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THE PHASES DIFFERENTIAL ASTROMETRY DATA ARCHIVE. II. UPDATED BINARY STAR ORBITS AND A LONG PERIOD ECLIPSING BINARY

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ABSTRACT

Differential astrometry measurements from the Palomar High-precision Astrometric Search for Exoplanet Systems have been combined with lower precision single-aperture measurements covering a much longer timespan (from eyepiece measurements, speckle interferometry, and adaptive optics) to determine improved visual orbits for 20 binary stars. In some cases, radial velocity observations exist to constrain the full three-dimensional orbit and determine component masses. The visual orbit of one of these binaries—α Com (HD 114378)—shows that the system is likely to have eclipses, despite its very long period of 26 years. The next eclipse is predicted to be within a week of 2015 January 24.

Key words: astrometry – binaries: close – binaries: eclipsing – binaries: visual – techniques: interferometric

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Accurate measurements of fundamental properties of stars are necessary to develop models of stellar formation, structure, and evolution. These are also key parameters in understanding galactic mass–luminosity relationships. Combined visual–radial velocity (RV) orbits of binary stars provide measures of component masses and the distances to the systems (determining the intrinsic stellar luminosities), while visual-only orbits coupled with parallax measurements can be used to measure the total mass of the system (see, for example, Boden et al. 1999; Pourbaix & Jorissen 2000; Benedict et al. 2001). Widely separated binaries are particularly important because the stars are more likely to have evolved like single stars. The accuracies with which the stars' fundamental properties are known are improved by enhanced measurement precisions. Furthermore, establishing a set of high-precision orbits will be useful as calibration standards for future precision differential astrometry efforts being pursued (Lazorenko et al. 2009; Cameron et al. 2009; Hełminiak et al. 2009).

A technique has been developed to obtain high-precision (35 μas) astrometry of close stellar pairs (separation less than 1 arcsec; Lane & Muterspaugh 2004) using long-baseline infrared interferometry at the Palomar Testbed Interferometer (PTI; Colavita et al. 1999). This technique was applied to 51 binary systems as the Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) program during 2002–2008. PHASES science results included precision binary orbits and component masses, studies of the geometries and component physical properties in triple and quadruple star systems, and limits on the presence of giant planet companions to the binaries.

Astrometric measurements were made at PTI, which was located on Palomar Mountain near San Diego, CA. It was developed by the Jet Propulsion Laboratory, California Institute of Technology for NASA, as a testbed for interferometric techniques applicable to the Keck Interferometer and other missions such as the *Space Interferometry Mission* (*SIM*). It was operated in the J (1.2 μm), H (1.6 μm), and K (2.2 μm) bands and combined starlight from two out of three available 40 cm apertures. The apertures formed a triangle with one 110 and two 87 m baselines. PHASES observations began in 2002 and continued through 2008 November when PTI ceased routine operations.

This paper is the second in a series analyzing the final results of the PHASES project as of its completion in late 2008. The first paper describes the observing method, sources of measurement uncertainties, limits of observing precisions, derives empirical scaling rules to account for noise sources beyond those predicted by the standard reduction algorithms, and presents the full catalog of astrometric measurements from PHASES (Muterspaugh et al. 2010d). The current paper combines PHASES astrometry with astrometric measurements made by other methods as well as RV observations (where available) to determine orbital solutions to the binaries' Keplerian motions, determining physical properties such as component masses and system distance when possible. The third paper presents limits on the existence of substellar tertiary companions orbiting either the primary or secondary stars in those systems that are found to be consistent with being simple binaries (Muterspaugh et al. 2010a). The fourth paper presents three-component orbital solutions to a known triple star system (63 Gem = HD 58728) and a newly discovered triple system (HR 2896 = HD 60318; Muterspaugh et al. 2010b). Finally, the fifth paper presents candidate

Table 1
Number of PHASES and Non-PHASES Measurements and Unit-weight Uncertainties for Non-PHASES Measurements

HD Number	N_{P}	$N_{\mathrm{P,O}}$	N_{NP}	$N_{\mathrm{NP,O}}$	$\sigma_{\rho,\circ}$	$\sigma_{\theta,\circ}$
5286	18	0	645	34	0.094	1.82
6811	19	1	185	18	0.031	2.86
17904	45	1	150	20	0.017	3.95
26690	19	1	96	16	0.0088	3.11
44926	23	0	14	0	0.023	5.57
76943	16	0	217	9	0.060	4.17
77327	47	0	125	12	0.018	2.61
81858	12	0	580	46	0.090	2.23
114378	23	1	586	33	0.068	2.09
129246	16	1	682	45	0.092	1.95
137107	50	1	948	63	0.075	2.05
137391	22	1	12	0	0.0055	3.25
137909	73	0	93	13	0.016	2.96
140159	15	0	205	13	0.021	3.78
140436	37	6	409	26	0.078	3.08
155103	10	0	131	23	0.0093	3.44
187362	10	0	223	23	0.021	2.90
202444	39	0	286	13	0.123	4.37
207652	50	0	185	11	0.030	4.06
214850	48	5	253	21	0.036	3.18

Notes. The number of PHASES and non-PHASES astrometric measurements used for orbit fitting with each of the binaries being studied are presented in Columns 2 and 4, respectively, along with the additional numbers of measurements rejected as outliers in Columns 3 and 5. Columns 6 and 7 list the 1σ measurement uncertainties for unit-weight measurements from non-PHASES observations determined by iterating Keplerian fits to the measurements with removal of 3σ or greater outliers in either dimension. Columns 6 and 7 are in units of arcseconds and degrees, respectively. The subscripts "P" and "NP" stand for PHASES- and Non-PHASES-type measurements, respectively, while the subscript "O" stands for outlier and the subscript "$\circ$" represents that the uncertainties are for unit-weight measurements.

substellar companions to PHASES binaries as detected by astrometry (Muterspaugh et al. 2010c).

2. PHASES MEASUREMENTS

PHASES differential astrometry measurements were obtained using the observing method and standard data analysis pipeline described in Paper I. The measurements themselves and associated measurement uncertainties are also tabulated in Paper I. Analysis of binary orbits is limited to the 20 systems for which 10 or more PHASES observations were made, do not show convincing evidence of having tertiary companions, and are not δ Equ, which has already been the subject of other PHASES investigations (Muterspaugh et al. 2005, 2008). Those having stellar companions to the primary and/or secondary stars either have been presented in previous works (see Muterspaugh et al. 2006a, 2006b, 2008; Lane et al. 2007; B. F. Lane et al. 2010, in preparation) or in Paper IV. Those for which the PHASES measurements indicate substellar companions may be present are the subject of Paper V. The number of PHASES measurements available for each of the 20 systems being investigated are listed in Table 1.

3. NON-PHASES MEASUREMENTS

Measurements of binaries observed by PHASES made by previous astrometric techniques and cataloged in the Washington Double Star Catalog (WDS; Mason et al. 2001, 2010, and see references therein) were assigned weights according to the formula described by Hartkopf et al. (2001). Unit-weight uncertainties in separation and position angle were evaluated by the following iterative procedure. First, guess values for the unit uncertainties of 24 mas in separation and 1°.8 in position angle were assigned to the measurements of a given binary; these values corresponded to previous experience using this procedure on μ Ori (Muterspaugh et al. 2008). Second, the measurements were fit to a Keplerian model and the orbital parameters were optimized to minimize the fit χ^2. Third, the weighted scatter of the residuals in separation and position angle were evaluated, and the guessed unit uncertainties updated to make the rms scatter in each equal to unity. Fourth, the second and third steps were iterated two more times, at which point the values converged. Fifth, the final unit uncertainties were multiplied by the square root of the reduced χ^2 ($\sqrt{\chi_r^2}$) of the fit and refit one more time using these slightly larger weights. Sixth, if no residuals deviated by more than 3σ, the process ended, otherwise, the single measurement with the largest separation or position angle residual (weighted by its uncertainty) was flagged as an outlier and removed from future fits. Seventh, the process was repeated at the first step. The resulting weights are listed in Table 1 and the measurements themselves are listed in Table 2.

Table 2
Non-PHASES Astrometric Measurements

HD Number	Date (yr)	ρ (arcsec)	θ (deg)	σ_ρ (arcsec)	σ_θ (deg)	Weight	Outlier
5286	1830.7400	0.850	305.00	0.297	5.77	0.1	0
5286	1831.7900	0.780	308.70	0.297	5.77	0.1	0
5286	1832.1400	0.850	307.80	0.086	1.67	1.2	0
5286	1835.9200	1.100	315.70	0.297	5.77	0.1	0
214850	2008.5377	0.363	77.10	0.008	0.72	19.4	0
214850	2008.5460	0.364	77.00	0.008	0.72	19.4	0
214850	2008.5460	0.364	77.10	0.008	0.72	19.4	0
214850	2008.8875	0.380	77.90	0.024	2.10	2.3	0

Notes. Non-PHASES astrometric measurements from the WDS are listed with 1σ measurements uncertainties and weights. Column 1 is the HD catalog number of the target star, Column 2 is the decimal year of the observation, Columns 3 and 4 are the separation in arcseconds and position angle in degrees, respectively, Columns 5 and 6 are the 1σ uncertainties in the measured quantities from Columns 3 and 4, Column 7 is the weight assigned to the measurement, and Column 8 is 1 if the measurement is a $>3\sigma$ outlier and omitted from the fit, 0 otherwise.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

4. ORBITAL SOLUTIONS

4.1. Binaries Without Radial Velocity Measurements

Binaries for which only astrometric measurements are available were fit to a single Keplerian orbit using a downhill χ^2 minimizing routine alternating between the standard Campbell and Thiele-Innes parameter sets for improved speed of convergence. When only a visual orbit is available, the sum of the component masses can be determined if a trigonometric parallax measurement is available. For each system evaluated, the trigonometric parallax and its associated measurement uncertainty, as measured by the revised *Hipparcos* analysis of van Leeuwen (2007), were taken as input parameters to the fit in order to evaluate the mass sums. When available, the revised parallax estimates based on the work of Söderhjelm (1999, hereafter S99) (HD 76943, HD 114378, HD 137391, HD 140159, HD 140436, HD 155103, HD 202444, and HD 207652) were

Table 3
Visual Orbit Parameters

HD Number	Period (d)	$T_\circ$ (HMJD)	Semimajor Axis (arcsec)	Eccentricity	Inclination (deg)	ω (deg)	Ω (deg)	$M_1 + M_2$ ($M_\odot$)	χ^2
	σ_P	$\sigma_{T_\circ}$	σ_a	σ_e	σ_i	σ_ω	σ_Ω	$\sigma_{M_1+M_2}$	dof
5286	61183	35543	0.9837	0.30603	44.57	358.62	173.66	1.86	1574.1
	(69)	(21)	(0.0011)	(0.00078)	(0.11)	(0.21)	(0.13)	(0.15)	(1319)
6811	202459	17740	0.573	0.385	142.2	112.6	337.2	6.5	464.1
	(24530)	(1837)	(0.051)	(0.043)	(2.8)	(9.1)	(3.2)	(2.8)	(401)
17904	11553.9	50255	0.2224	0.7560	120.48	265.54	26.62	3.88	360.7
	(8.7)	(12)	(0.0011)	(0.0023)	(0.20)	(0.11)	(0.24)	(0.58)	(383)
44926	339008	53508	0.5	0.7	80.7	14	342.18	2.53	43.1
	(3132095)	(2553)	(3.0)	(1.6)	(4.9)	(23)	(0.70)	(1.3)	(67)
76943	7691.0	49262.6	0.64566	0.15075	131.366	32.30	203.74	2.44	476.9
	(1.8)	(9.1)	(0.00065)	(0.00084)	(0.099)	(0.44)	(0.10)	(0.12)	(459)
77327	13007.2	50404	0.18194	0.5584	109.410	355.63	105.641	6.30	297.0
	(9.7)	(12)	(0.00025)	(0.0015)	(0.066)	(0.36)	(0.080)	(0.98)	337
114378	9485.68	47651.8	0.66132	0.4957	90.054	101.689	12.221	2.45	1162.3
	(0.97)	(2.6)	(0.00061)	(0.0010)	(0.010)	(0.059)	(0.015)	(0.18)	(1211)
129246	45460	60183	2.3	0.9977	102.3	262.9	8.2	122	1452.2
	(62)	(57)	(1.7)	(0.0034)	(9.2)	(5.9)	(2.6)	(275)	(1389)
137391	1368.02	53855.92	0.098837	0.27194	130.016	44.204	130.040	3.24	52.1
	(0.24)	(0.23)	(0.000034)	(0.00028)	(0.029)	(0.068)	(0.040)	(0.23)	(61)
140159	8015.0	54180	0.21033	0.0941	83.608	80.5	69.684	3.73	453.1
	(6.3)	(33)	(0.00047)	(0.0028)	(0.043)	(1.8)	(0.033)	(0.53)	(433)
140436	33701	59947	0.7315	0.4779	94.263	283.40	292.043	3.73	1017.4
	(61)	(63)	(0.0034)	(0.0067)	(0.028)	(0.36)	(0.036)	(0.37)	(885)
155103	2971.54	42567.9	0.10863	0.5338	121.221	53.81	309.30	3.32	274.3
	(0.84)	(3.4)	(0.00020)	(0.0015)	(0.077)	(0.16)	(0.11)	(0.39)	(275)
187362	8487.9	44199.6	0.13605	0.7948	132.33	355.3	340.97	2.23	467.3
	(4.9)	(5.9)	(0.00044)	(0.0019)	(0.41)	(1.0)	(0.68)	(0.35)	(459)
202444	18122.6	47527	0.9160	0.2413	134.11	298.28	339.72	2.63	994.7
	(8.8)	(18)	(0.0013)	(0.0013)	(0.14)	(0.20)	(0.14)	(0.12)	(643)
207652	9622.8	47848.3	0.36245	0.2300	70.379	250.23	230.698	2.65	431.8
	(4.1)	(6.2)	(0.00026)	(0.0011)	(0.029)	(0.14)	(0.028)	(0.21)	(463)

Note. The model parameters and fit uncertainties derived from a simultaneous fit to PHASES and non-PHASES measurements.

used instead of the revised *Hipparcos* values because the S99 analysis made more complete use of non-*Hipparcos* differential astrometry values to separate the binary orbit signal from that of parallax.

For each of the 15 binaries, the PHASES and non-PHASES astrometric measurements, and *Hipparcos*-based parallax measurements were combined in a single orbital fit to evaluate the Campbell orbital parameters and system distance. Alternatively, the orbit semimajor axis was replaced with the total system mass; repeating the fit with this substitution allowed a natural way of evaluating the uncertainties of the total mass. While the system distance is entirely dependent on the parallax measurement, including this as an input value with its associated uncertainty was necessary to evaluate the resulting mass uncertainties properly at the conclusion of the fitting procedure. The best-fit parameters and their uncertainties are listed in Table 3.

4.1.1. HD 5286

HD 5286 (36 And, HR 258, HIP 4288, and WDS 00550 + 2338) is a pair of subgiant stars with spectral types G6 and K6. The total system mass of $1.86 \pm 0.15\ M_\odot$ is in reasonable agreement with this classification (Cox 2000).

4.1.2. HD 6811

HD 6811 (ϕ And, 42 And, HR 335, HIP 5434, and WDS 01095 + 4715) is a pair of B stars (B6IV and B9V). The total mass is $6.5 \pm 2.8\ M_\odot$; while not well constrained, this value is reasonable for these stars.

4.1.3. HD 17904

HD 17904 (20 Per, HR 855, HIP 13490, and WDS 02537 + 3820) was reported to have a 1269 day subsystem by Abt & Levy (1976). The companion was further investigated by Scarfe & Fekel (1978) and Morbey & Griffin (1987) who found no evidence of such a companion, nor is such an object found by astrometry. The single-component velocities from those works were consistent with constant velocity, providing no constraint on the binary orbit, and were not used for the present orbit fitting. HD 17904 is a pair of mid F dwarfs; the total system mass of $3.88 \pm 0.58\ M_\odot$ is a bit high for such stars, though the uncertainty in this is large enough to still be in reasonable agreement.

4.1.4. HD 44926

While the orbital parameters of HD 44926 (HIP 30569, WDS 06255 + 2327) are not well constrained due to few observations covering a short fraction of the orbit, this is the first time an orbital solution has been evaluated for which the fit converged.

4.1.5. HD 76943

Heintz (1981) published four single-component spectroscopic velocities of HD 76943 (10 UMa—though it is now in the constellation Lynx (Griffin 1999), HR 3579, HIP 44248, and WDS 09006 + 4147); the first was taken a year before the others, which were all on the same night. More recently, Tennessee State University's Automatic Spectroscopic Telescope

(AST; Eaton & Williamson 2007) collected 66 blended spectra of 10 UMa spanning 1843 days (23% of the binary orbit). Upon inspection, the single set of absorption lines appeared asymmetric due to the binarity, but remained blended by an amount substantial enough to cause systematic errors in attempts at component velocity determinations. Higher resolution observations at times of maximal velocity separation or individual component spectroscopy behind an Adaptive Optics system may allow better modeling of each component's lines, in which case these measurements could be recovered, but at this time the system remains without useful velocity measurements.

The spectral type is consistently listed as F5V, consistent with the total system mass of $2.44 \pm 0.12\ M_{\odot}$ (Cox 2000) and the S99 component mass values of $1.37 \pm 0.08\ M_{\odot}$ and $1.04 \pm 0.06\ M_{\odot}$.

4.1.6. HD 77327

A few single-component RV measurements of HD 77327 (κ UMa, 12 UMa, HR 3594, HIP 44471, and WDS 09036 + 4709) have been published by Abt et al. (1980) and Heintz (1981). However, these are small in number, span a short time period, and appear to be consistent with constant velocity. As a result, the system is treated as a visual binary only.

HD 77327 is composed of a pair of early ($\sim$ A0) dwarf stars. The total mass of $6.30 \pm 0.98\ M_{\odot}$ is not constrained very well, and while the value is a bit high for stars of this type, the large uncertainty indicates there is no cause for alarm.

4.1.7. HD 114378

CORAVEL produced 22 two-component RV measurements of HD 114378 (α Com, 42 Com, HR 4968, HIP 64241, and WDS 13100 + 1732) spanning nearly half (46%) of the binary orbit, making it both a visual binary and double-lined spectroscopic binary (Duquennoy et al. 1991). However, despite the anticipated velocity amplitude of each star being $\sim$8 km s^{-1}—several times larger than the $\sim$1 km s^{-1} typical measurement uncertainty—no significant velocity changes appear in the CORAVEL velocities. As a result, the velocities did not agree well with the visual orbit (after orbit fitting, over half have residuals marking them as outliers of $>4\sigma$ compared to the published measurement uncertainties) and produced a system distance that was much too distant to agree with that of S99 (55.9 ± 1.4 mas) based on *Hipparcos* astrometry. Thus, these do not appear to be useful in orbit fitting.

Alternatively, Tokovinin & Smekhov (2002) measured nine single-component RVs spanning $\sim$13% of the binary orbit that were consistent with the visual orbit, though these are clustered at two observing epochs and showing little variation, making spurious orbit fitting likely. Using these velocities and the parallax of 55.9 ± 1.4 mas from S99 yielded a result that is almost certainly spurious; for example, the binary mass ratio was a very low value (0.02). Thus, only the visual orbit is presented at the current time, and additional investigations will need to concentrate on improving the velocity results.

The total mass was found to be $2.45 \pm 0.18\ M_{\odot}$, near the value of $2.54\ M_{\odot}$ of S99, though this is not surprising given that the parallax values used were identical. The system is a pair of F5 dwarf stars, and this mass range is reasonable for that spectral type.

Most interesting of all, it is likely that this long period (26 years) binary eclipses! This has been anticipated before (Hartkopf et al. 1989; Hoffleit 1996), but previously the orbit was not determined well enough to demonstrate that eclipses are likely. The visual orbit parameters from the present investigation predict a closest approach of 0.32 mas around 2015 January 24 (to within about a week), when the star is observable during early morning hours and lasting about 1.5 days. Mid F dwarfs have physical sizes about 1.3 times larger than the Sun. At a distance of 17.9 pc, this corresponds to diameters of 0.7 mas. Eclipses are likely even if one considers the 1σ upper limits of distance and orbital inclination, for which closest approach increases only to 0.38 mas and the apparent stellar diameters decrease by 2.5%, an amount much smaller than the uncertainty in the stars' physical sizes; see Figure 1. Unfortunately, only one eclipse per orbit is likely for this pair; the eccentric orbit causes the alternative closest separation to be 0.9 mas, and a likely near-miss. α Com, the brightest star in its constellation, with an orbital period of 26 years (nearly as long as ϵ Aur) is likely to join ϵ Aur as representing long period eclipsing binaries, despite the low probability of such a configuration. Unlike ϵ Aur, in which the chance of eclipse is enhanced by the presence of an extended disk around one star, the eclipses in α Com result purely from orbital geometry and the overlapping of the stars themselves.

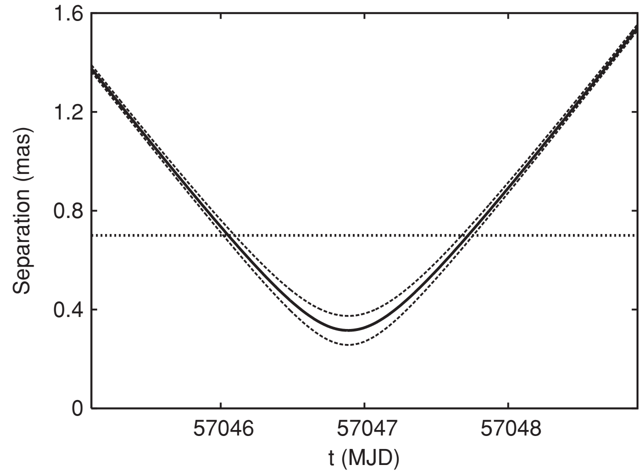

Figure 1. Time of the predicted eclipse of HD 114378 (α Com) in late 2015 January. The solid line shows the projected sky separation of the stars in the binary as a function of time for the best-fit orbital solution. The thinner dashed lines show the separation predicted by changing the value of the orbital inclination by $\pm 1\sigma$. Varying other elements of the orbital solution by their 1σ uncertainties does not significantly change the angle of closest approach, but does change the predicted time of the eclipse. The horizontal line at 0.7 mas corresponds to the expected physical diameter of the stars.

4.1.8. HD 129246

HD 129246 (ζ Boo, 30 Boo, HR 5477, HIP 71795, and WDS 1411 + 1344) has an extremely high eccentricity of 0.9977 ± 0.0034. The distance of closest approach is only 0.3 AU. Projected on the sky, the distance of closest approach is 1 mas; in this case, eclipses are unlikely, though the uncertainty on the inclination is large. The next time of closest approach is 2023 August, though at that time the star is not up at night.

Though the system has a very long orbital period of 124 years, nearly two orbits have been observed; the first measurement was from 1796. Despite this time coverage, and as a result of the large eccentricity, the semimajor axis remains poorly determined. As a result, the total mass is found to be very large ($122\ M_{\odot}$) but also very uncertain ($\pm 275\ M_{\odot}$) to the point of being unconstrained.

4.1.9. HD 137391

The AST attempted observations of HD 137391 (μ Boo, 51 Boo, HR 5733, HIP 75411, and WDS 15245 + 3723) several

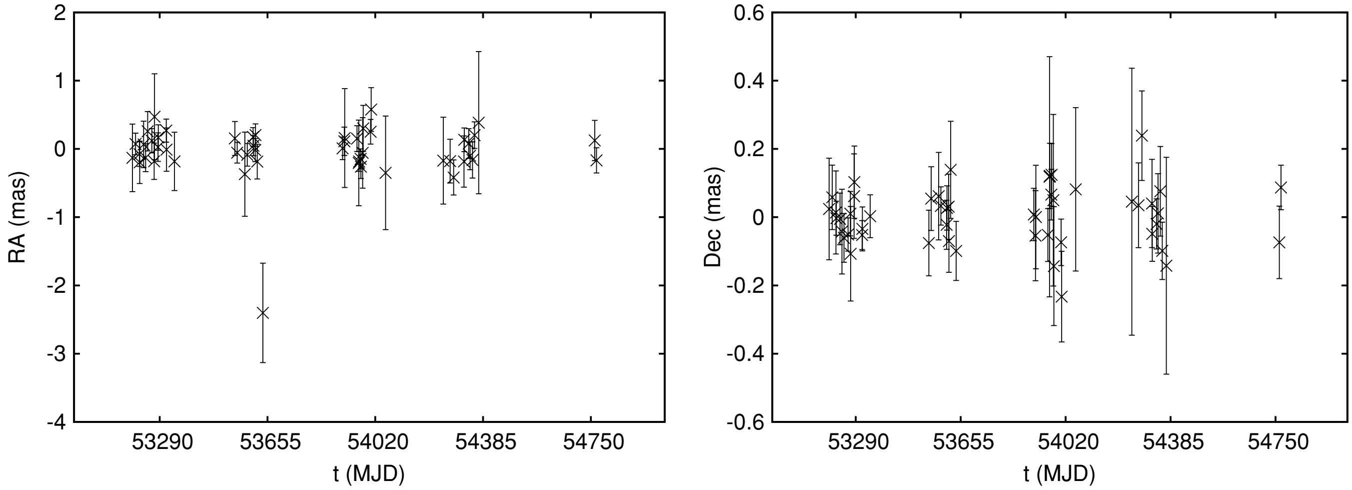

Figure 2. Fit residuals to HD 207652 (13 Peg) along the differential right ascension (left) and differential declination (right) axes for the PHASES measurements. The residuals have low scatter indicating that stellar variability did not affect the astrometry measurements.

times, but the absorption lines were always too broad and blended for RV measurements. The mass sum of $3.24\pm0.23\ M_\odot$ is smaller than the value of $3.70\ M_\odot$ from S99 despite using the same distance to the system. The current value of the semimajor axis is smaller than that from S99, explaining the discrepancy.

4.1.10. HD 140159

HD 140159 (ι Ser, 21 Set, HR 5842, HIP 76852, and WDS 15416 + 1940) is a pair of early A dwarfs with mass $3.73 \pm 0.53\ M_\odot$, consistent with both the S99 value of $3.79\ M_\odot$ and their spectral types, though slightly on the low side for the latter (Cox 2000).

4.1.11. HD 140436

HD 140436 (γ CrB, 8 Crb, HR 5849, HIP 76952, and WDS 15427 + 2618) is a pair of early A stars. The total mass of $3.73 \pm 0.37\ M_\odot$ is slightly lower than the value of $4.23\ M_\odot$ of S99, though still in reasonable agreement. Like HD 140159, this mass is a bit low for their spectral types.

4.1.12. HD 155103

With only 10 PHASES measurements being available, the orbit model of HD 155103 (c Her, HR 6377, HIP 83838, and WDS 17080 + 3556) was not much altered by their addition. The total mass of $3.32 \pm 0.39\ M_\odot$ is identical to that from S99. The spectral types are early (A or F), though the spectral class has been reported as either dwarf or giant. The total mass appears to be more consistent with dwarf stars.

4.1.13. HD 187362

HD 187362 (ζ Sge, 8 Sge, HR 7546, HIP 97496, and WDS 19490 + 1909) is a pair of early A dwarfs, though the measured total mass of $2.23\pm0.35\ M_\odot$ is a bit lower than one would expect for such stars (Cox 2000). This may be due to a remaining error in the parallax: if the original *Hipparcos* parallax is used instead, the total mass is found to be $4.7 \pm 1.2\ M_\odot$, which seems more consistent (Perryman et al. 1997).

4.1.14. HD 202444

Though the binary period of HD 202444 (τ Cyg, 65 Cyg, HR 8130, HIP 104887, and WDS 21148 + 3803) is long and the velocity amplitudes are low, it is possible to use spectroscopy to determine individual velocities for both components. This is because one star is extremely broad lined while the other has very sharp spectral features. Though the spectral lines are always blended, this odd pairing makes a very distinctive line profile that can be fit as the sum of two very different Gaussians. Fekel et al. (2003) published two two-component RVs of the system. The Tennessee State University (TSU) AST recently observed τ Cyg with high cadence to better constrain the mass ratio and search for short period companions to either star. No significant changes were observed in the velocities, and the span of observations was too short to contribute to orbital modeling, so at this time only the system's visual orbit was evaluated.

There is some indication that τ Cyg may have a substellar companion orbiting one of the two stars (see Paper V). There are reasons to doubt the authenticity of this proposed companion, so the visual orbit obtained by modeling the system with only a single Keplerian model has been presented here in addition to the double Keplerian model presented in Paper V. If real, the companion has a long orbital period. This signal could be absorbed into that of the wider binary when only the shorter timespan PHASES data were analyzed to search for tertiary companions, so no compelling evidence for a companion was present when only PHASES measurements were analyzed. However, the continued large value of χ^2 that results when the combined PHASES and non-PHASES astrometry set described in Section 3 was analyzed prompted a second search for tertiary companions, this time using all the astrometric measurements. The longer timespan non-PHASES astrometry reduced the amount by which the binary orbit parameters could absorb motion of an intermediate period companion (short compared to the binary motion, long compared to the timespan of PHASES measurements) and indicated the presence of a companion with mass corresponding to that of a giant planet.

4.1.15. HD 207652

HD 207652 (13 Peg, HR 8344, HIP 107788, V373 Peg, and WDS 21501 + 1717) is a variable flare star. It has been suggested by Tamazian et al. (1999) that the secondary may be a T Tauri-type variable. However, the variability does not appear to have affected the astrometry measurements; see Figure 2. The total mass is $2.65 \pm 0.21\ M_\odot$, in good agreement with the value of $2.67\ M_\odot$ from S99. For the system's early F spectral type, this

Table 4
Single-line Spectroscopic Binary Orbit Parameters

HD Number	Period (d) σ_P	$T_\circ$ (HMJD) $\sigma_{T_\circ}$	Semimajor Axis (arcsec) σ_a	Eccentricity (deg) σ_e	Inclination σ_i	ω (deg) σ_ω	Ω (deg) σ_Ω	M_2/M_1 σ_{M_1/M_2}	$M_1 + M_2$ ($M_\odot$) $\sigma_{M_1+M_2}$	M_1 ($M_\odot$) σ_{M_1}	M_2 ($M_\odot$) σ_{M_2}	χ^2 DOF
26690	2633.34	53415.37	0.13302	0.3301	66.942	306.658	144.296	0.60	2.20	1.38	0.82	264.2
	(0.50)	(0.39)	(0.00015)	(0.0010)	(0.039)	(0.071)	(0.040)	(0.23)	(0.23)	(0.26)	(0.21)	(251)
81858	43089	36649	0.8599	0.5619	65.347	302.54	325.982	0.14	2.20	1.92	0.28	1236.4
	(26)	(11)	(0.0022)	(0.0014)	(0.093)	(0.14)	(0.074)	(0.55)	(0.27)	(0.96)	(0.92)	(1195)
137909	3848.54	44412.8	0.204008	0.53971	111.452	180.21	148.041	0.779	3.04	1.71	1.330	1023.5
	(0.52)	(1.4)	(0.000034)	(0.00021)	(0.014)	(0.13)	(0.030)	(0.039)	(0.25)	(0.18)	(0.074)	(1045)

Note. The model parameters and fit uncertainties derived from a simultaneous fit to PHASES and non-PHASES measurements.

mass and the overall system luminosity are more consistent with dwarf stars, though the spectral classification is giant or subgiant.

4.2. Binaries With Single-component Radial Velocity Measurements

Spectroscopic RVs can improve orbit fitting and enable component masses to be measured. If only one star's spectral features can be observed (single-lined spectroscopic binaries), the masses can be measured if the system's distance has been measured via trigonometric parallax and if a sufficient part of the orbit has been studied spectroscopically. Such measurements are available in the literature for three PHASES binaries: 46 Tau (HD 26690), ω Leo (HD 81858), and β CrB (HD 137909). Of these, a large number of measurements covering several orbital periods were available for β CrB, while the others had only small amounts of data available spanning a fraction of the orbital period. For β CrB, including RV measurements aids constraining all aspects of the orbit, whereas for 46 Tau and ω Leo most orbital elements are unaffected, but the mass ratio (and thus individual masses) can be constrained (though at a limited level). A separate system velocity parameter $V_\circ$ was used for each velocity data set of a given star to allow for instrumental offsets (for example, there are six independent $V_\circ$ parameters for β CrB, one for each paper from which velocity data were obtained). The results of these fits are presented in Table 4.

4.2.1. HD 26690

Five single-component velocity measurements covering 488 days (18% of the binary orbit) of HD 26690 (46 Tau, HR 1309, HIP 19719, and WDS 04136 + 0743) were published by Heintz (1981). An additional 26 unpublished measurements covering 256 days (10% of the binary orbit) have been made by TSU's AST and are presented for the first time in Table 5. A combined fit between the astrometric and velocimetry measurements found typical uncertainties of 1.6 km s^{-1} and 0.65 km s^{-1} were needed for these data sets, respectively, to make the weighted rms of the velocimetry residuals equal to 1. The revised *Hipparcos* parallax by S99 of 27.41 $\pm$ 0.93 mas was used as a weighted input in orbit fitting, as an observation with associated uncertainty. The combined fit solved for the system distance as a parameter, and both the direct parallax measurement and orbital fit were used to constrain this in an optimal manner. The component masses are 1.38$\pm$0.26 $M_\odot$ and 0.82$\pm$0.21 $M_\odot$, a mass ratio larger than that from S99, in which masses of 1.15 $\pm$ 0.14 $M_\odot$ and 1.10 $\pm$ 0.14 $M_\odot$ were found.

4.2.2. HD 81858

Abt & Levy (1976) published 20 spectroscopic measurements covering 1467 days (3.4% of the binary orbit) of HD 81858

Table 5
AST Velocities of 46 Tau

Day (HMJD)	RV (km s^{-1})	σ_{RV}(km s^{-1})
55024.46106	−4.16	0.65
55052.38144	−4.70	0.65
55063.44779	−5.13	0.65
55089.51270	−5.60	0.65
55094.51579	−5.02	0.65
55095.30008	−4.34	0.65
55099.50654	−4.48	0.65
55102.41085	−4.81	0.65
55118.43687	−3.66	0.65
55121.46221	−5.93	0.65
55122.46229	−5.94	0.65
55135.38774	−5.35	0.65
55136.26277	−4.51	0.65
55137.28781	−4.90	0.65
55139.37828	−4.93	0.65
55141.42839	−4.72	0.65
55156.33458	−5.30	0.65
55157.11192	−5.57	0.65
55162.26850	−5.83	0.65
55183.28776	−3.83	0.65
55201.39165	−7.01	0.65
55236.11569	−5.27	0.65
55245.16062	−5.58	0.65
55258.19066	−5.43	0.65
55271.17012	−5.70	0.65
55280.11226	−5.55	0.65

Note. Single-component RV measurements of 46 Tau (HD 26690) from the AST.

(ω Leo, 2 Leo, HR 3754, HIP 46454, and WDS 09285 + 0903). The combined astrometric and velocimetry orbital fit revealed that a measurement uncertainty of 1.0 km s^{-1} yielded a weighted rms of 1 for the velocity residuals. The short span of the spectroscopic measurements compared to the orbital period resulted in only loose constraints being placed on the binary mass ratio and individual component masses. The S99 parallax of 27.5 $\pm$ 1.1 mas was used as a weighted input in orbit fitting. The masses are only poorly constrained as 1.92 $\pm$ 0.96 $M_\odot$ and 0.28 $\pm$ 0.92 $M_\odot$; RV measurements covering more of the binary orbit and/or double-line RV measurements are needed to improve these values. The total system mass could be better determined by improved parallax measurements, but additional RV measurements are necessary for improved evaluation of the mass ratio.

4.2.3. HD 137909

A considerable number of RV measurements of HD 137909 ("Peculiar Rosette Stone," β CrB, 3 CrB, HR 5747, HIP 75695,

Table 6
Double-line Spectroscopic Binary Orbit Parameters

HD Number	Period (d)σ_P	$T_\circ$ (HMJD) $\sigma_{T_\circ}$	Semimajor Axis (arcsec)σ_a	Eccentricity σ_e	Inclination (deg)σ_i	ω (deg) σ_ω	Ω (deg) σ_Ω	M_2/M_1 σ_{M_1/M_2}	$M_1 + M_2$ ($M_\odot$) $\sigma_{M_1+M_2}$	M_1 ($M_\odot$) σ_{M_1}	M_2 ($M_\odot$) σ_{M_2}	d (parsec) σ_d	χ^2 DOF
137107	15204.9	42612.9	0.86226	0.27907	58.084	39.885	202.827	0.885	2.343	1.243	1.100	18.50	2102.6
	(1.4)	(3.4)	(0.00033)	(0.00026)	(0.026)	(0.064)	(0.024)	(0.031)	(0.084)	(0.054)	(0.039)	(0.22)	(2049)
214850	7607.7	45531.7	0.287980	0.73499	139.861	22.31	251.540	1.089	2.246	1.075	1.171	34.43	633.4
	(1.1)	(1.2)	(0.000049)	(0.00014)	(0.032)	(0.12)	(0.076)	(0.080)	(0.067)	(0.058)	(0.047)	(0.34)	(627)

Notes. The model parameters and fit uncertainties derived from a simultaneous fit to PHASES and non-PHASES astrometry and two-component RV measurements.

and WDS 15278 + 2906) have been published, spanning nearly a century. These include the following:

1. 91 measurements by Cannon (1912) ($\sigma \sim 4.3\,\mathrm{km\,s^{-1}}$),
2. 352 measurements by Neubauer (1944) ($\sigma \sim 1.2\,\mathrm{km\,s^{-1}}$),
3. 25 measurements by Wolff (1978) ($\sigma \sim 0.8\,\mathrm{km\,s^{-1}}$),
4. 60 measurements by Oetken & Orwert (1984) ($\sigma \sim 1.0\,\mathrm{km\,s^{-1}}$),
5. 121 measurements by Kamper et al. (1990) (unit uncertainty $\sigma \sim 1.2\,\mathrm{km\,s^{-1}}$), and
6. 78 measurements by North et al. (1998) (uncertainties as given in that paper),

where the measurement uncertainties in all but the last case were derived based on that which yields a weighted rms of 1 for the velocity residuals from a combined orbital fit to the astrometric and velocity data. The S99 parallax of 29.31 ± 0.82 mas was used as a weighted input in orbit fitting.

The PHASES and non-PHASES astrometric measurements, velocity measurements, and S99 parallax measurement were combined in a single orbital fit to evaluate the Campbell orbital parameters as well as binary mass ratio and system distance. Alternatively, the orbit semimajor axis and mass ratio were replaced with either the total system mass and mass ratio or the masses of each component; repeating the fit with these substitutions allowed a natural way of evaluating the uncertainties of these degenerate quantities. While the system distance is entirely dependent on the parallax measurement, including this as an input value with its associated uncertainty was necessary to properly evaluate the resulting mass ratio and mass uncertainties at the conclusion of the fitting procedure. The masses are $1.71 \pm 0.18\,M_\odot$ and $1.330 \pm 0.074\,M_\odot$, values a little smaller than those from North et al. (1998).

4.3. Double-lined Spectroscopic Binaries

When the visual orbit of a binary as well as the RVs of both components are available, the component masses and distance to the system can be determined to very high precision. The distance can be used to convert apparent brightnesses to absolute magnitudes, offering very strong constraints on the stars' physical properties. Two PHASES binaries have RV measurements available for both components and the resulting orbital solutions are presented here.

One additional double-line spectroscopic binary observed with PHASES is δ Equ (HD 202275). Nineteen new PHASES measurements of δ Equ were made since its orbit was last updated in Muterspaugh et al. (2008), which included 49 measurements. However, none of the orbital elements, the component masses, the system distance, nor any of their associated uncertainties, are significantly different when all 68 measurements were included as compared to that previous work, so it was not included in Table 6 because no updated information was needed.

4.3.1. HD 137107

At least one substellar companion has already been detected in the HD 137107 (η CrB, 2 CrB, HR 5727, HIP 75312, and WDS 15232 + 3017) system, though it has no impact on the PHASES study. Kirkpatrick et al. (2001) imaged a faint L8 dwarf of mass $0.060 \pm 0.15\,M_\odot$ at 194″ southeast of the A–B pair. They concluded that the pair is physically associated with a separation of ~3600 AU. It is a circumbinary companion to the A–B binary.

CORAVEL produced 31 two-component velocity measurements of HD 137107 A and B, reported first by Duquennoy et al. (1991) and revised by Pourbaix (2000). The TSU AST observed this system 33 times, but unfortunately these observations took place at a time when the lines were blended and thus are not used for orbit fitting. The CORAVEL measurements have been combined with the astrometry to develop a full three-dimensional orbit. The S99 parallax of 53.5 ± 0.9 mas was also used as an additional measurement with associated uncertainty.

The masses are $1.243 \pm 0.054\,M_\odot$ and $1.100 \pm 0.039\,M_\odot$. As reported in Paper I, the differential magnitude of η CrB was measured in the K band using Keck Adaptive Optics. The differential magnitude is $\Delta K_p = 0.185 \pm 0.001$. The apparent K magnitude from Skrutskie et al. (2006) is 3.714 ± 0.216. Combined with the orbit-derived distance of 18.50 ± 0.22 pc (which is consistent with the trigonometric parallax), these correspond to absolute magnitudes of $K_1 = 3.04 \pm 0.22$ and $K_2 = 3.23 \pm 0.22$.

4.3.2. HD 214850

Batten et al. (1985) published 10 single-component velocities and 12 two-component velocity measurements of HD 214850 (HR 8631, HIP 111974, and WDS 22409 + 1433) spanning 1614 days (~21% of the binary period) and 271 days (~3.6% of the binary period), respectively. Four more measurements are omitted, as done by the original authors, due to partial blending of the spectral lines. Unit uncertainties of $0.19\,\mathrm{km\,s^{-1}}$ for component A and $0.72\,\mathrm{km\,s^{-1}}$ for component B were assigned to these measurements, resulting in the weighted rms scatters of each being unity after orbit fitting. The S99 parallax of 29.5±0.8 mas is consistent with the orbital solution and has been included as an input constraint for orbit fitting and is reflected in the orbital parameters and their uncertainties in Table 6. Component masses are measured at the 7% level.

5. CONCLUSIONS

The high-precision nature of the PHASES measurements and the long timespan of the previous astrometric measurements that aid in closing the orbits determine the visual orbits of many long period binaries with high accuracies. These orbital solutions will benefit future astrometric programs by acting as calibration sources. Future astrometric studies of these systems will aid the orbits presented by extending the time baseline of the precision observations. Unfortunately, it is unlikely the European *GAIA* mission (Lindegren & Perryman 1996) will contribute to the study of these specific systems because its detectors saturate on bright stars, though it is possible the proposed J-MAPS mission could do so (Gaume & Hennessy 2009). In most cases, the stellar astrophysics applications are limited by the RV data available. In some cases, the lack of RV could be addressed simply by pursuing these measurements over the next decade or so.

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