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PREDICTING THE α COMAE BERENICES TIME OF ECLIPSE: HOW 3 AMBIGUOUS MEASUREMENTS OUT OF 609 CAUSED A 26 YEAR BINARY'S ECLIPSE TO BE MISSED

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ABSTRACT

The dwarf stars in the 26 year period binary α Com were predicted to eclipse each other in early 2015. That prediction was based on an orbit model made with over 600 astrometric observations using micrometers, speckle interferometry, and long baseline optical interferometry. Unfortunately, it has been realized recently that the position angle measurements for three of the observations from ~100 years ago were in error by 180°, which warped the orbital fit. The eclipse was likely 2 months earlier than predicted (MJD 56979, 2014 November 18 UT, 7 days before the first photometric observations of this system for the season were made at Fairborn Observatory), at which point the system was low on the horizon at sunrise.

Key words: astrometry

1. INTRODUCTION

α Comae Berenices has long been suspected of eclipsing, despite being a 26 year binary, due to the system having an inclination extremely close to edge-on. Struve (1875) reported that "occultations" were observed, though it is not clear from his text if occultations were inferred based on the orbit or if a decrease in brightness was actually observed. Hartkopf et al. (1989) and Hoffleit (1996) both suggest α Com is an eclipsing system. The most recent orbital calculation by Muterspaugh et al. (2010) showed the eclipses to be highly likely, with a predicted closest projected approach in late 2015 January (Muterspaugh & Henry 2014). As the event approached, new observations and reanalysis of old observations began to suggest the eclipse prediction might be in error. It was realized that among the over 600 observations used to determine the orbital model by Muterspaugh et al. (2010), the measurements from 1896.33, 1911.4, and 1937.16 were listed with position angles in error by 180°. All three of these were the last measurements made before closest approach of the binary at their respective epochs, marking a transition from measurements with position angles near 192° to those with 12° or vice-versa. The stars are nearly equal magnitude, making such mistakes understandable (Struve 1875). While efforts were made to find and correct such errors by examining fit residuals (see Figure 1, top panel), these three were missed because the orbit model skewed to compensate, as is possible near closest approach, and thus the fit residuals escaped detection (several other 180° discrepant measurements were successfully corrected through this method). The final orbital solution was similarly skewed, which caused errors in the timing of the eclipse.

2. CATCHING THE MISTAKE

Three developments led to identifying these erroneous measurements and the skewed orbit solution. First, Henrichs & Wijngaarden (in preparation) refit the α Com observations from the WDS using only the separations, excluding the position angle measurements (except to choose a positive or negative sign for the separations). They fixed the inclination at 90° and ignored the longitude of the ascending node. As this method ignores erroneous position angles, the three errant measurements did not skew the fit. In a private communication to Muterspaugh on New Year's Eve 2014, they calculated that the eclipse had in fact already passed based on this separation-only orbit evaluation. However, their orbital solution did not agree well with a full fit including the position angles; seeding a full fit with their parameters led to fitting iterations which eventually converged on the orbital solutions of the Muterspaugh et al. (2010) model. For two weeks it was unclear how to resolve the discrepancy.

The second development occurred on 2015 January 7 when the system was observed by the Navy Precision Optical Interferometer (NPOI, Armstrong et al. 1998). The visibility trends indicated a binary separation much larger than anticipated by the Muterspaugh et al. (2010) orbit model, and it was unclear if the system was still in approach or had already passed conjunction.

Finally, a measurement of the binary separation by the CHARA Array (Center for High Angular Resolution Astronomy, ten Brummelaar et al. 2005) was made on 2015 January 16 as a separated fringe packet binary using the CLIMB beam combiner. The data were reduced and analyzed following the methods described by Farrington et al. (2010). This resulted in a separation of 45.53 milli-arcseconds (mas) and position angle

Table 1
New Speckle/CHARA Measurements

MJD (day)	ρ (arcsec)	θ (deg)	σ_ρ (arcsec)	σ_θ (deg)	Source
56862.52	0.0906	12.2	0.00127	1.41	Horch et al. (2015)
56862.52	0.0908	12.2	0.00127	1.41	Horch et al. (2015)
57038.4870368	0.04553	192.85	0.00081	1.02	(This Paper)
57043.4431444	0.04855	193.78	0.00065	0.77	(This Paper)
57044.48408989	0.04947	193.19	0.00043	0.50	(This Paper)

Note. New measurements from Speckle Interferometry (originally published in Horch et al. 2015, with uncertainties as assigned in that work, with the time in Modified Julian Day (JD-2400000.5), converted from their use of Besselian years), and the CHARA Array (presented for the first time in this paper).

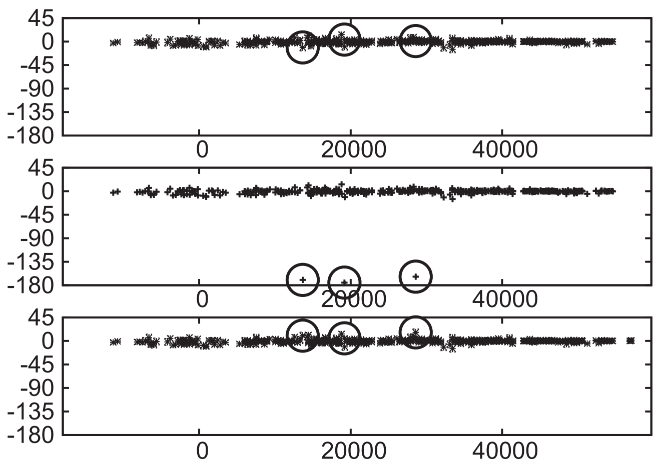

Figure 1. Fit residuals (observed-computed) for the positional angles of α Com for various orbit models and 180° ambiguities. The horizontal axis is Modified Julian Day and the vertical axis is residual angle in degrees. In each case, the 3 problematic measurements from 1896.33, 1911.4, and 1937.16 are circled. (Top) Fit residuals as the data were presented for the model by Muterspaugh et al. (2010). Even though the three measurements were input with 180° errors, the model fitting procedure resulted in a model skewed enough that the measurements do not appear as obvious outliers. (Middle) Fit residuals for a model fit using only the separation measurements and PHASES observations, then applied to the positional angle data. The problem observations are clear. (Bottom) Residuals to our new orbital model presented here after correcting the three 180° ambiguities and including the new measurements. Measurements from sources other than the PHASES program, CHARA Array, and NPOI are from the WDS (Mason et al. 2001).

of 192°85 (which could be 180° ambiguous, though this value is now consistent with our revised orbit below), at a time when the predicted separation from the 2010 orbit was only 7 mas. Two additional measurements were obtained by CHARA and have been included in the orbital solution. The new observations also show the binary to be growing further apart. In the CHARA observations, the fringe packet of component "B" is about 5% larger than that historically defined by the vast majority of observers as "A"; this is a function of the stars' differential brightness, diameters, and also may be impacted by the fact that the CHARA measurements were at infrared wavelengths. To avoid (further) confusion, the historical designations are maintained.

As a result of these developments, the original data set used in Muterspaugh et al. (2010) was refit with the uncertainties for position angle artificially increased to absurdly large values (to 10,000°), essentially removing them from the fit, and a model was evaluated using just the separation measurements (with no positive or negative signs) and the PHASES measurements (the Palomar High-precision Astrometric Search for Exoplanet Systems, which took place at a time when the quadrant was unambiguous). The resulting model was used to calculate predicted position angles for all observation times for comparison with those in Muterspaugh et al. (2010). It was discovered that the measurements from 1896.33, 1911.4, and 1937.16 were listed with position angles in error by 180°, namely 21°1, 196°4, and 208°3. The corrected values are 201.1, 16.4, and 28.3, respectively (see Figure 1, middle panel). A new fit with these corrections was performed with the position angle uncertainties returned to their original values, resulting in an improved χ^2 goodness-of-fit.

3. UPDATED ORBIT

The new orbital parameters for α Com were obtained from a combined fit based on the (corrected) previously tabulated non-PHASES and PHASES astrometry as well as the new Speckle Interferometry, CHARA Array, and NPOI measurements listed in Tables 1 and 2. The results are presented in Table 3. There are 1231 degrees of freedom and $\chi^2 = 1134$. For comparison with the previous model's epoch of periastron passage, which was listed one full orbit prior, the new model predicts MJD 47614.4 $\pm$ 3.0 (the increased uncertainty compared to Table 3 reflects the uncertainty of the period which impacts this). The leading indications of the previously predicted eclipse timing being incorrect are the resulting decreases to both the period and the epoch of periastron passage.

4. NEW ECLIPSE TIMINGS FOR 2014 AND BEYOND

To evaluate the likelihood of eclipses and the ranges of eclipse lengths and timings one might expect based on the updated orbit, 100,000 random sample sets of binary orbit parameters were generated to evaluate whether each combination would produce an eclipse event. In each set, random values were selected for each orbital element using a Gaussian-distributed random number generator with 1σ width corresponding to the parameter's formal uncertainty and centered at the best-fit value (e.g., values of the period were selected as $9442.4 + 3.0 \times g$ days, where g is a standard normal deviate random number). The resulting set of parameters was then used to calculate the sky-projected separation of the binary every minute from MJD 56955 to 57005 (50 days), to ensure all likely eclipse times were included. For each set, the time of closest approach, the distance of closest approach, and the duration over which the binary separation was less than 0.7 mas (the approximate diameters of the stars) were recorded. If any set failed to produce a minimum separation less than 0.7 mas, it was

Table 2
New NPOI Measurements

Epoch (year)	ρ	θ	δR.A.	δDecl.	$\sigma_{\rm min}$	$\sigma_{\rm maj}$	ϕ	$\sigma_{\rm R.A.}$	$\sigma_{\rm Decl.}$	$\frac{\sigma^2_{\rm R.A.,\,Decl.}}{\sigma_{\rm R.A.}\sigma_{\rm Decl.}}$
1998.27196	0.17877	191.96	−0.037046	−0.174889	0.000159	0.000678	173.7	0.0001747	0.0006741	−0.402370
2014.97833	0.02772	193.06	−0.006264	−0.027003	0.000262	0.000572	180.0	0.0002620	0.0005720	0.000000
2014.98654	0.03028	192.76	−0.006688	−0.029532	0.000280	0.000599	180.7	0.0002801	0.0005990	0.020419
2014.98928	0.03098	192.86	−0.006895	−0.030203	0.000270	0.000587	179.8	0.0002700	0.0005870	−0.005983
2015.01666	0.03874	192.62	−0.008464	−0.037804	0.000260	0.000592	174.3	0.0002653	0.0005896	−0.178697

Note. New measurements from the Navy Precision Optical Interferometer (NPOI). The uncertainty ellipses are not oriented along either R.A.-decl. nor ρ-θ; column 8 is the position angle of the major axis of the uncertainty ellipse. The corresponding covariances between R.A. and decl. measurements are listed in column 11. Column 1 is in Julian Years, columns 2–7 and 9–10 are in arcseconds, with column 8 in degrees.

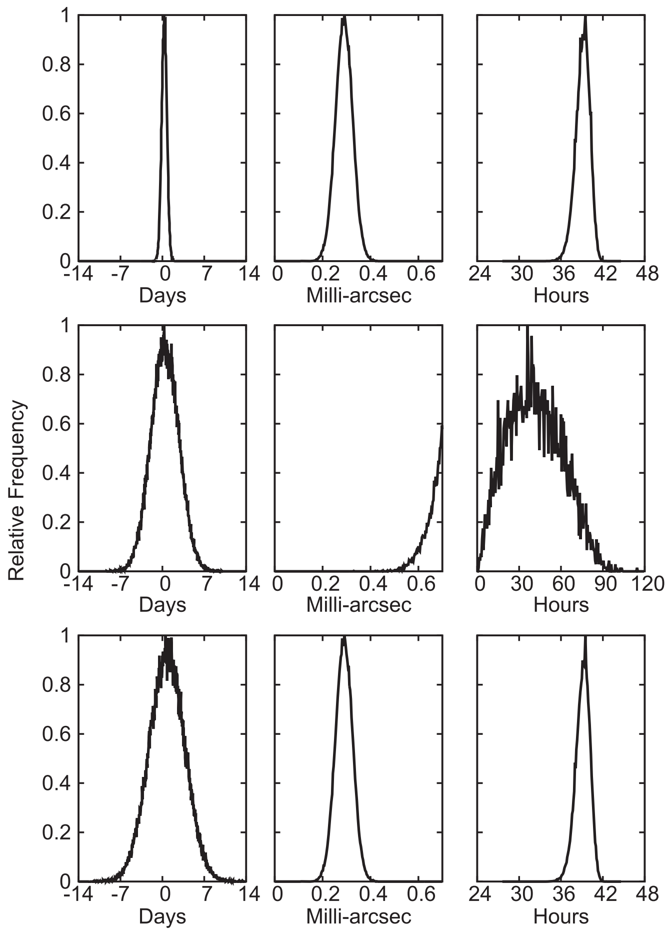

Figure 2. (Top Left) Histogram of the predicted time of the eclipse mid-point vs. days since 2014 November 18 (MJD 56979). (Top Middle) Histogram of the modeled closest projected separation of the binary (maximum eclipse) in units of milli-arcseconds. (Top Right) Histogram of the predicted duration of the eclipse from ingress at 0.7 mas separation to egress at the same, in units of hours. (Middle Row) Same as top row, except for the secondary eclipse centered at MJD 61051. (Bottom Row) Same as top row, except for the eclipse centered at MJD 66421.

flagged as non-eclipsing. However, in 100,000 trials, no such combination was found.

The ranges of eclipse durations and depths were evaluated based on the times of first contact and last contact, and the distance of closest approach. Based on a calculation of the areas of two partially overlapping circles, the distance of closest approach is related to the eclipse depth as

$$\Delta m = 2.5\log_{10}\left(1 - \frac{\beta - \sin\beta}{2\pi}\right)$$

where

$$\beta = 2\cos^{-1}\frac{b}{d_*}$$

with b the projected separation between the centers of the stars and d_* the diameter of one star. For the simplicity of this model, it is assumed the stars have the same size and are equally luminous (approximately correct for this system). The top row of Figure 2 shows histograms for the time of maximum eclipse, distance of closest approach, and eclipse durations.

The most likely time of eclipse was MJD 56979 (2014 November 18, UT). Unfortunately, the observing season for Tennessee State University's photometric observations of α Com at Fairborn Observatory did not begin until seven days after this predicted time of eclipse due to the star's low elevation and long atmospheric path near the eastern horizon at sunrise. The observations were acquired with TSU's T4 0.75 m Automatic Photoelectric Telescope (APT). T4 successfully observed α Com in good conditions for six consecutive nights beginning 2014 November 25, UT. Those six observations scatter about their mean with a standard deviation of 0.0031 mag and show no evidence for dimming. APT observations beginning a week or so earlier would have been difficult but perhaps not impossible.

The secondary eclipse is now also a possibility, and is predicted to occur just eleven short years to the week of when the error in the 2014/2015 timing was discovered. The 100,000 simulations were repeated for a 50 day window beginning on MJD 61025. The secondary eclipse has only a 5.4% probability of happening—in only 5436 simulations did the stars come within 0.7 mas of each other. If the secondary eclipse does occur, the mean predicted time of eclipse is MJD 61051 (2026 January 11); see Figure 2.

The next primary eclipse will be in late 2040 September, a time of year which makes this system quite difficult to observe from Earth. Cameras on distant spacecraft could be used instead. The 100,000 simulations were repeated for a 50 day

Table 3
Visual Orbit Parameters

Period (day) 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
9485.68	47651.8	0.66132	0.4957	90.054	101.689	12.221
(0.97)	(2.6)	(0.00061)	(0.0010)	(0.010)	(0.059)	(0.015)
9442.4	57056.84	0.67144	0.51060	90.0501	100.563	12.2272
(3.0)	(0.36)	(0.00033)	(0.00061)	(0.0062)	(0.026)	(0.0098)

Note. The previous (top, erroneous) and revised (bottom) model parameters and fit uncertainties for the binary orbit of α Com.

window beginning on MJD 66397. The average time of eclipse is MJD 66421 (2040 September 24); see Figure 2.

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