Measures of Known and Discovered Double Stars Found Incidentally in Images Collected by the InStAR Astronomy Research Seminars

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Abstract:
Images collected by the Institute for Student Astronomical Research (InStAR) Double Star Astrometry Seminars from December 2017 through April 2021 were examined for possible double stars within their fields of view which had not been measured by prior seminar participants. Astrometric measurements of double star systems listed in the Washington Double Star Catalog (Mason et al, 2001, WDS) were made. Astrometric measurements of a new double star, which is not listed in the WDS but whose Gaia parallax, proper motion values, and other characteristics indicate it may be a physical system, are presented as a candidate double star for inclusion in the WDS.

Introduction:
InStar is a non-profit organization which conducts research seminars targeted to high school and college students and their teachers. The goal of the seminars is to promote a community of practice so participants may carry out a research project and publish the results in a peer-reviewed journal (Genet, et al, 2018). In the Double Star Astrometry Seminar, participants select a known double star, take its Theta and Rho measurements, compare their results with the historical record, and write a scientific paper of their results. Since December 2017, most of the measurements were collected using Flexible Image Transport System (FITS) images taken by the Los Cumbres Observatory Global Telescope (LCOGT), a network of robotic telescopes positioned at observatories around the world for use in research. Over 100 sets of images have been collected as of April 2021. The participants' target double star is typically centered in the field of view of the images. At the suggestion and with the permission of the seminar instructor, Rachel Freed, these images were examined for additional double stars incidentally in the fields of view. Eight known and one new double star were found in the process of examining the images. An analysis was made of all the double stars to estimate if they were gravitationally bound.

Equipment:
The FITS images used in this study were obtained using 0.4m robotic telescopes operated by the LCOGT. The telescopes are identical Meade 16-inch (40cm) RCS optical tube assemblies, mounted in LCOGT-designed equatorial C-ring mountings. The cameras used were SBIG STL6303 CCDs with 29.2x19.5 arcminute fields of view, and pixel sizes of 0.571 arcseconds. Most of the images by seminar participants were of short 1-4 second exposure times, limiting the number of stars which could be seen. Some images were of longer 1–4-minute exposures, providing considerably more stars to be reviewed.

Figure 1: The 0.4m LCOGT telescope and mount, Haleakala Observatory, Hawaii (Credit: LCOGT)

Procedures:
The FITS image files were retrieved from the LCOGT's Observer's Portal and examined using AstroImageJ (Collins et al., 2017). The image was zoomed-in and examined methodically using a grid search pattern.

Any stars which appeared to be double, such as being very closely separated or of near separation and similar magnitude, were noted. Using the Set of Identifications, Measurements, and Bibliography for Astronomical Data (SIMBAD) search function embedded in AstroImageJ, the star was checked whether SIMBAD listed a WDS designation for it. If one was found, the WDS designation was checked in StelleDoppie to confirm whether the separation and position angle in the InStar image comported to the known double to confirm which stars in the image were the known double. SIMBAD sometimes did not list a WDS number, in which case the StelleDoppie Database Advanced Search function was used to search the WDS in a 30" radius of the suspect primary star's celestial coordinates for any possible known double star.

To provide new useful measurements to the WDS, measurements were made only if the known WDS double star was listed in StelleDoppie as either "physical" or "uncertain" (those which were "not physical" were rejected), and whose last measurement was in the year 2015 or before. Measurements were collected from the InStar images in AstroImageJ using the Howell centroid method (Howell 1989). The mean, standard deviation, and standard error of the mean for the separation and position angle were calculated. The historical observational data was obtained from Dr. Brian Mason of the U.S. Naval Observatory and was input, along with the new measures, into Plot Tool 3.19 (Harshaw 2020, Plot Tool) to analyze the parallax, proper motions, and historical trend of these known pairs to indicate whether they might be gravitationally bound, as discussed further below.

In cases where no WDS designation could be found, a computation of the probability the star being part of a physically bound system was conducted to only present candidate pairs which had a high likelihood of being physical. While the Plot Tool was designed to analyze the historical measures of known double stars, its weighted distance and separation portions provided a convenient set of calculations to screen a suspected new double star for its probability of being physical. The Gaia Early Data Release 3 (Gaia Collaboration 2020, EDR3) data for the suspect double star was retrieved using the VizeR portal and the data were entered into the Plot Tool. If the distance analysis showed "no overlap" in its parallax range, it was rejected for this study, since the stars are too far apart from each other to be gravitationally bound (Harshaw 2020). If the data showed overlapping parallax ranges, Theta and Rho measurements were taken from the InStar images using AstroImageJ as noted above, using the date of the image as the epoch. The mean Rho value obtained from the measure was entered into the Plot Tool to calculate a weighted separation. To add additional measurement data points for the candidate pair, Theta and Rho were also computed for the 2016.5 epoch using the stars' celestial coordinates from EDR3, as follows:

$$\rho_{sec} = \sqrt{(15 \cdot \Delta\alpha \cdot cos\delta_1)^2 + \Delta\delta^2} \qquad [1]$$

(Gottlieb, 2021), where Δα is the difference in RA in seconds of time, δ_1 is the Dec of the primary star in arcseconds, and Δδ is the difference between the primary and secondary star declinations in arcseconds.

$$\theta^\circ = tan^{-1}(\Delta\alpha \cdot \left(\frac{cos\delta_1}{\Delta\delta}\right)) \qquad [2]$$

(Gottlieb, 2021), where Δα is the difference in RA in decimal degrees, δ_1 is the Dec of the primary star in decimal degrees, and Δδ is the difference between the primary and secondary star declinations in decimal degrees. The resulting epoch 2016.5 Theta and Rho are provided in the results as a first observation, and the measurements obtained from the more recent image in AstroImageJ were entered as the second, latest measurement. (Equations 1 and 2 are modified from those found in Buchheim, 2008).

An analysis of the likelihood of the double stars in this study are gravitationally bound was undertaken. The Plot Tool was relied on heavily for this analysis, however additional computation was performed for some elements:

1) **Parallax**: Using the EDR3 parallax and parallax error data for each star, the Plot Tool was used to compute the minimum, maximum, mean, and weighted distance to the stars in parsecs and calculate a percent of overlap of the minimum to maximum ranges. Because the brighter primary star generally has a lower parallax error value in EDR3, and to use a more rigorous limit to estimate physicality, the primary star's error value was used to compute the minimum and maximum range for both the primary and secondary stars. The result for the known and candidate double stars is provided below. If any suspected double star failed to show a parallax overlap, it was rejected for this study.

2) **Separation**: The Plot Tool was used to calculate a weighted separation in Astronomical Units (AU) by multiplying the weighted distance in parsecs by the latest Rho measurement in arcseconds. In the Sixth Orbit Catalog (Matson et al., 2021), there is no physically bound binary pair which has a separation greater than 5,000 AU (Harshaw, 2020). However, it is possible for a binary pair to have many times this separation limit (Knapp, 2019), especially if the stars are of high mass. It therefore was necessary to evaluate the mass of the stars, as described below, to describe whether the 5,000 AU limit influences the analysis.

3) **Proper Motion**: For known double stars, the historical observational data was kindly provided by Dr. Brian Mason of the U.S. Naval Observatory (Mason 2013) and entered into the Plot Tool. The data was graphically represented in the Plot Tool to show how well the historical measures fit along a trend line, which could show a Short Arc Binary (SAB) pattern, making a strong case

for gravitational binding, or a Linear (LIN) pattern, weakening the case. Since there are no historical measures for candidate pairs, only the similarity of the proper motion values is noted.

4) **Stellar Mass & Spectral Type Estimates**: The Plot Tool calculates the absolute magnitude using the EDR3 GMag value and the Mean Distance of the star calculated in the parallax module. Luminosity in solar units ($L_{\odot}$) is calculated from this absolute magnitude. Mass for each star is then estimated by the equation

$$M_{\odot} = L_{\odot}^{0.25} \qquad [3]$$

(Rowe, 2020). Where possible, the spectral type of the star was obtained from SIMBAD (with a letter and number), otherwise the estimate as calculated by the Plot Tool was used (represented by a letter only). In cases where there was no spectral tyle in SIMBAD, and EDR3 did not provide a T_{eff} value for a star (which is needed to estimate the spectral type), the star's absolute magnitude, $L_{\odot}$, and the Gaia BP-RP color were plotted in the Gaia Hertzsprung-Russell Diagram to derive a T_{eff} value to input into the Plot Tool to estimate a spectral type.

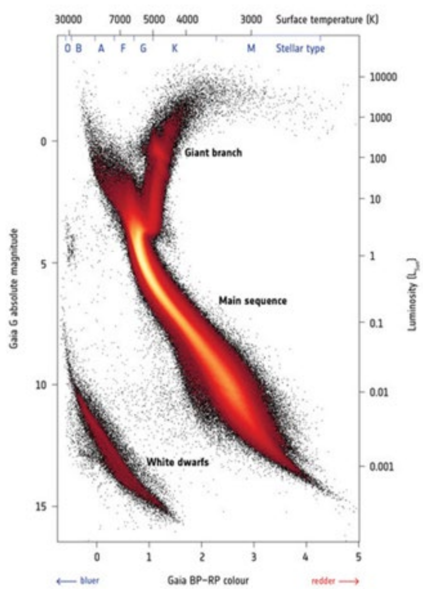

Figure 2: Gaia's Hertzsprung-Russell Diagram

5) **Escape Velocity:** To determine if the mass of the system can bind the two stars together gravitationally, the escape velocity and radial velocities of the stars are evaluated. The escape velocity of the system is computed:

$$V_{esc} = \sqrt{\frac{2GM_{tot}}{r}} \qquad [4]$$

(Rica 2011[1]) where G is the gravitational constant ($G \approx 0.0043 \frac{pc}{M_{\odot}} (km/sec)^2$), M_{tot} is the sum of the estimated mass of the primary and secondary stars, and *r* is the distance between the two stars in parsecs. For *r*, the mean separation in AU from the Plot Tool is multiplied by 0.00000485 to convert it into parsecs. The resulting value is compared against the delta of the radial velocity values for the primary and secondary stars as provided by the EDR3. If the delta in radial velocities exceeds the escape velocity, the system is probably not gravitationally bound (Harshaw, 2018). This comparison can only be made if there is a radial velocity given in EDR3 for both primary and secondary stars.

Results:

The measures of known double stars noticed in the field of view of the images collected by participants in the InStar Double Star Astrometry Seminars from December 2017 through April 2021 is presented in Table 1. The table includes the date of observation, number of images used for measurement, and the resulting Theta and Rho.

Table 1: New measures of known pairs:

WDS Catalog Number	Designation	pair	Date of Observation	number of images	Theta (°)			Rho (arcsec)		
					Mean	Standard Deviation	Standard Error	Mean	Standard Deviation	Standard Error
07045+4137	ES 1631	AB	2021.26	29	232.28	0.215	0.040	7.68	0.034	0.006
08573+3236	SEI 513	AB	2019.91	12	196.90	0.111	0.032	27.26	0.041	0.012
08573+3254	STF 1294	AB	2019.91	12	340.43	0.220	0.063	15.60	0.076	0.022
10130-5045	I 1197	AB	2019.81	14	181.40	2.395	0.640	3.44	0.175	0.047
18148+8035	SKF 1316	AB	2020.53	10	205.37	0.078	0.025	54.56	0.145	0.046
22284+5825	ARN 79	AC	2019.33	10	320.29	0.043	0.014	78.72	0.060	0.019
23596+5359	ES 703	AB	2020.79	14	271.33	0.592	0.158	7.37	0.097	0.026
23596+5359	ES 703	AC	2020.79	14	265.82	0.066	0.018	50.75	0.062	0.017

[1] Gottlieb (2021) noticed these discrepancies in the Rica paper and subsequent studies which referred to it:

1) Rica (2011) has a typographic error in equation 19, where "μ" should read as "*M*".
2) In Wiley and Rica (2015), equation 20 is mistakenly written as

$$V_{esc} = \frac{\sqrt{2GM_{tot}}}{r}$$

when it should read as:

$$V_{esc} = \sqrt{\frac{2GM_{tot}}{r}}$$

3) Harshaw (2018) used the mistakenly written Wiley and Rica equation 20 as his equation 3.

Using Harshaw's Plot Tool and Gaia EDR3 data, the stars' parallax, weighted distances, and weighted separations were taken and are summarized in Table 2. The percent distance overlap is calculated by the Plot Tool and represents the amount in overlap in distance the A and B stars are from Earth given the range in error in the Gaia EDR3 parallax data. The weighted distance is the estimated distance in parsecs of the pair from Earth given the Gaia EDR3 data, and the weighted separation is the distance between the A and B components in Astronomical Units (AU); both values are calculated by the Plot Tool using Gaia EDR3 data.

Table 2: Results of Parallax and Proper Motion analysis of known pairs:

WDS Catalog Number	Designation	pair	Proper Motions (mas/yr, Gaia EDR3)				Parallax (mas, Gaia EDR3)		Plot Tool Results		
			PM RA A	PM RA B	PM DEC A	PM DEC B	Px A	Px B	% Distance Overlap	weighted distance (parsecs)	weighted separation (AU)
07045+4137	ES 1631	AB	1.18	1.88	-3.61	-3.43	2.45	2.40	-9%	413	3,173
08573+3236	SEI 513	AB	-19.78	-9.10	-21.96	-28.36	1.63	1.35	-75%	672	18,310
08573+3254	STF 1294	AB	4.05	4.04	-3.02	-2.10	3.31	3.33	37%	301	4,698
10130-5045	I 1197	AB	-0.62	-0.84	1.63	1.76	2.48	2.47	34%	404	1,390
18148+8035	SKF 1316	AB	16.12	15.52	-7.82	-8.05	3.66	3.67	89%	273	938
22284+5825	ARN 79	AC	17.44	-4.31	4.79	5.48	4.11	2.16	-95%	319	25,123
23596+5359	ES 703	AB	-7.62	-6.68	3.22	2.01	3.14	3.20	-22%	315	2,324
23596+5359	ES 703	AC	unable to provide as data is missing in EDR3								

Table 3 presents the spectral class, estimated mass, and radial velocity and escape velocity comparison of known double stars. If the spectral class is a letter only it is estimated by the Plot Tool; otherwise it was taken from SIMBAD.

Table 3: Spectral class, estimates mass, and radial velocity and escape velocity comparison of known double stars:

WDS Catalog Number	Designation	pair	Spectral Class (estimated if letter only)		Luminosity (L☉)		Estimated Mass (M☉)		Radial Velocity (from EDR3, km/s)			Escape Velocity, Vesc km/s	Note
			A	B	A	B	A	B	RV A	RV B	Δ RV		
07045+4137	ES 1631	AB	F	F2 D ~	12.86	7.40	1.89	1.65	N/A	-8.64	N/A	1.41	lacking RV A
08573+3236	SEI 513	AB	F	K	14.65	15.78	1.96	1.99	23.58	49.75	26.17	0.62	not gravitationally bound
08573+3254	STF 1294	AB	G5 D ~	G	28.90	3.91	2.32	1.41	-28.45	-27.59	0.86	1.19	gravitationally bound
10130-5045	I 1197	AB	A9V C	F	19.78	5.92	2.11	1.56	N/A	N/A	N/A	2.16	lacking RV data
18148+8035	SKF 1316	AB	A0 D ~	F	19.81	7.45	2.11	1.65	N/A	-0.94	N/A	2.67	lacking RV A
22284+5825	ARN 79	AC	A0 E	K	20.18	24.40	2.12	2.22	N/A	-53.21	N/A	0.55	lacking RV A
23596+5359	ES 703	AB	K0 E	G	55.28	0.89	2.73	0.97	0.46	6.56	6.10	1.68	not gravitationally bound
23596+5359	ES 703	AC	K0 E	unable to provide as data is missing in EDR3									

Tables 4-6 shows the same measurement analysis done for the known pairs above, but for a new double star candidate.

Table 4: Measurements of the Candidate Pair:

Candidate		_RAJ2000	_DEJ2000	Source	Date Observed	# measures	Gmag	Theta (°)			Rho (arcsec)		
#	Component	"h:m:s"	"d:m:s"	Gaia EDR3			mag	Mean	Std. Dev.	Std. Error	Mean	Std. Dev.	Std. Error
1					2016.5	1		327.54			9.71		
	A	09 00 03.6328695138	-49 21 20.854614666	5325374278676703488	2021.28	8	9.79	327.02	1.49	0.40	9.67	0.11	0.03
	B	09 00 03.0992816709	-49 21 12.660115232	5325374274372936064			12.12						

Table 5: Proper Motion and Parallax analysis of the Candidate Pair:

Candidate	Proper Motions (mas/yr, Gaia EDR3)				Parallax (mas, Gaia EDR3)		Plot Tool Results		
#	PM RA A	PM RA B	PM DEC A	PM DEC B	Px A	Px B	% Distance Overlap	weighted distance (parsecs)	weighted separation (AU)
1	-13.78	-12.97	7.44	7.51	2.62	2.62	75%	381	3,689

Table 6: Spectral Class, Estimated Mass, and Radial Velocity analysis of the Candidate pair:

Candidate		Spectral Class (estimated if letter only)		Luminosity (Lʘ)		Estimated Mass (Mʘ)		Radial Velocity (from EDR3, km/s)			Escape Velocity, Vesc km/s	Note
#	Star Name	A	B	A	B	A	B	RV A	RV B	Δ RV		
7	HD 77345	A1Vn C	G	15.17	1.78	1.97	1.16	N/A	20.28	N/A	1.23	Lacking RV A

Screen captures of the known and candidate double star measurements are provided in Appendix A.

V. Discussion:

In the Plot Tool graph figures which follow, the A star is at the origin and the B star's prior measures are indicated with green diamonds, while the new measures are in red crosses. The red vector indicates the direction and distance the B star should have moved according to the Gaia EDR3 proper motions, while the green vector shows the direction and distance according to the first and last historical measures used in the Plot Tool. Black lines, when present, are trend lines.

The nature of **07045+4137 = ES 1631** is listed in StelleDoppie as uncertain, with 21 measures made since its 1896 discovery. The new measures comport with the trend of the historical measures, which is a slowly increasing Rho and stable Theta. Using the EDR3 data entered in the Plot Tool, the A and B components are shown not to share a common parallax range, with a -9% overlap. The radial velocity for the primary component was not provided in EDR3, so it was not able to compare with the escape velocity. The proper motion of the measures is divergent from the Gaia EDR3 data (see Figure 3). Based on the lack of parallax overlap, it is unlikely this is a gravitationally bound pair.

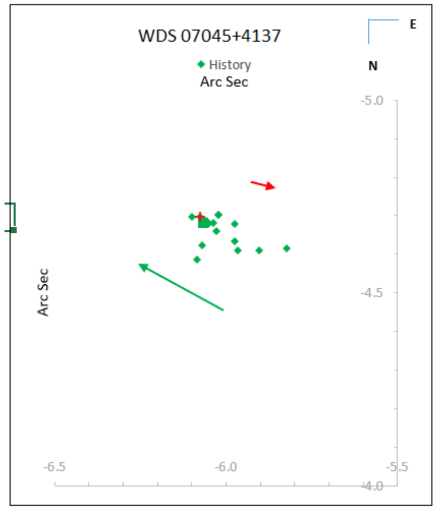

Figure 3: 07045+4137 Plot Tool graph

08573+3236 = SEI 513 is also listed in StelleDoppie as uncertain, with 15 measures made since 1894. The new measures are in line with the recent historical measures as shown in Figure 4, which are a decreasing Theta and Rho. The Plot Tool returns a -75% parallax overlap, and the proper motion in EDR3 and the measures are divergent. The computed escape velocity is far below the difference in radial velocity. These results indicate 08573+3236 is not gravitationally bound.

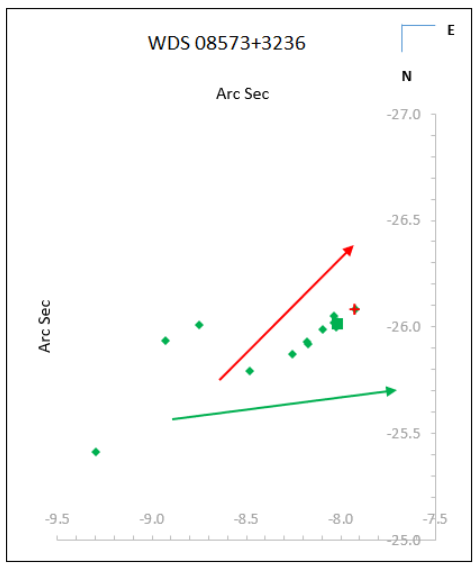

Figure 4: 08573+3236 Plot Tool graph

08573+3254 = STF 1294 is listed in StelleDoppie as uncertain with 18 observations since 1827 discovery. The Plot Tool shows a parallax overlap of 37%. The weighted separation is 4,698 AU, which is on the high end of known binary pairs in the Sixth Orbital Catalog. However, the primary star is a very luminous G5 D type with an estimated 2.32 $M_{\odot}$, so it may be able to bind its 1.41 $M_{\odot}$ secondary. The polynomial trend line is arced (see Figure 5). Furthermore, the escape velocity exceeds the difference in the radial velocity of the two stars, indicating this is a gravitationally bound double star.

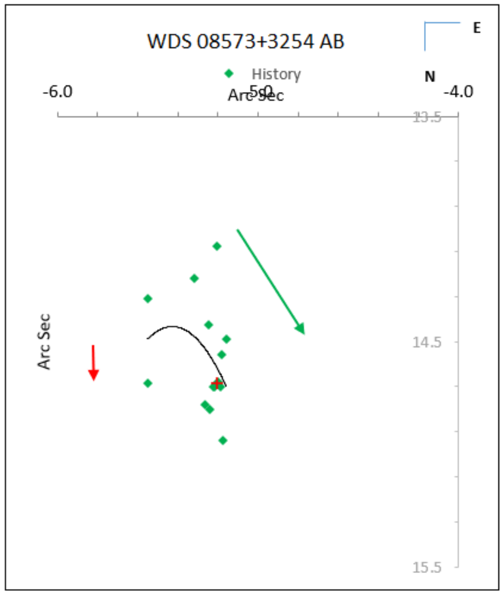

Figure 5: 08573+3254 Plot Tool graph

10130-5045 = I 1197 is listed in StelleDoppie as uncertain, with 5 measures since discovery in 1926. The Plot Tool returns a 34% parallax overlap, with a 1,390 AU weighted separation. With the primary star's mass estimated at 2.11 M☉, it is possible it could bind its 1.56 M☉ companion given the relatively close separation. The EDR2 parallax and proper motion values are nearly identical. As there are no radial velocity data in EDR3, it is not possible to compare the difference to the escape velocity. There are yet too few measures to establish an orbit, but the indications are this is likely a gravitationally bound pair.

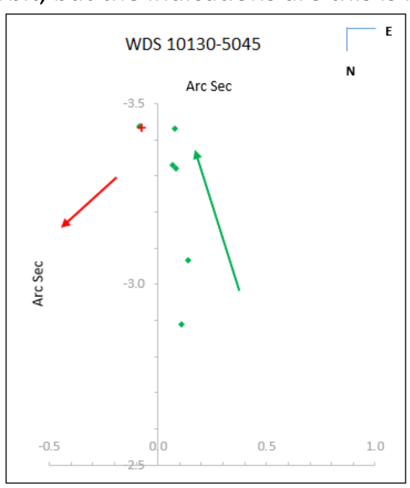

Figure 6: 10130-5045 Plot Tool graph

18148+8035 = SKF 1316 is listed in StelleDoppie as having a rPM=0.054 (< 0.3, Physical double). There is a strong 89% parallax overlap, the double star components have a very far separation from each other, with a weighted separation of 14,885 AU. The primary star (BD+80 577) is spectral class A0 D ~, with L☉ of 19.81 and an estimated mass of 2.11 M☉. The proper motion trends are nearly parallel though the measures are significantly longer than the proper motion since first observation. The polynomial trend line has a very slight arc (see Figure 7). Unfortunately, there is no radial velocity data for the primary star, so the difference in radial velocity cannot be compared to the escape velocity. Further observations are necessary to determine if these stars are gravitationally bound or co-moving.

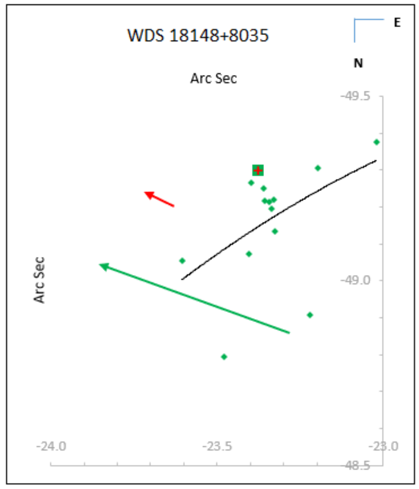

Figure 7: 18148+8035 Plot Tool graph

22284+5825 = ARN 79 AC is listed in StelleDoppie as rPM=0.271 (< 0.3, Physical double). However, the Plot Tool shows no overlap in their parallax, giving a -95%. The weighted separation is 25,123 AU, with stellar mass 2.12 Mʘ and 2.22 Mʘ. There is significant proper motion difference in both RA and Dec. It is not likely this is a gravitationally bound pair.

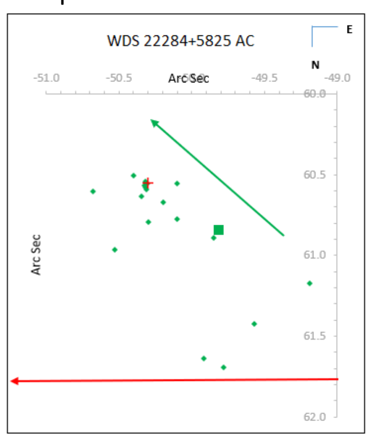

Figure 8: 22284+5825 Plot Tool graph

23596+5359 = ES 703 AB is listed in StelleDoppie as uncertain, with 8 measures since 1908. The parallax of the two stars do not overlap, -22%, and the difference in radial velocity is much higher than the escape velocity. It is not likely to be a gravitationally bound system.

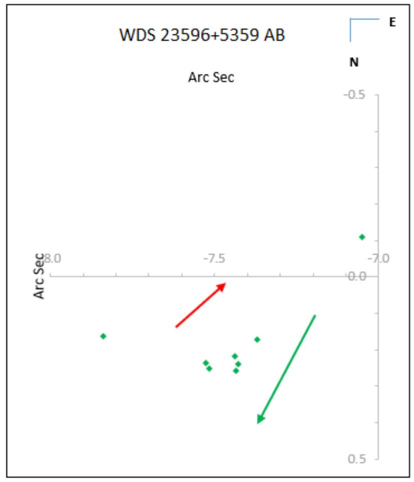

Figure 9: 23596+5359 Plot Tool graph

Candidate 1: The new double star candidate returned has 75% of the parallax ranges of the primary and second stars overlapping. The weighted distance is 3,689 AU, however the primary star's estimated mass is 1.97 $M_{\odot}$, perhaps enough to bind the secondary star to it. Unfortunately, the EDR3 data lacks radial velocity for the primary star, so it is not possible to compare the difference of radial velocities with the escape velocity.

VI. Conclusion:

The images collected by InStar Double Star Astrometry participants were examined closely for additional double stars to be measured, in hopes of making the most use of the data. While examining the Gaia data during the study, one candidate double star was identified and measured.

Acknowledgments

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This work has 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.

Las Cumbres Observatory. (2021). Las Cumbres Observatory Observation Portal was used to retrieve the InStar images in this study, https://observe.lco.global/?limit=20

Extensive use of Stelle Doppie, (2020 December 25) version 2.7, a search engine for the WDS, was used https://www.stelledoppie.it/index2.php?section=1 (accessed April 2021)

Extensive use was made of VizieR, a search portal for astronomical databases maintained by Centre de Données astronomiques de Strasbourg, Gaia, https://vizier.u-strasbg.fr/viz-bin/VizieR (accessed April 2021)

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Appendix A:

Images of AstroImageJ Measures of Known Double Stars

Figure 10: 08573+3236

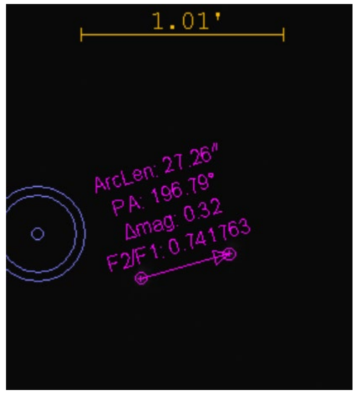

Figure 11: 07045+4137

Figure 12: 10130-5045

Figure 13: 08573+3254

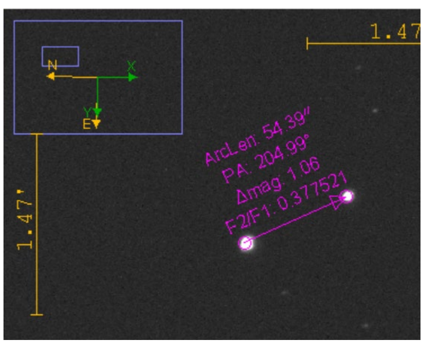

Figure 14: 22284+5825

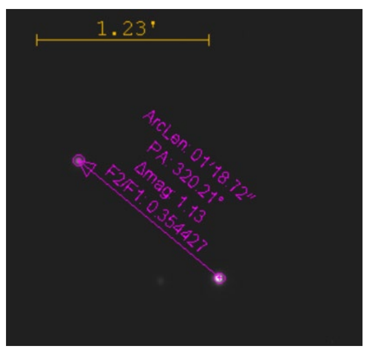

Figure 15: 18148+8035

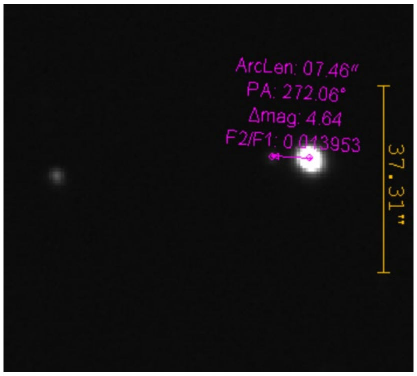

Figure 16: 23596+5359AC

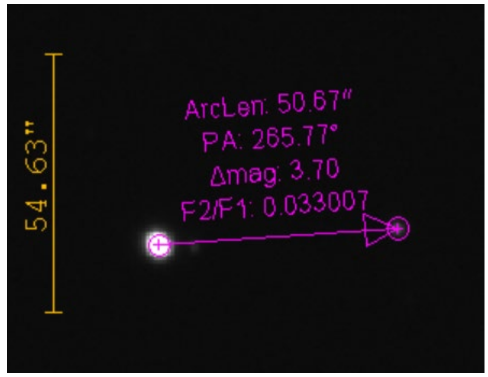

Figure 17: 23596+5359AB

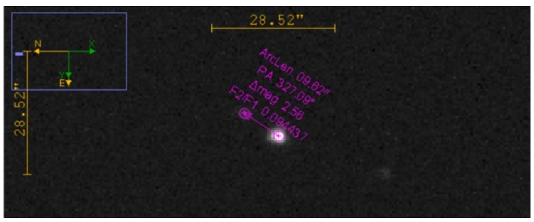

Figure 18: Candidate 1 AstroImageJ measurement