Analysis of the Double Star WDS 23166-0135 STF 2995

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Abstract

Positions, proper motions, parallaxes, position angles, separations and radial velocities have been acquired for the double star WDS 23166-0135 STF 2995. Analysis of the data using several techniques provides considerable evidence that STF 2995 is a gravitationally linked binary star system.

Introduction

The Washington Double Star Catalog (WDS) system 23166-0135 STF 2995 (SAO 146605, PPM 181601, ADS 16642, HD 219542A&B) has 96 position angle and separation measurements dating from 1830 to the present. The apparent visual magnitudes of the components are listed as +8.20 and +8.61 with spectral types G2V for the primary and G7V for the secondary. During the 186 year measurement history position angles (PA) changed by just 4° and the separations (SEP) by just 0.5". These values were derived from a least squares trend line fit from the measurement history. With these small changes in PA and SEP this double star was not considered a gravitationally bound system in which an orbit could be computed, thus it is not listed in the *Sixth Catalog of Orbits of Visual Binary Stars* (Matson, et. al., 2022). Even with the close proximity of the components to the Sun (55 pc), neither are listed in the *General Catalog of Trigonometric Stellar Parallaxes* (van Altena, et. al., 1995).

Methodology

New measurements of position angle and separation were made using the author's Meade 14-inch LX200 telescope located in Ft. Davis, Texas. The observation was 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 stars(s) as close to the meridian as possible to minimize the amount atmosphere the telescope/camera system is looking 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 video drift method. 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. Several 25-30 second videos were recorded at the standard video frame rate of 30 frames per second. A separate PA and SEP was computed for each video frame resulting in hundreds of measurements per video. 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 is presented in Table 1. The Gaia Early Data Release 3 (EDR3) parallaxes, proper motions, radial velocities and associated errors of the components are listed in Table 2.

PA°	SD°	SEP″	SD″	Date	Mag Pri	Mag Sec	Nights
32.46	1.79	5.26	0.18	2021.753	+8.20	+8.61	1

Table 1. WDS 23166-0135 measurements using the video drift method. Measurements are from Equator and Equinox of date. Magnitudes from WDS.

	Parallax (mas)	error (mas)	pmra (mas)	Pmra error (mas)	pmdec (mas)	pmdec error (mas)	Radial velocity (km/sec)	error (km/sec)
Primary	18.27123	0.025732	165.3932	0.031212	20.76121	0.02177	-12.09	0.252
Secondary	18.27449	0.022724	168.1337	0.026996	23.16193	0.01725	011.729	0.698

Table 2. Gaia EDR3 data for WDS 23166-0135.

Using the new measured separation angle along with the EDR3 distances, the physical separation between the components was derived using the law of cosines (Nugent 2022). The calculated physical separation between the components is 2,083 AU.

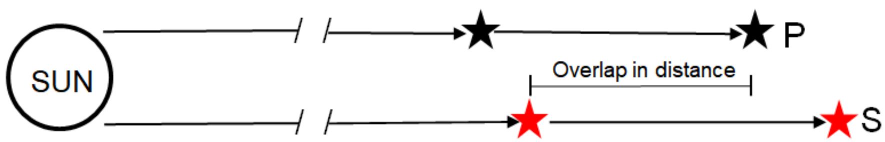


Figure 1. Gaia distances for WDS 23166-0135. Parallax errors show substantial overlap in distance.

Taking into account the errors in the Gaia parallaxes, the physical separation between the components ranged from 289AU to 31,971AU. There is substantial overlap in the component distances from the Table 2 parallax errors also shown in Figure 1. The 289AU separation would be the minimum distance between the primary and secondary and this assumes that both components are equidistant from the Sun.

Computation of Orbital Period

Assuming the physical separation of the component stars of WDS 23166-0135 is 2,083AU, then it may be a gravitationally linked binary star system. The orbital period is derived using Newton's version of Kepler's 3rd law:

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

[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 units were computed from the empirical relation (Lang, 1992),

$$Mass_{\odot} = 10^{0.48 - 0.105 M_{bol}}$$

[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] comes from an analysis of the mass-luminosity relation by McCluskey & Kondo, 1972. It is only valid for stars with absolute bolometric magnitudes from $-8 < M_{bol} < +10.5$. The bolometric magnitude is derived from:

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

where M is the absolute magnitude and BC is the bolometric correction.

The absolute magnitudes M were derived using the distance modulus: $m - M = 5 \log R - 5$, where m is the apparent magnitude and R is the known distance to the components in parsecs. From the tables in Lang 1992, the bolometric correction BC used for the primary was –0.012mag and for the secondary –0.19mag. With M and BC known for each component, equation [3] was used to get M_{bol}.

In computing absolute magnitudes from the distance modulus, a correction was applied to the apparent magnitude for interstellar absorption. The components of STF 2995 have a galactic latitude of $b = -55.8°$, far off the galactic plane. Using the method of Schlegel, Finkbeiner & Davis 1998, the absorption correction to the apparent magnitudes was small at +0.033 from the online calculator https://irsa.ipac.caltech.edu/applications/DUST/. This correction was applied to the apparent magnitudes of both components to derive absolute bolometric magnitudes. The absolute bolometric magnitudes were used in equation [2] to derive the mass of the components. The results are Primary: *Mass* = $1.08_{\odot}$ and Secondary: *Mass* = $1.02_{\odot}$.

Several researchers have published *BC* tables (see Torres 2010 for a summary). There are slight differences from the various researchers in the *BC*'s amounting to 0.1 mag for a given spectral type. For STF 2995, a 0.1 mag change causes a mass change of approximately $0.05M_{\odot}$ for each component. This can cause a change in the orbital period of up to ±1,500 years.

Using these estimated masses of the components and the 2,083AU physical separation, equation [1] was used to calculate the orbital period of the system: 23,191 years. This long orbital period could explain the small changes of angular separation and position angle observed over the 186 year measurement history (See Historical Measurements section below).

With the component masses known, the eccentricity and semi-major/semi-minor axes can be derived from celestial mechanics: Semi-major axis: 1,171 AU, semi-minor axis: 1,012 AU, eccentricity: 0.029. However, with the estimated mass errors of 0.05 $M_{\odot}$, this could place the component masses at nearly equal values at 1.05 $M_{\odot}$ – 1.06 $M_{\odot}$. For the purposes of orbit calculation and for the remainder of this paper, component masses will be assumed equal and that STF 2995 has a circular orbit.

Proper Motions

The 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 2016 calculation was used to determine if the components share a common proper motion, the result was 2.15. This indicates a common proper motion pair, CPM (see Harshaw 2016 for explanation). This is an expected result with the physical separation of the components being very close as the stars are moving through space together. The proper motions provide evidence that STF 2995 could be gravitationally connected as a binary star system.

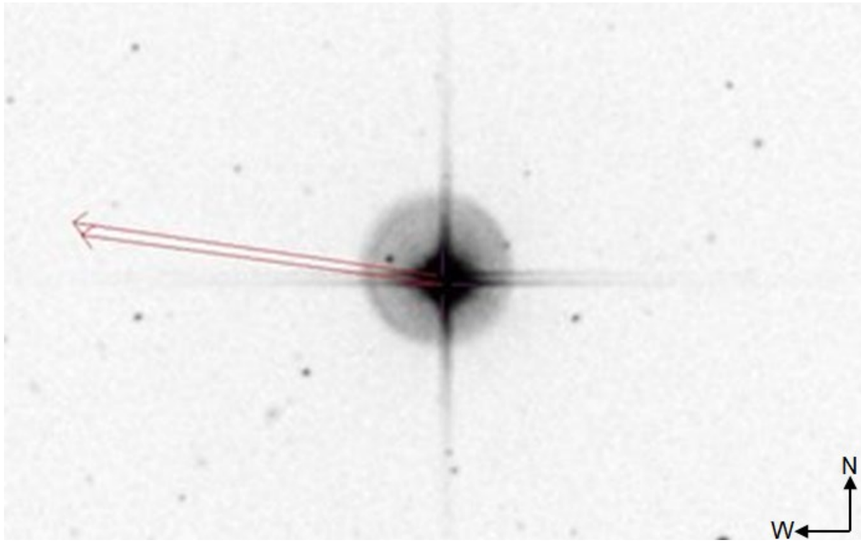


Figure 2. Proper motions of components overlaid on DSS2 blue image. DSS2 image date: Aug 17, 1988.

Effect of Errors in the Measured Angular Separation

The measured angular separation of the components using the video drift method (Table 1) is 5.26 ± 0.18". As previously shown, applying this value with the Gaia EDR3 distances of the components gives a physical separation (excluding parallax errors) of 2,083AU. Now suppose the measured angular separation was twice the 5.26" value at 10.52". How would this affect the actual physical separation? Figure 3 shows the geometry. Applying the law of cosines, the revised physical separation is 2,141AU. At 20" measured angular separation, the physical separation increases to 2,334AU just 12% larger than the original value from the 5.26" actual measured angular separation. This shows to an extent, the larger the difference in component distances as seen from Earth, the less influence the measured angular separation has upon the component physical separation.

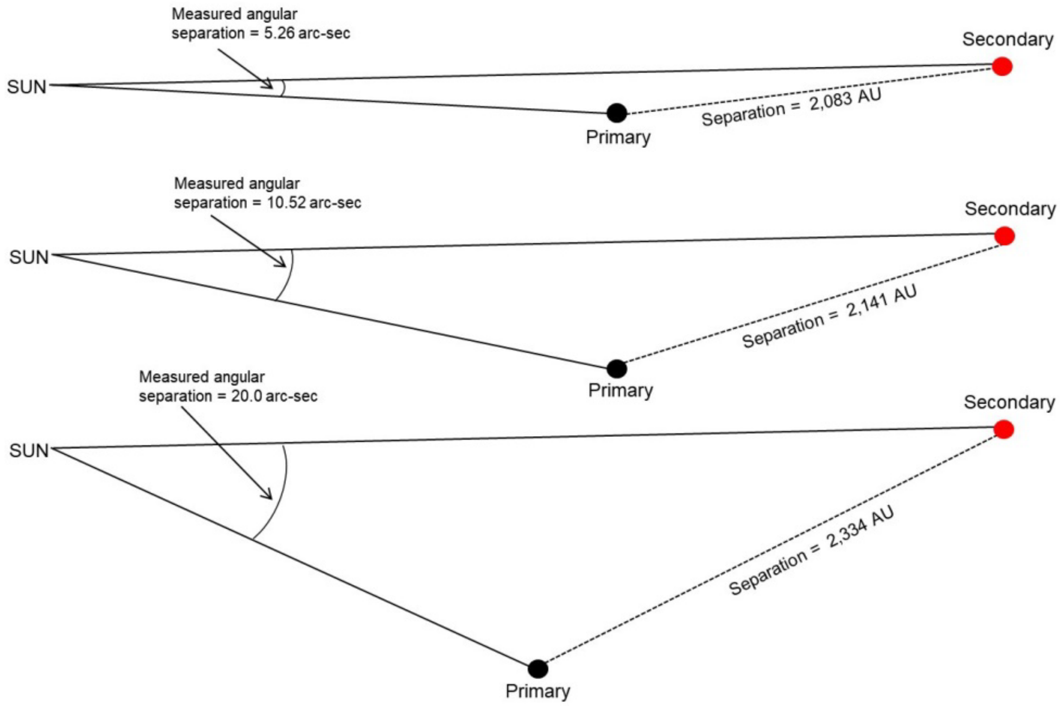


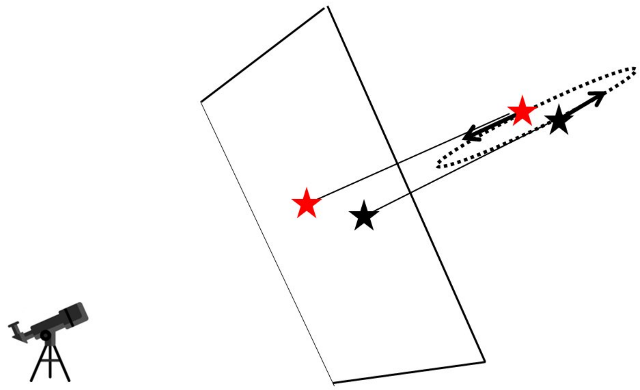
Figure 3. Effect of Primary/Secondary physical separations from differing measured angular separations (not to scale).

Gaia EDR3 provides accurate RA and DEC coordinates for stars. Gaia's RA and DEC coordinates of the components, epoch 2016 were used to solve for PA and SEP. The derived SEP was 5.37" and the PA was 32.33° both falling within one standard deviation of the measured values.

Orbital Velocity from Radial Velocity

Assuming WDS 23166-0135 is a binary star system, in this section I will postulate that the component radial velocities V_r can be used to estimate the orbital velocity. Proper motions (tangential velocity) are neglected as they only show the direction both stars are traveling through space. The radial velocity (line of sight velocity) represents the speed the components are moving toward or away from the Sun. Furthermore, as stated above, it will be assumed that STF 2995 has a circular orbit with equal mass components revolving around a common center of mass.

To illustrate this concept, assume that Earth and STF 2995 are motionless in space with the orbit edge on to our line of sight as shown in Figure 4 (i = 90°). Then any difference in V_r can be attributed to orbital motion. For example, if the primary's V_r is –0.5 km/sec and the secondary's V_r is +0.5 km/sec, then each component's orbital velocity would be 0.5 km/sec. From Earth, we would see an absolute difference in velocities of 1 km/sec: +0.5 – (–0.5) = 1. Thus the orbital velocity is one half of the absolute difference.



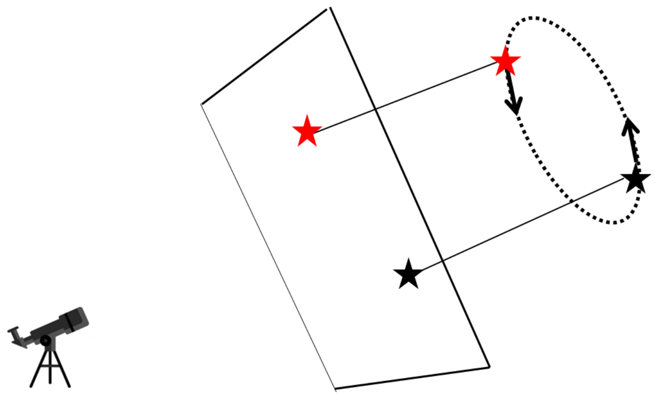


Figure 4. Top. View of orbit edge on to our line of sight, inclination = 90°. Radial velocities would be unequal or opposite directions for the components. The trapezoid represents the plane of the sky as seen from Earth.

Figure 5. Bottom. Orbit inclination = 0°, face on to our line of sight. Any orbital velocities would be 0 as viewed from Earth.

The radial velocities (not including errors) from Gaia EDR3 are primary: 12.09 km/sec and secondary: –11.72 km/sec, the absolute difference being 0.37 km/sec. It will be assumed this absolute difference in V_r can be interpreted that one component is moving toward us and the other component away from us. If the orbit inclination $i = 0°$ (Figure 5), there should be no measurable difference in radial velocity between the components, as such orbital velocity would be perpendicular to our view. The 0.37 km/sec is a *projected* difference in orbital velocity. The projected velocity of each component (one moving toward us, one moving away from us) is 0.185 km/sec. This is half the V_r difference value of 0.37 km/sec as outlined in above example. This projected orbital velocity 0.185 km/sec is not the actual orbital velocity. The actual orbital velocity will depend on the inclination of the orbit as viewed from Earth.

Now assume the orbit is inclined by 45°, as shown in Figure 6. The orbital velocity can be computed from the radial velocity. Using the 0.185 km/sec projected velocity, the component orbital velocity along the 45° inclined orbit is 0.26 km/sec. Again assuming a circular orbit, and a 2,083 AU separation, the circumference of the orbit is 6,544 AU. Moving at 0.26 km/sec, the components will make one complete revolution in 118,177 years, which is inconsistent with the 23,191 year period from Kepler's 3rd law. This large difference in period indicates an error in the orbital inclination.

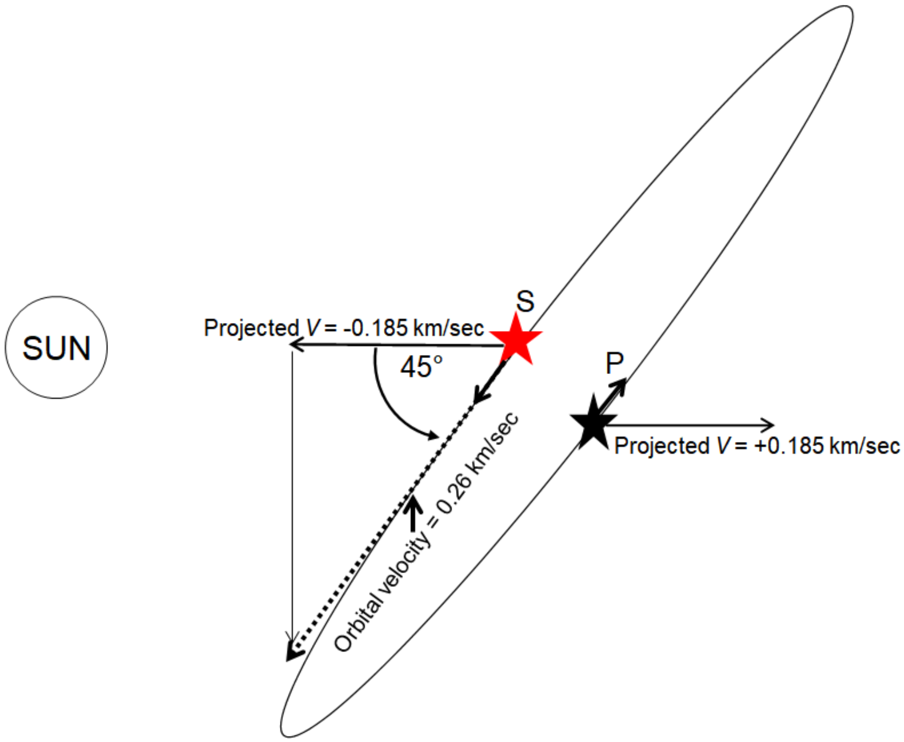


Figure 6. With inclination = 45°, the projected orbital velocity of the components = 0.185 km/sec, and the actual orbital velocity (dotted line) = 0.26 km/sec.

After some trial and error, an inclination of i = 8° (nearly face on to our line of sight) gives an orbital velocity of 1.33 km/sec and a period of 23,260 years using the above method. This period is in remarkable agreement with the 23,191 years using Kepler's 3rd law with the same separation of 2,083 AU. The 2,083 AU separation, calculated orbital velocity and the 8° inclination angle are realistic estimates offering evidence that STF 2995 is a binary star system.

In the next section, this method is combined with the historical PA measurements to provide additional evidence that STF 2995 is a gravitationally bound system.

Using radial velocities as shown here to derive an orbital velocity has drawbacks: 1) the STF 2995 radial velocities with their associated errors have overlap, 2) there is a range of values for the component separation from the Gaia parallax errors, and 3) the eccentricity of the orbit is unknown. Considering the range of data values that could be used in this calculation, orbit periods can differ substantially. It is recommended that future investigators consider these factors when applying this technique.

Historical Measurements

Historical measurements for STF 2995 separations are shown in Figure 7. Over the 186 year history there is a trend showing a slight increase in separation amounting to 0.5". Two of the separations were substantially different from the remaining 94 points: 6.95" in 1881 and 6.573" in 1908 (Figure 7). Comparing these two separations to a 10-year window surrounding these dates, the average separation measurement for the 1881 window is 4.99" and the 1908 window is 5.06". It is thus assumed that the 1881 and 1908 separations measurements were of poor quality.

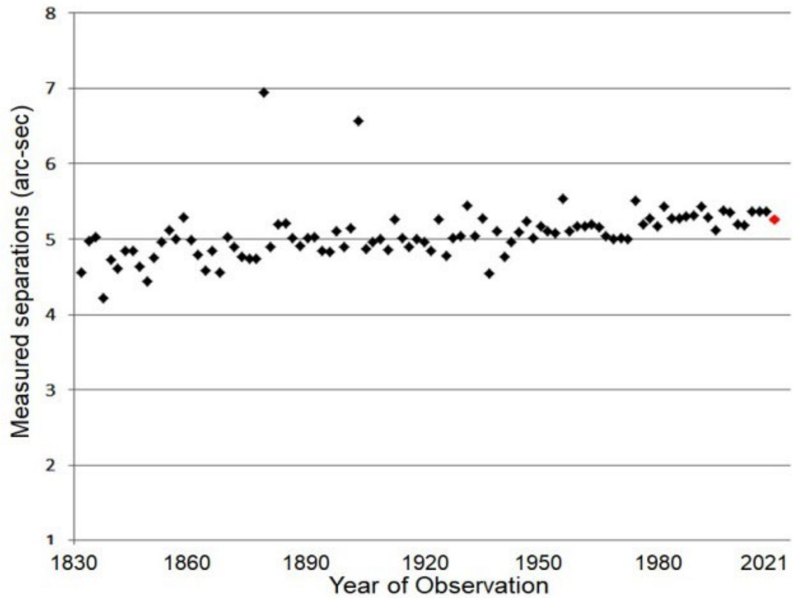


Figure 7. Historical separations measurements

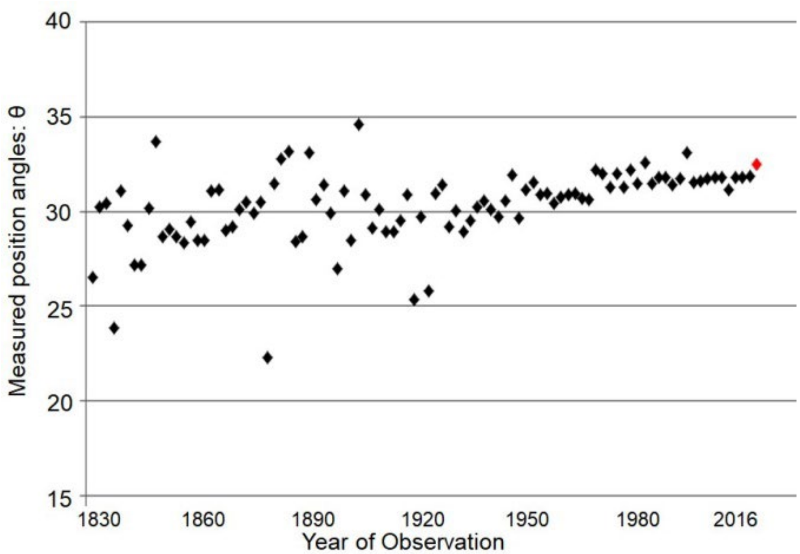


Figure 8. Historical position angle history. Red data points are measurements from this author, see Table 1.

Figure 8 shows historical position angle measurements corrected for proper motion and reduced to Equator 2000.

For a circular orbit with an inclination = 90° (Figure 4), the SEP's would be expected to decrease and increase over time as the stars appear to approach and recede from one another in a periodic manner. The PA's would only have 2 values 180° apart as the components pass each other twice per orbit. 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.

This is exactly what the historical measurements show even with a small portion of an orbit measured. The PA is changing and the SEP is remaining fairly constant. This is what one would expect for an orbit with an inclination close to 0°.

More evidence for a binary system is asserted from the 4° PA change during the 186 measurement history. With a physical separation between the components, this leads to an orbital period from Kepler's 3rd law. The component separation also gives the circumference of the orbit in AU's. With the orbit circumference and the period, the orbital velocity can be computed. With the orbital velocity of the components and the projected radial velocity known, we can solve for the orbit inclination.

Using the 2,083 AU separation from the Gaia EDR3 data, the components traveled 360° in one orbit of 23,191 years. This corresponds to a component orbital velocity of 1.33 km/sec. Using the 0.185 km/sec projected orbital velocity, we can solve for the inclination angle *i* of the orbit (refer to Figure 6):

$$i = cos^{-1}\left[\frac{0.185}{1.33}\right] \qquad [4]$$

The inclination angle is ≈ 8°. Moving at 1.33 km/sec, in 186 years, the components will have traveled 2.9° along in the orbit. The historical change in PA is approximately 4°. Projection effects could account for this difference.

Using the same approach, a 5,000 AU component separation equates to a period of 86,246 years. This corresponds to an orbital velocity of 0.86 km/sec. At this slower velocity, in 186 years the components would have moved 0.78° in the orbit. At 0.86 km/sec, a PA change of 4° would take 958 years. The historical 4° PA change is not supported by the 5,000 AU separation.

An even larger 10,000 AU separation equates to a period = 244,000 years, 0.60 km/sec orbital velocity and a PA change of 0.3° in 186 years. To move 4° along in the orbit would take the components 2,711 years.

A better example is a 1,609 AU component separation. The orbit period is 15,740 years and the component's orbital velocity is 1.52 km/sec. At this velocity, the components would have moved 4° in 186 years in agreement with the historical PA change. Using equation [4], with the projected orbital velocity of 0.185 km/sec and a derived orbit velocity 1.52 km/sec, the inclination angle is ≈ 7°.

As can be seen from the numbers, separations exceeding 2,100 AU do not support the historical 4° PA change with their decreasing orbital velocities. The smaller component separations of 1,610 and 2,083 AU's cited above provide evidence that STF 2995 is a gravitationally bound system.

Discussion

The availability of the Gaia EDR3 data for STF 2995 has shed new light on its probability of being gravitationally bound. The evidence presented here to support this includes:

1. The EDR3 proper motions are very similar in direction and magnitude.

2. The similar radial velocities along with the similar proper motions show the components moving through space together.

3. The difference in radial velocity between the components allows the computation of orbital velocity. Using the orbital velocity with various inclination angles and a range of separations

presents an alternative method to match the historical PA change. The examples cited in the previous section demonstrate that the larger separations do not support the 4° historical PA change.

4. An inclination = 90° implies that only the separations would change and the PA's would flip with values 180° apart. This is the opposite of what the measurement history shows. The PA's are changing and the SEP's are fairly constant. As the above calculations show, this adds to the evidence that STF 2995 is a binary star system with a nearly face on orbit as seen from Earth.

5. All the evidence above combined with the EDR3 parallaxes indicates a close physical separation exists between the components.

Several investigators have criticized that some parallaxes in the Gaia DR2 release are not accurate or trustworthy. With the EDR3 release, the Gaia astrometry team maintains the accuracy issues from the DR2 have been resolved (especially for close double stars) and that parallax errors are on the order of 0.02-0.03 mas for stars with apparent magnitude $m < +15$. For details, see https://gea.esac.esa.int/archive/documentation/GEEEDR3/index.html.

On a recent historical note, an investigation into differential radial velocity variations from the secondary component of STF 2995 (HD 219542 B) was done by Desidera and Gratton et. al. 2003. They found low-amplitude radial velocity oscillations on the order of 10-15 meters/sec and speculated that this could be due to the presence of a Saturn-mass planetary companion. As they continued their work into this hypothesis with additional radial velocity data, just one year later, Desidera et. al. 2004 withdrew their planet hypothesis. With all the data, they determined the cause of the radial velocity oscillations could be attributed to variations in stellar activity.

Incidentally, an observer on a planet in orbit around either component of STF 2995 would see the other component (angular size 0.1") shining at apparent magnitude –10.5 at 2,083 AU distance.

Acknowledgements

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