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Orbits of Four Visual Binaries Determined from Observations along Short Arcs

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Abstract—The orbits of the four visual binaries ADS 246 (GL 15), ADS 7724 (γ Leo), ADS 10386 (GJ 659), and ADS 14909 (1 Peg) have been determined using the apparent motion parameters (AMP) method. The orbital periods of these stars are 1200, 550, 7500, and 18 000 yr, respectively. The orbits were calculated based on observations along short arcs obtained with the 26-inch refractor of the Pulkovo Observatory and Hipparcos parallaxes, supplemented with radial-velocity measurements for the components of these pairs taken from the literature. All visual and photographic observations of these stars after 1830 from the WDS catalog have been taken into consideration. The new orbits of ADS 246 and ADS 7724 are compared with the orbits computed in other studies. The orbits of ADS 10386 and ADS 14909 have been determined for the first time. The orientation of the planes of the computed orbits in Galactic coordinates have also been calculated.

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1. INTRODUCTION

In addition to measurements of the stellar positions, determining the orbit of a visual binary using the parameters of the apparent motion (AMP) method [1] requires knowledge of additional parameters, namely, the parallax of the star and the difference of the component radial velocities at a single epoch, as well as an estimate of the sum of the component masses. This total mass is first specified, and then verified and improved during the calculations.

In 1992, we searched for binary stars with such data in catalogs and other publications, with the aim of including them in a program of observations with the 26-inch refractor of the Pulkovo Observatory. We selected about ten such stars and began photographic observations of them. Later, the results of Hipparcos space observations were published [2], which contained improved trigonometric parallaxes for the binary stars in our program. It also became possible to obtain global position measurements, thanks to the annually updated Washington Double Star (WDS) catalog [3].

This study is part of the Pulkovo program of observations of visual binaries in the solar neighborhood [4–6], and continues the earlier studies [7–12]. Details of the calculation algorithm are presented in [7].

2. OBSERVATIONAL MATERIAL

This work is aimed at dynamical studies of four visual binaries near the Sun: ADS 246 (GL 15), ADS 7724 (γ Leonis), ADS 10386 (GJ 659), and ADS 14909 (1 Pegasi). These stars were discovered as binaries long ago, but still do not have reliably determined orbits, due to their slow orbital motion.

Table 1 provides general data on the binary stars studied here: their magnitudes and spectral types from the WDS catalog [3], their parallaxes and their errors from the Hipparcos catalog [2], the proper motions of the components according to [3], and the component radial velocities and their errors from [14] for ADS 246, [15] for ADS 7724, [16] for ADS 10386, and [13] for ADS 14909. The table shows that components of all four visual binaries have a common motion, both in the plane of the sky and along the line of sight. There is no doubt that these pairs are physical.

Table 2 characterizes the observational material at our disposal. The parameters listed are: the initial (T_i) and final (T_f) epochs in the WDS catalog [3] and for the Pulkovo observations (Pul), the number of observations (in the former case) or of photographic plates (in the latter case) n, the middle of the corresponding set of observations T, the change in the position angle of component B relative to the main component A (in degrees) $\Delta\theta$ during the corresponding observation period Δt, the series considered, and the errors of a single observation (or a single plate).

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Table 1. General data on the four binaries

ADS WDS	Component	m_V	Sp	π_{Hip}	μ_x, mas/yr	μ_y, mas/yr	V_r, km/s	$\varepsilon(V_r)$, km/s
ADS 246	A	8.07^m	M2 V	$0.279''$	2860	390	11.97	±0.22
(WDS 00184+4401)	B	11.04	M6 V	$\pm 0.001''$	2884	410	10.98	±0.16
ADS 7724	A	2.12	K1 III	0.026	311	−153	−37.14	±0.11
(WDS 10200+1950)	B	4.23	G7 III	±0.001	306	−161	−37.43	±0.17
ADS 10386	A	8.99	K0 V	0.047	083	−112	2.69	±0.13
(WDS 17102+5430)	B	9.36	K8 V	±0.001	087	−106	1.73	±0.12
ADS 14909	A	4.09	K1 III	0.021	106	063	−76.50	±0.30
(WDS 21221+1948)	B	9.14	K0 V	±0.001	110	067	−76.84*	±0.12

* Mean radial velocity of spectroscopic-binary component B from [13].

Table 2. Position series for the four binaries

ADS	T_i, yr	T_f, yr	n	T, yr	$\Delta\theta$	Δt, yr	Series	$\sigma_{1\rho}$	$\sigma_{1\theta}$
246	1860	2011	112	1935	12.0°	152	WDS	$0.50''$	0.37°
	1994	2006	7	2000	1.3	13	Pul	0.06	0.52
7724	1782	2010	803	1919	22.0	229	WDS	0.27	1.08
	1992	2006	20	1998	1.1	15	Pul	0.04	0.29
10386	1830	2006	40	1918	3.0	177	WDS	0.23	0.64
	1961	2002	24	1987	0.9	42	Pul	0.02	0.07
14909	1780	2011	69	1896	3.0	232	WDS	0.35	0.61
	1994	2007	11	2001	0.0	14	Pul	0.09	0.09

These data confirm the advantage of using uniform sets of observations (in this case, the Pulkovo data).

It is obvious that the first two stars have more appreciable orbital motions than the last two. However, classical methods for orbital determination are not suitable for all four stars, due to the short arcs for which observations are available.

Table 3 lists the apparent motion parameters for the four pairs, namely, the mean epoch T_0 and number of observations used to determine the parameters n, the polar coordinates of component B relative to the main component A ρ and θ, the value and position angle of the apparent motion of B relative to A μ and ψ, defined for the mean epoch T_0, the length of the short arc along which observations are available $\Delta\theta$, the time interval over which observations are available, Δt, and the observation series considered. The angles θ and ψ have been reduced to the equator at epoch 2000.0.

For ADS 246 and ADS 10386, we supplemented our Pulkovo data with photographic observations from the US Naval Observatory in Washington (USNO). It is important for the AMP method that both the USNO and Pulkovo observations are uniform. The Pulkovo data appear to be sufficient to determine the orbit of ADS 7724. For ADS 14909, we used all available observations from the WDS catalog and Pulkovo (except for two erroneous measurements). The value $\Delta\theta$ characterizes the length of the short arc (basis) used to determine the orbital parameters, and ranged from 1° to 4°.

We estimated the component masses based on their known spectral types, see Table 4. In the case of ADS 14909, it is known [13] that component B is a spectroscopic binary. We took the masses of its components from [17]. We used the component masses from Table 4 and the parallaxes and radial

Table 3. The apparent (relative) motion parameters for the four pairs

ADS	T_0, yr n	ρ $\pm\varepsilon(\rho)$	$\theta_{2000.0}$ $\pm\varepsilon(\theta)$	μ, arcsec/yr $\pm\varepsilon(\mu)$, arcsec/yr	$\psi_{2000.0}$ $\pm\varepsilon(\psi)$	$\Delta\theta$	Δt, yr	Series
246	1985.13	35.924″	62.735°	0.0733	193.3°	3.8°	43	USNO + Pul
	53	±0.005″	±0.008°	±0.0003	±0.3°			
7724	1994.06	4.619	125.083	0.0086	175.9	1.1	15	Pul
	20	±0.009	±0.066	±0.0011	±8.2			
10386	1987.70	22.180	133.734	0.0078	30.5	0.9	42	Pul + USNO
	28	±0.003	±0.012	±0.0004	±2.2			
14909	1980.12	36.249	311.328	0.0045	63.2	3.0	232	WDS + Pul
	78	±0.037	±0.072	±0.0007	±7.7			

Table 4. Orbital elements for the four pairs

β	a	P, yr	e	ω	i	Ω	T_Π, yr	l_Q	b_Q	Author
ADS 246 ($M_{\rm AB} = 0.56M_\odot$)										
0°	26.73″	1253	0.59	331°	46°	243°	2327	325°	60°	Romanenko
	±3.54	±259	±0.19	±32	±11	±25	±81	±39	±6	
	41.15	2600	0.00	0	61	45	1745	(259)	(−30)	Lippincott
ADS 7724 ($M_{\rm AB} = 5.5M_\odot$)										
38	3.10	554	0.90	309	49	347	1750	32	−6	Romanenko
	±0.10	±27	±0.03	±6	±6	±9	±16	±7	±6	
−38	3.10	554	0.93	114	41	188	1769	133	−72	Romanenko
	±0.10	±27	±0.02	±10	±5	±14	±13	±28	±6	
(−12)	2.51	618	0.84	162	36	143	1743	(312)	(−79)	Rabe
(−52)	4.24	510	0.85	118	76	143	1671	(242)	(−47)	Mason et al.
ADS 10386 ($M_{\rm AB} = 1.3M_\odot$)										
72	∞	∞	1.00	196	108	234	44351	176	37	Romanenko
28	19.63	7485	0.55	289	129	288	3936	130	8	Romanenko
0	16.20	5610	0.39	347	129	314	4360	115	−5	Romanenko
−28	19.63	7485	0.36	62	124	335	−671	101	−17	Romanenko
−72	∞	∞	1.00	173	106	11	−25750	66	−37	Romanenko
ADS 14909 ($M_{\rm AB} = 6.24M_\odot$)										
80	∞	∞	1.00	241	81	240	10532	131	68	Romanenko
30	26.06	17500	0.70	265	30	212	8212	257	50	Romanenko
0	21.97	13500	0.70	351	18	131	7315	269	20	Romanenko
−30	26.06	17500	0.61	47	38	85	9717	276	−8	Romanenko
−80	∞	∞	1.00	241	81	66	−3102	292	−51	Romanenko

velocities from Table 1 to determine the AMP-orbits of the four binaries.

One of the necessary parameters for orbit determination using the AMP-method is the radius of curvature of the visible arc of the orbit close to the point (ρ, θ) at epoch T_0. This parameter cannot be determined for any of the four binaries considered here. However, as we showed in [7], we can replace the directly determined spatial distance r between the components with the estimate given below, which yields a family of the orbits that depend on r:

$$r_{\min} = \frac{\rho}{\pi_t} \leq r < r_{\max} = \frac{8\pi^2}{V^2} M_{\mathrm{AB}}. \qquad (1)$$

Here, $r_{\min}$ is the minimum value of the distance r (projection of the vector $\mathbf{r}$ onto the plane of the sky), $r_{\max}$ is the maximum value of r that still admits elliptic motion according to the energy integral in the two-body problem, π_t is the trigonometric parallax, M_{AB} is the total component mass (in solar units), and V is the spatial velocity of component B relative to component A (in AU/year), derived from position measurements and spectral observations:

$$V^2 = \left(\frac{\mu}{\pi_t}\right)^2 + \left(\frac{\Delta V_r}{4.74}\right)^2, \qquad (2)$$

where $\Delta V_r = V_{r\mathrm{B}} - V_{r\mathrm{A}}$ is the relative radial velocity of the components in km/s.

We denote β to be the inclination of the vector $\mathbf{r}$ to the plane of the sky at mean epoch T_0. The value of β can be estimated from the relation

$$r \cos\beta = \frac{\rho}{\pi_t}, \qquad (3)$$

where r must satisfy condition (1) for a given ρ, π_t, V, and M_{AB}. The value of β is confined between $\beta_{\min} = 0$ and $\pm\beta_{\max}$. We denote β_{mdl} to be the angle β corresponding to the middle of the spherical belt of all possible orbits.

Note that relation (3) yields two values $\pm\beta$ corresponding to the location of component B relative to the main component A at epoch T_0, one behind the plane of the sky ($\beta > 0$) and one in front of this plane ($\beta < 0$). As a result, we obtain two equally probable orbits, which are identical in a dynamic sense but differ geometrically.

If observations far enough from the basic series are available, it is possible to determine a unique solution by selecting the β value that satisfies all the observations best.

Orbital determination using the AMP method requires knowledge of the difference of the component radial velocities at some epoch T_{Vr} [see Eq. (2)]. For stars with constant radial velocity, any time near the middle of the interval of spectral observations of the component can serve as this epoch. For a component that is a spectroscopic binary, the epoch T_{Vr} must be the time when this star passes through the periastron of the spectroscopic orbit.

When the epoch of the middle of the series of positions T_0 does not coincide with T_{Vr}, the value ΔV_r must be corrected for the orbital motion, separately for the cases $\beta > 0$ and $\beta < 0$. To avoid these difficulties and additional errors, we choose $T_0 = T_{Vr}$ for all four binaries studied (Table 3).

3. RESULTS

ADS 246 is the closest binary, with a very large proper motion for its components (Table 1) and the most reliable orbital motion. The basic observations of ADS 246 (USNO + Pul), the old observations (from 1860 to 1959), and the last (2011) observations from the WDS catalog [3] are shown in Fig. 1, as well as our three solutions for the AMP-orbits (E0, E1, and E2, corresponding to $\beta = 0°$ and $\beta_{mdl} = \pm 28°$) from the family of all possible orbits. All three orbits coincide in 1959–2011. It is obvious that only the E0-orbit satisfies the old observations; it is close to the circular orbit of Lippinkott [18], obtained in 1972, but agrees better with the modern observations. Figure 2 shows our E0 AMP-orbit and the orbit of Lippinkott [18], as well as all the WDS observations [3] and Pulkovo observations.

It is interesting that, if we add to the joint USNO + Pul series photographic observations made at the Sproul Observatory (1939–1962, eight normal places) and the McCormick Observatory (1925–1965, four normal places) [18], we are able to determine the radius of curvature, and derive a AMP-orbit that is identical to E0. If we add all the WDS data to the Pulkovo observations, the derived AMP-orbit satisfies both the old and modern observations less well.

ADS 7724 is a very bright ($m_{\mathrm{A}} \sim 2^m$, $m_{\mathrm{B}} \sim 4^m$) and close ($\rho \sim 5''$) binary. Owing to difficulties with the position measurements for this star, they form an arc with a larger scatter (Fig. 3). As we will see below, the Pulkovo observations were made close to apastron (where the curvature is very large). No expansion of the basis, i.e. supplementing the Pulkovo observations with the USNO or Dearborn observations, or even with all the observations from the WDS catalog [3], provides good AMP-orbits that pass through all the observed points. Therefore, to obtain our final orbit, we limited our analysis to the Pulkovo observations.

Figure 3 shows all the observations for ADS 7724 from the WDS-catalog obtained in 1782–2010, including five normal places obtained by Struve, our

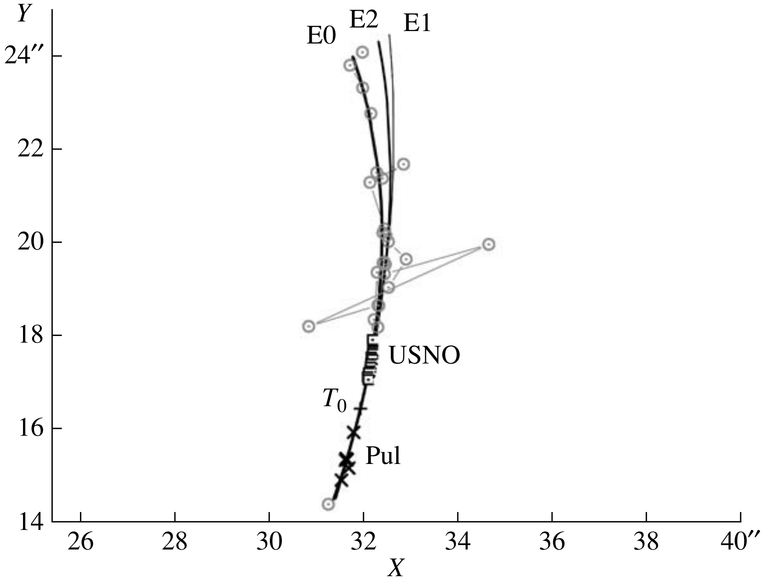

Fig. 1. ADS 246: position measurements in 1860–2011. X and Y are directed to the East and North, and the coordinate origin coincides with component A. The circles show observations from the WDS catalog [3] made prior to 1959 and the last measurement made (2011), squares show the Washington USNO observations [3], and crosses the Pulkovo observations (normal places, Pul). T_0 is the the middle of the unified USNO + Pul series. The arcs E0, E1, and E2 are the ephemerides of the AMP-orbits for a given segment of the orbit, corresponding to $\beta = 0°$, $+28°$, and $-28°$.

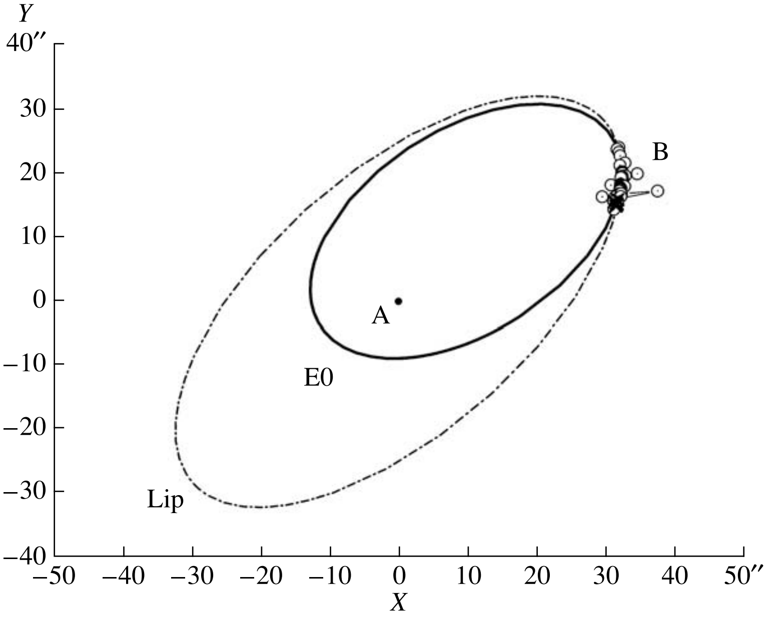

Fig. 2. ADS 246: projection of orbits onto the XY plane. The solid ellipse shows the E0 AMP-orbit, and the dot-dashed ellipse the orbit of Lippincott [18] (Lip). The remaining notation is as in Fig. 1.

Pulkovo observations, and our E0, E1, and E2 AMP-orbits, corresponding to $\beta = 0°$ and $\beta = \pm 38°$. The E0 orbit does not pass through the old observations. The projections of the E1 and E2 orbits onto the plane of the sky coincide, and describe well all the available observations. We also show in Fig. 3 orbits obtained by other authors. The orbit of Rabe [19] is in poor agreement with modern observations, whereas the orbit of Mason et al. [20] satisfies these observations within the errors. Additional observations obtained

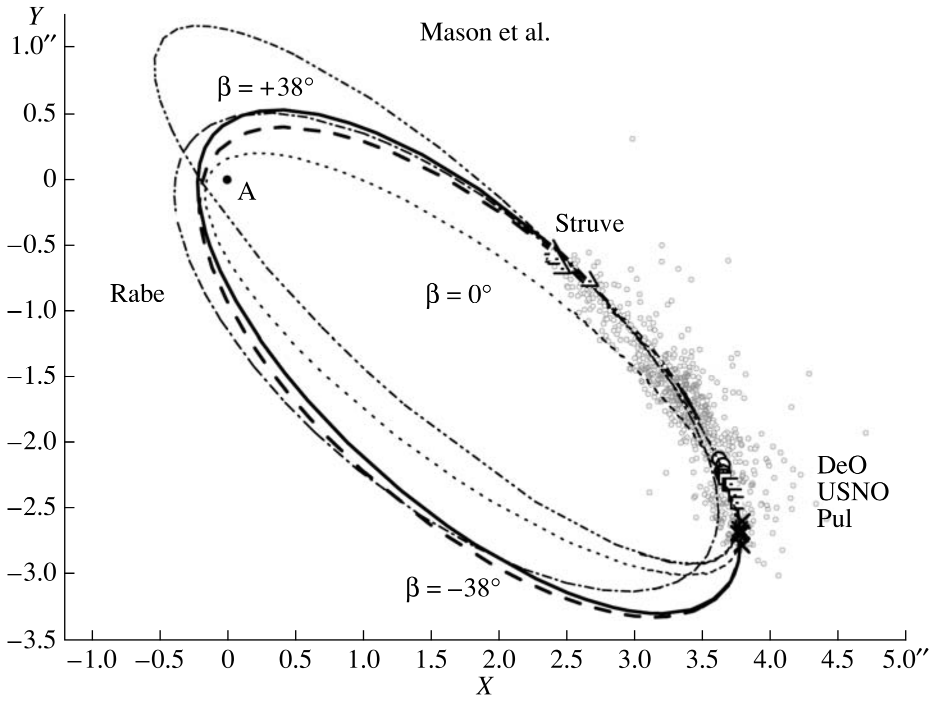

Fig. 3. ADS 7724: position measurements during 1782–2010 and projections of the orbits onto the plane of the sky. Pulkovo observations (crosses) and observations from the WDS catalog [3] (filled circles) are shown. The observations of Struve (triangles, Struve), the Dearborn Observatory (open circles, DeO), and the Washington USNO (squares) are identified separately (see [3]). The dotted, solid, and dashed lines show our E0 ($\beta = 0°$), E1 ($\beta = +38°$), and E2 ($\beta = -38°$) AMP-orbits; the dot-dash-dot line shows the orbit found by Rabe [19] (Rabe), and the double-dot-dash line shows the orbit found by Mason et al. [20] (Mason et al.).

over the next 10 years will demonstrate which of the computed orbits is closer to the true one.

Note that, if we take into account the Hipparcos parallax for this star, $\pi_t = 0.026''$, the orbit of Rabe [19] will correspond to the dynamical mass of the system $M_{\rm AB} = 2.34 M_\odot$, while the orbit of Mason et al. [20] will correspond to $M_{\rm AB} = 16.66 M_\odot$. We have no data suggesting an excess of the sum of the component masses over the normal mass corresponding to the mass–luminosity relation, $M_{\rm AB} = 5.5 M_\odot$.

ADS 10386 is an ordinary binary star, with a small proper motion and radial velocity, which, however, provide evidence for the physical nature of the binary (Table 1). Due to the small relative motion of the components in this pair, the radius of curvature of the visible arc of the orbit cannot be determined, as for the previously considered stars. However, since all the orbits of the family of solutions we have obtained coincide in the segment 1830–2006 (which 40 measurements from the WDS catalog and 8 normal places from the Pulkovo observations, Fig. 4), it is not possible to choose a unique solution.

It is interesting that, in the above-mentioned segment of the orbit (Fig. 4), the ephemeris of the AMP-orbit for $\beta = 0°$ obtained for the combined Pul + USNO dataset coincides with the ephemeris of the AMP-orbit based on the combined WDS + Pul dataset; both solutions describe all the observations well. The ephemeris of the orbit based on the WDS catalog alone is in poorer agreement with the Pulkovo observations.

Figure 5 shows several characteristic orbits of the families of solutions obtained for ADS 10386 using the combined Pul + USNO and WDS + Pul datasets ($\beta = 0°$ and $\beta_{mdl} = \pm 28°$). These families coincide within the errors, and further we will use the solutions from the first of these families, since it is the most uniform (Table 4).

Like ADS 7724, the bright pair ADS 14909 is difficult for photographic observations (Table 1): component A is bright, while component B is 5 magnitudes weaker (!); i.e., it is practically impossible to find an optimal exposure. We believe this explains the absence of any other series of observations (apart from the Pulkovo series), in contrast to the other three stars studied.

An additional difficulty is related to the fact that component B is a spectroscopic binary with a period three years [13]. As a result, we have 69 observations

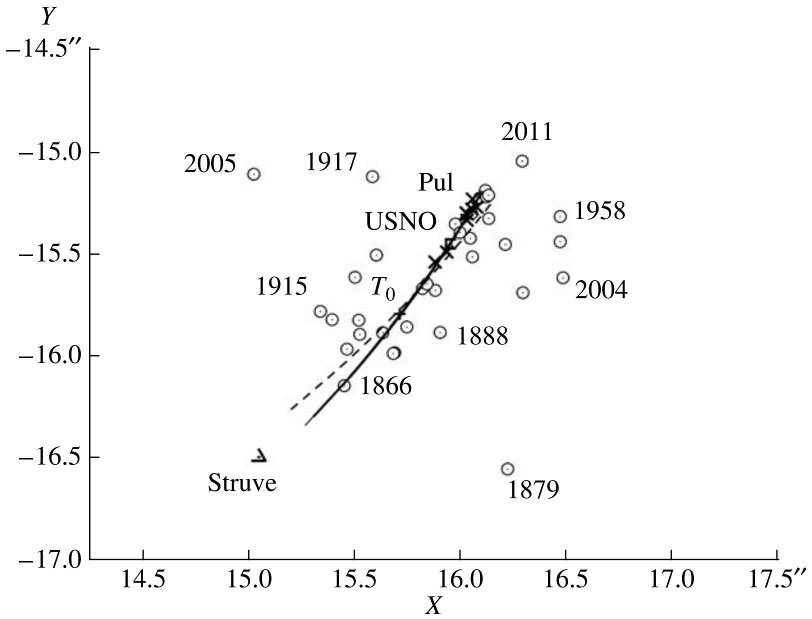

Fig. 4. ADS 10386: position measurements in 1830–2006. The lines show the ephemerides of the AMP-orbits for this period. The bold solid line is obtained from the Pul + USNO data, the thin solid line, which coincides with the bold one, from WDS + Pul data (T_0 is the middle epoch), and the dashed line from WDS catalog without two observations (1879 and 2005) which have been left out. The remaining notation is as in Fig. 3.

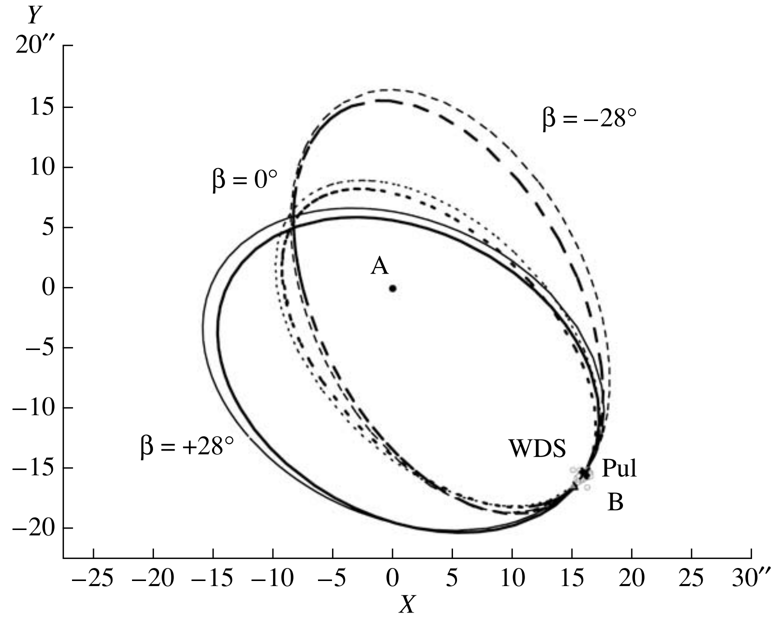

Fig. 5. ADS 10386: typical orbits in the plane of the sky. The bold ellipses show orbits obtained from the unified Pul + USNO dataset, and the thin ellipses show orbits obtained from the WDS + Pul dataset. The dotted, solid, and dashed ellipses show the E0 ($\beta = 0°$), E1 ($\beta = +28°$), and E2 ($\beta = -28°$) orbits, respectively. The remaining notation is as in Fig. 3.

from the WDS catalog [3] displaying a large scatter of about 0.4″ (Fig. 6). However, disregarding two observations dated 1993 and 2009, which lie beyond the limits of Fig. 6 and are apparently erroneous, we obtained the AMPs from the combined WDS + Pul dataset (Table 3) and a family of possible AMP-orbits (Table 4). All the orbits of the obtained family coincide in the 1780–2011 segment. Figure 7 shows the

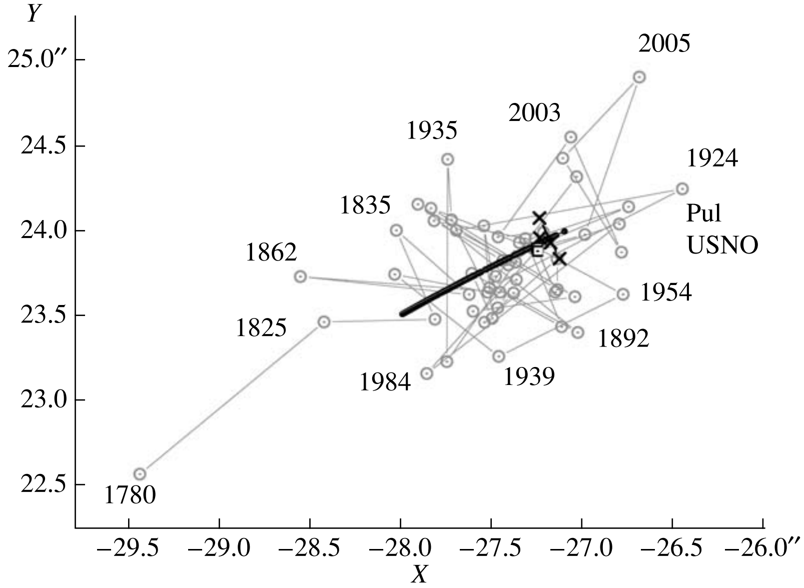

Fig. 6. ADS 14909: position measurements in 1780–2011. The bold solid arc shows the ephemerides of the AMP-orbits, which coincide in the given segment of the orbit. The remaining notation is as in Fig. 3. See also the comments in the text.

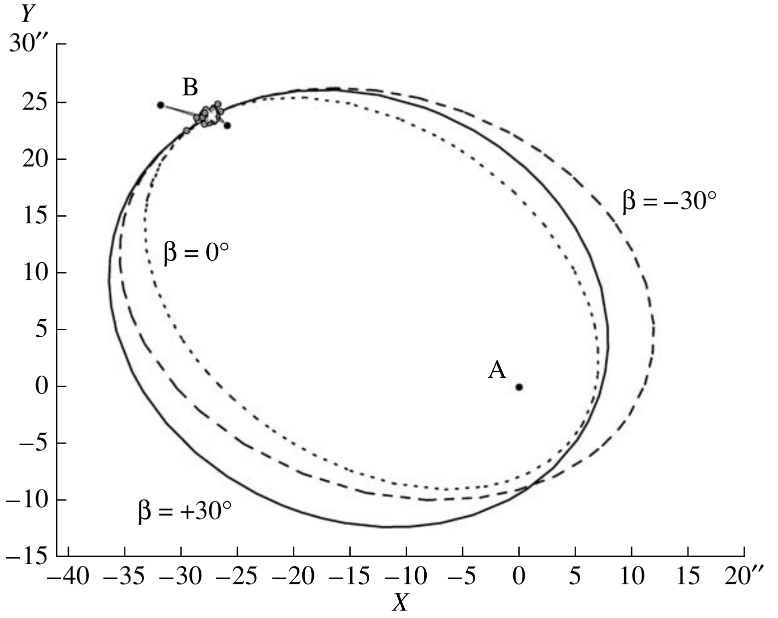

Fig. 7. ADS 14909: typical orbits in the plane of the sky. The dotted, solid, and dashed ellipses are our E0 ($\beta = 0°$), E1 ($\beta = +30°$) and E2 ($\beta = -30°$) AMP-orbits, respectively. The Pulkovo observations are marked by light crosses against the background of all the observations (open circles).

three characteristic orbits for ADS 14909 ($\beta = 0°$ and $\beta_{mdl} = \pm 30°$). The short arc covered by all the observations proves to be close to the apastron of all orbits of the family.

Table 4 lists the elements for both our AMP-orbits and orbits derived by other authors. The headings of the sections of the table for each star provide the sum of the component masses $M_{\rm AB}$ in $M_\odot$. The first column of the table indicates the inclination of the vector $\mathbf{r}$ to the plane of the sky β, and the last columns give the Galactic coordinates $l_{\rm Q}$ and $b_{\rm Q}$ of the direction to the pole of the orbit Q. Values computed by us using the data of other authors are provided in brackets.

For ADS 246 we obtained only one sufficiently reliable solution for $\beta = 0°$. Our E0 AMP orbit has a period that is half the period of the orbit of Lippinkott [18], and is not circular. Both of the AMP-orbits for ADS 7724 have average values of the semi-major axis a, period P, and inclination i, compared to the orbital elements obtained by other authors: a large semi-major orbital axis a, period P and inclination i, and have a larger eccentricity e.

Table 4 also presents the elements of typical AMP-orbits for ADS 10386 and ADS 14909 for five symmetric cases: $\beta = 0°$, $\beta = \pm\beta_{mdl}$, and $\beta = \beta_{\max}$. We consider the orbits for $\beta = \pm\beta_{mdl}$ (which correspond to the middle of the spherical belt formed by all possible orbits) to be most plausible; i.e., $\beta = \pm 28°$ for ADS 10386 and $\beta = \pm 30°$ for ADS 14909.

4. CONCLUSION

This paper has continued our earlier studies [7–12]. As was shown earlier, the AMP-method can be used to determine the orbit of wide or close visual binaries ($\rho > 3''$) based on a short arc of position measurements ($\Delta\theta \sim 1°–5°$). This also requires knowledge of the relative radial velocity of the binary components and the binary's trigonometric parallax. The sum of the component masses is also required; it is initially specified, then verified and refined as needed in the course of calculations. When the radius of curvature of the observed arc of the orbit cannot be determined, it is possible to find *a family* of orbits that depends on the adopted spatial distance r between the components satisfying condition (1).

This study confirms that the existence of a large number of non-uniform measurements distributed over a short arc ∼10°–20° does not enable reliable determination of the orbit. We used only *uniform* sets of observations over short arcs (from 1° to 4°) to determine the orbits of the four stars studied using the AMP-method: the Pulkovo and WDS data. The required additional data—the component radial velocities and parallaxes of the binary stars—were taken from the literature (Table 1). The resulting orbits are presented in Table 4.

If old measurements are available and are further than 10° from the main set (basis) used, it should be possible to identify a unique orbit from the entire family. In the case of an overall arc that is shorter than 3°, the AMP-method is able to determine only a *family* of orbits satisfying all the observations.

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