Investigation of 10 Systems in the Washington Double Star Catalog

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Abstract: We studied 10 double star systems from the Washington Double Star Catalog, fitting trendlines for each in Excel and cross-referencing Gaia Data Release 2 for parallax and proper motion information. LPM 629 and STT 327 lack measurements in Gaia but have complete orbits. STF 42AB and STF 1985 are short arcs that show promise of a physical relationship. GIC 129 is a likely physical system with only 7 observations. HJ 5438, although not currently classified as physical, appears to be so and merits further observations. J 868, D 6, and AG 87 appear to be optical based on Gaia. HDO 182 is inconclusive. We imaged GIC 129 on March 12, 2019 (position angle: 150.47 ± 0.161 degrees, separation: 9.96 ± 0.013"). We also imaged STF 1985 on March 14, 2019 (position angle: 355.52 ± 0.836 degrees, separation: 5.84 ± 0.175").

Introduction

In April 2018, data from the Gaia space telescope were released to the public, allowing for access to measurements of parallax and proper motion (PM) for more than a billion stars. Parallax allows determination of how far stars are from Earth, while proper motion describes how they appear to move on the celestial sphere. These measurements reveal the nature of optical doubles that would otherwise have been unknown from the WDS (Washington Double Star) catalog alone. For example, Gaia data were used by Dugan, et. al. to reclassify J 703 (WDS 07106+1543) to an optical double (Dugan, 2018).

Target Selection

In choosing systems to study, we were looking for stars that were interesting or mysterious. This included a wide range of orbital types from relatively certain (Grade 2) to provisional (Grade 9) or nonexistent. We also looked into doubles for which PM was only listed on one of the system's stars. Some of our systems had a clearly curving historical data plot and some did not. Some of the selected stars had corresponding data in Gaia while other systems did not, as shown in Table 1. We also attempted to find star systems that would be visible by the robotic telescope we were using in Northern Chile during the early part of 2019. However, we found other stars that were interesting and have investigated some of these as well. In total, we found ten systems to study. These are color-coded in Table 1 according to some of their salient features, to be discussed.

Stelledoppie, a search engine for the WDS catalog, was used to find the most recent observation of each star system. Then, the systems were looked up on the US Naval Observatory Ephemerides, which keeps track of the predicted position angle and separation of binary systems with solved orbits.

The values of position angle and separation from the Ephemerides are plotted on a Desmos graph together with the last observed measurements of PA and Sep from Stelledoppie as seen in Figure 1. The last observed measurements of PA and Sep are expected to be similar to those predicted by the Ephemerides for that year. As seen in Figure 1, this is not the case for HDO 182.

Parallax and Radial Separation

Consider the system STF 42AB. From the Gaia measurements in Table 1, the parallaxes of the A and B stars are 18.5581 mas and 19.0305 mas, putting them at 53.88 pc and 52.55 pc from Earth, respectively. There-

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Discoverer Code and Orbit Grade	Type	WDS Magnitude	Gaia Magnitude	Gaia Parallax (mas*)	Gaia Parallax Error (mas)	Gaia PM RA (mas/yr)	Gaia PM RA error (mas/yr)	Gaia PM Dec (mas/yr)
STT 327 Grade 2	Primary	8.29	7.7	N/A	N/A	N/A	N/A	N/A
	Secondary	8.95	N/A	N/A	N/A	N/A	N/A	N/A
LPM 629 Grade 4	primary	11	N/A	N/A	N/A	N/A	N/A	N/A
	secondary	11.2	N/A	N/A	N/A	N/A	N/A	N/A
STF 42AB Grade 5	Primary	8.39	8.18	18.5581	0.0996	185.505	0.289	-408.101
	Secondary	9.05	9.02	19.0305	0.0719	178.664	0.351	-402.461
STF 1985 Grade 5	primary	7.03	6.856	26.063	0.0508	-91.446	0.081	-61.315
	secondary	8.65	8.4018	26.1413	0.061	-75.227	0.101	-57.666
GIC 129 N/A	primary	14.4	13.1299	27.0904	0.157	-333.125	0.293	-490.43
	secondary	15.4	14.1512	27.0016	0.0556	-314.739	0.11	-499.913
HJ 5438 N/A	primary	10.99	10.75	2.2445	0.0253	11.712	0.033	-17.926
	secondary	14.7	13.799	2.2267	0.0184	11.754	0.025	-18.288
J 868 Grade 5	Secondary	12.62	12.0642	3.5488	0.0441	-28.622	0.067	-12.53
	Primary	12.42	11.453	1.8935	0.0527	14.644	0.079	-2.777
D 6 N/A	primary	9.11	8.9454	3.5251	0.2217	-2.589	0.466	-1.631
	secondary	9.46	9.3203	5.3741	0.3387	-7.62	0.766	-1.879
AG 87 N/A	primary	9.15	8.9649	9.6738	0.1782	49.021	0.333	-66.759
	secondary	10.74	10.475	3.1059	0.0401	11.347	0.079	-19.699
HDO 182 Grade 5	Primary	6.6	6.4654	N/A	N/A	N/A	N/A	N/A
	Secondary	7.01	6.8583	6.3737	0.5868	2.662	1.427	-9.503

* mas = milliarcseconds

Table 1: Ten double star systems: red have complete orbits, orange are physical systems with short arc solutions, green are promising physical systems with sparse observations, blue are optical systems, and purple is inconclusive.

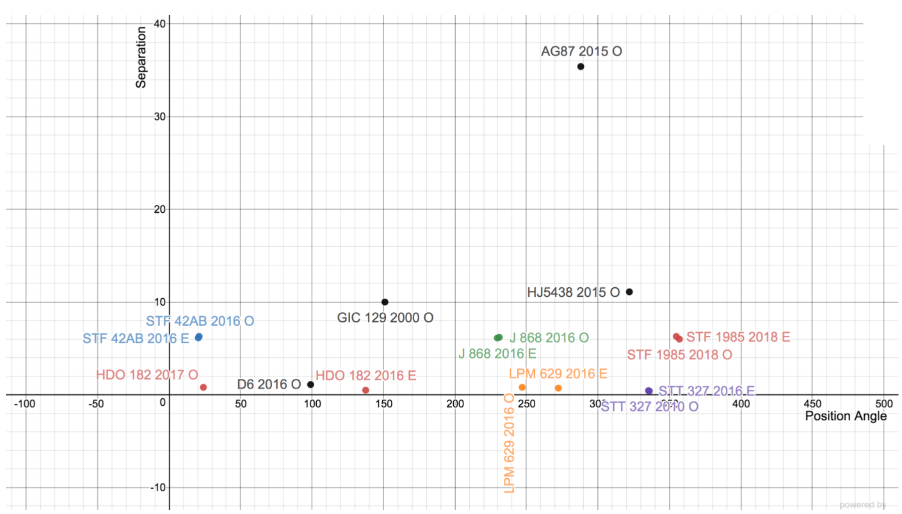

Figure 1: Observed ("O") values and ephemerides ("E") values for our 10 systems with their corresponding years labeled. (https://tinyurl.com/yyucz82u)

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fore, this system has a radial separation of 53.88 pc - 52.55 pc ≈ 1.3 pc. We estimated the error on radial separation using the tangent line approximation on the function relating the distance from Earth, D, to the parallax P. Specifically, if D = f(P), the error on D is equal to the error on P times the derivative of D with respect to P. Because,

$$D(P) = \frac{1}{P}, \quad \frac{dD}{dP} = \frac{-1}{P^2}$$

so the error in D is

$$e(D) = \frac{e(P)}{P^2}.$$

Radial separations on all of the systems are shown in Table 2.

As is evident from the table, the large radial separations of the blue systems make them unlikely to be physically connected.

Proper Motion and Difference Vectors

Another value that can inform an assessment of whether the system is likely to be binary or an optical double is the difference in proper motion (PM) of the stars. Proper motion is a vector quantity that shows the direction and rates the stars are moving across the sky in mas/year. If one were to graph the proper motion in RA and Dec of the primary star and compare it to that of the secondary star, the degree to which their movements are similar would be apparent. Stars whose proper motions are very different are less likely to have a physical relationship.

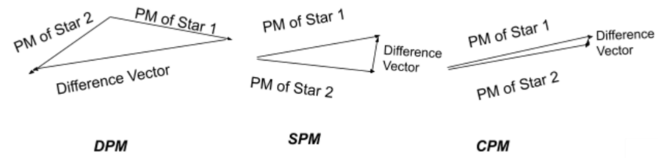

Figure 2: Sample PM Vectors for DPM, SPM and CPM systems.

Relative proper motion (rPM) is an estimate of how the stars in the system move relative to one another. This value is calculated in three steps. First, the magnitude of each star's PM vector is computed as . This results in two different magnitudes for the primary and secondary stars in the system. Then, the difference vector between the primary and secondary PM is calculated. This difference vector magnitude is divided by the larger of the two PM vector magnitudes. The resulting fraction scales the extent to which the stars' PM vectors differ by their magnitude. If the proper motion ratio is less than 0.2, the stars can be classified as having common proper motion, or CPM. Common proper motion is a necessary criterion for inferring a physical connection between the stars. An rPM between 0.2 and 0.6 indicates SPM, or similar proper motion. Finally, any value of rPM that is larger than 0.6 indicates that the stars have DPM, or different proper motion. DPM stars are unlikely to be physical (Harshaw, 2016). Examples of each type of relative motion can be seen in Figure 2, and the rPM is computed for each of our systems in Table 3.

As is evident from Table 3, proper motion suggests

System	Distance to primary with error (pc)	Distance to secondary with error (pc)	Separation with error (pc)
STT 327	N/A	N/A	N/A
LPM 629	N/A	N/A	N/A
STF 42AB	53.8848 ± 0.2892	52.5472 ± 0.1985	1.3376 ± 0.2892
STF 1985	38.3686 ± 0.0748	38.2536 ± 0.0893	0.115 ± 0.0893
GIC 129	36.9134 ± 0.2139	37.0348 ± 0.0763	0.1214 ± 0.2139
HJ 5438	445.5335 ± 5.0221	449.0951 ± 3.711	3.5616 ± 5.0221
J 868	281.7854 ± 3.5017	528.1225 ± 14.6987	246.3371 ± 14.6987
D 6	283.6799 ± 17.8411	186.0777 ± 11.7275	97.6022 ± 17.8411
AG 87	103.372 ± 1.9042	321.9679 ± 4.1569	218.5959 ± 4.1569
HDO 182	N/A	156.8947 ± 14.4446	N/A

Table 2: The radial separations of the components of the systems from Table 1.

System	rPM	Classification
STT 327	N/A	N/A
LPM 629	N/A	N/A
STF 42AB	0.020	CPM
STF 1985	0.151	CPM
GIC 129	0.035	CPM
HJ 5438	0.013	CPM
J 868	1.422	DPM
D 6	0.646	DPM
AG 87	0.728	DPM
HDO 182	N/A	N/A

Table 3. The proper motion ratios of the components of the systems from Table 1.

a physical connection for the orange and green systems, but not the blue systems.

Historical Observations and New Measurements

A plot of historical observations can give further evidence as to whether or not the stars are physical. To construct such a plot, we put ourselves into the reference frame of the primary star by placing it at the origin. Then, we document the position angle and separation of the secondary star in Cartesian coordinates over time. If the secondary star appears to start curving around the primary, then we suspect that it might be in a mutual orbit. To find more evidence as to whether the star is orbiting or not, we can fit both a polynomial (curved) path and also a linear path. The fit with the higher value gives an indication of which type of solution might be more appropriate: an orbital or linear solution. In these fits, it is important to weight the measurements according to their presumed accuracy based on the method of measurement, the aperture of the telescope used, and number of nights of measurement. However, with the short arc binaries covered in this study, the value can be somewhat ambiguous. Due to the small amount of relative movement observed for these systems over time, the secondary star might simply pass the primary on the celestial sphere without orbiting it and still give a high value for the polynomial fit. This is why the other criteria must also be considered. Figure 3 shows an example of what type of fit is most appropriate for given types of historical data.

Instruments Used

The SkyNet (https://skynet.unc.edu) network of robotic telescopes was used for the measurements presented here. There are multiple telescopes and filters to choose from, though we did not use any filters for our images. The two telescopes we used were PROMPT8 and PROMPT3. PROMPT stands for Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes, which were built by the University of North Carolina at Chapel Hill. They are 0.41m Ritchey-Chrétien telescopes, with rapid-readout (< 2 sec) Alta U47+ cameras. PROMPT8 is based in the Cerro Tololo Inter-American Observatory (Coquimbo Region, Chile). It has an aperture of 0.6m, a focal length of

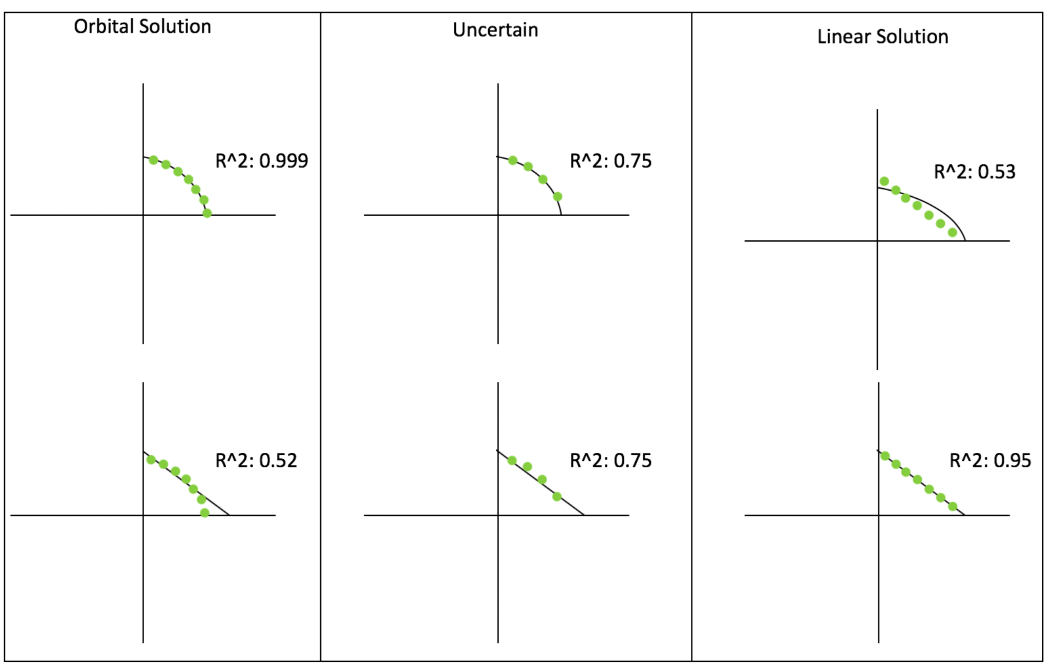

Figure 3: Sample Historical Data Fits with an Orbital Solution, Uncertain, and Linear Solution.

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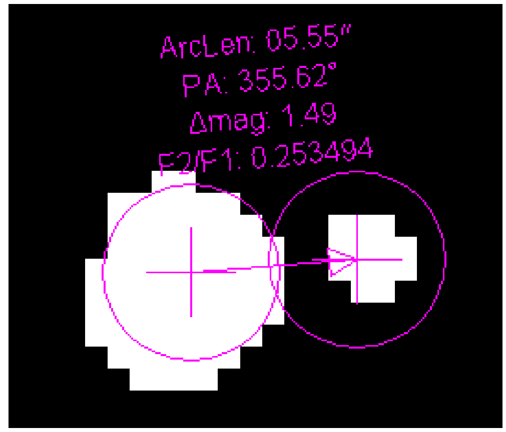
STF 1985	PA °	Sep "
1	355.79	5.88
2	357.61	5.48
3	356.11	5.82
4	352.49	6.47
5	355.62	5.55
Average	355.52	5.84
Standard Error	0.836	0.175



GIC 129	PA °	Sep "
1	150.34	10.01
2	150.38	9.92
3	150.26	9.9
4	151.18	10.02
5	150.19	9.97
Average	150.47	9.96
Standard Error	0.161	0.013

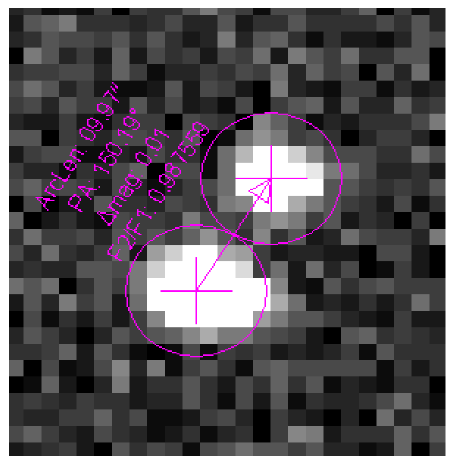


Table 4. Measurements of short arc binary STF 1985 using a 0.5s exposure time on the Prompt 8 Telescope on JD 2458557 (March 14, 2019), and measurements of promising physical system GIC 129 using a 4.17s exposure time on the Prompt 3 Telescope on March 12, 2019.

4200 mm, and a CCD size of 2048 x 2048 pixels. PROMPT3 is in Siding Spring Observatory (Coonabarabran NSW 2357, Australia). It has a 0.4m aperture and a focal length of 2939 mm, with a 1024 x 1024 pixel CCD. While PROMPT's primary use is to follow up gamma ray bursts, it can be used for many other purposes when it is not doing that, such as double star observations.

Measurements Made

Measurements on the systems that were able to be imaged by PROMPT at the time of this study can be seen below in Table 4. The tables are colored according to the scheme of Table 1.

Table 1 Red Systems: Binary Despite Lack of Gaia DR2 Data

Although Gaia DR2 does not have parallax or PM data, the red systems of Table 1 are binary because a sufficient amount of the orbit has been observed, as shown in Figures 4 and 5. It would possible, but highly unlikely, for the stars to move in this way if they were in fact at different distances from Earth. Excel's linear and polynomial fits are not done for the historical data on these systems because performing such fits involves the implicit assumption that the stars' trajectories do not double back on themselves as happens in an orbit. With the exception of an outlying point for STT 327 (which might represent a quadrant flip), their observations fall very close to the predictions of their respective Ephemerides.

Table 1 Orange Systems: Likely Physical with Short-Arc Orbital Solutions

As opposed to binary double star systems, physical doubles are gravitationally related, but not necessarily in an orbit around each other. The term "physical" can

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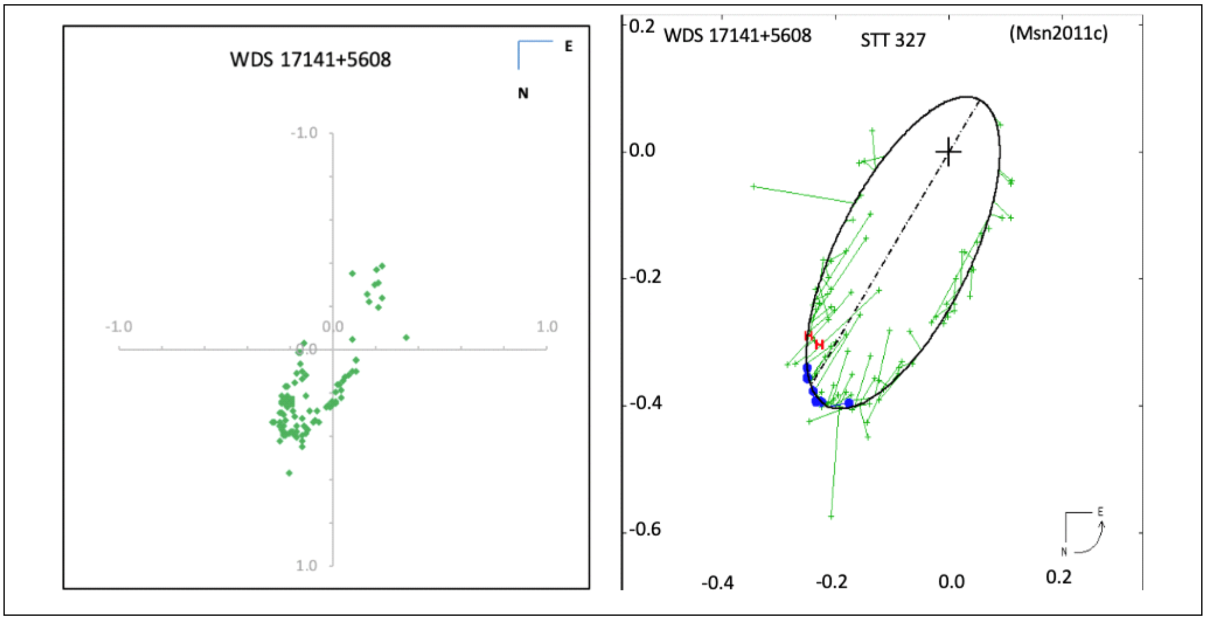

Figure 4: A plot of STT 327's historical data (left) and its proposed orbital solution (right).

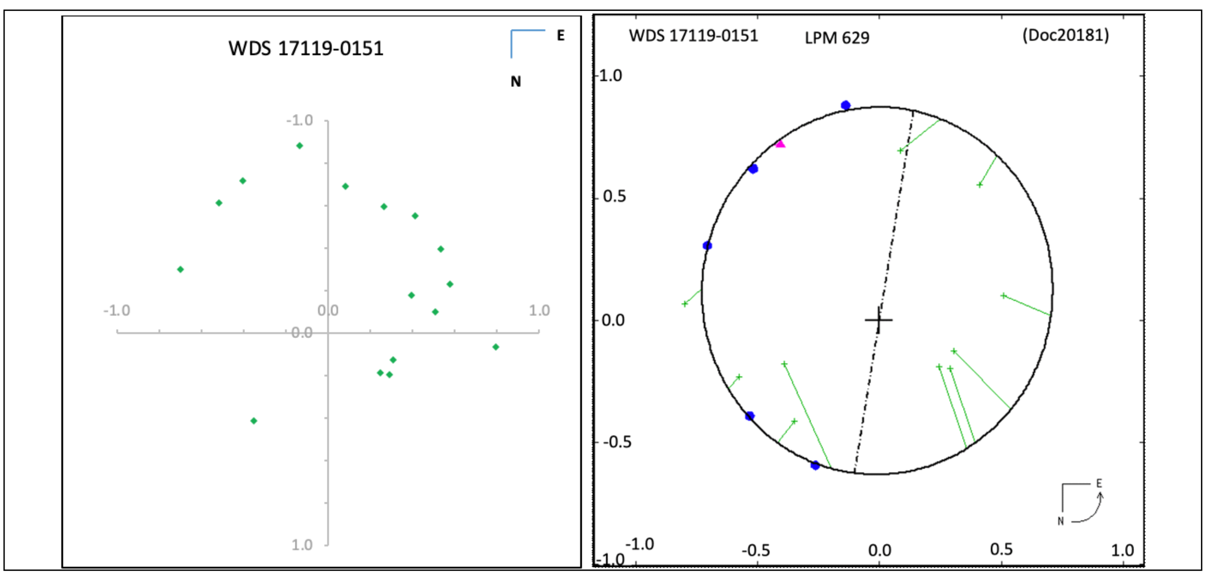

Figure 5: A plot of LPM 629's historical data (left) and its proposed orbital solution (right).

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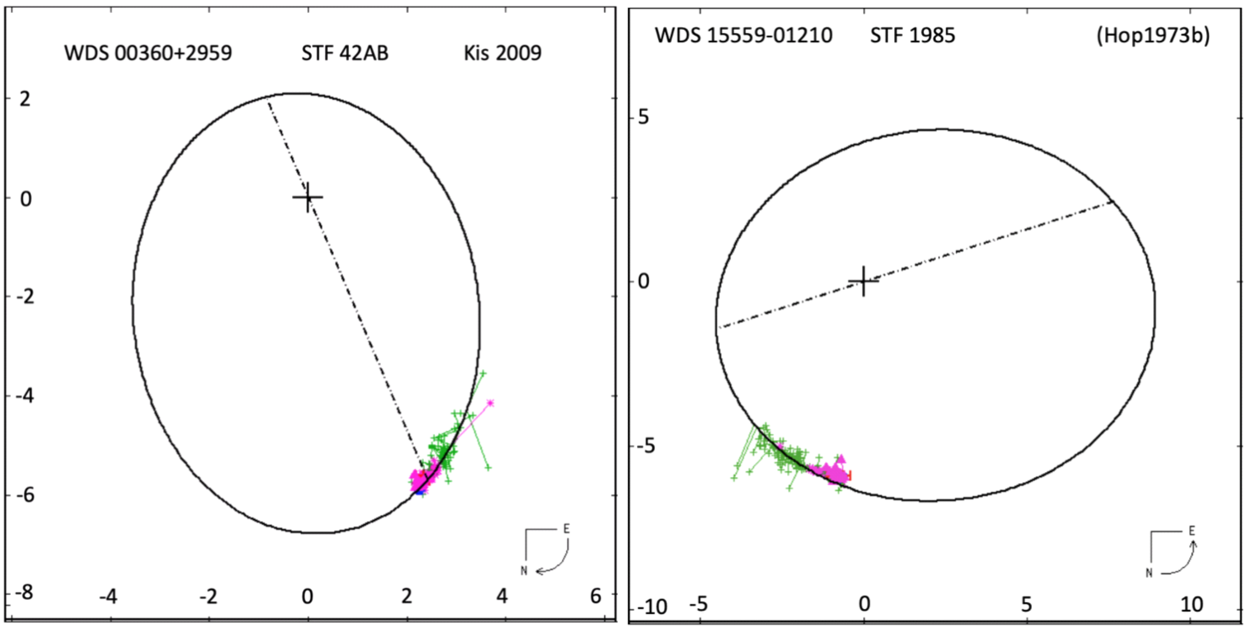

Figure 6: Short-arc binary solutions for physical systems STF 42AB (Kisselev, 2009) and STF 1985.

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either mean that the stars are affecting each other gravitationally, or that they were born in the same gas cloud. The fact that they are in the same region of space and moving in the same direction might be due to their shared history. As is clear from Table 2, the orange and green stars are likely physical, though the amount of arc that the secondary has traversed in the last hundred years is too short to definitely classify them as binary.

For the orange systems, plots of the historical measurements do appear to exhibit curvature. These systems have common proper motion (STF 1985 has rPM 0.151, STF 42AB has rPM 0.020). The components of STF 1985 are less than a parsec apart from each other radially, while the components of STF 42AB are about a parsec apart from each other. However, insufficient time has passed for a large portion of their arcs to have been observed. The current short-arc orbital solutions for these systems are shown in Figure 6.

From examination of the plots, it appears that the more recent data for STF 1985 are deviating from the proposed orbit ephemerides. Some slightly better-fitting parameters were found using Hensley's Desmos tool (Hensley, 2018). They are shown in Figure 7 and at this link, https://www.desmos.com/calculator/csieeekyi1..

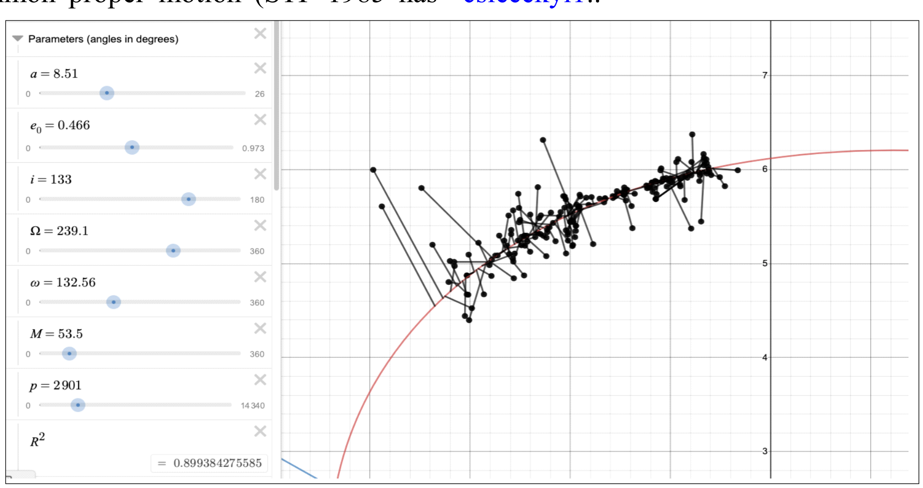

Figure 7: Better-fitting parameters for STF 1985 found using Hensley's Desmos tool (Hensley, 2018). (https://tinyurl.com/y2jkc6es)

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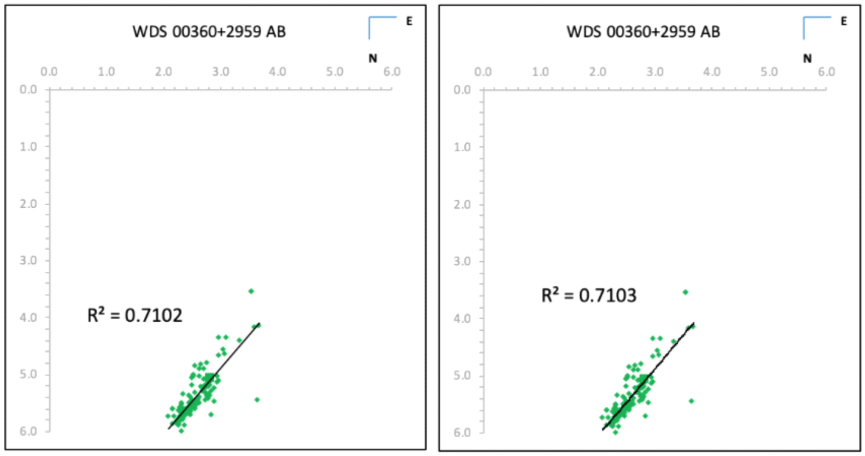

Figure 8: STF 42AB The position of the secondary relative to the primary with a linear line of best fit (left) and with a 2nd order polynomial fit (right).

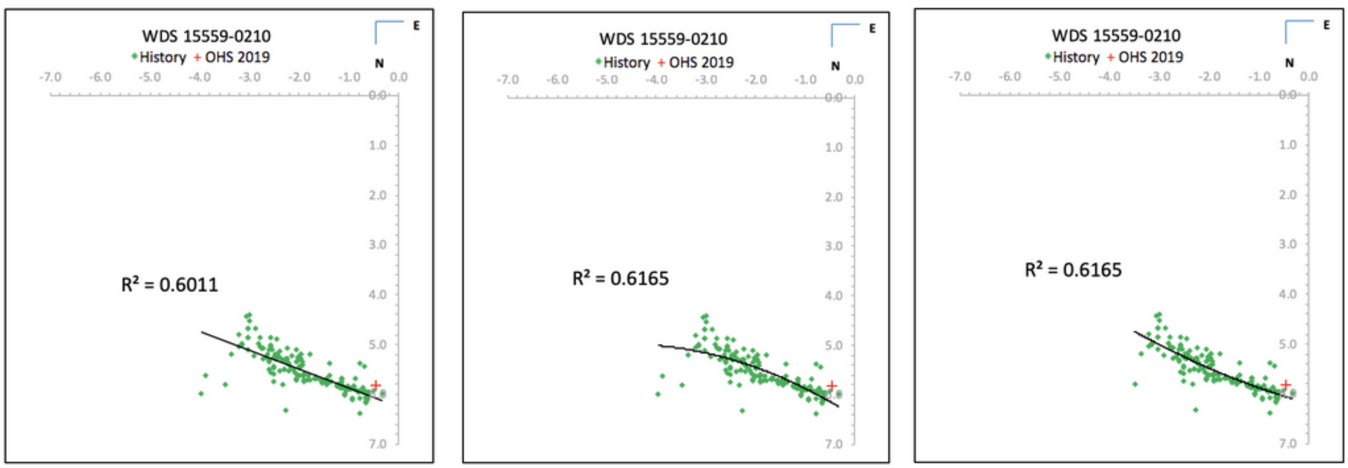

Figure 9: STF 1985 linear (left) and polynomial (right) fits. The polynomial fit at the far right has three outliers removed. The outliers were identified by the fact that they were more than 3 standard deviations from the mean of the other measurements.

However, even with the improved parameters, the data do not definitively show an arc for either of these systems. The early points have a lot of scatter. Linear and polynomial fits for both STF 42AB and STF 1985 are shown in Figures 8 and 9. For STF 1985, the polynomial fit initially appears to curve away from the primary star, which does not bode well for physicality. Removal of the three most egregious outliers (from the years 1823, 1830, and 1872, respectively) causes the polynomial trajectory of the secondary to curve around the primary star as would be expected for a binary system. However, the R^2 values are in all cases so similar that it is not possible to draw a conclusion from the fits. For STF 42AB, the values of both fits are also too close to be discriminant, having a difference of 0.0001. While this system's proposed orbit seems to be following its proposed ephemeris, there is substantial uncertainty because the proposed orbit indicates a period of roughly 1900 years.

Table 1 Green Systems: Candidates for Physicality, In Need of Time and Measurements

The green systems from Table 1 are likely to be physical and possibly even bound based on parallax and proper motion. However, not enough time has passed for an orbital solution to be convincing. Their historical data are too sparse and noisy for the seeming curvature of the fits shown in Figures 11 and 12 to be indicative of their actual trajectories. These systems are shown in Figures 10 and 11.

Harrington et. al. inferred the existence of another, unseen companion for the $0.3M_{\odot}$ dwarf star GIC 129 from its sinusoidally deviating proper motion and paral-

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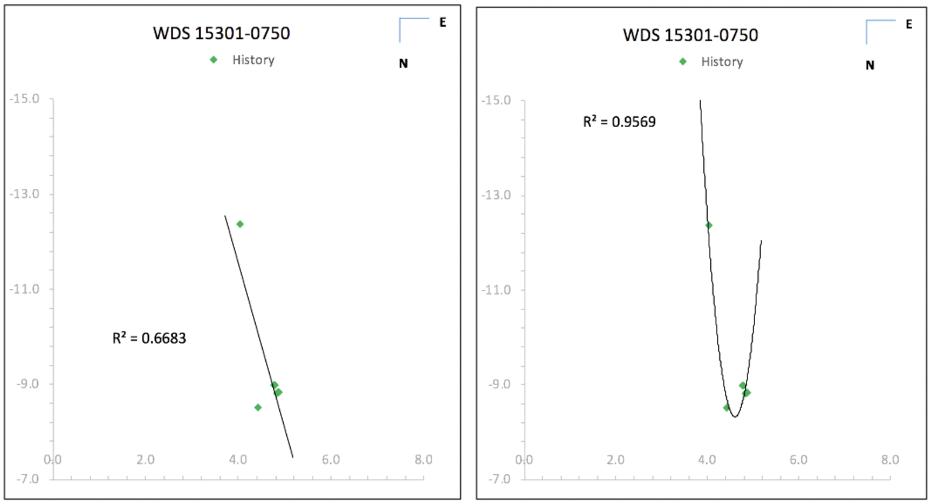

Figure 10. The position of the secondary with respect to the primary star of GIC 129 with a linear line of best fit (left) and a 2nd order polynomial fit (right).

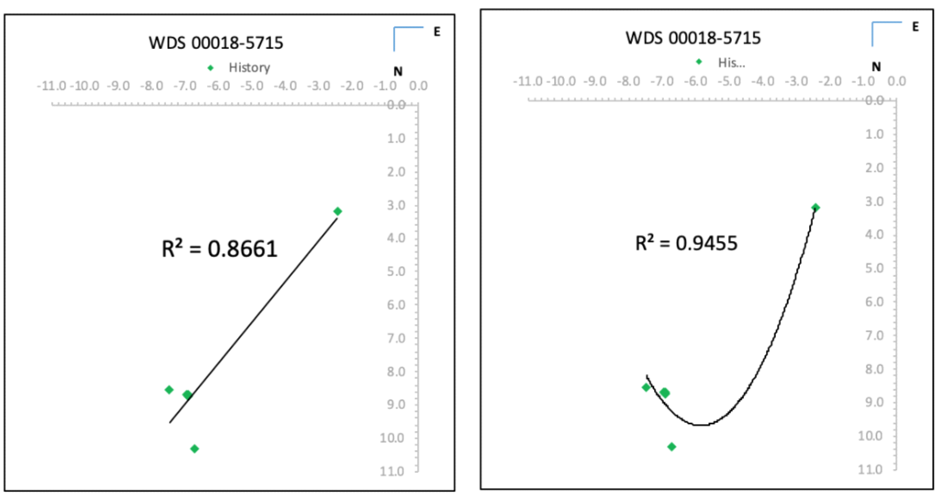

Figure 11. The position of the secondary with respect to the primary star of HJ 5438 with a linear line of best fit (left) and a 2nd order polynomial fit (right).

lax (Harrington et. al., 1988). They plotted the residuals (meaning the error from what would be predicted if the primary star was moving in a straight line and had a constant parallax), and found that those residuals had a sinusoidal variation that was consistent with another mass of approximately $0.1M_{\odot}$ tugging gravitationally on the primary. They were able to solve the orbit, which has a period of 6 years. Follow up observations of GIC 129 could confirm the association of both the WDS secondary and also possibly the unseen companion of this interesting, nearby dwarf star.

Table 1 Blue Systems: Optical Doubles

All three of the blue systems from Table 1 are optical based on the parallax and PM data from Gaia DR2 referenced above. One of these, J 868, has a solved orbit, shown in Figure 12 below, but this system should be reclassified to an optical double.

Purple: Unknown

The purple system, HDO 182, has very strange orbital solution on file, which is shown in Figure 13. When we plot the historical observations, the system appears to be following a different trajectory, as shown in Figure 12 at the right. The two observations at the upper left of the historical data plot were made a long time ago (1901 and 1910, respectively). It is reasona-

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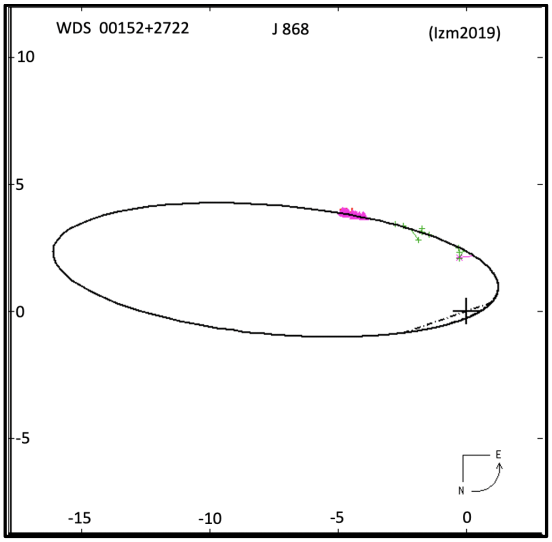

Figure 12: Orbital solution for J868.

ble to assume that with the instruments available at the time, the error of the measurements for such a close double would be large. Therefore, although the fits seem to imply curvature, the curvature should be approached with skepticism, both because of the presumed measurement error and also because of the low R2 values. This system also does not currently have any parallax or PM data, making any further analysis impossible. Thus, we are classifying this system as uncertain.

Conclusion

This project has explored several types of double star systems and we have classified them by color. The red stars (STT 327 and LPM 629) are clearly orbiting, despite lack of parallax or PM data. The orange systems (STF 42AB and STF 1985) are short arc binaries which might be confirmed as they traverse their orbits over time. The green systems (GIC 129 and HJ 5438) are likely physical and possibly gravitationally bound, and are in need of further measurement to confirm their status. The blue systems (J 868, D 6, and AG 87) are optical, and the purple system (HDO 182) is interesting but uncertain. We were able to contribute PA and separation measurements for STF 1985 (a short arc) and GIC 129 as part of this study.

Acknowledgements

This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory, the SkyNet Robotic Telescope Network, the Stelledoppie catalogue maintained by Gianluca Sordiglioni, and AstroImageJ software written by Karen Collins and John Kielkopf at the University of Louisville, updated for double star astrometry by Karen Collins.

This work has also made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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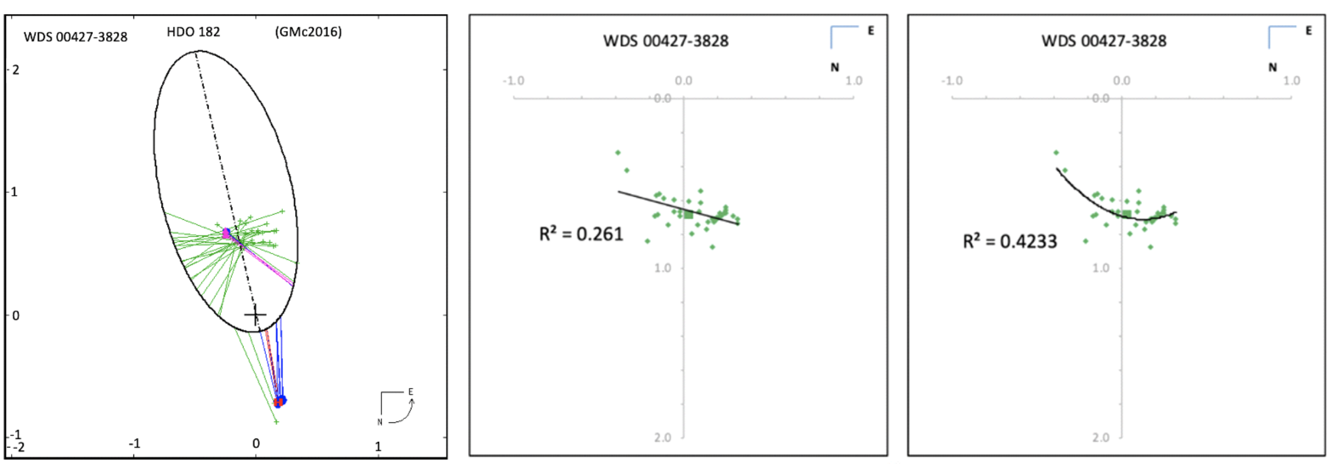

Figure 13. HDO 182's orbital solution (left) and the historical data with a linear line of best fit (middle) and the 2nd order polynomial fit (right).

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