ABSTRACT

We present the first results of a long-term program of a radial velocity (RV) study of Cepheid Polaris (F7 Ib), with the aim of finding the amplitude and period of its pulsations and the nature of its secondary periodicities. A total of 264 new precise RV measurements were obtained during 2004–2007 with the fiber-fed echelle spectrograph Bohyunsan Observatory Echelle Spectrograph (BOES) of the 1.8 m telescope at Bohyunsan Optical Astronomy Observatory (BOAO) in Korea. We find a pulsational RV amplitude and period of Polaris for the three seasons 2005.183, 2006.360, and 2007.349 as $2K = 2.210 \pm 0.048$ km s$^{-1}$, $2K = 2.080 \pm 0.042$ km s$^{-1}$, and $2K = 2.406 \pm 0.018$ km s$^{-1}$ respectively, indicating that the pulsational amplitudes of Polaris that had decayed during the last century are now increasing rapidly. The pulsational period was also found to be increasing. This is the first detection of a historical turnaround of a pulsational amplitude change in the Cepheids. We clearly find the presence of additional RV variations on a timescale of about 119 days and an amplitude of about $\pm 138$ m s$^{-1}$, which is quasi-periodic rather than strictly periodic. From our data, we do not confirm the presence of the variation on a timescale of 34–45 days found in the RV data obtained in the 1980s and 1990s. We assume that both the 119 day quasi-periodic, noncoherent variations found in our data and the 34–45 day variations found previously can be caused by the 119 day rotation periods of Polaris and by surface inhomogeneities such as single- or multiple-spot configuration varying with time.

Key words: Cepheids – stars: individual (Polaris, Alpha Ursae Minoris) – techniques: radial velocities

1. INTRODUCTION

Polaris (α UMi, HIP 11767, HD 8890, HR 724) is one of the most famous Cepheid variable stars. In addition to its special location on the celestial sphere, Polaris has many interesting astrophysical features. It is a member of a triple system, and it is the brightest and closest Cepheid variable with very low pulsational amplitude. It has been extensively studied over one and a half centuries for pulsational amplitude and period changes using photometric and spectroscopic observations. Perhaps the most remarkable feature of Polaris as a Cepheid variable is that the period and amplitude of pulsation changes very rapidly. The pulsation period rapidly increases at a rate of about 4.5 s yr$^{-1}$ (Turner et al. 2005 and references therein). More interesting is the change of amplitude. It has been discovered that the pulsational amplitude has been decreasing dramatically during the 20th century (Arellano Ferro 1983; Dinshaw et al. 1989). So it was predicted that the pulsation of Polaris would completely stop by the end of the century. However, Kamper & Fernie (1998) noted that the decline in the radial velocity (RV) amplitude had stopped abruptly. Figure 5 of Hatzes & Cochran (2000) shows the increase of amplitude, but they did not state this explicitly. Some recent photometric observations also indicate the same trend in the amplitude (Davis et al. 2002; Engle et al. 2004).

2. OBSERVATIONS AND DATA REDUCTION

The new RV observations of Polaris were carried out during 2004 November to 2007 June using the fiber-fed high-resolution ($R = 90,000$) echelle spectrograph Bohyunsan Observatory Echelle Spectrograph (BOES) (Kim et al. 2007) attached to the 1.8 m telescope at Bohyunsan Optical Astronomy Observatory (BOAO). Using a 2k × 4k CCD, the wavelength coverage of BOES is 3600–10500 Å with ~80 spectral orders in one exposure. Observations were acquired through an iodine absorption cell ($I_2$) to provide precise RV measurements. A total of $N = 264$ spectra were recorded; the exposure time varied from 60 to 300 s depending on the sky conditions to get a typical signal-to-noise ratio (S/N) of 250. The extraction of normalized 1D spectra was carried out using the Interactive Reduction and Analysis Facility (IRAF) (Tody 1986) software package. After extracting normalized 1D spectra, the RV measurements were undertaken using a code called RV12CELL (Han et al. 2007) which was developed at BOAO. RV12CELL adopts basically the same algorithm and procedures described by Butler et al. (1996). However, we model the instrument profile using the matrix formula described by Endl et al. (2000). We solved the matrix equation using singular value decomposition instead of the maximum entropy method adopted by Endl et al. (2000).

With these configurations, we achieved a typical internal RV accuracy between 10 and 15 m s$^{-1}$ depending on the quality of the spectra.

3. RESULTS

Figure 1 plots the relative RV measurements for the 2004–2007 season of observations. The solid line is a zero-point-adjusted trend for a binary orbit calculated according to the period of 29.59 years and orbital elements given by Wielen et al. (2000). To study pulsations, we first removed the RV variation due to orbital motion. Next, we applied the discrete Fourier transform (DFT) analysis for unequally spaced data to all de-trended 2004–2007 RV data. We used for analysis the computer code PERIOD04 (Lenz & Breger 2005). The top panel in Figure 2 shows the resulting DFT periodogram of all
data. We easily found a main frequency of \( f_1 = 0.251757 \pm 0.000008 \, \text{c d}^{-1} \) \((P_1 = 3.97208 \pm 0.00013 \, \text{days})\). The whole 2004–2007 data phase diagram of Polaris phased with this period is plotted in Figure 3. There are visible scatters, and two order values (near JD 2453902) exceed the accuracy of our individual RV measurements \((\sim 10 \, \text{m s}^{-1})\). This scatter seems to be due to additional intrinsic RV variations to the dominant pulsation mode, already known for Polaris (Dinshaw et al. 1989; Kamper 1996; Kamper & Fernie 1998; Hatzes & Cochran 2000).

We removed the best-fit sine-wave signal from the dominant period from the whole data string. The DFT analysis of RV residuals is shown in the second from top panel in Figure 2. The highest peak at \( f_2 = 0.00799 \pm 0.00010 \, \text{c d}^{-1} \) \((P_2' = 125.1 \pm 0.1 \, \text{days})\) has an amplitude of \(2K = 0.38 \pm 0.02 \, \text{km s}^{-1}\).

One might suspect that the secondary signal at \( f_2' \) found in our 2004–2007 data residuals is due to the removal of dominant pulsations with fixed amplitude and period which actually vary during this time interval. Here, our main concern is to estimate the amplitude and period of the dominant pulsations for short subsets as accurately as possible and remove them from RV variations in order to study possible residual signals. In determining the period and amplitude variation, the data were divided into three subsets: Set 1, Set 2, and Set 3. These subsets are marked in Figure 1. The RV data characteristics are given in the second, third, and fourth columns of Table 1. Then, for each data set, we tried to find the best-fit frequency and amplitude for a dominant pulsation. Figure 4 shows a dominant period fit to every subset of the data. The rms residuals after the sinusoidal fitting of Sets 1–3 are 111 m s\(^{-1}\), 149 m s\(^{-1}\), and 63 m s\(^{-1}\) respectively, much larger than the typical error of RV data, 10–15 m s\(^{-1}\). This is because there exists unmodeled RV variation in addition to the sinusoidal signal. Table 1 shows the result of the period analysis; periods and amplitudes of pulsations found for all three sets. We applied the same period analysis to the most recent RV data published for Polaris. The period and amplitude found during our re-analysis are also given in Table 1.

To study the additional variability, the residuals after removal of the best-fit dominant period and amplitude from each set were combined, resulting in the data string shown in Figure 5. As seen by eye, there is still very strong \( \sim \pm 350 \, \text{m s}^{-1} \) and about 120 days timescale variability. A steep rise of RV from negative to positive values and a rapid drop back to negative values can be seen in the shape of RV variability. This type of variability resembles closely the RV variations due to a contrast surface spot passing across the visible disk in some types (e.g., Ap) of stars. To get the accurate period, the DFT analysis was applied to the residual data. The DFT amplitude spectrum is shown in the third panel from the top panel in Figure 2. The largest

![Figure 1](image1.png)

**Figure 1.** RV measurements of Polaris during 2004–2007. The solid line shows the decline of orbital RVs within the interval of observations.

![Figure 2](image2.png)

**Figure 2.** The amplitude spectra of the DFT analysis for the entire RV measurements for Polaris. Left panel: (top) DFT of the original data. The largest peak is at \( f_1 = 0.251757 \, \text{c d}^{-1} \). (Second) DFT of RV residuals after removal of the contribution from \( f_1 \). The second peak is at \( f_2 = 0.00799 \, \text{c d}^{-1} \). (Third) DFT of the merged residual RV after removal of the best-fit \( f_1 \) contribution from individual subsets (Sets 1–3). The secondary peak is at \( f_2' = 0.00840 \, \text{c d}^{-1} \). (Bottom) DFT of the residuals after removal of \( f_1 \) and \( f_2' \). Right panel: (top) the amplitude spectrum of an artificial sine-wave signal having the same frequency, amplitude, and data point sampling as the dominant \( f_1 \) mode but co-added with normally distributed noise of amplitude 138 m s\(^{-1}\). (Bottom) DFT of the residual RV after removal of the contribution from \( f_1 \).
Figure 3. Entire RVs of Polaris de-trended for orbital variations. The solid line is a dominant period fit to every subset of the data.

| Data    | Mean epoch (duration) | Nσ  | Semi-amplitude (km s\(^{-1}\)) | Dominant period (days) | Period in residuals (days) |
|---------|------------------------|-----|---------------------------------|------------------------|-----------------------------|
| Dinshaw | 1987.674 (0.660)       | 174 | 0.661                           | 0.742 ± 0.068          | 3.97206 ± 0.00307           |
| Hatzes  | 1992.693 (1.698)       | 40  | 0.140                           | 0.755 ± 0.032          | 3.97212 ± 0.00056           |
| Kamper1 | 1994.492 (0.414)       | 71  | 0.098                           | 0.786 ± 0.017          | 3.97208 ± 0.00081           |
| Kamper2 | 1995.973 (1.249)       | 129 | 1.107                           | 0.825 ± 0.013          | 3.97200 ± 0.00029           |
| Set 1   | 2005.183 (0.575)       | 34  | 0.111                           | 1.105 ± 0.024          | 3.97300 ± 0.00080           |
| Set 2   | 2006.360 (0.870)       | 117 | 0.149                           | 1.040 ± 0.021          | 3.97284 ± 0.00047           |
| Set 3   | 2007.349 (0.168)       | 113 | 0.063                           | 1.203 ± 0.009          | 3.97394 ± 0.00098           |

Note. \(\sigma\) is rms residuals after main signal fitting.

138 ± 8 m s\(^{-1}\) peak is at \(f_2 = 0.00840 \pm 0.00003\) c d\(^{-1}\) (\(P_2 = 119.1\) days). The residual data phased to this period are shown in Figure 6. The DFT of residuals after removing the secondary periodicity is shown in the bottom panel of Figure 2; it does not show any significant peaks.

To check whether secondary periodicity may be due to an unrecognized aliasing problem and unfavorable time sampling of RV data (note that the strongest sidelobes of the spectral window function are 1 c d\(^{-1}\) equally spaced), we modeled the dominant mode pulsations by a mono-periodic sinusoidal signal having the same time sampling as the original Polaris RV data.
Note that the DFT of this mono-periodic signal is actually the spectral window function centered at $f_1$. We added to this mono-periodic signal the normally distributed noise with an amplitude of 138 m s$^{-1}$. The DFT analysis of these artificial data is shown in right panels (top and bottom) of Figure 6. As can be seen from the bottom panel, after removal of the artificial signal, the amplitude spectrum does not show any significant signal at 0.008 c d$^{-1}$, confirming that the secondary 119 day periodicity we found is not an artifact.

Figure 7 shows century-long variations of the pulsational amplitude and period of Polaris. As seen, our new data obtained for three subsets of our 2004–2007 observations reveal that, after a decade of standstill, the amplitude of pulsation now rapidly increases. We can now safely claim that the era of amplitude decrease of Polaris finished at the end of the 1980s and was replaced with a new, rapidly rising amplitude trend at the beginning of the 1990s.

4. DISCUSSIONS

A historical change of the sign of amplitude variations in Polaris, which we detected convincingly, does not yet have an analogy among other Cepheids. Polaris crosses the instability strip for the first time and lies well in its center for fundamental mode pulsators or well inside and near the hot bounds of the instability strip for first overtone pulsators (Turner et al. 2005). We suggest that the switching of the amplitude change from decay to growth found in our observation is not a direct result of evolution to a red border and the decrease of the efficiency of the excitation mechanism, but might be relevant to the unrecognized effect of mode interaction. We also confirm the increase of the pulsational period.

The detected long-term characteristic period of 119 days is much longer compared to the 9.75 days period of Kamper et al. (1984), 45.3 days of Dinshaw et al. (1989), 34.3 days of Kamper & Fernie (1998), or 40.2 days of Hatzes & Cochran (2000) reported in the 1980s and 1990s data. We do not confirm the existence of any of the aforementioned periods in our data. Dinshaw et al. (1989) argue that an approximately 45 day period, which is not coherent, arises from one or more surface features
on Polaris carried across the disk by rotation. Hatzes & Cochran (2000) have found very reliable bisector variations with the same period as in the RVs and re-discussed three mechanisms of the low-amplitude residual RV variations in Polaris: a low-mass companion, long-periodic nonradial stellar pulsations, or rotational modulation by surface features. They modeled the residual RV and bisector variations for all hypotheses—namely, the existence of a surface microturbulence, cool or hot spots and 45 day rotation period, or the $l = 4, m = 4$ nonradial mode pulsations and found a reliable RV amplitude fit for all of them. However, the bisector span velocity for all hypotheses had unmodeled phase shifts, indicating that none of these models completely satisfies the observations. Hatzes & Cochran (2000) concluded that among the hypotheses considered, the nonradial pulsations have better agreement with modeling.

In our work based on long-term high-precision RVs, we do not confirm any of the secondary periods found earlier, but clearly find a 119.1 day characteristic time of variation. This is the longest period of intrinsic variations of Polaris found so far.

Summarizing all previous investigations, we can claim that the secondary variations seen in Polaris are not coherent on long timescales, so we can firmly reject the first two hypotheses involving the companion and coherent non-radial pulsations. Note that a period of 119 days is too long compared to a period of fundamental mode pulsations of Polaris and cannot belong to normal acoustic modes.

We suggest two possible explanations of secondary RV variations.

1. The diversity in secondary periods found in Polaris is likely the result from the rotational modulation of RVs by single- or multiple-surface spots and assume that the rotation period is about 119 days. In the case of multiple spots, the observed periods of about 40 days or about 34 days are close to fractions of a 119 day period. The rotational velocity of Polaris is $\sin i = 8.4$ km s$^{-1}$ (Hatzes & Cochran, 2000). The radius of Polaris $33 \pm 2 R_\odot$ was found by Turner et al. (2005) from the distance to Polaris $94 \pm 4$ pc and the angular diameter $3.28 \pm 0.02$ mas given by Nordgren et al. (2000).

2. With these parameters and an assumed rotation period of 119 days, the equatorial rotation velocity $v_{\text{eq}} = 14$ km s$^{-1}$ which yields the inclination angle of the rotation axis $i = 38^\circ$. The projected rotational and expected equatorial velocities of Polaris are in quite good agreement with the determined mean-projected rotational velocities $v\sin i = 15.8 \pm 1.4$ km s$^{-1}$ of a sample of 11 F6-F7 Ib supergiants selected from the Ib supergiant list of De Medeiros et al. (2002).

3. We also cannot exclude that long-term cyclic variations of radial velocities of Polaris are the result of oscillatory variations of the mean radius of Polaris stochastically driven with a yet unrecognized physical mechanism. It is not excluded that such long-term, non-coherent and small radius variations are intrinsic to many F type supergiant stars and Cepheids, but in classical Cepheids they are hidden in a large amplitude of the dominant mode pulsations and have not been detected due to limited RV accuracy and sparse time sampling of RV curves in previous RV investigations. If this is true, Polaris might be the first Cepheid star with well-documented observational detection of such a modulation. Another good example might be the F5 Ib supergiant $\alpha$ Per which shows long-term (see Figure 1 in Hatzes & Cochran 1995) variations. The detailed comparative precise RV study of a sample of F-type supergiant stars including Cepheids can provide additional constraints on the nature of the long-term radius variations detected in Polaris.

Checking of the spot hypothesis and detailed analysis of line profile and surface temperature variations in Polaris-based BOES observations is beyond the scope of the current work, which is devoted to the study of pulsational amplitude of RVs, and will be presented in our next paper.

5. CONCLUSIONS

The first results of our long-term monitoring of Polaris show remarkable changes in the amplitude and the period of pulsations that occurred at the end of the 20th and the beginning of the 21st century. The half-century-long pulsational amplitude decay was replaced with a rapid amplitude growth while the growth of the pulsational period continues. We also detected a 119 day secondary RV variation which is about three times longer than previously reported secondary periodicities. We conclude that the 119 day variations are not coherent on long timescales and have discussed the possible nature of these variations.

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REFERENCES

Aretiano Ferro, A. 1983, Apj, 274, 755
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Davis, J. J., Tracey, J. C., Engle, S. G., & Guinan, E. F. 2002, BAAS, 34, 1296
De Medeiros, J. R., Udry, S., Burki, G., & Mayor, M. 2002, A&A, 395, 97
Dinshaw, N., Matthews, J. M., Walker, G. A. H., & Hill, G. M. 1989, AJ, 98, 2249
Endl, M., Kürster, M., & Els, S. 2000, A&A, 362, 585
Engle, S. C., Guinan, E. F., & Koch, R. H. 2004, BAAS, 36, 744
Fernie, J. D., Kamper, K. W., & Seager, S. 1993, Apj, 416, 820
Han, I., Kim, K.-M., & Lee, B.-C. 2007, Apj, 655, 1096
Hatzes, A. P., & Cochran, W. D. 1995, Apj, 416, 201
Hatzes, A. P., & Cochran, W. D. 2000, AJ, 120, 979
Kamper, K. W. 1996, JRASC, 90, 140
Kamper, K. W., Evans, N. R., & Lyons, R. W. 1984, JRASC, 78, 173
Kamper, K. W., & Fernie, J. D. 1998, AJ, 116, 936
Kim, K. M., et al. 2007, PASP, 119, 1052
Lenz, P., & Breger, M. 2005, Commun. Asteroseismol., 146, 53
Nordgren, T. E., Armstrong, J. T., German, M. E., Hindes, R. B., Hajian, A. R., Sudil, J. J., & Hummel, C. A. 2000, Apj, 543, 972
Roemer, E. 1965, Apj, 141, 1415
Tody, D. 1986, Proc. SPIE, 627, 733
Turner, D. G., Savoy, J., Derrah, J., Abdel-Saab, Abdel-Latif, M., & Berdnikov, L. N. 2005, PASP, 117, 207
Wiehl, R., Jahreiß, H., Dettbarn, C., Lenhardt, H., & Schwan, H. 2000, A&A, 360, 399