

HIPPARCOS AND MAP STUDIES
OF THE TRIPLE STAR PI CEPHEI

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ABSTRACT

We reexamine the visual, and radial velocity data for the pi Cephei triple star system and derive the masses of the three components. Our study is based upon the analysis of Hipparcos Intermediate Astrometric Data (IAD), measurements obtained with the red-light Thaw refractor's Multichannel Astrometric Photometer (Thaw/MAP), and positions obtained from photographic plates acquired with the Thaw refractor's original photographic objective. The weighted mean parallax of the star system is now 13.8 ± 0.41 mas, corresponding to a distance modulus of 4.30 ± 0.065 , yielding absolute visual magnitudes of 0.24 ± 0.065 and 2.50 ± 0.070 for the A and B components respectively and a total system mass of $8.81 \pm 0.87 M_{\odot}$. The 58 year span of the plate collection makes possible the first detection of the photocentric motion caused by the 160 yr orbit of pi Cephei A/B yielding masses of $6.88 \pm 0.69 M_{\odot}$ and $1.93 \pm 0.23 M_{\odot}$ respectively for the central spectroscopic giant binary star and the late A secondary component. Though of shorter time span, the higher precision of the IAD and Thaw/MAP data allow the first detection of the astrometric motion caused by the spectroscopic companion of the A component. A comparison of the astrometric, spectroscopic, and photometric studies of the pi Cephei suggests that the spectroscopic binary is composed of a pair of red giants with similar masses, $A_a = 3.63 \pm 0.53 M_{\odot}$, $A_b = 3.27 \pm 0.48 M_{\odot}$, and a red magnitude difference of approximately 1.7 magnitudes. The importance of long term astrometric coverage is pointed out by the fact that the motion of both the A/B system and Aa/Ab system were missed during the compilation of the Hipparcos Catalogue and are only revealed in that data after its detection in the MAP/Thaw measurements.

Subject Headings: Stars: Late-Type, Binaries: Visual and Spectroscopic, Stars: Individual
PiCephei

1. BACKGROUND

Pi Cephei (HR 8819, HIP 114222) was discovered to be a visual binary by Otto Struve (Struve 1843, Crossley, et al. 1979). That the G2 III primary was itself a spectroscopic binary was first noted from spectroscopic plates taken at the Lick 0.91-m refractor (Campbell, 1901). The first spectroscopic orbit of the Aa/Ab system, was published by Harper (1925). In 1969, Trimble and Thorne noted that the mass function of the spectroscopic binary primary star indicated the presence of a massive third component. Abt et al. (1980) confirmed Harper's orbit. The mass function was confirmed and the spectroscopic orbit improved by Scarfe et al. in 1983. Visual observers would have to wait for the A/B periastron in 1934 before a meaningful visual orbit could be derived. The orbital parameters of the most recent full analysis (Baize 1992) still represent new observations reasonably well.

As part of Schlesinger's plan to observe the stars brighter than the 5th magnitude, the Allegheny Observatory began regular photographic observation of the pi Cephei triple star in 1916, well before periastron. This program was extended, and the precision of the data increased by an order of magnitude, with the successful installation of the new objective of the Thaw refractor and the Multichannel Astrometric Photometer (Thaw/MAP) in 1986. Thus pi Cephei has now been observed at the Allegheny Observatory for more than one-half of the visual binary's 160 year orbit. Pi Cephei is Hipparcos star 114222. At a visual magnitude of 4.41 it is an ideal target and the parallax error is listed with a standard error of ± 0.62 , giving us some pause when we found a 10 mas (0.01 arcsec) perturbation in the MAP data. Upon checking the IAD, however, we found that the Hipparcos residuals had an rms error of 19 mas!

Since the spectroscopic binary has not been resolved, our approach will be to determine the parallax of the triple star system and the photocentric shift of the primary subsystem by the visible companion. From the orbital parameters of the visual binary and its parallax we will

derive the total mass of triple system. From the photocentric shift induced by the visual companion (B) we will find its mass and that of the Aa/Ab spectroscopic pair primary. The period and the mass of the spectroscopic subsystem will then be used to derive the size of the semimajor axis of this unresolved inner binary. The short period photocentric shift and the spectroscopic mass function will then be used to derive the magnitude difference and masses of Aa and Ab.

2. DATA AND THE DETERMINATION OF INITIAL PARAMETERS

Our first step was to check the spectroscopic and visual orbits. A reduction of all published radial velocity measurements, allowing for individual differences in the means of each set, resulted in parameters that were in good agreement with those of Scarfe et al. (1983). Our reduction of the available visual measurements of the A/B pair is in general agreement with the orbit of Baize (1992) but, as noted by Söderhjelm (1999), the interferometric measurements seem to favor a slight decrease in the semimajor axis. Because they cover a limited part of the orbit, introducing the latter at higher weight would distort the orbital solution. If the effect is confirmed by future measurements, a more direct approach might be to adopt the Baize orbit with a 3% reduction in the estimated semimajor axis. This would lead to a small reduction of the masses found here.

Unlike most photographic programs, with few exceptions, the 8 by 10 inch plates (0.8 X 1.0 degrees) used at the Allegheny Observatory have a uniform limiting magnitude of approximately 13 (Kamper, 1984). Including most stars brighter than the 5th visual magnitude, north of -10 degrees declination, the targets star's exposure is, where necessary, limited by rotating sectors. The plates are measured on a specially designed granite PDS utilizing a dual

frequency laser interferometer. Image precision is limited by photographic characteristics to approximately 22 mas per exposure with no evidence of correlation of images exposed on the same piece of glass. The specifics of the 265 photographic exposures obtained during the years 1916 through 1973 and the observed standard coordinates are listed at the Allegheny Observatory web site <http://www.pitt.edu/~aobsvtry>

A full description of the Hipparcos mission, instrumentation and resulting data are given in the first volume of the Hipparcos Catalogue (ESA 1997). The instrumentation and reduction procedures utilized for the MAP/Thaw astrometric observations have been described extensively (Gatewood 1987). The transformation of the phase data produced by the MAP to the star constants listed below utilizes the central overlap technique (eg. Eichhorn 1974). The Observatory web site also lists the epochs of the Thaw/MAP observations and the standard coordinates derived from them.

The algorithm by which the absolute parallaxes are determined from the Thaw/MAP data includes the estimation of the intrinsic luminosities of the reference stars. Much of the information for the latter is obtained from a parallel series of reports detailing intermediate band photometry results for Thaw/MAP reference stars (Castelaz and Persinger 1989, Persinger and Castelaz 1990, Castelaz et al. 1991). To estimate the triple star's distance, nine stars were chosen from bright background objects. At the high precision level of the Thaw/MAP instrumentation, stellar parallax causes significant residuals in the positions of the reference frame. Thus we include the best estimate of the spectroscopic parallax of each reference star starting with the first iteration in the reduction algorithm. Parallax terms remain, in all following iterations, among the unknowns that model each star's position and motion. Like the catalog positions, the estimates of the parallax of the reference stars are subject to verification and

possible adjustment. Although differences between the predicted and observed parallax can lead to a re-evaluation of the spectroscopic parallax of a reference star, no such adjustments were made in the current study.

The initial estimates of the parallaxes of AO 990 and AO 991, both B9 stars, came from the Hipparcos catalogue. The spectroscopic parallaxes of stars AO 989, AO 992 and AO 995 are taken from Persinger and Castelaz (1990). An initial pass indicated that both the photometry and preliminary parallax of star AO 988 were indicative of a late G or early K giant. Persinger and Castelaz were inconclusive about the spectral parallaxes of stars AO 993, AO 994, and AO 997. They were not used in the adjustment to absolute.

An unweighted estimate of the adjustment to absolute parallax is used during the computation of the individual sets of field variates. Thus the adjustment of the parallaxes to absolute can still be improved (e.g. Stein 1991). Listed in Table 1 are the Allegheny Observatory (AO) catalog star number and the adopted spectral classification-luminosity type of the reference stars for which spectroscopic parallaxes are estimated. Next we list the visual absorption found by fitting the photometry to the intrinsic colors published by Johnson (1966) and Bessell and Brett (1988). The spectroscopic parallaxes are listed in the next column of Table 1. The estimated standard error of the photometric parallax is 35% of the parallax, see Castelaz et al. It includes an allowance for the spread of luminosities within a luminosity class. The provisional absolute parallax and its calculated standard error, listed in columns six and seven, are the result of the astrometric reduction before the weighted adjustment. Since the calculated standard error, in column 7, does not yet contain an allowance for the standard error of the adjustment being calculated in Table 1, it is somewhat smaller than the standard error listed in Table 2. Column eight, the weighted adjustment is calculated by multiplying the difference

between the provisional parallax and the spectroscopic parallax by the weight, listed in the following column. The weights are the inverse of the sum of the variances of the provisional parallax and of the estimated spectroscopic parallax expressed in thousands of an arc second. The adjustment to a weighted mean, +0.55 mas adjustment, and its standard error, ± 0.22 mas, are listed at the bottom of the Table. The adjustment is based upon the luminosity classifications adopted in Table 1, the absolute magnitudes given by Allen (1976) and the estimated individual interstellar absorption corrections. The adjustment, which is applied throughout Table 2, yields a MAP based parallax of 13.47 ± 0.69 mas.

The positions and motions, at the epoch and equinox of J2000, of the stars observed with the Thaw/MAP are listed in the last four columns of Table 2 above their corresponding standard errors. The positions and motions are on the system of the ICRS as realized in the optical part of the spectrum by the ACT Reference Catalog (Urban et al. 1997) and the Hipparcos Catalogue (ESA 1997). The standard errors are given in units of the last shown digit of the parameter to which they pertain and are strictly internal at J2000. We note that they do not include an allowance for the zero-point, scale, orientation, or proper motion uncertainties of the reference system. Easy cross identification of these stars is afforded by Table 3 which lists the AO, Bonner Durchmusterung (Argelander 1862), and Hipparcos numbers for the stars in this study.

Two Hipparcos based parallax estimates, differing by 3 standard errors, have been published for π Cephei. The main Catalogue lists the parallax as 14.83 ± 0.62 mas while a more recent study (Söderhjelm 1999) lists 12.3 ± 0.7 mas. To resolve this difference and to investigate the residuals noted above two of us, IH and DP, reduced the IAD to the orbital elements of Scarfe et al. (1983). Several different approaches are available (eg. Pourbaix and Jorissen 2000,

Gatewood et al. 2000) including the use of information made available from the NDAC and or FAST Consortium and the adoption of various of the orbital parameters developed from the radial velocity study of Scarfe et al. Since the Hipparcos measurements are one dimensional, their interpretation is more dependent upon the model chosen for the reductions. Each residual is from the measured position along a great circle to the position predicted by the adopted motion model. Combining the 74 IAD from both consortia and forcing the eccentricity, the period, and the angle of periastron passage, IH finds a Hipparcos based parallax of 14.00 ± 0.52 mas. Instead of omega, DP forced the time of periastron passage deriving a Hipparcos based parallax of 13.81 ± 0.52 mas. In the following we will adopt the mean of the parallax estimates and the average of their errors, 13.90 ± 0.52 . which is well within its error of the mean of the published values noted above.

The General Catalogue of Trigonometric Stellar Parallaxes (Van Altena et al. 1995) notes a Greenwich Observatory parallax for pi Cephei of 8.8 ± 12.0 mas (Dyson and Jones 1970), and a Sproul Observatory value of -16.4 ± 20.9 (Pitman and Rogers 1930). The only estimate of the parallax, based upon the earliest plates in the series presented here 8.7 ± 8.7 mas (Burns and Crissman 1932), is superceded by the photographic value 16.2 ± 2.4 mas derived from the full plate set used in the present study. Applying these weights in Table 4, we find that the weighted mean parallax of all studies of the pi Cephei system is 13.8 ± 0.41 mas for a distance modulus of 4.30 ± 0.065 magnitudes. From the orbital parameters of Baize, and the parallax found here, we find the total mass of the triple star to be $8.81 \pm 0.87 M_{\odot}$.

3. ANALYSIS OF THE PHOTOCENTRIC MOTION

Because astrometry chronicles the motion of the photocenter, the first task is to determine the contribution of each star to the combined light of the system. To find the masses of the primary

binary star and the more distant component, we require an estimate of the blending of the light from their images in the blue bandpass of the original photographic objective of the Thaw refractor. Hipparcos lists the light from the binary star that is the primary as 2.26 magnitudes brighter than the visual companion. Thus it dominates the characteristics of the combined light whose characteristics we take to approximate those of the primary star. The magnitudes of objects observed with the original objective of the Thaw refractor are, except for the hottest stars, quite similar to those found in Johnson's B filter. Those determined with the new objective are similar to those found in the R band. The Hipparcos Catalogue lists the photometric characteristics of the combined light of the triple star as: G2 III, $m_V = 4.412 \pm 0.031$, $B-V = 0.802 \pm 0.001$, $V-I = 0.84 \pm 0.03$ magnitudes. The B-V and V-I indices are both in keeping with the suggested spectral classification and we can assume that the star's light is not significantly obscured or reddened. Applying the parallax estimate computed in Table 4 we find the absolute visual magnitudes of the primary and secondary are $+0.24 \pm 0.065$ and 2.50 ± 0.070 respectively. Thus the primary seems rather bright for a G2 III giant while the absolute magnitude of the B component is in line with Scarfe et al.'s suggestion that the secondary may be an F0 V star.

Following Scarfe et al.'s assumption that the secondary is a main sequence star, we can extend their model of this triple star. To estimate the magnitude difference of the visual components in blue light we require an estimate of the visual companion's temperature class. We note that the derived absolute visual magnitude of the secondary is approximately that of an A9 V. Using the approximate B-V of an A9V star we find a blue magnitude difference of 1.70. This value was then used to estimate the blending of the light of the components in a computation of their relative masses. The photocentric motion indicated by the 58 years of photographic exposures, Figure 1, is $+39 \pm 3.9$ mas. With a blue magnitude difference of 1.70 and an

adopted error of ± 0.1 magnitudes we find masses of $6.88 \pm 0.69 M_{\odot}$ and $1.93 \pm 0.23 M_{\odot}$ respectively. The resulting mass of the visual companion suggests that the companion might be as early as an A7 V star. Since this is well within our errors we adopted the solution.

Because of its small extent, the photocentric motion produced by the spectroscopic orbit is poorly represented by the photographic data and our astrometric study of this motion is confined to the Hipparcos and MAP data. While the extent of the perturbation is easily within the limitations of the electronic astrometric data, the high inclination of the orbit renders the astrometric perspective almost as one dimensional as that of the spectroscopic data and some of the orbital parameters are difficult to determine. Thus for example the two solutions of the Hipparcos data suggest a difference with either the spectroscopically determined time of, or angle of, the periastron passage. While the MAP data is in fair agreement with the spectroscopically determined angle of periastron passage it indicates a time of passage that is neither in agreement with the spectroscopic or the Hipparcos value. Thus we forced the eccentricity, period, and time of periastron passage on the Thaw/MAP data. Although the effects were insignificant, the photocentric motion due to the visual orbit was included in the analysis of the MAP data.

While the longer time span and larger number of observations (85 orthogonal pairs) yield slightly smaller errors in the parameters derived from the Thaw/MAP data, there is good agreement in the values of the parameters derived from the two independent sets of data. Indeed, the slight difference, in the approximately visual wavelength Hipparcos based semimajor axis and the red bandpass MAP based semimajor axis, suggests that the Aa and Ab components are of similar temperature. In other words, the similarity in the results in the two bandpasses suggests that the magnitude difference is similar in the two colors. Figure 2 shows

the Hipparcos residuals. The relatively large Hipparcos residuals probably result from signal confusion caused by the resolved A/B pair. Figure 3 shows the MAP data plotted in phase with the spectroscopically determined period.

4. CONCLUSION

The mass and orbital period of the primary give us an interesting look at the binary system formed by the inner pair. From Kepler's third law we find the semimajor axis of the 1.524 year orbit to be 2.52 ± 0.085 AU. At the 72.5 ± 2.2 parsec distance of π Cephei the semimajor axis of the spectroscopic orbit thus subtends an angle of 34.8 ± 1.24 mas. The photocentric motion due to the spectroscopic orbit is less than 30% of the size of the derived full orbit. Scarfe et al., however, find a spectroscopic mass function of $0.712 \pm 0.014 M_{\odot}$. Thus the astrometric motion is that of the photocenter of a blended image and not that of a star attended by a degenerated star. Fitting the astrometric motion to the spectroscopic orbit, we find an orbital inclination of 99.0 ± 2.5 degrees. From this value and the Spectroscopic mass function we find the mass of the spectroscopic companion (Ab) to be $3.27 \pm 0.48 M_{\odot}$. The same value results from the astrometric data alone if we set the red light (650 nm) magnitude difference at 1.68. Adopting this red light difference results in an absolute visual magnitude of 0.4 for the Aa spectroscopic primary, approximately the brightness (and mass) of a K0 III star. The spectroscopic secondary, however, remains an enigma. Although its mass is nearly identical to that of Aa, Ab is 1.7 magnitudes fainter at 6500 Angstroms. That Ab is probably red is also suggested by the fact that its spectra was not seen by Scarfe et al. at shorter wavelengths. This would seem to rule out the binary of similar F stars suggested by Scarfe et al. The most likely companion would seem to be a star of slightly lower mass, than Aa, that is in a slightly earlier phase of its evolution on to the red giant branch. The absolute magnitude of Ab is similar to that of a luminosity class IV star at the approximate temperature of the Aa component. We note that, at

the adopted parallax, component Aa (and possibly Ab) are overmassive but underluminous compared to other G III binaries. Also suggesting a rather interesting evolution of the system is the fact that the inner companion's orbit is tilted at approximately 70 degrees to that of the larger orbit.

By combining nearly 85 years of photographic and photoelectric astrometric data we have been able to model the motion and characteristics of the long period triple star π Cephei. Assuming that it is a main sequence star, the visual companion has a temperature and luminosity classification of approximately A8 V. The system's primary (Aa) star has the mass and luminosity of a K0 III. Although it is of similar mass, and possibly of similar temperature, the spectroscopic secondary (Ab) is 1.7 magnitudes fainter than Aa. Perhaps more important, during this time of increased emphases on high precision but short duration astrometric missions, is that this study once again illustrates the value of the long term study of an object. The astrometric signal of a long period orbital motion increases with the square of time. Thus old data, even if of lower precision, may often resolve that which can not be seen during the short mission of an astrometric satellite.

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with example, for the reduction of the astrometric parameters of an acceleration star from the IAD. Some of the references used in this study were retrieved through SIMBAD, the database of the Strasbourg, France, Astronomical Data Center.

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TABLE 1

Adjustment to Weighted Absolute Parallax of Thaw/MAP stars in the π Cephei Region

AO#	Spectral Class	A_v mag	Spectral Parallax mas	est. S.E. mas	Provisional Parallax mas	cal. S.E. mas	Weighted Adjustment mas	Weight	Observed Parallax mas	Spectral-Observed mas
988	K0 III	0.82	1.7	0.60	0.87	1.05	+0.69	0.83	1.42	-0.27
989	A3 V	0.50	4.0	1.40	5.82	1.01	-1.06	0.58	6.37	-2.37
990	B9 V	*	2.08	0.64	1.61	0.77	+0.47	1.00	2.16	-0.08
991	B9	*	2.05	0.53	0.54	0.96	+1.37	0.91	1.51	0.57
992	B8 V	0.55	1.0	0.35	0.14	3.61	+0.24	0.28	0.69	+0.31
995	A2 V	0.30	3.0	1.05	2.08	0.74	+0.72	0.78	2.63	+0.37
Weighted adjustment to mean							= +0.55	mas.		
Standard error of weighted adjustment to mean							= 0.22	mas.		
As in the Castelaz and Persinger (see text) photometric calibrations, $A_v = 3.10E(b-v)$.										
* Hipparcos parallax used, see text.										

TABLE 2

THAW/MAP STAR PARAMETERS IN THE REGION OF PI CEPHEI

AO#	d	V	B-V	parallax	R.A. (2000)			PM(r.a.)	Dec. (2000)			PM(Dec.)
		mag		mas	h	m	s	s	o	'	"	"
988	2	10.21	0.91	1.4 1.0	23	3	13.946255	-.0002248 .0000392	75	20	23.45567	-.013058 .000152
989	2	9.24	0.16	6.4 1.0	23	3	38.064332	.0031488 .0000380	75	26	33.33250	.002862 .000147
990	2	7.67	-0.15	2.2 0.8	23	4	15.911350	.0030757 .0000290	75	31	1.96284	.004430 .000112
991	2	6.81	0.03	1.1 1.0	23	6	16.679575	.0033773 .0000357	75	34	53.05119	.003163 .000137
992	2	9.61	-0.29	0.7 3.6	23	6	37.982406	-.0019434 .0002857	75	10	54.04049	-.000311 .001053
993	2	10.43	1.35	3.3 1.4	23	7	18.072929	-.0014147 .0000372	75	31	40.43293	-.003454 .000186
1301	2	4.41	0.80	13.5 0.7	23	7	53.846985	.0014715 .0000349	75	23	15.06666	-.032491 .000139
994	2	11.26	1.82		23	8	40.240692	.0002569 .0000915	75	20	23.63787	.003572 .000428
995	2	9.14	0.12	2.6 0.8	23	8	50.426283	-.0040069 .0000272	75	8	43.94685	-.004160 .000108
996	2	9.85	0.31	4.0 0.9	23	9	59.856196	.0234944 .0000331	75	41	26.26711	.029022 .000125
997	2	9.68	0.10	2.3 0.8	23	11	22.166389	-.0015388 .0000217	75	10	24.90025	.001900 .000109

AO numbers are part of a continuing series beginning with the use of the central overlap technique. The numbers are assigned with their first publication, all but 1301 have appeared in previous publications. The 2 in column "d" notes that the device used to gather the astrometric data was the Thaw/MAP. The parallax standard errors include the uncertainty of the adjustment to absolute. Except for the parallaxes, the standard errors, (second row of each entry) for example those of the positions, are strictly internal and do not allow for the zero point errors of the reference system.

TABLE 3

NUMBER CROSS INDEX

AO	BD	Hipparcos
988		
989	74 1000	
990	74 1001	113928
991	74 1002	114078
992	74 1004	
993		
994		
995	74 1008	
996		
997		
1301	74 1006	114222

TABLE 4

Parallax of π Cephei

Estimate mas	se mas	Observatory
-16.4	20.9	Sproul
8.8	12.0	Greenwich
16.4	2.4	Allegheny, photographic
13.90	0.52	Hipparcos, average
13.47	0.69	Allegheny, Thaw/MAP
13.79	0.41	Weighted mean

TABLE 5

Astrometric Orbital Elements of π Cephei

Element over its standard error	Hipparcos average	Thaw/MAP	Adopted
parallax	13.90	13.47	13.80
s.e.	0.52	0.69	0.41
node	107.9	109.2	
s.e.	3.7	3.5	
inclination	103.1	96.1	99.0
s.e.	3.9	3.3	2.5
photocentric semimajor axis	10.57	10.30	10.40
s.e.	.79	.65	.50
s.e.1	4.16	3.34	
r.m.s.e.	11.00	4.15	
photographic semimajor axis	39.0		
s.e.	3.9		

Table 5: node angle and inclination are in degrees, all other values are in mas. The orbital parameters derived by Baize (1992) for the visual A/B pair, and those of Scarfe et al (1983) for the spectroscopic Aa/Ab pair were adopted. The photocentric semimajor axis of the A/B orbit is from photographic plates spanning 58 years. Column 2 of the table lists the mean of the two reductions of the Hipparcos data, see text. Column 3 lists the values derived from the Thaw/MAP data. The last column lists the values adopted for the current study of the system.