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GOODBYE TO POLARIS THE CEPHEID

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ABSTRACT

New radial velocities and *uvby* photometry for Polaris are presented. These reveal that the pulsational amplitude of Polaris had declined to 0.59 ± 0.19 km s^{-1} and 0.010 ± 0.002 mag in V by 1992. Comparison with earlier determinations reveals an exponential change with time rather than any sudden onset of the decline, and suggests that Polaris had an amplitude near 0.12 mag (6.0 km s^{-1}) prior to 1900. There is no sign of the amplitude changing in a manner consistent with a beat phenomenon; instead, the star seems destined to stop pulsating in 1994.

Our data add new points to the O-C diagram of Polaris and show a continuation of the period increase known previously. We point out that departures of this diagram from a true parabola do not necessarily imply that factors other than stellar evolution are at work.

Finally, we lay to rest the myth that the amplitude of Polaris has declined because it is evolving across the red edge of the Cepheid instability strip. We show Polaris to be well within the strip and surrounded there by Cepheids of substantial amplitude. In particular, Polaris is virtually identical to RT Aur in M_V and color, yet RT Aur has an amplitude of 0.8 mag. We conclude that there is as yet no adequate understanding of what sets the amplitude of a Cepheid.

Subject headings: Cepheids — stars: individual (α Ursae Minoris)

But I am constant as the northern star,
Of whose true-fix'd and resting quality
There is no fellow in the firmament.
— Shakespeare, *Julius Caesar*

1. INTRODUCTION

Polaris (α UMi, HR 424) is arguably the best-known star in the sky. Among its properties is a low-amplitude variability with a 4 day period which, together with its spectral type of F7-F8 Ib-II (Kraft 1960) and the agreement of its absolute magnitude as derived from a main-sequence companion with that from the period-luminosity-relation (Turner 1977), leaves no doubt that it is a classical Cepheid. A striking abnormality, however, was the secular decrease in the star's pulsational amplitude discovered by Arellano Ferro (1983). In the course of 50 years or more the star's visual light amplitude had diminished from about 0.1 mag to about 0.05 mag. This diminishing amplitude was subsequently confirmed through radial velocities by Kamper, Evans, & Lyons (1984) and Dinshaw et al. (1989).

Arellano Ferro also corrected the O-C diagram of Polaris to show that the star has displayed an increasing period ever since its discovery as a variable. He speculated on possible explanations for why the O-C diagram is not strictly parabolic, and also—in company with most writers on Polaris—suggested that the decreasing amplitude is a sign of the star evolving redwards across the red edge of the instability strip in the HR diagram and thus exiting its Cepheid phase.

In this paper we provide new photometric and radial velocity observations to see what the amplitude had become by 1992. We also rediscuss the O-C diagram and its interpretation. Finally, we show that Polaris is not near the cool edge of the instability strip and moreover is coincident in the HR diagram with another Cepheid of much larger amplitude.

2. THE OBSERVATIONS

The photometric data were obtained in the *uvby* system using the twin photometer system mounted on the 0.6 and 0.5 m telescopes of the David Dunlap Observatory. Polaris was always observed with the larger telescope and through a neutral density filter that reduced its brightness to sixth magnitude. The comparison star, HR 286 (A3 V, $V = 6.45$, $B - V = 0.11$), which is about 0°.3 away from Polaris, was observed with the 0.5 m telescope. The relative sensitivity of the two telescope/photometer systems was monitored by observing the same (standard) star simultaneously in both systems before and after the Polaris/HR 286 observations. The neutral density filter was calibrated by standard stars observed with and without the filter. Absolute measures of HR 286 on many good nights over eight seasons revealed no variability and resulted in the absolute values

$$(y, b - y, m1, c1) = (6.447, 0.045, 0.215, 1.027) ,$$

which we adopted and applied to our differential measures to put the Polaris observations on an absolute scale. The standard errors of these numbers are 0.007, 0.004, 0.003, 0.008 mag, respectively.

Photon count rates were approximately 50,000 s^{-1} in y and b for Polaris and 30,000 s^{-1} for HR 286. On a typical night, weather permitting, the stars would be observed for five rotations of the filter wheel with 2 s integrations through each filter, and the process repeated 10–20 times. These produced internal standard errors of a few millimagnitudes for the mean difference between the stars in each filter. The fact that the external

TABLE 1

PHOTOMETRY OF POLARIS

HJD	V	$b-y$	$m1$	$c1$
2446269.637......	1.985	0.328	0.313	0.741
2446270.623......	1.991	0.328	0.328	0.767
2446294.616......	2.007	0.328	0.336	0.803
2446300.618......	1.964	0.331	0.305	0.749
2446364.546......	1.970	0.339	0.319	0.748
2446367.578......	1.938	0.339	0.337	0.762
2446377.638......	1.993	0.338	0.330	0.764
2447064.575......	1.987	0.337	0.314	0.776
2447082.551......	1.957	0.344	...	...
2447105.610......	1.997	0.345	...	...
2447306.594......	1.986	0.337	...	...
2447316.596......	2.000	0.354	...	...
2447760.601......	1.995	0.347	0.323	0.709
2447763.563......	1.982	0.335	0.327	0.714
2447781.545......	1.982	0.346	0.320	0.764
2447799.534......	1.979	0.340	0.318	0.721
2447812.532......	1.988	0.343	0.323	0.741
2448764.608......	1.981	0.353	0.323	0.722
2448765.593......	1.975	0.366	0.279	0.730
2448776.581......	1.979	0.362	0.297	0.790
2448783.581......	1.960	0.351	0.315	0.740
2448784.581......	1.984	0.351	0.291	0.781
2448785.616......	2.005	0.347	0.284	0.824
2448788.603......	1.989	0.362	0.284	0.786
2448789.577......	1.987	0.367	0.284	0.815
2448796.575......	1.976	0.342	0.373	0.720
2448798.573......	1.979	0.347	0.300	0.834
2448804.603......	1.978	0.359	0.262	0.801
2448821.745......	1.967	0.374	0.308	0.668
2448840.571......	1.977	0.365	0.302	0.771
2448841.568......	1.986	0.359	0.296	0.768
2448855.622......	1.971	0.356	0.276	0.804
2448856.612......	1.979	0.369	0.272	0.779
2448857.558......	1.994	0.360	0.297	0.789
2448889.552......	1.984	0.350	0.291	0.784
2448890.574......	1.966	0.360	0.301	0.752
2448909.548......	1.970	0.352	0.309	0.717
2448923.550......	1.975	0.366	0.282	0.779

error was at least twice this we ascribe mainly to Polaris always being near the fairly high air mass of 1.4, as well as the need to use a neutral density filter.

Photometry was obtained sporadically in 1985, 1987, 1989, and more frequently in 1992. The results are listed in Table 1. Since we shall be concerned hereafter with the $V(=y)$ magnitude only, we note for reference that the average color indices obtained from the data of Table 1 are $\langle b-y \rangle = 0.350 \pm 0.002$, $\langle m1 \rangle = 0.307 \pm 0.004$, and $\langle c1 \rangle = 0.761 \pm 0.006$, the quoted error being internal standard errors only.

TABLE 3

PHOTOMETRY NORMAL POINTS

⟨Phase⟩	⟨V⟩
0.081 ± 0.033......	1.976 ± 0.002
0.318 ± 0.026......	1.978 ± 0.003
0.501 ± 0.018......	1.983 ± 0.002
0.700 ± 0.019......	1.985 ± 0.002
0.909 ± 0.021......	1.985 ± 0.002

The radial velocity data were obtained entirely with the 1.88 m DDO reflector and consist of 281 velocities in nine sets obtained with various spectrographs and detectors between 1980 and 1992. A full discussion of these data will be published in a paper concerning the 30 yr binary orbit of Polaris (K. W. Kamper, in preparation.) Meanwhile, Table 2 summarizes the results obtained from these radial velocities. The data-set designations are the calendar years for photographic observations, RE for a Reticon/echelle combination, CF for CCD/fiber-fed, and CE for CCD/echelle. $\langle E \rangle$ is the mean cycle count based on the ephemeris described in § 3, Amplitude is the radial velocity pulsational amplitude (and its standard error) at $\langle E \rangle$, φ is the phase at which velocity maximum occurred based on the light maximum predicted by the ephemeris, and O-C the result obtained from φ using Arellano Ferro's rule that light maximum occurs 0.21 days earlier than velocity minimum, the latter taken to occur 0.5 in phase from the velocity maximum.

3. THE AMPLITUDE

We follow Arellano Ferro in counting cycles, E, from the ephemeris of Stebbins (1946), viz.,

$$JD_{\max} = 2431495.99 + 3.96961E .$$

The period is slowly increasing (Arellano Ferro 1983, eq. [4]), and an average value per season was adopted.

Our photometry was too sporadic to allow a meaningful year-by-year discussion, so we have combined it and formed averages in phase bins 0.2 wide. The normal points so formed are listed in Table 3 and shown in Figure 1. The curve is a least-squares first-order Fourier fit and has the equation

$$V = 1.9813 - 0.0050 \cos (2\pi\varphi - 1.32) .$$

The photometry thus yields a peak-to-peak V-amplitude of 0.010 ± 0.002 mag at an epoch of 1992.4 (the median date of our photometry.)

To analyze the radial velocity observations of the pulsation it is first necessary to remove the orbital motion, for which we

TABLE 2

RESULTS FROM RADIAL VELOCITIES

Data Set	n	$\langle E \rangle$	Amplitude (km s^{-1})	S.E.	$\varphi_{\rm vel\ max}$	O-C (days)	S.E
8082	29	3317	1.01	±0.28	0.18	1.96	±0.18
83	34	3522	1.41	0.27	0.19	1.97	0.13
8485	47	3702	0.82	0.13	0.77	2.54	0.11
8687	38	2869	1.26	0.19	1.21	2.99	0.09
88	10	3982	0.81	0.21	1.20	2.98	0.19
89	52	4069	0.78	0.11	1.45	3.22	0.08
RE	27	4083	1.07	0.18	1.71	3.48	0.09
CF	22	4278	0.70	0.15	2.32	4.10	0.15
CE	22	4366	0.24	0.29	2.20	3.98	0.80

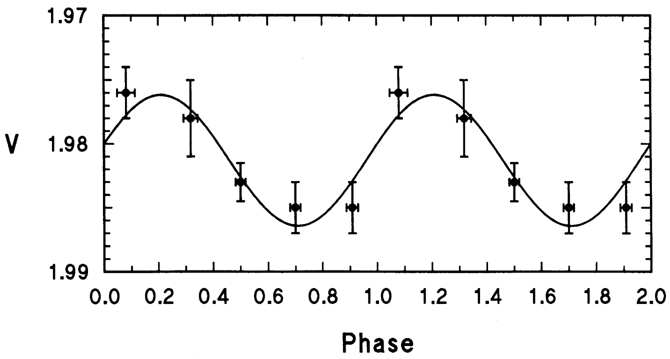

FIG. 1.—The V-magnitude light curve of Polaris at a median date of 1992.4. The amplitude is 0.010 ± 0.002 mag. The points are normal points formed from 38 individual measures. See Table 3.

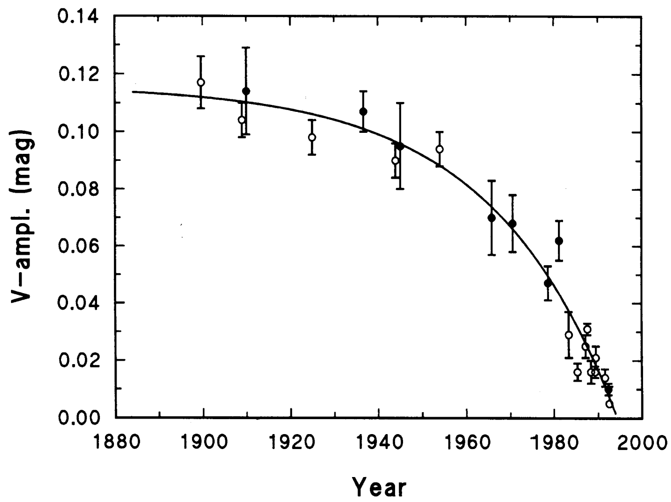

FIG. 2.—Declining amplitude of Polaris's pulsation through the twentieth century. *Filled circles*: photometric determinations; *open circles*: radial velocity determinations converted to their photometric equivalents by a conversion factor of 50. The curve has an exponential form and has been fitted by least-squares.

used a newly derived orbit with a period of 29.75 yr and a periastron at 1987.55 (K. W. Kamper, in preparation.) Then the remaining velocity variations were obtained for each of the nine data sets by fitting a simple sine wave with a period given by Arellano Ferro's ephemeris. Tests of our data, as well as of the Lick velocities (Roemer 1965) and of those from Dinshaw et al. (1989), had shown the second harmonic to be negligible (<0.1 km s^{-1}).

Figure 2 illustrates the changing V-magnitude amplitude of Polaris through the twentieth century. Closed circles are photometric determinations, and open circles are radial velocity amplitudes converted to V-magnitude amplitudes by $\Delta V = \Delta(\text{r.v. in km s}^{-1})/50$. Data sources other than this paper are listed in Table 4. Results determined by eye alone are not included since, as may be seen from Arellano Ferro's Figure 4, such visual observations are not at all reliable.

Arellano Ferro and Dinshaw et al. each concluded from their own versions of the diagram that the decline in amplitude set in suddenly around 1945 or later, while Kamper et al. found evidence against a sudden decline. The curve in Figure 2 is a least-squares fit to the points and has the equation

$$V_{\text{ampl}} = 0.116\{1 - \exp[-0.0355(1994.2 - \text{Year})]\} .$$

We suggest it fits the data as well as any other, and that its exponential form is physically the most likely. The curve predicts 1994 as the end of Polaris as a Cepheid, and that it has never had an amplitude exceeding 0.12 mag. There are no reliable pre–twentieth-century measures that we know of, but it seems almost certain that the amplitude could never have been as much as, say, 0.5 mag without some comment from the innumerable meridian-circle observers, navigators, and land surveyors who observed the star continually for centuries. Additionally, when Schmidt (1856) discovered the variability of Polaris from visual observations beginning in 1843 he reported it as being "weak." (He does not give the original observations and his smoothed data are not useful today, having been smoothed after his decision that the period was 1 year.) We conclude that such historical evidence as there is does not contradict an amplitude of 0.12 mag.

With the data available to him at the time, Arellano Ferro suggested that Polaris might bear some resemblance to V473 Lyr (HR 7308), a 1.5 day classical Cepheid whose amplitude steadily rises and falls by a factor of 15 on a time scale of nearly 4 yr (Burki et al. 1986.) Our data, however, give no hint of Polaris' amplitude flattening out toward a minimum prior to again rising; the plunge toward zero seems irrevocable.

RU Cam is another Cepheid that went from an amplitude of about 1 mag to near zero in only 4 yr (Demers & Fernie 1966), but it is a Population II star with peculiar spectral character-

TABLE 4

PREVIOUS AMPLITUDE DETERMINATIONS

Epoch	ΔV-Magnitude	RV or Photometry	Source
1899.65	0.117 ± 0.009	RV	Campbell 1899
1909.0	0.104 ± 0.006	RV	Roemer 1965
1910.0	0.114 ± 0.015	Ph	Hertzsprung 1911
1925.0	0.098 ± 0.006	RV	Roemer 1965
1936.67	0.107 ± 0.007	Ph	Stebbins & Whitford 1938
1944.0	0.090 ± 0.006	RV	Roemer 1965
1945.09	0.095 ± 0.015	Ph	Stebbins 1946
1954.0	0.094 ± 0.006	RV	Roemer 1965
1965.89	0.070 ± 0.013	Ph	Fernie 1966
1970.62	0.068 ± 0.010	Ph	Feltz & McNamara 1980
1978.68	0.047 ± 0.006	Ph	Henden 1980
1981.27	0.062 ± 0.007	Ph	Arellano Ferro 1983
1983.39	0.029 ± 0.008	RV	Kamper et al. 1984
1987.61	0.031 ± 0.002	RV	Dinshaw et al. 1989

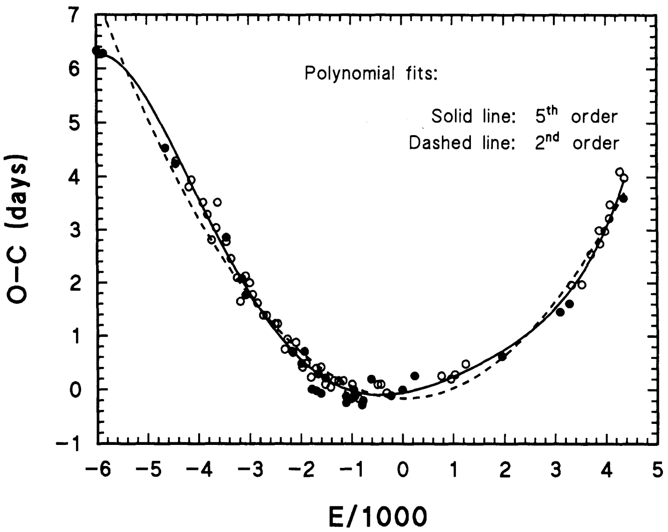

FIG. 3.—O-C diagram of Polaris brought up to date. *Filled circles*: photometric determinations; *open circles*: from radial velocities. The departure from a true parabola (*dashed line*) is slight and, as argued in the text, no cause for concluding that anything other than evolutionary factors are responsible.

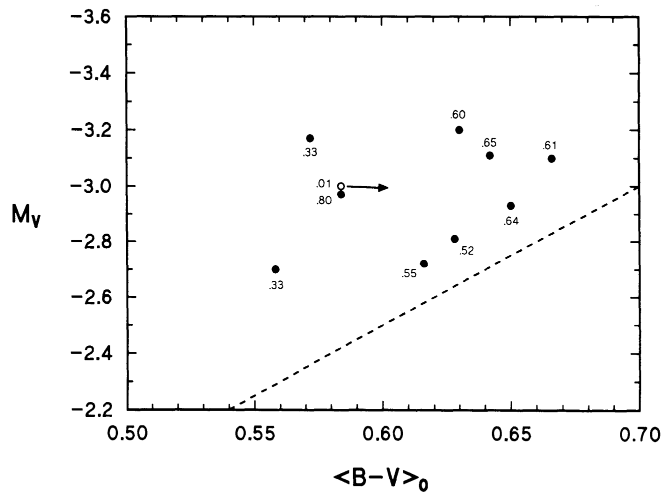

FIG. 4.—HR diagram in the immediate vicinity of Polaris (*open circle*.) The arrow indicates the predicted direction of its evolution, and the dashed line is the empirical red edge of the instability strip. The blue edge is off the top, left of the diagram. Numbers next to each point give that Cepheid's amplitude of pulsation in V-magnitudes. Note RT Aur with a 0.80 mag amplitude, slightly offset in the figure, but in fact essentially coincident with Polaris.

istics, and sputtered back to irregular variability a few years later. It is no match to Polaris, but is a reminder that the latter should in the future be checked for any return of its variability. Meanwhile, it seems destined to become the first incontrovertible case of a nonvariable star in the Cepheid instability strip.

4. THE O-C DIAGRAM

Figure 3 updates the O-C diagram of Polaris. The new data show a return of the point distribution to a more nearly parabolic form than had seemed the case at the time of Arellano Ferro's work. Even so, a fifth-order polynomial is required to achieve an adequate fit. Fernie (1990a) has argued that such departures from a strictly parabolic form do not necessarily vitiate an interpretation based on stellar evolution, and we believe that the most natural interpretation of Polaris's O-C diagram is that its increasing period is caused by evolution redwards in the H-R diagram.

5. POLARIS AND THE INSTABILITY STRIP

An increasing period implies that Polaris is evolving redwards in the HR diagram. This, coupled with the diminishing amplitude, has led most recent writers on Polaris to suggest that the star is crossing the red edge of the instability strip into the domain of nonvariability. We wish to point out that the evidence is against this. Figure 4 shows the HR diagram in the immediate vicinity of Polaris as taken from the more extended HR diagram in Figure 6 of Fernie (1990b). The dashed line is the empirical red edge of the instability strip, Polaris is the open circle, and the arrow shows its direction of evolution based on the models of Bertelli et al. (1986). Clearly, Polaris has quite some way to evolve before reaching the red edge of the strip. Moreover, between it and the red edge are to be found a number of Cepheids with amplitudes over half a magnitude (the numbers next to the points in the diagram.)

Most striking, however, is the existence of RT Aur, which has $P = 3.73$ days, $\langle B-V \rangle_0 = 0.584$, as compared to Polaris' values of 3.97 and 0.584. Both stars are naked-eye objects and very well studied, with very low reddenings of 0.051 and 0.000, respectively. Thus by any period-luminosity-color relation of choice, the two stars are coincident in the HR diagram to within about 0.01 mag in M_V. (Their points in Figure 4 have been slightly offset to show the presence of both.) Yet RT Aur has an amplitude of 0.80 mag in V compared to Polaris's 0.01! The only other difference we have noted is that while Polaris shows a period change, none is discernible for RT Aur. However, a plot of amplitude versus rate of period change for shorter-period Cepheids showing a period change reveals no correlation, so this difference is probably not significant.

There is at least one other case of an extremely low-amplitude variable in the instability strip: Butler (1992) has found at γ Cyg is most likely an 11.9 day Cepheid with a radial velocity amplitude of 0.20 km s^{-1} ($\Rightarrow$ 0.004 mag in V). Placed on the HR diagram it would, like Polaris, be surrounded by Cepheids of much higher amplitude. In any case, Fernie (1990b) found almost no correlation of Cepheid amplitudes with color across the instability strip. It seems that we simply do not know what sets a Cepheid's amplitude of pulsation.

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