
NEW $O-C$ DATA FOR RT AURIGAE

HJD_{max}	Cycles E	$O-C$ (days)	Weight	Data Pts n	Source
2,421,300.634	−5478	+0.240	0.5	43	AAVSO (AH06)
2,421,647.171	−5385	+0.051	0.5	29	AAVSO (AH06)
2,422,747.108	−5090	+0.157	0.5	25	AAVSO (AH06)
2,426,419.438	−4105	+0.170	2.0	18	Dufay (1947)
2,426,971.249	−3957	+0.202	2.0	46	Dufay (1947)
2,427,504.400	−3814	+0.215	1.0	6	Dufay (1947)
2,429,249.163	−3346	+0.161	3.0	204	Bennett (1941)
2,429,625.692	−3245	+0.138	3.0	98	Bennett (1941)
2,432,955.026	−2352	+0.154	3.0	14	Eggen et al. (1957)
2,434,405.262	−1963	+0.104	3.0	9	Eggen et al. (1957)
2,435,821.997	−1583	+0.108	3.0	40	Prokof'eva (1961)
2,437,126.806	−1233	+0.034	3.0	10	Mitchell et al. (1964)
2,438,010.307	−996	−0.059	2.0	4	Williams (1966)
2,438,424.195	−885	−0.005	3.0	13	Wisniewski & Johnson (1968)
2,439,132.508	−695	−0.058	3.0	20	Takase (1969)
2,439,147.429	−691	−0.050	3.0	19	Wisniewski & Johnson (1968)
2,440,079.464	−441	−0.075	0.5	16	AAVSO (AH06)
2,440,351.595	−368	−0.105	0.5	50	AAVSO (AH06)
2,440,675.924	−281	−0.133	0.5	57	AAVSO (AH06)
2,440,981.756	−199	−0.016	2.0	20	Feltz & McNamara (1980)
2,440,996.641	−195	−0.045	3.0	5	Evans (1976)
2,441,030.238	−186	−0.001	0.5	44	AAVSO (AH06)
2,441,250.206	−127	+0.000	3.0	88	Winzer (1973)
2,441,705.070	−5	+0.019	3.0	20	Szabados (1977)
2,441,854.201	+35	+0.020	1.0	177	AAVSO (AH06)
2,442,137.473	+111	−0.054	0.5	119	AAVSO (AH06)
2,442,525.277	+215	+0.013	0.5	234	AAVSO (AH06)
2,442,920.412	+321	−0.045	0.5	179	AAVSO (AH06)
2,443,241.186	+407	+0.100	0.5	123	AAVSO (AH06)
2,443,539.286	+487	−0.059	2.0	7	Moffett & Barnes (1984)
2,443,975.518	+604	−0.031	3.0	23	Moffett & Barnes (1984)
2,444,135.795	+647	−0.069	0.5	99	AAVSO (AH06)
2,444,378.093	+712	−0.106	0.5	171	AAVSO (AH06)
2,444,534.792	+754	+0.007	3.0	7	Eggen (1985)
2,444,758.522	+814	+0.042	1.0	147	AAVSO (AH06)
2,445,108.977	+908	+0.043	1.0	190	AAVSO (AH06)
2,445,463.189	+1003	+0.072	1.0	168	AAVSO (AH06)
2,445,835.952	+1103	+0.011	1.0	153	AAVSO (AH06)
2,446,190.169	+1198	+0.045	1.0	159	AAVSO (AH06)
2,446,398.941	+1254	+0.035	2.0	23	Minsk archives
2,446,563.027	+1298	+0.079	1.0	166	AAVSO (AH06)
2,446,842.574	+1373	+0.008	2.0	26	I. Bryukhanov
2,446,935.870	+1398	+0.098	1.0	161	AAVSO (AH06)
2,447,308.614	+1498	+0.018	1.0	182	AAVSO (AH06)
2,447,465.342	+1540	+0.160	3.0	27	Barnes et al. (1997)
2,447,562.026	+1566	−0.091	1.0	54	Odessa archives
2,447,707.593	+1605	+0.076	1.0	124	AAVSO (AH06)
2,447,942.456	+1668	+0.059	1.0	92	I. Sergey
2,447,949.853	+1670	+0.000	1.0	54	Odessa archives
2,447,949.888	+1670	+0.035	1.0	314	A. Kosa-Kiss et al.
2,448,061.730	+1700	+0.029	1.0	161	AAVSO (AH06)
2,448,251.930	+1751	+0.089	1.0	69	I. Sergey
2,448,270.569	+1756	+0.087	1.0	114	V. Schukin, I. Sergey, A. Kosa-Kiss, V. Mamedov
2,448,304.135	+1765	+0.098	2.0	94	Minsk archives
2,448,382.431	+1786	+0.102	1.0	131	AAVSO (AH06)
2,448,490.52	+1815	+0.078	3.0	69	Hipparcos
2,448,617.050	+1849	−0.158	0.5	28	I. Sergey
2,448,632.137	+1853	+0.015	1.0	57	N. Narkevich
2,448,662.024	+1861	+0.076	1.0	105	Minsk archives
2,448,710.490	+1874	+0.076	1.0	44	V. Grigorenko
2,448,796.305	+1897	+0.142	1.0	117	AAVSO (AH06)

TABLE 3 (*Continued*)

HJD_{max}	Cycles E	$O-C$ (days)	Weight	Data Pts n	Source
2,448,997.475	+1951	−0.014	1.0	53	N. Narkevich
2,448,997.622	+1951	+0.133	1.0	53	Minsk archives
2,449,016.242	+1956	+0.112	1.0	36	I. Sergey
2,449,083.323	+1974	+0.084	1.0	289	AAVSO (AH06)
2,449,269.725	+2024	+0.075	1.0	52	Minsk archives
2,449,269.785	+2024	+0.135	1.0	52	A. Kosinski
2,449,362.956	+2049	+0.100	1.0	48	I. Sergey
2,449,530.673	+2094	+0.045	0.5	334	AAVSO (AH06)
2,449,735.831	+2149	+0.151	1.0	68	Minsk archives
2,449,888.560	+2190	+0.022	0.5	362	AAVSO (AH06)
2,450,015.384	+2224	+0.086	3.0	9	Berdnikov et al. (1997)
2,450,112.202	+2250	−0.031	1.0	55	Minsk archives
2,450,164.357	+2264	−0.071	1.0	64	I. Sergey
2,450,198.098	+2273	+0.116	3.0	19	Kiss (1998)
2,450,242.841	+2285	+0.120	1.0	418	AAVSO (AH06)
2,450,511.291	+2357	+0.137	1.0	343	AAVSO (AH06)
2,450,757.365	+2423	+0.147	1.0	156	AAVSO (AH06)
2,450,865.339	+2452	+0.002	1.0	47	I. Sergey
2,450,884.076	+2457	+0.098	1.0	283	AAVSO (AH06)
2,451,126.393	+2522	+0.079	1.0	206	AAVSO (AH06)
2,451,245.622	+2554	+0.004	0.5	597	AAVSO (AH06)
2,451,488.012	+2619	+0.059	1.0	110	AAVSO (AH06)
2,451,674.434	+2669	+0.069	1.0	333	AAVSO (AH06)
2,452,036.067	+2766	+0.063	1.0	392	AAVSO (AH06)
2,452,371.704	+2856	+0.158	1.0	269	AAVSO (AH06)
2,452,815.341	+2975	+0.135	1.0	205	AAVSO (AH06)
2,453,128.586	+3059	+0.207	0.5	232	AAVSO (AH06)
2,453,438.082	+3142	+0.259	1.0	28	A. Semenyuta
2,453,478.956	+3153	+0.122	2.0	57	I. Balyuk
2,453,508.822	+3161	+0.163	0.5	282	AAVSO (AH06)
2,453,780.985	+3234	+0.164	0.5	138	AAVSO (AH06)
2,454,131.557	+3328	+0.282	2.0	13	Abbey Ridge data
2,454,153.871	+3334	+0.226	1.0	45	I. Bryukhanov

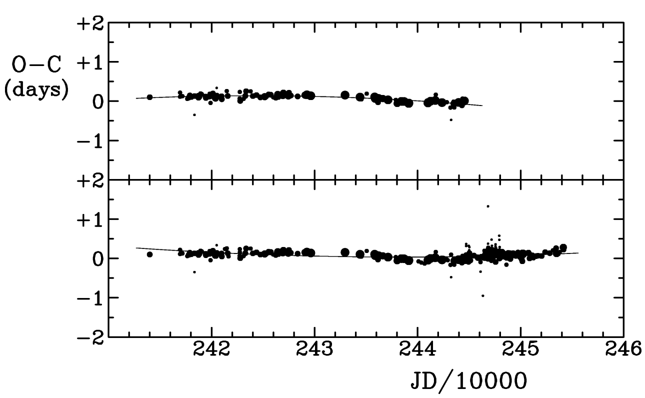

FIG. 6.—Available $O-C$ data for RT Aur prior to 1980 (*top*) and at present (*bottom*), with symbol size as in Figs. 1 and 4. The negative parabolic trend (*top*) and positive parabolic trend (*bottom*) are least-squares fits to the data in each case. The lower trend indicates a regular period *increase* for the Cepheid, with a superposed sinusoidal trend.

near the center of the instability strip; in fact, slightly toward the hot edge from strip center (Turner et al. 2006). The location of the $O-C$ datum for RT Aur in Figure 7 is almost exactly that expected for a 3.7 day Cepheid in the third crossing of the instability strip, lying slightly blueward of strip center.

It is possible to remove the parabolic evolutionary trend in the $O-C$ data of Figure 6 (*bottom*) and also correct for errors in the adopted ephemeris. The resulting $O-C$ residuals for RT Aur are plotted in Figure 8 and are analyzed below.

The sinusoidal trend of the $O-C$ data residuals for RT Aur is a feature observed in a few other Cepheids. In some cases, such trends arise from random fluctuations in pulsation period for the stars, e.g., SV Vul (Turner & Berdnikov 2001; Turner & Berdnikov 2004). One can test for the effect by analyzing the residuals using the procedure developed by Eddington & Plakidis (1929); see Turner & Berdnikov (2001). One examines the temporal differences $a(r)$ of each rth observed light maximum residual from the null relation to compute the accumulated delays $u(x) = a(r+x) - a(r)$ between maxima separated by x cycles. According to Eddington & Plakidis (1929), the average value $\langle u(x) \rangle$ for the accumulated delays between light maxima separated by x cycles, without regard for sign,

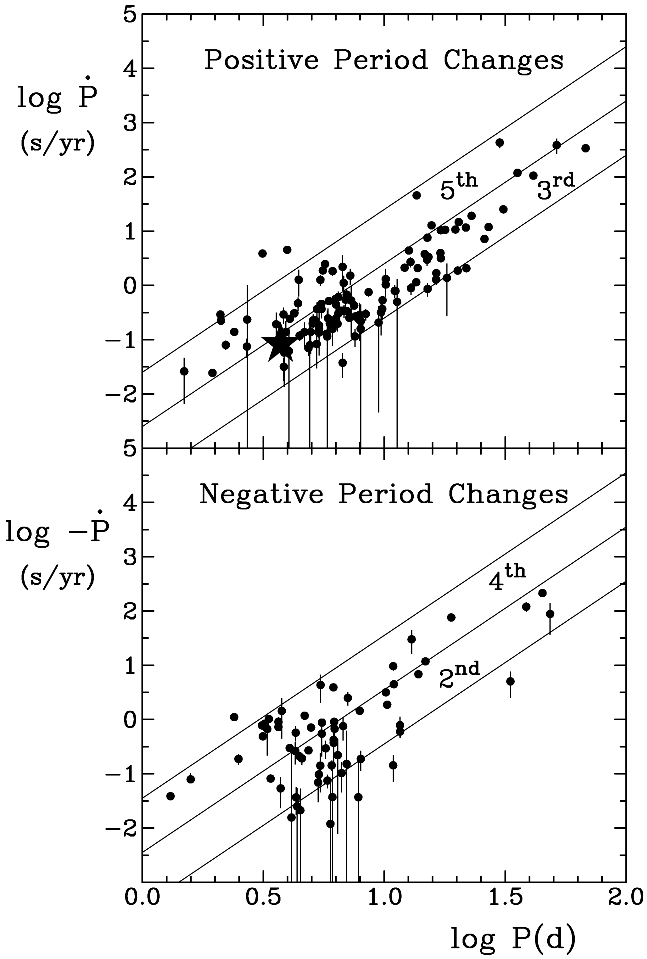

FIG. 7.—Observed rates of period change for well-studied Galactic Cepheids (Turner et al. 2006), with the present result for RT Aur plotted as a star symbol. The plotted lines indicate the empirical delineation derived by Turner et al. (2006) for different instability strip crossing modes.

is correlated with any random fluctuations in period e by

$$\langle u(x)\rangle^2 = 2a^2 + xe^2,$$

where a is the size of the random errors in the measured times of light maximum.

For RT Aur, the results over 1000 cycles (not shown) yield a best-fitting weighted relation given by

$$\langle u(x)\rangle^2 = 0.017(\pm 0.023) + 0.0000(\pm 0.0001)x.$$

The zero-point for the relation, $a = 0.092 \pm 0.108$, implies uncertainties in the calculated times of light maximum of order ± 0.34 days (~8 hr), which is reasonable although significantly larger than the uncertainties generated by Hertzsprung's method. The slope of the relation corresponds to a value for the randomness parameter of magnitude $e = 0.002 \pm 0.006$, consistent with a null result. It appears that the sinusoidal trend

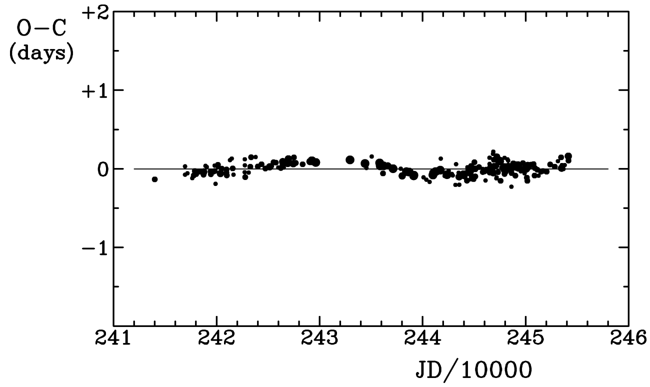

FIG. 8.—Available $O - C$ data residuals for RT Aur, with the parabolic evolutionary trend removed and corrected for errors in the adopted ephemeris. Symbol size is the same as that used in Figs. 1, 4, and 6, except that zero-weight points are not plotted.

in the $O - C$ residuals for RT Aur cannot be attributed to random fluctuations in period, according to an Eddington test performed on the observational data.

Alternatively, the trend may arise from light travel time effects in a binary system. The $O - C$ residuals were examined for periodicity through a Fourier analysis, which produced a strong, well-defined signal for $P = 26{,}429 \pm 89$ days, or 72.36 ± 0.24 yr. The data phased to that period and an arbitrary zero point of HJD 2,410,000 are shown in Figure 9 (*top*). A least-squares fit of a sine wave to the data gives a value of $a_1 \sin i = 0.0619 \pm 0.0090$ light-days $= 10.72 \pm 1.56$ AU $= 1.60\ (\pm 0.23) \times 10^9$ km for the orbit of the Cepheid about the system barycenter. Of course, the orbit need not be circular; the adoption of $e = 0$ in the analysis was predicated by the scatter in the $O - C$ residuals and the lack of solid evidence for a nonsinusoidal trend.

The sine wave solution also yields, for the putative binary system, a mass function of $M_2^3 \sin i(M_1 + M_2)^{-2} = 0.236 \pm 0.059\ M_\odot$. Such a large mass function implies a relatively high mass for the companion, as well as a strong likelihood that the orbit is nearly edge-on. With a mass of $M_1 = 4.7 \pm 0.3\ M_\odot$ for a fundamental mode Cepheid with the pulsation period of RT Aur (Turner 1996), the implied minimum mass for the secondary is of order $M_2 = 2.25 \pm 0.35\ M_\odot$, typical of a B9–A0 dwarf. Such a large mass for the companion is ruled out, however, both by the color variations of the Cepheid (Leonard & Turner 1986), which display no indication of a blue secondary, and by its ultraviolet spectrum (Evans 1992), the latter indicating that any main-sequence secondary for RT Aur must be cooler than spectral type A4, or ~$1.7\ M_\odot$. Conceivably there is an additional factor affecting the $O - C$ variations other than random fluctuations in period or light travel time effects.

Radial velocity observations may provide a resolution to the paradox. Szabados (1991) has summarized the available systemic velocities for RT Aur to 1991, to which we have added

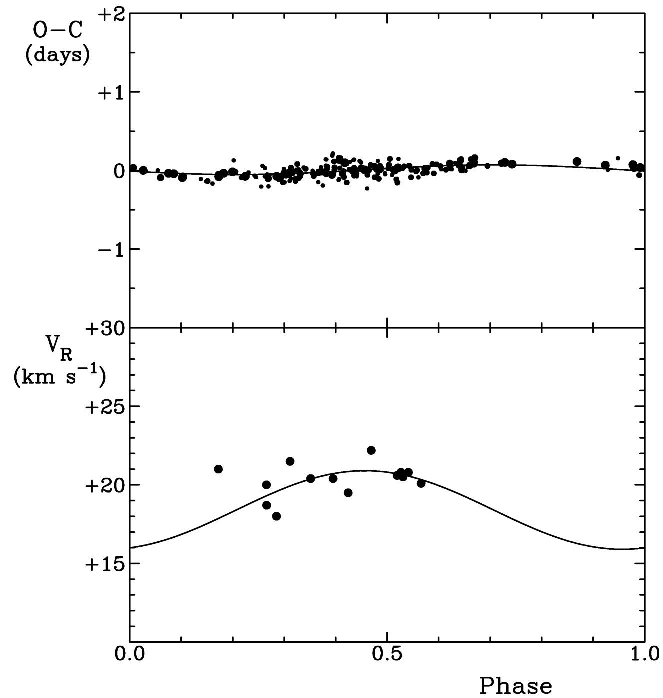

FIG. 9.—Phased $O - C$ data residuals (*top*, with zero-weight points omitted) and systemic radial velocities (*bottom*) for RT Aur for an adopted zero-point epoch of HJD 2,410,000 and $P = 26{,}429$ days. Sine wave fits to the data are depicted, with an adopted quarter-cycle offset in the lower plot.

additional measurements from the radial velocities tabulated by Gorynya et al. (1998) and Kiss & Vinko (2000), with pulsational variations removed. The combined data phased to the ephemeris adopted for the $O - C$ residuals are plotted in Figure 9 (*bottom*). For orbital motion, the radial velocity variations are a quarter cycle out of step with the $O - C$ residuals, and leading them, so a sine wave with those characteristics was crudely fitted by eye to the observations. The expected radial velocity half-amplitude according to the orbital solution is ∼4.4 km s^{-1}, but the observations appear to permit only a smaller value, which we estimate as $K = 2.5 \pm 0.5$ km s^{-1}, with an implied systemic velocity of 18.4 km s^{-1}. The projected orbital radius for the primary in this case is $a_1 \sin i = 9.09\ (\pm 1.82) \times 10^8$ km $= 6.07 \pm 1.21$ AU, which results in a mass function of $M_2^3 \sin i(M_1 + M_2)^{-2} = 0.043 \pm 0.015\ M_{\odot}$.

The radial velocity solution implies a minimum mass for the secondary of order $M_2 = 1.15 \pm 0.25\ M_{\odot}$, typical of an F7 dwarf. Such a solution is permitted by the lack of a companion detected through color variations and ultraviolet spectra, but rests on an incomplete radial velocity solution. By chance, the archival radial velocity observations of RT Aur are roughly coincident in orbital phase with more modern measurements, so only a third of the orbital cycle is covered observationally. There is also a potential zero-point offset for the earliest observations, which are those of Duncan (1908), remeasured by Petrie (1934) with similar results. The 1908 measurements agree with the trend of the other radial velocity data only if they are systematically ∼3 km s^{-1} too positive. Given that zero-point offsets of order 1–2 km s^{-1} are present even in some modern radial velocity measurements, a correction of that amount seems reasonable. Of course, it is conceivable that the effect may also indicate the presence of a third star in the system, but that is difficult to test with the available data. Certainly an improved spectroscopic orbital solution is only possible with a focused observational spectroscopic program on RT Aur over the next half-century, clearly a challenging task.

4. DISCUSSION

The value of continued monitoring of Cepheid variables in an era when professional observations of such stars are declining is illustrated clearly by the case of RT Aur. Circa 1993, when Fernie reviewed the situation (Fernie 1993), the available observations implied a regular period decrease for the Cepheid. Yet observations since then imply exactly the opposite: RT Aur appears to be undergoing a regular period increase. The calculated rate of $+0.082 \pm 0.012$ s yr^{-1} is exactly that expected for a Cepheid in the third crossing of the instability strip, lying near strip center, despite a superposed sinusoidal trend in the $O - C$ data implying an additional complication.

The possibility that RT Aur is undergoing random fluctuations in pulsation period is eliminated by an Eddington test on the residuals. The trend is consistent, however, with light time effects expected if RT Aur is orbiting an unseen companion. The inferred minimum mass for the unseen companion is of order $2.25 \pm 0.35\ M_{\odot}$ from the $O - C$ residuals, but only of order $1.15 \pm 0.25\ M_{\odot}$ according to the orbital radial velocity variations. The latter value is consistent with the lack of any evidence for a hot companion evident in the Cepheid's color variations and ultraviolet spectra. Additional observations of the star, and spectroscopic measurements in particular, may provide a more definitive estimate for the companion's characteristics.

The remarkable change in the $O - C$ trend for RT Aur, namely the switch from a period decrease prior to 1980 to a dominant period increase since then, is unusual but not without precedent. The 23 day Cepheid WZ Car, for example, appears to have changed from a regular period increase prior to 1973 to a regular period decrease since then (Turner et al. 2003), while the 4 day Cepheid Polaris underwent an astonishing glitch in its regular period increase circa 1963–1966 (Turner et al. 2005) that is difficult to explain. Other surprises may be in store when a complete sample of Cepheid period changes is examined.

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