Hubble Space Telescope Trigonometric Parallax of Polaris B, Companion of the Nearest Cepheid*

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Abstract

Polaris, the nearest and brightest Cepheid, is a potential anchor point for the Leavitt period–luminosity relation. However, its distance is a matter of contention, with recent advocacy for a parallax of ~10 mas, in contrast with the Hipparcos measurement of 7.54 ± 0.11 mas. We report an independent trigonometric parallax determination, using the Fine Guidance Sensors (FGS) on the Hubble Space Telescope. Polaris itself is too bright for FGS, so we measured its eighth-magnitude companion Polaris B, relative to a network of background reference stars. We converted the FGS relative parallax to absolute, using estimated distances to the reference stars from ground-based photometry and spectral classification. Our result, 6.26 ± 0.24 mas, is even smaller than that found by Hipparcos. We note other objects for which Hipparcos appears to have overestimated parallaxes, including the well-established case of the Pleiades. We consider possible sources of systematic error in the FGS parallax, but find no evidence they are significant. If our “long” distance is correct, the high luminosity of Polaris indicates that it is pulsating in the second overtone of its fundamental mode. Our results raise several puzzles, including a long period end for zero-point calibration of the Leavitt period–luminosity relation. We discuss possibilities that B is not a physical companion of A, in spite of the strong evidence that it is, or that one of the stars is a merger remnant. These issues may be resolved when Gaia provides parallaxes for both stars.

Key words: astrometry – stars: distances – stars: evolution – stars: individual (Polaris) – stars: variables: Cepheids

1. Polaris: Nearest Cepheid, Controversial Distance

Cepheid variables are among the primary distance indicators for the extragalactic distance scale, and they provide critical tests of stellar-evolution theory. The North Star, Polaris (α Ursae Minoris), is of special interest as the nearest and brightest Cepheid. It has a relatively short pulsation period of 3.969 days (Fernie et al. 1995). Because it is so nearby, Polaris can potentially serve as one of the anchor points near the short-period end for zero-point calibration of the Leavitt period–luminosity relation (e.g., Feast & Catchpole 1997; van Leeuwen et al. 2007). However, it is necessary to consider several peculiarities presented by Polaris, as described below. In particular, it is crucial to determine whether it pulsates in the fundamental mode or an overtone.

The majority of classical Cepheids have characteristic asymmetric light curves with high amplitudes. It was recognized many years ago—for a historical review, see Beaulieu et al. (1995)—that there is a separate class of Cepheids with low pulsation amplitudes and nearly symmetric sinusoidal light curves. These objects are interpreted as Cepheids pulsating in the first overtone of the fundamental period. They can be recognized from examination of the light curves, or more rigorously by calculating a Fourier decomposition (e.g., Simon & Lee 1981; Poretti 1994). However, this approach has been difficult for Polaris itself, because its pulsation amplitude is very small, making the Fourier coefficients difficult to determine. If the distance is known, overtone Cepheids can also be distinguished because of luminosities lying above the classical Cepheids in the Leavitt relation.

Polaris belongs to a triple system. Its well-known visual companion, Polaris B, is an eighth-mag F3 V star, lying 18” from the Cepheid. The Cepheid itself was known for many years to be a single-lined spectroscopic binary with a period of ~30 years (Roemer 1965; Kamper 1996, hereafter K96, and references therein). But the close companion remained unseen until it was finally detected directly in the Hubble Space Telescope (HST) ultraviolet images by members of our team (Evans et al. 2008), at a separation of 0″17 from Polaris A. We inferred a spectral type of F6 V for the close companion, designated Polaris Ab, based on its UV brightness and dynamical mass.

The extensive literature on Polaris was reviewed by K96 and Wielen et al. (2000), both of whom presented strong evidence that Polaris B is a true physical companion of the Cepheid. The physical association with A is supported by agreement in radial velocity, proper motion, metallicity, and approximate distance estimates based on photometry and the spectral type of Polaris B. An examination of the position angle and angular separation of Polaris B relative to A (K96; Evans et al. 2008) showed that the position angle has remained essentially constant for more than the past two centuries, and there has

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been a slow reduction in the separation at a rate of $-1.67 \pm 0.19$ mas yr$^{-1}$ (Evans et al. 2008), consistent with orbital motion at a period of the order of $10^3$ years. Since the absolute proper motion of Polaris A is about 46 mas yr$^{-1}$, the angular tangential motions of A and B agree to within $\pm 4\%$. Usenko & Klochkova (2008) provided additional evidence that the radial velocities of A and B are very similar. A more recent, extensive review of our knowledge of the Polaris system is given by Turner (2009).

The distance of Polaris has been controversial. Historical ground-based photographic trigonometric parallaxes of Polaris have such large uncertainties that they are of limited utility. The Yale catalog (van Altena et al. 1995) gives an average parallax of $4.0 \pm 3.3$ mas from several determinations. However, Turner et al. (2013, hereafter TKUG13) argue that magnitude-dependent corrections to the Allegheny Observatory parallaxes would increase the ground-based value to $11 \pm 4$ mas.

The Hipparcos astrometric mission yielded an absolute parallax for Polaris A of $7.56 \pm 0.48$ mas (ESA 1997), modified to $7.54 \pm 0.11$ mas in the re-reduction by van Leeuwen (2007), corresponding to a distance of $d = 132.6 \pm 1.9$ pc. Because of this “long” distance and correspondingly high implied luminosity, Feast & Catchpole (1997) and van Leeuwen (2007) concluded that Polaris is a first-overtone pulsator.

However, TKUG13 argue that the parallax of Polaris is considerably larger, $10.10 \pm 0.20$ mas ($d = 99 \pm 2$ pc). The evidence cited by TKUG13 for this “short” distance includes (1) a photometric parallax for Polaris B based on measured photometry, spectral classification, and main-sequence fitting; (2) a claim that there is a sparse cluster of A-, F-, and G-type stars within 3$^2$ of Polaris, with proper motions and radial velocities similar to that of the Cepheid, for which the Hipparcos parallaxes combined with main-sequence fitting give a distance of 99 pc; and (3) a determination of the absolute visual magnitude of Polaris based on line ratios in high-resolution spectra, calibrated against supergiants with well-established luminosities. On the basis of the short distance, and thus a fainter absolute magnitude, TKUG13 concluded that Polaris is a fundamental-mode pulsator.

The angular diameter of Polaris has been measured interferometrically (Nordgren et al. 2000; Mérand et al. 2006). For the short distance, the radius implies that Polaris pulsates in the fundamental mode, whereas the larger radius, if the long distance is adopted, means that it pulsates in the first overtone (e.g., Bono et al. 2001; Neilson 2014).

In a critique of the TKUG13 paper, van Leeuwen (2013, hereafter L13) defended the Hipparcos parallax by presenting details of the solution, concluding that “the Hipparcos data cannot in any way support” the large parallax advocated by TKUG13. Using Hipparcos data, L13 also questioned the reality of the sparse cluster proposed by TKUG13, presenting evidence against it both from the color versus absolute-magnitude diagram for stars within 3$^2$ of Polaris, and their non-clustered distribution of proper motions. Lastly, L13 examined the absolute magnitudes of nearly 400 stars of spectral type F3 V in the Hipparcos catalog with parallax errors of less than 10%, and showed that the absolute magnitude of Polaris B would fall well within the observed $M_V$ distribution for F3 V stars, based on either the Hipparcos parallax of A or the larger parallax proposed by TKUG13. Thus, he concluded that the photometric parallax of B does not give a useful discriminant.

Neilson (2014) has given an extended discussion of the astrophysical issues related to the distance of Polaris, including a consideration of the measured rate of change of the pulsation period. He concluded that the properties of Polaris are inconsistent with it being in the early evolutionary stage of the first crossing of the Cepheid instability strip. Instead, Neilson argued that it must be in the third crossing. This would require it to be more luminous, its distance to be at least 118 pc (parallax less than $\sim 8.5$ mas), and it to be pulsating in the first overtone. However, Fadeyev (2015), based on hydrodynamic pulsation models, reached the opposite conclusion: Polaris is crossing the instability strip for the first time and is a fundamental-mode pulsator.

In this paper, we present a measurement of the trigonometric parallax of the Polaris system based on astrometric observations of the companion, Polaris B, with the Fine Guidance Sensors (FGSs) on HST. After discussing the data acquisition and analysis, we present the parallax result—which favors the long distance or indeed an even larger distance than that found by Hipparcos. We conclude with brief discussions of the astrophysical implications for the Cepheid, the apparent peculiarities of Polaris B, and the possibilities that Polaris actually pulsates in the second overtone or that Polaris B is not actually a physical companion of A.

## 2. Hubble Space Telescope Astrometry of Polaris B

### 2.1. FGS Observations and Data Analysis

As part of an astrometric program on the trigonometric parallaxes of overtone Cepheids, we observed Polaris with the FQS system on HST. The FGSs are a set of three interferometers that, in addition to providing guiding control during imaging or spectroscopic observations, can measure precise positions of a target star and several surrounding astrometric reference stars with one FGS while the other two guide the telescope. The FGS system has been shown capable of yielding trigonometric parallaxes, in favorable cases, with better than $\pm 0.2$ mas precision (e.g., Benedict et al. 2007, hereafter B07; Soderblom et al. 2005; Benedict et al. 2011, 2017; McArthur et al. 2011; Bond et al. 2013).

The Cepheid Polaris A, at a mean brightness ($V = 1.982$ (Fernie et al. 1995), is too bright to be observed with the FGS system. Because of the strong evidence that Polaris B is a physical companion at the same distance as the Cepheid (see above), we chose it instead as our astrometric target. We made FGS observations of Polaris B during two HST visits at each of five epochs between 2003 October and 2006 September (program numbers GO-9888, –10113, and –10482; PI H.E. B.), at dates close to the biannual times of maximum parallax factor. We used FGS1r for the measurements, in its wide-angle astrometric POSITION mode. There was no sign of duplicity of B in the FGS acquisition data. In addition to Polaris B, we observed a network of 10 faint background reference stars lying within $\sim 5'$ of the target. Of the 10 reference stars, two were rejected because of acquisition failures, faintness, binarity, or interference from the diffraction spikes of Polaris A, and we retained eight (with magnitudes of $V = 14.1–16.5$) for the final solution. They are listed in Table 1.

Our FGS astrometric solution procedure is outlined by Bond et al. (2013), and described in detail by B07 and Nelan (2017).
The first step is to correct the positional measurements from the FGS for differential velocity aberration, geometric distortion, thermally induced spacecraft drift, and telescope pointing jitter. Because of refractive elements in the FGS optical train, an additional adjustment based on the $B - V$ color of each star is applied. Moreover, as a safety precaution due to its proximity to Polaris A, Polaris B itself was observed with the F5ND neutral-density attenuator, while the much fainter reference stars were observed only with the F583W filter element. Thus it was necessary to apply “cross-filter” corrections to the positions of Polaris B relative to the reference stars; the corrections are slightly dependent on location of the star in the FGS field.

The adjusted measurements from all 10 visits were then combined using a six-parameter overlapping-plate technique that solves simultaneously for scale, translation, rotation, and proper motion and parallax of each star. Full details, including the equations of condition, are given in B07, their Section 4.1. We employed the least-squares program GAUSSFIT (Jefferys et al. 1988) for this analysis. Parallax factors are obtained from the JPL Earth orbit predictor, version DE405 (Standish 1990).

Since the FGS measurements provide only the relative positions of the stars, the model requires input estimated values of the reference-star proper motions and parallaxes, in order to determine an absolute parallax of the target. These estimates (Section 2.2) were input to the model as observations with errors, which permits the model to adjust their parallaxes and proper motions (to within their specified errors) to find a global solution that minimizes the resulting $\chi^2$.

### Table 1

| ID   | R.A. (J2000) | Decl. (J2000) | $V$ | $B - V$ | $V - I$ | Sp.Type | $\mu_x$ (mas yr$^{-1}$) | $\mu_y$ (mas yr$^{-1}$) | $\pi_{\text{rad}}$ (mas) |
|------|-------------|---------------|-----|---------|---------|---------|-------------------------|-------------------------|------------------------|
| R1   | 02:37:32.4  | +89:20:00.1   | 13.42 | 0.762  | 0.890  | F8 V    | $0.9 \pm 0.4$           | $-0.6 \pm 0.4$          | $1.16 \pm 0.15$        |
| R2   | 02:34:04.9  | +89:18:09.5   | 16.504 | 0.734  | 0.820  | F7: IV: | $7.0 \pm 0.5$           | $0.5 \pm 0.8$           | $0.28 \pm 0.11$        |
| R3   | 02:19:11.6  | +89:14:30.2   | 14.147 | 0.825  | 0.957  | G2 V    | $1.0 \pm 0.4$           | $0.7 \pm 0.7$           | $0.28 \pm 0.04$        |
| R7   | 02:25:26.6  | +89:13:37.5   | 14.958 | 0.903  | 1.070  | G1 IV   | $13.3 \pm 1.0$          | $1.5 \pm 0.7$           | $0.73 \pm 0.07$        |
| R8   | 02:21:18.2  | +89:14:26.2   | 13.675 | 1.360  | 1.633  | K5 V    | $35.0 \pm 0.6$          | $15.6 \pm 0.6$          | $6.32 \pm 0.42$        |
| R10  | 02:25:58.3  | +89:12:9.2    | 19.490 | 1.051  | 1.140  | G5: V   | $3.5 \pm 0.8$           | $-2.0 \pm 0.7$          | $1.2 \pm 0.17$         |
| B    | 02:30:43.5  | +89:15:38.6   | 8.65  | 0.42   | 0.280  | F3 V    | $41.1 \pm 0.4$          | $-13.8 \pm 0.4$         | $6.26 \pm 0.24$        |

Notes.

a Proper motions in R.A. and decl. from our astrometric solution.
b Input estimated absolute parallax (top entry), and adjusted absolute parallax from astrometric solution (bottom entry).
c R7 is cataloged as Polaris D, which was identified as a possible companion of Polaris by Burnham (1894), and discussed more recently by Evans et al. (2002, 2010). The latter did not detect X-ray emission from Polaris, which was identified as Polaris D, suggesting that it is not a young low-mass companion of the Cepheid. Our spectral type and photometry, giving an estimated distance of $\sim960$ pc, and our measured proper motion, definitively rule out Polaris D as a physical companion of Polaris A and B.
d Polaris B, V magnitude from Evans et al. (2008) and $B - V$ from the literature compilation by Turner (2005); spectral type from Turner (1977).

2.2. Reference-star Proper Motions and Parallaxes

The initial proper-motion estimates for the reference stars were taken from the UCAC5 catalog (Zacharias et al. 2017). In order to estimate the distances to the reference stars, we employed spectral classification and photometry, and as a lower-weight criterion, their reduced proper motions. For spectral classification, we obtained digital spectra with the WIYN 3.5 m telescope and the Hydra multi-object spectrograph at the Kitt Peak National Observatory (KPNO), on the night of 2003 November 22. The classifications were accomplished through comparison with a network of MK standard stars obtained with the same spectrograph, assisted by equivalent-width measurements of lines sensitive to temperature and luminosity. The results are given in the sixth column in Table 1.

Photometry of the reference stars in the Johnson–Kron–Cousins BVI system was obtained at KPNO on one photometric night in 2007 October (0.9 m telescope), and on three photometric nights in 2008 October (2.1 m telescope). Each star was measured between 9 and 13 individual CCD frames. The photometry was calibrated to the standard-star network of Landolt (1992), and the results are presented in Table 1. The internal errors of the photometry, tabulated in Table 1, are generally quite small, but the systematic errors are probably larger because of (a) the high airmass at which the Polaris field has to be observed, and (b) the presence of a very bright star at the center of the field, giving rise to PSF wings, diffraction spikes, and charge-bleeding columns across much of the field.

Although Polaris itself is unreddened (e.g., Fernie 1990; Laney & Caldwell 2007), or very lightly reddened (e.g.,
Gauthier & Fernie 1978 find $E(B - V) = 0.02 \pm 0.02$, and TKUG13 give $E(B - V) = 0.02 \pm 0.01$, it is known to lie just in front of a molecular cloud, the "Polaris Circle Cloud" or "Polaris Flare" (e.g., Sandage 1976; Heithausen & Thaddeus 1990; Zagury et al. 1999; Cambresy et al. 2001; Ward-Thompson et al. 2010; Panopoulou et al. 2016, and references therein). Thus significant reddening of the reference stars is expected.

To estimate their reddening, we compared the observed $B - V$ color of each star with the intrinsic $(B - V)_0$ color corresponding to its spectral type (Schmidt-Kaler 1982), from which we calculated an average $E(B - V) = 0.25$. We also used the extinction map of Schlafly & Finkbeiner (2011), as implemented at the NASA/IPAC website, to determine the reddening in the direction beyond Polaris. The Schlafly & Finkbeiner map gives a range of reddening values across the field covered by the reference stars of $E(B - V) = 0.26$ to 0.30, which is the total reddening for a hypothetical star at a very large distance. We adopted a reddening of $E(B - V) = 0.25$ for all of the reference stars, except for R10, the nearest one, for which we used $E(B - V) = 0.21$ based on its spectral type and observed $B - V$.

The distances to the reference stars were then estimated as follows: (1) For the four stars classified as dwarfs, we used a calibration of the visual absolute magnitude, $M_V$, against $B - V$ and $V - I$ colors derived through polynomial fits to a large sample of nearby main-sequence stars with accurate photometry and Hipparcos or USNO parallaxes, which is described in more detail in Bond et al. (2013). This algorithm corrects for effects of metallicity. (2) For the four subgiants, we searched the Hipparcos data for all stars classified with the same spectral types that had parallaxes greater than 15 mas, and calculated their mean absolute magnitude for use in the distance estimate. For the dwarfs, our $M_V$ versus $BVI$ calibration reproduces the known absolute magnitudes of the sample of nearby dwarfs with an rms scatter of 0.28 mag. The scatter in the subgiant $M_V$ calibrators was larger, ~0.8 mag. Our final estimated input parallaxes and their errors, based on the scatter in the $M_V$ calibrators, are given in the last column of Table 1, along with the output parallaxes given by the $\chi^2$ solution.

2.5. Possible Sources of Systematic Error in the FGS Parallax

In this subsection, we comment on possible causes of a systematic error in our FGS parallax measurement for Polaris B, which could potentially explain the discordance with the Hipparcos value for the Cepheid Polaris A.

(1) Could our input estimated parallaxes of the reference stars be systematically too low by ~1.3 mas? Omitting the star R10, which is unusually nearby, we find a mean estimated parallax of the other seven reference stars of 0.89 mas. This agrees quite well with the value of 1.0 mas for the mean parallax of field stars at $V = 15$, at the Galactic latitude of Polaris, recommended by Altena et al. (1995, their Figure 2) based on a statistical model of Galactic structure. Increasing our reference-star parallaxes by a mean of about 1.3 mas would give serious disagreement with the van Altena et al. model values. Moreover, it would require the reference stars to be systematically about 1.9 mas fainter in absolute magnitude than in our calibration, which appears astrophysically unlikely —it would require all of the main-sequence stars to be extreme subdwarfs, in conflict with their spectral types.

(2) Was our ground-based CCD photometry affected by the presence of the bright Polaris A in the frames? The required

2.4. The Discrepancy with Hipparcos

Our result for the parallax of Polaris B (6.26 ± 0.24 mas) is 1.28 mas smaller than found by Hipparcos for Polaris A (7.54 ± 0.11 mas). Is it plausible that the Hipparcos result could be in error by such a large amount?

Hipparcos parallaxes have usually agreed with the results of HST/FGS measurements, or of other parallax techniques, to within their respective errors (e.g., Benedict et al. 2002; McArthur et al. 2011; Bond et al. 2013). However, there have been a few notable exceptions: (1) For the Pleiades cluster, Melis et al. (2014) obtained a precise cluster parallax of 7.35 ± 0.07 mas from very-long-baseline radio interferometry (VLBI) astrometry of four radio-emitting cluster members. FGS parallaxes of three other Pleiades stars gave an average absolute parallax of 7.43 ± 0.17 (random) ±0.20 (systematic) mas (Soderblom et al. 2005), in accord with the VLBI result. However, van Leeuwen (2009), based on Hipparcos astrometry of over 50 Pleiads, found a mean cluster parallax of 8.32 ± 0.13 mas, larger by 0.97 mas than the VLBI result.

(2) Benedict et al. (2011) used FGS to measure a parallax of the Type II Cepheid κ Pavonis of 5.57 ± 0.28 mas; the Hipparcos parallax of 6.52 ± 0.77 mas is larger by a similar 0.95 mas (although this is of lower statistical significance because of the relatively large Hipparcos uncertainty).

(3) VandenBerg et al. (2014) used FGS to measure parallaxes of three halo subgiants. For two of them, the results agreed very well with Hipparcos, but for HD 84937, the Hipparcos value of 13.74 ± 0.78 mas was larger by 1.50 mas than the FGS measurement of 12.24 ± 0.20 mas. (4) Zhang et al. (2017) used VLBI astrometry to derive a parallax of 4.42 ± 0.13 mas for the semi-regular variable RT Virginis, for which the Hipparcos parallax is 7.38 ± 0.84 mas, or 2.96 mas larger.

In summary, there are indeed isolated examples of the Hipparcos parallax measurement being shown to be anomalously too large.
sense to give agreement with Hipparcos would be that the reference stars are actually systematically brighter than indicated by our measurements. Here we have a check, because the FGS measurements provide independent estimates of the $V$ magnitudes, based on the observed count rates and an approximate absolute calibration. Setting aside R7 and R8, which are the angularly closest of the reference stars to the very bright Polaris A, we find our measured FGS magnitudes are an average of only 0.09 mag brighter than the ground-based $V$ magnitudes. Such an amount is likely consistent with contamination of the FGS photometric measurements by background scattered light from Polaris. (Background scattered light is not subtracted from the measured counts in the FGS reductions.)

(3) Did scattered light or dark counts affect the FGS astrometry? The Polaris astrometric field is unique among those measured with the HST/FGS system, because of the presence of the extremely bright Polaris A near the center of the field. In addition to the magnitude measurements noted in the previous paragraph, we indeed see evidence of scattered light across the field. This shows up as enhanced count rates detected as the instantaneous $5' \times 5'$ FGS field of view is slewed across the blank sky from one reference star to the next. However, this background light is faint, incoherent with the light from the FGS target stars, and displays no significant gradient over the ~1'' scale length of FGS interferometric measurements. Thus, the background only slightly reduces the amplitude of the interference fringes, without significantly displacing the measured positions. This is the same effect that dark counts from the photomultiplier tubes have on the fringe amplitude of faint stars ($V \gtrsim 14.5$), but likewise without systematically affecting their measured positions. To verify these conclusions, we conducted extensive tests whereby each reference star, as well as pairs and triplets of reference stars, were removed from the solution to reveal any unusually affected individual exposures. Removing reference stars increased the errors in the parallax measurements but did not systematically change the parallax of Polaris B by more than 0.3 mas. We therefore conclude that the FGS measurement of the Polaris B parallax was not significantly affected by the presence of Polaris A.

(4) What evidence does Gaia provide? The recent first Gaia data release (DR1; Gaia Collaboration et al. 2016a, 2016b) provides an additional test of our results. Positions of Polaris B and the FGS reference stars were tabulated in DR1, but none of them are contained in the Tycho-Gaia Astrometric Solution (TGAS), and thus none have as yet a Gaia-based parallax or proper motion. (Polaris A was also not included in DR1 or TGAS, as it is too bright for the standard Gaia pipeline processing.) However, we used the epoch 2015.0 Gaia positions for the reference stars and Polaris B to simulate an additional FGS observation set, and then combined them with the rest of our data. We found excellent agreement of the FGS astrometry with the Gaia catalog positions (to better than 1 mas), but resulting in an even slightly smaller parallax for Polaris B of 5.90 ± 0.29 mas. Since we note that DR1 flags the positions of Polaris B and the reference stars as being based upon a “Galactic Bayesian prior for parallax and proper motion relaxed by a factor of ten,” we decided not to include the Gaia measurement in our final solution. Nonetheless, the excellent agreement of the FGS and Gaia DR1 astrometry strengthens our conclusion that our measurements have not been contaminated by the presence of Polaris A.

3. Discussion: Puzzles of the Polaris System

3.1. Does Polaris Pulsate in the Second Overtone?

Assuming the FGS parallax of 6.26 ± 0.24 mas, a mean apparent magnitude of $\langle V \rangle = 1.982$, and a reddening of $E(B-V) = 0.01 \pm 0.01$ (see Sections 2.1–2.2), we find the mean absolute magnitude of Polaris A to be $M_V = -4.07 \pm 0.09$. In Figure 1, we plot (black filled circles) the Leavitt period–luminosity relation ($\langle M_V \rangle$ versus logarithm of the fundamental pulsation period) for the following Galactic Cepheids with well-determined distances: (1) those for which B07 measured trigonometric parallaxes with FGS; (2) SY Aurigae and SS Canis Majoris, for which parallaxes have been measured with HST spatial scans by Riess et al. (2014) and Casertano et al. (2016), respectively; (3) the long-period Cepheid RS Puppis, for which the distance was determined from light echoes in the surrounding dust (Kervella et al. 2014). The three red filled circles in Figure 1 show the positions of Polaris under the assumptions that it pulsates in the fundamental mode (marked “F”), first overtone (“1O”), or second overtone (“2O”). For the first overtone, we “fundamentalized” the period using the relation given for Galactic Cepheids by Alcock et al. (1995), based on beat Cepheids pulsating in both the fundamental and first overtone: $P_{1O}/P_{fund} = 0.720 - 0.027 \log P_{fund}$. For the second-overtone period, we adopted the ratio $P_{2O}/P_{1O} = 0.8007$ from Antonello et al. (1986), based on their data on the double-mode (first and second overtones) Cepheid CO Aurigae.

Figure 1 indicates that, assuming the FGS parallax of B to be correct and applicable to A, Polaris A is likely to be pulsating in the second overtone, in order for it to agree with the Leavitt

Figure 1. Location of Polaris in the Leavitt period–luminosity relation (mean absolute $V$ magnitude vs. logarithm of the fundamental-mode pulsation period), assuming the FGS parallax of 6.26 ± 0.24 mas measured for the companion star, Polaris B. The observed period is 3.969 days ($\log P = 0.599$). If this is the period of the fundamental mode, Polaris lies at the red filled circle marked “F.” If instead it pulsates in the first overtone, the corresponding “fundamentalized” period is the one marked “1O.” If the pulsation is at the second overtone, the fundamentalized period is the one marked “2O.” The black filled circles show the Leavitt relation for Galactic Cepheids, based on the FGS trigonometric parallaxes of Benedict et al. (2007), the HST spatial-scan parallaxes of Riess et al. (2014) and Casertano et al. (2016), and the light-echo distance of RS Puppis (Kervella et al. 2014).

9 For reasons given in, e.g., VandenBerg et al. (2014, their Section 5), we have not applied a Lutz–Kelker correction to the absolute magnitude. In any case, the correction to the $M_V$ of Polaris, using the formulation of Hanson (1979), would be only about $-0.015$ mag, much smaller than the uncertainty of the value.
law based on well-determined parallaxes of Galactic Cepheids. (The Hipparcos parallax of Polaris A yields an \( (M_V) \) of \(-3.66\), consistent with either first- or second-overtone pulsation. The large parallax advocated by TKUG13 gives \( (M_V) = -3.03 \) and implies fundamental-mode pulsation, as they have argued.)

The second-overtone pulsation suggested for Polaris by Figure 1 is surprising and puzzling. The MACHO and OGLE surveys have identified a number of first-, second-, and third-overtone Cepheids in the Large and Small Magellanic Clouds (e.g., Soszyński et al. 2015a, 2015b). These data indicate a trend toward higher overtones with decreasing stellar metallicity. Theoretically, this can be explained by an increase in the temperature range of the blue loop in the H-R diagram to higher temperatures at lower metallicity. This results in a larger fraction of overtone pulsators, which are hotter than fundamental-mode pulsators. However, the longest periods observed for first-overtone pulsators in the Magellanic Clouds are about 6 to 6.5 days. The longest periods for second-overtone pulsators are about 1.6 days, considerably shorter than the 3.969-day period of Polaris. Moreover, the higher Galactic metallicity should result in shorter upper-limit periods for first-overtone pulsators, and even shorter ones for the second overtone.

In addition, the radius of Polaris A can be inferred from the angular diameter given by interferometry (3.123 ± 0.008 mas; Mérand et al. 2006). For our FGS-based distance, this implies a radius of 53.6 \( R_\odot \). At this radius, the (non-canonical) period-radius relation of Boni et al. (2001) implies better agreement with a first-overtone than a second-overtone pulsator.

On the other hand, our suggestion that Polaris pulsates in the second overtone appears to be in accord with some known properties of overtone pulsators. In fact, Polaris has a number of characteristics that are uncommon in fundamental-mode Cepheids, and might indicate pulsation in a mode beyond the normal fundamental and first overtone:

1. Polaris has an unusually rapid rate of period change, much faster than would be expected for evolution through the instability strip (e.g., Neilson et al. 2012). Overtone pulsators are known to have larger fluctuations and instabilities in their pulsation cycles than fundamental-mode pulsators (e.g., Evans et al. 2002, 2015). This leads to the suggestion that the observed period changes in overtone pulsators may be partly driven by evolution through the instability strip, and partly caused by instability in the pulsation cycles. Evans et al. (2002) argued that this is a natural consequence of the different envelope locations—deeper in the envelope for the fundamental mode—that dominate pulsation growth rates. This effect could plausibly be expected to be even more pronounced in a second-overtone pulsator.

2. Polaris is also virtually unique in having shown a long-term decrease in pulsation amplitude, followed in recent years by a partial recovery (e.g., Evans et al. 2002; Turner et al. 2005; Bruntt et al. 2008; Neilson et al. 2016, and references therein). The only other known Galactic Cepheid with a remotely similar variable amplitude is V473 Lyrae, which Molnár & Szabados (2014) and Molnár et al. (2017) have argued is a second-overtone pulsator. A more extensive discussion of these properties will be given in a paper currently in preparation (N. R. Evans et al.).

Second-overtone Cepheids pulsating at a single period are at best rare. On the other hand, without additional information such as a distance, they are not easy to identify among Galactic Cepheids, so our sample may be seriously incomplete. This is particularly true for very small-amplitude variables, for which Fourier light-curve parameters, typically used as mode diagnostics, are not available.

### 3.2. Peculiarities of Polaris B

Figure 2 shows a color–magnitude diagram (CMD; absolute \( V \) magnitude versus \( B - V \) color) for Polaris A and B, using absolute magnitudes calculated by applying our FGS parallax to both stars. We also plot isochrones for solar metallicity and ages of 75 Myr and 2.1 Gyr, obtained from the MIST website\(^\text{10}\) (Choi et al. 2016; Dotter 2016). The 75 Myr age was chosen so that the isochrone would pass through Polaris A, assuming it to be on the third passage through the Cepheid instability strip. The 2.1 Gyr isochrone passes through our point for Polaris B.

Although the 75 Myr isochrone satisfactorily reproduces the position of Polaris A, it fails badly for Polaris B. The latter’s absolute magnitude, for our parallax of 6.26 ± 0.24 mas, an apparent magnitude of \( V = 8.65 \pm 0.02 \) (Evans et al. 2008 and references therein) and \( E(B − V) = 0.01 \), is \( M_V = 2.60 \pm 0.08 \). The isochrone magnitude at the color of Polaris B [taken to be \( (B − V)_0 = 0.41 \pm 0.02 \)] is 3.73, with an uncertainty of about \( ±0.13 \) mag due to the uncertainty in the \( B − V \) color and the steepness of the main sequence.

The 2.1 Gyr isochrone passing through Polaris B has an age far too large to be consistent with Polaris A. This is true even if we adopt the Hipparcos parallax, which would give Polaris B an absolute magnitude of \( M_V = 3.00 \), still too bright. The large

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\(^{10}\) http://waps.cfa.harvard.edu/MIST/interp_isos.html
parallax advocated by TKUG13 gives $M_v = 3.64$, in good agreement with the young isochrone—which was one of their arguments for the large parallax—but the direct parallax measurements by Hipparcos and FGS are both considerably smaller.

We consider three alternatives to explain the apparently discrepant ages of Polaris A and B that arise if we assume that the FGS parallax applies to both stars: (1) In spite of the strong evidence presented in the literature and summarized in Section 1, B is actually not a physical, coeval companion of the Cepheid, but instead an unrelated, slightly evolved F dwarf with an age of $\sim 2.1$ Gyr. This interpretation requires a set of extraordinary coincidences in angular separation, metallicity, radial velocity, and proper motion. This appears highly improbable, but it is not physically impossible. (2) Polaris B is a physical companion with the same young age as the Cepheid, but it is unusually luminous. One possibility might be that it is an unresolved (even by FGS) binary, but the FGS parallax places it more than the maximum possible 0.75 mag above the main sequence. This would seem to require that B is currently in a transitory state of high luminosity, perhaps because of a recent stellar merger. This scenario may in principle be testable, e.g., by searching for a rapid rotation rate or variability, or for an infrared excess; but such tests are made difficult by the presence of the nearby, very bright Cepheid. (3) The system’s age is in fact given by Polaris B, $\sim 2.1$ Gyr, and it is Polaris A that appears anomalously young. In this picture, A could be descended from a blue straggler that merged at some time in the past. However, the position of A in the CMD of Figure 2 requires a mass of about 5.9 $M_\odot$. The mass of B from its position on the 2.1 Gyr isochrone in Figure 2, is $\sim 1.5 M_\odot$. This makes it difficult to understand how Polaris A could be descended from a blue straggler of more than about 3 $M_\odot$.\footnote{The 75 Myr isochrone plotted in Figure 2 is for nonrotating stars. The effects of rotation and main-sequence convective overshoot on the evolution of Cepheids and their progenitors have been studied by many authors (e.g., Anderson et al. 2014 and references therein). Inclusion of rotation in the evolutionary sequences could reduce the implied mass of Polaris A by $\sim 10$–20% (Anderson et al.), but a blue-straggler scenario would still be inconsistent with the low mass of Polaris B.} We could speculate that Polaris A might have merged very recently and could still be temporarily overluminous, but there is no direct evidence for this, such as a high rotational velocity for the star.

3.3. Summary

We have used the FGS system on HST to measure the trigonometric parallax of Polaris B. We find a parallax of 6.26 $\pm$ 0.24 mas, which is 1.28 mas smaller than that found by the Hipparcos mission for the primary star, the Cepheid Polaris A. Under the assumption that the Cepheid is a physical companion of B, our result implies a high luminosity and suggests it is pulsating in the second overtone of its fundamental mode. However, the location of B in the HR diagram indicates that it is an evolved star with an age of $\sim 2.1$ Gyr. The discrepancy with the young age of the Cepheid appears to suggest one of two possibilities: (1) Polaris B is actually a background star that is physically unrelated to A (in spite of the strong evidence that it is a true companion); or (2) one of the stars in the system is peculiar: either the system is young and B is in a transitory state of high luminosity, or the system is old, and it is A that appears anomalously young. It should be noted that even if the Hipparcos parallax of A is correct, these puzzles still exist as long as B is considered to be a physical companion. These issues may be resolved once Gaia parallaxes of both stars are available.

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