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# ORBITS OF WIDE BINARIES – NEW POSSIBILITIES

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**Abstract.** We use the Apparent Motion Parameters (AMP) method for the determination of orbits of visual double stars (Kiselev & Kiyaeva 1980). The quality of AMP orbits is completely dependent on the precision of parameters of relative positions and motions at the same instant. They are calculated on the basis of a short arc of observations. To determine these parameters, we use recent high precision observations obtained with the best modern techniques. New orbits of three stars are presented.

**Key words:** binaries: visual – stars: individual (HIP 50, HIP 15058, HIP 66195)

## 1. INTRODUCTION

Regular photographic observations of visual double stars were performed with the 26-inch Pulkovo refractor between 1960 and 2007 (Kiselev et al. 2014; Izmailov et al. 2016). CCD observations have been performed since 2003 (Izmailov et al. 2010). This telescope is now completely automated, and CCD observations are continuing.

Possibilities of the Pulkovo 26-inch refractor allow us to observe wide binaries ($\rho > 2''$) with large orbital periods. These stars are studied poorer than the close ones. There are 2660 orbits of visual double stars in the 6th catalog of orbits (ORB6, ad.usno.navy.mil/wds/orb6.html, version 2016), but only 80 pairs (3%) have periods exceeding 2000 years (see Table 1). A. A. Kiselev suggested the AMP method specially for such stars.

The algorithm of the Apparent Motion Parameters (AMP) method to determine the orbit from a short arc was described repeatedly (see Kiselev & Kiyaeva 1980; Kiselev et al. 2012). The input data are apparent motion parameters at the same instant $t_0$ corresponding to the middle of the short arc, that are determined from positional observations: the apparent separation between the components ($\rho$), the position angle of the relative position ($\theta$), apparent relative motion ($\mu$), the position angle of the direction of relative motion ($\psi$), and, sometimes, the radius of curvature ($\rho_c$). Also, it is necessary to know the relative radial velocity $\Delta V_r$ at the instant $t_0$, that can be determined from spectroscopic observations additionally, parallax $\pi_t$ (from the *Hipparcos* catalog), and the sum of masses of the components $M_{A+B}$ (from their spectral types). If it is possible to determine

**Table 1.** Distribution of stars with known orbits by orbital period, based on the ORB6 catalog data.

| Period, yr | Number of orbits | Fraction (%) of all orbits |
|---|---|---|
| $< 1$ | 144 | 5.4 |
| 1 – 100 | 1054 | 39.6 |
| 100 – 500 | 639 | 24.0 |
| 500 – 1000 | 193 | 7.2 |
| 1000 – 2000 | 88 | 3.3 |
| 2000 – 10 000 | 50 | 1.9 |
| $> 10\,000$ | 30 | 1.1 |

$\rho_{\rm c}$, then we can calculate the spatial distance between the components, $r$:

$$r^3 = 4\pi^2 M_{\rm A+B} \frac{\rho\rho_{\rm c}}{\mu^2} |\sin(\theta - \psi)| \,, \tag{1}$$

and there are two orbits, corresponding to the angles $\beta = \pm \arccos(\rho/r\pi_{\rm t})$.

If it is impossible to determine $\rho_{\rm c}$, then

$$\frac{\rho}{\pi_{\rm t}} \leq r \leq \frac{8\pi}{V^2} M_{\rm A+B}, \tag{2}$$

$$V^2 = \left(\frac{\mu}{\pi_{\rm t}}\right)^2 + \left(\frac{\Delta V_{\rm r}}{4.74}\right)^2. \tag{3}$$

The drawback of this method is impossibility of obtaining masses from the orbit, but properties of stars are sufficiently known for making use of the mass–luminosity–spectral type relation to estimate masses and to get the orbit in a first approximation.

There is an important advantage of this method. To determine the orbit, we use not all observations but only the best, high-precision ones. Other archive observations are used to check the quality of the orbit, to test the fitting of all input parameters, to estimate unknown parameters ($\Delta V_{\rm r}$ or $\beta$), and to select the unique orbit if the arc of all observations is long enough. The algorithm to use archive observations was described in detail by Kiyaeva (1983) and Kiyaeva & Gorynya (2015).

Now double and multiple stars are observed with large telescopes intensively, mainly in the search for exoplanets, and it is possible to use only these observations as short arcs for the determination of apparent motion parameters.

The new orbits of the wide double stars HIP 50, HIP 15058, and HIP 66195 were obtained by the AMP method on the basis of the best contemporary observations. They are presented in this paper. Also, as a test example, we consider below a short-period binary star.

## 2. THE SHORT-PERIOD BINARY STAR T TAURI Sa-Sb

This star was observed by the VLT: since 2002 till 2008 by the NAOS/CONICA (NACO) unit and then by the SPHERE unit. Note that this pair was discovered in 1983, but reliable observations have been performed since 1997 (Koehler et al.

2008). We obtained the orbit of this star using only six uniform VLT/NACO observations ($t_0 = 2005.5$ in the middle of 2002–2008) as the main short arc (Zhuchkov et al. 2010). Schaefer et al. (2014) obtained a new orbit including all observations. We want to check out when our AMP orbit will no longer satisfy modern observations.

Both orbits are shown in Fig. 1; the orbital elements are presented in Table 2. We see that our AMP orbit begins to deviate from observations at $t_1 \approx 2011$, $t_1 - t_0 \approx 0.2P$, where the orbital period is $P = 29$ years. Note, however, that the orbital elements agree sufficiently well, within error intervals (see Table 2).

Thus, we can hope that, in the case of accurate observations, the AMP orbit can be used during $\Delta t \approx 0.2P$ from the instant $t_0$, but it depends specifically on the positions of the components in the orbit. Then, in the case of $P = 1000$ years, the AMP orbit could be reliable for $\Delta t \approx 100 - 200$ years.

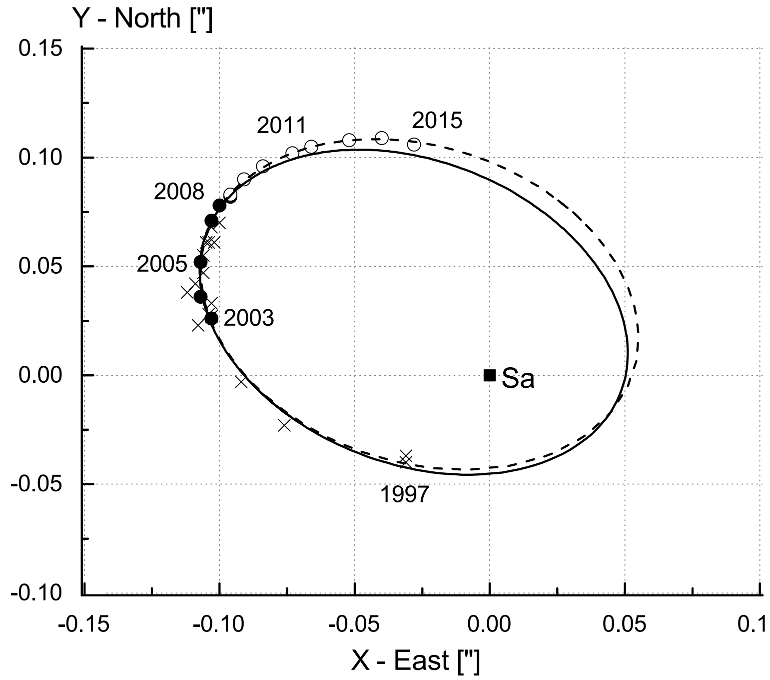


**Fig. 1.** Comparison of the orbits of T Tauri Sa-Sb: AMP (solid curve), Shaefer et al. (2014) (dashed curve). Observations: VLT/NACO (filled circles), VLT/SPHERE (open circles), other observations (crosses).

**Table 2.** Orbital elements of the star T Tauri Sa-Sb.

| Orbit | $a$, mas | $P$, yr | $e$ | $i°$ | $\omega°$ | $\Omega°$ | $T$, yr |
|---|---|---|---|---|---|---|---|
| AMP, 2010 | 87 | 27 | 0.47 | 31 | 198 | 300 | 1995.8 |
| | ±7 | ±3 | ±0.09 | ±11 | ±45 | ±23 | ±3.3 |
| Schaefer et al. (2014) | 89 | 29 | 0.49 | 29 | 218 | 287 | 1995.8 |
| | ±7 | ±4 | ±0.12 | ±12 | ±14 | ±19 | ±0.9 |

**Table 3.** Data on the binaries HIP 50, HIP 15058, and HIP 66195.

| WDS<br>HIP | $t_1 - t_2$<br>$N$ | $m_A$<br>$m_B$ | $Sp_A$<br>$Sp_B$ | $\mu_{xA}$, mas/yr<br>$\mu_{xB}$, mas/yr | $\mu_{yA}$, mas/yr<br>$\mu_{yB}$, mas/yr | $\pi_t$<br>mas | $M_A$, solar<br>$M_B$, solar |
|---|---|---|---|---|---|---|---|
| 00006–5306<br>50 | 1836–2015<br>26 | 6.55<br>9.85 | G0/2IV<br>– | +60<br>+53 | –28<br>–21 | 16.8<br>±0.5 | 1.5<br>0.9 |
| 03140+0044<br>15058 | 1831–2012<br>156 | 8.14<br>8.17 | F8<br>– | +76<br>+76 | –14<br>–14 | 15.2<br>±1.4 | 1.2<br>1.2 |
| 13341+6746<br>66195 | 1832–2013<br>48 | 9.26<br>9.56 | G1V<br>– | –180<br>–183 | +19<br>+15 | 14.4<br>±1.1 | 1.1<br>1.0 |

**Table 4.** Input data: apparent motion parameters and relative radial velocities.

| WDS<br>HIP | $t_1 - t_2$<br>$N$ | $t_0$ | $\rho$<br>$''$ | $\theta$<br>$^\circ$ | $\mu$<br>mas/yr | $\psi$<br>$^\circ$ | $\rho_c$<br>$''$ | $\sigma_\rho$<br>$\sigma_\tau$ | $\Delta V_r$<br>km s$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| 00006–5306<br>50 | 1991–2015<br>8 | 2003.0 | 1.565<br>±0.007 | 330.2<br>±0.3 | 17.8<br>±1.0 | 101.2<br>±3.3 | 2.3<br>±0.1 | 20.0<br>23.6 | (2.0)<br>(±0.5) |
| 03140+0044<br>15058 | 1989–2012<br>21 | 2000.5 | 1.179<br>±0.004 | 136.4<br>±0.1 | 9.5<br>±0.5 | 81.0<br>±3.2 | 0.9<br>±0.1 | 16.3<br>11.1 | (2.6)<br>(±0.2) |
| 13341+6746<br>66195 | 1971–2014<br>118 | 2000.0 | 4.196<br>±0.003 | 345.06<br>±0.01 | 5.1<br>±0.2 | 217.5<br>±2.1 | –<br>– | 33.7<br>9.0 | −0.4<br>±0.4 |

## 3. NEW ORBITS OF THE BINARIES HIP 50, HIP 15058, AND HIP 66195

The most precise observations of the stars HIP 50 and HIP 15058 for AMP determination (short arc) were taken from the WDS catalog (Mason et al. 2001, version 2016). They include *Hipparcos* and *Tycho* observations, SOAR observations (Tokovinin et al. 2010), speckle observations of the 24-inch Lowell observatory reflector (Horch et al. 2006, for HIP 50), and uniform series of USNO speckle interferometric observations after 1989 (for HIP 15058).

The apparent motion parameters for the star HIP 66195 were computed from a uniform series of individual photographic and CCD observations obtained with the Pulkovo 26-inch refractor. Series of photographic observations were preliminary transformed to the system of CCD observations.

A summary of the data for the selected stars, according to the WDS catalog, are presented in Table 3. The columns of the table list: identification in the WDS and *Hipparcos* catalogs (Col. 1); time interval of all WDS observations and the number of all WDS observations (Col. 2); magnitudes of the components (Col. 3); spectral types (Col. 4); proper motions of the components (Cols. 5 and 6); trigonometric parallax and its uncertainty taken from van Leeuwen (2007)(Col. 7); masses of the components in solar masses (Col. 8).

The input data obtained from observations are presented in Table 4: identification in the WDS and *Hipparcos* catalogs (Col. 1); time interval of the main arc of observations and the number of these observations (Col. 2); $t_0$ (Col. 3); apparent motion parameters and their uncertainties (Cols. 4–8); dispersions in radial and tangential directions (Col. 9); relative radial velocity and its uncertainty (Col. 10). In Table 4,

$$\sigma_\tau = \sigma_\theta \rho \pi / 180.$$

There are no radial velocity data for HIP 50 and HIP 15058, but the radius of curvature is obtained from the main short arc of observations. Therefore, the relative radial velocities are estimated using all archive observations. They are

**Table 5.** Orbital elements.

| WDS<br>HIP | $\beta$<br>° | $a$<br>″ | $a$<br>au | $P$<br>yr | $e$ | $i$<br>° | $\omega$<br>° | $\Omega$<br>° | $T_{\rm p}$<br>yr | $v_\rho$, mas<br>$v_\tau$, mas |
|---|---|---|---|---|---|---|---|---|---|---|
| 00006–5306 | +5 | 2.17 | 129.2 | 948.6 | 0.62 | 31.3 | 113.7 | 322.2 | 1138.0 | 35.4 |
| 50 | | ±0.43 | ±25.6 | ±284.6 | ±0.17 | ±15.1 | ±18.3 | ±20.4 | ±292.6 | 21.0 |
| | –5 | 2.17 | 129.2 | 948.6 | 0.67 | 24.7 | 99.5 | 340.9 | 1134.9 | 37.4 |
| | | ±0.43 | ±25.6 | ±284.6 | ±0.06 | ±8.2 | ±25.3 | ±26.8 | ±286.4 | 20.5 |
| 03140+0044 (1) | +37 | 1.14 | 75.0 | 419.9 | 0.30 | 119.7 | 128.6 | 110.9 | 1775.1 | 21.9 |
| 15058 | | ±0.12 | ±7.9 | ±66.0 | ±0.11 | ±5.6 | ±38.9 | ±4.6 | ±57.9 | 13.9 |
| (2) | | 1.32 | 86.7 | 753. | 0.281 | 132.5 | 254.0 | 123.7 | 1883. | 21.3 |
| | | | | | | | | | | 13.1 |
| 13341+6746 | –41 | 4.04 | 280.4 | 3242 | 0.47 | 127.6 | 213.5 | 27.0 | 3252 | 57.0 |
| 66195 | | ±0.67 | ±46.4 | ±797 | 0.18 | ±9.1 | ±17.2 | ±11.0 | ±580 | 41.1 |
| | +41 | 4.04 | 280.4 | 3242 | 0.67 | 133.8 | 46.2 | 232.0 | 2831 | 57.5 |
| | | ±0.67 | ±46.4 | ±797 | ±0.10 | ±10.9 | ±13.2 | ±19.1 | ±762 | 41.1 |

given in parentheses.

For the star HIP 66195, we have a different case. The radial velocities of the components were measured on December 15, 2013 during spectroscopic observations with the Kazan Federal University's 1.5-m telescope at the TUBITAK National Observatory of Turkey, but the angle $\beta = \pm 41^\circ$ was estimated using archive observations.

The orbital elements are presented in Table 5. The mean deviations of observations relative to the ephemeris in radial and tangential directions ($v_\rho$ and $v_\tau$) are presented in the last column of the table. They were calculated from the following formulas:

$$v = \sqrt{\frac{\sum_{i=1}^{N} p_i (O-C)_i^2}{\sum_{i=1}^{N} p_i}}, \qquad p_i = \frac{0.001}{(O-C)_i^2}.$$

Here, deviations $(O-C)_i$ are expressed in arcseconds, $N$ is the number of all observations, $i$ is the index of the observation; the weight is $p_i = 1$ if $(O-C)_i \approx 0.03''$. We adopted also the limits on weights: $0.1 \le p_i \le 10$, and if $(O-C)_i > 1''$, then $p_i = 0$.

Comparisons of orbits with all observations are presented in Figs. 2–4.

It is natural that the scatter of observations for HIP 66195 is larger than for the other stars due to different possibilities of the telescopes, but the accuracy of AMP is rather good thanks to the large number of individual uniform observations.

The orbits of the stars HIP 50 and HIP 66195 are determined for the first time. There are two orbital solutions for each of the stars.

Our orbit of HIP 15058 (line (1), Table 5) has the single orbital solution and it is in agreement with adopted parallax and masses (see Table 3). The orbit (2) was determined by Riddle et al. (2015), but there is a contradiction. If one uses the parallax from the *Hipparcos* catalog, then the sum of masses of the components is equal to $1M_\odot$, in disagreement with the spectral type F8. This orbit is denoted in the WDS catalog as a preliminary one. The differences in $v_\rho$ and $v_\tau$ are negligible (see Table 5); therefore, we assume that our orbit (1) is more acceptable.

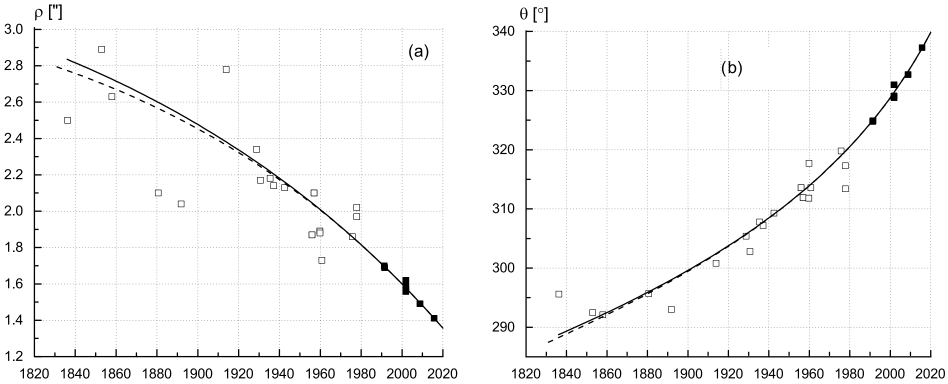


**Fig. 2.** HIP 50. Comparing orbits with observations: $\rho(t)$ (a), $\theta(t)$ (b). The coordinates of the main arc for AMP determinations are plotted as filled squares and other WDS observations, as open squares. The curves are ephemerides of the orbits: the orbit fits $\beta = +5^\circ$ (solid curves); the orbit fits $\beta = -5^\circ$ (dashed curves).

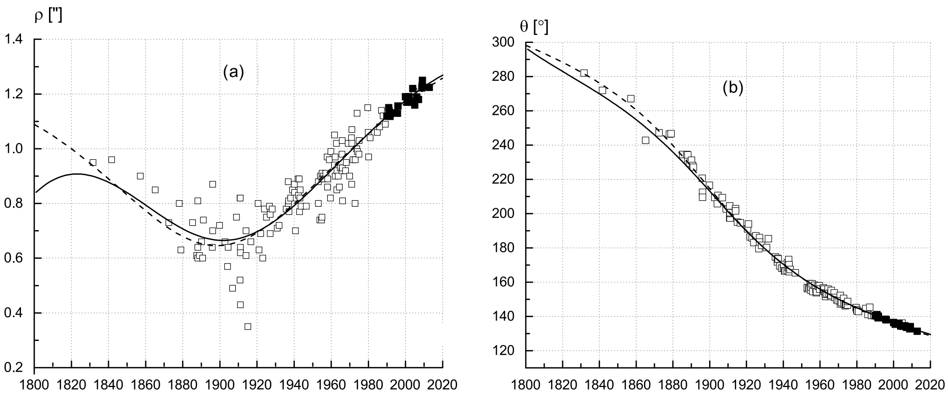


**Fig. 3.** HIP 15058. Same notations as in Fig. 2. The solid curves fit the AMP orbit of this study, the dashed curves fit the orbit of Riddle et al. (2015).

## 4. CONCLUSIONS

In this study, it is shown that the described combination of new technical capabilities of modern telescopes with the AMP method of calculation of orbits allows us to obtain rather reliable orbits of stars with the periods of several hundred years or thousands of years. The next improvement in accuracy will happen when *Gaia* provides new data on radial velocities of the components.

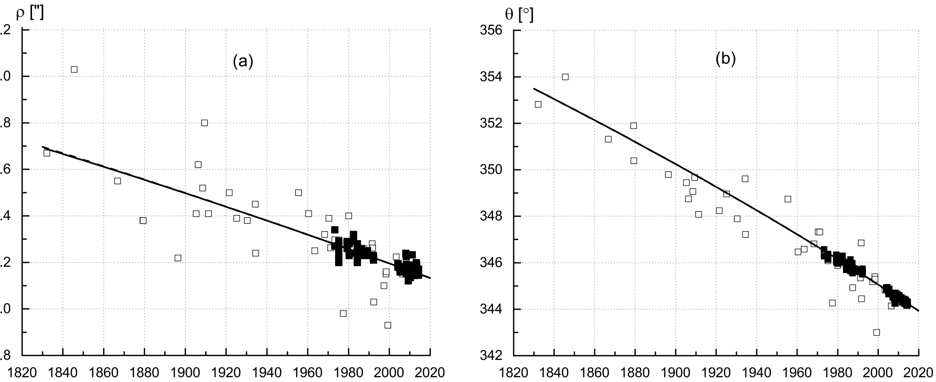


**Fig. 4.** HIP 66195. Same notations as in Fig. 2. The solid curves fit ephemerides of both orbits.

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