Astrometric Observations of WDS 16012+4150 STF 2001 AB Double Star System Using the Great Basin Observatory

Bradyn Livingston[1] and Jerry Hilburn[2]
[1]Indiana University, Indianapolis, Indiana; bradynlivingston0053@gmail.com
[2]Great Basin Observatory, White Pine County, NV

Abstract

The previous status of WDS 16012+4150 STF 2001 AB as a gravitationally bound system or a chance alignment has historically remained uncertain. We collected 20 images of the system using the Great Basin Observatory and performed astrometric analysis, confirming that a new position angle of $\theta = 167.77 \pm 0.02°$ and an angular separation of 11.62 ± 0.01". We utilized multiple methodologies to evaluate the system, and our results reveal that the system fits the criteria of a Common Space Motion (CSM) pair. Additionally, calculated orbital velocities remain below the escape velocities across all four approximated separations. The evidence supports the system could be a gravitationally bound wide binary.

1. Introduction

We selected the WDS 16012+4150 STF 2001 AB double star system for observation and analysis. This system was selected from the Washington Double Star Catalog based on specific criteria including magnitude and separation which would allow the Great Basin Observatory an ideal observation window. With 23 historical observations from 1829 to 2017, we provided the 24th observation with 20 captured images in 2026. We compared the observations to the historical measurements, as well as *Gaia* DR3 data (Gaia Collaboration et al. 2016b, 2023j) to determine consistency and to determine any significant astrometric findings. Our other goal in studying this system is to determine its status as a physical or optical binary pair.

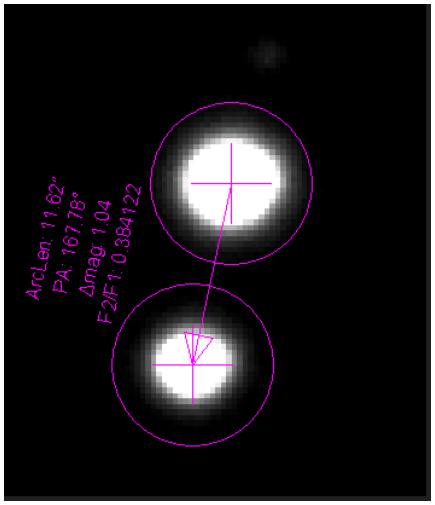

Figure 1: AstroImageJ measurements

2. Equipment and Methods

The Great Basin Observatory recorded the measurements for this star system. We utilized a Planewave CDK 700 telescope with an aperture of 27 in. Located in the Great Basin National Park, the observatory is partnered with Southern Utah University, University of Nevada-Reno, Great Basin National Park, and the Great Basin National Park Foundation. (Anselmo, 2018). The image provided in Figure 2 is the observatory.

Figure 2: The Great Basin Observatory (Paul Gardner)

This star system was chosen as it fit several narrow criteria. The first having the Right Ascension (RA) between 12h and 21h, as well as a Declination (DEC) between 0° and +75 °. This was to ensure an optimal observation window for June 2 in Nevada. Other parameters were chosen to ensure the observation would be able to contribute reliable and meaningful results such as having the Primary Magnitude between 10.0 and 15.0, the Delta Magnitude below 2.5, and the Angular Separation between 4" and 50".

STF 2001 was observed on 2026 June 2 through Sloan g' and I' filters with 60 s exposures for each filter. We utilized Astrometric Stacking Program (Kleijn, n.d.) for image calibration with dark, flat, and calibration frames. Once we calibrated the images for plate solving, AstroImageJ (Collins et al. 2017) was used to measure the position angle (PA) and angular separation (SEP) between star A and B. Provided in figure 2 is the measurements recorded. We measured the PA and SEP in each frame and then calculated the mean and standard deviation respectively. A comparison of the historical data and our current measurements have been recorded and visualized into a plot. (Harshaw, 2020)

2.1 Implementation of El-Badry's criteria

El-Badry et al. (2021) created a filtered catalogue using binary star systems found in *Gaia* eDR3 containing about 1.3 million binaries with a 90% probability of being gravitationally bound. We ran analysis with WDS 16012+4150 STF 2001 AB on whether the system satisfies El-Badry's criteria:

(i). Angular separation (θ) must satisfy:

$$\left(\frac{\theta}{\text{arcsec}}\right) \leq 206.265 \times \left(\frac{\varpi_1}{\text{mas}}\right),$$

where ϖ_1 represents the parallax of the brightest star. El-Badry chose a maximum search radius of 1 pc as it is rare to see many bound binaries at wider separations. At such wide distances, the Galactic tidal field may dominate over a binary's gravitational influence.

Furthermore, we evaluate the Jacobi radius (r_J) for our binary star system and compare it to its separation. This is found by

$$r_J \approx 1.35 \text{ pc} \times \left(\frac{M_{\text{tot}}}{M_\odot}\right)^{1/3}$$

where M_{tot} represents the total estimated mass of the binary. The Jacobi radius provides an upper boundary as to when a given system's gravitational influence is overcome by the Galactic tidal field. To ensure a sufficient degree of gravitational influence remains undisturbed, the system's separation should be well below this boundary.

(ii). Parallax uncertainties within 3 sigma:

We ensure that the parallax uncertainties of the two components satisfy

$$|\varpi_1 - \varpi_2| < b\sqrt{\sigma_{\varpi,1}^2 + \sigma_{\varpi,2}^2},$$

where $\sigma_{\varpi,1}^2$ represents the parallax uncertainty of the first star, and $\sigma_{\varpi,2}^2$ represents the second star. El-Badry recommends using b = 3 for pairs with an angular separation greater than 4 arcsec compared to b = 6 for pairs with angular separation less than 4 arcsec. This is because at closer angular separations parallax uncertainties are underestimated.

(iii). Consistent proper motions:

We analyze the proper motions to ensure consistency with a Keplerian orbit.

$$\Delta\mu \leq \Delta\mu_{\text{orbit}} + 2\sigma_{\Delta\mu},$$

where $\Delta\mu$ is the observed scalar proper motion difference with $\sigma_{\Delta\mu}$being the uncertainty. $\Delta\mu_{\text{orbit}}$ is the maximum proper motion difference from the result of orbital motion. We calculate the observed scalar proper motion difference as

$$\Delta\mu = \left[\left(\mu_{\alpha,1}^* - \mu_{\alpha,2}^*\right)^2 + \left(\mu_{\delta,1} - \mu_{\delta,2}\right)^2\right]^{1/2}$$

where $\mu_{\alpha,1}^* - \mu_{\alpha,2}^*$ is the difference of proper motion in Right Ascension (pmra) between the two stars, and $\mu_{\delta,1} - \mu_{\delta,2}$ the difference of proper motion in Declination (pmdec).

The uncertainty is found by

$$\sigma_{\Delta\mu} = \frac{1}{\Delta\mu}\sqrt{\left(\sigma_{\mu_{\alpha,1}^*}^2 + \sigma_{\mu_{\alpha,2}^*}^2\right)\Delta\mu_\alpha^2 + \left(\sigma_{\mu_{\delta,1}}^2 + \sigma_{\mu_{\delta,2}}^2\right)\Delta\mu_\delta^2},$$

which $\Delta\mu_\alpha^2$ and $\Delta\mu_\delta^2$ are the respective pmra and pmdec calculated before. $\sigma_{\mu_{\alpha,1}^*}^2 + \sigma_{\mu_{\alpha,2}^*}^2$is the difference of uncertainty of the proper motion in Right Ascension (e_pmra), and $\sigma_{\mu_{\delta,1}}^2 + \sigma_{\mu_{\delta,2}}^2$the uncertainty of the proper motion in Declination (e_pmdec).

To find the maximum proper motion difference due to orbital motion we first begin with El-Badry's equation

$$\Delta\mu_{\text{orbit}} = 0.44 \text{ mas yr}^{-1} \times \left(\frac{\varpi}{\text{mas}}\right)^{3/2} \left(\frac{\theta}{\text{arcsec}}\right)^{-1/2},$$

The maximum proper motion difference is expected for a circular orbit of total mass $5\,M_{\odot}$.

This corresponds to the physical velocity difference of:

$$\Delta V_{\text{orb}} = 2.1 \text{ km s}^{-1} \times \left(\frac{s}{1000 \text{ au}}\right)^{-1/2},$$

Where s = 1000 au multiplied by the angular separation divided by the parallax is the projected separation.

2.2 Nugent's Space Velocity Vectors

With El-Badry's methods we only examine the star through a two-dimensional analysis. To provide a three-dimensional analysis we utilize Nugent's work with space velocity vectors. (Nugent, 2025).

$$V_{\text{space}} = \sqrt{RV^2 + \left(4.74\frac{\mu}{\pi}\right)^2},$$

where V_{space} is the space velocity, combining proper motions and the radial velocity in relation to the Sun. RV is the radial velocity, π being the parallax and μ being the total proper motion, combining RA and DEC. This allows us a better understanding of whether the pair is traveling together through space at near the same speed. We can also determine the direction of each star component through their three-dimensional space velocity vector, which Nugent claims is fundamental for determining whether a binary pair is both traveling together and to be considered gravitationally bound.

$$\theta = \cos^{-1}\left[\frac{\text{PRI}\cdot\text{SEC}}{|\,\text{PRI}\,|\cdot|\,\text{SEC}\,|}\right],$$

where θ is the angle between each star's three-dimensional space velocity vector. PRI· SEC represents the dot product between the primary and secondary star's space velocity vectors. $|\,\text{PRI}\,|\cdot|\,\text{SEC}\,|$ represents the magnitude of the primary and secondary star's space velocity vectors. The dot product of PRI· SEC is found through:

$$\text{PRI}\cdot\text{SEC} = \left(PM_{(RA:\text{PRI})}\cdot PM_{(RA:\text{SEC})}\right) + \left(PM_{(DEC:\text{PRI})}\cdot PM_{(DEC:\text{SEC})}\right) + (RV_{\text{PRI}}\cdot RV_{\text{SEC}}).$$

$|\,\text{PRI}\,|\cdot|\,\text{SEC}\,|$ is found through the product of:

$$|\,\text{PRI}\,| = \sqrt{PM^2_{(RA:\text{PRI})} + PM^2_{(DEC:\text{PRI})} + RV^2_{\text{PRI}}}$$

$$|\,\text{SEC}\,| = \sqrt{PM^2_{(RA:\text{SEC})} + PM^2_{(DEC:\text{SEC})} + RV^2_{\text{SEC}}}$$

If the calculated θ value be < 15°, we would label the binary pair as a Common Space Motion pair, increasing the likelihood that they are a part of a gravitationally bound system. To further analyze the nature of whether the system is gravitationally bound, we used the mass-luminosity relation (Lang 1992) to calculate the stellar masses to find the escape velocity. We then compared that to the observed velocity found through the difference in each star's space velocity vectors.

Escape velocity:

$$v_{\text{esc}} = \sqrt{\frac{2G(M_1 + M_2)}{r}}$$

Observed velocity:

$$v_{\text{obs}} = \sqrt{\left(PM_{(RA:\text{PRI})} - PM_{(RA:\text{SEC})}\right)^2 + \left(PM_{(DEC:\text{PRI})} - PM_{(DEC:\text{SEC})}\right)^2 + (RV_{\text{PRI}} - RV_{\text{SEC}})^2}$$

We compare these values across four separations for STF 2001 AB through the methodology described in Nugent (2024). Utilizing the Law of Cosines, we find the nominal bound and the maximum-difference bound utilizing Gaia DR3 uncertainties. We calculate the minimum bound through the assumption that both stars are equidistant from the Sun and calculate the projected physical distance. A fourth separation is obtained through examining the historical observations for the orbital period and then calculating the difference in Nugent's space velocity. We assume a circular orbit with a conservative value of $i = 0°$

$$\text{Orbital velocity} = \frac{V_{\text{space}}}{\cos i}.$$

Using *Gaia* DR3 data, we use the mass-luminosity relation to calculate mass (Lang, 1992). We also determine its spectral type from the temperature with the table provided by Pecaut and Mamajek. (Pecaut & Mamajek, 2013). Finally, we analyze the mass, temperature, and spectral type to form a conclusion on its likelihood of being a co-natal pair.

3. Data

With 20 images collected we provide the current 2026 astrometric observations for WDS 16012+4150 STF 2001 AB, including the mean, standard deviation, and the standard error of the mean for position angle and angular separation.

Table 1. Measurements of position angle and angular separation of WDS 16012+4150 STF 2001 AB for the year 2026.41.

WDS 16012+4150 STF 2001 AB	**Position Angle (θ°)**	**Separation (ρ'')**
Mean	167.77°	11.62″
Standard Deviation	± 0.022°	± 0.01″
Standard Error of the Mean	0.005°	0.002″

4. Discussion

We requested historical data from the US Naval Observatory. The results are showcased in both Table 2 and a plot in Figure 3. 23 historical observations were recorded, resulting in a total of 24 since 1829 with our most recent observation in 2026. The differences in motion between the position angle and angular separation are extremely minimal, both 1.8° and 0.05″ respectively over the course of 197 years.

Table 2. Historical data for WDS 16012+4150 AB.

Epoch (Julian)	Position Angle (θ°)	Separation (ρ'')
1829.66	169.6	11.57
1845.56	168.8	12.20
1868.02	169.4	11.47
1878.29	168.8	11.93
1879.35	170.0	11.39
1894.72	168.7	11.868
1895.65	167.1	11.624
1902.36	169.6	11.96
1904.59	171.5	11.45
1929.39	168.8	11.80
1960.55	168.1	11.70
1991.71	167.4	11.78
1998.32	167.5	11.65
2002.40	167.8	11.65
2011.52	167.8	11.72
2012.42	168.0	11.65
2013.39	167.7	11.64
2014.33	167.8	11.65
2015.00	167.8	11.64
2015.30	167.8	11.62
2015.50	167.8	11.637
2016.00	167.8	11.64
2017.37	167.8	11.53
2026.41	167.8	11.62

Figure 3 provides the plot of measurements using Harshaw's Plot Tool (Harshaw 2020). The historical measurements range from 1829-2026. The left plot demonstrates the issue when comparing astronomical observations over the course of two hundred years. As astronomical equipment becomes more advanced and precise, we see that in the right plot the historical observations become less scattered as the data become more closely clustered. However, as the historical data has a low R^2 value, as well as little change over time, we cannot confidently state that it supports or refutes binarity.

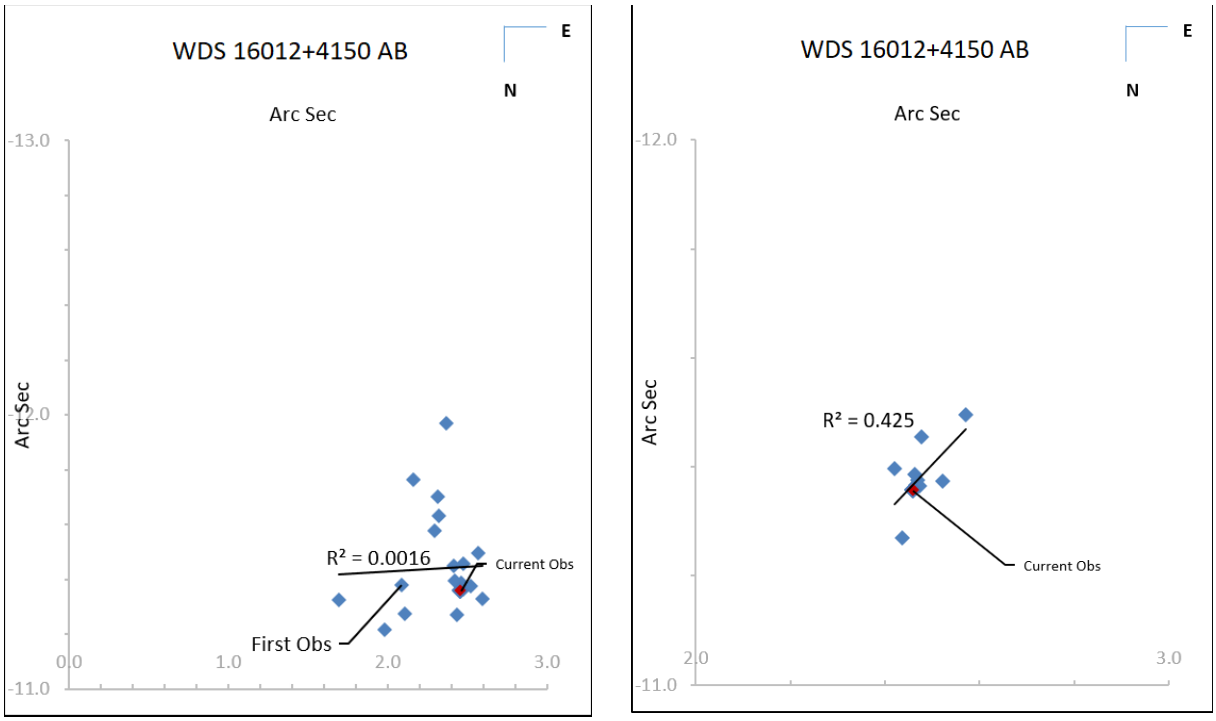

Figure 3: Historical and current measurements for WDS 16012+4150 AB. The left plot represents all 24 measurements. The right plot removes the data points between and including 1829.66-1960.55.

We examined the binary system further with the inclusion of *Gaia* DR3 data, found in Table 3. When determining if astrometric data has a good fit, we examine the renormalized unit weight error (RUWE) to determine if a given dataset can be reliable or not. This is especially important for the parallax measurement, as it is a primary proponent of constraining the distance of a star. (El-Badry, 2025). Provided in El-Badry's analysis of RUWE, a parallax with RUWE > 1.4 is often deemed unreliable. At a RUWE value > 1.25, it is recommended to inflate the uncertainties. In the case of WDS 16012+4150 AB with a respective RUWE of < 1.0, El-Badry does not recommend deflating the uncertainties despite them being slightly overestimated. His empirical tests have found that data with RUWE < 1.0 have similar uncertainties to data with RUWE ≈ 1. (El-Badry, 2025) We conclude that this binary system is of good astrometric fit.

Table 3. Gaia DR3 data for WDS 16012+4150 AB.

Star	Gaia DR3 Source ID	Plx (mas)	Dist (pc)	PMRA (mas/yr)	PMDEC (mas/yr)	RV (km/s)	RUWE
STF 2001 A	1383500126723906944	5.0136 ± 0.0121	199.4575	-30.227 ± 0.013	30.159 ± 0.017	-9.01	0.91
STF 2001 B	1383500126723906560	5.0123 ± 0.0122	199.5092	-30.110 ± 0.012	31.298 ± 0.019	-8.39	0.79

The methodology we adopted to determine the physicality of the system is sourced from the three criteria found in (El-Badry et al., 2021) and an analysis of Space Velocity Vectors from (Nugent, 2025).

4.1 El-Badry's analysis of WDS 16012+4150 AB

To satisfy El-Badry's criteria, we must calculate whether the angular separation of the system is less than or equal to the brightest star's parallax multiplied by 1pc. Our calculations result in $11.62'' \leq 1034.13''$. We conclude that the projected physical separation of the system is well below the 1 pc threshold. The Jacobi radius provides the upper boundary for a system's gravitational influence. With $\boldsymbol{r_J \approx 1.83}$ pc $\approx$ $\boldsymbol{377,000}$ AU, even at the maximum separation it is well below the upper boundary of the Jacobi radius. It is important to also determine their approximate distance from Earth. To satisfy El-Badry's second criteria we examine whether the parallax uncertainties are within 3 sigma. Utilizing his provided equation, our calculations resulted in 0.0013 mas < 0.05154 mas. We conclude the two stars are approximately the same distance from Earth. This reduces the likelihood that it is an optical pair.

Finally, to satisfy El-Badry's third criteria we examine whether the proper motions are consistent with a Keplerian orbit. We compare the observed scalar proper motion difference with the maximum proper motion difference and uncertainty. Our calculations resulted in 1.145 mas/yr $\leq \boldsymbol{1.196}$ mas/yr. This places the system's proper motion within the bounds of a Keplerian orbit.

4.2 WDS 16012+4150 AB Space Velocity Vector Analysis

When finding the space velocities of each star our calculations must include the combination of proper motions and radial velocity in relation to the sun. We utilized the space velocity equation as provided from (Nugent, 2025). Our total proper motions, calculated through the Pythagorean theorem, result in 42.70 mas/yr for Star A, and 43.43 mas/yr for Star B. Continuing with the space velocity formula, we find for Star A the space velocity is 41.36 km/s and 41.92 km/s for Star B. With only a difference of ~0.56 km/s, we conclude that the two stars are traveling through space at nearly the same speed.

Though the two stars are traveling at similar speeds, it is critical to find the directions of each star to determine if they are traveling in the same direction. We must calculate the angle between each star's three-dimensional velocity vector. Using the equation provided by Nugent (2025), the angle between the space velocity vectors for this star system results in 1.51°. The angle is well below the threshold of 15°, so we can conclusively label these two stars as a Common Space Motion pair.

4.3 Analysis of Orbital Velocity and Escape Velocity

We calculated four separations to compare orbital velocity to escape velocity. This is to gather examples across multiple boundaries to build a case for whether the system is gravitationally bound or not. Our results can be found in Table 4. We calculated the minimum separation through converting the mean parallax to physical distance in AU and then multiplying by the angular separation. We then use methodology from Nugent (2024), assuming that it is a circular orbit with an inclination of $i = 0°$ and equating the orbital velocity to the space velocity difference. We then find both the nominal separation and the maximum separation through the law of cosines. In each separation, we found that the orbital velocities are within the boundary of the escape velocity. In addition, taking into consideration the uncertainties we found that there is a distance overlap of approximately 188,782 AU. The wide distance overlap provides evidence that the two stars are sharing the same space.

Table 4. Calculated separations, orbital velocities, escape velocities, and orbital periods for WDS 16012+4150 AB.

Separations	Orbital Velocities	Escape Velocities	Orbital Period
2314.01 AU	0.976 km/s	1.1381 km/s	70,570.41 yrs
7119.40 AU	0.552 km/s	0.791 km/s	380,837.67 yrs
10,918.50 AU	0.450 km/s	0.636 km/s	723,301.36 yrs
210,143.60 AU	0.102 km/s	0.145 km/s	61,072,973.56 yrs

4.4 Mass, Temperature, Spectral Type

We calculated the mass through the mass-luminosity relation (Lang 1992), first determining the bolometric luminosity of each star. *Gaia* DR3 lists the effective temperatures (T_{eff}) as 5,788 K for star A and 5783 K for star B. When examining Table 5 provided by Pecaut and Mamajek (2013) we find that as the system has a difference of only 5 K, they share the same spectral type of G2V. For this spectral type, the bolometric correction is -0.083 which we used to calculate the absolute bolometric magnitudes. Following with the mass-luminosity relation, the mass of the primary star is 1.41 solar masses, and the mass for the secondary star is 1.07 solar masses. Plotting them on the Hertzsprung-Russell Diagram in Figure 4 we see that they both reside on the main sequence, with the primary star starting to transition off into a subgiant.

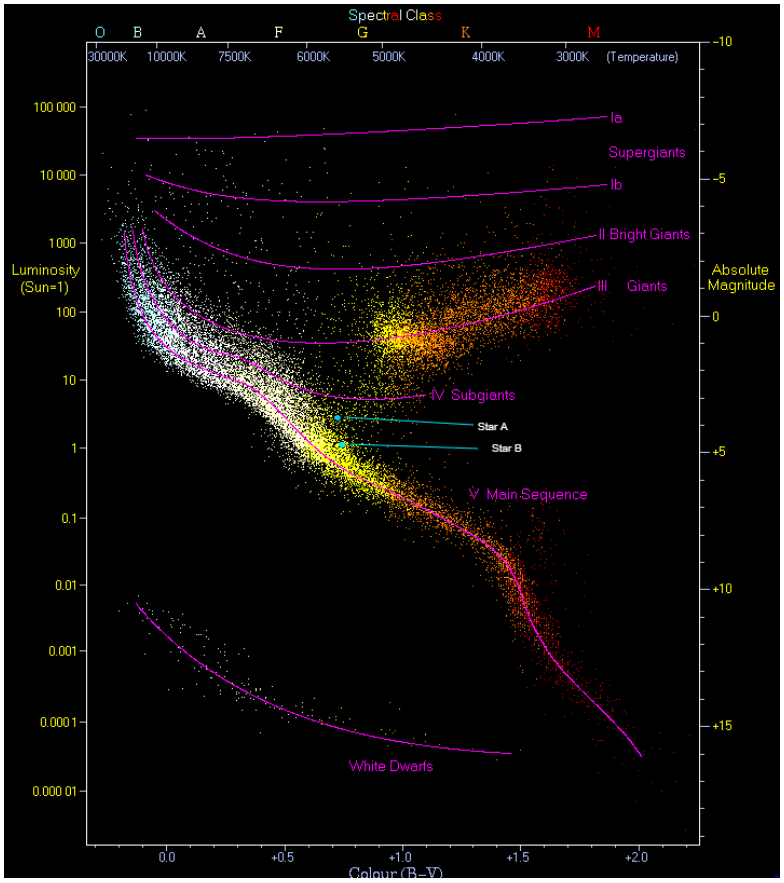

Figure 4: Hertzsprung-Russell Diagram of WDS 16012+4150 AB which has been annotated with both the primary and secondary stars.

5. Conclusions

The previous status of binarity with STF 2001 AB is considered uncertain. With *Gaia* DR3 data, the parallaxes provide more accurate and precise measurements for physical separations, as well as further constraining the uncertainties. Recent methodology from El-Badry and Nugent along with the new data release allows for a justified conclusion of the star system's status. Even at the minimum projected separation, the orbital period is at least 70,570 years. This explains as to why there has been little change in 197 years of historical observations. Conclusions cannot be made alone with historical data. Three-dimensional kinematic vector analysis confirms that the system can be classified as a Common Space Motion pair, and orbital velocities remain below escape velocities across four separation bounds. Furthermore, both stars have matching effective temperature and spectral classification, increasing the likelihood that both stars formed together. The evidence provided helps conclude that the WDS 16012+4150 STF 2001 AB system could be a gravitationally bound physical pair and not a chance alignment or optical double. Further research is recommended.

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