Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

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Abstract: The Gaia satellite provides a great leap forward in combining astrometric, parallax, photometric and spectroscopic measurements of stellar properties with greater accuracy than ever before. Data Release 2 (DR2) in 2018 made preliminary but consistent data available for an extraordinary number of stars.

In 2019 we began a campaign to identify and observe "new Gaia binary" candidate systems containing a red or white dwarf star. New red dwarf binary candidates are defined as not listed in the WDS catalog, but having the following Gaia parameters: two stars with separation < 10", similar proper motions, similar parallax (greater than 10 mas, i.e., within 100 parsecs of the Sun), and at least one component with Gaia color index Bp-Rp > 2.0. More than 800 Gaia candidate binaries have been identified in the northern sky; about ¾ of them have a red dwarf component, and several white dwarfs are also included. We have observed thirty-five of the brighter systems so far with the OCA 22" Kuhn telescope; about half of these do not appear in the WDS Catalog and are thus believed to be "new" Gaia binaries. Methods and results of the observations are presented and discussed.

Introduction

Although normal K and M dwarf stars ("red dwarfs") are the most numerous stars in our galaxy, their population even near the Sun is still incompletely known (Cooper, 2019). The brighter stars (i.e., earlier spectral types and red giants) have been well studied; but the later types, particularly late K and M dwarfs, are intrinsically faint and difficult to observe.

The census of all stars within 10 parsecs (32 light years) of the Sun, pursued by the RECONS consortium, is now considered complete, and the ongoing campaign to extend the census out to 25 parsecs (80 light years) is nearing completion (Winters et al., 2019). However, it is not certain that all these stars have been identified yet, because binaries closer than the resolution of large surveys (typically a few arc-seconds) may have escaped detection. Further RECONS work is continuing and planned for completing the census out to 100 parsecs (322 light years), and accurate data from the Gaia satellite – especially parallax and astrometric resolution – will play a crucial role in that search.

The Gaia satellite, designed and operated by the European Space Agency, dramatically expands the great success of the Hipparcos and Tycho programs. It is producing highly accurate five-parameter astrometry for 1.3 billion sources, including parallax measurements better than 0.1 milliarcsecond (mas) for good distance determination.

Data Release 2 (DR2) is the first comprehensive release of Gaia observations of stars, covering July 2014 through May 2016, with epoch of 2015.5 precessed to 2000.0 coordinates. Although it is only a preliminary release – with a limited number of observations and only stars brighter than 18th magnitude – DR2 is still the highest quality, most complete catalog of stellar position, parallax, proper motion, radial velocity, color, temperature and size ever produced. Subsequent releases will improve on DR2 quality and completeness through more observations, refined accuracy, and more detailed analysis.

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Gaia (DR2) Double Star Search Tool

Upon the public release of DR2 in April 2018, one of the authors (Rowe) wrote software to access, analyze and organize the original information on 1.3 billion stars, creating a sub-set of 6,820,000 double stars with separation (ρ) less than 10 arc-sec. He then wrote a program "Gaia Double Stars," GDS1.0 (Rowe, 2018) to extract from this sub-set, all the double stars which meet specified parameters. The program then writes their Gaia properties to a spreadsheet (.csv file).

The GDS1.0 tool also cross-references the Washington Double Star (WDS) Catalog and can include the WDS data line in its output. However, the WDS cross-reference is not always complete, presumably because the WDS designation is approximate, or high PM stars may have moved since discovery. Precise J2000 coordinates can be used to check whether Gaia double stars are in the WDS Catalog.

GDS1.0 enabled those interested in double stars to easily access the vast Gaia database in a manageable way. The GDS1.0 program is available to double star observers by request from the author. Although the GDS1.0 Double Star database is a small subset of the Gaia DR2 data, each hour of RA still contains hundreds of thousands of optical doubles.

Target Selection

Although red dwarf stars are the most common type, they are intrinsically faint, so all the red dwarfs near the Sun may not have been discovered yet. The goals of this campaign were to identify double star systems which might satisfy the following criteria:

a) Observable by Speckle Interferometry with the OCA 22-inch Kuhn Cassegrain telescope (Wasson, 2018 and 2019).
b) Might contain a "red dwarf" star, i.e., spectral type M or late K.
c) Might be real gravitationally bound binaries.

The Speckle Interferometry technique has been successfully used on modest aperture telescopes on stars as faint as 14th magnitude with filters, and 15th magnitude without filters (Serot et al., 2018). It was assumed that only the very nearest and brightest red dwarfs were within reach of the 22" telescope; therefore, four major requirements were imposed on this Gaia (DR2) search with GDS1.0:

1) Gaia G<15 for the primary star.
2) Zenith angle < 35 deg, to minimize atmospheric dispersion when observed near the meridian (Declination 0 to +70 deg).
3) Gaia parallax > 10 mas (within 100 parsecs).
4) Gaia (DR2) includes data for both Bp and Rp photometry for both stars, so that color index, a strong indicator of spectral type, can be calculated, and red dwarf targets identified (see following discussion).

Many of the double stars in DR2 do not have radial velocity (RV) listed, perhaps because it is difficult to do accurate absolute spectroscopy for close stars; more observations and further analysis will likely improve the Gaia RV data in future releases. Similar RV would be a valuable indicator of true binary nature, but the lack of data for both stars would unnecessarily eliminate many good candidates, so RV was not required.

After searching the DR2 double star database with GDS1.0, tens of thousands of "bright" pairs were found within each RA hour; however, most of them are very far away. The long list was sorted according to parallax (π) of the primary star. Then, deleting all the double stars with π < 10 mas shortened the list very dramatically – down to a few hundred candidates.

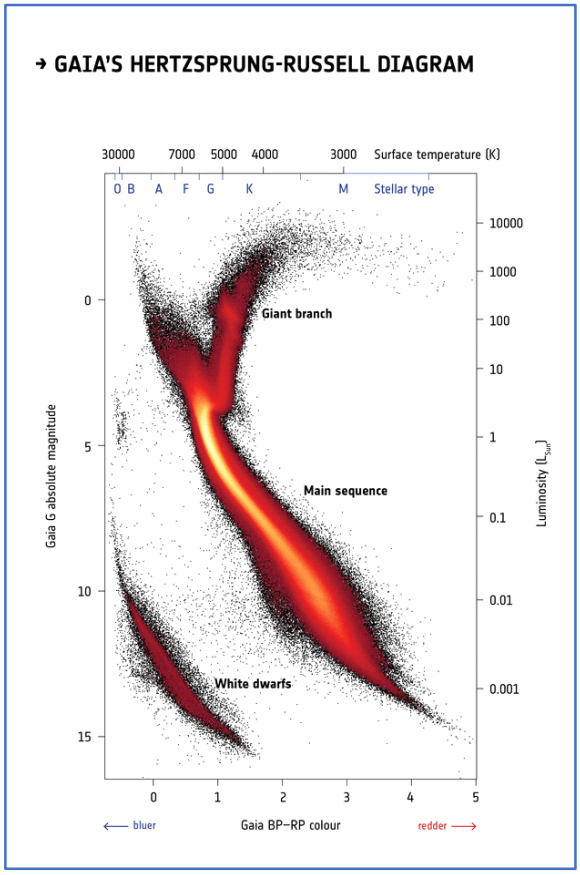

Figure 1. Gaia (DR2) H-R Diagram, based on Gaia self-consistent G, Bp, Rp photometry, and its accurate parallax (distance) measurements. For stars within 100 parsecs, "Red Dwarfs" are assumed to be those stars with (Bp-Rp) > 2, which includes late K and all M spectral types on the Main Sequence.

Each remaining pair was then checked for similarity of parallax (π) and proper motion (PM) of the two components. In this way many "optical" pairs with chance alignment were easily eliminated because of obvious large differences in π and PM. The last step in organizing the spreadsheet of possible candidates was to use the Bp and Rp photometric magnitudes to create the (Bp-Rp) color index for each component.

Figure 1 is the H-R Diagram released with DR2, summarizing the characteristics of all the stars observed by Gaia so far. The (Bp-Rp) color index is used as an approximation of spectral type and temperature for normal main sequence dwarf stars. K dwarfs have (Bp-Rp) between 1.0 and 2.3, while M dwarfs have (Bp-Rp) > 2.3. Red Giants are easily distinguished from Red dwarfs by their intrinsic brightness, resulting from their large size; if they are within 100 parsecs of the Sun, they will be very bright indeed - like Arcturus!

Surprisingly, a handful of these doubles contained a star with a color index near zero or negative – indicating a white dwarf in the lower left corner of the H-R diagram. Even though near the Sun and very hot, these tiny degenerate stars appear even fainter than most of the red dwarfs.

New Gaia Binaries Observed

The double star targets that were selected for observation were generally the "low-hanging fruit" – those systems which are nearest, brightest, or unique in some other way, but were not noted as WDS double stars in the GDS1.0 output files.

Unfortunately, the cross-reference within the GDS1.0 search tool was not always successful in identifying WDS stars – perhaps because the WDS Catalog number is approximate, or because the stars with high parallax typically also have high proper motion and may have moved significantly since their discovery. After the observations were completed, about half the stars in Table 1 were found in the WDS Catalog by comparing exact J2000 coordinates. These observations of WDS doubles are hopefully useful measures, but only 18 of the 35 binaries are confirmed as "new" Gaia binaries.

The Gaia (DR2) measured characteristics of the 35 doubles for which observations have been made (or attempted) are summarized in Table 1. Late type M Dwarfs, (Bp-Rp) > 3.0 are in red; two White dwarf candidates are in blue. Approximate spectral types are estimated from the (Bp-Rp) color index and Figure 1.

Those systems which are already known WDS doubles, based on comparison of precise J2000 coordinates, have WDS and Discovery designations noted in the right column of Table 1. Several of these were discovered by Nanson (NSN) and Knapp (KPP), who produced a large catalog of probable binaries based on data mining the Gaia DR2 database (Knapp & Nanson, 2019).

Correlations of the primary and secondary components in each of the observed systems, for Gaia (DR2) parallax and proper motion are shown in Figures 2 and 3, respectively. The π correlation is nearly perfect – within a few percent in all cases – as a result of the unprecedented accuracy of Gaia parallax measurements. The Proper Motion correlation is also excellent. This high degree of correlation is strong evidence that these double stars are very likely true gravitationally bound binaries.

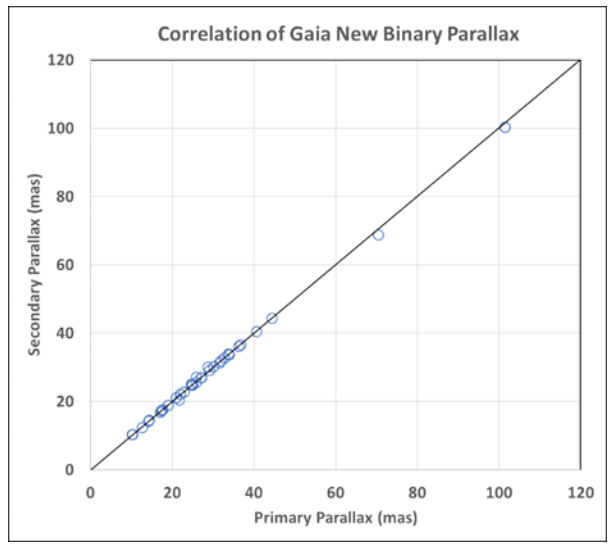

Figure 2. Correlation of Gaia Parallax measurements for the two components of the Gaia binaries observed.

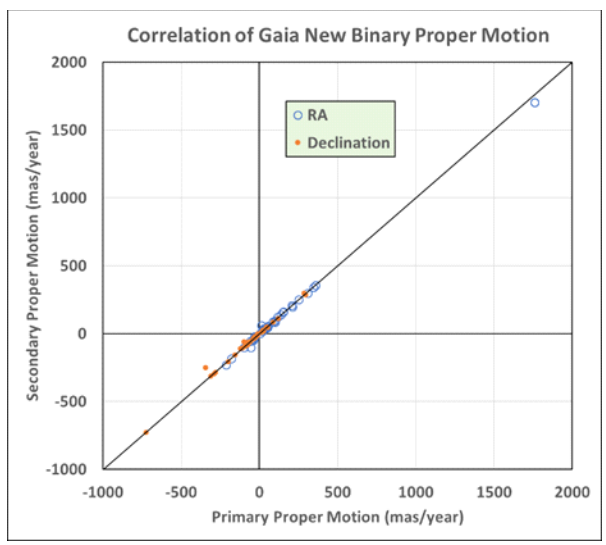

Figure 3. Correlation of Gaia Proper Motion measurements for the two components of the Gaia binaries observed.

Imaging Instrumentation

The telescope and speckle camera optical train were the same as previously used for speckle observations on the Orange County Astronomers (OCA) 22" Cassegrain telescope (Wasson, 2019), except for the Barlow and filters. A lower-power 1.5x Barlow, providing an image scale of approximately 0.091"/pixel with the ZWO ASI 290MM CMOS camera, was used in place of the 2x Barlow normally used in speckle work. The reduced magnification helped record extremely faint stars, but still provided adequate resolution for these relatively "wide" binaries. The smallest separation in Table 1 is ρ ~ 0.9", several times greater than the diffraction limit of the 22" telescope; however, resolution is restricted by seeing in the long (1-second) exposures.

Sloan Digital Sky Survey g′ r′ i′ z′ Generation 2 photometric filters manufactured by Astrodon were used for all observations. Their characteristics are summarized in Table 2. The par-focal "luminance" (L) filter, commonly used for astrophotography, transmits all wavelengths except UV; it was used for finding targets, and for taking full-frame images to verify target identity by recording other faint stars in the small field.

Coords (2000) UCAC4	ρ θ	GA GB	(Bp-Rp)A (Bp-Rp)B	SPECA SPECB	PMRAA PMRAB	PMDECA PMDECB	π_A π_B	TA TB	WDS Disc
002158.2+491237	2.275	11.857	2.466	M	208.8	-35.0	33.83	3753	00220+4913
697-002696	300.89	14.372	2.984	M	210.0	-29.3	33.76	4163	SKF 1600AB
003234.2+671404	3.837	9.517	2.311	K/M	1757.9	-344.8	101.43	3837	00321+6715
787-000996	183.60	11.099	2.625	M	1703.4	-250.8	100.41	3505	VYS 2AB
003317.5+341910	3.147	13.304	2.999	M	100.4	-56.9	40.63	4305	
622-001629	174.64	13.430	3.012	M	82.7	-59.5	40.54	4283	
020228.1+103452	0.904	11.865	2.932	M	-54.6	-97.0	70.43	3766	02025+1035
503-003059 (60)	24.9	12.330	2.994	M	-101.4	-59.0	68.79	4030	SLE 263
032829.3+351519	1.230	12.137	2.209	K/M	99.2	-121.1	20.90	4294	
627-011673	200.15	12.171	2.584	M	95.5	-108.5	21.14	4008	
042700.7+485249	1.109	12.968	2.630	M	10.9	-198.8	28.71	3709	
695-029258	46.65	13.140	2.803	M	59.3	-206.6	30.09	3635	
054756.4+183917	1.852	13.810	2.983	M	-58.0	-309.5	24.69	4013	05479+1839
544-019051	53.0	13.868	2.611	M	-55.4	-311.1	25.16	4171	NSN 561
064647.9+640826	0.901	12.243	2.010	K	-212.4	-73.5	21.65	4849	
771-031370	67.7	12.286	2.170	K/M	-230.3	-62.3	20.55	4498	
071717.2+682747	2.402	9.793	1.418	K	251.4	25.1	24.70	4593	07173+6828
793-019551	69.6	12.930	2.217	K/M	252.2	19.8	24.81	3800	NSN 574
154604.6+044127	2.335	13.967	2.999	M	153.7	-282.0	29.11	4305	15461+0441
474-054387	232.5	14.936	3.268	M	162.5	-282.7	29.27	4359	LDS 4590
160412.0+462015	6.494	9.025	1.213	G/K	-177.7	-80.0	27.13	4830	16042+4620
SAO 45877	58.2	13.526	2.631	M	-182.0	-85.9	27.02	3729	LEP 148
164650.6+053123	4.472	10.545	1.844	K	-37.7	-155.8	30.13	3966	16468+0531
478-063262	170.0	11.205	2.067	K/M	-47.0	-156.1	30.23	3910	NSN 683
164940.5+280004	3.512	11.464	1.702	K	-98.8	-35.4	17.45	4147	
591-057298	43.3	14.419	2.458	M	-102.4	-37.6	17.44	3693	
170648.9+321159	3.279	10.779	1.822	K	53.2	-74.7	31.93	4153	
612-054165	27.3	12.624	2.310	M	46.0	-82.8	31.93	3471	
171044.6+272743	2.120	13.525	2.656	M	45.4	-40.6	14.22	3698	
588-057624	269.0	14.294	2.540	M	44.2	-39.6	14.26	3489	

Table 1. Gaia (DR2) characteristics of the candidate binaries observed. Left column: Primary RA and Dec coordinates for 2000.0 (hhmmss.s+ddmmss format)[above] and UCAC4 Catalog ID of Primary [below]. Column 2: Gaia DR2 ***ρ*** *(arc-sec) [above] and Gaia* ***θ*** *(degrees) [below]. The remaining seven columns give Gaia data for the Primary (A) [above] and Secondary (B) [below]: G magnitude, (Bp-Rp) Color Index, Spectral Type based on the Gaia H-R diagram (Fig. 1), Proper Motion in RA (mas/year), Proper Motion in Declination (mas/year), Parallax (mas), and effective surface Temperature (K). The last column gives WDS and Discovery designations, if the pair is already recognized as a double star in the WDS Catalog. Late M Dwarfs are noted in red, and White Dwarfs are in blue.*

Table 1 concludes on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Coords (2000) UCAC4	ρ θ	GA GB	(Bp-Rp)A (Bp-Rp)B	SPECA SPECB	PMRAA PMRAB	PMDECA PMDECB	π_A π_B	TA TB	WDS Disc
180512.0+180719	5.020	11.063	1.871	K	32.5	-91.8	25.00	4065	
541-068543	18.8	15.061	3.209	M	36.9	-95.4	24.79	4285	
180931.7+040045	2.580	13.096	2.292	M	44.2	-9.4	17.06	3647	
471-071611	132.4	13.177	2.287	M	43.0	-1.3	16.97	3505	
182044.1+320633	2.764	12.337	2.120	K/M	4.2	86.5	17.71	4084	
611-060598	44.6	14.066	2.634	M	3.5	84.9	17.66	3994	
191659.0+022216	4.388	12.041	1.534	K	56.3	-23.8	10.24	4364	
462-091772	311.6	14.637	2.400	M	57.8	-24.4	10.36	3729	
192427.0+252550	3.612	10.305	1.768	K	-30.5	-74.9	31.53	4168	19244+2526
578-085046	269.2	13.796	2.639	M	-21.9	-69.8	31.34	4013	KPP 4147
193027.3+172340	1.491	12.137	2.093	K/M	37.2	12.8	14.33	4045	
537-095063	205.8	12.636	2.481	M	37.2	11.7	14.58	4034	
193846.1+264754	3.474	12.637	1.751	K	19.4	20.3	10.19	4062	
584-089998	238.8	15.621	-0.125	B(WD)	20.0	20.1	10.34	8983	
195852.2+513050	2.769	12.805	1.952	K/M	37.6	21.8	12.56	3978	
708-069903	130.2	15.176	2.753	M	35.7	25.0	12.44	3994	
205039.5+262045	3.888	9.363	1.098	G/K	118.5	-108.7	18.92	5056	20507+2621
582-111657	276.76	12.827	2.264	K/M	122.7	-106.3	18.89	3554	KPP 3362
205716.6+120013	3.441	11.648	1.993	K/M	346.8	-726.3	27.01	4160	20573+1200
511-133518	164.25	14.401	2.655	M	341.3	-728.4	27.02	3844	KPP 3365
210532.1+060916	5.095	11.452	2.571	M	27.9	45.1	44.34	3616	
481-129140	166.0	14.876	3.589	M	37.6	49.0	44.46	3533	
210957.5+032122	2.657	11.859	2.089	K/M	137.6	-27.4	21.95	3976	
467-128537	185.3	13.770	2.679	M	140.7	-21.8	22.13	3824	
211723.1+205359	4.330	11.547	2.426	M	308.5	285.4	32.69	3690	21174+2053
555-126112	341.2	12.479	2.724	M	299.5	297.5	32.82	3980	KUI 106
211848.1+001849	2.739	12.539	2.207	M	24.2	-63.5	25.85	3850	
452-118515	36.2	13.783	2.654	M	32.8	-62.0	27.13	3805	
220745.6+252026	8.204	10.955	1.481	K	85.5	-25.3	17.24	4397	22077+2521
577-125927	238.13	14.664	-0.395	dA1.9	87.6	-26.5	17.37	8869	POU 5641
220919.8+641017	2.884	13.604	2.825	M	358.6	296.9	36.20	4163	22093+6410
771-056717	212.63	14.357	3.081	M	355.6	287.3	36.20	4456	KPP 3376
222113.2+374451	1.983	11.838	2.283	M	150.9	51.5	25.80	3598	22212+3745
639-113594	250.41	12.179	2.643	M	159.3	45.1	25.61	3562	NSN 753
232936.3+154802	1.581	13.106	2.492	M	209.6	119.4	33.79	3780	23296+1548
530-151039	303.27	13.203	2.356	M	198.8	110.1	33.97	3644	NSN 770
234314.8+233625	5.790	11.979	2.069	K/M	-30.6	-10.7	22.85	4029	
569-130481	327.70	15.116	3.089	M	-28.6	-11.7	22.79	4344	
235144.7+065812	2.181	12.324	2.591	M	-39.0	-289.6	36.67	3994	23517+0658
485-137304	102.86	12.342	2.590	M	-39.3	-296.7	36.72	3809	CRC 77

Table 1 (conclusion). Gaia (DR2) characteristics of the candidate binaries observed. Left column: Primary RA and Dec coordinates for 2000.0 (hhmmss.s+ddmmss format)[above] and UCAC4 Catalog ID of Primary [below]. Column 2: Gaia DR2 ρ (arc-sec) [above] and Gaia θ(degrees) [below]. The remaining seven columns give Gaia data for the Primary (A) [above] and Secondary (B) [below]: G magnitude, (Bp-Rp) Color Index, Spectral Type based on the Gaia H-R diagram (Fig. 1), Proper Motion in RA (mas/year), Proper Motion in Declination (mas/year), Parallax (mas), and effective surface Temperature (K). The last column gives WDS and Discovery designations, if the pair is already recognized as a double star in the WDS Catalog. Late M Dwarfs are noted in red, and White Dwarfs are in blue.

Photometric System	Manufacturer	Type	Filter	Wavelength (nm)	Width (nm)	Equiv QE
Sloan	Astrodon	Interference	g′2	481	140	0.66
Sloan	Astrodon	Interference	r′2	626	130	0.77
Sloan	Astrodon	Interference	i′2	764	165	0.56
Sloan	Astrodon	Interference	z′2	896	185	0.32
Luminance	Astrodon	Interference	L	~650	~600	0.72

Table 2. Characteristics of the filters used for all observations. The three right-hand columns are: Equivalent "center" Wavelength (nm) [i.e., weighted average wavelength of convolved filter transmission and camera Quantum Efficiency], Band-pass Width at 50% transmission (nm), and estimated overall Quantum Efficiency at the "center" wavelength.

Observing & Calibration Procedures

In the first attempt to observe some of these red dwarfs, the exposures required with normal speckle magnification were explored. A G=10.5/11.2 pair was successfully observed with short speckle exposures. However, this pair was a relatively bright "easy" target, with moderate color index, (Bp-Rp) ~ 1.8/2.0. Therefore, the components were probably spectral type K rather than M.

Approximately doubling the speckle exposures provided better S/N, of course. However, exposures longer than about 0.1 second, even in the i′ and z′ bands, allowed significant movement from atmospheric turbulence to show up; the star images began to degenerate into seeing disks, losing their diffraction-limited information.

True M dwarfs, (Bp-Rp) > 2.3, are generally in the G = 13-15 magnitude range, unless very near to us, as seen in Table 1. Therefore, it became clear that the 22" telescope, with short speckle exposures, could not reach more than a handful of early M Dwarf targets – and none of the late M types. Longer exposures up to ½ second were explored, but the S/N results were still disappointing beyond G = 13. At ½ second, all high-resolution speckle information has already been lost; swirling atmospheric turbulence smears the fragmented Airy Disk images so much that they degenerate into the "seeing disk" of normal long-exposure images.

The combination of still longer 1-second exposures, together with reduced magnification of the 1.5x Barlow, was reasonably successful for stars brighter than G=15. Therefore, the procedure used for most of the observations in this paper was to take 200 to 300 frames of 1 second each, in all 5 filters. For faint red stars (G>13) the Sloan g′ filter was not generally used, however, because the S/N was too low for useful results.

The FireCapture image acquisition program (Edelmann, 2017) communicated with the ZWO electronic filter wheel under ASCOM protocols (Denny, 2019), automatically rotating to the next filter before each new multi-frame sequence; this provided a systematic order for output image files. A sequence of "Dark" frames was taken after the double, then a Reference (single) star was observed in each filter. The efficient and consistent observing procedure helped greatly to organize the large volume of stored images for post processing.

All images were saved as 16-bit FIT files; the camera only provides 12-bit A/D output, but FireCapture fills the least-significant-bits with zeros to create standard FIT files. Reference (single) stars were chosen from nearby field stars brighter than the target primary component.

The Drift Calibration technique was used for accurate astrometry: with telescope drive stopped, many short (typically 30 msec) exposures were taken while a bright star drifted across the camera field at the sidereal rate. Linear regression of the star pixel position, declination, and computer time (written to the FITS header by FireCapture), determines image scale. Likewise, linear regression of star images relative to the camera pixel rows gives camera orientation from true east-west. Both calibration constants were easily determined in a convenient Speckle Tool Box (STB) routine (Harshaw, Rowe and Genet, 2017). Five to ten drifts were made each night, and the average calibration was applied to all images for that night.

Results

From July 2019 to January 2020, the 35 candidate binaries of Table 1 were observed to confirm their double star characteristics. One system was observed twice. In two systems the B component was too faint to be detected in any Sloan band because the exposure was too short and the magnification too high; the L fil-

ter may have revealed the star, but it was not tried. Confirmation observations of the binary stars discovered by Gaia — nearer than 100 parsecs and containing one or two Red dwarfs — are presented in Table 3.

Because most of these systems are faint (red dwarf component 11 < G < 15), the quality of the observations varied widely, generally based on brightness of the secondary star at each wavelength, and on the seeing. Therefore, a Quality Code is included in Table 3, offered as an aid to interpreting these observations:

1. Good quality, comparable with moderate-resolution speckle.
2. Lower quality, faint or seeing-smeared images.
3. Marginal quality, because of low S/N of very faint or smeared images.
4. Poor quality, secondary star barely detectable above the noise.
5. Faint component Not Detected.

(Text continues on page 223)

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.764	002158.2+491237	AC	L	Not Observed			
	UCAC4 697-002696		g'	Not Observed			
	WDS 00220+4913		r'	302.12	2.373		1
	SKF 1600AB		i'	302.66	2.364		1
			z'	302.84	2.321		1
		BSA	L	Not Observed			
			g'	Not Observed			
			r'	303.07	2.260	1.55	3
			i'	302.81	2.293	1.28	2
			z'	302.72	2.280	1.32	1
	Average			302.70	2.315		
	Std Dev			0.32	0.046		
2019.764	003234.2+671404	AC	L	Not Observed			
	UCAC4 787-000996		g'	186.13	3.577		1
	WDS 00321+6715		r'	185.58	3.564		1
	MCY 1Aa,Ab		i'	185.65	3.578		1
	VYS 2AB		z'	185.52	3.580		1
		BSA	L	Not Observed			
			g'	185.63	3.589	1.20	1
			r'	185.63	3.569	0.75	1
			i'	185.65	3.570	0.54	1
			z'	185.55	3.583	0.64	1
	Average			185.67	3.576		
	Std Dev			0.19	0.008		
2019.846	003234.2+671404	AC	L	185.88	3.553		1
	UCAC4 787-000996		g'	185.92	3.535		2
	WDS 00321+6715		r'	185.51	3.591		1
	MCY 1Aa,Ab		i'	185.56	3.556		1
	VYS 2AB		z'	185.65	3.565		1
		BSA	L	185.75	3.538	0.79	1
			g'	185.73	3.539	1.54	2
			r'	185.63	3.569	0.96	1
			i'	185.62	3.588	0.83	1
			z'	185.61	3.552	0.74	1
	Average			185.69	3.559		
	Std Dev			0.13	0.020		

Table 3. Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arc-sec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 continues on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.846	003317.5+341910	AC	L	176.29	3.170		1
	UCAC4 622-001629		g′				5
			r′	176.87	3.153		3
			i′	175.57	3.185		1
			z′	175.39	3.158		1
		BSA	L	176.46	3.221		2
			g′				5
			r′	175.74	3.142	0.19	2
			i′	176.29	3.182	0.08	1
			z′	175.75	3.148	0.10	1
	Average			176.04	3.170		
	Std Dev			0.51	0.026		
2019.846	020228.1+103452	AC	L	6.26	0.930		1
	UCAC4 503-003060		g′				5
	WDS 02025+1035		r′	7.62	0.997		4
	Aa,Ab Resolved		i′	6.42	0.957		1
	(AB not binary)		z′	6.78	0.953		1
		BSA	L	6.13	0.972		2
			g′				5
			r′	6.07	0.994	0.90	3
			i′	5.32	0.994	0.50	1
			z′	6.76	0.984	0.74	1
	Average			6.42	0.973		
	Std Dev			0.67	0.024		
2020.074	032829.3+351519	AC	L	Not Observed			
	UCAC4 627-011673		g′	203.43	1.155		3
			r′	202.16	1.205		1
			i′	201.93	1.246		1
			z′	203.30	1.263		2
		BSA	L	Not Observed			
			g′	200.40	1.320	0.17	3
			r′	200.45	1.372	0.27	2
			i′	202.27	1.376	0.09	2
			z′	202.23	1.342	0.10	2
	Average			202.02	1.285		
	Std Dev			1.12	0.081		
2020.074	042700.7+485249	AC	L	Not Observed			
	UCAC4 695-029258		g′	50.22	1.241		1
			r′	51.36	1.282		1
			i′	49.92	1.244		2
			z′	48.27	1.297		1
		BSA	L	Not Observed			
			g′	52.82	1.270	0.36	3
			r′	48.99	1.297	0.10	2
			i′	50.36	1.278	-0.05	1
			z′	48.72	1.315	0.06	1
	Average			50.08	1.278		
	Std Dev			1.49	0.026		

Table 3 (continued). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 continues on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2020.074	042700.7+485249	AC	L	Not Observed			
	UCAC4 695-029258		g'	50.22	1.241		1
			r'	51.36	1.282		1
			i'	49.92	1.244		2
			z'	48.27	1.297		1
		BSA	L	Not Observed			
			g'	52.82	1.270	0.36	3
			r'	48.99	1.297	0.10	2
			i'	50.36	1.278	-0.05	1
			z'	48.72	1.315	0.06	1
	Average			50.08	1.278		
	Std Dev			1.49	0.026		
2020.074	054756.4+183917	AC	L	Not Observed			
	UCAC4 544-019051		g'				5
	WDS 05479+1839		r'	56.99	2.371		4
	NSN 561		i'	54.93	2.301		2
			z'	54.35	2.142		2
		BSA	L	Not Observed			
			g'				5
			r'	54.48	2.149	0.42	4
			i'	56.57	2.248	0.33	2
			z'	55.34	1.941	0.32	1
	Average			55.44	2.192		
	Std Dev			1.10	0.151		
2020.074	064647.9+640826	AC	L	Not Observed			
	UCAC4 771-031370		g'				5
			r'	62.70	0.836		2
			i'	61.84	0.851		2
			z'	59.39	0.802		2
		BSA	L	Not Observed			
			g'	58.29	0.838	0.74	4
			r'	63.19	0.888	0.10	1
			i'	63.53	0.904	0.05	1
			z'	58.17	0.885	-0.54	2
	Average			61.02	0.858		
	Std Dev			2.34	0.036		
2020.074	071717.2+682747	AC	L	Not Observed			
	UCAC4 793-019551		g'	68.04	2.441		3
	WDS 07173+6828		r'	69.83	2.409		1
	NSN 574		i'	70.42	2.408		1
			z'	70.52	2.410		1
		BSA	L	Not Observed			
			g'	69.84	2.367	3.59	2
			r'	69.38	2.420	2.70	1
			i'	70.21	2.411	2.09	1
			z'	70.33	2.399	2.36	1
	Average			69.82	2.408		
	Std Dev			0.81	0.021		

Table 3 (continued). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 continues on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.501	154604.6+044127	AC	L	Not Observed			
	UCAC4 474-054387		g'				5
	WDS 15461+0441		r'				5
	LDS 4590		i'	231.32	2.336		2
			z'	231.80	2.283		2
		BSA	L	Not Observed			
			g'				5
			r'				5
			i'	233.00	2.437	0.88	2
			z'	236.25	2.365	1.04	3
	Average			233.09	2.355		
	Std Dev			2.22	0.064		
2019.575	160412.0+462015			Red Dwarf Not Detected			
	WDS 16042+4620			In Speckle Exposures			
2019.501	164650.6+053123	AC	L	Not Observed			
	UCAC4 478-063262		g'	170.54	4.525		1
	WDS 16468+0531		r'	170.42	4.487		1
	NSN 683		i'	170.33	4.492		1
			z'	170.23	4.485		2
		BSA	L	Not Observed			
			g'	169.94	4.493	0.65	1
			r'	170.42	4.520	0.73	1
			i'	170.50	4.493	0.47	1
			z'	170.61	4.471	0.39	2
	Average			170.38	4.496		
	Std Dev			0.21	0.018		
2019.575	164940.5+280004			Red Dwarf Not Detected			
	UCAC4 591-057298			In ½-sec Exposures			
2019.600	170648.9+321159	AC	L	Not Observed			
	UCAC4 612-054165		g'	27.19	3.235		3
			r'	26.85	3.254		1
			i'	26.86	3.228		1
			z'	27.09	3.255		1
		BSA	L	Not Observed			
			g'	26.81	3.207	1.98	3
			r'	26.75	3.221	1.76	1
			i'	27.07	3.257	1.67	1
			z'	27.19	3.242	1.46	2
	Average			26.98	3.237		
	Std Dev			0.18	0.018		
2019.600	171044.6+272743	AC	L	Not Observed			
	UCAC4 588-057624		g'	Not Observed			
			r'	256.91	2.171		4
			i'	265.61	2.103		3
			z'	265.25	2.102		3
		BSA	L	Not Observed			
			g'	Not Observed			
			r'	265.95	2.136	2.75	3
			i'	263.75	2.134	1.06	1
			z'	269.73	2.290	0.99	2
	Average			264.53	2.156		
	Std Dev			4.23	0.070		

Table 3 (continued). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 continues on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.600	180512.0+180719	AC	L	Not Observed			
	UCAC4 541-068543		g′	Not Observed			
			r′	17.11	5.214		4
			i′	20.32	4.992		4
			z′	18.80	5.067		3
		BSA	L	Not Observed			
			g′	Not Observed			
			r′	17.71	5.174	4.28	4
			i′	19.43	5.007	3.28	3
			z′	17.14	5.226	2.90	3
	Average			18.42	5.113		
	Std Dev			1.31	0.104		
2019.600	180931.7+040045	AC	L	Not Observed			
	UCAC4 471-071611		g′	Not Observed			
			r′	130.16	2.624		2
			i′	132.16	2.592		2
			z′	131.85	2.565		3
		BSA	L	Not Observed			
			g′	Not Observed			
			r′	132.47	2.631	0.52	3
			i′	130.91	2.560	0.33	2
			z′	136.53	2.597	0.44	2
	Average			132.35	2.595		
	Std Dev			2.22	0.029		
2019.575	182044.1+320633	AC	L	Not Observed			
	UCAC4 611-060598		g′	41.39	2.706		3
			r′	41.44	2.641		2
			i′	45.00	2.787		1
			z′	44.45	2.793		1
		BSA	L	Not Observed			
			g′	43.88	2.713	2.73	4
			r′	43.81	2.804	2.25	3
			i′	44.88	2.788	1.94	1
			z′	45.46	2.781	1.91	2
	Average			43.79	2.752		
	Std Dev			1.57	0.058		
2019.663	191659.0+022216	AC	L	311.76	4.321		3
	UCAC4 462-091772		g′				5
			r′	311.57	4.395		2
			i′	311.19	4.433		2
			z′	311.81	4.350		2
		BSA	L	309.51	4.494	1.25	3
			g′	307.69	4.275	2.64	4
			r′	311.99	4.396	2.05	1
			i′	311.15	4.363	1.61	1
			z′	311.99	4.364	1.67	2
	Average			310.96	4.377		
	Std Dev			1.45	0.063		

Table 3 (continued). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 continues on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.600	192427.0+252550	AC	L	Not Observed			
	UCAC4 578-085046		g'				5
	WDS 19244+2526		r'	269.55	3.545		2
	KPP 4147		i'	269.21	3.598		1
			z'	270.05	3.607		2
		BSA	L	Not Observed			
			g'				5
			r'	269.99	3.566	2.85	3
			i'	269.27	3.585	2.24	1
			z'	269.39	3.560	2.42	3
	Average			269.58	3.577		
	Std Dev			0.36	0.024		
2019.575	193027.3+172340	AC	L	Not Observed			
	UCAC4 537-095063		g'	207.99	1.515		3
			r'	203.51	1.517		2
			i'	206.34	1.525		1
			z'	206.08	1.521		1
		BSA	L	Not Observed			
			g'				5
			r'	204.98	1.492	0.48	4
			i'	207.13	1.533	0.36	3
			z'	206.64	1.529	0.37	3
	Average			206.10	1.519		
	Std Dev			1.47	0.013		
2019.728	193846.1+264754	AC	L	234.88	4.267		2
	UCAC4 584-089998		g'	235.01	4.101		3
			r'	231.62	3.936		4
			i'	Not Observed			
			z'	Not Observed			
		BSA	L	239.95	3.900	3.01	3
			g'	230.79	4.074	1.69	4
			r'				5
			i'	Not Observed			
			z'	Not Observed			
	Average			234.45	4.056		
	Std Dev			3.61	0.146		
2019.728	195852.2+513050	AC	L	Not Observed			
	UCAC4 708-069903		g'	Not Observed			
			r'	Not Observed			
			i'				5
			z'	132.14	2.979		3
		BSA	L	Not Observed			
			g'	Not Observed			
			r'	Not Observed			
			i'	132.17	2.926	2.95	3
			z'	127.32	2.609	0.91	4
	Average			130.54	2.838		
	Std Dev			2.79	0.200		

Table 3 (continued). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 continues on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.663	205039.5+262045	AC	L	276.74	4.005		3
	UCAC4 582-111657		g′	276.84	3.859		4
	WDS 20507+2621		r′	276.82	3.899		1
	KPP 3362		i′	276.97	3.898		1
			z′	276.91	3.879		1
		BSA	L	277.03	3.971	2.06	3
			g′	277.11	3.877	2.06	3
			r′	276.98	3.897	2.11	1
			i′	277.27	3.849	1.48	1
			z′	277.03	3.896	1.20	1
	Average			276.97	3.903		
	Std Dev			0.15	0.049		
2019.728	205716.6+120013	AC	L	Not Observed			
	UCAC4 511-133518		g′	Not Observed			
	WDS 20573+1200		r′	169.01	3.756		3
	KPP 3365		i′	167.37	3.567		1
			z′	167.80	3.746		2
		BSA	L	Not Observed			
			g′	Not Observed			
			r′	168.06	3.330	2.22	3
			i′	167.46	3.505	1.97	3
			z′	172.92	3.439	2.09	4
	Average			168.77	3.557		
	Std Dev			2.12	0.170		
2019.663	210532.1+060916	AC	L	164.31	5.087		2
	UCAC4 481-129140		g′				5
			r′	165.59	5.035		2
			i′	165.14	5.107		1
			z′	165.20	5.064		1
		BSA	L	165.92	5.015	1.93	3
			g′				5
			r′	165.31	5.055	3.04	2
			i′	165.24	5.027	2.56	1
			z′	166.02	5.118	2.18	1
	Average			165.34	5.063		
	Std Dev			0.53	0.038		
2019.764	210957.5+032122	AC	L	Not Observed			
	UCAC4 467-128537		g′	185.10	2.656		3
			r′	185.03	2.691		2
			i′	185.07	2.685		1
			z′	184.88	2.666		1
		BSA	L	Not Observed			
			g′	189.43	2.436	1.59	3
			r′	185.46	2.638	1.23	2
			i′	186.07	2.642	0.81	1
			z′	184.79	2.649	0.71	3
	Average			185.73	2.633		
	Std Dev			1.55	0.082		

Table 3 (continued). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 continues on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.663	211723.1+205359	AC	L	340.50	4.346		2
	UCAC4 555-126112		g'	340.19	4.458		2
	WDS 21174+2053		r'	340.77	4.412		2
	KUI 106		i'	340.87	4.405		1
			z'	341.18	4.430		1
		BSA	L	342.02	4.487		2
			g'	341.61	4.385	0.76	3
			r'	340.93	4.419	0.53	1
			i'	340.73	4.397	0.38	1
			z'	340.58	4.431	0.39	1
	Average			340.94	4.417		
	Std Dev			0.54	0.039		
2019.663	211848.1+001849	AC	L	37.13	2.800		3
	UCAC4 452-118515		g'	38.07	2.625		4
			r'	37.27	2.845		2
			i'	37.03	2.859		2
			z'	36.66	2.850		2
		BSA	L	37.86	2.828	0.80	3
			g'	37.79	2.771	2.00	3
			r'	36.03	2.843	1.08	2
			i'	36.89	2.818	0.92	2
			z'	36.01	2.831	0.84	2
	Average			37.07	2.807		
	Std Dev			0.71	0.069		
2019.728	220745.6+252026	AC	L	Not Observed			
	UCAC4 577-125927		g'	238.77	8.352		2
	WD = 577-125925		r'	238.55	8.355		2
	WDS 22077+2521		i'	238.67	8.131		3
	POU 5641		z'				5
		BSA	L	Not Observed			
			g'	238.83	8.122	1.50	1
			r'	238.03	8.359	2.47	2
			i'	236.84	8.038	3.48	3
			z'				5
	Average			238.28	8.226		
	Std Dev			0.76	0.145		
2019.846	220919.8+641017	AC	L	212.45	2.927		1
	UCAC4 771-056717		g'	212.05	3.100		2
	WDS 22093+6410		r'	212.37	2.920		1
	KPP 3376		i'	212.91	2.929		1
			z'	212.52	2.935		1
		BSA	L	212.48	2.942	0.34	1
			g'	212.14	2.881	1.07	3
			r'	212.71	2.996	0.63	1
			i'	212.48	2.938	0.40	1
			z'	212.28	2.969	0.49	1
	Average			212.44	2.954		
	Std Dev			0.25	0.059		

Table 3 (continued). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

Table 3 concludes on the next page.

Observation of Gaia (DR2) Red and White Dwarf Binary Stars in the Solar Neighborhood

Date	Coord(2000)	Method	Filter	θ	ρ	ΔMag	Qual
2019.764	222113.2+374451	AC	L	Not Observed			
	UCAC4 639-113594		g'	248.17	2.096		1
	WDS 22212+3745		r'	249.19	2.048		1
	NSN 753		i'	249.02	2.073		1
			z'	248.93	2.065		1
		BSA	L	Not Observed			
			g'	247.56	1.996	0.25	2
			r'	250.05	2.031	0.20	1
			i'	249.66	2.052	0.14	1
			z'	248.50	2.064	0.16	1
	Average			248.89	2.053		
	Std Dev			0.80	0.030		
2019.728	232936.3+154802	AC	L	Not Observed			
	UCAC4 530-151039		g'	Not Observed			
	WDS 23296+1548		r'	306.40	1.881		4
	NSN 770		i'	308.96	2.363		1
			z'	308.84	1.768		3
		BSA	L	Not Observed			
			g'	Not Observed			
			r'				5
			i'				5
			z'	310.06	1.832	1.02	4
	Average			308.57	1.961		
	Std Dev			1.54	0.272		
2019.846	234314.8+233625	AC	L	327.62	5.826		2
	UCAC4 569-130481		g'				5
			r'	327.84	6.043		3
			i'	327.15	5.804		2
			z'	327.76	5.817		2
		BSA	L	326.87	5.821	1.26	2
			g'				5
			r'	327.59	5.726	2.23	3
			i'	326.75	5.893	1.45	2
			z'	328.36	5.760	1.61	2
	Average			327.49	5.836		
	Std Dev			0.54	0.097		
2019.764	235144.7+065812	AC	L	Not Observed			
	UCAC4 485-137304		g'	104.54	2.303		2
	WDS 23517+0658		r'	103.83	2.286		1
	CRC 77		i'	103.82	2.259		1
			z'	103.82	2.257		1
		BSA	L	Not Observed			
			g'	104.77	2.276	0.12	1
			r'	103.18	2.217	-0.02	1
			i'	103.36	2.226	-0.01	1
			z'	103.83	2.221	0.08	1
	Average			103.89	2.256		
	Std Dev			0.53	0.032		

Table 3 (conclusion). Observed characteristics of the Gaia binary stars observed in 2019-20. The first column is Besselian observation date. Column 2 includes RA and Dec Coordinates (2000.0) in hhmmss.s+ddmmss format, and UCAC4 Catalog number of the primary star [below]; WDS and discovery designations are also given for previously known doubles. The remaining columns are Method of speckle analysis [Autocorrelation (AC) or BiSpectrum Analysis (BSA)], Filter (Table 2), observed Position Angle (deg), observed Separation (arcsec), BSA Delta magnitude (secondary-primary), and Observation quality code (defined above). The Average and Standard Deviation results include all reported data, weighted equally regardless of quality.

(Continued from page 214)

Data Reduction Techniques

Two methods of speckle data processing were performed, using the Speckle Tool Box (STB) programs. STB1.05 (Harshaw, Rowe and Genet, 2017) was used for Speckle Autocorrelation (AC); STB1.13 (Rowe & Genet, 2020) was used for BiSpectral Analysis (BSA). Both types of analysis were done for each binary in each filter, giving as many as ten measures for some stars. Although the AC and BSA methods used the same original sequences of image frames for each filter, they always give slightly different results; they are not strictly independent measurements, but they were treated as such for calculation of the average and standard deviation shown in Table 3 for each star.

Table 3 also provides BSA delta magnitudes in each available filter. As expected, the delta magnitudes are generally smaller at longer wavelength where the fainter (usually redder) star emits more radiation. The Sloan i′ filter (near infrared) usually produced the best AC and BSA results, because the redder star is getting brighter and detector sensitivity (Table 2) is still high.

Because normal speckle exposures were too short for detection of most of these red dwarfs, long (1 sec) exposures were required, so the images were seeing-limited rather than diffraction-limited. Nevertheless, Speckle Fourier Transform processing was found to be generally successful. Perhaps this is because the images still contain approximately correct spacial frequency information — even when they are poorly exposed and even when separation of the wider binaries may be outside the isoplanatic patch.

In some cases, the AC and BSA images were distorted (noted as "smeared" in the Table 3 Quality code) which could be caused by different atmospheric distortion of the two components, i.e., not in the same isoplanatic patch. Distortion was also sometimes caused by telescope tracking errors, particularly periodic error of the drive gear, even for 1-sec exposures.

The Shift-and-Add stacking technique was used for the brighter stars, with some success. However, the faint targets were often mis-aligned because noisy pixels were mistaken as the primary centroid in automatic processing of underexposed images.

Analysis

Identification of the primary star in Table 1 is from the UCAC4 Catalog www.usno.navy.mil/ USNO-astrometry/optical-IR-prod/ucac (Zacharias et al., 2013) which was accessed through the C2A Planetarium program (Deverchère, 2018).

To check for additional components, all Gaia stars within about 1 arc minute radius of each binary were checked for similar parallax. The Aladin Interactive Sky Atlas (Bonnarel et al., 2000 and Boch and Fernique, 2014), available on-line through the SIMBAD Astronomical Database (Wenger, et al., 2000) has all Gaia (DR2) data for stars to magnitude 17. Within Gaia (DR2) resolution, only one system had another star whose parallax was similar to that of the binary: 234314.8+233625. See the discussion below.

The WDS Catalog was searched manually using the precise J2000 coordinates given in Gaia DR2 compared with the far-right J2000 coordinates of each WDS star. In this way, 17 of the 35 candidates observed were found to be previously discovered doubles. A preliminary search was also made in SIMBAD using the J2000 coordinates; only two stars were found cited as double in the literature — 003234.2+671404 = VYS 2AB MCY 1AaAb (see discussion below) and 211723.1+205359 = KUI106 — although 15 more are in the WDS Catalog, noted in Table 1. It was found that some recent catalogs, often prepared for exoplanet searches, still list these double stars as single.

One of the most useful results of observing these stars would be detection of orbital motion that proves their binary nature. For the "new" Gaia binaries, only two observations (Gaia in 2015.5 and our reported observations in this paper in 2019-20) cannot prove orbital motion; however, significant motion in only 4 years does indicate a possible orbit that should be observed frequently. In all cases the two components share approximately the same proper motion (Figure 3), but it would be interesting to check the individual Gaia observations to see whether there are additional short-term hints of orbital motion.

Figure 4 shows the correlations of Separation (ρ) and Position Angle (θ) between the current observations of this paper ("O" observed) and the Gaia observations ("G" Gaia). In these "O-G" plots, the error bars are the standard deviation of the current observations from Table 3; the Gaia uncertainties are assumed to be negligible. The small colored box contains most of the binaries; those data are shown with expanded scales in Figure 5.

Figure 4 indicates that at least 8 of the binaries show possible orbital motion, because the O-G displacement is greater than the observational errors for ρ, or θ, or both; these are plotted as filled blue circles. Nine more binaries in Figure 5 might have orbital motion, but the motions are small, with relatively large uncertainties. Open circles indicate those observations for which possible (O-G) motion is small, and orbital motion is buried in uncertainty of the current observations.

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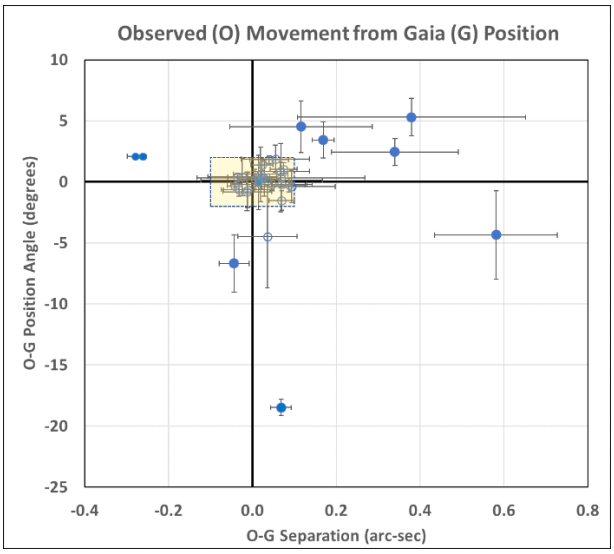

Figure 4. Comparison of the difference between Observed (2019-20) and Gaia (2015.5) Separation and Position Angle. Uncertainty bars are the standard deviations of the current observations in Table 3. Solid blue dots indicate significant change in position, possibly from orbital motion.

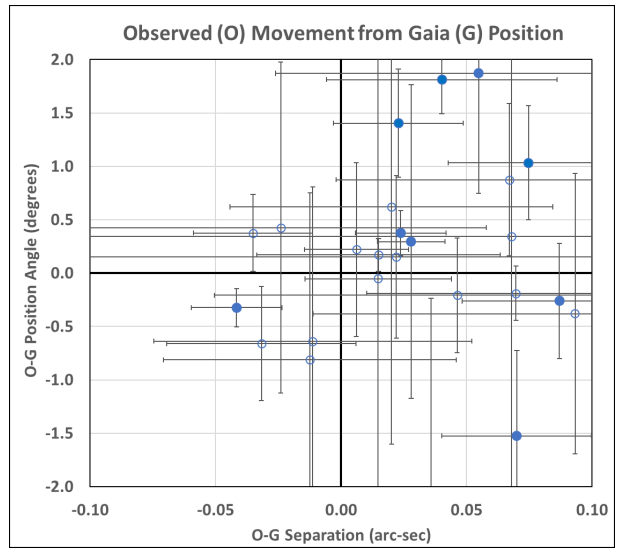

Figure 5. (O-G) data for the stars within the colored box of Figure 4, plotted on expanded scales. Solid blue dots indicate significant change in position, i.e., greater than ρ uncertainty or θ uncertainty, or both.

Discussion

Details of several individual binary systems are discussed below. All images shown are oriented with north up and east left, as on the sky. They were taken through Sloan g′, r′, i′, and z′ filters (Table 2), and were reconstructed from hundreds of frames using Bispectrum Analysis (BSA) in STB1.13.

The star *003234.2+671404 = UCAC4 787-000996 = WDS 00321+6715 = VYS 2AB* = MCY 1AaAb shown in Figure 6 is the closest and brightest Gaia binary system observed here (9.86 parsecs). It has extremely high proper motion (1.8"/year) and is a multiple system of at least three red dwarfs.

Orbital solutions were given by Docobo et al., 2008. The period of the grade 5 outer VYS 2AB orbit is 223 years. The grade 3 orbit of the inner pair MCY 1AaAb, fully covered by speckle observations, has a 15.64-year period and semi-major separation of 0.511″; The AaAb pair was not resolved by Gaia, but was resolved in the current observations because the exposures were only 100 msec (instead of 1.0 sec), resulting in the "long, low-resolution" speckle BSA images of Figure 6.

Current measurements of the AaAb pair in the r′, i′ and z′ filters agreed well, but they were not included in Table 3 because they were of sub-standard quality for such close stars, due to the low sampling resolution which had to be used to aid detection of much fainter red dwarfs.

However, it is significant that the average values, ρ = 0.478", θ = 14.0° on October 6, 2019, are close to the ephemerides in the 6th Orbit Catalog, except that θ is almost exactly 180° different. Somehow a 180° ambiguity seems to be present in the ephemerides or orbit solution, despite the inclusion of nine Hipparcos points, and other BSA measures (Horch et al, 2015) which also seem to be 180° different from the ephemerides. Indeed, the orbit solution paper itself (Docobo et al, 2008) has a diffraction-limited K-band image from the Russian 6-m telescope with θ = 45.5° taken in 2005.803, completing the first orbit. This was 14 years before the images in Figure 6 which are only 1.7 years before completion of the second orbit.

This star was observed twice, about one month apart; the two observations of AB agree well (they are the two farthest-left points in Figure 4), showing significant (O-G) displacement which is much larger than the

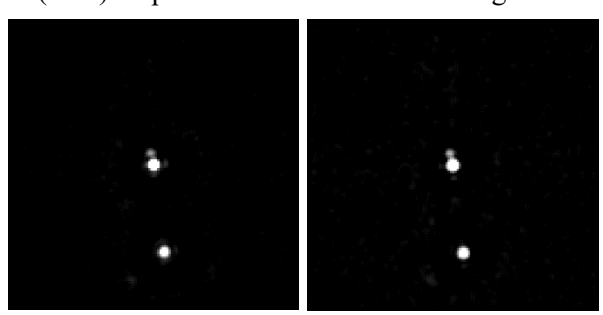

Figure 6. The triple star 003234.2+671404. The B component is below, and the AaAb pair is resolved in these 100 msec, BSA images. Sloan filters i' (left) and z' (right), field size is 12" x 12".

small uncertainties. This system deserves further regular observation to continue refining the AB orbit, which shows very large "wobble" due to motion of the AaAb components.

There is evidence that the B component may also be a binary with a brown dwarf or giant planet companion of about 16 M_J (Docobo et al., 2008) and (Horch et al., 2015). The 3 known components of this system are included in the "REDDOT" list of the RECONS comprehensive census of red dwarf stars within 25 parsecs of the Sun (Winters, et al., 2019).

003317.5+341910 = UCAC4 622-001629, a "new" Gaia binary, has nearly identical red dwarf components (G = 13.304/13.430 and Bp-Rp = 2.999/3.012), as shown in the BSA images of Figure 7. This system is quite close to us, at 24.6 parsecs. There appear to be several other faint stars in this small field; however, only the star west (right) of the binary is in the DR2 database. Its parallax puts it at more than 1000 parsecs; Bp-Rp = 1.07 (late G or early K), all but disappearing in the z′ filter.

The two other pairs of stars in the Figure 7 field (left and upper left) seem to become brighter at longer wavelengths, like the binary; but their additional similarity to the binary ρ and θ betrays them as processing artifacts.

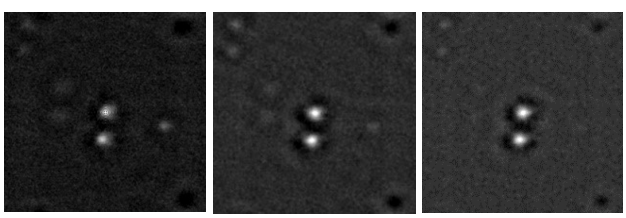

Figure 7. The binary 003317.5+341910 has very nearly equal red dwarf components. Left to right: Sloan r′, i′, z′ filters. The field size is 23"x23".

The binary *020228.1+103452 = UCAC4 503-003060 = SLE 263* is a WDS double, previously observed 7 times, including the visual micrometer discovery, the large UCAC and 2MASS surveys, and USNO CCD imaging. This system is very nearby (Table 1), with Gaia parallax of the A star approximately 70 mas. However, the AB pair cannot be a binary because the Gaia parallax of B is only 5.795 mas, about 12 times farther than A from the Sun. The BSA images of this system, Figure 8, show 3 components. All 7 observations before Gaia resolved only the AB pair and are consistent with linear motion toward the current position seen at center and bottom, respectively (ρ ~ 4.08″, θ ~ 188°).

The Aa and Ab stars at the center of the Figure 8 images were not resolved until Gaia, thus forming the

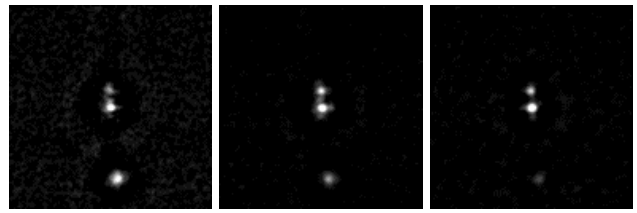

Figure 8. The 020228.1+103452 = SLE263 system. Left to right: Sloan r′, i′, z′ filters. The field size is 12"x12". The AaAb stars at center are the "new" Gaia binary, while the B component of SLE263AB at bottom is a background star.

"new" Gaia binary of Table 1; these components show the largest (O-G) motion of any system observed here: 0.067" ± 0.024" for ρ, and 18.48 ± 0.069 deg – a very large change in θ over 4.4 years. It is seen standing alone at the bottom of Figure 4. This binary is well worth frequent observations because of its apparently rapid orbital motion.

In the Gaia characteristics summary of Table 1 there are larger-than-usual differences in proper motion – for both RA and Dec – and there is also a large difference in parallax (greater than 2%). Such discrepancies may be caused by the small separation (~0.9", the smallest observed), combined with the large apparent movement in θ noted above. These circumstances may have compromised the normal accuracy of the preliminary data of DR2. Individual Gaia measurements or refined data analysis will be welcome in DR3.

0547564+183917 = UCAC4 544-019051 = WDS 05479+1839 = NSN 561 is shown in Figure 9, where it appears as triple. However, the true AB components have θ = 55°, while the star near θ ~ 90° is more than 10 times farther away. The binary B component is now about 1.0" north of this star and moving nearly due south at 0.31"/year, so will pass in front of the distant star in 2023. Speckle with large telescopes will then be required to resolve the two.

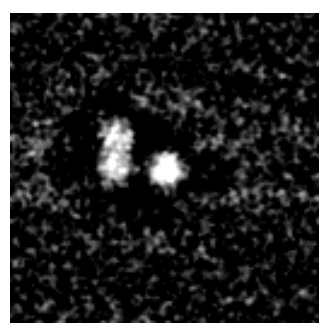

Figure 9. The Red Dwarf Binary NSN 561 is traveling with high proper motion almost due south (downward), toward the background star at left, which is best seen (although underexposed) in this r′ BSA image. The B component (upper left) will pass in front of the distant star, along our line of sight, in 2023.

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This system is also somewhat unusual in that the primary Red dwarf is the slightly brighter one (G=13.810/13.868) but is also much redder than the secondary: Bp-Rp = 2.983/2.611.

Two stars were attempted, but the secondary was not detected in any of the Sloan filter bands.

160412.0+462015 = WDS 16042+4620 = LEP148 = SAO 45877 (G = 9.0/13.5, Bp-Rp = 1.2/2.6) was observed, but only with short speckle exposures; the red dwarf companion was not detected. 164940.5+280004 = UCAC4 591-057298 (G=11.4/14.4, Bp-Rp=1.7/2.5) was observed with ½-second exposures, but again the red dwarf was too faint to give a measurable detection.

193846.1+264754 = UCAC4 584-089998 was one of two binaries observed that contain a White dwarf. At nearly 100 parsecs, this system was the most distant attempted; the white dwarf was only detected in the L (clear) and Sloan g′ filters, and these were marginal detections at best.

210532.1+060916 = UCAC4 481-129140 in Figure 10, is a binary of two red dwarfs, one of which is the reddest star observed (G=11.452/14.876, Bp-Rp=2.571/3.589). It is also one of the closest binaries to the Sun, only 22.5 parsecs. The primary star is probably M0-M2, but the companion's very red color index places it in the mid-late M class, perhaps M5-M7; it was only accessible with the 22" telescope because it is very nearby.

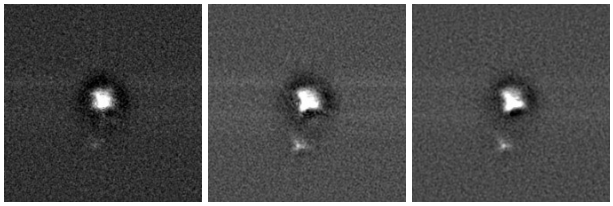

Figure 10. The very late type M dwarf B component of the Gaia binary star 210532.1+060916 is barely detected in r′ (left), but brighter in i′ (mid) and z′ (right) BSA images. The field size is 23″ x 23″.

220745.6+252026 = UCAC4 577-125927 = WDS 22077+2521 = POU 5641 consists of a K dwarf primary and a White dwarf of spectral class dA1.9 (A. Gianninas et al, 2011), separately identified as UCAC4 577-125925 because of its relatively wide separation, more than 8". This system is fairly near the Sun, at 57.8 parsecs. G = 10.955/14.664, and color index Bp-Rp = 1.481/-0.395. As seen in Figure 11, the White dwarf is clearly visible in the Sloan g′ and r′ filters, but barely there in i′ and was not detected in z′.

The faint companion about 9" east (left) of the primary, is UCAC4 577-125928, a type G star more than 1600 parsecs distant, based on Gaia color index and parallax.

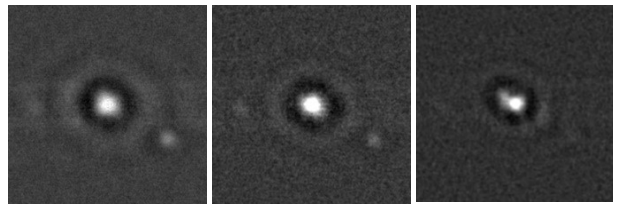

Figure 11. The primary star 220745.6+252026 = UCAC4 577-125927 and White dwarf secondary UCAC4 577-125925 comprise the binary POU 5641. Left to right: Sloan filters g′, r′, i′. The field size is 23″x23″ (256x256 pixels).

The red dwarf Binary *234314.8+233625 = UCAC4 569-130481* was found to have a nearby "C" companion north of the B component, seen in Figure 12, which is a stack of 20 full size frames in the L filter. Remarkably, it was found that C is *not* part of the AB Binary but is *closer* than AB and directly along the same line of sight, only 10" north of the primary.

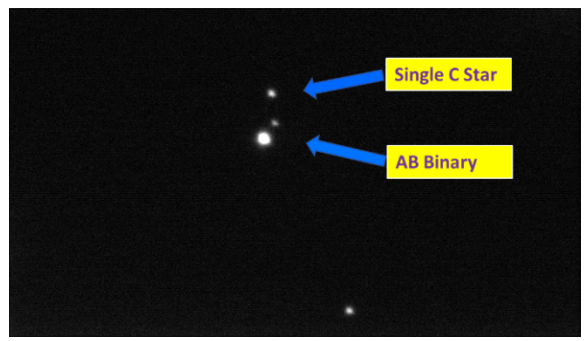

Figure 12. The A and B components of the Gaia binary star 234314.8+233625 have a nearby "C" component in our line of sight in this full-frame (2.9′x1.7′) L (clear filter) image (north up, east left). While the third C star is also a red dwarf, it is actually closer to us, not part of the binary.

Gaia (DR2) identifies C as a single star closer to us by 8.2pc; the binary $\pi_{A/B}$=22.85/22.79mas, while π_C = 28.05mas. C is also a Red dwarf star; $(Bp\text{-}Rp)_{A/B/C}$ = 2.069/3.089/2.878. However, the proper motion of C is much faster and in a different direction than AB. Such close proximity of three Red dwarfs near the Sun, and along our line of sight, must be an extremely rare coincidence!

Future observations of faint binary candidates should be improved by longer exposures – perhaps 2 to 10 seconds; the S/N would be greatly improved. Although the point spread function may be enlarged, it could also be more consistently round because of longer sampling, improving the odd shapes of some star images. However, telescope tracking errors (periodic error) will likely determine the upper exposure limit. In this way, perhaps fainter and redder red dwarfs within

binary systems might be reached with the 22" telescope.

Another limitation will be camera dynamic range, which is limited by small pixels and 12-bit output in the ZWO ASI 290MM camera. New "full-frame" (35mm format) back-illuminated CMOS cameras with somewhat larger pixels and 16-bit A/D output should improve the capability to observe large delta magnitude binaries.

The possibility of using a larger telescope would improve the S/N for faint stars if the seeing is good, because the seeing disk should not grow as fast as the mirror area in good seeing.

Conclusions

Hundreds of "new" binary stars (i.e., not yet in WDS) have been discovered by the Gaia satellite within 100 parsecs of the Sun. Thirty-five of the nearest and brightest of these binaries, in which at least one component is a Red dwarf, were successfully confirmed by 2019-20 observations with the OCA 22" telescope, using Sloan filters, multiple 1-second exposures and speckle processing techniques. Two White dwarf components were observed with marginal success. Several of these binaries show significant orbital movement since the Gaia (DR2) epoch of 2015.5; these deserve frequent observation.

Further improvements, such as longer exposure, higher camera dynamic range, and telescope aperture should make many more red dwarf observations possible.

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This research has made use of the "SIMBAD Astronomical Database," operated at CDS, Strasbourg, France, and the "Aladin Sky Atlas," also developed at CDS, Strasbourg Observatory, France.

This research has made use of the Washington Double Star Catalog, the 6th Orbit Catalog, and the UCAC4 Catalog, maintained at the U.S. Naval Observatory.

References

Edelmann, Torsten, 2017, FireCapture2.6. http:// firecapture.wonderplanets.de.

Boch, T.; Fernique, P., 2014. "Aladin Lite: Embed your Sky in the Browser," *ASPC*, **485**, 277.

Bonnarel, F.; Fernique, P.; Bienaymé, O.; et al., 2000, "The ALADIN Interactive Sky Atlas". *Astronomy and Astrophysics Supplement Series*, 143: 33–40. doi:10.1051/aas:2000331. http://aladin.u-strasbg.fr

Cooper, K., 2019, "Meet the Neighbors," *Sky and Telescope*, January 2019, 35.

CDS, Strasbourg Observatory, France, 2000, "Aladin Sky Atlas," *A&AS*, **143**, 33B. and 2014, *ASPC*, **485**, 277B.

Denny, R., 2019, "ASCOM – Standards for Astronomy," www.ascom-standards.org.

Deverchère, Philippe, 2018, "C2A Planetarium Software," www.astrosurf.com/c2a/english/ information.htm.

Docobo, J.A., Tamazian, V.S., Balega, Y.Y., et al., 2008, "A Methodology for Studying Physical and Dynamical Properties of Multiple Stars. Application to the System of red dwarfs Gl 22," *Astronomy & Astrophysics*, **478**, 187–191.

A. Gianninas, A., Bergeron, P., and Ruiz, M.T., 2011. "A Spectroscopic Survey and Analysis of Bright, Hydrogen-Rich White Dwarfs," *ApJ*, **743**, 138.

Harshaw, Richard; Rowe, David; Genet, Russell, 2017, "The Speckle Toolbox: A Powerful Data Reduction Tool for CCD Astrometry," *Journal of Double Star Observations*, **13**, 52-67, January 1, 2017.

Horch, E.P., van Altena, W.F., Demarque, P., et al., 2015, "Observations of Binary Stars with the Differential Speckle Survey Instrument. V. Toward an Empirical Metal-Poor Mass-Luminosity Relation," *The Astronomical Journal*, **149**, 151.

Knapp, Wilfried R.A. and Nanson, John, 2019, "A Catalog of High Proper Motion Stars in the Northern Sky (HPMSNS Catalog)," *Journal of Double Star Observations*, **15**, 42-58, Jan 2019.

Rowe, D., 2018, "GDS1.0 Gaia (DR2) Double Stars Search Program." Private communication.

Rowe, D., Genet, R., 2020, "STB1.13 Bispectrum Processing," in preparation for submittal to *JDSO*.

Serot, J., Wasson, R., Rowe, D., Genet, R., 2018. "Bispectrum-based Measurements of Close Large Differential-Magnitude Visual Double Stars," *JDSO*, **14**-4, 711-727.

Wasson, R., 2018, “Speckle Interferometry with the OCA Kuhn 22" Telescope,” *JDSO*, **14**-2, 223-241.

Wasson, R., 2019, “Speckle Interferometry with the OCA Kuhn 22" Telescope – II,” *JDSO*, **15**-2, 273-286.

Wenger et al., 2000, "The SIMBAD Astronomical Database", *A&AS*, **143**, 9.

Winters, J.G., Henry, T.J., Jao, W.C., et al, 2019, “The Solar Neighborhood - XLV. The Stellar Multiplicity Rate of M Dwarfs Within 25pc,” *AJ*, **157**, 216.

Zacharias, N. Finch, C. T. Girard, et al., 2013. “The Fourth US Naval Observatory CCD Astrograph Catalog (UCAC4),” *The Astronomical Journal*, **145**, 44.