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POLARIS THE CEPHEID RETURNS: 4.5 YEARS OF MONITORING FROM GROUND AND SPACE

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ABSTRACT

We present the analysis of 4.5 years of nearly continuous observations of the classical Cepheid Polaris, which comprise the most precise data available for this star. We have made spectroscopic measurements from ground and photometric measurements from the WIRE star tracker and the SMEI instrument on the *Coriolis* satellite. Measurements of the amplitude of the dominant oscillation ($P = 4$ days), which go back more than a century, show a *decrease* from $A_V = 120$ to 30 mmag around the turn of the millennium. It has been speculated that the reason for the decrease in amplitude is the evolution of Polaris toward the edge of the instability strip. However, our new data reveal an *increase* in the amplitude by ∼30% from 2003 to 2006. It now appears that the amplitude change is cyclic rather than monotonic and most likely the result of a pulsation phenomenon. In addition, previous radial velocity campaigns have claimed the detection of long-period variation in Polaris ($P > 40$ days). Our radial velocity data are more precise than previous data sets, and we find no evidence for additional variation for periods in the range 3–50 days with an upper limit of 100 m s^{-1}. However, in the WIRE data we find evidence of variation on timescales of 2–6 days, which we interpret as being due to granulation.

Subject headings: Cepheids — stars: individual (HD 8890, Polaris)

Online material: color figures, machine-readable table

1. INTRODUCTION

In addition to being arguably the most famous and in practice useful star other than the Sun, Polaris has a number of properties that may provide insights that are important to stellar astrophysics. It is the nearest and brightest classical Cepheid, oscillating in a single mode of pulsation with a period around 4 days. The *Hipparcos* parallax constrains its luminosity and allowed Feast & Catchpole (1997) to argue that the mode of pulsation must be the first overtone, which is upheld by the recent reevaluation of the *Hipparcos* data (van Leeuwen et al. 2007). As discussed by Evans et al. (2002), Polaris has a number of unusual pulsation properties, including a very small pulsation amplitude, and similar to other overtone pulsators, it has a rapid period change. It has been clear from studies as far back as Parenago (1956) and Szabados (1977) that overtone pulsators ("s Cepheids" as they were then called) had rapid period changes, more rapid than can be explained by evolution during a second or third crossing of the instability strip.

It was found by Arellano Ferro (1983) that the main period of Polaris is increasing (316 s per century) and that its peak-to-peak amplitude has decreased significantly, from about 140 to 70 mmag (Johnson *B* filter), based on photoelectric measurements collected in the period 1930–1980. Kamper & Fernie (1998) analyzed radial velocity measurements from 1900 to 1998 and could confirm the decrease in amplitude. However, their radial velocity data from the end of the period showed that the decrease had apparently stopped. Turner et al. (2005) analyzed both radial velocity and photometry data and found evidence for a sudden change in oscillation period around 1963–1966, and that the amplitude change became steeper at the same time.

Our aim is to shed light on the properties of the oscillation of Polaris, based on the analysis of a nearly continuous data set spanning 4.5 years. We have photometry from two satellite missions and simultaneous spectroscopic monitoring from the ground, each data set being superior to previous data available for Polaris.

2. OBSERVATIONS AND DATA REDUCTION

Polaris (α Ursae Minoris) was observed with the star tracker on the Wide-field InfraRed Explorer (WIRE; Bruntt 2007) satellite in 2004 January and February, 2004 July, and 2005 February. These runs lasted about 4, 3, and 2 weeks, respectively. In addition, Polaris was monitored using 3.8 years of nearly continuous photometry from the SMEI instrument on the *Coriolis* satellite. These observations were obtained between 2003 April and the end of 2006. We further used the 2 m Tennessee State University Automatic Spectroscopic Telescope (AST; Eaton & Williamson 2004, 2007) to collect 517 high-dispersion spectra of Polaris over a period of 3.8 years, from late 2003 to late 2007. A log of the photometric and radial velocity observations is given in Table 1. We also list data sets from two previous radial velocity campaigns that we have used for comparison in our analysis in § 5 (D89: Dinshaw et al. 1989; H00: Hatzes & Cochran 2000).

The complete photometric light curve from SMEI and WIRE and the radial velocity data from AST are shown in the top panel of Figure 1. Note that different units for the photometry (mmag) and velocities (km s^{-1}) are given on the left and right abscissas, respectively. The right abscissa is adjusted by the ratio of the measured amplitudes in the AST spectroscopy and the SMEI photometry. The bottom panel of Figure 1 shows the details of the variation during 40 days. It shows the last run done with WIRE and illustrates the typical coverage with SMEI and the AST. The

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TABLE 1
Observing Log

Source	Date Start	Date End	T_{obs} (days)	Data Points	σ
WIRE	2004 Jan 17	2004 Feb 15	29.0	41 162	0.88
WIRE	2004 Jul 10	2004 Jul 30	20.2	33 937	0.30
WIRE	2005 Jan 31	2005 Feb 12	12.6	14 240	0.29
SMEI	2003 Apr 6	2006 Dec 31	1365.4	13 543	6.4
AST	2003 Dec 25	2007 Oct 26	1401.0	517	0.15
D89............	1987 May 6	1988 Jan 3	241.0	175	0.44
H00............	1991 Nov 21	1993 Aug 2	640.4	42	0.07

Note.—The point-to-point scatter, σ, is given in mmag (WIRE+SMEI photometry) and km s^{-1} (spectroscopy).

thick gray curve is the fit of a single sinusoid to the complete SMEI data set.

The WIRE data set consists of about 3 million CCD stamps extracted from the 512×512 CCD SITe star tracker camera. Each window is 8×8 pixels, and we carried out aperture photometry using the pipeline described by Bruntt et al. (2005). The resulting point-to-point scatter range from 0.3 to 0.9 mmag (see Table 1). The noise is somewhat higher than the Poisson noise; for example, the high noise in the first WIRE data set is due to a high background sky level.

Data from the AST consist of echelle spectra covering the wavelength range 5000–7100 Å at a resolution of about 30,000. The velocities are derived from the correlation between the observed spectrum and a list of 74 mostly Fe I lines. More details about the pipeline used to extract the radial velocities are given by Eaton & Williamson (2007). We find that the velocities deviate slightly from the IAU velocity system ($\Delta v = -0.35 \pm 0.09$ km s^{-1}). The drift of the velocities due to the motion of Polaris in its binary orbit (Kamper 1996) was subtracted before the time series analysis was carried out.

The Solar Mass Ejection Imager (SMEI; Eyles et al. 2003; Jackson et al. 2004) is a set of three cameras mounted on the side of the *Coriolis* satellite. Each camera covers a $3^\circ \times 60^\circ$ strip of sky, and this is projected onto 1260×40 pixels of a CCD. As the nadir-pointing satellite orbits every 101 minutes in its Sun-synchronous polar orbit the cameras take continuous 4 s exposures, which result in roughly 4500 images per orbit covering most of the sky. After bias and dark removal and flat-fielding processing, the pixels about the target star are selected from about 10 images that contain the star for each orbit. These pixels are then aligned and a standard PSF is fitted by least-squares. Thus, the result is one brightness measure every 101 minutes. There are problems with particle hits and a complex PSF, which shows temporal variations that are not fully understood. The short-term ($t < 1.0$ days) accuracies are of the order of a few mmag, but there are longer term systematic errors of the order of 10 mmag on the timescales of days and months, which are not yet well understood. Allowing for time allocated for calibrations and satellite operation, a time coverage of about 85% was maintained.

3. PERIOD CHANGE OF THE MAIN MODE

Observed epochs of maximum light in Polaris, spanning more than a century, have indicated a significant change in period (Arellano Ferro 1983; Fernie et al. 1993; Turner et al. 2005). These studies have considered $O - C$ diagrams[7] and fitted a parabola, which is equivalent to assuming the period changes linearly with time. We have combined new measured epochs with those from Turner et al. (2005). A sudden change in the period has been noted in the 1960s, and therefore we have only used epochs observed since 1965.

We measured 223 and 16 epochs of maximum light in the SMEI and WIRE data sets, respectively. From the $O - C$ analysis by Arellano Ferro (1983) we expected the period to decrease by 14 s over the 4.5 year time span of our data set. Thus, when predicting the epochs of maximum light we could safely assume a constant period. The epochs were predicted by fitting a single sinusoid to the SMEI data. The fit is of the form $S(t) = A \sin\{2\pi[f(t - t_0) + \phi]\}$, where A is the amplitude,[8] t is the time

[7] $O - C$ diagrams display observed times of maximum light minus calculated times, assuming a constant period, plotted vs. time.

[8] Previous studies on Polaris have used peak-to-peak amplitudes. We use amplitudes unless otherwise specified.

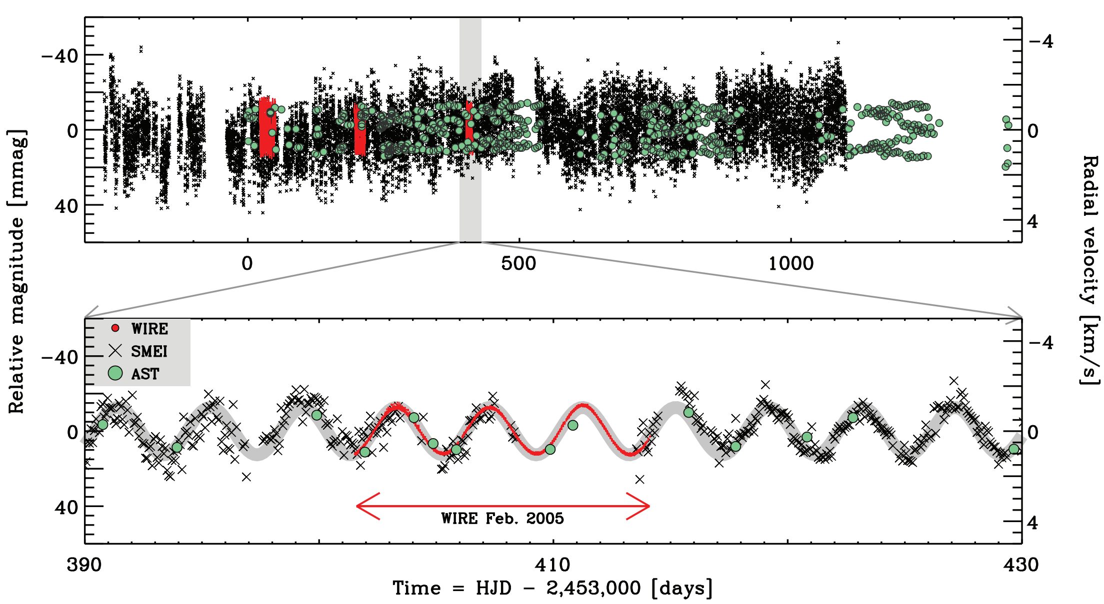

Fig. 1.—Photometry data sets from SMEI and WIRE and the radial velocities from AST. The bottom panel is an expanded view of 40 days of observations surrounding the last run with WIRE. The thick gray curve is the fit of a single sinusoid to the SMEI data.

TABLE 2
Times of Maximum Light in the SMEI and WIRE Data Sets

t_E (HJD −2,453,000)	Epoch	Source
391.327	6329	SMEI
395.339	6330	SMEI
399.387	6331	SMEI
403.323	6332	WIRE
407.274	6333	WIRE
411.262	6334	WIRE
415.418	6335	SMEI
419.160	6336	SMEI
423.215	6337	SMEI
427.152	6338	SMEI

Note.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

(Heliocentric Julian Date), t_0 is the zero point, $P = 1/f$ is the period, and ϕ is the phase. The result is $P = 3.972111 \pm 0.000054$ days and phase $\phi = 0.2158 \pm 0.0022$ for the zero point $t_0 = 2,530,000$. This fit is shown with a thick gray line in the bottom panel of Figure 1. The uncertainties were determined from simulations as discussed in § 4.1.

At each epoch, E, we selected all data points within half a period ($|t - EP| < P/2$). For the SMEI data we required that at least 30 data points were available with at least 10 data points before and after the maximum. To estimate the time of maximum light, we fitted these data with a sinusoid with fixed frequency and amplitude, while the phase was a free parameter. In Table 2 we list these times, including the epoch number following the definition by Turner et al. (2005) and the source of the data. The complete table is available in the electronic edition of the Journal, while the times listed in the print version correspond to the time interval covered in the bottom panel of Figure 1.

Since the quality of the three data sets are very different, we computed weights based on the uncertainty of the epoch times, t_E. This was determined by calculating the point-to-point scatter after subtracting a parabola fitted to the $O - C$ data of each data set. The uncertainty on t_E from Turner et al. (2005) is $\sigma(t_E) = 0.18$ days, while for SMEI and WIRE data the uncertainties are 0.12 and 0.014 days. Finally, we calculate the $O - C$ values using weights, $1/\sigma^2(t_E)$, and the most accurate value of the period, which is the one from SMEI: $O - C = (t_E - t_0) - (E - E_0)P_{\rm SMEI}$. We chose the reference epoch to be $E_0 = 6333$, and using the fit to the SMEI data found above, this corresponds to the time $t_0 = 2,453,407.277 \pm 0.009$.

Our final $O - C$ diagram is shown in Figure 2. The recent data continue to match the smooth period change as indicated by the weighted parabolic fit, corresponding to a period increase of $dP/dt = 365 \pm 27$ s century^{-1}. We note that the most recent SMEI data lie systematically below the fit, which is tightly constrained by the extremely well defined times from WIRE. Note that if we only use data more recent than 1985, we conclude that the period has not changed, i.e., $dP/dt = -19 \pm 95$ s century^{-1}.

4. AMPLITUDE CHANGE OF THE MAIN MODE

To analyze the time series in the frequency domain, we calculated the Fourier amplitude spectra for each data set. In the top panels of Figure 3 we show the amplitude spectra for the photometry from the WIRE (*red*) and SMEI (*green*) and the radial velocities from AST (*black*). The inset shows the prominent peak around 0.25 cycles day^{-1}, corresponding to the known 4 day period. Due to the long gaps between the three WIRE data sets, the spectral window shows a more complex pattern than the nearly continuous data sets from SMEI and AST.

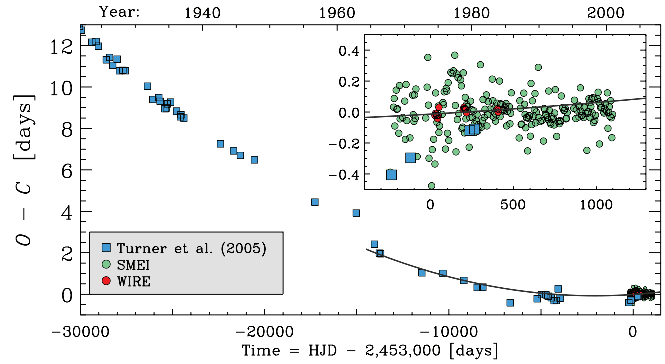

Fig. 2.—$O - C$ diagram. The solid line is a fit to the data taken after 1965. The inset shows the details of the new $O - C$ data from SMEI and WIRE.

We fitted a single sinusoid to the dominant peak, and the results for each data set are given in Table 3. We list the phase of the WIRE, SMEI, and AST data sets, relative to the zero point $t_0 = 2,453,000$. It is seen that the frequencies are in very good agreement. Although the point-to-point precision of the WIRE data is superior, the long span of the SMEI and AST data sets means the frequency is determined more accurately by a factor of 3–4. We also note that the phases from the fit to the SMEI and WIRE photometry are in good agreement, but the phase of the fit to the AST data is quite different. This corresponds to a shift in the times of maximum in the flux and radial velocity: HJD $(F_{\rm max}) = {\rm HJD}(RV_{\rm max}) + (1.744 \pm 0.016$ days). In comparison, Moskalik & Ogłoza (2000) found the offset to be 1.682 ± 0.017 days using combined photometry and radial velocity data from Kamper & Fernie (1998). The shifts appear to be marginally different (2.7 σ), but we note that the combined Kamper & Fernie (1998) data are calibrated to Johnson V, while SMEI has a filter response roughly centered at Johnson R but is wider (Tarrant et al. 2007).

We have subtracted the main oscillation mode, and the residual amplitude spectra are shown in the bottom panel of Figure 3. All spectra show a higher amplitude toward lower frequencies. This could be due to either instrumental drift or long-period variation intrinsic to Polaris, which we discuss in § 5. The left inset shows that the peaks in the SMEI data do not coincide with peaks in the AST data, so we cannot claim that they are due to coherent pulsations. The right inset shows the details around 0.25 c day^{-1}, where two significant residual peaks are seen in the SMEI and AST data sets. They are an indication that the frequency, amplitude, or phase of the oscillation has changed during the ∼4 years of observation.

To test the possible change in either frequency, amplitude, or phase of the main mode, we divided the data sets into subsets. Each of the SMEI and AST subsets contain 30 pulsation cycles, and the three WIRE data sets were analyzed independently. Each subset is fitted by a single sinusoid, and we analyzed the output parameters. We made the analysis for two different assumptions:

1. We assumed that the frequency, amplitude, and phase change with time, so each is a free parameter.
2. We assumed that only the amplitude changes with time, so the frequency and phase were held fixed.

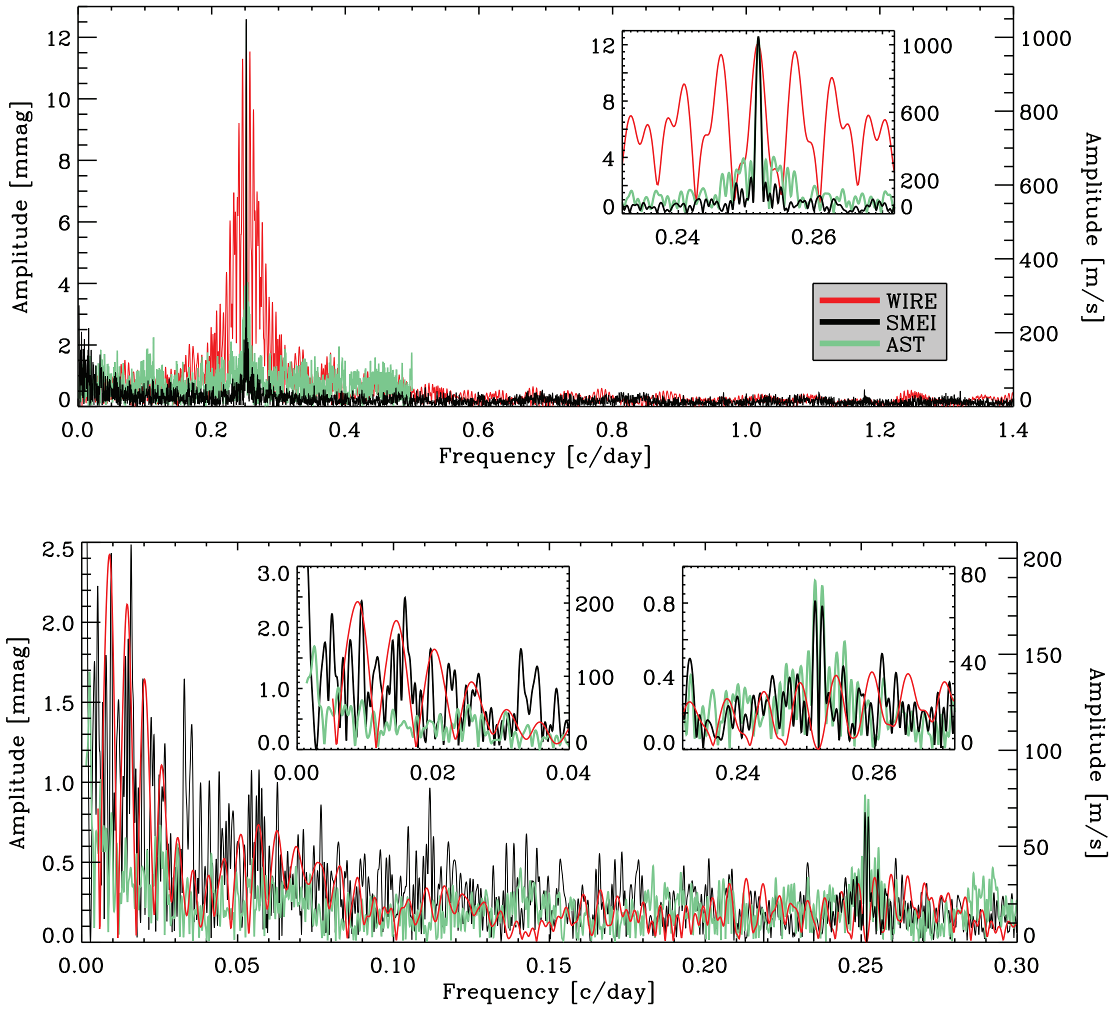

FIG. 3.—Amplitude spectra of the AST radial velocity data and the photometric data from SMEI and WIRE. The top panel is for the raw data, and the bottom panel is after subtracting the main mode at $\simeq$0.25 c day^{-1}. The insets show details of the amplitude spectra.

The first assumption allowed us to test the stability of the mode. We found that within the uncertainties both the frequency and phase do not change over the time span of the observations. However, the amplitude increases monotonically, and this result is confirmed by the analysis under the second assumption. A comparison of the measured amplitudes under the two assumptions gives nearly identical amplitudes for all subsets.

In Figure 4 we show the result obtained under the second assumption, i.e., for fixed frequency and phase. The cross symbols are the SMEI data, the filled circles are the AST data, and small dots are for the three WIRE runs. The dashed line is a weighted linear fit to the SMEI data yielding the amplitude change in mmag: $A_{\rm phot}(t) = (10.94 \pm 0.08) + (2.56 \pm 0.13) \times 10^{-3}(t - t_0)$, where t is the HJD with zero point $t_0 = 2,453,000$. The weighted fit to the AST data (*solid line*) gives $A_{\rm RV}(t) = (0.90 \pm 0.01) + (1.45 \pm 0.15) \times 10^{-4}(t - t_0)$ km s^{-1}. From this analysis we find that from 2003 to 2007 the amplitude measured in flux and radial velocity has increased by 34% $\pm$ 2% and 24% $\pm$ 3%, respectively. The single mode in Polaris has very low amplitude, and from linear theory it is expected that the rate of increase is the same in photometry and radial velocity. The measured increase over 4 years is only marginally different (8.1% $\pm$ 3.1%, or 2.6 σ), and continued monitoring is required to confirm this tentative result.

TABLE 3
RESULTS OF THE FREQUENCY ANALYSIS FOR THE FIVE DATA SETS

Source	f (c day^{-1})	a (mmag or km^{-1} s^{-1})	ϕ (0 to 1)
WIRE	0.251732(14)	12.26(18)	0.2195(34)
SMEI	0.2517553(34)	12.63(13)	0.2158(22)
AST	0.2517506(43)	0.998(14)	0.1550(34)
D89	0.25174(14)	0.808(58)	. . .
H00	0.251722(22)	0.781(22)	. . .

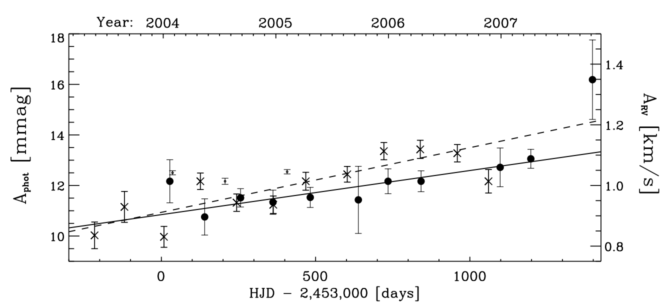

FIG. 4.—Increase in the amplitude of the 4 day main mode measured over 4.5 years with WIRE (*small dots*), SMEI (*crosses*), and AST (*filled circles*). [*See the electronic edition of the Journal for a color version of this figure.*]

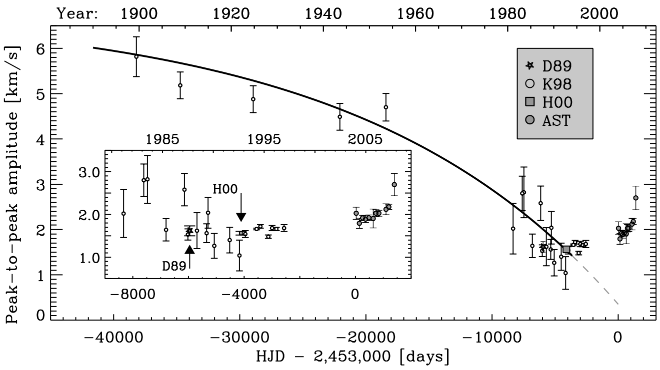

Fig. 5.— Peak-to-peak radial velocity amplitude for the main 4 day mode. The solid line is the fit from Kamper & Fernie (1998). The inset shows the most recent data in detail. Our measurements of the amplitude based on the Dinshaw et al. (1989) and Hatzes & Cochran (2000) are marked by arrows. [*See the electronic edition of the Journal for a color version of this figure.*]

In Figure 5 the measured peak-to-peak amplitudes in radial velocity from AST are compared with results from the literature. Kamper & Fernie (1998) found a monotonic decrease in the amplitude over the past 100 years.[9] To avoid confusion about the conversion factor, we compare our results directly in radial velocity, and we have reproduced their fit as the solid black line. The dashed line is an extrapolation, and as noted by Kamper & Fernie (1998) zero amplitude would be predicted in the year 2007. However, from 4 years of monitoring (1993.15–1996.96) in radial velocity, Kamper & Fernie (1998) found that the peak-to-peak amplitude was nearly constant. This is in agreement with the amplitudes we find from the analysis (see § 5.1) of the data sets by Dinshaw et al. (1989) and Hatzes & Cochran (2000). From the most recent high-precision data, it is evident that the amplitude in Polaris was constant in the period 1987–1997, while the increase we report here marks a new era in the evolution of Polaris.

4.1. *Uncertainties in Frequency, Amplitude, and Phase*

The uncertainties in the frequency, amplitude, and phase in Table 3 are determined from realistic simulations of each data set. The times of observation are taken from the observations and the simulations take into account the increase in noise toward low frequencies. We used the approach described by Bruntt et al. (2007, their Appendix B) to make 100 simulations of each data set, and the uncertainties are the rms value on the extracted frequency, amplitude, and phase.

We made simulations of the WIRE, SMEI, and AST data sets and also the radial velocity data sets from Dinshaw et al. (1989) and Hatzes & Cochran (2000), which we use for comparison in § 5.1. In all cases the uncertainties are somewhat higher than theoretical estimates that assume the noise to be white (Montgomery & O'Donoghue 1999). This is especially the case for the WIRE photometry due to low-amplitude variation on timescales comparable to the 4 day period, as will be discussed in § 5.2.

5. EVIDENCE FOR ADDITIONAL INTRINSIC VARIATION

In the following we will look at the evidence for variation in Polaris beyond the 4 day main mode. The analysis is based on the AST and WIRE data sets and data from two previous radial velocity campaigns. The AST data set is the most accurate at low frequencies and can be used to look for long periods (§ 5.1). The WIRE data set consists of three week-long runs with very high precision and can be used to study low-amplitude variation (§ 5.2). The noise in the SMEI data set is distinctly nonwhite, as mentioned briefly in § 2. Therefore, we did not use this data set in the following investigations, except for the subtraction of the 4 day mode, where SMEI provides the most accurate frequency and phase.

5.1. *Long-Period Variation*

In addition to the 4 day mode, a few studies have claimed variation at long periods, e.g., $P = 9.75$ days (Kamper et al. 1984), 45.3 ± 0.2 days (Dinshaw et al. 1989), and 40.2 ± 0.7 and 17.2 days (Hatzes & Cochran 2000). To confirm these claims we reanalyzed the original data sets of Dinshaw et al. (1989) and Hatzes & Cochran (2000). The basic properties of these data sets are listed in Table 1.

In Figure 6 we compare the amplitude spectra of the spectroscopic data from AST, Dinshaw et al. (1989), and Hatzes & Cochran (2000) after subtracting the 4 day period and the long-period trend due to the binary orbit. The AST spectrum was calculated taking the amplitude increase into account (cf. § 4). As a result, the residual double peak seen at $\sim$0.252 cycles day^{-1} is no longer visible (cf. Fig. 6 with the bottom panel of Fig. 3). In the AST amplitude spectrum we see no significant peaks from 0.02 to 0.3 c day^{-1} ($P = 3$–50 days). We set an upper limit on the amplitude at 100 m s^{-1}, which is 4 times the average level in the amplitude spectrum in this frequency interval.

The data set by Hatzes & Cochran (2000) consists of 42 data points distributed unevenly over 640 days, providing a very complicated spectral window. The data set comprises very precise radial velocities collected with an iodine cell as a reference (rms residuals are 70 m s^{-1}). Hatzes & Cochran (2000) detected two peaks with almost equal amplitude at $f^{\rm A}_{\rm H00} = 0.0249$ and $f^{\rm B}_{\rm H00} = 0.0581$ c day^{-1}. In the amplitude spectrum in Figure 6 we find only one of these peaks to be significant ($f^{\rm B}_{\rm H00} = 0.05834 \pm 0.00014$ c day^{-1} with amplitude $A = 163 \pm 25$ m s^{-1}). We made 100 simulations of the data including this frequency, white noise, and a $1/f$ noise component consistent with the observations. The inserted $f^{\rm B}_{\rm H00}$ frequency was only recovered in 49 of the 100 simulations. Interestingly, in the other simulations the highest peaks were clustered close to $f^{\rm A}_{\rm H00}$ (0.025 ± 0.007 c day^{-1} with amplitude $A = 167 \pm 22$ m s^{-1}), indicating that the two peaks detected by Hatzes & Cochran (2000) are due to the complicated spectral window.

The data set by Dinshaw et al. (1989) comprises 175 velocities distributed over 241 days. The precision is 440 m s^{-1}, as estimated from the rms of the residuals after subtracting the 4 day mode. In addition to this mode, we detect a peak at 1.02199 ± 0.00024 c day^{-1} with strong aliases at ± 1 c day^{-1}. Dinshaw et al. (1989) found one of the alias peaks ($f_{\rm D89} = 0.0221 \pm 0.0001$ c day^{-1}) to be the highest and suggested that it was intrinsic to Polaris. We measure the amplitude to be $A = 0.542 \pm 0.067$ km s^{-1}, but such a strong signal is not seen in the more recent data set by Hatzes & Cochran (2000) or in any of our data sets (see Figs. 3 and 6). For these reasons we believe that this peak is a 1 c day^{-1} artifact, likely caused by instrumental drift in combination with the spectral window.

5.2. *Low-Amplitude Variation*

The residuals in the WIRE light curves, after having subtracted the 4 day period, are shown in Figure 7. The drifts seen in the WIRE light curves correspond to periods from 2 to 6 days,

[9] Kamper & Fernie (1998) converted their radial velocity amplitudes to photometric amplitudes using an empirical factor 50 km s^{-1} mag^{-1}. The ratio of the amplitudes measured in our radial velocity and the SMEI photometric data is $A_{\rm RV}/A_{\rm phot} = 79.0 \pm 1.4$ km s^{-1}. The reason for the value being higher is that the filter response of SMEI is roughly Johnson *R*, while Kamper & Fernie (1998) used Johnson *V*.

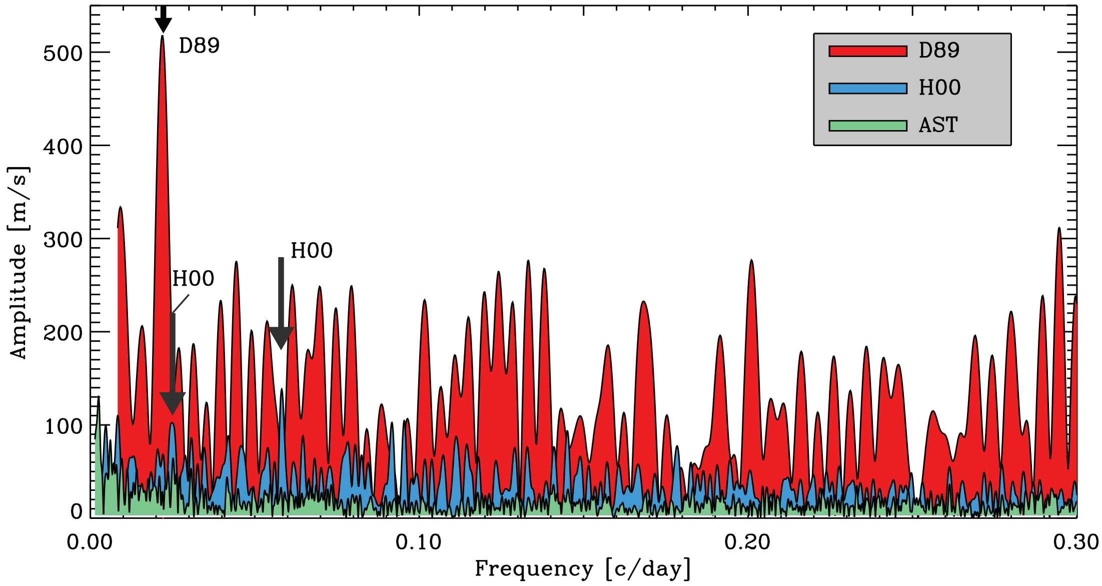

FIG. 6.—Residual amplitude spectra of the three radial velocity data sets from AST (*black*), Hatzes & Cochran (2000; *blue*), and Dinshaw et al. (1989; *red*). The low-frequency peaks claimed in the previous studies are marked by arrows.

i.e., similar to the 4 day main mode. Before interpreting this variation, it is important to investigate whether these variations are due to improper subtraction of the main period or due to instrumental drift.

To test the first caveat, we compared the residuals when subtracting the fit to the SMEI data and when subtracting fits to the individual WIRE data sets. We find that the residuals are quite similar, and the conclusions reached here are not affected by the adopted approach. In the following, we have used the most accurate value for the frequency and phase, which is from the fit of the main mode to the SMEI data, while we used the amplitudes fitted to the individual WIRE data sets.

The second caveat is instrumental drift, and we tested this by using a comparison star. During the observations with the WIRE star tracker four other stars were monitored on the same CCD. However, not all are suited as comparison stars: HD 5848 is a bright ($V = 4.3$) K giant star clearly showing solar-like oscillations (Stello et al. 2008). HD 51802 and HD 174878 are faint ($V = 5.1$ and 6.6) M giants showing variation with long periods. The only suitable comparison star is the A1 V star HD 166205 (δ UMi; $V = 4.4$). In Figure 7 we also show the light curve of this star with large filled circles. The star is 2 mag fainter than Polaris, so we binned the data collected within each orbit ($P_{\rm orbit} \simeq 93$ minutes) to be able to see any low-amplitude variation.

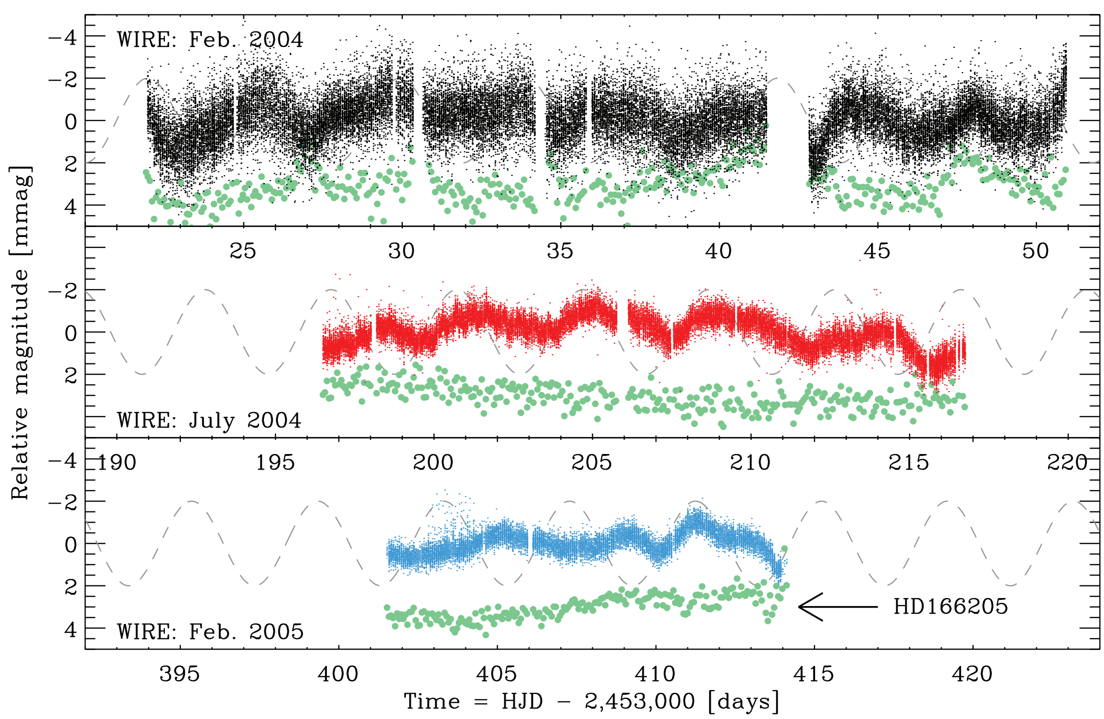

FIG. 7.—Residuals in the three WIRE light curves of Polaris and the comparison star HD 166205 (*large filled circles offset by* 3 mmag). The dashed curve is a sinusoid with the 4 day period and an amplitude set arbitrarily to 2 mmag.

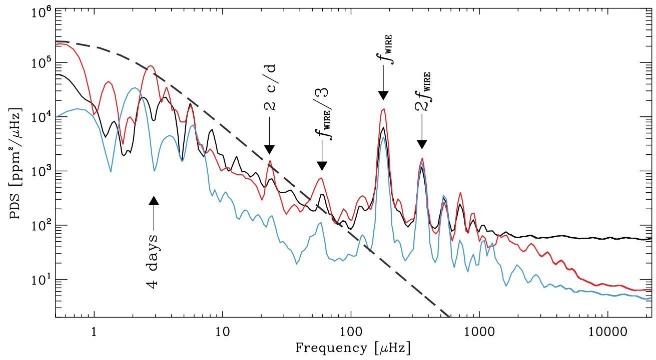

FIG. 8.—Power density spectrum (PDS) of the residual light curves from WIRE shown in Fig. 7. The dashed line is a scaling of the granulation measured in the Sun. The arrows mark the 4 day main period and frequencies that are due to the WIRE orbit.

The clear variation in the residuals of the WIRE photometry is not seen in the hot comparison star HD 166205. The fact that it is seen in three light curves obtained with WIRE at three different epochs spanning 1 year gives us some confidence that the signal is intrinsic to Polaris. We will discuss two possible explanations for the observed variation here, namely, granulation and star spots.

To investigate in detail how the variation in the WIRE light curves depends on frequency, we show their power density spectra (PDS) in Figure 8 in a logarithmic plot. The virtue of the PDS is that one can directly compare the properties of data sets, which have different temporal coverage and noise characteristics. Each PDS shows a clear increase from the white noise level around 10 mHz toward low frequencies. The arrows mark the harmonics of the orbital frequency of WIRE ($f_{\rm WIRE} = 178$ μHz), one-third of the WIRE orbital frequency, and 2 c day^{-1}. These frequencies are observed in almost all WIRE data sets and are due to a combination of a low duty cycle (typically 20%–40%) and scattered light from Earth shine. Also marked is the location of the 4 day mode ($f = 2.91$ μHz), which has been subtracted.

To see if granulation could explain the increase in the PDS toward low frequencies, we have used a scaling of the granulation observed in the Sun. This is based on *SOHO* VIRGO satellite observations of the Sun as a star, and the scaling is done in terms of both amplitude and timescale, following H. Kjeldsen & T. R. Bedding (2008, in preparation; see also Stello et al. 2007). This prediction is shown as the dashed line in Figure 8. This is a scaling over 3 orders of magnitude in luminosity from the Sun to the supergiant Polaris, so it is intriguing that the prediction of the granulation signal agrees with the observations within a factor of 3.0 ± 0.5 in amplitude.

Both Dinshaw et al. (1989) and Hatzes & Cochran (2000) discussed evidence for star spots on Polaris. We argue that this is not the cause of the observed variation in the WIRE data, since the timescale is only a few days. That would imply very rapid rotation, which is unlikely for such an evolved star.

6. DISCUSSION AND CONCLUSION

From 4.5 years of intensive monitoring of Polaris we find that the amplitude of the 4 day main mode has increased steadily by $\sim$30% in both radial velocity and flux amplitude. The rate of increase in the amplitude from 2003 to 2007 is slightly steeper than the decrease from the fit by Kamper & Fernie (1998) for the period 1980–1994. Other sources have also found a recent increase in the amplitude of Polaris (Engle et al. 2004; D. Turner 2007, private communication).

The result that the amplitude of Polaris is now increasing has implications for earlier explanations of the change in amplitude as a cessation of pulsation due to the Cepheid's evolution toward the edge of the instability strip. At the very least, whatever the process is, it is not a simple monotonic progression through the HR diagram, unless this stage of evolution is more complex than previously thought. The recovery of the amplitude suggests that the phenomenon is cyclic. As such, it is likely to be associated in some way with pulsation rather than with evolution.

A possible explanation for the increase in amplitude could be the beating of two closely spaced modes (Breger & Kolenberg 2006). To exhibit a beat period as long as the amplitude variation of Polaris (likely a few hundred years), the modes would have to be very closely spaced indeed. Among classical Cepheids, amplitude variation is extremely uncommon. The only case in which it is firmly established is in V473 Lyrae (Burki et al. 1986), where the variation occurs over only a few years. In RR Lyrae stars, the Blazhko effect is well known and thought to be the result of mode beating, although it is not completely understood. Since the amplitude changes in Polaris are well established, they require further observations and consideration theoretically to unravel the cause.

There are other interesting aspects to the main oscillation mode. The characterization of the period change is puzzling since analysis of $O - C$ diagrams spanning more than a century reveal that the period change is not linear. There may have been a "glitch" in both the period change and the amplitude in the mid-1960s (Turner et al. 2005), rather than smooth changes. We measured 239 epochs of maximum light, but the time span of the observations of 4.5 years is too short to investigate the period change. This is another aspect of the pulsation that demands further observation.

A few radial velocity campaigns have claimed the presence of additional long-period variations in Polaris. We have analyzed the original data sets by Dinshaw et al. (1989) and Hatzes & Cochran (2000), and we conclude that these long periods are likely spurious detections caused by instrumental drifts (Dinshaw et al. 1989) or insufficient data leading to a complicated spectral window (Hatzes & Cochran 2000). From our 3.8 years of monitoring with AST, we set an upper limit on the variation in radial velocity at 100 m s^{-1} for periods in the range 3–50 days (except for the 4 day main mode).

In the WIRE data we find evidence of low-amplitude variation (peak-to-peak 2 mmag) at timescales of 2–6 days, which are likely intrinsic to Polaris. We applied a simple scaling of observed solar values for the characteristic timescale and amplitude of the granulation. Although this is a scaling over 3 orders of magnitude in luminosity, the prediction agrees with the observed variation in Polaris within a factor of 3.0 ± 0.5. Thus, we conclude that the variation in the WIRE data could be due to granulation.

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