ORBITS OF SUBSYSTEMS IN FOUR HIERARCHICAL MULTIPLE STARS

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ABSTRACT

Seven spectroscopic orbits in nearby solar-type multiple stars are presented. The primary of the chromospherically active star HIP 9642 is a 4.8 day double-lined pair; the outer 420 year visual orbit is updated, but remains poorly constrained. HIP 12780 is a quadruple system consisting of the resolved 6.7 year pair FIN 379 Aa,Ab, for which the combined orbit, masses, and orbital parallax are determined here, and the single-lined binary Ba,Bb with a period of 27.8 days. HIP 28790 is a young quintuple system composed of two close binaries, Aa,Ab and Ba,Bb, with periods of 221 and 13 days, respectively, and a single distant component C. Its subsystem Ba,Bb is peculiar, having a spectroscopic mass ratio of 0.89 but a magnitude difference of ~2.2 mag. HIP 64478 also contains five stars: the A-component is a 29 year visual pair with a previously known 4 day twin subsystem, while the B-component is a contact binary with a period of 5.8 hr, seen nearly pole-on.

Key words: binaries: general – binaries: spectroscopic – stars: low-mass

Supporting material: machine-readable tables

1. INTRODUCTION

The radial velocities (RVs) of nearby solar-type multiple systems were monitored in 2014 and 2015 to determine the frequency of spectroscopic subsystems in visually resolved components and to follow their orbital motion. The resulting statistics were reported by Tokovinin (2015), while detailed analysis of individual systems was deferred to future publications. Four triple-lined multiples were featured in Paper I (Tokovinin 2016), and this is the second paper in this series. About a dozen of the remaining stars with variable RVs observed in this survey mostly have long orbital periods and still lack sufficient data for computing their orbits.

Identifications and basic data on the four multiple systems studied here are given in Table 1. They have solar-type primary components and are located within 50 pc of the Sun. The proper motions (PMs) and parallaxes are from van Leeuwen (2007), hereafter HIP2. The spectral types, V magnitudes, and B–V colors are taken from SIMBAD. Galactic velocities U, V, W in the last three columns are computed using the HIP2 astrometry and the center-of-mass RVs determined here (the U axis points away from the Galactic center). The following common abbreviations are used throughout this paper: SB1 and SB2—single—and double-lined spectroscopic binaries, AO—adaptive optics, PM—proper motion. As in Paper I, components of multiple systems are designated by single letters or strings, subsystems are denoted by their two components joined with a comma. Figure 1 depicts the hierarchical structure of objects featured here: one triple, one quadruple, and two quintuple systems.

The observational material and data analysis are briefly presented in Section 2, main results are tabulated in Section 3. Sections 4–7 are devoted to the individual systems. The paper is summarized in Section 8.

2. OBSERVATIONS AND DATA ANALYSIS

The observational material used here and the data reduction methods are covered in Tokovinin (2015) and in Paper I. They are recalled here briefly. Most spectra were taken with the 1.5 m telescope located at the Cerro Tololo Interamerican Observatory in Chile and operated by the SMARTS Consortium. The observing time was allocated through NOAO (programs 14B-0009, 15A-0055, 15B-0012). The observations were made with the CHIRON fiber-fed echelle spectrograph (Tokovinin et al. 2013) by the telescope operators in service mode. HIP 64478 was observed in the fiber mode with a spectral resolution of R = 28,000, while all of the other stars were observed in the slicer mode with R = 80,000. A few spectra taken in 2010 at the same telescope with the Fiber Echelle (FECH) with a resolution of R = 44,000 are used, as well as the RVs measured with the echelle spectrometer at the Du Pont 2.5 m telescope (Tokovinin et al. 2015b).

The RVs were derived from the cross-correlation function (CCF) of the spectrum with a binary mask in the spectral range from 4500 to 6500 Å. The CCF is approximated by one or several Gaussian functions; their centers give the RVs (after applying the barycentric correction), while the amplitudes a and dispersions σ characterize the depth and width of the spectral lines. Paper I gives approximate relation between σ and the projected rotational velocity V sin i.

The orbital elements and their errors were determined by the least-squares fit to the RVs with weights inversely proportional to the adopted errors. The IDL code orbit2 was used. It can fit spectroscopic, visual, or combined visual/spectroscopic orbits. Formal errors of orbital elements are determined from these fits. For combined orbits, the errors of orbital masses and parallax are computed by taking into account correlations between individual elements. Masses of the stars that are not derived directly from the orbits, as well as other parameters, are estimated from the absolute magnitudes using standard relations for main-sequence stars (see Paper I).

3. MAIN RESULTS

Table 2 contains the average parameters of the CCFs (unresolved CCFs from blended spectra are not used in the averaging). The last column lists individual V-band magnitudes

1 http://www.astro.yale.edu/smarts/
2 http://www.ctio.noao.edu/~atokovin/orbit/
of the components computed from the spectroscopic flux ratios (assumed to be proportional to \(a r \sigma\)) and the combined magnitudes. These estimates are accurate to \(\sim 0.1\) mag and would not be compromised by undetected small-amplitude photometric variability.

Spectroscopic orbital elements derived in this work are listed in Table 3, in common notation. Its first two columns contain the \textit{Hipparcos} number of the primary component and the subsystem designation. Then follow the orbital period \(P\), time of periastron \(T\) (for circular orbits it corresponds to the RV maximum), eccentricity \(e\), longitude of periastron of the primary component \(\omega_1\), RV amplitudes \(K_1\) and \(K_2\) of the primary and secondary components, respectively, and the center-of-mass velocity \(\gamma\). The last column gives the weighted rms residuals for both components. The visual orbits are assembled in Table 4 (\(a\)—seminajor axis, \(\Omega_\alpha\)—position angle of the node, \(\omega_\alpha\)—longitude of periastron, \(i\)—inclination). The combined orbit of HIP 12780 Aa,Ab is featured in both tables, duplicating the overlapping elements. In the combined orbit, the longitude of periastron \(\omega_\alpha\) corresponds to the primary, and the position angle of the visual orbit \(\Omega_\alpha\) is chosen accordingly to describe the motion of the secondary.

The observations used in orbit calculations are listed in two tables, published in full electronically. Table 5 gives, for each date, the RVs of the primary and secondary components \(V_1\) and \(V_2\), their errors used for relative weighting (unrealistically large errors are assigned to RVs corresponding to blended CCFs), and residuals to the orbit O–C. The first column contains the \textit{Hipparcos} number, the second column identifies the system. The dates are given in Julian days (minus 2,400,000). The last column of Table 5 specifies the data source. The resolved measurements are listed in Table 6 in a similar way as the RVs, with the first two columns identifying the system. Then follow the date in Besselian years, position angle \(\theta\), separation \(\rho\), position error \(\sigma_p\), residuals to orbit, and reference.

The following sections discuss each multiple system individually.

### 4. HIP 9642

This star is a visual binary RST 2272. Its preliminary visual orbit from Hartkopf & Mason (2011), revised here, has \(P = 549.83\) years and \(a = 3^\circ 2233\), leading to the unrealistically large mass sum of \(13 \, M_\odot\). The visual secondary B is much fainter than A \((\Delta H_P = 4.21, \quad \Delta y = 4.89, \quad \Delta l \sim 4.4\) mag), contributing little light to the combined spectrum. Its separation was last measured in 2015 at 1.5", and so the light of B is further attenuated by the 2.7' entrance aperture of the spectrograph. It has no detectable signature in the CCFs.

The star is a bright X-ray source and it has an extremely high chromospheric activity (Makarov 2003). The spectroscopic

### Table 1

| HIP     | HD      | WDS    | Spectral Type | V (mag) | \(B - V\) (mag) | \(i_0\) (mas yr\(^{-1}\)) | \(\mu_2\) (mas) | \(\gamma_{\text{HIP2}}\) (mas) | U (km s\(^{-1}\)) | V (km s\(^{-1}\)) | W (km s\(^{-1}\)) |
|---------|---------|--------|---------------|---------|-----------------|----------------------|-----------------|-----------------------------|----------------|----------------|----------------|
| 9642    | 12759   | 02039−4525 | G5V           | 7.31    | 0.69            | +328 +52             | 20.44 ± 0.55    | −63.4 −59.8 −27.4       |
| 12780   | 17134   | 02442−2530 | G3V           | 6.96    | 0.63            | +166 +51             | 24.20 ± 1.16    | −27.1 −14.1 −14.8       |
| 12779   | 9642    | 02442−2530 | KOV?          | 9.05    | 0.84            | +165 +52             | 22.86 ± 1.21    | ...                        |
| 28790   | 41742   | 06047−4505 | F4V           | 5.93    | 0.49            | −79 +255             | 37.18 ± 0.64    | −39.2 −11.0 −14.4       |
| 28764   | 41700   | 06047−4505 | F8V           | 5.35    | 0.52            | −81 +246             | 37.64 ± 0.25    | ...                        |
| 64478   | 114630  | 13129−5949 | G0V           | 6.22    | 0.59            | +7 −108              | 23.72 ± 0.60    | 11.1 −16.1 −20.7       |

### Table 2

| HIP     | Comp. | \(a\) (\(\text{km s}^{-1}\)) | \(\sigma\) (\(\text{km s}^{-1}\)) | \(\sigma a\) (\(\text{km s}^{-1}\)) | \(V\) (mag) |
|---------|-------|-----------------------------|-----------------------------|-----------------------------------|-------------|
| 9642    | Aa    | 0.262                       | 4.49                        | 1.174                             | 7.70        |
| 9642    | Ab    | 0.118                       | 4.10                        | 0.482                             | 8.66        |
| 12780   | Aa    | 0.237                       | 3.52                        | 0.835                             | 7.56        |
| 12780   | Ab    | 0.172                       | 3.60                        | 0.621                             | 7.88        |
| 12780   | Ba    | 0.429                       | 3.30                        | 1.570                             | 9.05        |
| 28790   | Aa    | 0.072                       | 14.84                       | 1.071                             | 6.02        |
| 28790   | Ba    | 0.337                       | 4.52                        | 1.510                             | 9.11        |
| 28790   | Bb    | 0.051                       | 3.93                        | 0.197                             | 11.32       |
| 64478   | Aa1   | 0.067                       | 10.19                       | 0.681                             | 6.99        |
| 64478   | Aa2   | 0.068                       | 10.20                       | 0.689                             | 6.99        |
| 64478   | Ab    | 0.011                       | 5.72                        | 0.065                             | 10.65       |
| 64478   | Bb    | 0.052                       | 24.80                       | 1.277                             | 9.97        |
| 64478   | Bb    | 0.043                       | 19.53                       | 0.851                             | 10.42       |
### Table 3
Spectroscopic Orbits

| HIP   | System | $P$ (days) | $T$ (JD − 2400000) | $e$ | $\omega_0$ (°) | $K_1$ (km s$^{-1}$) | $K_2$ (km s$^{-1}$) | $\gamma$ (km s$^{-1}$) | rms$_{1,2}$ (km s$^{-1}$) |
|-------|--------|------------|---------------------|-----|---------------|----------------------|----------------------|-------------------------|--------------------------|
| 9642  | Aa,Ab  | 4.78149    | 56970.0145          | 0   | 0             | 27.591               | 31.201               | 49.051                  | 0.13                     |
|       |        | ±0.00002   | ±0.0018             | fixed | fixed         | ±0.092               | ±0.092               | ±0.04                   | 0.12                     |
| 12780 | Aa,Ab  | 2.4431     | 54775.59            | ±2.1| ±0.0015       | ±0.59                | ±0.041               | ±0.040                  | 0.10                     |
| 12780 | Ba,Bb  | 27.7679    | 56999.062           | 0.274| 82.78         | 19.462               | ...                  | −0.322                  | 0.01                     |
| 12780 |        | ±0.0033    | ±0.077              | ±0.007| ±1.23        | ±0.129               | ...                  | ±0.066                  | ...                      |
| 28790 | Aa,Ab  | 221.385    | 57013.906           | 0.833| 195.99       | 21.128               | ...                  | 26.250                  | 0.04                     |
| 28790 |        | ±0.014     | ±0.218              | ±0.010| ±0.46        | ±1.63                | ...                  | ±0.081                  | ...                      |
| 28790 | Ba,Bb  | 13.2309    | 57004.908           | 0.231| 123.7         | 21.513               | 24.151               | 28.376                  | 0.27                     |
|       |        | ±0.0003    | ±0.118              | ±0.017| ±3.4         | ±0.596               | ±0.448               | ±0.218                  | 0.39                     |
| 64478 | Aa1,Aa2| 4.2334536  | 57120.507           | 0   | 0             | 85.172               | 85.364               | 15.364                  | 0.22                     |
| 64478 |        | ±0.0000018 | ±0.004              | fixed | fixed         | ±0.40                | ±0.40                | ±0.237                  | 0.18                     |
| 64478 | Ba,Bb  | 0.243524   | 57119.4786          | 0   | 0             | 29.545               | 63.076               | 19.589                  | 0.53                     |
|       |        | ±0.000003  | ±0.0004             | fixed | fixed         | ±0.182               | ±0.637               | ±0.160                  | 1.83                     |

(This table is available in machine-readable form.)

### Table 4
Visual Orbits

| HIP   | System | $P$ (year) | $T$ (year) | $e$ | $a$ (arcsec) | $\Omega$ (°) | $\omega_0$ (°) | $i$ (°) |
|-------|--------|------------|------------|-----|--------------|--------------|---------------|--------|
| 9642  | A,B    | 415.0      | 2327.57    | 0.2645| 1.659        | 301.3        | 175.5         | 36.0    |
| 12780 | Aa,Ab  | 6.68917    | 2008.846   | 0.4999| 0.1002       | 183.77       | 191.20        | 42.00   |
|       |        | ±0.0051    | ±0.007     | ±0.0015| ±0.0006      | ±0.49        | ±0.59         | ±0.72   |
| 64478 | Aa,Ab  | 29.11      | 1997.27    | 0.173 | 0.3134       | 279.7        | 326.4         | 89.0    |
|       |        | ±0.34      | ±1.55      | ±0.018 | ±0.0034      | ±0.2         | ±17.6        | ±0.4    |

(This table is available in machine-readable form.)

### Table 5
Radial Velocities and Residuals

| HIP   | System | Date (JD − 2400000) | $V_1$ (km s$^{-1}$) | $\sigma_1$ (km s$^{-1}$) | (O−C)$_1$ | $V_2$ (km s$^{-1}$) | $\sigma_2$ (km s$^{-1}$) | (O−C)$_2$ | Ref.* |
|-------|--------|---------------------|---------------------|---------------------------|-----------|---------------------|---------------------------|-----------|-------|
| 9642  | Aa,Ab  | 54782.5680         | 21.370              | 0.500                     | −0.254    | 79.860              | 0.500                     | −0.206    | L     |
| 9642  | Aa,Ab  | 56896.8724         | 41.060              | 0.200                     | 0.029     | 58.201              | 0.200                     | 0.080     | C     |
| 9642  | Aa,Ab  | 56938.8177         | 21.646              | 0.200                     | −0.140    | 79.949              | 0.200                     | 0.066     | C     |
| 12780 | Aa,Ab  | 55446.0506         | 0.235               | 10.000                    | −2.410    | ...                 | ...                       | ...       | F     |
| 12780 | Aa,Ab  | 56908.8456         | −3.938              | 0.050                     | −0.161    | 2.846               | 0.050                     | −0.179    | C     |

Note.* C: CHIRON; F: FECH; S: Saar et al. (1990); H: HARPS; L: Tokovinin et al. (2015b).

(This table is available in its entirety in machine-readable form.)

### Table 6
Position Measurements and Residuals

| HIP   | System | Date (year) | $\theta$ (°) | $\rho$ (") | $\sigma$ (") | (O−C)$_{\theta}$ (°) | (O−C)$_{\rho}$ (") | Ref.* |
|-------|--------|-------------|--------------|-------------|--------------|-----------------------|---------------------|-------|
| 9642  | A,B    | 1932.9100   | 177.9        | 1.020       | 0.500       | 34.9                  | −0.196               | Vis    |
| 9642  | A,B    | 1991.2500   | 218.0        | 1.332       | 0.010       | 1.6                   | 0.030                | HIP    |
| 9642  | A,B    | 2008.7700   | 233.9        | 1.427       | 0.002       | −0.1                  | −0.004               | SOAR   |
| 12780 | Aa,Ab  | 1963.0500   | 142.7        | 0.1140      | 1.0500      | 3.5                   | 0.0324               | Fin    |
| 12780 | Aa,Ab  | 1991.7240   | 186.1        | 0.1490      | 0.0020      | 0.2                   | 0.0006               | Spe    |
| 12780 | Aa,Ab  | 2015.0280   | 304.4        | 0.0520      | 0.0020      | −1.3                  | −0.0014              | SOAR   |

Note.* Fin: ocular interferometry by W. S. Finsen; HIP: Hipparcos; SOAR: speckle interferometry at SOAR; Spe: speckle interferometry at other telescopes; Vis: visual micrometer measures.

(This table is available in its entirety in machine-readable form.)
subsystem Aa,Ab was discovered by Nordström et al. (2004). These authors estimated the mass ratio of 0.86 from nine observations, but did not determine the orbit. Two observations reported by Tokovinin et al. (2015b) show a substantial RV variation in one day, hinting at short period. The monitoring with CHIRON leads to a circular orbit of Aa,Ab with a period of 4.78 days (Figure 2). The eccentricity and longitude of periastron were fixed at zero in the orbit adjustment.

Using the HIP2 parallax, the magnitudes of Aa and Ab, and the Dartmouth isochrone for solar metallicity (Dotter et al. 2008), I estimated the masses of Aa and Ab at 1.12 and 0.94 $M_\odot$. The spectroscopic orbit leads to $M_\text{sin}i$ of 0.05 $M_\odot$. Therefore, the inclination of the spectroscopic pair is small, about 22°. The mass of B is estimated at 0.56 $M_\odot$ (a late-K dwarf), the system mass sum is 2.62 $M_\odot$. However, the system model based on the isochrones predicts the $V - K_s$ and $B - V$ colors of 1.39 and 0.53 mag, respectively, while the actual color indices are 1.78 and 0.69 mag. So, the stars are redder than normal main-sequence dwarfs (possibly evolved), and the estimates of their masses may be inaccurate. The semimajor axis of Aa,Ab is 1.5 mas, so the inner pair can be resolved by long-baseline interferometers.

The visual orbit of the outer system A,B lacks coverage. Figure 3 illustrates an alternative orbit that corresponds to the mass sum of 3.10 $M_\odot$, using the HIP2 parallax. It was obtained by weighting speckle data more strongly, in agreement with their realistic errors, and by fixing some elements. The visual orbit remains provisional (for this reason no errors are listed in Table 4), but the new elements are preferable because they will give a more accurate ephemeris in the near term. The inclination of the outer orbit, 36°, if trustworthy, differs from the estimated inclination of 22° in the inner orbit.

The kinematics (Table 1) and the absence of the 6708 Å lithium line suggest that this multiple system is not very young. Its high chromospheric activity likely results from the tidal coupling of stellar rotation and orbit.

The primary component HIP 12780 is a bright visual binary, FIN 379 Aa,Ab, with a known 6.7 year orbit (Hartkopf et al. 2012). The tertiary component B = HIP 12779 is located at 12°5 from A. The two stars have common parallax and PM. However, the first RV measurements with CHIRON have demonstrated that RV(B) differs substantially from RV(A). Further monitoring revealed that B is an SB1. Therefore, this multiple system is a 2 + 2 quadruple.

The spectroscopic orbit of Bb with $P = 27.8$ days is shown in Figure 4. The very small rms residuals of 6 m s$^{-1}$ are
partially explained by the fact that six orbital elements are derived from only 11 RV measurements. The estimated mass of Ba, $0.87 \, \text{M}_\odot$, corresponds to the minimum mass of $0.25 \, \text{M}_\odot$ for Bb. It is natural that Bb is not detected in the CCF. The component B was observed with speckle interferometry at SOAR and unresolved.

The visual orbit of the main pair Aa,Ab has been recently revised by Hartkopf et al. (2012). It is in excellent agreement with the RVs of Aa and Ab deduced from double CCFs. Adding recent data from speckle interferometry at SOAR (Tokovinin et al. 2015a), I computed the combined orbit depicted in Figure 5. The weighted rms deviations are 1.2° in angle, 1.2 mas in separation, and 92 and 96 m s$^{-1}$ for the RVs of Aa and Ab, respectively. The combined orbit leads to the masses of $1.05 \pm 0.05$ and $0.98 \pm 0.04 \, \text{M}_\odot$ for Aa and Ab and the orbital parallax is $22.26 \pm 0.40$ mas. Note that the parallax of B = HIP 12779 is $22.9 \pm 1.2$ mas, close to the orbital parallax of Aa,Ab. The Hipparcos parallax of the main star A, 24.2 mas, could be slightly biased by its fast orbital motion. The $\gamma$-velocities of A and B differ by only 0.17 km s$^{-1}$.

The spectroscopic magnitude difference of Aa,Ab deduced from the areas of the CCF dips is 0.32 mag. The five speckle measures lead to the mean $\Delta y = 0.37$ mag, with rms scatter of 0.09 mag. Adopting the spectroscopic $\Delta V$ and the orbital parallax, the Dartmouth isochrones (Dotter et al. 2008) lead to the masses that are 5% larger than the actually measured ones. On the other hand, the combined colors of the component A deduced from the measured masses and the isochrones are in excellent agreement with the actual colors. The 6708 Å lithium line is not detectable in the spectra of Aa, Ab, and Ba.

6. HIP 28790

HIP 28790 is a young quintuple stellar system. The 5′9 pair HJ 3834 A,B (V = 6.02; 8.98) is accompanied by the bright (V = 6.39) component C = HIP 28764 at a distance of 196°. Both A and B are spectroscopic binaries. The RV variation of A was discovered by Lagrange et al. (2009) and the binarity of B was found by Tokovinin et al. (2015b), see Figure 6. Spectroscopic orbits of both subsystems are determined here. Common PM, parallax, and RV establish the physical nature of the wide pair AB,C. The orbital periods of AB,C and A,B estimated from projected separations are 180 kyr and 1 kyr, respectively. The binary A,B was observed with AO by two groups (Ehrenreich et al. 2010; Tokovinin et al. 2010) and no additional resolved components were found. The component B was also unresolved by speckle interferometry at SOAR. According to the Washington Double-Star Catalog, WDS (Mason et al. 2001), the pair A,B was at 1°1, 246° when it was discovered in 1837 and opened up to 5′9, 215° in 2010.

The component A has a fast axial rotation: the width of its CCF dip corresponds to $V \sin i = 26.0$ km s$^{-1}$ according to the formula of Paper I. Ammler-von Eiff & Reiners (2012) measured $V \sin i = 26.7$ km s$^{-1}$ and $T_{\text{eff}} = 6324$ K. Gray et al. (2006) determined spectral types of F5.5V, K4.5V, and F9V for A, B, and C, respectively, and estimated effective temperatures of A and C at 6446 K and 6241 K. They found
that C is chromospherically active. This has been established earlier by Cutispoto et al. (2002), who measured the rotation of C as $V \sin i = 16.2 \text{ km s}^{-1}$. Mannings & Barlow (1998) detected thermal emission from dust and identified the main star as “Vega-like.” Kalas et al. (2002) mentioned that the system belongs to the β Pictoris group, but its spatial velocity (Table 1) does not support this claim; instead, it is close to that of the Hyades cluster. The spectrum of the component A contains the line of lithium at 6708 Å (it is broadened by fast rotation and difficult to measure), while no such line is present in the spectrum of B.

Figure 7 (top) shows the orbital solution for the subsystem Aa,Ab. RVs from CHIRON are used together with the RVs measured by Lagrange et al. (2009) with HARPS. These authors have kindly provided individual RVs, not given in the paper, on my request. However, they measured RVs relative to the mean velocity. An offset of $+29.62 \text{ km s}^{-1}$ was found iteratively to place those HARPS RVs on the absolute scale. The two data sets together cover well the descending branch of the RV curve in this eccentric ($e = 0.83$) orbit, with rms residuals of only 39 m s$^{-1}$ despite fast stellar rotation. More observations should be planned to cover the periapsis. If the mass of Aa is 1.2 $M_\odot$, the minimum mass of Ab is 0.47 $M_\odot$.

The component B is an SB2. The RV of the main CCF dip is variable, and sometimes there is a weak detail moving in anti-phase with the main dip. Figure 6 shows examples of such CCFs. The SB2 orbit with $P = 13.2$ days is illustrated in the bottom plot of Figure 7. Approximation of the CCF by two Gaussians is not very good, the fit fails in some cases without fixing the width of the secondary dip. The rms residuals to the orbit are larger than usual. The variability of the CCF amplitude is caused by contamination by the light of the component A, three magnitudes brighter than B and only at 5.9 distance. The entrance aperture of CHIRON has a diameter of 2″. Depending on the position of B on the aperture (while guiding on the component A) and on the seeing, a variable fraction of the light from A enters the aperture and dilutes the spectrum of B. The CCFs of strongly contaminated spectra contain a wide and weak dip corresponding to the A-component.

The RV amplitudes of Ba,Bb indicate a mass ratio $q = 0.89$, but the CCF dips are very unequal: the ratio of their areas corresponds to $\Delta V \approx 2.2$ mag. The component Bb must have a somewhat later spectral type than Ba, contributing to the smaller area of its CCF dip. Still, the substantial difference of the CCF areas of Ba and Bb has no explanation.

The $\gamma$-velocities of A and B are 26.25 and 28.38 km s$^{-1}$, respectively, while the RV of C is 27.4 km s$^{-1}$ and constant according to Nordström et al. (2004). The wide pair AB,C is certainly physical, while the small RV difference between A and B is explained by the orbital motion of A,B. The agreement of RVs makes it unlikely that this system contains undiscovered close components, unless they have a very low mass or a highly inclined orbit. The component C was observed with the speckle camera at SOAR and unresolved.

7. HIP 64478

The quintuple system HIP 64478 is also known as HR 4980 or HD 114630. When Saar et al. (1990) determined the 4.2 day SB2 orbit of this chromospherically active G0V binary, its close visual companion had not yet been discovered by Hipparcos, while the companion B located at 25″ and 146° from A appeared irrelevant. Those authors wrongly denoted the spectroscopic components as A and B, while WDS had not yet assigned any designation for B and denoted the visual pair as COO 152. The outer system A,B is definitely physical, keeping the same position since its discovery in 1892; its period estimated from projected separation is about 17 kyr. The PM of B is $(+1, -97)$ mas yr$^{-1}$, its photometry: $V = 9.42$, $K_s = 6.68$ mag.

The 0″2 resolved binary Aa,Ab is designated in the WDS as HDS 1850. Its preliminary orbit with a period of 31.6 years determined by Tokovinin (2012) is updated here using recent speckle interferometry from SOAR and the RVs. So, the component A contains in fact three stars, all appearing in the CHIRON CCFs as distinct dips. The weak dip corresponding to...
Ab has not been detected with CORAVEL by Saar et al. (1990). Considering that B is now known to be an SB2, there are five stars in this multiple system. Several RVs of the components Aa1 and Aa2 measured with CHIRON are in excellent agreement with the SB2 orbit by Saar et al. (1990). There is no need to plot this circular orbit; its elements derived from the CHIRON data alone, with a fixed period, are listed in Table 3. Combining published and new data, the accurate period of 4.2334536 \pm 0.0000018 days is determined. With a mass ratio of 0.998, the components of this twin binary are practically indistinguishable. Saar et al. (1990) estimated the orbital inclination as 85°, so there are no eclipses. The spectroscopic masses $M\sin^3 i$ of Aa1 and Aa2 are 1.085 $M_\odot$.

The faint and close companion Ab has an average RV of 27.97 km s$^{-1}$ with the rms scatter of 0.26 km s$^{-1}$. Its difference from the $\gamma$-velocity of Aa, 15.36 km s$^{-1}$, is caused by the motion in the 30 year orbit Aa,Ab. Using the RVs of Aa1 and Aa2 measured by Saar et al. (1990) with CORAVEL and here with CHIRON, I computed the RV of Aa (center of mass of the inner binary) as a weighted average, as explained in Paper I. Although the CORAVEL data cover a substantial time span from 1981.1 to 1989.2, only a minor RV change caused by the motion in the 30 year orbit occurred during that time (Figure 8); naturally, no trend in the RV residuals of Aa1 and Aa2 has been noted so far.

New observations with CHIRON made 30 years later unfortunately fall on the same orbital phase, but contribute the RVs of Ab. The RV data, insufficient by themselves, are combined here with relative astrometry to update the orbit of Aa,Ab (Figure 8). It is seen almost exactly edge-on. I fixed the $\gamma$-velocity of Aa,Ab at 18.5 km s$^{-1}$ to get the expected mass ratio of $\sim 1/3$ and obtained the RV amplitudes of 3.93 ± 0.23 and 11.06 ± 0.34 km s$^{-1}$ for Aa and Ab, respectively. As these spectroscopic elements of Aa,Ab are only a guess, they are not presented in Table 3.

Relative photometry of Aa,Ab at SOAR results in $\Delta V = 3.66$ mag, with a 0.06 mag rms scatter of the measures. As Aa1 and Aa2 are equal, the individual magnitudes of all three stars in the aggregate component A are estimated from the speckle photometry. The ratio of the CCF areas leads to $\Delta V_{Aa,Ab} = 3.30$ mag, slightly under-estimated because Ab is cooler than Aa1 and Aa2 and its lines are a bit stronger. The absolute magnitudes imply masses of about 1.2 and 0.7 $M_\odot$ for Aa1 and Ab, respectively. However, the combined color index $V - K_s = 1.14$ mag estimated for three dwarf stars of such masses using the Dartmouth isochrone differs substantially from the actual color $V - K_s = 1.41$ mag. Apparently the components of the 4.3 day binary are larger and cooler than normal dwarfs.

Spectroscopic observations of the component B with CHIRON in 2015 revealed it as a double-lined binary. Figure 9 shows three CCFs of B plotted on the same scale. The dips of Ba and Bb are obviously widened by the fast axial rotation. Gaussian fits to the CCFs are not very accurate. The stronger component Ba has a detail in its CCF that moves in anti-phase with Bb. The mean ratio of the areas of those Gaussians is 0.69, or $\Delta m = 0.40$ mag, for what it is worth.

The subsystem Ba,Bb has an unusually short period of 0.2435 days, found after several failed attempts to search for longer periods. Figure 10 shows the RV curve. Blended CCFs have not been used in the orbit fit, but these RVs are kept in the plot. The rms residuals to the circular orbit are rather large, 0.53 and 1.84 km s$^{-1}$ for Ba and Bb, respectively.

The product $\sigma \Delta \sigma$ is a measure of the CCF area. The sum of areas of Ba and Bb varies between 2.0 and 2.5 km s$^{-1}$, with an even lower value around 1.6 km s$^{-1}$ measured on JD 2457121. Shallow CCFs correspond to the orbital phases when Ba is approaching and Bb is receding. Curiously, the spectrum of B has no H$_\alpha$ absorption line.

The subsystem Ba,Bb is a contact binary with a period of 5.8 hr, seen almost from the pole. Components of contact binaries are not normal dwarfs and do not follow standard relations. The secondary Bb is much brighter than follows from the mass ratio of 0.47. However, the complexity of an interacting binary means that the RVs measured here do not reflect the motion of the center of mass of each star.

Figure 8. Orbit of HIP 64478 Aa,Ab = HDS 1850, $P = 29$ years. Top (a) orbit in the plane of the sky, bottom (b) the RV curve.

Figure 9. CCFs of HIP 64478B on three representative dates.
The orbital inclination is \(0.7^\circ\). The stars apparently rotate synchronously with the orbit and the projected rotational velocity is then \(0.013\) and \(0.006\) \(\text{v}\). The system 1SWASP J093010.78\textnormal{b} bears some resemblance to the quintuple doubly eclipsing system, and its projected separations of a few solar radii at periastron and the orbits have a large mutual inclination. It leaves a population of triples with periods at the lowest hierarchical levels \(15^\circ\). This could be a combined result of the formation process, where inner subsystems form first and shrink rapidly before acquiring outer companions, and the posterior dynamical evolution involving tidal friction and Kozai–Lidov cycles (Fabrycky & Tremaine 2007). This latter process works when inner pairs have separations of a few solar radii at periastron and the orbits have a large mutual inclination. It leaves a population of triples with inner periods of a few days and relative inclinations clustered around 39° and 141°. The inner binaries continue to interact tidally and their orbits are rapidly circularized. HIP 9642 Aa,Ab could result from such evolution, but not all inner subsystems match this scenario, being too wide and/or having eccentric orbits. So, tidal evolution cannot be a unique way to form close inner subsystems and some of them should be primordial. Considering large period ratios, formation of close subsystems by dynamical interactions in unstable small groups of nascent stars is unlikely, unless they evolved subsequently to much shorter periods.

Two secondary subsystems featured here are noteworthy. HIP 28790 Ba,Bb is an SB2 with a mass ratio of 0.89, yet very unequal components (Figure 6). There is no explanation of this paradox. This multiple system may be relatively young, as evidenced by its kinematics, the rotation of Aa, and the presence of lithium in its photosphere.

The binary HIP 64478 Ba,Bb is even more exotic, being a contact pair of 5.8 hr period observed at low orbital inclination of \(\sim 15^\circ\). This is probably a unique case, as other contact binaries are discovered photometrically by eclipses or by ellipsoidal variation. Contact binaries are relatively rare, about one per 500 stars of spectral types F, G, K (Rucinski 2002, 2006). Compared to the majority of known contact binaries, HIP 64478 Ba,Bb has a rather short period and a faint absolute magnitude of \(M_V = 6.3\) mag. As its distance is well known, it can improve the currently known relation between period and absolute magnitude for contact systems. The sample of 4847 solar-type stars within 67 pc (Tokovinin 2014) contains 14 eclipsing systems with periods shorter than one day. The period of HIP 64478 Ba,Bb is the shortest in the whole sample. This bright, nearby, and unusually oriented system, if studied in greater detail, may provide interesting insights into physics of such merging pairs.

Looking at the mobile diagrams in Figure 1, we notice that when both visual components contain close subsystems, the period of the more massive primary is longer than the period of the secondary subsystem. Such a trend is expected from the general correlation between mass and angular momentum. It should be studied on a larger sample, as the evidence from only three cases is circumstantial.

Yet another feature of this diagram is a large \((\sim 10^3)\) ratio of periods at the lowest hierarchical levels (i.e., a large vertical distance between the lowest and the next nodes). This could be a combined result of the formation process, where inner subsystems form first and shrink rapidly before acquiring outer companions, and the posterior dynamical evolution involving tidal friction and Kozai–Lidov cycles (Fabrycky & Tremaine 2007). This latter process works when inner pairs have separations of a few solar radii at periastron and the orbits have a large mutual inclination. It leaves a population of triples with inner periods of a few days and relative inclinations clustered around 39° and 141°. The inner binaries continue to interact tidally and their orbits are rapidly circularized. HIP 9642 Aa,Ab could result from such evolution, but not all inner subsystems match this scenario, being too wide and/or having eccentric orbits. So, tidal evolution cannot be a unique way to form close inner subsystems and some of them should be primordial. Considering large period ratios, formation of close subsystems by dynamical interactions in unstable small groups of nascent stars is unlikely, unless they evolved subsequently to much shorter periods.

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