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Astrometric investigation of visual binaries at Pulkovo

L.G. Romanenko*, O.A. Kalinichenko

Main (Pulkovo) Astronomical Observatory, Russian Academy of Sciences, 65 Pulkovskoe Shosse, St. Petersburg, 196140 Russia

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In the last 40 years the team headed by A.A. Kiselev at Pulkovo determined the orbits of 65 wide visual binaries and multiple stars. In most of the cases these studies are based on series of photographic observations made with the 26-inch refractor of Pulkovo observatory. Positional observations from Washington Double Star Catalog (WDS) were used for slowly moving star pairs. At the first stage of the preparation of Pulkovo Catalog of Orbits of Wide Pairs we compared the orbits of 53 of the 65 stars determined by our team with both the CCD observations made with the same telescope and the new WDS data. Our comparison based on 28 available sets of CCD observations demonstrated high quality of the data. No refinement is needed for most of the orbits (42 of the stars studied). The method of apparent motion parameters (AMP) allows determining the orbit if positional data are supplemented with information about the trigonometric parallax, component masses and radial velocities. HIPPARCOS parallaxes are available for only 201 of the 428 binary and multiple stars of the Pulkovo program. Once released, the results of GAIA mission may stimulate the determination of new orbits. In the future we plan to determine the orientation of the inferred orbits in the Galactic coordinate system and report the statistics of the orientation parameters.

Keywords: Stars, visual binaries, short-arc orbits

1 Introduction

The studies of the orbital motions in binary stars are traditionally aimed at the determination of the masses and dynamical parallaxes of these systems and their components. However, this is true only for stars where a large arc of the orbit is observed. In the case of wide pairs with periods of several hundred or several thousand years we have the data for only a short arc of the entire orbit. We thus have to address the inverse problem: given the parallax of the stellar system and spectral types of its components we estimate their masses in accordance with the average statistical mass–luminosity relation, try to fit the observed arc by a portion of Keplerian orbit

*Email: lrom@gaoran.ru

and compute its elements. In some of the cases excess mass is found, which can be explained by the following factors: incorrect adopted parallax, presence of an unseen companion, deviation from the average statistical relation (heavy stars), or the optical nature of the pair.

Based on a statistical analysis of the first 30 Pulkovo orbits of binary stars, Kiselev and Romanenko (2004) showed that these orbits are mostly steeply inclined to the Galactic plane: the Galactic latitudes of the poles of many such orbits lie in the $|b| \leq 30^\circ$ interval. Previously the preferred direction of the distribution of orbital poles of visual binaries in the solar neighborhood was studied by Mädler (1838), Dommanget (1968, 1988), and Glebocki (2000). Based on more extensive data, Glebocki (2000) confirmed the results of previous studies by Mädler (1838), Dommanget (1968), Dommanget (1988) and showed that the poles of 19 systems located within 10 pc from the Sun concentrate toward $(l, b) \sim (110^\circ, -10^\circ)$ and $\sim (245^\circ, -5^\circ)$, although the global distribution of the poles of 252 systems is isotropic. Agati et al. (2015) analyzed the data of the Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf and Mason (2016)) and showed that the poles of 20 systems located within 8 pc from the Sun concentrate toward $(l, b) \sim (46^\circ, +37^\circ)$, whereas the concentration of poles disappears for the full sample of 51 systems located within 18 pc. The above authors (Agati et al. (2015)) concluded that at this stage the reality of the anisotropy cannot be assessed with certainty because the number of systems with known orbital elements and with known position of the ascending node of the orbit is too small. It is therefore worth increasing the amount of these data and analyzing the results.

Close systems with short orbital periods have already been studied extensively, whereas wide binaries are valuable objects to investigate from the viewpoint of the study of the origin and evolution of wide pairs aimed not only at determining stellar masses, but also at gaining insight into the evolution of stellar matter and Galactic dynamics.

Furthermore, determination (refinement) of the orbits of visual binaries in the solar neighborhood brings us closer to solving the important problem of today's astronomy – the study of these stars as possible parent objects for finding eventual exoplanets (Shakht et al. (2016)).

2 The apparent motion parameter method and the available amount of data for astrometric studies of visual binaries at Pulkovo

To compute the orbit of a visual binary via the apparent motion parameters method (AMP) (Kiselev and Kiyaeva (1980)) the results of positional observations have to be supplemented with additional data including the parallax of the star, the component radial velocity difference at some time instant, and an estimate of the sum of component masses. The latter quantity has to be set in advance, but it is validated or refined in the process of computations. Ideally, positional observations should have the form of a highly precise series that would allow one to determine not only the relative positions, but also their derivatives – the relative motion in the sky plane. For correct computation of the relative space velocity radial velocities should be measured with an accuracy of about 0.1 km/s. Thus the study of the dynamics of wide stellar pairs is based on the results of both astrometric and astrophysical observations.

Initially, the determination of AMP orbits by the team of A.A. Kiselev was based on series of photographic observations of visual binaries carried out with the 26-inch refractor of the Main Astronomical Observatory of the Russian Academy of Sciences in 1957–2007. As of now, plates with images of 487 stellar systems have been measured (Kiselev et al. (2014), Izmailov et al. (2016)). Archive data from Washington Double Star Catalog (WDS) (Mason et al. (2016)) were used mostly to validate the quality of the inferred AMP orbits. When we started the dynamical analysis of more distant stellar pairs with slow orbital motion we had to use these data partially or fully (combined with Pulkovo data) as the main (reference) arc. In recent years we used CCD observations carried out at our telescope since 2003 (Izmailov et al. (2010), Izmailov and Roshchina (2016)) as the reference data for stars with faster orbital motion.

We planned to adopt additional data from the literature. However, by early 1980s, when the catalog of positions and motions of 200 stars (Kiselev et al. (1988)) was being prepared for publication and when the paper of Kiselev and Kiyaeva (1980) about the AMP method was published, many stars of the Pulkovo program lacked not only component radial-velocity measurements, but even parallax measurements. It turned out later that the HIPPARCOS catalog (ESA SP-1200 (1997)) provided parallaxes only for 201 of the 428 stars of our program. The release of the results of the GAIA mission may stimulate the determination of new orbits.

Radial velocities of Pulkovo program stars were observed with:

- the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences by E.L.Chentsov (1982–1987, Romanenko and Chentsov (1994)),
- Radial-velocity meter (RVM SAI) by A.A. Tokovinin (1985–1998, Tokovinin (1994), Kiyaeva et al. (1998)) and then by N.A. Gorynya (1999–2007, Kiselev et al. (2009a), Kiyaeva et al. (2010), Kiselev et al. (2012)),
- and currently by R.Ya. Zhuchkov from Kazan University at RTT-150 telescope in Turkey (Kiyaeva et al. (2017), Kiyaeva and Zhuchkov (2017)).

A.A. Tokovinin was the main contributor of radial-velocity measurements for the stars of our program. Over 14 years he provided us with radial-velocity measurements for components of 30 binary and multiple systems; he discovered at least 10 spectroscopic binaries and eight optical components. Using the data, we computed and published AMP orbits for more than 20 of the systems studied (Kiyaeva et al. (1998), Kiselev and Romanenko (1996), Kiselev et al. (2000), Kiselev et al. (2009b)). Later we used such reliable sources of radial velocities as Marcy and Benitz (1989), Duquennoy and Mayor (1991), Tokovinin and Smekhov (2002), etc.

The dynamical analysis of stars of our program performed by the team of A.A. Kiselev revealed the following features of these systems:

(1) Optical (non-physical) nature of some pairs established by comparing proper motions of the components and relative motion in such pairs as ADS 6700 AB and ADS 7361 AC (Kiyaeva et al. (2012)),

(2) Perturbations in positional observations, which can be explained by the presence of an unseen companion in such pairs as, e.g., ADS 10759 (Kiselev et al. (2009b)) and ADS 11061 (Afanasyeva and Grosheva (2012)),

(3) Slow relative motion (in these cases we obtain a family of AMP orbits) in such pairs as, e.g., ADS 10044 (Kiselev et al. (2000)) and GL 745 (Kiyaeva et al. (2012)),

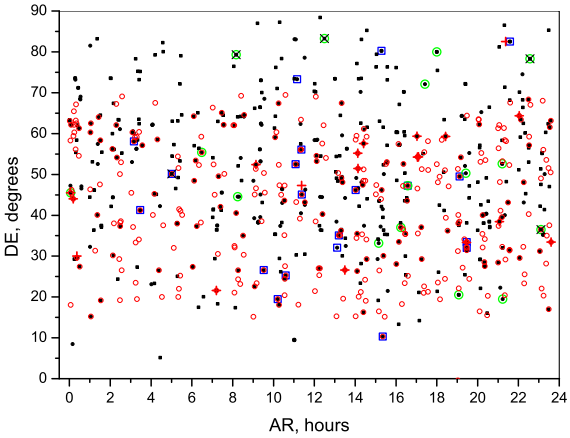


Figure 1 Distribution of the visual binaries of the Pulkovo program in the sky. Designations: the points show the binaries for which photographic plates have been measured (487 systems: Kiselev et al. (2014), Izmailov et al. (2016)), the small circles show the systems for which CCD observations are available (332 systems: Izmailov et al. (2010), Izmailov and Roshchina (2016)), the crosses show the systems for which one AMP orbit has been computed (20 pairs), the squares show the systems for which two AMP orbits have been computed (17 pairs), the large circles show the systems for which a family of AMP orbits has been computed (20 pairs), and the slanted crosses show five systems (ADS 3593, 6646, 8682, 16407, and 16558) excluded from further analysis (see Section 3).

(4) Excess mass in such pairs as, e.g., ADS 497 and ADS 14878 (Kiselev et al. (2009b)).

Figure 1 shows the distribution of stars of the Pulkovo program on the sky. Here objects with measured photographic observations and with measured CCD observations and also stars with computed AMP orbits are marked. We thus have quite substantial groundwork for further studies.

3 Pulkovo Catalog of the Orbits of Wide Pairs. The first stage of the preparation

The team of A.A. Kiselev has currently computed the AMP orbits for a total of 65 wide visual binaries and multiple stars. At the first stage of the preparation of the Pulkovo Catalog of the Orbits of Wide Pairs we revised the AMP orbits of 53 stars studied before 2016 (i.e., this work does not include recently published orbits (Kiyaeva et al. (2017) and Kiyaeva and Zhuchkov (2017)) of stars that were not observed in Pulkovo). A comparison of these orbits with the new data from WDS catalog (Mason et al. (2016)) and with the results of CCD observations made in 2003–2014 at the 26-inch refractor in Pulkovo (Izmailov et al. (2010), Izmailov and Roshchina (2016)) demonstrate the high quality of Pulkovo CCD data sets (see Table 1). Subsequent use of CCD observations made it possible to reveal fine effects in the multiple system ADS 9173 (Kiyaeva and Zhuchkov (2017)). We also concluded that the orbits of 11 stars (ADS 246, 2427, 5436, 8002, 8236, 8242, 9167, 9346, 9559,

10329, and 15600) have to be refined, and three stars with very slow orbital motion and unreliable orbits (ADS 6646, 8682, and 16407) have to be excluded from further statistical analysis, whereas ADS 3593 and ADS 16558 should be excluded as optical pairs, see Kiselev et al. (2009b).

Table 1 Parameters of Pulkovo series for some of the visual binaries studied.

ADS	WDS	m_V	ρ''	Series	T_1	T_2	n	$\Delta\theta^0$	$\sigma''_{1\rho}$	$\sigma''_{1\tau}$
48	00057+4549	8.98		WDS	1876	2013	399	75.5		
		9.15	6.0	Photo	1961	2000	148	16.7	.0331	.0179
				CCD	2003	2012	48	3.5	.0104	.0029
246	00184+4401	8.31		WDS	1860	2012	122	12.0		
		11.36	35.2	Photo	1994	2006	7	0.1	.0633	.3192
				CCD	2003	2013	67	0.9	.0061	.0080
2427	03162+5810	10.30		WDS	1919	2011	49	35.8		
		11.38	4.8	Photo	1971	1999	100	6.7	.0597	.0399
				CCD	2004	2013	53	3.4	.0172	.0055
2757	03470+4126	8.20		WDS	1822	2011	125	10.0		
		8.82	7.4	Photo	1960	2001	101	2.5	.0479	.0379
				CCD	2004	2014	41	0.8	.0076	.0030
3593	05013+5015	9.51		WDS	1830	2013	109	52.6		
		9.88	4.2	Photo	1970	2001	76	10.9	.0523	.0314
				CCD	2004	2013	48	3.2	.0148	.0043
5436	06482+5542	6.28		WDS	1821	2014	126	4.1		
		6.34	4.6	Photo	1962	2003	33	0.8	.0491	.0175
				CCD	2003	2014	49	2.6	.0104	.0044
7251	09144+5241	7.79		WDS	1821	2013	447	50.7		
		7.88	17.6	Photo	1963	1996	195	9.7	.0271	.0083
				CCD	2004	2014	47	3.0	.0088	.0052
8002	10592+2527	8.57		WDS	1899	2011	99	38.5		
		9.22	5.2	Photo	1970	1998	61	9.3	.0349	.0695
				CCD	2004	2013	45	3.2	.0097	.0052
8065	11080+5249	7.65		WDS	1832	2008	74	12.8		
		9.03	5.2	Photo	1970	2000	25	1.3	.0783	.0263
				CCD	2004	2013	43	0.6	.0122	.0057
8250	11387+4507	6.53		WDS	1830	2013	112	22.2		
		8.23	9.2	Photo	1969	2004	50	4.2	.0397	.0254
				CCD	2003	2014	70	1.6	.0080	.0087
8861	13196+3507	9.62		WDS	1896	2012	53	13.1		
		11.90	17.7	Photo	1971	2004	81	3.0	.0341	.0252
				CCD	2004	2014	117	0.9	.0180	.0069
9031	13491+2659	7.36		WDS	1823	2013	863	384.2		
		8.15	3.5	Photo	1962	1996	97	25.5	.0457	.0456
				CCD	2003	2014	105	9.1	.0199	.0068
9167	14131+5520	9.06		WDS	1831	2012	201	77.4		
		9.42	2.5	Photo	1971	1998	73	10.1	.0528	.0216
				CCD	2003	2011	51	2.5	.0115	.0069
9173	14135+5147	4.53		WDS	1779	2015	191	1.3		
		6.62	13.6	Photo	1982	2004	51	0.2	.0320	.0321
				CCD	2003	2012	55	0.2	.0210	.0114
9346	14410+5757	7.53		WDS	1830	2015	96	12.8		
		8.32	7.6	Photo	1979	2005	18	1.9	.0220	.0185
				CCD	2003	2012	59	0.6	.0087	.0033

Table 1 (continued from previous page)

ADS	WDS	m_V	ρ''	Series	T_1	T_2	n	$\Delta\theta^0$	$\sigma''_{1\rho}$	$\sigma''_{1\tau}$
9701	15348+1032	4.17		WDS	1819	2015	485	27.4		
		5.16	4.0	Photo	1981	1997	15	1.5	.0561	.0166
				CCD	2004	2014	83	1.5	.0289	.0175
10044	16242+3702	8.43		WDS	1823	2009	99	2.6		
		8.79	8.3	Photo	1962	1996	26	0.7	.0118	.0145
				CCD	2003	2014	131	0.2	.0072	.0010
10329	17033+5935	8.76		WDS	1830	2006	54	11.2		
		10.34	12.0	Photo	1970	1999	22	1.9	.0593	.1052
				CCD	2005	2013	29	0.6	.0121	.0055
10345	17053+5428	5.66		WDS	1819	2015	792	206.4		
		5.69	2.0	Photo	1965	1985	19	27.4	.0587	.0230
				CCD	2003	2013	101	11.1	.0085	.0103
10386	17102+5430	8.99		WDS	1830	2012	42	3.1		
		9.36	22.2	Photo	1961	2002	27	0.9	.0198	.0239
				CCD	2004	2013	24	0.3	.0127	.0087
11632	18428+5938	9.11		WDS	1831	2012	603	49.4		
		9.96	14.2	Photo	1961	1997	189	10.5	.0641	.0416
				CCD	2003	2013	95	3.9	.0125	.0039
12169	19121+4951	6.54		WDS	1819	2013	284	20.1		
		6.67	7.8	Photo	1961	1999	97	4.8	.0228	.0115
				CCD	2003	2013	89	1.5	.0046	.0032
12889	19456+3337	8.47		WDS	1831	2015	450	20.3		
		8.58	2.6	Photo*	1995	2005	8	4.9	.4399	.0131
				CCD	2003	2013	76	4.7	.0194	.0059
(Gl767)	19464+3201	10.38		WDS	1937	2015	81	7.7		
		11.15	4.8	Photo	1971	2006	35	2.6	.0772	.0345
				CCD	2003	2013	119	0.5	.0108	.0020
14636	21069+3845	5.20		WDS	1753	2013	1667	125.9		
		6.05	29.2	Photo	1958	1997	338	7.9	.0398	.0487
				CCD	2003	2013	123	1.8	.0128	.0082
15600	22038+6438	4.45		WDS	1779	2015	274	22.2		
		6.40	7.8	Photo	1963	2003	89	2.0	.0321	.0384
				CCD	2003	2013	109	0.6	.0157	.0142
16558	23100+3651	7.78		WDS	1825	2007	30	0.4		
		8.26	67.2	Photo	1995	2005	14	0.1	.0278	.0577
				CCD	2009	2013	73	0.1	.0196	.0102
17149	23595+3343	6.46		WDS	1832	2015	601	30.9		
		6.72	2.0	Photo*	1980	1996	10	18.7	.1975	.0348
				CCD	2003	2013	40	5.7	.0081	.0107

*Binary is not suitable for photographic observations.

Table 1 characterizes the observational data at our disposal concerning 28 binaries for which series of Pulkovo observations – both photographic and CCD – are available. It contains the following information: Aitken and WDS (Mason et al. (2016)) star numbers; m_V magnitudes of components A and B according to Mason et al. (2016); ρ, the mean separation between the components; the name of the series; the initial (T_1) and final (T_2) epochs according to WDS and Pulkovo observations; the number of observations (photographic plates or CCD series) n; $\Delta\theta$, the change of the position angle of secondary B relative to the primary A during the period of observations considered. The last two columns give Pulkovo-series single-observation errors in the

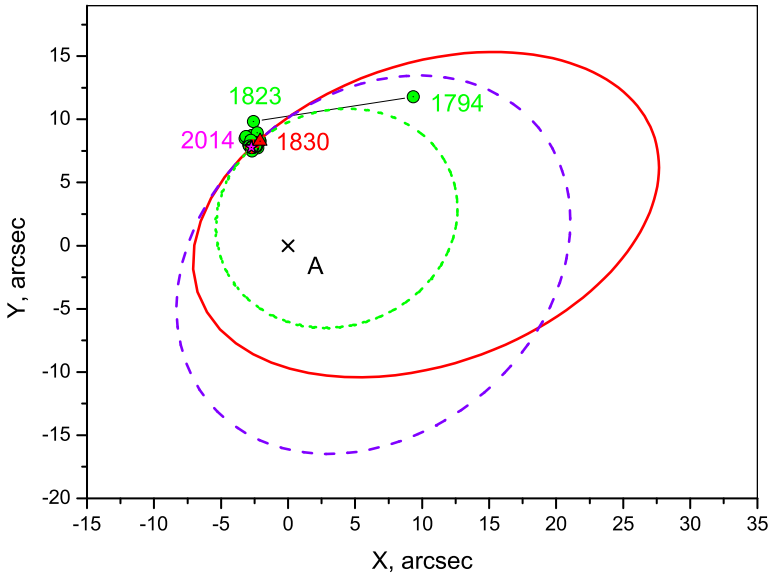


Figure 2 Positional observations and AMP orbits of ADS 10044. The X- and Y-axes point toward East and North, respectively, and the coordinate origin coincides with component A. Designations: the circles show observations adopted from WDS catalog (Mason et al. (2016)), the triangle shows the visual observations performed by V.Ya. Struve in 1830 (Mason et al. (2016)), the asterisks show the Pulkovo CCD observations made in 2003–2014 (Izmailov et al. (2010), Izmailov and Roshchina (2016)); the dotted, solid, and dashed lines show the ephemeris of the orbits corresponding to $\beta_{\min} = 0°$, $\beta = +38°$ and $\beta = -38°$, where β is the angle between the position vector and the sky plane. The ephemeris of all AMP orbits of the orbit family coincide over the 1830–2014 period (Kiselev et al. (2000)). The minimum orbital period is $P_{\min} = 18400$ years and the orbits require no refinement.

radial ($\sigma_{1\rho}$) and tangential ($\sigma_{1\tau}$) directions, where $\sigma_{1\tau} = (\pi/180) \cdot \rho \cdot \sigma_{1\theta}$. These data confirm the high quality of Pulkovo CCD observations.

The computational algorithm described in detail in Kiselev and Romanenko (1996) combined with the size of the observed arc of relative motion in each particular pair allow us to obtain one or two equally probable orbits or a family of orbits.

Here we show, by way of example, the family of AMP orbits for ADS 10044 (Fig. 2. The entire observed arc spans less than 3°) and two AMP orbits for ADS 2757 (Fig. 3, the entire arc spans 10°). In both cases Pulkovo photographic observations (Kiselev et al. (2014)) are used as the reference data. CCD observations (Izmailov et al. (2010), Izmailov and Roshchina (2016)) confirming that the above orbits were obtained after 2000, when this dynamic study was performed. Figure 3 clearly demonstrates the scatter of visual observations according to WDS data and the high accuracy of the Pulkovo photographic and CCD observations.

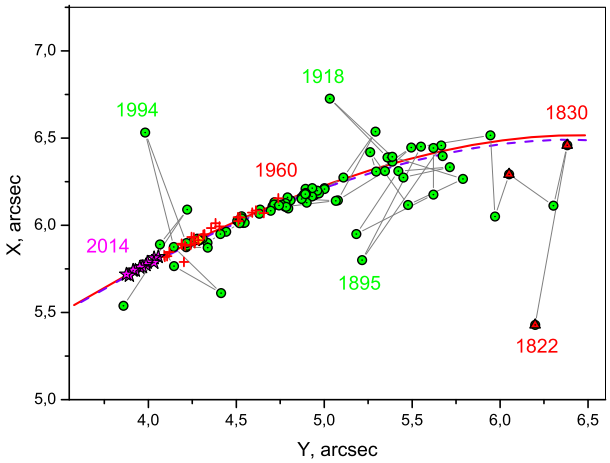


Figure 3 Positional observations and the AMP orbits of ADS 2757. Designations: the crosses show the photographic observations made in Pulkovo (1960–2001) (Kiselev et al. (2014)); the solid and dashed lines show the ephemeris of the orbits corresponding to $\beta = +3^\circ$ and $\beta = -3^\circ$, and the remaining designations are as in Fig. 2. The ephemeris of these two equally probable orbits with the period of $P = 1090$ years practically coincide in the 1830–2014 interval (Kiselev et al. (2000)) and require no refinement. The figure clearly demonstrates the scatter of visual observations according to WDS (Mason et al. (2016)) data and the high accuracy of Pulkovo photographic (Kiselev et al. (2014)) and CCD (Izmailov et al. (2010), Izmailov and Roshchina (2016)) observations.

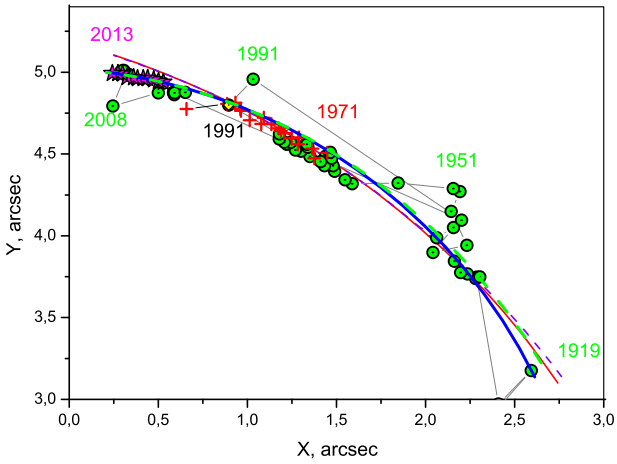


Figure 4 Positional observations and AMP orbits of ADS 2427. Designations: the diamond sign shows HIPPARCOS space-born observations (1991) (Mason et al. (2016))); the thin solid and the thin dashed lines show the ephemeris of the orbits corresponding to $\beta = +44^\circ$ and $\beta = -44^\circ$ (Kiselev et al. (2009b), $P = 540$ years), the thick solid and thick dashed lines show the ephemeris of AMP orbits corresponding to $\beta = +32^\circ$ and $\beta = -32^\circ$ with $P = 400$ years that we computed this year. Other designations are as in Fig. 2. This figure clearly demonstrates that the 2009 orbits have to be refined using Pulkovo CCD observations (Izmailov et al. (2010), Izmailov and Roshchina (2016)).

Figure 4 illustrates our refinement of the AMP orbits for ADS 2427 performed this year. Note that the reference data for the refined version include CCD observations (Izmailov et al. (2010), Izmailov and Roshchina (2016)) supplemented with HIPPARCOS spaceborne observations of 1991 (Mason et al. (2016)) (the base arc spans 8°).

4 Conclusions

As a result of this work we:

• Demonstrated the current importance of computing the orbits of wide visual binaries.

• Based on 28 available CCD sets demonstrate the high quality of the CCD observations of the 26-inch Pulkovo refractor (see Table 1), which allows us to find fine effects in visual binary and multiple systems. Hence series of CCD observations of wide pairs should be continued with an accuracy at least as good as that currently achieved.

• Of the 53 stars that we analyzed within the framework of this study at least 42 need no refinement of the orbits, whereas the orbits of 11 stars have to be refined, and three stars with very slow orbital motion and unreliable orbits (ADS 6646, 8682 and 16407) as well as two optical pairs (ADS 3593 and ADS 16558 have to be excluded from further statistical analysis.

The release of the GAIA mission results may stimulate the determination of new orbits. In the future we plan to determine the orientation of the computed orbits in the Galactic coordinate system and report the results of its statistical analysis.

This research has made use of the Washington Double Star Catalog (Mason et al. (2016)) maintained at the U.S. Naval Observatory, and we are deeply grateful to its creators.

We are sincerely grateful to all the observers at the 26-inch refractor of the Main Astronomical Observatory of the Russian Academy of Sciences, especially to the coauthors of catalogs Kiselev et al. (2014), Izmailov et al. (2016), Izmailov et al. (2010), and Izmailov and Roshchina (2016). We are grateful to I.S. Izmailov for automating the telescope and continuing CCD observations, and to the people who measured the radial velocities for stars of the Pulkovo program: E.L Chentsov, A.A. Tokovinin, N.A. Gorynya, and R.Ya. Zhuchkov.

We are also grateful to O.V. Kiyaeva and E.A. Roshchina for valuable comments and advice. We plan to continue our observations and studies of visual binaries of the Pulkovo program including wide pairs with slow orbital motion, as well as our work on the Pulkovo catalog of the orbits of wide pairs.

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