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DOUBLE STARS IN THE USNO CCD ASTROGRAPHIC CATALOG

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ABSTRACT

The newly completed Fourth USNO CCD Astrographic Catalog (UCAC4) has proven to be a rich source of double star astrometry and photometry. Following initial comparisons of UCAC4 results against those obtained by speckle interferometry, the UCAC4 catalog was matched against known double stars in the Washington Double Star Catalog in order to provide additional differential astrometry and photometry for these pairs. Matches to 58,131 pairs yielded 61,895 astrometric and 68,935 photometric measurements. Finally, a search for possible new common proper motion (CPM) pairs was made using new UCAC4 proper motion data; this resulted in 4755 new potential CPM doubles (and an additional 27,718 astrometric and photometric measures from UCAC and other sources).

Key words: astrometry – binaries: general – binaries: visual – catalogs

Online-only material: color figure, machine-readable and VO tables

1. THE USNO CCD ASTROGRAPHIC CATALOG PROJECT

The USNO CCD Astrographic Catalog (UCAC; Zacharias et al. 2013) is a compiled, all-sky star catalog covering mainly the 8–16 mag range in a single bandpass between *V* and *R*. Positional errors are about 15–20 mas for stars in the 10–14 mag range. Since the release of UCAC2 (Zacharias et al. 2004), the UCAC catalogs have been widely used in the community, mainly for astrometric reference stars extending the optical reference frame beyond *Hipparcos* and *Tycho-2*.

Observations for UCAC were obtained using the USNO's 1970s vintage 8 inch Twin Astrograph, originally designed for photographic survey work. The astrograph has two lenses and tubes (both $f/10$, 2 m focal length) mounted in parallel on a Boller and Chivens 24 inch mount. For the UCAC project, the visual bandpass corrected lens was used for guiding, while the five-element "red lens" (a 1990s replacement of the original "blue lens"), equipped with a 579–643 nm bandpass filter, was used for imaging. The detector was a Kodak 4k × 4k CCD with 9 μm square pixels, giving a scale of 0.905 arcsec pixel^{-1}. Although the lens was designed for 8 × 10 inch photographic plates and gives a 9° field of view, only the ~1 deg^2 area covered by the single CCD was used for the program, providing uniform optical quality with all stellar images close to the optical axis.

The entire southern hemisphere and up to about $\delta = +20°$ was observed first from the Cerro Tololo Inter-American Observatory between 1998 and 2001, followed by observations of the remaining parts of the northern hemisphere from the USNO Flagstaff, AZ Station. Observations were completed in 2004.

The ~85,000 UCAC all-sky survey fields were laid out in a two-fold center-to-corner overlap pattern. Each survey field was observed with both long (100–150 s integration) and short (one-fifth integration time of the long) exposures. Saturation was reached at about 8.0 and 9.5 mag for the short and long exposures, respectively. Thus, depending on the brightness of stars, UCAC astrograph observations should provide two or four images per star, sometimes more in the case of repeat observations of fields or in the overlapping areas of adjacent fields.

The fourth and final catalog (UCAC4) was released at the 2012 IAU General Assembly and is described in Zacharias et al. (2013). UCAC4 is a corrected and updated (better northern proper motions) version of the previous UCAC3 release (Zacharias et al. 2010) following the same pixel data (Zacharias 2010) and astrometric reductions (Finch et al. 2010).

UCAC astrograph data were combined with many earlier epoch catalog positions to derive proper motions. Thus the published UCAC catalogs contain mean positions based on the astrograph observational program and other data dating back in some cases a century or more. UCAC4 lists over 113 million objects, mainly stars with accurate positions. About 110 million of these also have accurate proper motions. UCAC data are supplemented by Two Micron All Sky Survey (2MASS)[1] near-IR photometry and APASS[2] five-band optical photometry.

1.1. Blended Images and Doubles in the UCAC

For this paper we analyzed UCAC astrograph data to identify double stars. Instead of the published mean catalog positions, object detections on individual astrograph exposures form the basis of this investigation. Depending on the seeing, the typical FWHM of a UCAC astrograph observed stellar profile is about 1$''$.5–2$''$.2. (Note that the diffraction limit of the 206 mm aperture for the "red lens" is already about an arcsecond.)

For detected objects, first and second moments were calculated to obtain centroids and a measure of image elongation. The centroids served as starting values for two-dimensional image profile fits to the pixel data. Instead of a Gaussian profile, a modified Lorentz profile was used with the same number of parameters to fit after determining two more shape parameters; these parameters were based on pilot investigations over a large sample of the UCAC pixel data. Thus the utilized profile model function resembles the observed image profile much better than the Gaussian function, avoiding "pixel-phase errors" and allowing double star fits with significantly reduced bias. For more details see Zacharias (2010).

An image is suspected of duplicity and subjected to further investigation when (1) the image includes 10 or more pixels above detection threshold, and (2) the elongation of the image is larger by 0.12 than the mean image elongation of "good,

[1] 2MASS Point Source Catalog, 2003 all-sky release (http://www.ipac.caltech.edu/2mass/releases/allsky/).
[2] AAVSO Photometric All-Sky Survey (APASS), Data Release 6 (http://www.aavso.org/apass).

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well-exposed" stars on that frame. Here, image elongation is defined as the ratio of minor to major axes resulting from a moment analysis. (The typical mean image elongation is about 1.03–1.08 for most UCAC exposures.)

For these suspected blended images, a double star fit was performed to the pixel data, determining the centers and amplitudes of each component plus a common FWHM and background level in a least-squares adjustment. Only successfully fit stars are considered for this investigation, supplemented by detected close doubles from the list of successful single image fits in the case of non-blended doubles.

2. SPECKLE INTERFEROMETRY OF UCAC DOUBLE STAR DETECTIONS

As tests of the fitting routines used with the astrograph data, several hundred UCAC-identified pairs, covering a range in separation, primary magnitude, and magnitude difference, were observed with the USNO speckle cameras in 2008 and 2009. The sample was "blind," in that no prior determination was made as to whether the pairs were known doubles in the Washington Double Star (WDS)[3] database.

2.1. Secondary Camera

The first sample of UCAC pairs was examined using the secondary USNO speckle camera (Mason et al. 2008) mounted on the 26 inch telescope in Washington. While the magnitude limit of the secondary camera restricted our observing sample, the separation regime of pairs detectable by the USNO Astrograph was in the "sweet spot" of detection space for the camera.

Data were taken on 365 UCAC double star candidates over eight observing nights. These resulted in 238 total measured peaks of 162 different systems; the remainder were found to be single. Thirty-eight brighter pairs with smaller separation and magnitude difference were also inspected. These were all found to be single stars as well.

2.2. Primary Camera

In late 2008 the primary speckle camera was returned to USNO. This camera has a more sensitive intensifier camera which allows additional pairs to be observed while also using a filter with a smaller FWHM, thus decreasing dispersion. The primary camera also contains Risley prisms to correct for atmospheric dispersion, further improving the image quality and detection capability. The primary camera detector used initially was an NVSI 9540 Gen IIIc ICCD (Mason et al. 2000). Due to possible degradation of this decade-old ICCD, it was replaced with a new, fiber-optically controlled NVSI 9540 Gen III ICCD in late 2008, as described in Mason et al. (2011). Pairs were observed in 2009 using both detectors, covering regions of the sky not adequately sampled earlier by the secondary camera.

2.3. Overall Detection Statistics

As noted above, the list of these UCAC detected pairs was made without restriction as to whether the pair was previously known. Those subsequently identified as known pairs are listed in Table 1, which presents the mean relative position of the members of 101 systems. The first two columns identify the system by providing its epoch-2000 coordinates and discoverer designation. Columns 3 through 5 give the epoch of observation

[3] Available online at http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/WDS.

Table 1
ICCD Speckle Measurements of Double Stars

WDS Designation α, δ (2000)	Discoverer Designation	Epoch 2000.+	θ (°)	ρ (″)	n	Detector
00057+1750	STF 3061	9.8715	149.2	7.61	2	cam1new
00156+4426	SMA 4	8.9261	158.7	9.61	1	cam2
00187+2545	HJ 1015 AB	9.8716	290.8	5.36	2	cam1new
00220+2711	HDS 48	9.8788	242.6	9.65	1	cam1new
00373+2718	BU 230	9.8022	325.3	3.87	2	cam1old
00440+6244	STI 120	8.8333	55.7	7.16	1	cam2
00489+2745	BRT 2	9.8022	26.3	3.44	1	cam1old
01058+2655	BRT 121	9.8022	192.6	2.73	1	cam1old
01063+2233	HDS 140	9.8788	120.1:	13.29:	2	cam1new
01127+5311	HJ 2025 AB	8.8333	59.0	11.62	1	cam2
01264+5929	STI 213	8.7816	282.6	11.39	2	cam2
01303+1239	STF 129	9.8788	283.3	8.64	1	cam1new
01425+4813	BJN 27	8.8798	47.3	4.01	2	cam2
01443+6652	HAU 10	8.8334	100.8	9.10	1	cam2
01550+4611	BJN 9	8.9030	344.6:	14.52:	2	cam2
01553+4647	BJN 4	8.9261	169.2	7.27	1	cam2
02016+2405	STF 200	9.8789	124.4	7.98	1	cam1new
02076+1535	STF 214	9.8789	189.3	5.16	1	cam1new
02216+2338	STF 254	9.8789	14.7	11.82	1	cam1new
02405+5533	STI 1923	8.8799	255.9	12.33	1	cam2
02440+5903	STI 1930	8.7819	90.3	10.55	2	cam2
02529+1040	AG 56	9.8790	290.5	6.70	1	cam1new
03003+1432	AG 60	9.8790	160.0	6.33	1	cam1new
03040+2831	STF 339 AB, C	9.8790	328.7:	13.26:	2	cam1new
03040+7611	LDS 1562	8.9237	163.7	6.15	2	cam2
03093+6849	WFC 13	8.8799	287.9	7.81	1	cam2
03187+1527	LDS 9151	9.8790	61.6	8.58	1	cam1new
03201+3611	BVD 34	8.7819	62.7	15.33	1	cam2
03229+2949	STF 379	9.8790	102.2	10.21	1	cam1new
03345+1948	STF 414	9.8790	186.3	7.37	1	cam1new
03392+2757	STF 424	9.8790	314.4	9.88	1	cam1new
03431+2541	STF 435	9.8790	3.1	12.84	1	cam1new
03474+2440	STF 449	9.8790	330.5	6.79	1	cam1new
03495+1255	AG 74	9.8790	196.2	11.88	1	cam1new
03598+1133	STF 478 AB	9.8790	138.5	9.53	1	cam1new
04022+2808	STF 481 AC	9.8792	316.3	15.93	1	cam1new
04225+5043	BAZ 4	8.7682	357.4	9.14	2	cam2
04404+6830	HJ 1148	8.9265	321.0	8.94	1	cam2
04447+5610	STI 2067	8.7683	289.2	11.19	2	cam2
05039+3353	HU 1221 AB	8.7821	37.8	3.75	1	cam2
19503+2240	BU 361 AB	9.8021	347.3	3.78	1	cam1old
19537+2805	ES 494 AB	9.8064	198.0	3.78	5	cam1old
19542+1744	J 830	9.8021	194.3	3.40	2	cam1old
19595+4548	HJ 1463	8.7646	311.1	8.90	2	cam2
20000+1736	SMR 7	9.8021	265.1	4.00	2	cam1old
20102+1536	J 1874	9.8021	115.5	2.89	1	cam1old
20155+2437	POU 4315	8.8328	92.0	4.49	1	cam2
20209+1948	HJ 2954 AB	9.8021	303.3	2.97	1	cam1old
20308+1347	STF 2688	9.8895	175.4	7.60	2	cam1new
20366+1027	AG 258	9.8021	9.4	4.14	1	cam1old
20372+1250	A 1680	9.8021	296.2	3.83	2	cam1old
20396+2143	STF 2709	9.8895	297.2	9.86	2	cam1new
20405+1240	HEI 278	9.8022	134.7	3.42	1	cam1old
20418+1231	STF 2715	9.8895	3.0:	12.03:	2	cam1new
20419+1931	COU 226 AC	9.8895	337.7:	13.53:	2	cam1new
20427+2427	POU 4905	8.8328	92.4	9.18	1	cam2
20436+1944	STF 2722	9.8785	307.0	7.34	1	cam1new
20454+4816	UC 254	8.7646	182.2:	17.74:	1	cam2
20493+2026	HJ 926	9.8785	190.1	5.73	2	cam1new
20499+2711	HJ 1579	9.8022	129.6	3.84	1	cam1old
20519+3327	WSI 47 AC	8.8329	338.6:	10.92:	1	cam2
20541+1402	J 846	9.8022	155.4	3.65	1	cam1old
21046+2053	AG 269	9.8785	173.2:	8.16:	1	cam1new
21074+2429	STF 2761	9.8785	112.1	5.49	1	cam1new
21160+1600	HO 284	9.8022	87.0	3.84	2	cam1old

Table 1
(Continued)

WDS Designation α, δ (2000)	Discoverer Designation	Epoch 2000.+	θ (°)	ρ (″)	n	Detector
21230+2858	STF 2792 AB	9.8785	331.0	7.11	1	cam1new
21360+3319	HJ 1664	8.7484	83.2	9.22	2	cam2
21374+2340	HJ 1668	9.8785	36.5	8.02	1	cam1new
21391+2036	STT 444	9.8785	277.7:	7.97:	1	cam1new
21399+1427	AG 419	9.8022	222.5	3.64	2	cam1old
21420+1617	J 287	9.8022	347.9	2.95	1	cam1old
21561+2420	STT 454 AB	9.8785	277.9:	7.05:	1	cam1new
21567+1607	STT 455	9.8785	271.4	9.72	1	cam1new
22057+2954	HJ 1721	9.8785	266.0:	12.14:	1	cam1new
22060+2036	STF 2859	9.8022	343.8	3.74	1	cam1old
22207+2457	STF 2895 AB	9.8785	48.0	13.30	1	cam1new
22223+1105	STF 2898	9.8785	283.2	12.31	1	cam1new
22282+1716	STF 2908	9.8785	113.7	8.94	1	cam1new
22328+2625	HO 475 AB	9.8787	306.6	0.91	1	cam1new
22328+2625	HO 475 AC	9.8787	229.0	8.17	1	cam1new
22328+2625	HO 475 BC	9.8787	218.4	7.96	1	cam1new
22340+2945	HO 477	9.8787	166.1:	12.33:	1	cam1new
22346+2944	HJ 1785	9.8787	172.3	13.76	1	cam1new
22407+2959	STF 3134	9.8787	77.3	6.25	1	cam1new
22413+1311	STF 2931 AB	9.8787	149.1	4.38	1	cam1new
22493+2152	BRT 2508	9.8022	255.5	3.06	1	cam1old
22513+2914	HJ 1819 AB	9.8787	72.8:	14.30:	1	cam1new
22546+2020	BU 847	9.8787	36.8	6.70	1	cam1new
23171+2045	BRT 2512	9.8022	351.9	3.67	2	cam1old
23249+5430	ES 2728	8.7649	247.4	10.11	2	cam2
23279+1108	STF 3104	9.8787	278.0:	7.94:	1	cam1new
23314+1613	STF 3021 AB	9.8787	309.0	8.43	1	cam1new
23363+6202	STI 1190	8.8333	113.1:	10.98:	1	cam2
23397+7842	WSI 41	8.8333	110.5	11.90	1	cam2
23402+7843	WFC 243	8.8333	228.2	5.20	1	cam2
23425+1840	STT 504	9.8787	177.4:	7.55:	2	cam1new
23470+1615	J 300	9.8022	10.6	3.51	1	cam1old
23527+2920	AG 429	9.8787	269.5	6.19	1	cam1new
23539+1559	J 214	9.8022	112.4	3.33	1	cam1old
23565+5517	ES 701	8.8331	309.2	4.00	1	cam2
23581+2840	HJ 995	9.8787	126.7:	7.76:	1	cam1new

Notes.
Detector:
cam1old = primary speckle camera, original ICCD.
cam1new = primary speckle camera, new ICCD.
cam2 = secondary speckle camera.

(expressed as a fractional Besselian year), the position angle (in degrees), and the separation (in arcseconds). Note that the position angle has not been corrected for precession, and is thus based on the equinox for the epoch of observation. Objects whose measures are of lower quality are indicated by colons following the position angle and separation. These lower-quality observations may be due to one or more of the following factors: close separation, large Δm, one or both components being very faint, a large zenith distance, and poor seeing or transparency. The sixth column indicates the number of independent measurements contained in the mean, and the seventh column identifies the camera and detector used in the observation. The 101 mean positions in Table 1 range from 0.″91 to 17.″74, with a median separation of 7.″81.

Because a typical separation (ρ) versus Δm (Öpik style) plot is of limited value for distinguishing the false positives, Figure 1 provides a plot of separation versus the "total" magnitude (where this is the arithmetic magnitude sum, i.e., mag-A + mag-B). For non-detected systems, an "X" is plotted at the UCAC4

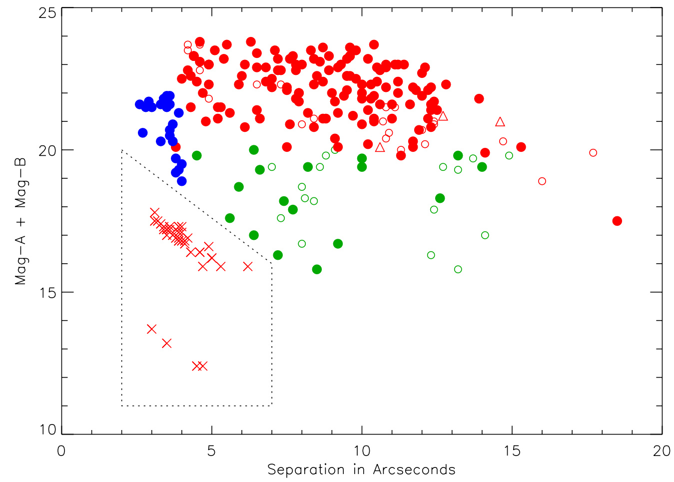

Figure 1. Separation (ρ) vs. arithmetic combined magnitude (mag-A+mag-B) for all observed pairs having UCAC photometry. The separations are measurements from Table 1 (plus non-WDS random pairs not tabulated there), while the magnitudes are UCAC values. Open circles ("ok") and triangles ("weak") are measurements that are adequate for confirmation only. These typically correspond to the larger Δm pairs, although a few are at small magnitude difference. These may indicate pairs that have a significantly different magnitude difference in the V band, as opposed to that of the "red lens," or those that were observed in substandard conditions (poor transparency and/or seeing). For non-detected systems, an "X" is plotted at the UCAC separation and combined magnitude. Objects observed with the secondary camera in 2008 are plotted in red while those observed with the primary camera are plotted in blue and green. Those in blue were done in early fall 2009 with the original NVSI 9540 Gen IIIc ICCD. Those in green were observed in late fall with the ICCD. The dashed region surrounds the area where there were no binary confirmations and all are presumed false positives.

separation and total magnitude. These are all clustered in the lower left of the figure. Those in red were observed with the secondary camera in 2008. Those in blue were observed with the primary camera and the original NVSI 9540 Gen IIIc ICCD. Those in green were observed with the primary camera and the new ICCD. Note that in addition to the known pairs from Table 1, Figure 1 also includes additional optical pairs that were observed for testing and evaluation of the UCAC reduction. These were determined to be merely random pairings of unrelated stars, so were not added to the WDS database in order to avoid further cluttering the double star database with irrelevant chance alignments.

As indicated above, although all pairs did not produce measured results of the same quality, all UCAC targets examined were verified as real, with the exception of the sample of bright, small ρ and Δm pairs. The presence of these non-real "double" stars in UCAC3 was among the reasons for the reduction modifications which led to UCAC4.

Multiple observations were obtained for several measured pairs in order to improve positional accuracy and to attempt different reduction methodologies (i.e., digitization parameters, different physical filters, or the software "notch" filter; see Germain & Douglass 2001).

2.4. Examples of Confirmed Pairs

Figure 2 illustrates a few examples of directed vector autocorrelations (DVA) of USNO speckle camera observation of UCAC doubles. The views are background-subtracted and rescaled images for three binary stars observed on December 3 as well as a triple observed on the night of October 31. The wider pair of the triple was detected in UCAC, while the close pair was previously unknown.

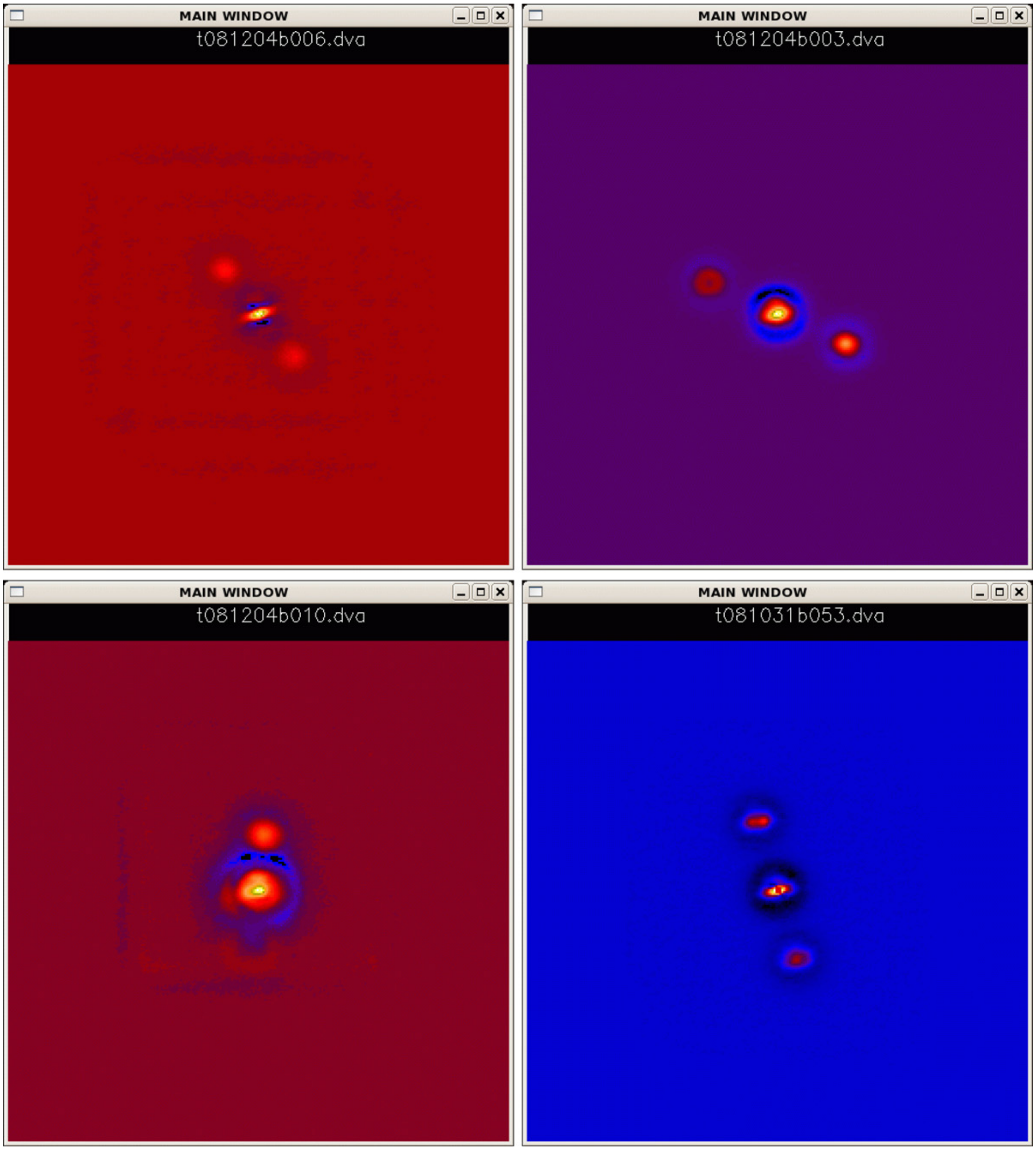

Figure 2. Surface plots of UCAC pairs confirmed with the USNO speckle camera and 26 inch telescope. The image at top left is U0044+635 ($\Delta m = 0.1$), top right is U0026+494 ($\Delta m = 0.9$), bottom left is U0153+731 ($\Delta m = 2.7$), and bottom right is a new triple, U0120+751 (wider pair $\Delta m = 0.2$). Magnitude differences are from UCAC4.

(A color version of this figure is available in the online journal.)

2.5. *Quadrant Assignment and Magnitude Differences*

Although the DVA (Bagnuolo et al. 1992) is unable to ascertain magnitude differences due to non-linearity effects (especially with an intensified CCD), it is quite useful for making crude estimates of magnitude difference. Figure 3 shows in profile the same images of the first three objects of Figure 2.

3. UCAC4 MEASURES OF KNOWN WDS PAIRS

Following the final checks of the UCAC4 catalog, an attempt was made to match it against the 120,000+ known double stars in the WDS catalog. Matches against all pairs are not possible, of course—some WDS pairs are too close to be resolved by UCAC, while others have components that are either too bright or too faint. Based on an earlier check of the WDS against the 2MASS Catalog (Wycoff et al. 2006), however, it was anticipated that approximately half the pairs could be matched.

Following an initial culling of obviously too-close, too-bright, and too-faint pairs, coordinate matches (to within a few arcseconds) were attempted. Matches were further refined based on magnitude and, occasionally, proper motion information; especially useful in this effort was a comparison of 2MASS magnitudes in the UCAC4 catalog with those of 2MASS matches in the WDS. This eventually yielded about 60,000 probable UCAC matches.

Unlike 2MASS, the UCAC catalog is composed of information from multiple catalogs (such as, for example, *Hipparcos* data used to supplement UCAC at the bright end);

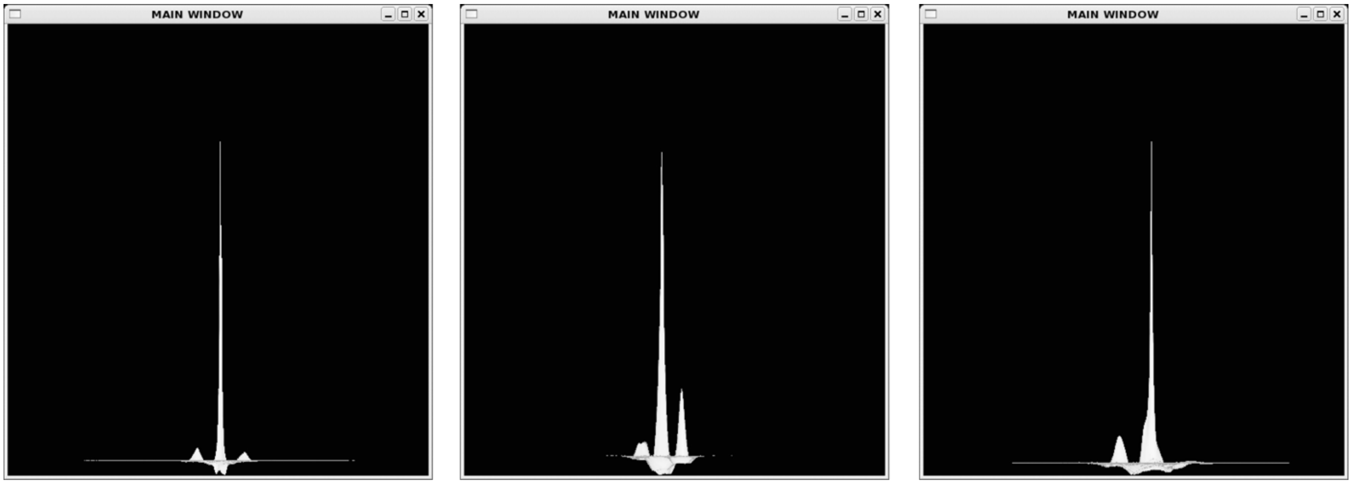

Figure 3. Profiles of UCAC4 pairs confirmed with the USNO speckle camera and 26 inch telescope. Images (left to right) include U0044+635 ($\Delta m = 0.1$), U0026+494 ($\Delta m = 0.9$), and U0153+731 ($\Delta m = 2.7$).

Table 2
Astrometry and Photometry of Known WDS Pairs

WDS Designation	Discoverer Designation	Date (BY)	θ (°)	σ_θ (°)	ρ ($''$)	σ_ρ ($''$)	Mag$_1$ (mag)	$\sigma_{\rm mag1}$ (mag)	Mag$_2$ (mag)	$\sigma_{\rm mag2}$ (mag)	Filter	Tel (m)	N	Source
00000+4004	ES 2543 AB	2002.648	253.2	0.1	4.523	0.038	12.16	0.05	12.16	0.13	R_u	0.2	4	UCAC4
00000+4004	ES 2543 AC	2002.648	66.2	0.2	14.389	0.033	12.16	0.05	14.18	0.13	R_u	0.2	4	UCAC4
00001+5400	ES 704	2003.597	116.0	0.5	4.494	0.056	10.66	0.01	10.65	0.04	R_u	0.2	10	UCAC4
00001−0122	CLZ 1	2000.567	347.4	...	5.986	...	12.24	0.09	15.46	...	R_u	0.2	1	UCAC4
00002−2519	COO 273	1999.557	10.7	0.1	8.463	0.007	11.12	0.41	11.12	0.41	R_u	0.2	4	UCAC4
00003+1642	HJ 318	2000.889	61.6	0.1	26.532	0.032	9.32	0.04	12.91	0.08	R_u	0.2	4	UCAC4
		2010.	...	...	...	...	10.535	0.030	13.457	0.020	B	0.2	1	APASS
		2010.	...	...	...	...	10.080	0.010	13.139	0.010	g'	0.2	1	APASS
		2010.	...	...	...	...	9.764	0.080	12.878	0.020	V	0.2	1	APASS
		2010.	...	...	...	...	9.531	0.060	12.773	0.050	r'	0.2	1	APASS
00003+5651	CTT 1	2003.607	92.5	0.3	46.550	0.135	8.92	0.05	11.38	0.04	R_u	0.2	4	UCAC4
		2010.	...	...	...	...	9.166	0.180	11.787	0.100	B	0.2	1	APASS
		2010.	...	...	...	...	9.693	0.200	11.592	0.030	g'	0.2	1	APASS
		2010.	...	...	...	...	8.977	0.070	11.465	0.060	V	0.2	1	APASS
		2010.	...	...	...	...	9.158	0.030	11.383	0.030	r'	0.2	1	APASS
		2010.	...	...	...	...	8.696	0.080	11.360	0.010	i'	0.2	1	APASS

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

the epoch-2000 coordinates in the final catalog may therefore be the means of data taken at multiple epochs. Such coordinates are therefore inappropriate for deriving astrometric measures. Fortunately the 404.8 million individual UCAC measures used to create the catalog are available.

Coordinate matches were made against this database to extract all individual sets of component coordinates. Relative astrometric measures were generated for pairs of coordinates from the same CCD frame then these measures were averaged into means. If the span of measures for a given pair exceeded 0.4 yr, measures were grouped into multiple means spanning shorter date ranges. Errors for θ and ρ were determined from rms scatter in individual measures comprising each mean, and adopted precisions of date, θ, ρ, were based on date ranges and these rms errors.

Although ideally all pairs of coordinates for a given measure should be taken from the same CCD frame, this becomes less feasible (and eventually impossible) for wider pairs. Following the extraction and meaning process described above, average numbers of measures per mean were plotted against separation. An obvious falloff was noted beginning at separations of about 30$''$.

A second attempt at generating measures was then made for ~3000 pairs with separations >30$''$ whose means were composed of two or fewer individual measures. In this attempt, coordinates were matched if their dates of observation were within 0.1 yr, even if they were extracted from different CCD frames. In this manner, measures could be generated even for pairs much wider than the angular size of the CCD used for the catalog.

A total of 62,319 mean measures for 58,525 WDS pairs are listed in Table 2. Columns in this table include WDS designation, discover designation and components, mean date (as fractional Besselian year), θ and its error in degrees, ρ and its error in arcseconds, UCAC magnitudes and their errors, a code for the filter used, the telescope aperture in meters, the number of measures combined into that mean, and finally the source of the measure. Specifications (including effective wavelength and FWHM, in nm) for this and other filters cited in this paper are given in Table 3.

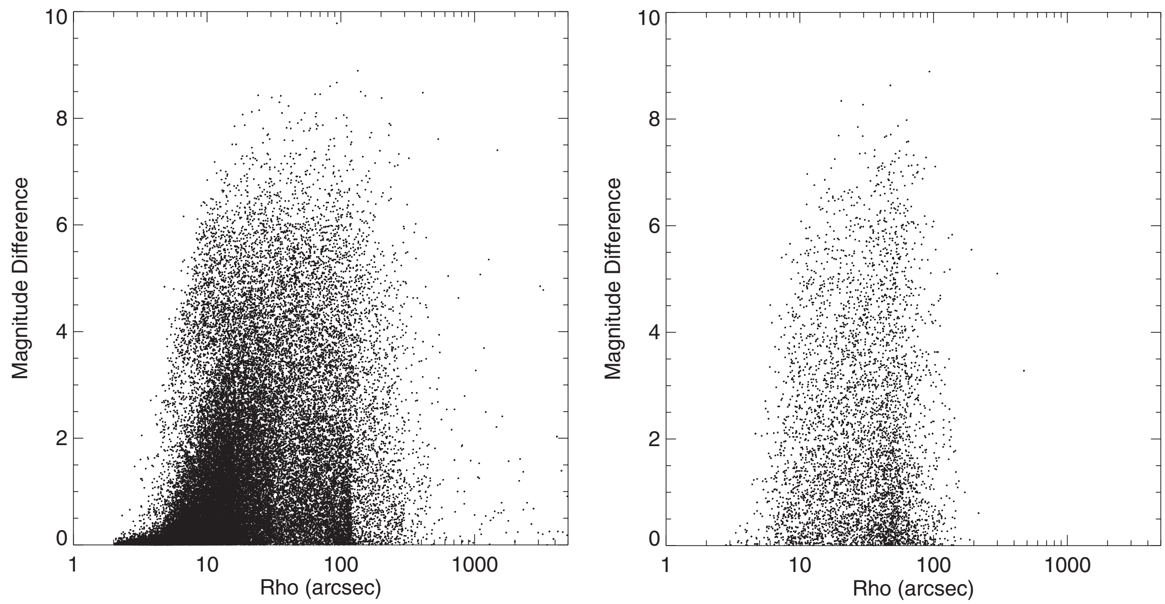

Figure 4. Distribution in separation and magnitude difference for UCAC4 matches to known WDS pairs (left) and new common proper motion candidates (right). The new pairs are discussed in Section 4 below.

Table 3
Filter Specifications

Catalog	Filter	λ_0 (nm)	FWHM (nm)
UCAC	R_u	609	70
APASS	Johnson B	440	98
	SDSS g'	477	280
	Johnson V	550	89
	SDSS r'	623	280
	SDSS i'	762	300
2MASS	J	1256	245
	H	1633	160
	K_s	2210	300
WFC	B_p	photo. blue	

Figure 4 (left) illustrates the distribution in separation and magnitude difference for those UCAC matches that included photometry for both components. There appears to be a sudden cutoff in number of pairs above a separation of about 2′. The two components of pairs this wide will definitely fall on well-separated CCD frames; a possible explanation for the drop in number of matches may be that the time difference between observations of such widely separated frames may be larger than the date difference allowed in the match routines. This would be especially likely for pairs separated in a north–south direction, given the declination-band observing scheduled used for the catalog. The effect is also somewhat exaggerated in appearance due to the semi-log plot in separation.

Five-color APASS photometry is given in Table 2 for pairs wider than 10″; this minimum separation was chosen due to the aperture method used in determining APASS magnitudes (A. Henden 2012, private communication). Negative values for magnitude errors indicate the star was observed on only one night for that magnitude; therefore, the error is purely Poisson rather than nightly scatter. The table includes a total of 69,612 photometric measurements for 19,741 pairs.

The fraction of the WDS matched against UCAC—50.2%—was much as expected. Additional matches will be attempted as new pairs are added to the WDS; undoubtedly matches will also eventually be made to some pairs that were not successful in this initial attempt, through improved catalog coordinates, better matching routines, etc.

As an example of continuing growth, an earlier USNO data mining effort (Wycoff et al. 2006) included 41,924 astrometric measures from the 2MASS Catalog (TMA), plus 72,294 measures from the 144 astrographic (WFC; $N = 66{,}973$) and transit circle (WFD; $N = 5321$) catalogs which comprise the Washington Fundamental Catalog. These catalogs, dating as far back as the late 1890s, were reduced to the International Celestial Reference System, then used in the generation of proper motions for the *Tycho-2* Catalog (Hog et al. 2000). Continuing efforts to extract measures as new pairs were discovered or positions were corrected have resulted in an additional 29,401 measures (WFC +9%; WFD +5%; TMA +54%). The growth from these sources is reflective of their respective magnitude limits and the increase in number of fainter pairs in the double star database (Mason et al. 2001).

4. NEW COMMON PROPER MOTION PAIRS FROM UCAC4

In the summer of 2012, intern D. Hsu mined the UCAC4 catalog for new possible common proper motion (CPM) pairs, under the direction of mentor N. Zacharias. Search criteria are described below.

First, the full catalog was cut to remove sources likely to be falsely matched, including

1. flagged extended sources,
2. flagged possible streak objects,
3. sources flagged as having poor/no proper motion solution,
4. sources having proper motions within 4σ of 0 mas yr^{-1},
5. sources having proper motions <50 mas yr^{-1},
6. sources having proper motion errors >20 mas yr^{-1}, and
7. sources within 15° of the galactic plane.

A modified set of criteria based on the work of Halbwachs (1986) in determining CPM pairs was then applied to the

Table 4
New Possible CPM Pairs from UCAC4

WDS Designation	Discoverer Designation	θ (°)	ρ ($''$)	V_1 (mag)	V_2 (mag)	PM_1 (mas yr^{-1})	PM_2 (mas yr^{-1})	R.A., Decl. (2000)
00001−2432	UC 301	283	47.0	10.5	13.0	−072 −055	−074 −054	00 00 05.16 −24 31 45.0
00003+0800	UC 302	131	51.5	8.3	14.4	+061 +000	+056 −004	00 00 15.93 +08 00 26.0
00006+4539	UC 303	311	52.2	13.1	15.9	+066 +010	+072 +010	00 00 33.92 +45 39 27.7
00013+0504	UC 304	54	15.4	12.1	13.5	−057 −028	−050 −026	00 01 18.85 +05 04 12.7
00014−2602	UC 305	196	39.5	14.9	16.4	+039 −055	+040 −051	00 01 25.52 −26 02 13.7
00022+3622	UC 306	79	46.2	11.7	15.5	+071 −004	+052 −023	00 02 11.10 +36 21 55.8
00024−3657	UC 307	223	76.4	10.1	14.7	+082 +005	+083 +003	00 02 24.90 −36 56 55.3
00030−5741	UC 308	250	8.8	13.6	15.7	+048 +062	+041 +060	00 03 00.62 −57 40 38.1
00035−0308	UC 309	326	43.5	15.0	16.4	+017 −052	+036 −036	00 03 27.38 −03 07 59.0
00042+3732	UC 310	15	31.2	13.2	14.1	+066 +020	+071 +006	00 04 10.88 +37 32 21.5

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

remaining objects. These criteria include

1. $\frac{\text{angular separation}}{\text{smaller proper motion of two components}} < 1000\,\text{yr}$,
2. total proper motion matches within 3σ,
3. proper motion components match within 4σ, and
4. proper motion direction matches within 45°.

A final cut was made to remove all pairs where one or both components were missing 2MASS identifiers after preliminary checks found that nearly all such pairs were false positives.

4.1. Initial Results

A total of 12,464 candidate pairs were found, out of which about 98.7% are expected to be physical systems (Halbwachs 1986). Binned data of proper motion components, magnitudes of primary and secondary component sources, angular separation, and magnitude difference between stellar components all showed distributions expected for the chosen search criteria.

This list was then cross-referenced against the WDS using a position-, magnitude-, and proper-motion-limited search. A total of 3098 matches were made with the candidate list, with 392 candidate pairs matching with multiple WDS entries.

Some 61 pairs were identified with separations larger than $3'$. The pair with the largest separation ($488''$) was the known Luyten (1975) double WDS 13470+0621 = LDS 3101. The second largest separation pair ($474''$) was the high-proper-motion pair WDS 02290−1959 = UC 744, whose primary is the subarcsecond binary RST 2280.

4.2. Additional Checks and Final Results

Further checks were later made against Hsu's initial results, including an additional comparison against the WDS (for pairs added to that database subsequent to his summer project, as well as any whose coordinates may have been updated). Coordinates of all potential new CPM pairs were plotted in order to identify possible grouping. Through this process, a substantial fraction of the pairs were determined to be probable members of clusters. This effort also aided in merging those pairs sharing common components into multiple systems. The final list of 4027 possible CPM doubles and multiples is given in Table 4. These comprise a total of 4758 pairs, albeit with some redundancy (e.g., AB, AC, and BC pairings may all be listed for some wide triples). Columns in Table 4 include WDS and discoverer designations, component, approximate position angle (in degrees) and separation (in arcseconds), and magnitudes of both components (APASS *V*-band magnitudes if available, otherwise UCAC magnitudes). Proper motions in R.A. and decl. are listed for both components, followed by precise epoch-2000 coordinates of the primary star.

Note that discoverer designations in Table 4 begin with UC 301. The first 300 CPM pairs discovered in the UCAC catalog were published by Caballero (2010). His pairs were found through an analysis of proper motions in the UCAC3 catalog; however, virtually all his astrometry was generated from 2MASS, due to the multiple epochs used in generating UCAC3 coordinates. New UCAC4 astrometry (included in Table 2) was determined for all of Caballero's pairs and supplants the few UCAC3 measures he published. APASS photometry for all pairs is also included in that table.

Further analysis determined that a few of the pairs were not CPM doubles, and one was a known pair. Notes to these systems are as follows.

1. 01041+4408 = UC 493: the A component is a close double, leading to a spurious proper motion (B. Skiff 2013, private communication).
2. 01044−4703 = UC 495: proper motion of the B component is effected by a nearby bright star (B. Skiff 2013, private communication). The AB and BC pairs were removed, but the AC pair retained.
3. 06406−3911 = UC 1467: this was determined to be the same pair as 06405−3921 LDS 170, following an update to the coordinates of the Luyten pair.
4. 11545+2154 = UC 2230: the proper motion of the E component was incorrect (B. Skiff 2013, private communication).

Figure 4 (right) illustrates the distribution in separation and magnitude difference for those UCAC matches which included photometry for both components. Few pairs were discovered at separations above $2'$, so the feature noticed in the left plot is not apparent.

As described in Section 3 above, individual observations were extracted from the main UCAC database and averaged; these mean measures (as well as APASS photometry) are given in Table 5, whose format is the same as Table 2. All components were also matched against the 2MASS catalog; Table 5 includes the resulting astrometry and *JHK* photometry.

Finally, all pairs were checked against the Washington Fundamental Catalog. Although most of the new CPM candidates fall below the magnitude limits of these databases, matches were made to 162 pairs; the 286 measures are given in Table 5. Nearly all of these measures resulted from observations made on blue-sensitive astrographic plates, denoted by the filter B_p.

Table 5
Astrometry and Photometry of New Possible CPM Pairs

WDS Designation	Discoverer Designation	Date (BY)	θ (°)	σ_θ (°)	ρ (″)	σ_ρ (″)	Mag$_1$ (mag)	$\sigma_{\rm mag1}$ (mag)	Mag$_2$ (mag)	$\sigma_{\rm mag2}$ (mag)	Filter	Tel (m)	N	Source/Reference
03539−5517	UC 1085	1998.789	114.3	0.5	26.147	0.224	10.86	0.03	14.07	0.09	$R_{\rm u}$	0.2	7	UCAC4
		1999.84	114.1	...	26.19	...	9.730	0.024	12.446	0.023	J	1.3	1	2MASS
		1999.84	...	...	...	...	9.389	0.025	11.905	0.025	H	1.3	1	2MASS
		1999.84	...	...	...	...	9.298	0.023	11.780	0.025	$K_{\rm s}$	1.3	1	2MASS
		2010.	...	...	...	...	11.745	0.030	15.404	0.060	B	0.2	1	APASS
		2010.	...	...	...	...	11.386	−0.010	14.956	0.040	g'	0.2	1	APASS
		2010.	...	...	...	...	11.013	0.040	14.394	0.060	V	0.2	1	APASS
		2010.	...	...	...	...	10.851	−0.010	13.963	0.060	r'	0.2	1	APASS
		2010.	...	...	...	...	10.623	0.040	13.649	0.050	i'	0.2	1	APASS
03546−2144	UC 1086	1920.03	125.5	...	44.310	...	...	...	...	...	$B_{\rm p}$	0.2	1	Urban et al. (1998)
		1920.79	125.9	...	45.121	...	...	...	...	...	$B_{\rm p}$	0.2	1	Urban et al. (1998)
		1921.98	126.0	...	44.534	...	...	...	...	...	$B_{\rm p}$	0.2	1	Urban et al. (1998)
		1969.17	125.6	...	44.623	...	...	...	...	...	$B_{\rm p}$	0.2	5	Zacharias et al. (1992)
		1998.94	125.6	...	44.59	...	9.103	0.041	9.382	0.027	J	1.3	1	2MASS
		1998.94	...	...	...	...	8.889	0.044	9.139	0.023	H	1.3	1	2MASS
		1998.94	...	...	...	...	8.847	0.024	9.076	0.023	$K_{\rm s}$	1.3	1	2MASS
		1999.76	125.8	0.1	44.594	0.009	10.10	0.03	10.34	0.03	$R_{\rm u}$	0.2	4	UCAC4
		2010.	...	...	...	...	10.461	0.030	10.757	0.030	B	0.2	1	APASS
		2010.	...	...	...	...	10.334	−0.010	10.543	−0.010	g'	0.2	1	APASS
		2010.	...	...	...	...	10.033	0.030	10.286	0.010	V	0.2	1	APASS
		2010.	...	...	...	...	9.974	−0.010	10.198	−0.010	r'	0.2	1	APASS
		2010.	...	...	...	...	9.799	0.010	10.088	0.030	i'	0.2	1	APASS
03551−1855	UC 1087	1998.94	252.4	...	10.27	...	11.093	0.023	13.499	0.029	J	1.3	1	2MASS
		1998.94	...	...	...	...	10.806	0.022	12.865	0.025	H	1.3	1	2MASS
		1998.94	...	...	...	...	10.738	0.019	12.644	0.032	$K_{\rm s}$	1.3	1	2MASS
		1999.803	253.3	...	10.203	...	12.28	0.08	16.35	...	$R_{\rm u}$	0.2	1	UCAC4

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Two observations made using transit telescopes are denoted by blanks in the filter column.

All 27,716 astrometric and photometric measures for these pairs have been added to the WDS database.

The catalogs used in this project represent the work of innumerable astronomers and technicians spanning well over 100 years, and we gratefully acknowledge their contributions to our field. Thanks to Sean Urban, Tom Corbin, and all those who made the catalogs of the WFC useful to a new generation, and who wrote much of the software used in extracting the double star measures quoted here. Thanks to the USNO Instrument Shop for building and maintaining the instruments used for both the UCAC and USNO speckle projects.

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