IS POLARIS LEAVING THE CEPHEID INSTABILITY STRIP?

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ABSTRACT. Although Polaris is generally regarded as an overtone pulsator that may soon switch to pulsation in the fundamental mode, it is argued that the variable is actually crossing the instability strip for the first time and is in the process of leaving the instability strip altogether. The luminosity of Polaris inferred from its optical F3 V companion, as well as from A, F, and G-type stars lying within a few degrees of it and populating a group main sequence coincident with that for Polaris B, is $\langle M_V \rangle = -3.07 \pm 0.04$ s.e., consistent with fundamental mode pulsation. The star's rate of period increase, 4.5 s yr^{-1}, is also consistent with predictions from stellar evolutionary models for a fundamental mode pulsator crossing the instability strip for the first time, and its location redward of strip center agrees with similar predictions supporting a bluer instability strip for such stars. The onset of a much-reduced and irregular pulsation amplitude that began shortly after 1963–1966, when there was a glitch in the star's O–C data, suggests that the process of leaving the instability strip may have begun at that time. High quality photometric and radial velocity data for Polaris show no evidence for a second periodicity in its light signal that might indicate overtone pulsation. In summary, Polaris seems most likely to be a Cepheid that is crossing the instability strip for the first time and is now beginning the lengthy process of departing the instability strip altogether.

Key words: stars: variable: Cepheids — stars: individual (Polaris).

1. Introduction

The North Star, Polaris (α UMi), as well as being the brightest and closest of 40 Cepheids visible without optical aid, is one of the most intriguing, extensively discussed, frequently studied, and perhaps misinterpreted objects in the sky. Its light variability was suspected a century and a half ago by Seidel (1852) and Schmidt (1857), as well as by Pannekoek in the 1890s (Pannekoek 1913), from visual comparisons with β UMi, and was confirmed in a photographic study by Hertzsprung (1911). The light amplitude a century ago was small, only $0^m.11 \pm 0^m.01$, and has decreased in recent years. In the *General Catalogue of Variable Stars* it was originally listed as a Type II Cepheid, although it is definitely a Type I pulsator.

Many current ideas about the nature of Polaris are tied to the parallax derived for it by the *Hipparcos* mission (ESA 1997). But a recent investigation of the evolutionary period increase in the star reaches different conclusions (Turner et al. 2005). This paper summarizes the known properties of the star in order to clarify the true nature of the variable.

2. Companion Stars

Polaris is a stellar triple, with an unseen AF-type dwarf orbiting it every 29.6 yrs according to radial velocity observations, and an F3 dwarf, 19 arcsec distant, sharing its space motion (Kamper 1996; Weilen et al. 2000). Two fainter optical companions may also be part of the system, but would be of very late spectral type if *bona fide* members (Fernie 1966).

The optical companion to Polaris is an F3 V dwarf (Turner 1977) that can be used to establish the reddening and distance of the Cepheid (Gascoigne & Eggen 1957; Fernie 1966; McNamara 1969; Turner 1977; Turner 1984). But existing photometry for Polaris B is often contaminated by stray light from the much brighter Cepheid. Photometry by McNamara (1969) indicates that his data may be unaffected by that influence. He finds $V = 8.60$ for Polaris B, a result confirmed from CCD imaging by Kamper (1996).

Table 1: Properties of Polaris B.

V	B–V	U–B	Data Source
···	0.41	···	Gascoigne & Eggen (1957)
···	0.42	0.01	Fernie (1966)
8.60	0.41	0.01	McNamara (1969)
8.60	···	···	Kamper (1996)
···	0.42	···	Turner et al. (2005)
8.60	0.42	0.01	Best Values
Sp.T.	F3 V		Turner (1977)

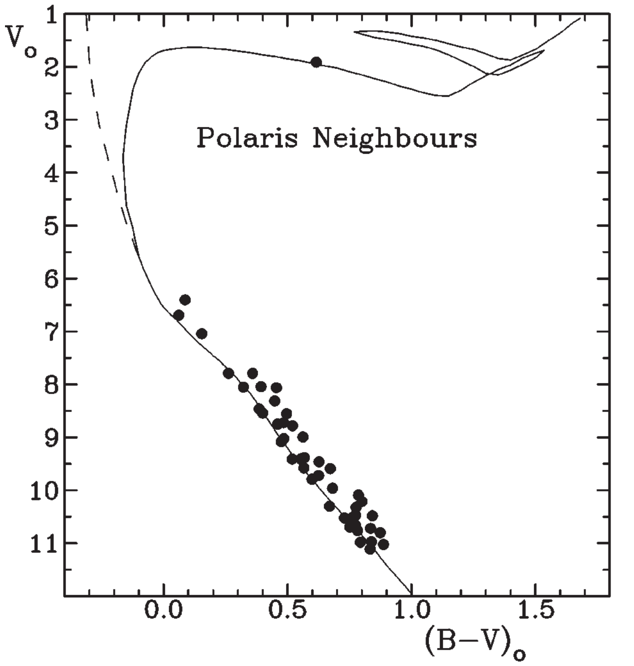

Figure 1: Unreddened colors and magnitudes for A, F, and G-type stars in the field of Polaris (E_{B-V} = 0.02) along with a ZAMS fit for $V_0 - M_V = 4.98$. The isochrone corresponds to log t = 7.9, the dashed line to the ZAMS.

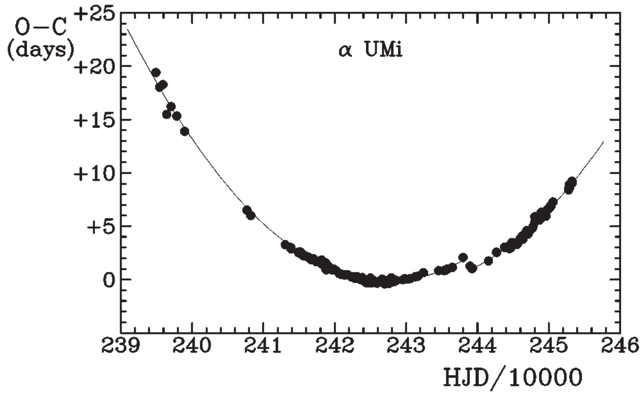

Figure 2: O–C data for Polaris from 1844 to 2004 obtained from the analysis of photometric and radial velocity observations and corrected for the star's orbital motion. The plotted curves depict the parabolic trend of the data resulting from evolutionary effects. A glitch occurs between 1963 and 1966.

Table 1 gives the results of a new analysis of existing photometry for the companion after adoption of V = 8.60 for the star. Existing observations include the transformed *PV* data of Gascoigne & Eggen (1957), Fernie's (1966) *UBV* observations (by private communication) newly reanalyzed, McNamara's (1969) Strömgren photometry adjusted to the system of Schmidt (see Turner et al. 1987) and transformed to the *UBV* system (Turner 1990), and new *BV* observations obtained in connection with the study by Turner et al. (2005).

The various adjusted observations agree well, and in conjunction with the star's F3 V spectral type, imply a reddening of $E_{B-V} = 0.02 \pm 0.01$ s.e. and $V_0 - M_V = 5.02 \pm 0.07$ s.e. to the system, or $d = 101 \pm 3$ pc. The *Hipparcos* parallax for Polaris implies a larger distance of $d = 132 \pm 8$ pc, which is inconsistent with the adopted zero-age main-sequence (ZAMS) luminosity for Polaris B. The implied absolute magnitude for Polaris is $\langle M_V \rangle = -3.09 \pm 0.07$ s.e. as tied to the companion, and $\langle M_V \rangle = -3.68 \pm 0.14$ s.e. according to the *Hipparcos* parallax. The predicted luminosity for fundamental mode pulsation is $\langle M_V \rangle = -2.93 \pm 0.08$, and $\langle M_V \rangle = -3.40 \pm 0.08$ for first overtone pulsation (Turner 1992).

It may be possible to refine those estimates, since there is evidence suggesting the existence of a loose group of A, F, and G-type stars lying within three degrees of Polaris that may constitute the remains of a sparse cluster containing the Cepheid (Turner et al. 2005). Polaris B is a very likely member of the group. The implied distance modulus for the cluster from ZAMS fitting of *Hipparcos BV* data for likely group stars, including the results of Table 1 for Polaris B and adopting its reddening for the group, is $V_0 - M_V = 4.98 \pm 0.04$ s.e., or $d = 99 \pm 2$ pc, as illustrated in Fig. 1. The implied luminosity for Polaris is $\langle M_V \rangle = -3.07 \pm 0.04$ s.e., consistent with fundamental mode pulsation. The implied age of the group is $\sim 8 \times 10^7$ yr when Polaris is included as a member.

3. Period Changes

The rapid period changes in Polaris have a lengthy history (see Turner et al. 2005), and are consistent with a period increase amounting to 4.5 s yr^{-1}. Fig. 2 illustrates the regularity of the parabolic (evolutionary) trend in the O–C data once the times of maximum light and minimum radial velocity have been adjusted for light travel time in the unseen binary system and the displacement between light and radial velocity curves for the star (see Turner et al. 2005). The rate of period increase agrees closely with predictions from published stellar evolutionary models for a Cepheid crossing the instability strip for the first time (Turner et al. 2006), as illustrated in Fig. 3. The brief glitch in the O–C data between 1963 and 1966 is a puzzle, but, if attributed to the assimilation of a 7 Jovian mass planet, provides an additional argument that Polaris is a first crosser.

At roughly the same time as Polaris was experiencing a glitch in its pulsational period increase, the star's

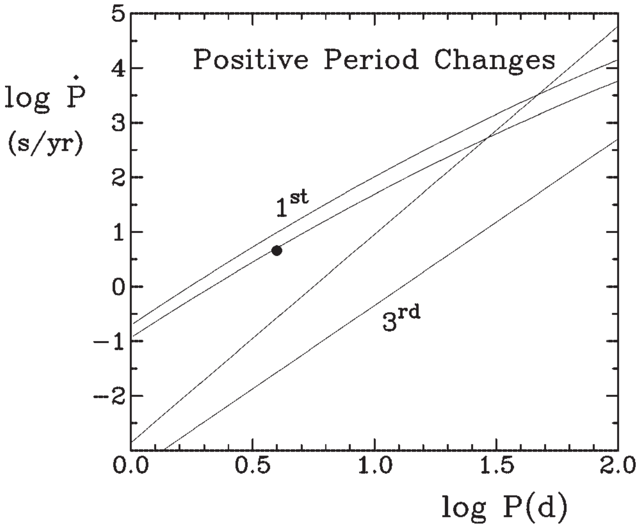

Figure 3: Expected period changes for Cepheids in first and third crossings of the instability strip as predicted from stellar evolutionary models. The bands denote the range of model predictions for the rates of period change, while the point is the observed result for Polaris.

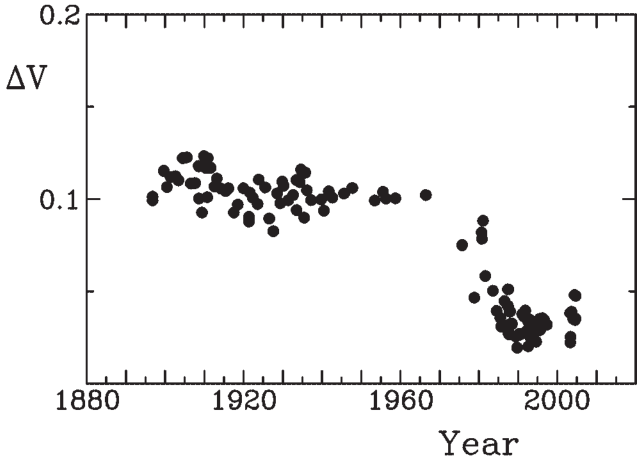

Figure 4: Observed secular trends in the amplitude of visual brightness variability for Polaris.

light amplitude began a marked decline from previous levels, as illustrated in Fig. 4. The light amplitude ΔV is presently irregular, and varies slowly on a cycle-to-cycle basis, but always at levels between $0^{m}.02$ and $0^{m}.05$ (Evans et al. 2004; Turner et al. 2005). The abrupt change in character of the star's pulsation amplitude around 1970 suggests that at that time it may have undergone a sudden change in the manner in which it is crossing the Cepheid instability strip.

The atmospheric composition of Polaris (Usenko et al. 2005) displays the usual characteristics of a gas that has been associated with hydrogen burning via the CNO cycle, but that cannot be tied to its instability strip crossing mode, for example by arguing that atmospheric contamination from the stellar core is produced by dredge-up during evolution through the red supergiant stage. As noted by Maeder (2001), the observed atmospheric signatures of CNO burning are found in many intermediate-mass stars near the terminal stages of hydrogen burning, and can be matched to models of meridional mixing in rapidly rotating stars. Additionally, many current stellar evolutionary models for intermediate-mass stars predict that convection in the outer layers of red supergiants does not penetrate deep enough to produce atmospheric contamination through dredge-up. The observed atmospheric signatures of CNO burning in Cepheids certainly display no obvious trends that can be tied to instability strip crossing mode (Turner & Berdnikov 2004).

4. Pulsation Mode

A number of factors have conspired to imply that Polaris is an overtone pulsator. First, the *Hipparcos* parallax implies a luminosity well in excess of that for fundamental mode pulsation. Second, the intrinsic color of Polaris for overtone pulsation places it on the blue side of the instability strip, consistent with the location of double-mode and overtone Cepheids. Lastly, arguments are made occasionally that the signature of incipient fundamental mode pulsation may be detected in its light and/or radial velocity variations.

Regarding the last point, observations of Polaris are notoriously difficult to obtain, and in most data samples one can find examples of spurious observations that may have deleterious effects on period-finding routines. Seasonal effects and the 29.6-yr orbital motion of Polaris about its unseen companion can also conspire to create alias periods in periodogram analyses for the star.

An exception appears in the tellurically-calibrated CCD eschelle radial velocity measurements of Kamper & Fernie (1998), which are of very high precision and accuracy. Fig. 5 presents a periodogram analysis of the *residuals* from Kamper & Fernie's measures after fitting the main signal to the known 4-day pulsation period of Polaris and accounting for seasonal effects on the zero-point for the measures as well as orbital motion about the companion. Kamper & Fernie cite a minimum uncertainty for the observations of about ± 0.004 km s^{-1}, which is depicted by the level of the dotted line in Fig. 5. The frequencies corresponding to pulsation periods of 4 and 5.7 days are indicated, the latter being the appropriate period for fundamental mode pulsation if the observed periodicity is that for first overtone pulsation.

It can be seen that there is no residual signal in the data of any significance, particularly around a

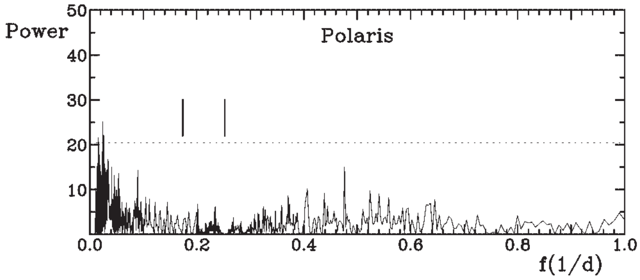

Figure 5: A periodogram analysis for the radial velocity observations of Kamper & Fernie (1988) adjusted for seasonal and orbital variations in zero-point and prewhitened by the removal of the sinusoidal 4-day periodicity in the data. The dotted line depicts the strength of a signal generated by uncertainties in the observations, and vertical lines denote the frequencies corresponding to periods of $5^d.75$ (left) and $4^d.00$ (right).

putative fundamental mode period of 5.7 days. The prewhitening of the radial velocity data is also seen to remove all evidence for the primary 4-day periodicity in the velocities. It seems clear that Polaris does not exhibit any unambiguous evidence for overtone pulsation, as also confirmed by the high precision photometric observations of the star by Evans et al. (2004) using the star camera on the *Wide Field Infrared Explorer* satellite.

5. Discussion

Taken together, all of the various observed characteristics of Polaris can be attributed to fundamental mode pulsation in a Cepheid that is crossing the instability strip for the first time and seems likely to be in the process of leaving it on the cool (redward) side. The intrinsic colors of Polaris place it slightly redward of center in the instability strip observed for other Galactic Cepheids, but outer-layer convection tends to damp out pulsation in first crossers much more efficiently than in stars in higher strip crossing modes (Alibert et al. 1999). There is therefore no ambiguity between the star's location in the H-R diagram and the conjecture that it is a first-crossing, fundamental-mode pulsator.

Of greater interest is the possibility of using Polaris as a Galactic calibrator for the Cepheid period-luminosity relation. The star's unique characteristics — closest and brightest Cepheid, one of only a few stars identified as likely first crossers, extremely small light amplitude, and imminent departure from the instability strip — distinguish it from all other Galactic Cepheids known to belong to open clusters. It therefore seems imperative to study the space motions of the stars around Polaris in order to establish if they are physically associated with the Cepheid, as is the case for its optical F3 V companion.

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