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Speckle Observations with PISCO in Calern (France): Orbits and Masses Determinations for 22 Visual Binaries

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ABSTRACT

This paper presents orbits and masses for 22 visual double stars, partly derived using their last observations made with the speckle camera PISCO. For 13 of them we have determined their first-time orbits. Masses were calculated from Hipparcos and Gaia parallaxes when available, and from dynamical parallaxes otherwise. They are compared with masses deduced from spectral types. Other physical and orbital properties are also considered.

Key words: *binaries: visual – binaries: orbits – fundamental parameters: masses – stars: individual WDS 01151+3416 (HU 803), WDS 01450+5707 (BU 453 AB), WDS 01570+3101 (A 819 AB), WDS 09349+0515 (A 2757), WDS 10131+2725 (STT 213 AB), WDS 10163+1744 (STT 215), WDS 10287+4558 (A 1993), WDS 11468+1500 (BU 602), WDS 12194+1744 (A 2059), WDS 12335+0901 (REU 1), WDS 14358+0015 (BU 941 AB), WDS 15002+2129 (HU 907), WDS 15075+5516 (HU 143 Aa,Ab), WDS 15186+2356 (COU 307), WDS 16468+0821 (A 2784 AB), WDS 16497+5816 (MLR 430), WDS 19389+3514 (HU 953), WDS 20198+4522 (STT 406), WDS 20216+2346 (STF 2672), WDS 20550+2805 (BU 367 AB), WDS 22025+2612 (A 307), WDS 23009+3522 (HU 991)*

1. Introduction

The orbits of visual binary stars are the fundamental tool for obtaining stellar masses, which are, in turn, the cornerstone for studies of stellar evolution. Knowing

the orbital elements of long period binaries, even in a preliminary way from short arcs of orbit or few measurements is also an important stimulus for monitoring the future behavior of their relative movements. This will allow us to refine the determination of the masses. It thus behooves us to keep adding to the various orbits and ephemerides catalogs maintained by International Astronomical Union (IAU) Commission G1 (Binary and Multiple Star Systems).

During the last years, we have been pursuing our efforts to continually monitor long period visual binary systems, as well as to compute the orbits of the measured stars, using the Pupil Interferometry Speckle camera and COronagraph (PISCO) on the 104-cm “Epsilon” (East) telescope, part of the Centre Pédagogique Planètes Univers (C2PU, Bendjoya *et al.* 2012) platform located at the Calern site of the Côte d’Azur Observatory (OCA, France). This paper continues the series opened in Scardia *et al.* (2019b). We present orbital elements and star masses derived therefrom, for the visual double stars WDS 01151+3416 (HU 803), WDS 01450+5707 (BU 453 AB), WDS 01570+3101 (A 819 AB), WDS 09349+0515 (A 2757), WDS 10131+2725 (STT 213 AB), WDS 10163+1744 (STT 215), WDS 10287+4558 (A 1993), WDS 11468+1500 (BU 602), WDS 12194+1744 (A 2059), WDS 12335+0901 (REU 1), WDS 14358+0015 (BU 941 AB), WDS 15002+2129 (HU 907), WDS 15075+5516 (HU 143 Aa,Ab), WDS 15186+2356 (COU 307), WDS 16468+0821 (A 2784 AB), WDS 16497+5816 (MLR 430), WDS 19389+3514 (HU 953), WDS 20198+4522 (STT 406), WDS 20216+2346 (STF 2672), WDS 20550+2805 (BU 367 AB), WDS 22025+2612 (A 307), WDS 23009+3522 (HU 991). They have been observed for almost a century, except for COU 307 and MLR 430, which were the more recently discovered (about 50 years ago). Most of the available measurements are visual, although all pairs have been observed by speckle interferometry or electronic imaging in recent years. In this work we have used as the last measurement the one made by PISCO at the Calern observatory in order to obtain the orbit solution.

2. Methods

Twelve orbits, marked by “L” (Ling *et al.* 2017abc, 2018, 2019abc) in Section 4, were calculated using Docobo’s (1985, 2012) analytical method, dynamical parallaxes using the Baize-Romani (1946) method, and total masses using Hipparcos parallax (van Leeuwen 2007ab) or Gaia parallax (EDR3 Gaia Collaboration 2021, DR2 Gaia Collaboration 2018) when available, or dynamical parallaxes otherwise. In Docobo’s method, from the set of Keplerian orbits whose corresponding apparent orbits pass through three base points (θ_i, ρ_i, t_i) ($i = 1, 2, 3$), the solution is chosen according to several selection criteria: minimal root mean squared (*rms*) residuals of the $O - C$ residuals from all of the weighted observations, matching dynamical and trigonometric (Gaia or Hipparcos) parallaxes, and/or the agreement between the calculated masses and those that correspond to the spectral types. Then, with all these quality controls, the interval of most probable orbits is delimit-

ited by the algorithm and the standard errors of each orbital element are deduced.

For the other ten orbits marked by “S” (Scardia *et al.* 2003, 2008ab, 2017ab, 2018, 2019a) in Section 4, we first computed the preliminary orbital elements with the analytical method of Kowalsky (1873). We then used them as initial values for the least-squares method of Hellerich (1925). When convergence was achieved, Hellerich’s method led to an improvement of the orbital elements (with the exception of the semi-major axis) and to an estimation of the corresponding errors. The final value of the semi-major axis was then set to the value that minimized the residuals in separation of Hellerich’s solution. For each double star the sum of the masses is calculated using the trigonometric parallax values, when available, measured by the astrometric satellites Gaia and Hipparcos, and the period and semi-major axis calculated in our orbital determination. To evaluate the astrophysical accuracy of our new orbit, the sum of the masses calculated by us (taking into account the spectral type and the luminosity class of the binary star as listed in the WDS) is compared with the values derived from the evolutionary tracks published in Table VI of Straizys and Kuriliene (1981).

In both cases, the magnitudes and spectral types from the “Washington Double Star Catalog”* (hereafter WDS catalog) have been used. Furthermore, since all the stars belong to our close solar neighborhood, the galactic interstellar absorption correction has been considered negligible and has not been taken into account in our calculations.

3. Results

The orbital elements calculated for the 22 binaries are listed in Table 1. It contains 10 columns: the WDS number of each pair (Col. 1), its discoverer’s designation (Name, Col. 2), the orbital elements (Cols. 3–9), the precession correction used to refer position angles to the 2000.0 equinox (Col. 10). On the second line there are the estimated standard errors, and the date of the last observation made by the PISCO group used in the solution obtained.

As they concern visual binaries, the periods are relatively long, ranging from 15 yr for REU1 to about 2100 yr for A1993. Only a third of the stars have a high eccentricity (greater than 0.8), the highest eccentricity belongs to STT 213 AB (0.958) and COU 307 (0.955). They are well distributed in a $e - \log P$ diagram, as shown in Fig. 1 (left panel). The semi-major axes vary between $0''.258$ to $2''.069$, although the set of angular separations available to calculate the orbits range between $0''.13$ close to the diffraction limit for the “Epsilon” telescope (MLR 430) and $1''.51$ (STT 215). There are eight stars with $i > 90^\circ$, so their orbital motion is in the opposite sense than the others.

Table 2 shows astrometric measurements made in 2016–2022 with the PISCO speckle camera at Calern Observatory and the residuals with the orbit calculated in this work and with the previous orbit if applicable. For each object, we report

*<http://www.astro.gsu.edu/wds>

Table 1
Orbital elements

WDS	Name	P [yr] σ_P	T[yr] σ_T	e σ_e	a ["] σ_a	i [°] σ_i	Ω [°] σ_Ω	ω [°] σ_ω	Precession [°] Last observation
01151+3416	HU 803	360.3 ± 11.5	2130.12 ± 10.7	0.465 ± 0.029	0.799 ± 0.014	66.5 ± 1.3	49.3 ± 0.2	297.7 ± 3.3	0.0022 2021.893
01450+5707	BU 453 AB	576.43 ± 166.14	1953.80 ± 0.43	0.657 ± 0.071	1.098 ± 0.086	31.4 ± 4.2	18.6 ± 9.1	332.7 ± 9.0	0.0045 2020.634
01570+3101	A 819 AB	138.6 ± 3.7	2010.80 ± 0.41	0.546 ± 0.006	0.421 ± 0.026	48.8 ± 2.3	154.1 ± 1.5	186.8 ± 2.3	0.0032 2020.675
09349+0515	A 2757	254.3 ± 33.5	2069.48 ± 11.2	0.176 ± 0.151	0.324 ± 0.044	133.0 ± 11.0	56.6 ± 0.5	101.0 ± 6.3	0.0033 2022.273
10131+2725	STT 213 AB	206.2 –	1939.52 –	0.958 –	0.924 –	126.8 –	59.0 –	111.1 –	0.0028 2022.181
10163+1744	STT 215	702.4 –	1826.63 –	0.707 –	1.035 –	180.0 –	90.6 –	116.5 –	0.0025 2022.060
10287+4558	A 1993	2137. –	1991. –	0.822 –	2.046 –	52.6 –	124.3 –	29.1 –	0.0031 2022.060
11468+1500	BU 602	603.5 ± 60.5	2158.05 ± 27.0	0.757 ± 0.064	0.904 ± 0.119	72.3 ± 4.3	170.6 ± 0.8	84.2 ± 2.0	0.0033 2022.282
12194+1744	A 2059	253.0 ± 1.0	2046.32 ± 0.13	0.600 ± 0.004	0.590 ± 0.004	51.2 ± 0.3	63.7 ± 0.9	79.3 ± 0.5	–0.0005 2020.294
12335+0901	REU 1	15.811 ± 0.007	2008.12 ± 0.04	0.301 ± 0.002	0.910 ± 0.069	102.8 ± 0.2	143.2 ± 0.3	347.7 ± 1.1	–0.0008 2022.386
14358+0015	BU 941 AB	525.7 –	2007.69 –	0.787 –	0.640 –	138.3 –	115.6 –	57.1 –	–0.0035 2022.277
15002+2129	HU 907	173.2 ± 16.8	2038.66 ± 4.94	0.474 ± 0.124	0.259 ± 0.027	47.1 ± 8.2	146.5 ± 4.7	238.8 ± 10.4	–0.0043 2022.282
15075+5516	HU 143 Aa,Ab	246.4 ± 40.6	2003.36 ± 5.32	0.374 ± 0.045	0.652 ± 0.029	72.6 ± 0.9	140.5 ± 8.0	123.6 ± 24.9	–0.0072 2021.523
15186+2356	COU 307	147.2 –	1964.83 –	0.955 –	0.768 –	104.7 –	97.9 –	277.2 –	–0.0047 2022.060
16468+0821	A 2784 AB	400.1 –	1895.6 –	0.120 –	0.407 –	44.0 –	139.7 –	276.6 –	–0.0054 2020.387
16497+5816	MLR 430	127.8 –	2022.40 –	0.677 –	0.258 –	54.0 –	162.8 –	258.8 –	–0.0102 2022.060
19389+3514	HU 953	780.5 ± 268.0	2000.36 ± 0.42	0.830 ± 0.055	1.198 ± 0.248	26.5 ± 3.8	58.9 ± 16.3	263.5 ± 19.0	–0.0062 2017.608
20198+4522	STT 406	112.16 ± 0.76	1915.57 ± 0.47	0.855 ± 0.019	0.300 ± 0.019	141.2 ± 6.4	124.0 ± 6.9	184.4 ± 8.6	–0.0065 2021.551
20216+2346	STF 2672	764.0 ± 50.4	2121.6 ± 40.18	0.436 ± 0.083	0.898 ± 0.027	41.4 ± 1.7	40.6 ± 33.2	41.0 ± 25.0	–0.0050 2018.728
20550+2805	BU 367 AB	104.0 ± 0.2	1934.61 ± 0.33	0.277 ± 0.002	0.410 ± 0.024	68.2 ± 0.4	119.9 ± 0.5	185.8 ± 1.4	–0.0046 2021.573
22025+2612	A 307	1647. –	1916.7 –	0.539 –	2.069 –	104.1 –	169.2 –	4.1 –	–0.0031 2022.060
23009+3522	HU 991	631.8 –	1976.85 –	0.829 –	1.425 –	44.8 –	124.0 –	48.4 –	–0.0018 2021.693

Table 2

PISCO measurements at Calern and residuals

WDS Name	Julian epoch	Fil	Eyep. [mm]	ρ ["]	σ_ρ ["]	θ [°]	σ_θ [°]	$\Delta\rho_{(O-C)}$ ["]		$\Delta\theta_{(O-C)}$ [°]		Ref.
								this work		previous orbit		
01151+3416 HU 803	2016.702	R	20	0.912	0.006	214.9	0.4	-0.001	0.0	-0.002	-0.1	Cir 195
	2021.879	R	24	0.906	0.008	217.9	0.4	-0.011	1.5	-0.013	1.5	
	2021.893	R	24	0.905	0.008	217.7	0.3	-0.012	1.3	-0.014	1.3	
01450+5707 BU 453 AB	2017.041	R	20	0.799	0.005	112.2	0.3	0.011	0.9	0.061	-4.3	Sle1984
	2017.047	R	20	0.800	0.005	112.5	0.3	0.012	1.2	0.062	-4.0	
	2020.631	R	24	0.821	0.008	115.2	0.7	0.004	1.2	0.063	-4.8	
	2020.634	R	24	0.819	0.009	115.4	0.4	0.002	1.4	0.061	-4.6	
01570+3101 A 819AB	2017.833	R	15	0.179	0.003	38.3	0.6	0.011	2.5	-0.077	35.4	Hrt2009
	2018.816	R	15	0.191	0.002	43.7	0.8	0.021	-0.8	-0.067	37.1	
	2020.675	V	15	0.190	0.003	59.1	0.5	0.011	-1.1	-0.070	45.7	
09349+0515 A 2757	2017.146	R	20	0.312	0.005	51.9	1.2	-0.005	-0.2	0.002	-1.1	Cir 192
	2022.273	R	15	0.302	0.003	46.6	1.5	-0.004	-0.2	0.005	-0.9	
10131+2725 STT 213 AB	2016.133	R	20	1.130	0.006	121.3	0.3	0.011	0.1	0.053	0.8	Cir 166
	2019.158	R	24	1.130	0.009	121.0	0.3	-0.004	0.4	0.042	1.2	
	2019.273	R	24	1.142	0.007	121.3	0.3	0.008	0.7	0.053	1.5	
	2022.181	R	24	1.144	0.006	120.8	0.3	-0.003	0.8	0.045	1.6	
10163+1744 STT 215	2018.224	R	24	1.510	0.006	176.0	0.3	0.010	-0.3	-0.063	-2.0	Zae1984
	2020.136	R	24	1.487	0.005	175.6	0.3	-0.020	-0.4	-0.095	-2.1	
	2022.060	R	24	1.502	0.005	175.6	0.3	0.011	0.0	-0.088	-1.8	
10287+4558 A 1993	2017.266	R	15	0.299	0.003	220.9	0.7	0.001	1.0			Izm2019
	2022.074	R	24	0.339	0.008	233.3	1.3	0.009	1.4			
11468+1500 BU 602	2016.338	R	20	0.536	0.007	307.8	0.5	0.006	0.8	0.006	0.8	Cir 197
	2022.282	R	24	0.556	0.005	129.6	0.3	0.020	0.5	0.020	0.6	
12194+1744 A 2059	2016.338	R	20	0.453	0.004	219.4	1.6	0.003	-0.2	0.007	-1.2	Cir 191
	2020.294	R	15	0.413	0.003	46.8	0.3	-0.017	2.1	-0.010	1.4	
12335+0901 REU 1	2017.269	W	24	1.155	0.021	320.9	0.3	-0.007	-1.4	-0.005	-0.9	TrC1999
	2019.344	W	24	0.879	0.005	314.0	0.3	0.003	-0.7	0.065	0.9	
	2019.363	W	24	0.859	0.005	314.2	0.3	-0.012	-0.4	0.050	1.2	
	2019.421	W	24	0.859	0.005	313.4	0.3	0.001	-0.9	0.065	0.8	
	2022.380	W	15	0.246	0.005	181.9	1.5	0.002	-1.0	-0.107	14.6	
	2022.386	W	15	0.241	0.004	182.9	1.4	-0.004	0.4	-0.114	15.8	
14358+0015 BU 941 AB	2017.419	R	15	0.173	0.003	341.5	0.3	0.009	1.9			
	2017.419	V	15	0.163	0.003	342.6	1.4	-0.001	3.0			
	2019.418	V	15	0.173	0.003	332.9	0.3	-0.015	1.7			
	2022.277	V	15	0.184	0.003	319.5	0.3	-0.038	-2.9			
	2022.388	W	15	0.187	0.003	320.0	0.8	-0.037	-2.1			
15002+2129 HU 907	2019.421	R	15	0.182	0.003	303.5	0.7	-0.006	2.0			
	2022.282	V	15	0.175	0.003	312.7	0.5	-0.076	4.2			
15075+5516 HU 143 Aa,Ab	2016.491	R	20	0.430	0.006	316.0	0.3	0.000	0.6	0.000	0.6	Cir 197
	2021.523	R	24	0.492	0.015	320.9	0.3	0.026	0.3	0.036	0.4	
15186+2356 COU 307	2017.518	R	24	0.352	0.007	354.3	0.8	-0.017	-1.5	-0.010	-1.3	Cir 193
	2017.608	R	24	0.362	0.007	354.9	1.9	-0.007	-0.8	0.000	-0.6	
	2021.526	W	24	0.350	0.005	351.9	1.2	-0.030	-0.8	-0.018	0.2	
16468+0821 A 2784 AB	2016.387	R	20	0.388	0.004	168.5	0.5	0.001	-0.1			
	2017.482	R	24	0.395	0.007	170.0	0.8	0.009	0.6			
	2020.387	R	24	0.378	0.007	171.1	0.6	-0.005	-0.4			
16497+5816 MLR 430	2016.387	R	10	-	-	-	-	(0.135)	(339.2)			
	2016.387	V	10	0.135	0.006	161.6	1.5	0.004	2.6			
19389+3514 HU 953	2017.510	R	24	0.372	0.005	55.9	2.0	-0.017	0.3	-0.024	0.8	Cir 193
	2017.608	R	24	0.389	0.005	56.9	1.0	-0.002	1.1	-0.017	0.5	
20198+4522 STT 406	2017.679	R	15	0.229	0.003	89.1	0.3	-0.006	-0.8	-0.059	-6.8	Hei1976
	2021.551	V	15	0.184	0.003	76.7	0.3	0.022	-1.4	-0.021	-11.5	
20216+2346 STF 2672	2016.855	R	20	0.648	0.009	350.1	0.6	0.000	0.6			
	2018.728	R	24	0.656	0.006	352.5	0.3	0.010	1.9			
20550+2805 BU 367 AB	2021.570	V	15	0.157	0.003	222.1	1.5	0.012	-1.8	-0.027	-36.5	Cir 151
	2021.573	V	15	0.158	0.003	224.7	1.6	0.013	0.7	-0.026	-34.0	
22025+2612 A 307	2016.675	R	20	0.401	0.004	125.3	0.8	-0.031	-0.8	-0.005	0.0	Cir 198
	2020.768	R	24	0.375	0.005	120.5	0.7	-0.035	-1.1	-0.013	-0.3	
23009+3522 HU 991	2017.507	R	24	0.986	0.005	303.4	0.3	0.026	0.4	0.194	-42.2	Baz1985
	2017.611	R	24	0.991	0.005	303.1	0.3	0.030	0.0	0.198	-42.5	
	2020.637	R	24	1.046	0.008	305.0	0.3	0.036	0.5	0.219	-42.9	
	2021.693	R	24	1.058	0.005	305.6	0.3	0.032	0.6	0.220	-43.1	

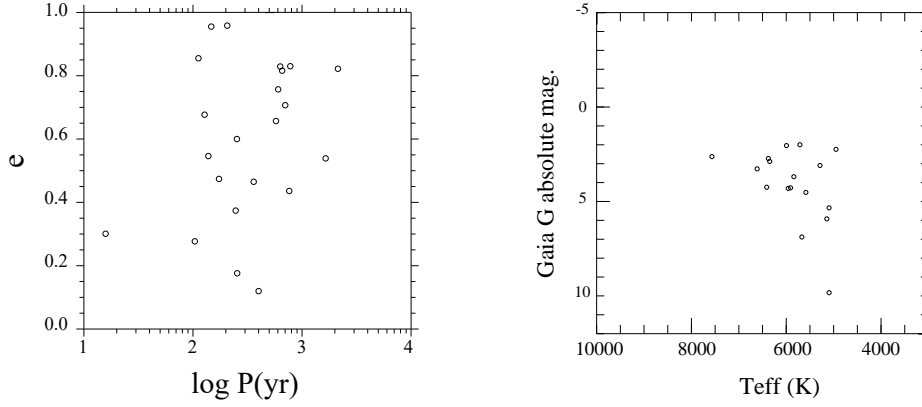


Fig. 1. $e - \log P$ diagram (*left panel*). H-R diagram for the main components of the binaries (*right panel*).

in Col. 1 its WDS name (first line) and the official double star designation (second line, sequence is discoverer-number). For each observation, we then give the date in Julian epoch (Col. 2), the filter (Col. 3), the focal length of the eyepiece used for magnifying the image (Col. 4), the angular separation ρ (Col. 5) with its error (Col. 6), and the position angle θ (Col. 7) with its error (Col. 8). In Cols. 9 and 10 the $O - C$ residuals of the ρ and θ measurements are displayed for the orbit obtained in this work, and for the previous orbit if it exists with its reference (IAUDS Circular number or other authors using the bibliographic style of the “Sixth Catalog of Orbits of Visual Binary Stars”[†] (hereafter OC6 catalog) in columns 11–13.

Table 3

Measurements for mean epoch J2016 obtained from Gaia EDR3, and their residuals

WDS	Name	ρ [$''$]	θ [$^\circ$]	$\Delta\rho_{(O-C)}$ [$''$]		$\Delta\theta_{(O-C)}$ [$^\circ$]		Ref.
				this work	previous orbit	this work	previous orbit	
01151+3416	HU 803	0.920	215.2	0.008	0.4	0.007	0.4	Cir 195
01450+5707	BU 453 AB	0.797	110.8	0.016	0.3	0.065	-4.7	Sle1984
10131+2725	STT 213 AB	1.135	121.8	0.017	0.3	0.058	1.1	Cir 166
10163+1744	STT 215	1.488	176.2	-0.004	-0.5	-0.075 0.016	-2.1 0.1	Zae1984 Izm2019
12335+0901	REU 1	1.149	325.3	-0.008	-0.7	-0.033	-0.4	TrC1999
15075+5516	HU143AaAb	0.399	314.7	-0.026	-1.2	-0.027	-1.2	Cir 197
15186+2356	COU 307	0.340	355.7	-0.024	-1.3	-0.020	-1.4	Cir 197
20216+2346	STF 2672	0.655	348.5	0.060	-0.5			
23009+3522	HU 991	0.970	302.7	0.034	0.4	0.196	-41.7	Baz1985

[†]<http://http://www.astro.gsu.edu/wds/orb6.html>

Table 4
Stellar data

Star		WDS			Hipparcos	Gaia		
WDS	Name	m _A	m _B	Spectral type	Trig. Parallax [mas]	Trig. parallax [mas]	G-band [mag]	T _{eff} [K]
01151+3416	HU 803	9.12	10.02	G0 V	9.65 ± 1.28	{ (A) 12.0662 ± 0.0413 (B) 12.0206 ± 0.0379	{ (A) 8.918 (B) 9.982	5958.33
01450+5707	BU 453 AB	10.04	10.45	G5	9.83 ± 2.73	{ (A) 13.3707 ± 0.0418 (B) 13.7181 ± 0.1019	{ (A) 9.700 (B) 10.00	5095.63
01570+3101	A 819 AB	8.16	9.30	F5	11.62 ± 1.01	13.0400 ± 0.4756	7.615	6377.47
09349+0515	A 2757	9.42	10.11	K0	5.50 ± 1.73	...	8.538	4949.13
10131+2725	STT 213 AB	8.62	9.83	G5V	13.93 ± 1.22	14.7306 ± 0.0280	8.438	5908.67
10163+1744	STT 215	7.25	7.46	A9IV	8.73 ± 0.65	{ (A) 9.5146 ± 0.0355 (B) 9.4770 ± 0.0695	{ (A) 7.126 (B) 7.397	{ (A) 5711 (B) 5163.2
10287+4558	A 1993	9.25	10.22	G0	9.56 ± 1.13	16.8151 ± 1.2713 (DR2)	8.652	6411.09
11468+1500	BU 602	8.07	9.89	A5	7.12 ± 1.07	9.1119 ± 0.1815	7.823	7567.33
12194+1744	A 2059	8.33	10.22	F5	12.93 ± 1.10	11.2966 ± 0.0699	7.990	6613
12335+0901	REU 1	12.6	12.6	M5.5V	...	223.4774 ± 0.4664	11.240	...
14358+0015	BU 941 AB	9.44	9.57	F8	7.00 ± 1.33	3.3084 ± 1.2873 (DR2)	8.492	5994.68
15002+2129	HU 907	10.19	10.20	G0	6.30 ± 1.42	...	15.831	5095.63
15075+5516	HU 143 Aa,Ab	9.6	9.9	G5	...	...	8.833	5748.75
15186+2356	COU 307	9.5	9.6	G0	...	25.6882 ± 1.2198 (DR2)	9.831	5670
16468+0821	A 2784 AB	9.8	11.0	G0	...	...	...	...
16497+5816	MLR 430	10.2	10.5	F5	...	8.6192 ± 0.4288	9.313	5585.80
19389+3514	HU 953	8.8	9.2	G0	...	...	8.169	6191.81
20198+4522	STT 406	7.25	8.74	F5IV	10.81 ± 0.54	26.7756 ± 1.1855 (DR2)	6.869	6347.97
20216+2346	STF 2672	9.34	9.60	F8	...	{ (A) 6.5871 ± 0.1483 (B) 5.2421 ± 0.1940	{ (A) 9.231 (B) 9.455	5286.90
20550+2805	BU 367 AB	8.31	9.00	G1V	16.10 ± 1.13	...	7.655	5839.26
22025+2612	A 307	9.70	9.76	G	...	...	8.795	5876
23009+3522	HU 991	10.23	11.17	K2	17.01 ± 1.87	16.6737 ± 0.0302	{ (A) 9.809 (B) 10.530	{ (A) 5143.45 (B) 5095.63

To compare with the PISCO measurements, Table 3 includes those pairs for which it is possible to obtain the relative positions for mean epoch J2016, from the Gaia EDR3 recent data. The residuals with the corresponding orbits are also shown.

In Table 4 we report stellar data: the WDS number and name of each star (Cols. 1–2), WDS magnitudes (Cols. 3–4) and WDS spectral type (Col. 5). Columns 6 and 7 show the trigonometric parallaxes (with their standard errors) from Hipparcos or Gaia EDR3 (except if DR2 is indicated) if available. For information purposes columns 8 and 9 list the *G*-band mean magnitude and the stellar effective temperature, published in Gaia DR2. When disaggregated data exist, these are preceded by the letters A (primary component) and B (secondary component).

The range of visual magnitudes, between 7.2 and 12.6, and the values of the difference of magnitude that never exceed 1.9 (A 2059), make these stars very accessible for observation with the PISCO instrument. Almost all of them belong to the main sequence, half are solar type stars, there are two early type stars (STT 215 and BU 602), and three late type stars (A 2757, REU 1 and HU 991). Trigonometric parallax data have been found either provided by Hipparcos or by Gaia, except for four stars (HU 143 Aa,Ab, A2784 AB, HU 953 and A 307). We also retrieved the corresponding galactic absorption of those objects and found that the largest value was 0.528 mag for MLR 430 which validated the assumption that galactic absorption could be neglected in the previous calculations. Using the weighted averages of the Hipparcos and Gaia parallaxes values and their errors we have been able to compute the location of the main components in the Hertzsprung–Russell diagram (see Fig. 1, right panel). Fig. 1 shows that the main components of those 22 objects are mainly located in the lower left part of this diagram.

Table 5 contains the mean values of dynamic parameters of these stars calculated using the orbital periods and semi-major axis obtained in this work. Columns 1 and 2 are the WDS number and name of each star. Column 3 lists the dynamical parallaxes, column 4 the linear semi-major axis, column 5 the total mass, and columns 6 and 7 the absolute magnitudes for each component.

According to the dynamic parallaxes obtained, the distances of the stars are between 5.2 pc and 181.8 pc (191.5 mas and 5.5 mas) within our solar neighborhood. In general, the total dynamic sum of the masses and the derived absolute magnitudes fits acceptably to the corresponding spectral types listed in Table 4, except for A 2757, COU 307, A2784 AB and MLR 430 (see individual comments in Section 4).

As shown in Fig. 2, there is a very good agreement between the trigonometric parallaxes measured with the Hipparcos or the Gaia missions (see Table 4) and the dynamical parallax values that we derived from our calculations (see Table 5).

Table 6 displays statistics of the *O* – *C* residuals for each pair. Columns 1 and 2 are the WDS number and name of each star, followed by the *rms* residuals and mean absolute (*ma*) residuals of the position angles and angular separations

Table 5
Dynamical parameters

WDS	Name	Parallax [mas]	a [au]	Mass sum [M_{\odot}]	M_A [mag]	M_B [mag]
01151+3416	HU 803	12.6	63.41	1.96	4.62	5.52
01450+5707	BU 453	13.8	79.57	1.55	5.74	6.15
01570+3101	A819	11.9	35.38	2.47	3.54	4.68
09349+0515	A 2757	5.5	58.91	4.26	3.12	3.81
10131+2725	STT 213 AB	23.2	39.83	1.53	5.45	6.66
10163+1744	STT 215	9	115.00	4.19	2.02	2.23
10287+4558	A 1993	9.5	215.37	2.14	4.14	5.11
11468+1500	BU 602	9.1	99.34	2.42	2.87	4.69
12194+1744	A 2059	11.3	52.21	2.23	3.60	5.49
12335+0901	REU1	191.5	4.75	0.27	14.01	14.01
14358+0015	BU 941 AB	7.2	88.89	2.67	3.73	3.86
15002+2129	HU 907	6.3	41.11	2.32	4.19	4.20
15075+5516	HU 143 AaAb	13.5	48.30	1.87	5.25	5.55
15186+2356	COU307	25.2	30.48	1.23	6.51	6.61
16468+0821	A 2784 AB	5.7	71.40	2.48	3.58	4.78
16497+5816	MLR 430	8.1	31.85	1.95	4.74	5.04
19389+3514	HU 953	10.6	113.02	2.36	3.93	4.33
20198+4522	STT406	9.4	31.91	3.54	2.12	3.61
20216+2346	STF2672	7.9	113.67	2.52	3.83	4.09
20550+2805	BU 367 AB	14.3	28.67	2.30	4.09	4.78
22025+2612	A307	12.1	170.99	1.84	5.11	5.17
23009+3522	HU 991	16.5	86.36	1.66	6.32	7.26

of the observations used in the present work (Cols. 3–6). Weighted averages were calculated using the scheme described in Ling (2004) or in Scardia *et al.* (2008b) depending on the method used for the orbit calculation, mentioned in Section 2.

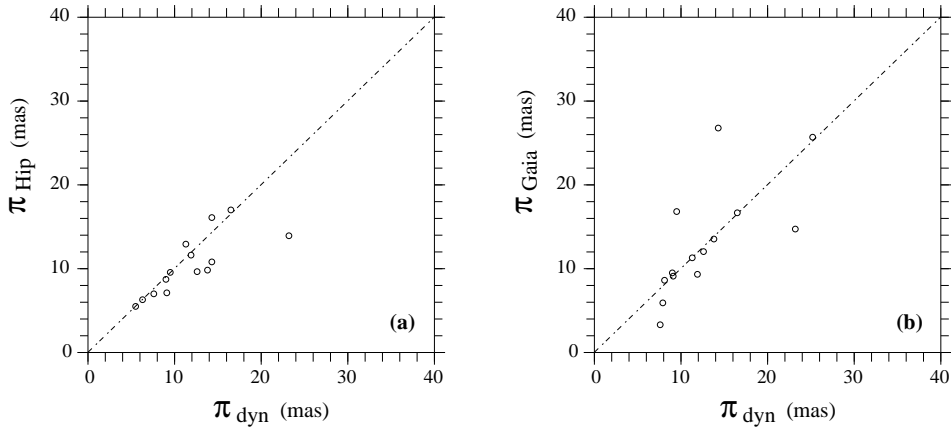


Fig. 2. Dynamical parallax vs. Hipparcos parallax (a), Dynamical parallax vs. Gaia parallax (b).

Table 6
Statistics of the $O - C$ residuals

Star		<i>rms</i>		<i>ma</i>	
WDS	Name	$\Delta\theta$ [°]	$\Delta\rho$ ["]	$\Delta\theta$ [°]	$\Delta\rho$ ["]
01151+3416	HU 803	1.6	0.025	0.9	0.017
01450+5707	BU 453 AB	1.9	0.046	1.4	0.034
01570+3101	A 819 AB	1.6	0.037	1.1	0.021
09349+0515	A 2757	4.6	0.032	2.9	0.019
10131+2725	STT 213 AB	2.5	0.063	1.9	0.046
10163+1744	STT 215	1.6	0.073	1.1	0.054
10287+4558	A 1993	1.4	0.032	0.9	0.015
11468+1500	BU 602	3.9	0.042	2.7	0.032
12194+1744	A 2059	2.8	0.044	1.6	0.034
12335+0901	REU 1	1.4	0.021	1.0	0.014
14358+0015	BU 941 AB	2.1	0.042	1.8	0.031
15002+2129	HU 907	4.6	0.029	3.0	0.025
15075+5516	HU 143 Aa,Ab	3.3	0.046	2.2	0.038
15186+2356	COU 307	2.9	0.023	2.0	0.014
16468+0821	A 2784 AB	6.3	0.054	4.4	0.028
16497+5816	MLR 430	4.4	0.019	3.8	0.010
19389+3514	HU 953	1.8	0.051	1.5	0.031
20198+4522	STT 406	2.0	0.040	1.5	0.032
20216+2346	STF 2672	2.1	0.052	1.6	0.040
20550+2805	BU 367 AB	2.7	0.034	2.1	0.026
22025+2612	A 307	4.8	0.064	3.4	0.055
23009+3522	HU 991	3.4	0.110	2.5	0.072

Columns 3 and 4 are *rms* residuals in position angle ($\Delta\theta$) and in separation ($\Delta\rho$).
Columns 5 and 6 are *ma* residuals.

Apparent orbits are drawn in Figs. 3–6 together with the observational data used. Micrometric observations are shown as dots, and interferometric, CCD, Hipparcos or Gaia EDR3 observations as stars. Arrows in the bottom-left corner show the direction of motion, and the dashed line the line of nodes. The last observations made by PISCO are represented by a red star and the previous orbital solution by a dashed curve.

Of the 22 stars plotted, 8 of them have retrograde orbital motion. The one with the largest number of observations is STT 215 (379 measurements) and the one with the fewest MLR 30 (6 measurements). Measurements are available for arcs between 50° (HU 803) and one or more full revolution (REU 1, STT 406, BU 367 AB). MLR 30 is the double star that has been discovered more recently (in 1973) while the oldest one was STF 2672 (in 1831). The grading system of the OC6 catalog assigns quality grade 4 or 5 to the orbits, except to A 819 AB, STT 213 AB and STT 406 which are grade 3 and REU 1 and BU 367 AB which are grade 2. For all the stars, except BU 453 AB, A 819 AB, STT 213 AB, STT 215, REU 1, HU

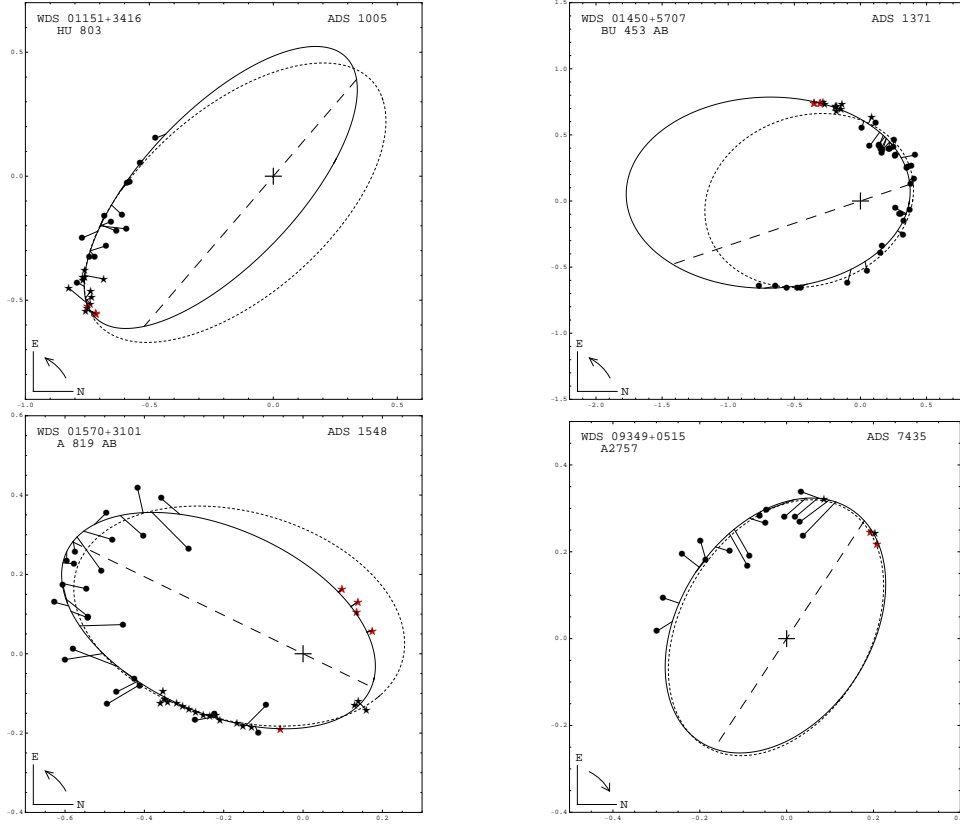


Fig. 3. Apparent orbits of stars (solid ellipses). Each observation (dots and stars indicate visual and interferometric, CCD, Hipparcos or Gaia EDR3 measurements, respectively) is connected by a line to the position predicted for the corresponding epoch by the present orbit. The last observations made by PISCO are represented by a red star. The dotted ellipse represents the previous orbit. The dashed line through the primary star (+) is the line of nodes. The curved arrow in the bottom-left corner shows the direction of orbital motion.

953, STT 406, BU 367 AB and HU 991 we have calculated their first orbit. All the orbits have been previously announced in the IAU Double Stars Information Circulars (IAUDS). Those that have not been modified in the present work, after this publication (A 1993, BU 941 AB, HU 907, A 2784 AB, MLR 430 and STF 2672) do not show the dashed ellipse in Figs. 3–6.

4. Comments on Individual Binaries

Below we comment on those systems. The orbital solution for some of them have been modified after their announcement in the IAUDS information circular, the reasons are indicated. The term “L” or “S” refers to the calculation method used as discussed in Section 2.

WDS 01151+3416 – HU 803 – ADS 1005 – HIP 5852 – L

This couple was discovered by Hussey with the 36-inch refractor of Lick Observatory (California, USA) in 1903. Since then it has described an arc of about 50° . In 2018 we announced a first orbital solution (Ling *et al.* 2018) with a period of 446.2 yr. Here we present a new orbit of period 360.3 yr, also taking into account a recent speckle measurement published by Harshaw (2019). The dynamical parallax is closer to the new parallax published in Gaia EDR3 for each component (12.0662 ± 0.0413 mas for component A and 12.0206 ± 0.0379 mas for component B) than the Hipparcos one. Furthermore, the absolute magnitudes derived from the Gaia parallax, $M_A = 4.62$ and $M_B = 5.52$, are in keeping with the calculated total mass of $1.96 \pm 0.08 M_\odot$ that correspond to spectral types G0 and G8, respectively in accordance with the WDS spectral type G0V. Gaia EDR3 also has published an annual proper motion value of 162.7 mas/yr for the A component and 166.3 mas/yr for the B component.

WDS 01450 +5707 – BU 453 AB – ADS 1371 – HIP 8166 – S

This double star was discovered by Burnham with the famous 6-inch Clark refractor at the Lowell observatory, Arizona “...in the latter part of 1876 and the first part of 1877...” (Burnham 1877). At the time of the discovery, Burnham estimated a separation of $1''.2$, but the instrument was not equipped with a wire micrometer. Later observations by the Italian observer Baron Ercole Dembowski, who measured the double stars discovered by Burnham with his 7.4-inch Merz refractor at Gallarate (near Varese, Lombardy, northern Italy) did not confirm the duplicity. Only the use of the 18.5-inch refractor of the Dearborn Observatory in Chicago allowed a reliable measurement of this difficult double. Up to now five orbits of this double star have been published, the last one calculated by Soulié (1984) has too short a period and now leaves systematic residuals both in separation and in position angle. The trigonometric parallax measured by Gaia corresponds to a mass sum of $2.58 \pm 2.02 M_\odot$ (uncertainty of 78.1%), in reasonable agreement with the spectral type G5 of the system, the parallax measured by the Hipparcos satellite leads instead to an excessive mass. The dynamic parallax calculated with the Baize-Romani method (Scardia *et al.* 2008b) is 13.8 mas. On the WDS, about $9''$ from A, the very faint component C is recorded, whose parallax, measured by Gaia, is very different from that of BU 453 AB.

WDS 01570+3101 – A 819 AB – ADS 1548 – HIP 9087 – S

This binary star was first measured at the Lick Observatory, on Mount Hamilton (California), by Aitken in 1904 with the 36-inch refractor, but most likely, given the brightness of the system and the relatively large separation between the components at the time of the first observation, it was discovered with the 12-inch refractor of the same observatory, much more manageable and practical than the large one (Aitken 1904) to search for new double stars. The WDS reports a very wide C

component, about $66''$ distant, whose proper motion and parallax differs little from those of A and B with which it probably forms a vast triple system. Already after a few decades the orbital motion became evident and the first orbit was calculated by Zulevic (1980). The orbit calculated by Hartkopf and Mason (2009), whose period is too long, has strong residuals in the position angle. Thus, using observations made at Calern in recent years with PISCO, we have calculated new orbital elements (Scardia *et al.* 2017b) which was further refined on the basis of unpublished observations at Calern, in 2018 and 2020. The quality of the old visual observations is modest, but since 1980 almost all measurements have been made with speckle interferometry and large diameter telescopes and are of good quality.

The spectral type of this system is F5. The parallax measured by the Gaia satellite and published in EDR3 (2021) is 13.0400 ± 0.4756 mas, in reasonable agreement with the value found at the time by the Hipparcos satellite (11.62 mas – van Leeuwen 2007ab). The mass sum of A 819 AB corresponding to this value is $1.75 \pm 0.39 M_{\odot}$, slightly lower than what is predicted by the theory ($2.40 M_{\odot}$ – Straizys and Kuriliene 1981) which could, however, be explained by the fact that the two components differ in brightness by 1.14 mag. The dynamic parallax calculated with the Baize-Romani method (Scardia *et al.* 2008b) is 11.9 mas which corresponds to a total “dynamic” mass of $2.47 M_{\odot}$. Of this system Malkov *et al.* (2012) calculated the total masses dynamic ($1.97 \pm 1.00 M_{\odot}$), photometric ($2.49 M_{\odot}$) and spectroscopic ($1.20 M_{\odot}$).

WDS 09349+0515 – A 2757 – ADS 7435 – HIP 47008 – L

Discovered by Aitken in 1914 at Lick Observatory (California) with the 36-inch refractor, the secondary component of this star has described a retrograde arc of about 130° in almost a century. A first orbit was calculated (Ling *et al.* 2017b) using a PISCO observation made in 2017.148. Tokovinin *et al.* (2019a) further published a new observation in 2018.234. We used both measurements to recalculate the orbit and improved the previous *ma* residuals ($\Delta\theta = 3^{\circ}.2$, $\Delta\rho = 0''.023$). Our solution has a dynamic parallax of 5.48 mas that matches the mean Hipparcos parallax. However, the Hipparcos parallax has a very large uncertainty (standard deviation of $\simeq 31\%$, the largest of our list in Table 4). As a consequence the total mass of $4.26 \pm 4.46 M_{\odot}$ has a very large error. The latter value does not fit with a K0 spectral type unless the stars are evolved.

WDS 10131+2725 – STT 213 AB – ADS 7685 – HIP 50052 – S

This double star was discovered by Struve with the great Merz-Mahler 15-inch refractor of the Pulkova Central Observatory (Russia) during the survey of the northern sky in search of new double stars which began on August 26, 1841 and finished on December 7, 1842 (Struve 1843). Struve noted only the magnitudes of the components and the estimated separation ($0''.8$) at the time of discovery. The first complete measurement was instead made by Maedler (1844) at the Dorpat

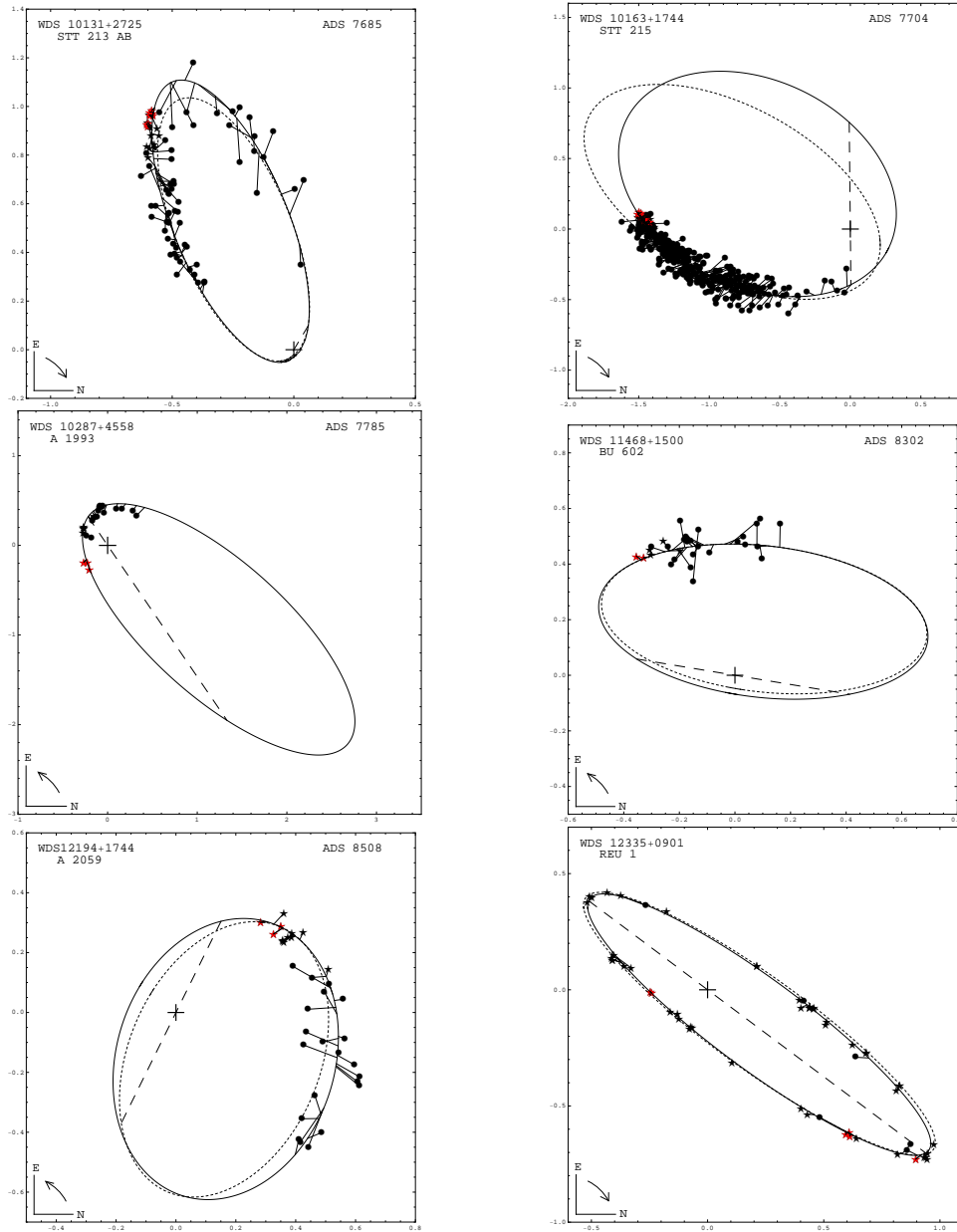


Fig. 4. Same as Fig. 3

Observatory (Estonia) with the famous 9.6-inch refractor built by Fraunhofer and used by Struve for the first big survey of visual binary stars started on February 11, 1825. The WDS reports a very faint C component ($m_V = 15.7$ mag), about $21''$ distant, whose parallax differs little from those of A and B with which it could form a vast triple system. The movement in position angle of the companion, initially slow, became very fast around 1930 with the approach to periastron and for about

twenty years this double star was not observed because the separation between the components was too small. The visual observations made before the passage to the periastron of 1939 are scattered and of modest quality and only since 1997 this double star has been observed with speckle interferometry. Currently the companion is slowly approaching apastron which should be reached within about twenty years. The orbit is very eccentric and the first orbital elements were calculated by Heintz (1962). The orbit calculated by Scardia *et al.* (2008a) is no longer good and so using new observations made with PISCO in Merate and Calern in the last years, we calculated the following new orbital elements (confirmed by a very recent observation made in 2022 at Calern) which were announced by Scardia *et al.* (2019a). The spectral type of this system, as reported in the SIMBAD database, is G5VD. The preliminary parallaxes measured by Gaia are 15.26 ± 0.11 mas (Gaia DR2) and 14.73 ± 0.03 mas (Gaia EDR3), from which we derive a mass sum for the system equal to $5.2 M_{\odot}$ and $5.8 M_{\odot}$, respectively, significantly in excess of what is predicted by the theory ($1.91 M_{\odot}$, Straizys and Kuriliene 1981). The dynamic parallax calculated with the Baize-Romani method (Scardia *et al.* 2008b) is 23.2 mas which corresponds to a total “dynamic” mass of $1.53 M_{\odot}$. Recently Izmailov (2019) calculated a group of orbital elements slightly different from ours, but with higher eccentricity, shorter period, longer semi-major axis, leading to a total mass of the system equals to $15.4 M_{\odot}$ and $17.1 M_{\odot}$ using the two cited Gaia parallaxes, frankly unacceptable for a G5VD spectral type system. All the orbits calculated so far have a high eccentricity and all provide an excessive value for the sum of the masses, but the most recent one, presented in this work, is the one that provides the best value, even if in excess. On the contrary, the “dynamic” sum of the masses, has a value in reasonable agreement with the theory. As it normally happens when the part of the orbit close to the periastron is not covered by the observations because the separation between the components is very small, the eccentricity of the orbit, the epoch T and the semi-major axis are poorly defined, but certainly new speckle observations made by large telescopes in a few decades will allow us to calculate an orbit capable of providing a correct sum of the masses.

WDS 10163+1744 – STT 215 – ADS 7704 – HIP 50305 – S

As in the previous case, this double star was discovered by Struve with the same telescope at the same observatory (Struve 1843). In his catalog Struve added to the magnitudes estimate the Latin comment *vix disjunctae* (just separated). Note that although the introduction of the catalog and the notes are written in French, any comments on the observations are written in Latin as in the previous great works “Catalogus Novus” (Struve 1827) and “Mensurae Micrometricae” (Struve 1837). As for STT 213 the first complete measurement was made by Maedler (1844). STT 215 is a long period binary and from the discovery the companion has covered an orbit arc, of noticeable curvature, of over 90° . The first, very preliminary orbit was calculated by Gore (1890). Zaera’s orbit (1984), plotted in dashed line in Figs.3–

6, is now outdated and begins to show systematic residuals both in separation and position angle. Using the observations made with PISCO in Merate and Calern, a new preliminary orbit has been calculated, which was announced by Scardia *et al.* (2018) and confirmed by a very recent observation made in Calern.

The spectral type of this system, as reported by SIMBAD Astronomical Database, is A9IVD. The parallax published in Gaia DR2 is 9.33 ± 0.01 mas from which we derive a mass sum of the system equal to $2.8 M_{\odot}$ and $2.6 M_{\odot}$ using the Gaia EDR3 parallax (see Table 4). Both values are in reasonable agreement with the previous ones ($3.32 M_{\odot}$ – Straizys and Kuriliene 1981). The dynamic parallax calculated with the formula of Scardia *et al.* (2008b) is 9.0 mas in good agreement with the parallaxes measured by Gaia. Recently Izmailov (2019) published a new orbit, different from ours, with a much shorter period, longer semi-major axis but the total mass of the system ($6.7 M_{\odot}$) is considerably greater than predicted by the theory.

WDS 10287+4558 – A 1993 – ADS 7785 – HIP 51301 – L

This is another star discovered by R.G. Aitken at Lick Observatory with the 36-inch refractor in 1909. Amongst all our stars this is the one with the highest orbital period, 2137 yr, covering an arc of a little more than 100° . The dynamical parallax obtained matches well the mean Hipparcos one. It leads to a total mass of $2.14 \pm 0.99 M_{\odot}$ that is in keeping with both the WDS listed spectral type (G0) and the absolute magnitudes of 4.14 and 5.11. However, the Gaia (DR2) parallax gives a total mass of $0.39 \pm 0.15 M_{\odot}$ incompatible with a G type star. Our orbit was previously announced by Ling *et al.* (2017b).

WDS 11468+1500 – BU 602 – ADS 8302 – HIP 57470 – L

S.W. Burnham discovered this star with the 18.5-inch refractor of the Dearborn observatory (Chicago, USA) in 1878. Until now the arc covered is only 55° . Our previous solution (Ling *et al.* 2019a) has been now modified so that the dynamic parallax better fits with the new value of the trigonometric parallax published by Gaia (EDR3). The mass sum of $2.68 \pm 0.19 M_{\odot}$ found using the Gaia EDR3 parallax is also compatible with the spectral type A5 (note that the Hipparcos parallax gave an unrealistic value of $5.6 \pm 2.5 M_{\odot}$).

WDS 12194+1744 – A2059 – ADS 8508 – HIP 60091 – L

This binary was discovered by R.G. Aitken at Lick Observatory in 1909 and has described an arc of almost 90° . The last 10 yr of observations are speckle measurements. In 2017 we published a first orbit (Ling *et al.* 2017a), using a PISCO observation made in 2016.340. The solution presented now has a slightly longer period than the previous orbit (244.8 yr). We have taken into account the measurement for 2018.288 published by Serot (2019) and obtained a dynamical parallax of 11.25 mas that fits quite well with the Gaia (EDR3) parallax ($11.2966 \pm$

0.0699 mas). This leads to a total mass of $2.23 \pm 0.06 M_{\odot}$ in keeping with both the WDS spectral type F5, and the absolute magnitudes of 3.60 and 5.49 corresponding to spectral types F3 and G5 respectively.

WDS 12335+0901 – REU 1 – S

In 1938 it was discovered that this star, which was already known to have a large proper motion (1.76 arcsec/yr towards the direction 277°), also had a large parallax ($0''.223 = 14.6$ light years). However, its duplicity was certainly discovered only on May 16, 1938 (Reuyl 1941) in the form of an elongation of the photographic images taken with the 26-inch refractor of the Leander McCormick Observatory in Charlottesville, Virginia. Examination of the photographic plates taken earlier made it possible to better understand the motion of this double star. Reuyl (1941) in particular, in a footnote, reports that he was informed by A. van Maanen that the first plate, taken with the Mount Wilson 60-inch telescope on May, 14, 1937, clearly shows the duplicity of REU 1 (with a separation $\rho = 0''.95$). The duplicity was later confirmed by Kuiper (1938) with visual observations made with the 40-inch refractor of the Yerkes Observatory. The analysis of the epochs of the maximum elongations of the photographic images of REU 1 allow an estimate for this double star of a minimum period of about 16 yr (Lippincott 1958). The first orbit was calculated by Heintz (1972). Having available new observations covering more than an entire revolution compared to the determination of Torres *et al.* (1999), the recent observation of Gaia and the very recent new accurate observations made in Calern in May 2022 with the PISCO speckle camera, as well as a much more precise measurement of the parallax, we decided to revise our 2019 orbital elements of this interesting double star of spectral type M5.5 to provide more precise sum-of-mass values. The orbit of Torres *et al.* (1999), with similar orbital elements, do not fit the latest PISCO measurements. Benedict *et al.* (2016) also calculated a set of incomplete orbital elements (as they are recorded in the OC6 catalog) using all available observations including the Hubble Space Telescope (HST) ones.

Since its discovery, the companion has already made more than five revolutions around the main star, but only since 1980 the orbit has been entirely covered by ground observations using speckle interferometry and by the HST. This system, consists of two dwarf stars of equal magnitude (12.6–12.6) and spectral type M5.5V. It is interesting because it is one of the visual systems with reasonably reliable orbit positioned in the lowest part of the H–R diagram where, due to the reduced intrinsic brightness of the stars, the observations are difficult to carry out and therefore numerically scarce. The sum of masses calculated using our orbital elements and the Gaia EDR3 parallax (223.48 ± 0.47 mas) is equal to $0.269 \pm 0.061 M_{\odot}$, in good agreement with the value $0.255 \pm 0.062 M_{\odot}$ obtained using the parallax reported in the General Catalogue of Trigonometrical Parallaxes (227.9 ± 4.6 mas) (van Altena *et al.* 1995) and with the value calculated by Torres *et al.* (1999) ($0.274 \pm 0.021 M_{\odot}$), while those obtained by Schultz *et al.* (1998)

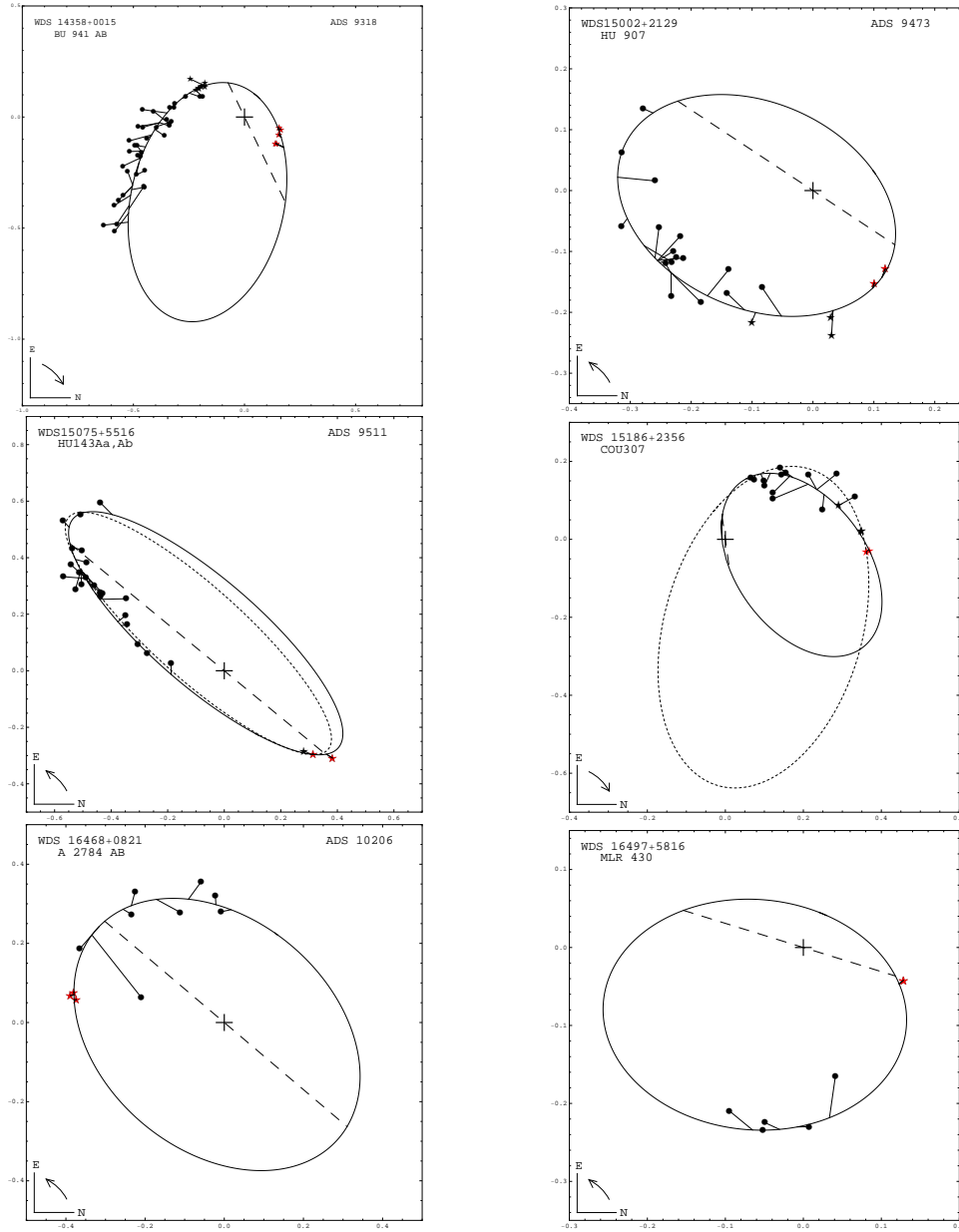


Fig. 5. Same as Fig. 3

($0.232 \pm 0.046 M_{\odot}$) and Benedict *et al.* (2016) ($0.237 \pm 0.01 M_{\odot}$) are significantly lower. We note that the uncertainty on the total mass, using the Gaia parallax, is dominated by the errors on the period and semi-major axis, and not by the one on the parallax. Since the components of REU 1 have the same magnitude and the same spectral type, the individual masses are reasonably equal ($0.135 \pm 0.032 M_{\odot}$) and above the sub-stellar limit.

WDS 14358+0015 – BU 941 AB – ADS 9318 – HIP 71377 – S

This double star was discovered in Chicago by S.W. Burnham (1883) with the 18.5-inch aperture refractor of the Dearborn Observatory. With the note “very unsteady during the second measure” Burnham reported that he had a greater difficulty in performing the second measure. In this regard it should be noted that in Burnham’s article (1883), in which he publishes the discovery of 151 new double stars, the average of the times of the two observations of this object is wrong. Since the discovery, this double star has been observed with regularity and the companion has described an arc of orbit of about 76° in 114 yr and closing in with a weakly curved trajectory. This binary was completely forgotten by observers between 1993 and 2017. In June 2017 Scardia measured this binary star at Calern with PISCO and he found the two stars almost at the limit of the instrument, although the speckle auto-correlation functions were clearly visible and measurable. Comparing his measurements with those performed by Hartkopf in the years 1990–1993 with 4-m telescopes he realized that his measurements were positioned about 20° “back” as if they were made around 1980. The search for a reasonable motivation to explain this anomaly led to conclude that during the gap of 24 yr in the data, the companion had rotated around the main star passing through the periastron and was arrived in the 4th quadrant in 2017. Using unpublished observations made at Calern in 2017, 2019 and 2022 a new preliminary orbital elements were calculated. This binary is formed by two stars of visual magnitude 9.44 and 9.57 and the spectral type is G0V. To our knowledge there are only two measured trigonometric parallaxes, the first (7.00 ± 1.33 mas) from the Hipparcos satellite (van Leeuwen 2007ab) and the other (3.31 ± 1.29 mas), a more recent, but preliminary, measurement from Gaia (DR2). The sums of the masses obtained using our orbit and the parallaxes measured by Hipparcos and Gaia are respectively $2.76 M_\odot$ and $26.16 M_\odot$. The first one is slightly in excess of what is predicted by the theory (Straizys and Kuriliene 1981), but it is still acceptable if we consider that the orbital elements are preliminary, while the second one is absolutely unacceptable. Probably there is a problem with the Gaia DR2 parallax. Indeed the most recent release EDR3 of Gaia does not report any value for the parallax of this pair. The dynamic parallax calculated with the Scardia *et al.* (2008b) formula is equal to 7.2 mas, in good agreement with the value measured by Hipparcos. To this value corresponds a sum of dynamic masses equal to $2.67 M_\odot$ in reasonable agreement with the theory.

WDS 15002+2129 – HU 907 – ADS 9473 – HIP 73411 – L

This is a double star discovered in 1904 by W.J. Hussey with the 36-inch refractor of the Lick observatory. The components have similar WDS magnitudes, and the star has covered an arc of orbit of about 122° . The orbit that we present here has already been announced in 2019 (Ling *et al.* 2019c). The dynamical parallax obtained is perfectly adjusted with the mean value of the Hipparcos parallax. The Hipparcos parallax has a standard error of around 22%, which produces an large

uncertainty in the sum of the masses of the system, $2.32 \pm 1.78 M_{\odot}$. For the source HIP 73411, Gaia (EDR3) gives a trigonometric parallax (1.0621 ± 0.0692 mas) corresponding to a star of G -band magnitude 15.8 that does not fit the magnitudes of this binary.

WDS 15075+5516 – HU143Aa,Ab – ADS 9511 – L

This is another couple discovered by W.J. Hussey at the Lick observatory in 1900. Hartkopf *et al.* (2013) have considered another component with an angular separation $\rho \approx 58''.6$ and a photometric V -band magnitude 15.08, as a new possible common proper motion pair from UCAC4 (Fourth U.S. Naval Observatory CCD Astrograph Catalog, Zacharias 2012), calling this system UC 2929AB. So the components discovered by Hussey have been renamed as Aa,Ab. The Ab component has covered an arc of more than 190° around the Aa component in a little more than 100 yr. A previous orbital solution for this star was announced by Ling *et al.* (2019a). In this paper, we improve the *rms* and *ma* residuals in the angular separations with respect to the previous ones ($0''.054$ and $0''.044$, respectively) as we can see in Table 6. Due to the lack of Hipparcos and Gaia’s trigonometric parallax values, the sum of masses of $1.87 \pm 0.67 M_{\odot}$ and the absolute magnitudes, $M_A = 5.25$ and $M_B = 5.55$, have been calculated with our dynamical parallax. All these data are in really good agreement with the spectral types G5V + G8V listed in the Catalogue of Stellar Spectral Classifications (Skiff, 2014) and the effective temperature of $T_{\text{eff}} = 5748$ K in Gaia DR2 (2018).

WDS 15186+2356 – COU 307 – L

Couteau (1970) discovered this star in 1968 with the 19.7-inch refractor telescope of the Nice observatory (France). The companion has moved about 60° in the retrograde sense since its discovery. In this paper, we refine our previous orbit announced by Ling *et al.* (2017c). The present orbit is much more eccentric and its dynamic parallax better fits the Gaia DR2 parallax. We also improve the *rms* and *ma* residuals in the angular separations with respect to the previous ones ($0''.030$ and $0''.021$ respectively). However, the total mass, $1.23 \pm 0.23 M_{\odot}$ is smaller than expected for G0-type stars.

WDS 16468+0821 – A 2784 AB – ADS 10206 – S

This double star was discovered by Aitken (1914) on Mount Hamilton with the 36-inch refractor of the Lick Observatory. No particular note accompanies the discovery of this binary in the “Twenty-Second List” of new double stars published by the great American observer. Observations are scarce and since 1992 no one has observed this binary star until 2016 when it was observed by Scardia in Calern with PISCO. The motion of the companion is slow and since discovery it has covered an orbit arc of about 80° , however, sufficient to calculate the preliminary orbital elements obtained using the latest unpublished PISCO observations. This

binary is composed of two stars of visual magnitudes 9.8 and 11.0 and its spectral type is G0. To date, no trigonometric parallax has yet been measured. The dynamic parallax calculated with the formula of Scardia *et al.* (2008b) equals to 5.7 mas and this value corresponds to a sum of dynamic masses equal to $2.48 M_{\odot}$, somewhat large for a pair of spectral type G0, but still acceptable since the orbit is preliminary.

WDS 16497+5816 – MLR 430 – L

Among all the stars studied, this is the most recently discovered, in 1973 by Muller (1973) with the 19.7-inch refractor of the Nice observatory. It is also the one with the fewest number of observations, only seven measurements in 42 yr, although the arc covered is almost 90° .

According to our solution, already announced by Ling *et al.* (2019a), this binary is close to the periastron (epoch 2022.4). The total mass of $1.64 \pm 0.26 M_{\odot}$, as well as the absolute magnitudes $M_A = 4.77$ and $M_B = 5.07$, obtained with the Gaia (EDR3) parallax, and similar to those obtained with our dynamic parallax (see Table 5), are smaller than expected for an F5 spectral type.

WDS 19389+3514 – HU 953 – ADS 12746 – L

This binary was discovered by Hussey (1905) with the Lick 36-inch refractor in 1904. The arc covered by the companion is more than 230° . One orbit was published by Mason and Hartkopf (2011). Using three additional speckle observations, two of them being made with PISCO at Calern in the middle of 2016, we computed another solution that was published in Ling *et al.* (2017c). The new orbit calculated in this work has a period greater than the 466.2 yr calculated before. There are no Hipparcos or Gaia parallaxes, but the Tycho catalog (ESA 1997) gives a parallax of 28.50 ± 6.30 mas. The mean value of the total mass $2.36 M_{\odot}$ inferred from the dynamic parallax, 10.62 mas, is in agreement with a G0-type star.

According to the update of the Multiple Star Catalog (MSC, Tokovinin 2018), HU 953 belongs to a multiple system with a C component (visual magnitude 18.7, $\rho \approx 7''.8$ from AB, Gaia EDR3 parallax 10.163 ± 0.141 mas, this value fits with the dynamic parallax we determined for the pair AB, confirming the accurate distance provided by Gaia). The A component is a single-lined spectroscopic binary. The masses of A and B are listed as $1.12 M_{\odot}$ and $1.04 M_{\odot}$, respectively, the spectral types of both AB and AB-C as G0. Gaia DR2 (2018) gives as effective temperature $T_{\text{eff}} = 6191 K$.

WDS 20198+4522 – STT 406 – ADS 13723 – HIP 100241 – S

This binary was discovered between August 26, 1841 and December 7, 1842 by Struve (1843) with the large 15-inch Merz-Mahler refractor of the Poulkova Central Observatory in Russia. No particular note accompanies the discovery of this double because Struve he noted only the magnitudes, which he estimated equal, and the separation between the components, estimated at $0''.6$. The first measurement was

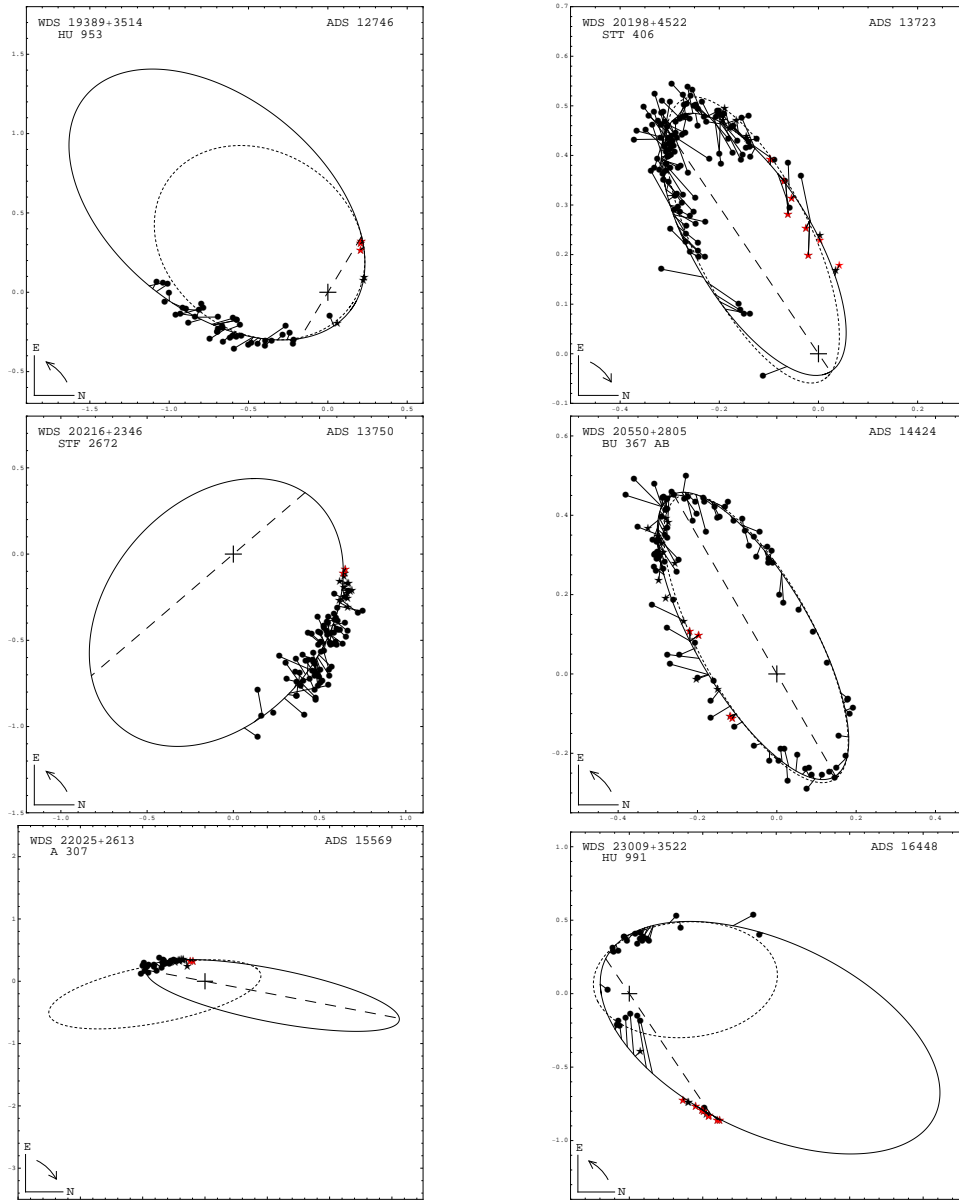


Fig. 6. Same as Fig. 3

instead made by Maedler (1844) in Dorpat (Estonia) with the 9.6-inch refractor. Since then, this pair has been followed regularly by observers, but mainly due to the difference in magnitude and the proximity between the components, measures prior to 1910 are few and far between. Since 1991 this pair has been predominantly observed with speckle interferometry and since 2005 the only known speckle observations have been made by Scardia with PISCO in Merate and Calern. The companion completed a first observed revolution around the year 1950 and due to the

high eccentricity of the orbit (0.86) the separation between the two components is now rapidly decreasing and in the coming years this double will only be observable with large apertures. The first orbit was calculated by van Biesbroeck (1936) while the one calculated by Heintz (1976) is now obsolete and no longer represents the observations of recent years. Using the observations after 1976 and two very recent observations, not yet published, made with PISCO in Calern, the orbital elements were recalculated.

STT 406 is made up of two stars of visual magnitudes 7.25 and 8.74 and the overall spectral type reported in the SIMBAD Astronomical Database is F5IV. As far as we know there only exist two measured trigonometric parallaxes, the first 10.81 ± 0.54 mas from the Hipparcos satellite and the other 26.78 ± 1.19 mas more recently measured by Gaia (DR2) although this is preliminary. The mass sums of STT 406 obtained using our orbit and the parallaxes aforementioned are respectively $1.70 \pm 0.41 M_{\odot}$ and $0.11 \pm 0.03 M_{\odot}$. The first value, significantly smaller than the theory predicted, is still acceptable if we consider the lower luminosity of the companion and which, as a first approximation, suggests a star of smaller mass. The second value, obtained with Gaia (DR2) parallax, is absolutely unacceptable. Indeed, the most recent release of Gaia (EDR3) does not report any value for the parallax of this double. The dynamic parallax calculated is 9.4 mas, in reasonable agreement with the Hipparcos one, and is essentially the same as that published by Heintz (1976) but considered by him to be doubtful. The corresponding sum of dynamic masses is equal to $3.54 M_{\odot}$. Malkov *et al.* (2012) calculated a dynamic mass sum of $2.33 \pm 1.30 M_{\odot}$ which has a large uncertainty but is compatible with our value. At this point we just have to wait and see if the next releases of the parallaxes measured by Gaia will clarify the doubts related to this system.

WDS 20216+2346 – STF 2672 – ADS 13750 – L

This double star was discovered by Struve (1837) in 1831 at Dorpat observatory (Estonia) with the 9.6-inch Fraunhofer refractor. This couple has 97 measurements made in almost 200 yr, covering an arc of a little more than 70° . There is no Hipparcos parallax. Gaia DR2 gives an unrealistic parallax of 0.4712 ± 1.0161 mas due to a big standard error. The total mass $2.52 \pm 0.08 M_{\odot}$ obtained using our dynamical parallax is in good agreement with main sequence F-type stars. Gaia EDR3 published parallax data for each component (see Table 4) which provide absolute magnitudes $M_A = 3.43$ and $M_B = 3.20$, that also fit well with the F spectral type.

WDS 20550+2805 – BU 367 AB – ADS 14424 – HIP 103247 – S

This double star was discovered in Chicago (USA) by Burnham on November 12, 1874 with the excellent 6-inch refractor built by Alvan Clark & Sons. Burnham estimated separation and position angle and commented on the discovery with the phrase “Excessively difficult pair in the field with 32 Vulpeculae” (Burnham 1875).

Since at the time of the discovery he did not have a wire micrometer, as for many of his other discoveries, the first real measurement was made by the great Italian observer Ercole Dembowski August 6, 1875 (Struve and Schiaparelli 1883). Since then this binary star has been followed regularly by observers and the first orbit was calculated by Finsen (1938). Around 1975 the companion ended its first revolution. The orbit of Scardia *et al.* (2003) is no longer good. We calculated a new set of orbital elements (Table 1), taking advantage of recent observations including two unpublished measurements by Scardia with PISCO at Calern.

The double star BU 367 AB consists of two stars of spectral type G2V (Christy and Walker 1969) and visual magnitudes 8.31 and 9.00. At the moment none parallax measured by the astrometric satellite Gaia have been published, while that measured by the Hipparcos satellite is 16.10 ± 1.13 mas (van Leeuwen 2007ab). For this value corresponds a sum of masses of $1.53 \pm 0.42 M_{\odot}$, significantly lower than that predicted by the theory (Straizys and Kuriliene 1981). The dynamical parallax is equal to 14.3 mas, in reasonable agreement with the Hipparcos parallax, and the total dynamic mass is $2.30 M_{\odot}$ significantly different from that calculated by Malkov *et al.* (2012) ($1.62 \pm 0.40 M_{\odot}$) which is instead in agreement with the sum of the masses inferred using the Hipparcos parallax.

WDS 22025+2612 – A 307 – ADS 15569 – L

Aitken (1902) discovered this binary in 1901, with the 12-inch and 36-inch equatorials of the Lick observatory. The secondary component has described a retrograde arc of about 50° . There are neither Hipparcos nor Gaia parallaxes. We announced the first orbit calculated for this star (Ling *et al.* 2019b) with a period of 1660 yr. Almost simultaneously Izmailov (2019) published another one with greater eccentricity 0.806. Here we include a new solution which slightly improves the *rms* residuals compared to our preliminary orbit ($\Delta\theta = 5''.2$, $\Delta\rho = 0''.070$). The total mass $1.84 \pm 0.39 M_{\odot}$, obtained using our dynamical parallax agrees a little better with a F8 spectral type (signaled in Kharchenko and Roeser 2009) or G0 type stars, than the values obtained by Izmailov (dynamic parallax of 25.30 mas and mass sum of $1.25 M_{\odot}$).

WDS 23009+3522 – HU 991 – ADS 16448 – HIP 113642 – S

This double star was discovered in 1904 by Hussey (1905) on Mount Hamilton (California) with the 36-inch refractor of the Lick Observatory. No particular note accompanies the discovery of this binary in the “Ninth Catalog” of new double stars published by the great American observer. The system, of spectral type K2, is formed by two faint stars (the WDS reports magnitudes of 10.23 and 11.17) and from the discovery the companion has already covered an arc of orbit of over 280° . The measures are few, and this is explained by the difficulty of the couple, faint and very close in the second half of the 20th century, and only since 2008 has it been followed with the speckle interferometry mainly at the OCA sites of Mont Gros

(Nice) and the Calern plateau. The only orbit to date has been calculated by Baize (1985), and predicts a relatively short period, but it no longer represents the observations. Using unpublished observations made after 2014 with the OCA 29.9-inch refractor by Gili and the 104-cm “Epsilon” telescope by Scardia, a new provisional solution was calculated. Although the observed arc of the orbit is over 280° and covers periastron, the period, the semi-major axis and the eccentricity are poorly determined as it is always the case when the orbit is “open” towards apastron. The orbital elements were announced in Scardia *et al.* (2017a), here the only difference is the value of the semi-major axis. The distance of HU 991 is reasonably well known because it is measured both by Hipparcos (parallax of 17.01 ± 1.87 mas, van Leeuwen 2007ab) and Gaia EDR3 (16.67 ± 0.03 mas). The total mass of the system calculated using the parallax of Gaia and our orbit is $1.56 M_\odot$, in good agreement with predictions (Straizys and Kuriliene, 1981). The dynamic parallax calculated with the formula of Scardia *et al.* (2008b) is 16.5 mas in excellent agreement with the value measured by the Gaia satellite.

5. Conclusions

We presented orbital elements for 22 binaries which were partly derived from PISCO observations. The secondary components of these double stars have described arcs ranging from 50° to more than 360° . Observed angular separations range in the interval $0''.13 \leq \rho \leq 1''.3$ and component magnitudes vary from 7.2 to 12.6. The largest magnitude difference, that of A 2059, is $\Delta m = 1.9$. Calculated periods range from 15 yr to 2140 yr. There are eight retrograde orbits (A2757, STT 213 AB, STT 215, REU 1, BU 941 AB, COU 307, STT 406 and A 307) and two very eccentric (STT 213 AB and COU 307). For these stars, except BU 453 AB, A 819 AB, STT 213 AB, STT 215, REU 1, HU 953, STT 406, BU 367 AB and HU 991, our group has announced their first orbit solutions. Although some of them are preliminary in general, the dynamical masses obtained agree with those expected on the basis of the component spectral types. In the present work we contribute to increase the databases of visual binary star orbits. In addition, the future publication of the Gaia astrometric mission (Gaia DR3) on data for non-single stars will provide an increase in the quality and quantity of trigonometric parallax measurements for binary systems as well as statistical studies on different distribution functions. In this sense, for the faintest binaries that the satellite will detect, and which in a first approximation would correspond to very distant stars, the galactic interstellar absorption correction would probably have to be considered. Consequently, this will allow refining the determination of the masses with studies like ours or others recently published by Tokovinin *et al.* (2019b), Cvetlović and Pavlović (2020) and Gómez *et al.* (2022).

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the “Washington Double Star Catalog”

<http://www.astro.gsu.edu/wds/>

the “Fourth Catalog of Interferometric Measurements of Binary Stars”

<http://www.astro.gsu.edu/wds/int4.html>

and the “Sixth Catalog of Orbits of Visual Binary Stars”

<http://http://www.astro.gsu.edu/wds/orb6.html>

maintained at the U.S. Naval Observatory.

We also used:

the SIDONie (Site Informatique des étoiles DOubles de Nice,

<http://sidonie.obs-nice.fr>)

and the SIMBAD Astronomical Database

<http://simbad.u-strasbg.fr/simbad>

operated by the Centre de Données Astronomiques de Strasbourg (France).

This work has made use of data from the European Space Agency (ESA) mission Gaia

<https://www.cosmos.esa.int/gaia>

processed by the Gaia Data Processing and Analysis Consortium (DPAC)

<https://www.cosmos.esa.int/web/gaia/dpac/consortium>.

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