

One-Milliarcsecond Precision Parallax Studies in the Regions of Delta Cephei and EV Lacertae

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ABSTRACT. Trigonometric parallaxes for stars in the regions of the variable stars δ Cephei and EV Lacertae are derived from data collected with the Multichannel Astrometric Photometer and the Thaw Refractor of the University of Pittsburgh's Allegheny Observatory. The weighted mean parallax of all trigonometric studies of δ Cephei is now $+0''.0030 \pm 0''.00093$, corresponding to a distance modulus of 7.61 ± 0.67 mag. This indicates that this luminosity standard star is approximately one standard deviation more distant than has been generally accepted. The weighted mean trigonometric parallax of all studies of the variable star EV Lacertae (BD +43°4305) is $+0''.1993 \pm 0''.00093$, implying a distance modulus of -1.498 ± 0.010 mag. The calculated absolute magnitude of this star is almost exactly that predicted by its $(R-I)_{\text{Kron}}$ magnitude and by the Gliese $(R-I)$ main-sequence value for stars in the solar neighborhood. We also find a parallax of $0''.0189 \pm 0''.0008$ for the F0 IVn star, HR 8666 (BD +43°4300). The derived luminosity of this star is midway between that expected for luminosity class IV and V stars at the indicated temperature.

1. INTRODUCTION

The prototype of a class of stars that serve as primary extragalactic distance indicators, δ Cephei, has been the subject of many parallax studies. Actually, until now the distance of this object has placed it outside the effective range of astrometric triangulation techniques; the weighted mean of all previous trigonometric parallax determinations is 5.2 ± 3.6 milliarcsec (mas). Clearly, the advent of astrometric techniques with 1-milliarcsec precision justifies a new effort to find the distance to this important stellar prototype. While the study reported below has not yet produced precisions similar to those quoted for some other techniques, it does represent the results of an independent procedure, one subject to different if not fewer sources of systematic error than embodied in such other techniques.

The second study is centered on EV Lacertae. A flare star and, intrinsically, the faintest star yet studied with the Multichannel Astrometric Photometer (MAP), it adds to our ongoing calibration of the lower HR diagram (Gatewood et al. 1993) and further confirms the conclusion that flare stars are main-sequence objects (Peterson 1980).

The instrumentation and reduction procedures utilized in this continuing astrometric series of the MAP and photographically determined astrometric stellar parameters have been described extensively (Gatewood 1987). The algorithm by which the absolute parallaxes are determined includes the estimation of the intrinsic luminosities of the reference stars. This need is the basis for a parallel series of reports detailing intermediate-band photometry results (e.g., Castelaz et al. 1991) and a further program by Stephenson based on the 10° objective prism of the Warner Swasey Observatory 24-in. (61-cm) Schmidt telescope and reported on in this parallax study, see Table 1.

Table 2 presents astrometric parameters determined in the regions of δ Cephei and EV Lacertae with the 0.76-m red-light Thaw refractor and associated MAP detector (Thaw/MAP). The Cartesian coordinates derived from the Thaw/MAP system are reduced by the iterative algorithm known as the central overlap technique (e.g., Gatewood and Russell 1974; Eichhorn 1988), and presented in a consistent format. The positions and motions, at the epoch and equinox of J2000, of the stars under study are listed in the last four columns of Table 2 above their corresponding standard errors. The system of the positions and motions is that of the PPM Catalog (Röser and Bastian 1991), ostensibly that of the FK5 Catalog. 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

TABLE 1
Objective-Prism Spectral Classifications^a

AO	BD	Spectrum
980	+57°2542	A2 V
981	+57 2541	M3 III
982	+57 2543	A7 p
983	+57 2545	F0 V
984	+57 2549	F5 V
1197	+43°4295	K0 III
1198	+43 4296	G, faint
1200	+43 4299	G7 III–IV
1201	+43 4301	F3 V
1202	+43 4303	G8 III, faint
1204		A0 V
1205	+43 4306	F9 V

^aObjective-prism classifications are by Stephenson.

TABLE 2
(a) Star parameters in the region of δ Cephei

AO#	d	<i>V</i>	<i>B</i> − <i>V</i>	Parallax (mas)	R.A. (2000) (h m s)	PM (r.a.) (s/yr)	Dec. (2000) (° ' ")	PM (Dec.) ("/yr)
978	2	10.30	0.48	1.3 1.5	22 27 24.66640 0.00099	−0.001546 0.000114	58 22 3.2401 0.0079	0.00262 0.00085
979	2	10.04	2.08	3.3 0.9	22 27 52.04324 0.00041	−0.000412 0.000039	58 24 56.6557 0.0033	0.01283 0.00031
980	2	8.49	0.03	4.3 0.9	22 28 25.97225 0.00040	0.002068 0.000039	58 25 20.5377 0.0032	0.00794 0.00030
981	2	9.70	1.95	1.7 0.8	22 28 26.40336 0.00039	0.000526 0.000038	58 6 49.5377 0.0031	0.00078 0.00030
982	2	7.95	0.15	4.5 0.7	22 28 34.54662 0.00033	0.002901 0.000032	58 32 24.1178 0.0026	0.01440 0.00025
1257	2	12.47	0.50	−3.8 2.8	22 28 50.08162 0.00234	−0.000099 0.000271	58 12 39.5576 0.0175	−0.00439 0.00188
983	2	9.92	0.46	1.2 0.8	22 29 1.99208 0.00038	0.003529 0.000037	58 2 2.7321 0.0031	0.00599 0.00029
1256	2	3.95	0.53	2.8 0.7	22 29 10.29291 0.00033	0.002349 0.000032	58 24 54.8471 0.0026	0.00519 0.00025
984	2	9.60	0.94	8.8 0.6	22 30 22.25715 0.00025	0.002019 0.000024	58 1 12.1293 0.0020	−0.04234 0.00019
985	2	10.52	1.37	5.2 1.0	22 30 39.15877 0.00046	0.002373 0.000044	58 35 52.5765 0.0036	−0.01275 0.00035
986	2	11.15	1.87	−1.1 1.0	22 31 1.09142 0.00060	0.001454 0.000063	58 28 43.1005 0.0048	−0.01217 0.00049
987	2	11.30	1.92	1.0 0.9	22 31 6.25920 0.00044	0.001806 0.000043	58 21 22.7586 0.0035	−0.000878 0.00034

(b) Star Parameters in the Region of EV Lacertae

AO#	d	<i>V</i>	<i>B</i> − <i>V</i>	Parallax (mas)	R. A. (2000) (h m s)	PM (r.a.) (s/yr)	Dec. (2000) (° ' ")	PM (Dec.) ("/yr)
1197	2	9.57	1.14	1.3 0.7	22 44 42.04965 0.00021	−0.000683 0.000021	44 31 25.9082 0.0023	0.01575 0.00022
1198	2	9.97	0.86	2.7 1.0	22 44 46.40350 0.00030	0.001302 0.000029	44 21 59.3240 0.0032	−0.01939 0.00031
1199	2	11.76	1.60	6.4 2.2	22 45 3.57916 0.00099	0.002819 0.000114	44 8 10.1488 0.0108	−0.03883 0.00121
1200	2	9.16	1.18	1.6 0.8	22 45 33.56333 0.00024	0.001445 0.000023	44 21 22.2739 0.0026	−0.03008 0.00025
1258	2	5.86	0.36	18.9 0.7	22 46 10.18382 0.00020	0.013232 0.000020	44 32 45.9669 0.0021	0.03535 0.00021
1201	2	10.12	0.52	8.5 1.1	22 46 15.06140 0.00033	0.005985 0.000032	44 2 7.1749 0.0035	−0.05253 0.00035
1202	2	9.84	1.40	1.9 0.9	22 46 32.08101 0.00027	0.003364 0.000026	44 17 32.4108 0.0029	−0.03677 0.00028
1203	2	10.23	1.59	199.0 0.9	22 46 49.77262 0.00026	−0.063405 0.000025	44 20 2.0110 0.0028	−0.48095 0.00027
1204	2	10.94	0.18	−1.4 1.8	22 47 24.48154 0.00061	0.001885 0.000066	44 22 12.7215 0.0066	−0.03214 0.00071
1205	2	9.57	0.57	10.6 0.6	22 47 31.62648 0.00017	−0.005126 0.000017	44 33 10.9755 0.0018	−0.08556 0.00018
1206	2	11.11	0.66	2.7 1.2	22 47 35.37626 0.00034	0.004274 0.000034	44 5 20.2098 0.0037	−0.08327 0.00036

All standard errors, for example, those of the positions, are strictly internal and do not allow for the zero-point errors of the reference system. A 2 in column "d" indicates that the data were obtained with the Multichannel Astrometric Photometer (MAP).

TABLE 3
(a) Adjustment to Weighted Absolute Parallax in the Region of δ Cephei

AO#	Spectral class	Spectral parallax (mas)	S.E. mas (est.)	Provisional parallax (mas)	S.E. (mas) (calc.)	Adjustment (mas)	Weight	Observed parallax (mas)	Spectral — observed (mas)
978	B0.5 V	0.20	0.09	1.26	1.51	−1.06	0.44	1.32	−1.12
979	M3 III	1.30	0.60	3.23	0.87	−1.93	0.90	3.29	−1.99
980	A1 V	3.20	0.74	4.19	0.86	−0.99	0.78	4.25	−1.05
981	M4 III	1.80	0.41	1.65	0.84	0.15	1.14	1.71	0.09
982	A5 p	6.50	1.50	4.46	0.70	2.04	0.36	4.52	1.98
983	F0 V	4.20	0.97	1.17	0.83	3.03	0.61	1.23	2.97
984	F5 V	5.80	5.34	8.78	0.55	−2.98	0.03	8.84	−3.04
985	G8 III	1.80	0.83	5.18	1.00	−3.38	0.59	5.24	−3.44
986	K3 III	1.30	0.60	−1.20	1.04	2.50	0.69	−1.14	2.44
987	K3 III	1.40	0.64	0.93	0.93	0.47	0.78	0.99	0.41
1257	Cepheid	0.40	0.18	−3.82	2.76	4.22	0.13	−3.76	4.16

Weighted adjustment to mean=0.06 mas. Standard error of weighted adjustment to mean=0.63 mas.

(b) Adjustment to Weighted Absolute Parallax in the Region of EV Lacertae

AO#	Spectral class	Spectral parallax (mas)	S.E. mas (est.)	Provisional parallax (mas)	S.E. (mas) (calc.)	Adjustment (mas)	Weight	Observed parallax (mas)	Spectral — observed (mas)
1197	K0 III	1.80	0.41	0.47	0.72	1.33	1.46	1.31	0.49
1198	G2 III	1.50	0.69	1.86	1.02	−0.36	0.66	2.70	−1.20
1200	G9 III	2.10	0.68	0.72	0.82	1.38	0.88	1.56	0.54
1201	F7 V	5.50	2.53	7.71	1.13	−2.21	0.13	8.55	−3.05
1202	K0 III	1.60	0.52	1.04	0.92	0.56	0.90	1.88	−0.28
1204	B9.5 V	1.10	0.25	−2.24	1.81	3.34	0.30	−1.40	2.50
1205	F9 V	8.70	2.80	9.80	0.58	−1.10	0.12	10.64	−1.94
1206	F6 V	4.00	1.84	1.89	1.15	2.11	0.21	2.73	1.27
1258	F0 IV	16.90	7.77	18.06	0.69	−1.16	0.02	18.90	−2.00

Weighted adjustment to mean=0.94 mas. Standard error of weighted adjustment to mean=0.46 mas.

the zero-point, scale, orientation, or proper-motion uncertainties of the reference system.

As detailed in the previous publication in this series (Gatewood et al. 1993), parallaxes were reduced directly into an absolute frame using our best estimate of the spectroscopic parallax of each reference star. These estimates are included in the formation of the first approximation to a MAP-based catalog, and 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 are subject to verification and possible adjustment. Differences between the predicted and observed parallax are handled like any other residual. If the parallax derived from the astrometric data is significantly different from that initially derived from the spectroscopic and photometric data, and the latter include indications that an alternate luminosity classification is possible, a re-evaluation of the spectroscopic parallax may be in order. Otherwise, one may decide to leave this reference star out of the initial parallax pass, letting later iterations converge on the parallax dictated solely by the astrometric constraints.

Because the weighing system in effect during the computation of the field variates reflects the effects of field position and photon count, instead of the errors of the estimated spectroscopic parallaxes, the frame of the absolute parallaxes can still be improved. Thus a final weighted

adjustment to absolute parallax is justified, see Tables 3.

2. THE DETERMINATION OF SPECTROSCOPIC PARALLAX

Listed in Tables 3 are the Allegheny Observatory (AO) catalog number and the adopted spectral classification-luminosity type of the reference stars for which trigonometric and spectrophotometric studies were meaningful. With the exceptions noted in the individual descriptions below, the tabulated spectral classifications either come from Table 1 or result from an evaluation of catalog-listed spectral types or derive from the multiband photometry of these regions given by Castelar and Persinger (1989), Persinger and Castelar (1990), and Castelar et al. (1991). Unless otherwise noted, the Castelar and Persinger spectral classifications have been adopted and the ratio $A_p/E(B-V)$ was assumed to be 3.1. In Tables 3 the spectral classification of the reference star is followed by the implied spectroscopic parallax, an estimate of its standard error, the provisional absolute parallax, its calculated standard error, the adjustment found by subtracting the observed parallax from the spectroscopic parallax, and an estimate of the statistical weight of that individual estimate of the mean adjustment. The weighted residuals to this adjustment are listed in the last column. The adjustment found for each region is based upon the luminosity classi-

TABLE 4
(a) Trigonometric measurements of the Parallax of δ Cephei

Observatory	Reference	Parallax ^a (mas)	S.E. (mas)
Allegheny	Henroteau 1920	8	9
Allegheny	Wagman et al. 1952	9	9
Allegheny	This study	2.8	0.96
Greenwich	Dyson 1925	11	13
McCormick	Mitchell et al. 1927	4	13
Yerkes	Moffitt 1932	5	7
Mt. Wilson	van Maanen 1926	0	7
Mean		3.0	0.93
Distance modulus = 7.61 ± 0.67			

(b) Trigonometric Measurements of the Parallax of EV Lacertae

Observatory	Reference	Parallax ^a (mas)	S.E. (mas)
Allegheny	Wagman and Crissman 1957	197	9
Allegheny	This study	199.1	1.0
McCormick	Mitchell and Reuyl 1940	205	13
McCormick	Mitchell et al. 1958	204	16
McCormick	Osvalds 1957	183	10
Sproul	van de Kamp and Worth 1971	200	6
Van Vleck	Weis et al. 1983	214	12.7
Yerkes	Jenkins 1952	197	15
Mt. Wilson	van Maanen 1931	211	9
Mean		199.2	0.93
Distance modulus = -1.496 ± 0.010			

^aPublished relative parallaxes have been converted to absolute by the addition of 2 mas.

fications adopted in the section of Table 3 addressed to that region, the absolute magnitudes given by Allen (1973) and the estimated individual interstellar absorption corrections. The adjustment to a weighted mean and its standard error are listed at the bottom of the table. The adjustments found for each of the two regions under discussion is applied throughout Table 2 and elsewhere in this paper.

3. THE REGION CENTERED ON δ CEPHEI

At a galactic latitude of less than 1 deg, δ Cephei sits in a region of variable and sometimes considerable interstellar absorption (Feltz 1976). This variation is apparent in the study by Persinger and Castelar (1990) and is evident in Table 3a. Five stars were classified on the basis of objective-prism spectra and ten were observed photometrically. There were no significant differences between the objective-prism and photometric classifications. The spectral classifications by Stephenson for stars AO 983 and 984, Table 3a, were adopted. Those of Persinger and Castelar were adopted for stars AO 978 and 981. The classifications adopted for stars AO 980 and 982 are midway in the small ranges of the classifications suggested by the above and listed in the SIMBAD database. For star AO 979 we adopted a luminosity class of III instead of the Ib suggested by Persinger and Castelar, and for star AO 985 we chose a temperature class three subclasses latter than that suggested by Persinger and Castelar. Only the photomet-

rically similar stars AO 986 and 987 had no previous classification. Both stars fall well within the heavier absorption region described by Feltz and appear to be reddened K3 III giants. Star AO 1257 is a Cepheid with a period of 7.23 days and a distance modulus of approximately 15 mag and is thus an ideal albeit faint reference star.

Table 4a lists the various trigonometric estimates of the parallax of δ Cephei (AO 1256). All of the older studies represent early photographic efforts and reflect the relatively large random errors of the measuring machines in use in those times. The weighted mean (using the standard errors suggested in each publication) of all of the studies listed in Table 4a is 3.0 ± 0.93 mas. Thus the best current trigonometric estimate of the distance of δ Cephei is 333 ± 103 parsecs, yielding a distance modulus of 7.61 ± 0.67 mag.

4. THE REGION OF EV LACERTAE

EV Lacertae (BD +43°4305, AO 1203) has a planetary detection index of 0.5 (Gatewood 1976) and is thus one the most intensely observed objects on the MAP program. van de Kamp and Worth (1971) noted that the residuals to the approximately biannual normal points resulting from a concentrated 35-yr Sproul Observatory photographic study were suggestive of a 29-yr periodicity with a projected semimajor axis of 39 mas. The Allegheny Observatory photoelectric astrometric study of this region reported here began in the summer of 1986 and extends through the fall of 1992. Ninety-four observations were made in slightly more than six years with many of these being done when the parallax factor on the meridian was relatively low. Thus, while these observations were effectively aimed at the detection of perturbations, they also make possible a high-precision distance estimate albeit with somewhat less weight than would be have been achieved had that been the specific intent.

At the galactic latitude of EV Lacertae, -13° , interstellar absorption is generally moderate and only slightly variable (Castelar et al. 1991). Seven of the stars in this region were classified on the basis of objective-prism spectra and all were observed photometrically. The objective-prism classifications and those suggested by the photometry of Castelar et al. were in excellent agreement. The spectral classifications by Stephenson for stars AO 1197 and 1205, Table 1, were adopted. Those suggested by Castelar et al. were adopted for stars AO 1198, 1199, 1204, and 1206 and are included in Table 3b. The adopted classifications for stars AO 1200 and 1202 lie midway between those suggested by Stephenson and Castelar et al. We adopted a somewhat less reddened F7 V classification for star AO 1201 than either Stephenson's class F3 V or the F4 V class chosen by Castelar et al. Star AO 1258 was too bright for both the Stephenson and Castelar et al. studies but Cowley (1976) classifies the star as F0 IV.

Table 4b lists the various trigonometric estimates of the parallax of EV Lacertae. None of the photographic studies utilized a modern measuring machine and the phenomenal precision of the Sproul study results from the use of 771

TABLE 5
Number Cross Index

BD#	AO#	HD#
+57°2536	978	
+57°2537	979	
+57°2541	981	
+57°2542	980	
+57°2543	982	213232
+57°2545	983	
+57°2548 ^a	1256	213306
+57°2549	984	
+57°2550	985	
+43°4295	1197	
+43°4296	1198	
+43°4299	1200	
+43°4300 ^b	1258	215664
+43°4301	1201	
+43°4303	1202	
+43°4305 ^c	1203	
+43°4306	1205	

^aδ Cephei, HR 8571.^bHR 8666.^cEV Lacertae.

multiexposure plates. The weighted mean (using the standard errors suggested in each publication) of all of the studies listed in Table 4b is 199.2 ± 0.96 mas. Thus the best estimate of the distance of this star is currently 5.02 ± 0.024 parsecs yielding a distance modulus of -1.496 ± 0.010 mag. While there are a number of photoelectric measures of EV Lacertae it is not clear which measures were conducted during its most quiescent state (it flares frequently). Weis (1988) suggests that values obtained when the star is relatively faint and red be used to describe the photometric nature of the star. He records an apparent visual magnitude of 10.26 and an $(R-I)_{\text{Kron}}$ value of 1.20 mag. Castela et al. seem to have caught the star in a similar state, the straight mean¹ of their two measurements is 10.25 and we adopt a standard error of 0.02 mag.

5. DISCUSSION

The brightest object in the EV Lacertae region is the F0 IVn (Cowley 1976) star HR 8666 (AO 1258), $m_V = 5.86$. This star's parallax was determined by Wagman and Crissman (1957), who found a parallax of 18 ± 9 mas. Its spectroscopic parallax is estimated at 16.9 mas, Table 4b. Allowing for the random error in the correction to absolute, we find a parallax of 18.9 ± 0.8 mas, yielding a distance modulus of 3.62 ± 0.09 mag or an absolute magnitude of 2.24 ± 0.09 . This assigns the star a luminosity halfway between that expected for class IV and class V stars (Allen 1973), suggesting that perhaps the star is evolving off the main sequence.

We find the absolute visual magnitude of EV Lacertae to be 11.74 ± 0.022 , with most of the uncertainty deriving from the photoelectric photometry of this variable star. In addition to EV Lacertae, five other nearby K and M main-

sequence stars have been studied with the Thaw/MAP (Gatewood et al. 1993). The absolute magnitude found in the present study extends the previous effort to an intrinsically fainter and redder star, further confirming the remarkable agreement with Gliese's (1971) $M_V/(R-I)_{\text{Kron}}$ relationship.

The MAP observations of EV Lacertae now extend over seven seasons. During that period the observed motion has been linear to better than 2 mas and has shown no hint of the 29-yr period motion suggested by van de Kamp and Worth. It is possible, however, that the suspected pattern has been relatively linear during the time covered by the observations. EV Lacertae will remain on the MAP program for the foreseeable future.

The parallax found here for δ Cephei is at variance with expectation (Wilson et al. 1991). We have performed several tests and examined the individual residuals in search of an explanation. Temporarily removing the most divergent observations from the data has little effect upon the derived parallax. Gathering the data into subsets of different time spans also has little impact as does using various sets of reference stars. While the divergence is only slightly greater than one standard error, the implications are obviously quite interesting. Three steps might be taken to improve the reliability of the result. First we intend to continue to add observations to the data set. The number of observations could be doubled over the next several years. Next, estimates of the spectral and luminosity classifications of the reference stars could be strengthened. Independent photometric and spectroscopic studies of these background stars would increase the confidence level of the transformation of the observed parallaxes to absolute values. These two steps could reduce the estimated parallax error by 40% or 50%, dropping the error in the distance modulus to 0.4 mag or less. Such precision exceeds that possible with existing space-borne instrumentation. The highest precision, however, can be obtained through the judicious use of large aperture telescopes at sites where superior seeing conditions prevail. Gatewood (1991) and Shao and Colavita (1992) have shown that, because of the high correlation between the motions of close stellar images, the field centers of such instruments offer a potential for astrometric precision ten times that currently being achieved. Thus there already exists at least the potential to begin a calibration of the Cepheid Period-Luminosity law to significantly better than 0.1 mag.

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¹The values listed in the SIMBAD data base average approximately 0.2 mag brighter.

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