Polaris and its Kin

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ABSTRACT

A review is presented of the past 165 years of observation of the 4-day Cepheid Polaris, including the exciting results of the last 50 years, an interval that has produced three orbital solutions for the spectroscopic binary subsystem, recently resolved by HST, parameters for the optical companion, precise measurement of the star’s trigonometric parallax and angular diameter, evidence for a rapid increase in its pulsation period, and observations of the dramatic decline and recent partial recovery of its light amplitude. There has been considerable discussion about the exact nature of the star, with potential resolutions summarized here. It is also noted that many of the star’s characteristics are shared by a small number of other Cepheids that display rapid period increases identical to those predicted for stars in the first crossing of the instability strip, small light amplitudes, and intrinsic colors typical of variables lying near the center of the strip, where Cepheids of largest amplitude reside. While all members of the group appear to display the canonical traits of first crossers of the instability strip, Polaris has one unique peculiarity: a brief hiatus in its monotonic period increment between 1963 and 1966 during which the pulsation period underwent a dramatic decrease. Has the average brightness of the Cepheid also increased over the last millennium?

Subject headings: stars: binaries: general—stars: variables: Cepheids—stars: individual: Polaris

1. Introduction

Polaris (α UMi, spectral type = F7 Ib) is the nearest and brightest of ∼ 40 classical Cepheids detectable without optical aid (Turner et al. 2005), and possibly the most enigmatic. It has a pulsation period of 3d.97 and the second smallest light amplitude (Turner et al. 2009b). Its light variability was suspected by Seidel (1852) from measures he made using a Steinheil eyepiece photometer that were corrected for atmospheric extinction and had a precision of about ±0.05. The accuracy of measures made with the photometer is somewhat uncertain (Zissel 1998), and in any case awaited the full development of the magnitude scale. Variability was also suspected in visual comparisons of the star with β UMi made by Schmidt between 1843 and 1856 (1144 estimates, Schmidt 1857) and Pannekoek between 1890 and 1894 (510 estimates, Pannekoek 1913), but confirmation of the star’s light variations would await photographic observations by Hertzprung (1911), after the star’s 4-day cycle of radial velocity variability had been announced previously (Campbell 1899). The original light amplitude was very small, only ∼ 10%, which is why it remained unnoticed for so long. In the General Catalogue of Variable Stars it was listed as a Type II Cepheid as recently as 1970 (Kukarkin et al. 1970), although its metallicity (Usenko et al. 2005) and distance (see below) confirm it to be a classical Cepheid.

Polaris is a triple system (Kamper 1996; Evans et al. 2008) consisting of an unresolved F6 V dwarf, Polaris Ab, in a 30-year spectroscopic binary orbit and a F3 V dwarf (Polaris B) (Turner 1977; Evans et al. 2008), 18" distant, as a visual physical companion. Polaris has a precise Hipparcos parallax of π_{abs} = 7.72 ± 0.12 mas (van Leeuwen et al. 2007) that yields a distance of 130 ± 2 pc. The corresponding luminosity, \langle M_V \rangle = -3.62 ± 0.05, implies overtone
(OT) pulsation, consistent with the Cepheid's sinusoidal light curve. But there is no indication in Fourier analyses of photometric or radial velocity measures of a signal at the putative fundamental mode (FM) period of $5.7^d$ (Turner 2006; Spreckley & Stevens 2008; Bruntt et al. 2008), and a sinusoidal light curve may not always imply overtone pulsation (Sandage et al. 2004). Classification through Fourier parameterization is not necessarily reliable for a light curve of extremely small amplitude consistent with a pure sine wave, and a preliminary investigation of nine other sinusoidal Cepheids associated with open clusters (Turner et al. 2006a) indicates that only four are likely OT pulsators. V1726 Cyg in the cluster Platais 1 is a good example of what might be the case for Polaris: a low-amplitude, sinusoidal Cepheid pulsating in the FM with $\langle M_V \rangle = -3.08 \pm 0.07$ (Turner et al. 2006b). What is the situation for Polaris?

2. Background Information

Polaris illuminates diffuse dust nebulosity (Witt et al. 2008) as well as a reflection nebula $\sim 1^\circ$ south (Zagury et al. 1999), presumably the associated dust clouds accounting for the Cepheid's small reddening of $E_{B-V} = 0.02 \pm 0.01$ (Gauthier & Fernie 1978; Usenko et al. 2005; Turner 2006). The star has been the object of numerous ground-based investigations of its variability (Turner et al. 2005), ranging from visual, photographic, and photoelectric brightness estimates to radial velocity measures (Roemer 1965; Kamper 1996; Turner et al. 2005). A selection of some of the best photometric observations is shown in Fig. 1 along with a variety of different radial velocity measures. Not illustrated are the many low-quality observations that have been made over the past century (Turner et al. 2005).

Recent years have witnessed great improvements in the quality of both the photometric and radial velocity monitoring of Polaris, including observations from space (Spreckley & Stevens 2008; Bruntt et al. 2008) and high resolution spectroscopy (Kamper 1996; Hatzes & Cochran 2000; Turner et al. 2006c; Lee et al. 2008). High quality radial velocity measurements are probably the optimum method for updating information on the period and amplitude changes of Polaris from ground-based observatories, although it is from exactly such data that evidence has been presented for an additional periodicity in the variability of Polaris, other than that arising from its pulsational and orbital motions. Is the 119-day periodicity found by Lee et al. (2008) evidence for a fourth star in the system, or is it attributable to seasonal effects on ground-based equipment? A similar feature was detected by Dinshaw et al. (1989) and Hatzes & Cochran (2000) in their radial velocity studies of Polaris, but with a shorter period near 40 days.

Fig. 1.— Photometric light curves for Polaris (left) from: Stebbins & Whitford (1938), de Vaucouleurs (1947), Feltz & McNamara (1980), Henden (1980), and Brown & Bochonko (1994); phased radial velocity variations (right) from Roemer (1965), Kamper (1996), and Turner et al. (2006c), with source telescopes indicated.

3. Period and Amplitude Changes

A recent study of the period changes in Polaris (Turner et al. 2005) updated and expanded upon more limited investigations by Ferro (1983) and others (Fernie et al. 1993; Brown & Bochonko 1994; Evans et al. 2002). The Turner et al. (2005) study included light travel time corrections for the orbital motion of Polaris about its F6 V companion (Kamper 1996), although it was noted in the analysis that such corrections did not appear to remove the effects entirely. The original analysis was redone for the present study with the inclusion...
of recent observations, but excluding the original light travel time corrections, in order to determine if they could be established independently. The results are presented in Fig. 2.

The long-term trend in the pulsation period of Polaris from O–C analysis is that it is constantly increasing, except for an unusual “glitch” circa 1965, during a gap in the observational coverage between 1963 and 1966. Prior to the glitch, the rate of period increase is calculated to have been $4.46 \pm 0.03$ s yr$^{-1}$. Following the glitch it is calculated to be $4.19 \pm 0.13$ s yr$^{-1}$. Both values are consistent with results from stellar evolutionary model calculations for a star in the first crossing of the instability strip (Turner et al. 2006d), provided that Polaris is a FM pulsator. If the Cepheid is in another crossing of the instability strip, say a third or fifth crossing, the observed rates of period increase are several times larger than predicted from model predictions (Turner et al. 2006d). The shift in the O–C data during the glitch corresponds to an abrupt decrease in pulsation period, which, according to simple calculations tied to the period-density relation, could be accommodated through the sudden acquisition by the Cepheid of about seven Jovian masses of matter (Turner et al. 2005). The true explanation remains a mystery, although it is interesting to note that the assimilation of any pre-existing planetary companions to Polaris is most likely to occur during the first crossing of the instability strip, when the star is growing to red supergiant dimensions for the first time.

A longer-term overall brightening of $\sim 1^{m}.7$ (from 3.6 to 1.9 in $V$ from $\sim 100$ CE to the present) has been suggested (Engle & Guinan 2004; Croswell 2006), based upon an analysis of archival and recent brightness estimates. Such a gradual brightening over the last millennium would make Polaris unique among Cepheids, but appears to conflict with two sets of observations: those of Schmidt (1857) that imply $\langle V \rangle \approx 2.0$ provided there is no color term in his comparison of Polaris with the much redder $\beta$ UMi (Turner et al. 2005), and those of Turner et al. (2009a) over the past seven years that imply $\langle V \rangle = 1.991 \pm 0.004$ s.d., a value which includes slight contamination from the light of Polaris B amounting to less than
0".006 (i.e., ⟨V⟩ ≈ 1.997 for the Cepheid alone). In other words, the mean brightness of Polaris appears to have been constant at V ≃ 2.00 at least over the past century and a half.

4. Basic Parameters

A model atmosphere analysis of Polaris by Usenko et al. (2005) finds an abundance pattern with [C/H] = −0.17, [N/H] = +0.42, [O/H] = −0.00, and [Na/H] = +0.09, with the nitrogen and sodium enhancement and carbon (and oxygen) depletion being a strong signature of CNO-processed elements. Usenko et al. (2005) argue that Polaris is a post red supergiant dredge-up star because of such a signature. Yet the presence of CNO-processed elements in Cepheid atmospheres appears to be unrelated to red supergiant dredge-up, which does not take place in some evolutionary models, the contamination occurring instead in late main-sequence phases (Maeder 2001; Turner & Berdnikov 2004). The most likely mechanism is meridional mixing in rapidly-rotating B-type stars. As noted earlier, the rapid rate of redward evolution indicated by its rate of period increase suggests that Polaris is in the first crossing of the instability strip (Turner et al. 2006d). The rate is almost two orders of magnitude larger than predicted by stellar evolutionary models for which the main-sequence turnoff mass is 5.9 M⊙. We have been unable to confirm a similar prescription that is entirely consistent with either of the values established by its cluster or trigonometric parallaxes, which is puzzling.

Polaris has a measured surface gravity of log g = 2.0 ± 0.3 (Usenko et al. 2005) from LTE model atmospheres. The corresponding mass estimates for Polaris using the relations described above are given in Table 4. All of the estimates appear reasonable, and imply a mass for the Cepheid lying somewhere between 4 and 7 M⊙.

5. The Polaris Cluster

The field surrounding Polaris appears to coincide with the remains of a poorly-populated star cluster. For example, the radial velocities of Polaris and its brightest companions are nearly identical: −16 km s⁻¹ (Polaris, Roemer 1965; Kamper 1996; Turner et al. 2006), −15 km s⁻¹ (Polaris B, Kamper 1996; Usenko & Klochkova 2008), and −11 km s⁻¹ (HD 5914, Abt & Biggs 1972). A color-magnitude diagram for possible cluster stars from Hipparcos photometry is shown in Fig. 4. Most of the stars, other than Polaris, have parallaxes corresponding to distances of ~ 100 pc. The age isochrone for t = 8 × 10⁷ years shown in Fig. 4 was chosen to correspond to Polaris as a first-crossing Cepheid.

Similar results are obtained using 2MASS photometry (Cutri et al. 2003), as shown in Fig. 5, although in this case the implied distance from the JHK color-color and color-magnitude diagrams is 106 ± 7 pc for E_B−V = 0.02.

Polaris is also argued to be a member of the Pleiades moving group (Engle & Guinan 2004), for which the main-sequence turnoff mass is 5.9 M⊙. We have been unable to confirm a similarity in U, V, and W motions between Polaris and Pleiades members from an independent analysis, so it is unclear if such a connection exists, despite the close agreement in implied evolutionary ages for Polaris and Pleiades members.

6. Polaris Kin?

Stothers (2009) argues that Polaris and a few
Table 1

Mass estimates for Polaris

| $M/M_\odot$ | Pulsation Mode | Technique                                      |
|------------|----------------|------------------------------------------------|
| 3.9 ± 2.9  | FM             | log $g$ and PR relation (Turner & Burke 2002) |
| 6.6 ± 4.9  | OT             | log $g$ and PR relation (Turner & Burke 2002) |
| 5.1 ± 0.5  | FM             | Cluster PM relation (Turner 1996)             |
| 6.1 ± 0.6  | OT             | Cluster PM relation (Turner 1996)             |
| 4.5 ± 1.8  | OT?            | $Hipparcos$ π and orbit (Evans et al. 2008)  |

Fig. 4.— $BV$ photometry from $Hipparcos$ for stars within 3° of Polaris. The ZAMS is plotted for $d = 99$ pc and $E_{B-V} = 0.02$, along with an isochrone for $t = 8 \times 10^7$ yrs.

other unusual Cepheids (e.g., V473 Lyr) may constitute a special class of “Blazhko Cepheids,” on the basis of their unusual period and amplitude changes, akin to the Blazhko Effect in RR Lyrae variables. In this mechanism the growth and decay of a strong magnetic field modulates surface convection, thereby modulating pulsation amplitude and period. For stars like Polaris the pulsation period should increase as amplitude declines (stronger convection), and decrease as amplitude rises (weaker convection). In Polaris the period changes are in the exact opposite sense, so the glitch and subsequent decline in light amplitude for the Cepheid over the past thirty years remain unexplained by such a mechanism. In fact, the dominant period changes observed in the large majority of Cepheids are readily explained by the evolutionary changes in radius that occur as massive stars evolve through the Cepheid instability strip (Turner et al. 2006).

It is possible to map the rate of period change diagram ($\dot{P}-\log P$) from stellar evolutionary models for individual crossings of the Cepheid instability strip, as in Fig. 6. The rapid first crossing occurs when the stars are undergoing rapid core contraction supported only by a surrounding, thin, hydrogen-burning shell. The crossing occurs at a rate almost two orders of magnitude faster than the slower second and third crossings, when the stars are undergoing core helium-burning, so a random sample of Cepheids should contain only a few objects in the first crossing, perhaps only a few

Fig. 5.— $JHK$ photometry (Cutri et al. 2003) for stars in Fig. 4. The ZAMS in this case is plotted for $d = 106$ pc for $E_{B-V} = 0.02$. 

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percent at most. Stellar evolutionary models predict specific rates of period increase for first crossings, identified by the gray area in Fig. 6. Three Cepheids fall within that region: DX Gem ($P = 3^d.14$), BY Cas ($P = 3^d.22$), and the double-mode pulsator HDE 344787 ($P1/P0 = 3^d.80/5^d.40$). DX Gem and BY Cas are suspected FM pulsators, the former as a possible outlying member of an anonymous open cluster. BY Cas lies near the cluster NGC 663, but seems unlikely to be a member.

The rates of period change for DX Gem, BY Cas, and HDE 344787 are consistent with expectations for a first crossing of the instability strip. Is that also true for Polaris? All four Cepheids have common characteristics: rapid period increases, small light amplitudes ($\Delta B = 0.49$ for DX Gem, $\Delta B = 0.53$ for BY Cas, $\Delta B = 0.06$ for Polaris, and $\Delta B \simeq 0.02$ for HDE 344787), and sinusoidal light curves. The putative first crossers also lie near the middle of the instability strip, according to their derived reddenings (Fig. 7). That is consistent with model predictions from Alibert et al. (1999) for stars lying towards the cool edge of the instability strip for first crossers. Alternatively, if the location of Polaris in Fig. 7 is adjusted upwards by, say, 0.6 to account for possible overtone pulsation (see Turner et al. 2005), an anomaly arises: the star would still lie redward of the hot edge of the instability strip, but in a region where the largest amplitude pulsators are located (Pel & Lub 1978; Turner et al. 2006d). There is very little leeway possible in such an interpretation, given the well-established spectral type and interstellar reddening of Polaris.

The interpretation of DX Gem, BY Cas, and Polaris as putative first crossers is not without problems. DX Gem has an inferred rate of period increase of $\dot{P} = 3^s.87 \pm 0^s.19$ yr$^{-1}$, consistent with a first crossing, but with strange O–C wanderings (Hacke 1989) and possible amplitude changes that may display a slow overall decrease with time. Its characteristics may match those proposed by
Served period dependence of the values of $\Delta \phi$ by Cz and turner (2009) have found that the ob-
the corresponding phase of velocity minimum.
maximum brightness in Cepheid light curves and
lead to a complete cessation of pulsation within a
few years’ time (turner et al. 2009a).

HDE 344787 is perhaps the best case for a first-
crossing Cepheid (Turner et al. 2009b). It is a
double-mode pulsator with an observed rate of pe-
period increase of $P = 12^{a}.96 \pm 2^{a}.41$ yr$^{-1}$, but also
with a declining light amplitude (Fig. 8) that may
lead to a complete cessation of pulsation within a
few years’ time (Turner et al. 2009a).

Fig. 8.— The declining light amplitude of HDE 344787 for FM pulsation (open circles) and OT pulsation
(filled circles) (Turner et al. 2009a).

The case for OT pulsation in Polaris may also
be addressed observationally by another method.
There is a well-known phase lag, $\Delta \phi_1$, between
maximum brightness in Cepheid light curves and the
corresponding phase of velocity minimum. Ogloza & Moskalik (2000) have found that the ob-
served period dependence of the values of $\Delta \phi_1$
for OT pulsators appears to differ from that of
FM pulsators, thereby enabling one to discrimi-
nate between FM and OT pulsation in Cepheids.
The general trends appear to be confirmed in
models by Szabo et al. (2007). According to this
criterion, the value of $\Delta \phi_1 = -0.45 \pm 0.06$ ob-
tained for Polaris by Moskalik & Ogloza (2000)
implies overtone pulsation. But the rapid period
changes in Polaris complicate the determination of $\Delta \phi_1$ for the Cepheid, and possibly others as well. The study by Turner et al. (2009a) accounted for such changes directly by carefully matching photometric and radial velocity O–C estimates closely adjacent temporally, and yielded a value of $\Delta \phi_1 = -0.10 \pm 0.01 (-0.383 \pm 0.027$ days), consis-
tent with the FM sequence of Ogloza & Moskalik
(2000), as well as that of Sachkov (2000). By this
criterion, Polaris would be considered as a funda-
mental mode pulsator.

As is ever the case with Polaris, the situation is somewhat more complicated. Radial velocities
also exist for the newly-discovered small amplitude
Cepheid HDE 344787 (Turner et al. 2009b), which
appears to display different phase lags for the FM
and OT modes, although the value obtained for
FM pulsation is uncertain because the FM signal
is much weaker than the OT mode signal. For the
FM pulsation in HDE 344787 ($P = 5^{d}.40$), $\Delta \phi_1 = -0.32$, whereas for the OT pulsation
($P = 3^{d}.80$), $\Delta \phi_1 = -0.09$. The value of $\Delta \phi_1$ for
the fundamental mode is roughly consistent with the
trend found by Ogloza & Moskalik (2000), but not with that of Sachkov (2000), whereas the value
of $\Delta \phi_1$ for the overtone mode disagrees markedly
with the trends of both Ogloza & Moskalik (2000)
and Szabo et al. (2007). If the corresponding situa-
tion for Polaris is decided in empirical fashion, i.e.,
by comparison with HDE 344787, then the simi-
larity of the value of $\Delta \phi_1$ for OT pulsation in
HDE 344787 with the value of $\Delta \phi_1 = -0.10$ for
Polaris, which has a similar pulsation period, sug-
gests that Polaris is likely to be an OT pulsator.

Or is it necessarily true that double-mode
Cepheids actually differ from single-mode pul-
sators in their $\Delta \phi_1$ properties? It may be that
there is no distinction in $\Delta \phi_1$ between FM and
OT pulsation, but further careful study of the
observational sample is needed to confirm that
possibility. The contradictions arising from the
arguments presented here clearly argue for the
need of improved observational data on $\Delta \phi_1$ for
Cepheids of known pulsation mode, in particular
data that implicitly account for the rapid period
changes in many of the variables, a factor that
directly affects the determination of reliable phase
shifts for them.
7. The Polaris Multiple System

The recent resolution of the Polaris A system by Evans et al. (2008) using the Hubble Space Telescope (HST) has made it possible to study the three previously-recognized components of the system directly. The two measured HST positions for Polaris Ab relative to the Cepheid are consistent with the astrometric orbital solution proposed by Wielen et al. (2000), in which a retrograde orbit with an orbital inclination of $i = 130^\circ$ was obtained. An orbital solution by Evans et al. (2008) combined HST observations with astrometric data to yield the parameters in Table 7. Matching the results to stellar evolutionary models presented some inconsistencies with the inferred mass of the Cepheid (Evans et al. 2008), possibly because it was assumed that Polaris is in the third crossing of the instability strip, which, as noted earlier, conflicts with the observed rapid rate of period change.

![Fig. 9.— Seasonal mean radial velocities for Polaris from 1888 to 2005. Filled circles represent the actual data, while open circles and crosses denote the same data folded forwards and backwards in time by one or two orbital cycles, respectively. The upper diagram illustrates the confusion introduced by literature velocities that do not appear to match the velocity system of Lick Observatory exactly. The lower diagram illustrates the data following the adoption of corrections to adjust the velocities to the Lick system.](image)

It is unclear how the results depend upon the orbital solution for the spectroscopic subsytem. The Evans et al. (2008) analysis of Polaris A adopted an earlier solution for the spectroscopic binary from Kamper (1996), but a new solution for the system has been obtained using more recent radial velocity measures (Turner et al. 2006c). The new orbital solution depends upon small zero-point adjustments to existing radial velocities, most notably the observations by Kamper (1996) and Kamper & Fernie (1998), as illustrated in the upper portion of Fig. 9. Correction for such zero-point offsets reduces the scatter in the velocity observations from one cycle to another (Fig. 9 lower), but leaves residual scatter that is frequently larger than expected from the uncertainties in the measurements. The resulting phased best data set is shown in Fig. 10, and is summarized in Table 7. Three separate solutions were made by the Lehmann-Filhê technique: one tied to recent observations, a second to the full data set (which gives a better match to the velocity amplitude $K$), and a third restricted to data that give the best overall visual match to the main velocity trend. An independent solution was made with the same data using a Bayesian Markov Chain Monte Carlo analysis (Turner et al. 2006e). The results, shown in the last column of Table 7, confirm the alternate solution based on the same data set (Turner et al. 2006c).

![Fig. 10.— The new orbital solution for Polaris A, shown as the solid curve in the diagram. Filled circles denote post-1970 data, open circles pre-1970 data.](image)

The new solution implies a less elliptical and larger orbit than was found in previous studies, but recent observations display kinks in the radial velocity curve for the orbit near velocity maximum that argue for the need of additional velocity coverage. It is possible to use the new orbital solution with the recent visual resolution of the companion (Evans et al. 2008) to constrain the distance...
Table 2

Orbital Parameters for Polaris A (Evans et al. 2008)

| Parameter                   | Value                      |
|-----------------------------|----------------------------|
| Orbital inclination, $i$   | $128^\circ \pm 21^\circ$  |
| Ascending node, $\Omega$   | $19^\circ \pm 15^\circ$   |
| Semi-major axis, $a$        | $0''.133 \pm 0''.015$      |
| Total system mass, $M_{tot}$| $5.8^{+2.2}_{-1.1} M_\odot$|
| Primary mass, $M_A$         | $4.5^{+1.2}_{-0.4} M_\odot$|
| Secondary mass, $M_B$       | $1.26^{+0.14}_{-0.07} M_\odot$|

to the system. For this analysis the mass of Polaris is assumed to lie between 3 and 6 $M_\odot$, while the mass of the F6 V companion is assumed to be less than $1.45 M_\odot$ (Evans et al. 2008). Such constraints produce the results shown in Fig. 11.

Fig. 11.— Permitted parameters for the Polaris system (the unshaded region) according to the orbital solution and HST detection of the companion. The sloped curves denote, from top to bottom in each plot, orbital inclinations of 50°, 60°, 70°, and 90°, respectively. Shaded regions denote implausible orbital solutions dictated by the observed faintness of the companion (upper cutoff) and the limiting orbital inclination of $i = 90^\circ$ (lower cutoff).

The results of the analysis can be summarized as follows. The allowable range of parameters yields $\langle d \rangle = 121 \pm 10$ pc and $\langle M_V \rangle = -3.49 \pm 0.18$ for Polaris, consistent with the Hipparcos parallax (van Leeuwen et al. 2007) and overtone pulsation. However, the most likely orbital inclination is $i \geq 60^\circ$, which conflicts with the astrometric estimate of $i = 50^\circ$ (Wielen et al. 2000) unless $M_{\text{Polaris}} \leq 3.5 M_\odot$. The permitted solutions are inconsistent with the inferred distance of the visual companion (Polaris B) (Turner 1977, 2006; Usenko & Klochkova 2008), the observed rapid rate of evolutionary period change (Turner et al. 2005), the lack of any signal tied to putative FM pulsation around 5.7 in the light and radial velocity observations (Turner 2006; Spreckley & Stevens 2008; Bruntt et al. 2008; Lee et al. 2008), and possible membership in the surrounding anonymous cluster (Turner 2006).

Another approach can be made using the O–C data of Fig. 2, since deviations from the O–C fit should also yield parameters for the binary system. The light travel time delays for a star orbiting in a binary system depend upon $a_1 \sin i$ in similar fashion to the radial velocities, although they are a quarter cycle out of phase. The largest weight O–C observations for Polaris do indeed follow such a trend, as shown in Fig. 12. What is remarkable is the magnitude of the deviations, which seem to reach almost 0.15 light day, or 26 A.U., a value that seems inordinately large for the motion of the most massive star in the system about its (presumably) less massive companion.

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The last result can be seen in greater detail in Fig. 13, which plots the O–C residuals as a function of orbital phase relative to expectations from
Table 3

Orbital Solutions for Polaris A

| Parameter                              | Roemer (1965) | Kamper (1996) | Turner et al. (2006c) | Turner et al. (2006e) | BMCMC Analysis |
|----------------------------------------|---------------|---------------|-----------------------|-----------------------|----------------|
| Period, $P$ (years)                    | 30.46 ± 0.10  | 29.59 ± 0.02  | 29.71 ± 0.09          | 29.80 ± 0.05          | 29.80 ± 0.05   |
| Period, $P$ (days)                     |               |               |                       |                       |                |
| Orbital eccentricity, $e$              | 0.639 ± 0.012 | 0.608 ± 0.005 | 0.543 ± 0.010         | 0.52 ± 0.01           | 0.52 ± 0.01    |
| Epoch of periastron, JD               | 1928.48 ± 0.08| 1928.48 ± 0.08| 1928.57 ± 0.06        | 2925453 ± 22          | 2925430 ± 44   |
| Longitude of node, $\omega$ (°)       | 307.24 ± 1.82 | 303.01 ± 0.75 | 309.6 ± 0.7           | 301 ± 2               |                |
| Semi-amplitude, $K$ (km s$^{-1}$)      | 4.09 ± 0.10   | 3.72 ± 0.03   | 4.41 ± 0.07           | 4.23 ± 0.07           |                |
| Projected semi-major axis, $a_1 \sin i$ (A.U.) | 3.22 ± 0.10 | 2.90 ± 0.03 | 3.69 ± 0.09 | 3.62 ± 0.06 |

Fig. 12.— The deviations of the high quality O–C data from the best-fitting parabolic trends matched to the observations. Tick marks denote epochs when the Cepheid primary should be crossing into the plane of the sky.

The most recent orbital solution (Turner et al. 2006e). It should be noted that some of the most deviant trends in Fig. 13 are tied to recent observations of the Cepheid from space-based platforms (Spreckley & Stevens 2008; Bruntt et al. 2008), so it is difficult to attribute them to “observational error.” A similar problem has been detected in O–C observations of the binary Cepheid RT Aur (Turner et al. 2007), although even in that case there is no satisfactory resolution of the problem by tying it to problems with the observations. Possibly the effect is simply another manifestation of the random fluctuations in pulsation period that are detected in almost all Cepheids (Turner et al. 2009c), although the trends in the O–C deviations seem to be too well organized for a “random” process.

8. Additional Considerations

The numerous contradictions noted here regarding the pulsation mode of Polaris suggest the possibility of a more fundamental problem. Some of the anomalies in the radial velocity measures may be a consequence of different sets of spectral lines (ionization and excitation states) and wavelength coverage used to infer the photospheric motion, or to the inevitable problems of establishing reliable systemic velocities for a pulsating star, where shock effects are detected at some phases (Hatzes & Cochran 2000). But that does not resolve the problems arising from the O–C offsets for the photometric observations, which are of relatively high precision for recent data sets. The presence of a third star in the spectroscopic subsystem, as surmised by the results of most previous radial velocity studies (e.g., Dinshaw et al. 1989; Hatzes & Cochran 2000; Lee et al. 2008), might resolve the various discrepancies in our current understanding of Polaris as a Cepheid, but would require continued spectroscopic and astrometric monitoring of the star for some years to come in order to provide confirmation. It is interesting to note that the “glitch” in the O–C observations

Fig. 13.— Phased deviations of the O–C data from the best-fitting parabolic trends, shown relative to the orbital solution of Table 7 (solid line), with the size of the symbol increasing in proportion to its assigned weight. A dashed line denotes expectations for $a_1 \sin i = 5\times$ the actual value.
for Polaris occurred only a few years after periastron passage for the spectroscopic subsystem in 1958, when the stars were near closest approach to one another. Presumably that would be the most likely interval of time when an interaction with another close companion would occur. But, of course, that is merely speculation.

The reasonable possibility that some of the stars near Polaris might be physically associated with the Cepheid was noted by Fernie (1966), but has not been pursued to a great extent, possibly because of the difficulties of observing stars in close proximity to the north celestial pole using ground-based facilities. The lack of detectable X-ray emission from the faint red stars C and D in the Polaris multiple system has been used by Evans et al. (2006) as evidence that they are not young, newly-arrived, main sequence dwarfs, as required by a possible association with Polaris, so are most likely field stars. There are several other brighter, potential members of the Polaris cluster lying outside the immediate field of the Cepheid, however, for which basic photometric and radial velocity observations do not exist. A program to obtain such data has been underway for a few years now, but the study is far from complete. Other low-amplitude sinusoidal Cepheids, the “Polaris kin,” are even less well-studied, although they could prove to be equally valuable for clarifying the nature of Polaris itself. Clearly the Polaris story is not yet over.

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