A New Approach to Determine Orbits of Wide Binary Stars
Case: WDS 19377+3022 BU 144

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Abstract

Astrometric, photometric and other data have been acquired for the double star WDS 19377+3022 BU 144, previously not considered to be a binary star system. Analysis of the data using new methods provides considerable evidence that BU 144 is a gravitationally connected binary star system. With the new methods, the data suggests a physical separation range of 1,075 – 1,100AU, an orbital inclination angle of ≈ 50°, and an orbital period ranging from 9,800 – 10,330 years.

1. Introduction

The Washington Double Star Catalog (WDS) system 19377+3022 BU 144 has 46 position angle and separation measurements dating from 1873 to the present. The Gaia DR3 G-band apparent magnitudes (Vallenari, A., et. al. 2022) of the components are +9.20 and +9.33 for the primary and the secondary. During the 149 year measurement history position angles (PA) changed by just 5.29° and the separations (SEP) by less than 0.4". With the limited range of PA and SEP data, BU 144 was not considered as a gravitationally bound binary star system hence it is not listed in the *Sixth Catalog of Orbits of Visual Binary Stars* (Matson, et. al., 2022). Further, with a Gaia distance of 49.1pc, BU 144 is not listed in The *General Catalog of Trigonometric Stellar Parallaxes Fourth Edition* (van Altena, et. al., 1995). This parallax catalog has stellar distances to 650 pc and higher, however the accuracies of distances beyond 150pc (which were measured with ground based telescopes) are highly questionable. It is not the objective of this paper to determine all seven orbital elements (a, e, i, ω, Ω, T_0, P) that define an orbit. Instead, all the available Gaia and observational data is used here as a starting point to derive the best estimates of physical separation, the orbit's orientation angles with respect to the Sun and its orbital period.

2. Data Acquisition

New measurements of position angle and separation were made using the video drift method and the author's Meade 14-inch LX200 telescope located in Ft. Davis, Texas. The observations were made under good seeing conditions with the target within 30 minutes of its passage across the local meridian. Astrometric observations should always be made with the target as close to the meridian as possible to minimize the amount of atmosphere the telescope/camera system is observing through.

Using a *Watec 902H Ultimate* video camera, (this camera typically used for occultations due to its highly sensitive chip) the scale factor was 0.56"/pixel using the telescope/camera/focal length system. The video drift method (Nugent and Iverson 2018, and other papers in the series) has the advantage of very little human intervention in determining the position angle and separation of the components.
The video drift method works as follows: The component stars are placed on the video camera chip corresponding to the far eastern part of the field of view (FOV). The telescope's motor drive is then turned off. As the components drift across the FOV, they will move precisely in the west direction (position angle 270°). In 25-30 seconds, (duration of the video depends on the focal length of the telescope/camera system) the stars will drift out of the FOV. The video is then saved. The components are re-positioned back at the east side of the camera chip and the process is repeated several times resulting in several 25-30 second videos.

Data from the videos are generated using the software program *Limovie* (Miyashita 2006). *Limovie* was written for occultation videos to measure brightness changes of stars during an occultation. In addition to brightness information, *Limovie* also outputs (x,y) Cartesian coordinates of each component for each video frame. With a 30 frame/sec video recording rate, a 25 second video outputs 750 video frames resulting in 750 pairs of individual (x,y) coordinates for each component. The software program *VidPro* (written by this author) analyses the (x,y) coordinates for each video frame and computes a position angle and separation for each video frame. All of the video frame output data are then combined resulting in a single position angle and separation along with statistical results.

An example on how the video drift method works using the software programs *Limovie* and *VidPro* is demonstrated in this YouTube video: https://www.youtube.com/watch?v=rlg_mrxnvU0.

The new position angle and separation for BU 144 is presented in Table 1. The Gaia Early Data Release 3 (Gaia Collaboration, A. Vallenari, A. G. A. Brown, et al. 2022) parallaxes, proper motions, radial velocities and associated errors of the components are in Table 2.

PA°	error°	SEP"	error"	Date	Mag Pri	Mag Sec	Nights
356.5	1.57	5.81	0.14	2022.65	+9.20	+9.33	1

Table 1. WDS 19377+3022 BU144 measurements using the video drift method. Measurements are from Equator and Equinox of date.

	Parallax (mas)	error mas	pmra mas/yr	pmra error mas/yr	pmdec mas/yr	pmdec error mas/yr	Radial velocity km/sec	error km/sec
Primary	20.37438	0.011583	71.41078	0.009319	39.21757	0.010964	-32.73	0.374
Secondary	20.37068	0.012532	76.72102	0.010137	35.24491	0.011941	-33.762	0.428

Table 2. Gaia ERD3 data for WDS 19377+3022 BU 144. Gaia Source IDs for Primary: 2032516891133712000, Secondary: 2032516895429129113

The Centre de Données astronomiques de Strasbourg (CDS) VizieR tables derived from Gaia EDR3 also contains data on each component's effective temperature (T_{eff}), radius and mass. These tables reveal the component's masses ranging from $0.78M_\odot$ - $0.80M_\odot$. The average component mass from the various VizieR data sets is listed in Table 3.

	Temp °K	Radius $R_\odot$	Mass $M_\odot$
Primary	5,038	0.83	0.795
Secondary	4,965	0.81	0.795

Table 3. VizieR (based on Gaia ERD3) effective temperature, radius and average mass.

Using the new measured separation angle along with the Gaia EDR3 distances, the physical separation between the components was derived using the law of cosines. The calculated physical separation between the components is 1,879AU and this value uses the Gaia mean parallaxes and not the errors. Taking into account the errors in the parallaxes, the physical separation between the components ranged from 285AU to 13,819AU.

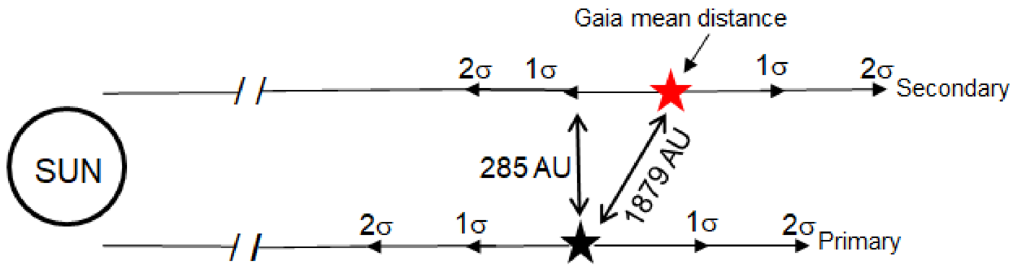

Figure 1. Gaia distances of components from the Sun including errors for WDS 19377+3022 BU 144. The 1σ and 2σ points show the standard deviations in distance at the 68% and 95% confidence levels. Diagram not to scale.

The separation 285AU would be the minimum distance between the primary and secondary and this assumes that both components are equidistant from the Sun. There is substantial overlap in the component distances from the Table 2 parallax errors shown in Figure 1 amounting to 10,148AU. The method used to derive the 1,879AU separation with the associated errors, hereinafter will be referred to the "Law of Cosines" method.

3. Proper Motions and Radial Velocity

The Gaia EDR3 proper motions were plotted on the Digital Sky Survey 2 (DSS2) blue image using the *Aladin Sky Atlas Version 11* interactive software program (Figure 2). The proper motions of the component stars are nearly identical in direction and magnitude (see Table 2). To confirm, Harshaw's (Harshaw 2016) calculation was used to determine if the components share a common proper motion. The derived value was 7.8%.

From Harshaw's reasoning, values < 20% = common proper motion (CPM) pair, 20% < value < 60% = similar proper motion (SPM) pair and a value > 60% = different proper motion (DPM) pair. BU 144's 7.8% value is an expected result with the physical separation of the components being very close as the stars are moving through space together.

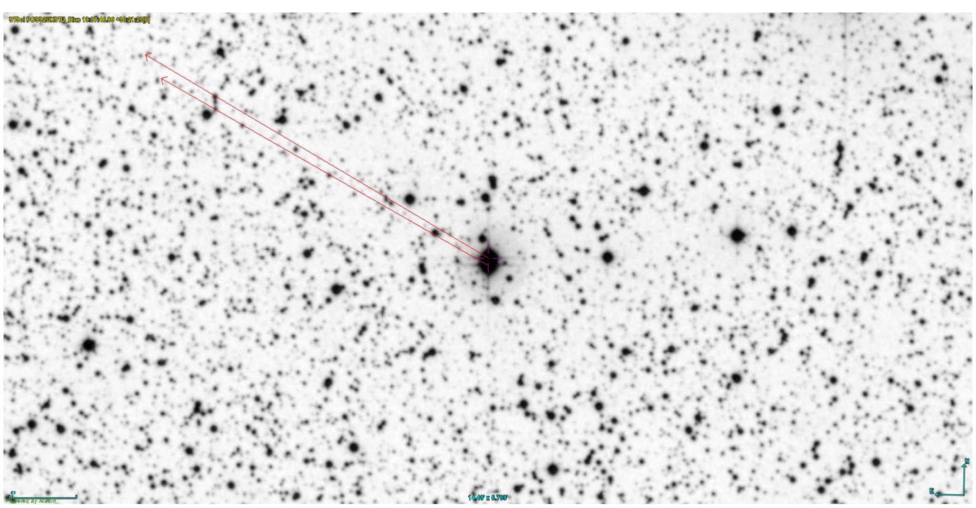

Figure 2. Gaia proper motions of components BU 144 overlaid on DSS2 blue image. DSS2 image date: July 14, 1988.

The radial velocities V_R of the components from Gaia ERD3 are: V_R primary: –32.73 ± 0.374km/sec and V_R secondary: –33.76 ± 0.43km/sec. The similar radial velocities, proper motions and close separation provide evidence that BU 144's components are moving through space together as a binary star system.

4. Estimating Absolute Magnitude, Bolometric Correction, Mass and Orbital period

Assuming the estimated physical separation of the component stars of BU 144 is 1,879AU, it may be a gravitationally connected binary star system. The orbital period of a binary is historically derived using Newton's version of Kepler's 3rd law:

$$P^2 = \left[\frac{4\pi^2 a^3}{G\left(Mass_{pri} + Mass_{sec}\right)} \right] \quad [1]$$

In equation [1], P is the period, π the mathematical constant, G the gravitational constant, $Mass_{pri}$, $Mass_{sec}$ are the masses of the primary, secondary and a is the semi-major axis of the orbit. Estimates for the component masses in solar mass units were computed from the empirical mass-luminosity relation (Lang, 1992, p. 116),

$$Mass_{\odot} = 10^{0.48 - 0.105 M\mathrm{bol}} \quad [2]$$

where M_{bol} is the absolute bolometric magnitude. The bolometric magnitude is the magnitude of a star from its total radiation over all wavelengths. Equation [2] is only valid for stars with absolute bolometric magnitudes from $-8 < M_{bol} < +10.5$. The bolometric magnitude is traditionally derived from:

$$M_{bol} = M + BC, \quad [3]$$

where M is the absolute magnitude and BC is the bolometric correction. The absolute magnitude M is derived using the distance modulus:

$$m - M = 5 \log R - 5 \quad [4]$$

where m is the apparent Gaia G-band magnitude and R is the known distance to the components in parsecs. From the tables in Pecaut and Mamajek (2013), Gaia effective temperatures (T_{eff}) were used to estimate the bolometric correction BC: Primary:–0.286mag, secondary: –0.317mag. With M and BC known for each component, equation [3] was used to get M_{bol}. The absolute bolometric magnitudes were then used in equation [2] to derive the mass of the components. The results are primary: $0.80M_{\odot}$ and secondary: $0.79M_{\odot}$ where both are nearly identical to the VizieR tabular values in Table 3. These nearly equal masses provide evidence that BU 144's components may be in a circular orbit.

Using the estimated masses from equation [2], and the 1,879AU physical separation, equation [1] was used to calculate the orbital period of the system: 22,813 years. From the Gaia range of physical separation (285AU – 13,840AU), the period ranges from 1,350 – 456,000 yrs. The long orbital period based on 1,879AU physical separation could explain the small changes of position angle observed over the 149 year measurement history.

The WDS catalog lists the spectral type for the primary component as K0V and no spectral type for the secondary. With the Gaia DR3, the T_{eff} are listed as primary: 5038°K and secondary: 4965°K. These temperatures are consistent with spectral types of the components as K2V – K3V. With nearly identical T_{eff} and spectral types, these stars may have formed and evolved together at some point in the galaxy's history.

5a. Developing an Orbit: Deriving Space Velocity

The computation of an orbit of a visual binary usually requires a large change of observed PA values over the measurement history along with the corresponding angular separations. Typical PA changes for orbits in the Sixth Orbit Catalog span 25°– 50° and larger. There are very few exceptions. These exceptions systems have large separations approaching 2,000AU – 3,000AU hence they have long periods and small changes in PA.

We begin by assuming BU 144 is a gravitationally connected binary star system. From the previously derived nearly identical masses of the components it will also be assumed that BU 144 has a circular orbit revolving around a common center of mass. It is proposed that the component space velocity differences (ΔV_{space}) can be used to estimate the orbital velocity. With the orbital velocity known of either component along with their physical separation, the period can be determined.

The V_{space} is found from combining the radial velocity V_R and proper motions. Proper motions represent tangential velocity as they are the projected velocity across the celestial sphere. The V_{space} is the actual velocity of the components (with respect to the Sun) through space in a given direction. See Figure 3 parts 1-4. The V_{space} is computed from the following formula:

$$V_{space} = \sqrt{V^2_R + (4.74\ \mu''/\pi'')^2} \quad [5]$$

In equation [5], V_R is the radial velocity in km/sec, μ is the total proper motion in arcsec/yr, and π is the parallax of component in arcseconds.

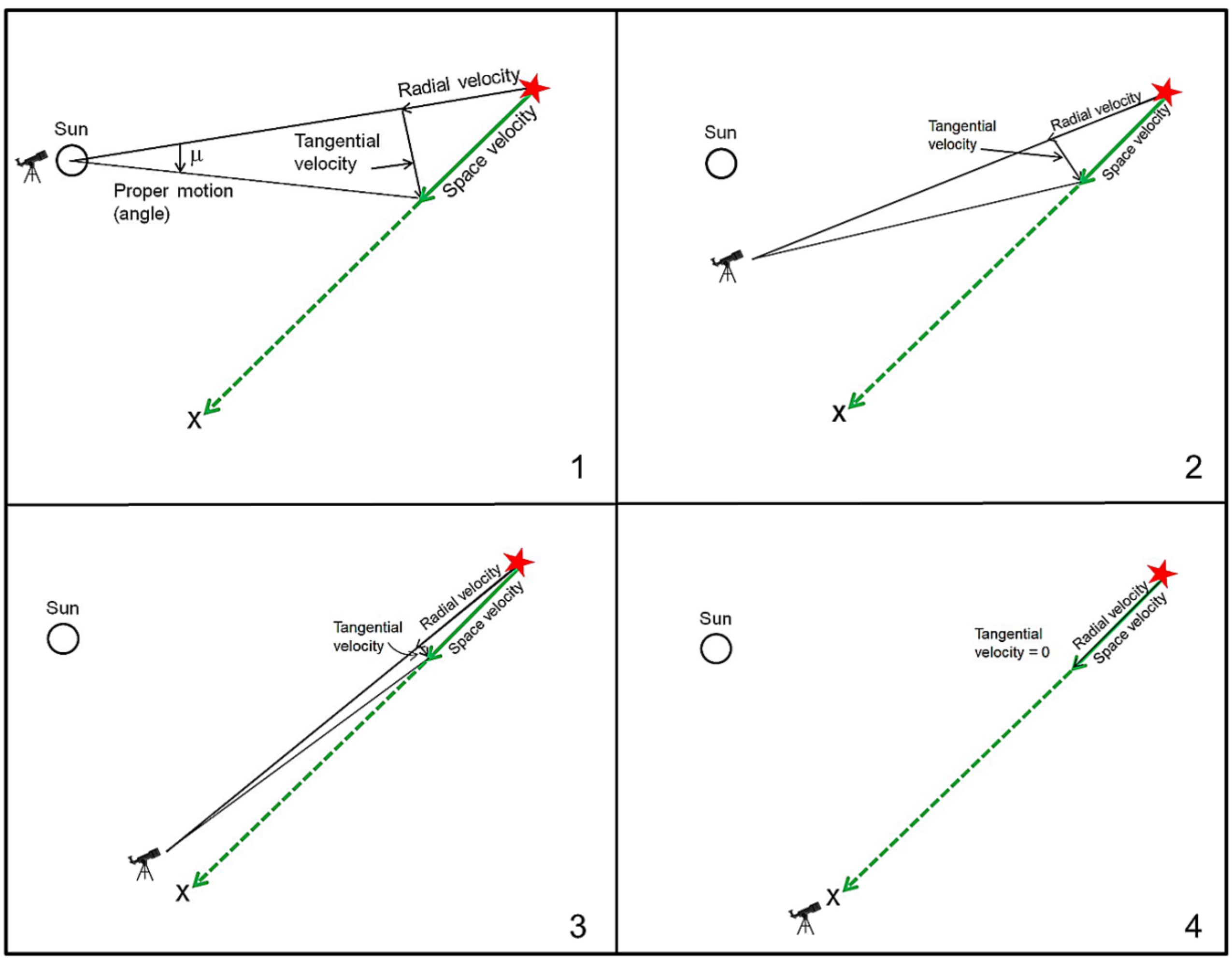

Figure 3. Part 1: The Observer at the Sun sees proper motion, radial velocity and computes V_{space} (space velocity) of the components. Parts 2, 3 and 4: The Observer is moved away from the Sun to the point "X" where the proper motions equal zero. At this point "X", the Observer views only the V_{space} which is the radial velocities of the components.

In Figure 3, the Sun and the point X are at different positions in the galaxy. Figure 3 illustrates that if an observer moves from the Sun at part 1 toward the point X (as shown in parts 2, 3 and 4), this reduces the tangential velocity (proper motion) to zero. Thus the observer at the point X in part 4 only sees the actual space velocity V_{space} of the components, which is their individual radial velocities at point X. The orbit viewed from the position X eliminates the space velocity projection effect seen from the Sun/Earth perspective. For the case of BU 144, the point X is 24.8 pc from the Sun. This creates a 30° angular separation on the sky between the Sun and point X as viewed from the BU 144 components.

5b. Orbital Velocity from Space Velocity

To illustrate the orbital velocity computation, we first assume that the orbit of BU 144 is edge on (inclination = 90°) to the line of sight as seen from the point X as shown in Figure 4. For an observer at the position of X in Figure 4 the space velocity V_{space} of the components is the radial velocity. Then any difference in V_{space} of the components can be attributed to orbital motion. For example, if the primary's V_{space} is +5 km/sec and the secondary's V_{space} is –5 km/sec at the point X, then each component's orbital velocity would be 5 km/sec (Figure 4 only). The Observer would see an *absolute difference* in V_{space} of 10 km/sec: +5 – (–5) = 10. Thus, the orbital velocity of each component is one-half of the absolute difference, in this example: 5 km/sec.

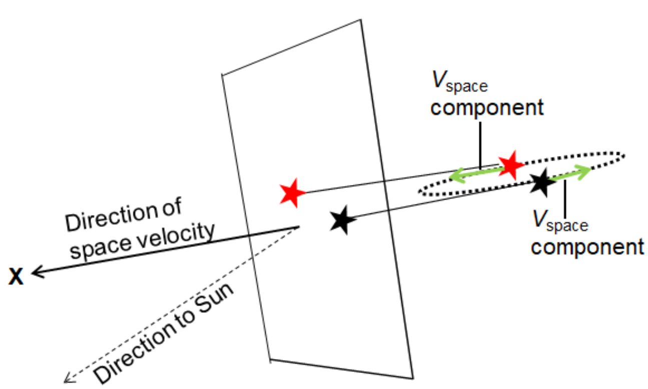

Figure 4. Net observed orbital/space velocities in opposite directions from X.

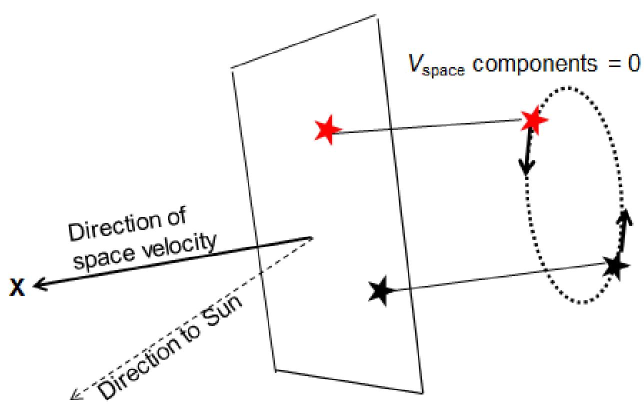

Figure 5. V_{space} = 0 at the point X

If the orbit was oriented as shown in Figure 5 (inclination = 0°, face on to our line of sight) there would be no measureable difference in the radial (V_{space}) velocity seen at point X.

BU 144's derived space velocities are primary: –37.82 ± 0.37km/sec and secondary: –39.06 ± 0.43km/sec, the absolute difference 1.24 ± 0.40km/sec. As reasoned above this absolute difference in V_{space} can be interpreted that one component is moving toward us and the other component away from us. Figure 6 illustrates this. The V_{space} velocity of each component is ½ of the absolute difference or 0.62 ± 0.40km/sec. Taking into account the errors, the range of projected component V_{space} is 0.22 km/sec – 1.02 km/sec. As Figure 6 shows, the actual orbital velocity will depend on the orientation (inclination angle, *i*) of the orbit as viewed from the observer at the point X. Note that the orbital velocity derived from this method is independent of the physical separation of the components.

5c. Orbital Period from Orbital Velocity and Inclination

Now consider the case where the orbit is inclined by 45° as viewed from point X, (not from the Sun), as shown in Figure 6. The orbital velocity can be computed from the space velocity:

$$\text{Orbital velocity} = \frac{V_{space}}{\cos 45°} \quad [6]$$

Using the range of projected V_{space}, 0.22 – 1.02 km/sec, the actual orbital velocities along the 45° inclined orbit will vary from 0.31 to 1.44 km/sec.

Assuming a circular orbit, and a 1,879 AU separation, the circumference of the orbit is 5,903AU. From the range of derived orbital velocities from equation [6], the components will make one complete revolution of 5,903 AU in 19,419 – 90,441 years.

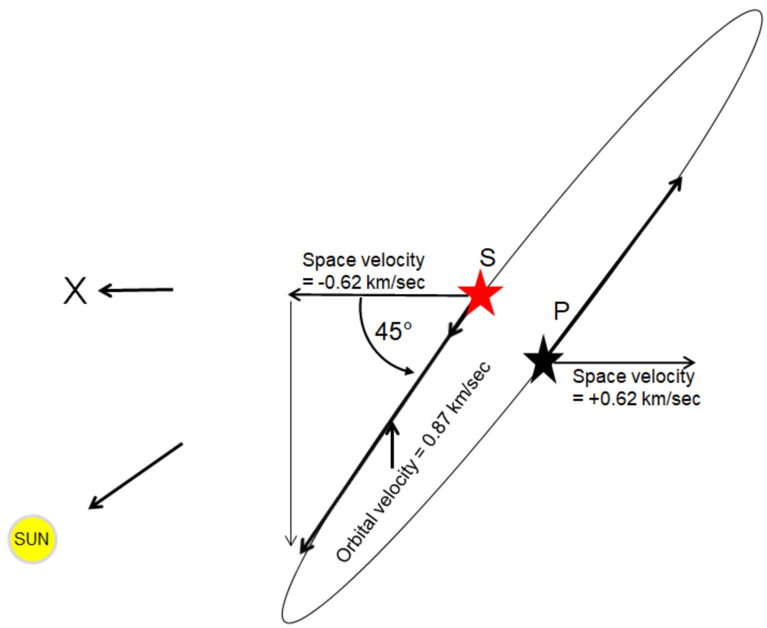

Figure 6. With inclination = 45°, the projected space velocity of the components = 0.62 km/sec. The resulting actual orbital velocity = 0.87 km/sec. Different inclination angles result in different orbital velocities.

6. Historical Measurements: Orbital Period from Position Angle

The angular separation change of BU 144 over its 149 year measurement history is 5.29°. Figure 8 shows the historical PAs. (PA values in 1913: 359.3°, 1928: 356° and 1984: 357.7° are several degrees different from the surrounding values and are outliers). Ignoring the physical separation, if the components moved 5.29° in 149 years, extrapolating to 360°, one full orbit would take 10,139 years. This orbital period is substantially smaller than the period from the V_{space} /inclination method above which derived an orbital velocity and used the 1,879AU separation. This result indicates that a smaller separation would be needed to match the extrapolated period from the historical PA's.

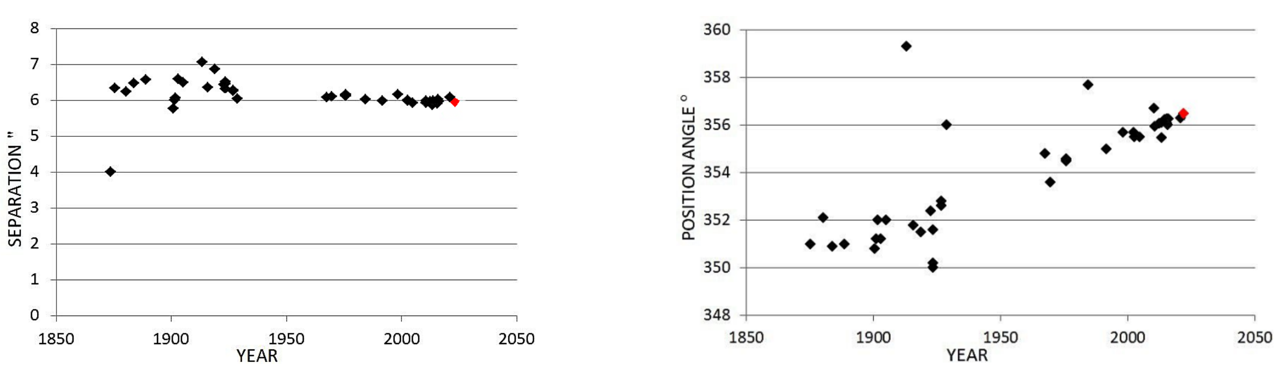

Figure 7. Historical separations. Red data point from this author.

Figure 8. Historical position angles. Red data point from this author.

7. Historical Measurements: Angular Separation

Historical angular separation measurements for BU 144 are shown in Figure 7. Over the 149 year history there is a trend showing a slight decrease in separation amounting to less than 0.4". The 1873–1928 measurements have a 1" scatter of ranging from 6.0"–7.0". This large scatter is likely due to personal error from the visual techniques used to make the measurements. The first reported separation in 1873 was 4". Compared to the remaining measurements, this observation is an outlier. After a nearly 40-year gap in measurements (1928-1967), the separations were again measured with more refined instruments and techniques. They remained similar, ranging from 5.9" to 6.15".

For a circular orbit with an inclination = 90° (or close to it, Figure 4), the angular separations will decrease and increase over time as the stars appear to approach and recede from one another in a periodic manner over the time scale of the orbit. This is analogous to eclipsing binaries. The PAs would only have two values 180° apart as the components pass each other twice per orbit. The historical data does not support this as the PA is changing and the SEP is remaining relatively constant. The opposite is also true. From Figure 5, for a circular orbit with an inclination = 0°, the PA's would be changing in a periodic manner and the SEP's would remain constant. The historical PA and SEP measurements demonstrate this. Along with Gaia data, this provides evidence that BU 144 is a binary system whose orbit is similar to Figure 6.

8. Estimating Longitude of the Ascending Node Ω

The 5.29° position angle change from the 149 year measurement history could be a projected position angle change, as shown in Figure 9. If the orbit is rotated in a left-right manner as shown in Figure 9, this will result in a smaller (projected) observed position angle change in the apparent orbit compared to the actual position angle change. In the terminology of orbit calculations, this rotation angle would be the longitude of the ascending node, Ω.

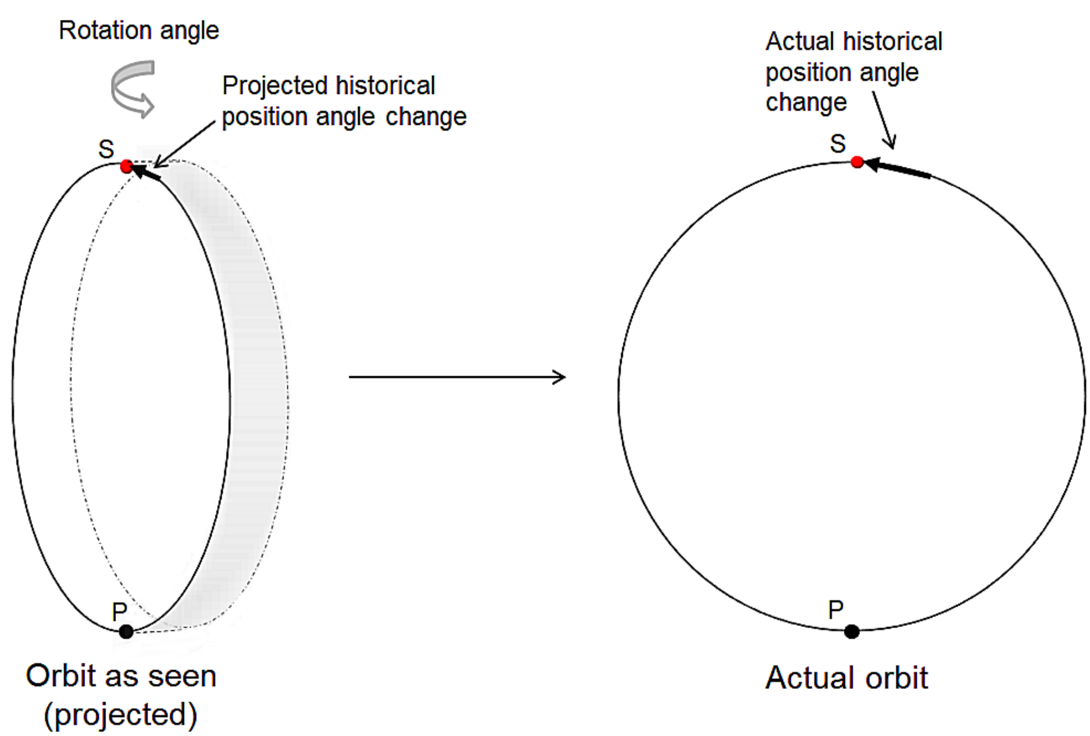

Figure 9. **Left:** Projected historical position angle change from a left-right rotation. **Right:** Actual historical position angle change in the true orbit. P = Primary, S = Secondary.

Using the historical PA change of 5.29°, a 0° rotation angle is the equivalent to the actual orbit on the right side of Figure 9: period = 10,139 years. A 5° rotation angle = 10,101 year period (5.31° actual PA change), 15° rotation angle = 9,794 year period (5.47° actual PA change) and a 25° rotation angle = 9,189 year period (5.84° actual PA change). This rotation angle (longitude of the ascending node Ω) is from the point X in space, not as viewed from the Sun. From the Sun, a 30° correction to the rotation angle (Ω) derived in Section 5a above will have to be applied.

The historical PA change and the rotation angle Ω described above place limitations on the orbital period. These two methods indicate an orbital period of approximately 10,000 years, which is inconsistent with the periods obtained from Kepler's 3rd law and the inclination/ V_{space} methods using the 1,879AU separation. From trial and error, the upper limit of the V_{space} (1.02 km/sec) at various inclination angles with smaller physical separations, provides orbital periods in good agreement with the historical PA/ rotation angle methods.

Using the 3 methods outlined above: Kepler's 3rd law period, inclination/V_{space} period and the PA/rotation angle period, we can proceed to determine the best match of orbital periods as follows:

1. For a given physical separation in AU's, equation [1] (Kepler's 3rd law), compute a period. The masses of the components ($Mass_{pri} + Mass_{sec}$) remain constant.

2. For a given physical separation, adjust the inclination angle (inclination/V_{space} method) to provide an orbital period for BU 144.

3. Compare Kepler's 3rd law period with the inclination/ V_{space} method period and note the differences.

4. By trial and error, we can minimize the orbital period differences between Kepler's 3rd law method and the inclination/ V_{space} method by adjusting the inclination angle and physical separation.

5. The historical PA's /rotation angle methods provide limitations on the range of orbital periods, thus a "best match" of physical separation, inclination angle and orbital period can be obtained.

9. Comparison of Techniques in Estimating Physical Separation and Orbital Period

Figure 10 illustrates for a given physical separation in AU's, the differences between the orbital periods from Kepler's 3rd law and the inclination/ V_{space} method.

Table 4 combines the three methods used for estimating the orbital period of BU 144: Method 1: Gaia parallaxes-Law of Cosines, Method 2: Inclination angle/ V_{space}, and Method 3: Rotation angle (Ω)/historical PA change. Taking into account the smallest differences from Figure 10, the best matches from the three methods for separation, inclination angle/ V_{space}, historical PA's and rotation angle are highlighted in Table 4.

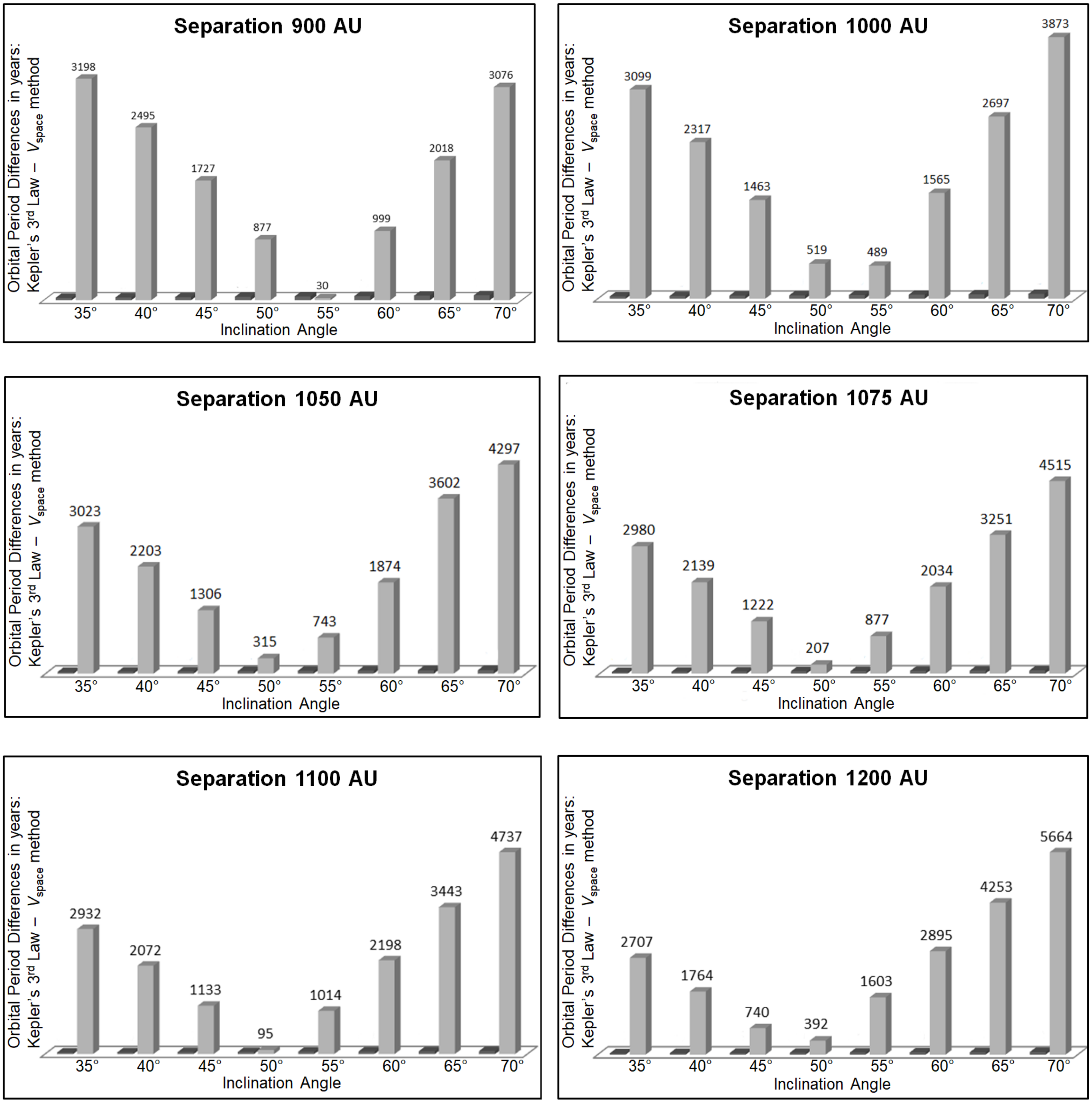

Figure 10. Orbital period differences in years from Kepler's 3rd law – inclination/V_{space} method for various inclinations. As stated in the text, the larger V_{space} of 1.02 km/sec was used to derive orbital velocities.

Method 1 Law of cosines		Method 2 Inclination-Space/Orb. Velocity		Method 3 Historical PA/Rot. angle	
Gaia Sep AU	Period yrs	Inclination Angle°	Period yrs	Rotation Angle°	Period yrs
900	7,574	45	9,301	0	10,140
		50	8,451	5	10,101
		55	7,543	10	9,985
		60	6,574	15	9,794
				20	9,528
1000	8,871	45	10,334	Rotation angles are uncorrected for the 29deg angular separation from the Sun to point X	
		50	9,390		
		55	8,381		
		60	7,305		
1050	9,544	45	10,851		
		50	9,860		
		55	8,801		
		60	7,670		
1075	9,887	45	11,110		
		50	10,095		
		55	9,010		
		60	7,583		
1100	10,234	45	11,368		
		50	10,329		
		55	9,220		
		60	8,035		
1200	11,661	45	12,401		
		50	11,268		
		55	10,058		
		60	8,766		

Table 4. Three methods in deriving the orbital period. The best matches for separation, inclination angle/ V_{space}, historical PA's and rotation angle are highlighted.

The results from the three methods in Table 4 show that the following quantities make a "best match" for BU 144's basic orbital elements:

Separation: 1,075 – 1,100 AU
Period: 10,065 ± 265 yrs
Inclination angle: ≈ 50°
Rotation angle/Longitude Ascending Node Ω: 0° to 5° (*plus a correction of 30° for the angle at point X - see Figure 3*)

10. Discussion

Prior to the Gaia data releases, BU 144 was not considered a gravitationally bound binary system. This is due to the small historical position angle change of just 5.29°. Gaia's DR3 parallaxes have now given accurate distances to the components resulting in a physical separation range of 285AU–13,819AU. This data justified a new look at BU 144's possible binary status. Considering parallax errors, the component separations have an overlap of over 10,000AU. The radial velocities and proper motions give accurate space velocities, and for specific cases, this provides an orbital period. The inclination angle/space velocity method provides an independent technique of estimating the orbital period. Figure 10 shows that the orbital period differences from Kepler's 3rd law and the inclination/ V_{space} methods for the various separations are minimized as the inclination angle approaches 50°.

Is it possible that BU 144's components are just passing each other and by chance are close to each other on the celestial sphere? This is highly unlikely as the data shows: 1) the radial velocities are very similar, 2) the proper motions are very similar, 3) the space velocity of the components are very similar showing they are moving through space together in the same direction and 4) the masses and spectral types of the component stars are nearly identical. If BU 144's components were just passing by each other in space, the radial velocities, space velocities and proper motions would be quite different.

It is certainly possible that one of BU144's components captured the other millions of years ago. Over time, with their nearly identical masses, it is possible that the orbit would have stabilized into a nearly circular orbit.

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