The Ellipsoidal Variable b Persei

Steven L. Morris
Los Angeles Harbor College, Physics Dept., Wilmington, CA 90744; MorrisSL@lahc.edu

Received February 26, 2014; revised March 19, 2014 and April 4, 2014; accepted May 1, 2014

Abstract The bright (V = 4.6) ellipsoidal variable b Persei is unique, as it is a triple system that experiences an eclipse of the primary and secondary stars every 701.76 days by the tertiary component. This paper analyses the ellipsoidal light variations to show that the mass ratio is q = 0.28 ± 0.02 and the inclination is i = 43 ± 3°. Modeling the system with the Wilson-Devinney computer code leads to similar values of q = 0.25 ± 0.03 and i = 49 ± 10°.

1. Introduction

The star b Persei should not be confused with the better-known β Persei (= Algol = HR 936), which is 15.3° southwest of b Persei and is the prototype of the Algol eclipsing variable stars. The star b Persei (= HR 1324) consists of a bright primary star close to a faint, unseen secondary star in an orbital plane that does not generate eclipses. This close pair is orbited by a faint, distant tertiary star that is now known to eclipse the inner pair.

Ellipsoidal variable stars are close binaries whose components are distorted by their mutual gravitation. Though physically similar to eclipsing binaries with out-of-eclipse light variations, they have orbital inclinations that are too small to create eclipses, resulting in light variations that are typically only a few hundredths of a magnitude.

The slight light variations and the paucity of information that can be obtained from them have left the ellipsoidal variables as a neglected class of variable stars. Morris (1985) presents tables of confirmed, suspected, and rejected ellipsoidal variables, and describes a method of combining photometric and spectroscopic information to determine the physical parameters of such systems.

2. Previous work

Until recently, b Persei shared in this general neglect, despite its brightness (V = 4.6), short period (P = 1.5273639 days), and its accessibility to northern observers (δ = +50°). Stebbins (1923) discovered the variability of this star and published a good but unfiltered photoelectric light curve. The only other published light curve is by Duerbeck and Schettler (1979) who found, after their observations were obtained, that their DC amplifier was unstable.

Their published normal points are too noisy to be of much use in analyzing this system. A good comprehensive study of the radial-velocity data of this single-lined spectroscopic system is by Hill *et al.* (1976), who found that this is a triple system, with the tertiary star orbiting the close binary with a period of 701.76 days. They noted that five spectrographic plates taken on 1973 October 3 showed discrepant velocities that could be due to a partial eclipse by the tertiary star.

This system is of particular interest because it belongs to the small class of close binary systems with weak, non-periodic, non-thermal radio emission flares. Hjellming and Wade (1973) discovered the intermittent emission at 8.085 GHz, and Spangler *et al.* (1977) lists a possible detection at 5.0 GHz. Gibson and Hjellming (1974) modeled this radio emission as due to gravitational energization of matter flowing from one star to the other through the inner Lagrangian point of the system. This provides an important constraint in modeling b Persei, by forcing either the primary or secondary star to be close enough to filling its inner Lagrangian surface that the star provides enough matter to generate detectable radio emission flares.

The projected rotational velocity of the primary also provides a valuable constraint on models of the system, as short-period binaries are expected to be in synchronous rotation. Published values of vsini range from 70 km/s (Abt and Morrell 1995) to 98 ± 4 (Olson 1968). Hill *et al.* (1976) use vsini = 87 ± 3 km/s in their analysis, and this value is adopted for the present paper.

A study of the system's radial velocities by Hill *et al.* (1976) determined a mass function f(m) = 0.00966 $M_\odot$ for the single-lined spectroscopic binary formed by the primary and secondary stars, and a mass function f(m) = 0.0987 $M_\odot$ formed by the inner pair and the tertiary star. More recent work has not substantially altered these values.

One other constraint on the entire system is the separation of the tertiary star from the inner pair. Halbwachs (1981) calculated a maximum separation of 0.044 seconds of arc, so it is not surprising that the system has only recently been resolved by Hummel *et al.* (2013) with the Navy Precision Optical Interferometer, at a separation of 0.0095 seconds of arc.

In February 2013, Collins (2013) observed an eclipse of the ellipsoidal pair by the tertiary star of this system. Thus, b Persei in future may provide a unique light curve of two primary eclipses, distorted by the rapidly-changing positions of the inner pair. The parameters of this inner pair are now of considerable interest, and a high-quality, modern light curve is needed. In the meantime, photometry obtained in the 1980's and not previously published are here presented, along with an analysis.

3. Observations

The b Persei system was observed by the author on eight photometric nights at the Kitt Peak #4 16-inch reflector during February 1981. λ Persei was used as the comparison star because it is similar in color and magnitude to b Persei, and because it was the comparison star used by Stebbins (1923). An RCA gallium arsenide model #C31034A-02 photomultiplier tube was used in conjunction with a set of Johnson UBVRI filters as described by Bessell (1979), and in conjunction with a glass neutral-density filter (3.00 magnitudes in the V bandpass) because of the brightness of these stars. On each night, two blue and red pairs of standard stars were observed at small and large airmass to obtain the nightly extinction and transformation coefficients. These standard stars were taken from the lists of Crawford *et al.* (1971) and Barnes and Moffett (1979).

The times of primary minimum (assuming a circular orbit) are calculated from the elements of Hill *et al.* (1976) to be Min. I (hel.) = 2440001.49 + 1.5273639E. Radial velocities indicate that this occurs when the primary (A2 V) star is farthest from the observer. The original 132 data points per filter may be seen in the light curves of Morris (1983).

4. Analysis

All available b Persei light curves were fitted by least-squares to obtain discrete Fourier series coefficients, to compare the light curves with each other and to derive parameters of the binary system by using the method of Morris (1985). Sine terms, and cosine terms higher than $4\pi\times\varphi$ were found to be insignificant and were discarded, and the coefficients of the significant terms are given in Table 1. The mean magnitudes of b Persei on the Johnson UBVRI system were found to be 4.644 ± 0.004, 4.655 ± 0.005, 4.622 ± 0.003, 4.506 ± 0.004, and 4.524 ± 0.004, respectively.

A comparison between the C_0 values shows that Stebbins' unfiltered system is most closely approximated by Johnson's B bandpass, and a comparison of

Table 1. The coefficients fitting $C_0 + C_1\cos(2\pi\times\varphi) + C_2\cos(4\pi\times\varphi)$ to the differential light curves, with λ Persei as the comparison star. The values in parentheses are the uncertainties of the last one or two digits.

Source	*Bandpass*	C_0	C_1	C_2
This paper	U	0.487(4)	0.009(2)	0.032(2)
	B	0.382(5)	0.003(2)	0.023(2)
	V	0.327(3)	0.007(1)	0.028(2)
	R	0.289(4)	0.010(2)	0.024(2)
	I	0.241(4)	0.015(2)	0.029(2)
Duerbeck & Schettler (1979)	U	0.491(8)	0.006(11)	0.034(12)
	B	0.368(10)	–0.008(15)	0.042(15)
	V	0.325(11)	–0.003(15)	0.038(16)
Stebbins (1923)	~B	0.374(1)	0.004(1)	0.024(1)

the C_1 and C_2 values indicate that the light curves have remained stable for several decades. The uncertainties of the C_1 and C_2 coefficients of Duerbeck and Schettler's data are so great that it seems reasonable to exclude them from further analysis.

The contributions to the luminosity of the system by the secondary and tertiary stars can be taken into account before modeling the variability of the primary. The secondary and tertiary lines are not clearly seen in the spectrum, but Hill *et al.* (1976) analyzed both the distortions in the hydrogen lines due to blending and the thirteen-color photometry of Mitchell and Johnson (1970) to find that the secondary and tertiary are best modeled as F0 V stars, with $\Delta B \sim 3.1$ between both the primary and secondary stars and the primary and tertiary stars.

5. System parameters

As previously mentioned, b Persei exhibits weak, non-periodic, non-thermal radio emission flares, and Gibson and Hjellming (1974) have modeled such radio emission as due to matter flowing through the inner Lagrangian point. The magnitude range of 0.057 ± 0.004 in the V bandpass is much too large to be due to variability of the faint secondary star, so it must be the primary that is filling, or close to filling, its inner Lagrangian surface. As shown below, the lack of eclipses indicates that the secondary star is indeed too small to fill its own inner Lagrangian surface.

If the primary star is assumed to fill its inner Lagrangian surface and to have a mass of $2.25M_{\odot}$ estimated from its spectral classification, the method of analysis in Morris (1985) determines that the system's mass ratio is $q = 0.28 \pm 0.02$, its inclination is $i = 43 \pm 3°$, and its projected rotational velocity is $v\sin i = 91 \pm 7$ km/s, which is reasonably close to the value of 87 ± 3 km/s from Hill *et al.* (1976). The radius of the primary star would be 4.1 ± 0.2 $R_{\odot}$, which is larger than expected for an A2 V star, but may be justified by the primary's recent reclassification as A1 III by Abt (2009). The inclination is larger than the maximum value of 34.45° for a non-eclipsing contact system (Morris 1999), implying that the secondary star does not fill its inner Lagrangian surface.

The Wilson-Devinney computer code as described by Wilson and Devinney (1971) was also used to analyze this system, and it was found that the values of the mass ratio are tightly constrained, as $q < 0.20$ generates eclipses and $q > 0.29$ creates overflow of the primary star's inner Lagrangian surface. The normals (binned averages) of the data points are presented in Table 2, and Figure 1 shows the V light curve normals, symmetric around $\varphi = 0.50$. If the primary star's temperature is assumed to be $T_1 = 9000$ K based on its spectrum, then the most probable model of the system has $T_2 = 5500 \pm 500$ K, $q = 0.25 \pm 0.03$, $i = 49 \pm 10°$, $R_1 = 3.4 \pm 0.4$ $R_{\odot}$ and, $R_2 = 2.1 \pm 0.3$ $R_{\odot}$.

Table 2. Normals of the Johnson UBVRI photoelectric photometry of b Persei obtained in February 1981. The phases are calculated from Primary Minimum = HJD 2440001.49 + 1.5273639E.

Phase	*U*	*Phase*	*B*	*Phase*	*V*	*Phase*	*R*	*Phase*	*I*
0.0566	4.670	0.0452	4.699	0.0579	4.642	0.0425	4.502	0.0475	4.563
0.0973	4.668	0.0779	4.664	0.1000	4.635	0.0754	4.527	0.0875	4.538
0.1181	4.657	0.1128	4.664	0.1217	4.633	0.1122	4.519	0.1163	4.536
0.1384	4.642	0.1327	4.661	0.1437	4.621	0.1322	4.517	0.1374	4.532
0.1569	4.628	0.1529	4.647	0.1602	4.612	0.1526	4.503	0.1565	4.516
0.1728	4.631	0.1680	4.644	0.1774	4.611	0.1676	4.501	0.1721	4.523
0.1952	4.624	0.1889	4.639	0.2008	4.604	0.1883	4.494	0.1941	4.515
0.2240	4.616	0.2165	4.632	0.2288	4.594	0.2151	4.485	0.2222	4.509
0.2527	4.620	0.2437	4.628	0.2609	4.593	0.2434	4.483	0.2551	4.496
0.3239	4.617	0.3049	4.635	0.3311	4.600	0.3052	4.489	0.3217	4.485
0.3679	4.631	0.3596	4.657	0.3668	4.610	0.3569	4.489	0.3634	4.500
0.4010	4.648	0.3926	4.667	0.3928	4.616	0.3896	4.497	0.3961	4.510
0.4219	4.653	0.4176	4.666	0.4170	4.630	0.4164	4.514	0.4207	4.527
0.4402	4.661	0.4345	4.664	0.4342	4.635	0.4338	4.508	0.4392	4.535
0.4623	4.659	0.4574	4.666	0.4575	4.641	0.4577	4.517	0.4627	4.539
0.4787	4.667	0.4756	4.673	0.4757	4.643	0.4755	4.526	0.4800	4.543
0.4919	4.668	0.4912	4.671	0.4913	4.647	0.4916	4.519	0.4939	4.542

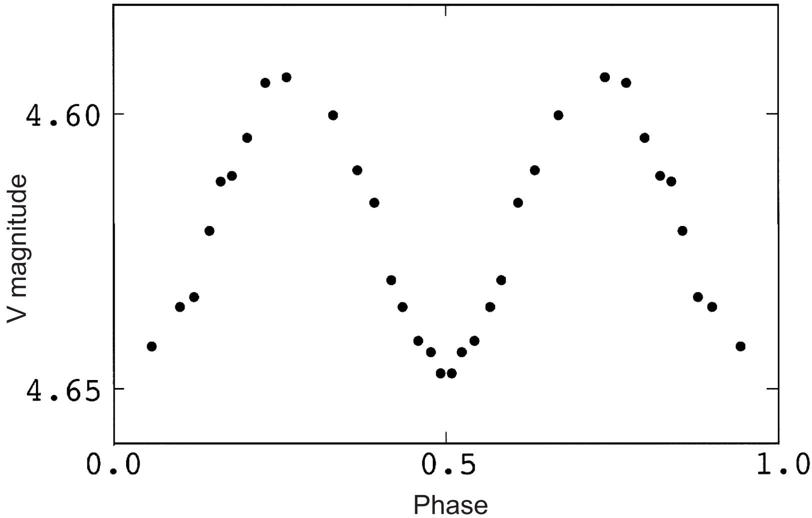

Figure 1. The light curve of b Persei (= HR 1324), symmetric around Phase = 0.5. The data for these normals were obtained in February 1981.

While these two different analyses are in reasonable agreement, a more accurate determination must await better light curves, a definitive value of vsini, and a mass ratio of the ellipsoidal pair, perhaps taken during mid-eclipse by the tertiary star.

6. Acknowledgements

The author thanks Dr. Eugene Milone for his assistance at all stages of his Ph.D. dissertation. The author also thanks Dr. Bruce Hrivnak for his assistance in learning how to use the Wilson-Devinney computer program.

References

Abt, H. A. 2009, *Astrophys. J., Suppl. Ser.*, **180**, 117.
Abt, H. A., and Morrell, N. I. 1995, *Astrophys. J., Suppl. Ser.*, **99**, 135.
Barnes, T. G., and Moffett, T. J. 1979, *Publ. Astron. Soc. Pacific*, **91**, 289.
Bessell, M. S. 1979, *Publ. Astron. Soc. Pacific*, **91**, 589.
Collins, D. F. 2013, *J. Amer. Assoc. Var. Star Obs.*, **41**, 391.
Crawford, D. L., Golson, J. C., and Landolt, A. U. 1971, *Publ. Astron. Soc. Pacific*, **83**, 652.
Duerbeck, H. W., and Schettler, A. 1979, *Acta Astron.*, **29**, 225.
Gibson, D. M., and Hjellming, R. M. 1974, *Publ. Astron. Soc. Pacific*, **86**, 652.
Halbwachs, J. L. 1981, *Astron. Astrophys., Suppl. Ser.*, **44**, 47.

Hill, G., Aikman, G. C. L., Cowley, A. P., Bolton, C. T., and Thomas, J. C. 1976, *Astrophys. J.*, **208**, 152.

Hjellming, R. M., and Wade, C. M. 1973, *Nature*, **242**, 250.

Hummel, C. A., Zavala, R. T., and Sanborn, J. 2013, *Cent. Eur. Astrophys. Bull.*, **37**, 127.

Mitchell, R. I., and Johnson, H. L. 1970, *Commun. Lunar Planet. Lab.*, **8**, 1.

Morris, S. L. 1983, *The Ellipsoidal Variable Stars*, Ph.D. dissertation, University of Calgary, 57–59.

Morris, S. L. 1985, *Astrophys. J.*, **295**, 143.

Morris, S. L. 1999, *Astrophys. J.*, **520**, 797.

Olson, E. C. 1968, *Publ. Astron. Soc. Pacific*, **80**, 185.

Spangler, S. R., Owen, F. N., and Hulse, R. A. 1977, *Astron. J.*, **82**, 989.

Stebbins, J. 1923, *Astrophys. J.*, **62**, 1.

Wilson, R. E., and Devinney, E. J. 1971, *Astrophys. J.*, **166**, 605.