

ORBIT ALIGNMENT IN TRIPLE STARS

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ABSTRACT

Statistics of the angle Φ between orbital angular momenta in hierarchical triple systems with known inner visual or astrometric orbits are studied. Correlation between apparent revolution directions proves partial orbit alignment known from earlier works. The alignment is strong in triples with outer projected separation less than ~ 50 AU, where the average Φ is about 20° . In contrast, outer orbits wider than 1000 AU are not aligned with the inner orbits. It is established that the orbit alignment decreases with increasing mass of the primary component. Average eccentricity of inner orbits in well-aligned triples is smaller than in randomly aligned ones. These findings highlight the role of dissipative interactions with gas in defining the orbital architecture of low-mass triple systems. On the other hand, chaotic dynamics apparently played a role in shaping more massive hierarchies. Analysis of projected configurations and triples with known inner and outer orbits indicates that the distribution of Φ is likely bimodal, where 80% of triples have $\Phi < 70^\circ$ and the remaining ones are randomly aligned.

Subject headings:

1. INTRODUCTION

Statistics of the angle Φ between orbital angular momenta of the inner and outer orbits in triple systems, considered jointly with other parameters such as eccentricity and mass, can inform us on the relative role of dynamical and dissipative processes in star formation. Orientation of angular momentum of stars, circumstellar disks, and planets is determined by the same processes, hence the study of hierarchical stellar systems is relevant to these problems.

Some hierarchical systems in the field have misaligned and even counter-rotating inner and outer orbits, e.g. σ Ori (Schaefer et al. 2016) or ζ Aqr (Tokovinin 2016). The *misaligned* triple systems could have been shaped by dynamical interactions between stars in clusters or in small groups. Antognini & Thompson (2016) show that typical triple stars resulting from dynamical interactions have small ratios of outer to inner separation and random relative orbit orientation. Both inner and outer eccentricities in such hierarchies have approximately thermal distributions $f(e) = 2e$, favoring eccentric orbits.

On the other hand, there are many hierarchies where the orbits have modest mutual inclinations and eccentricities (Tokovinin et al. 2015a; Tokovinin & Latham 2017). Those multiple systems with planetary-like architecture (call them *planar* for brevity) presumably formed or evolved in a gaseous disk. The role of dissipation in aligning multiple systems has been demonstrated by the large hydrodynamical simulations of Bate (2014). He found $\langle \Phi \rangle = 39^\circ \pm 7^\circ$, with closer triples being better aligned (see his Fig. 20). It is not known presently whether there are indeed two distinct families of multiple stars formed by these alternative scenarios, or if the misaligned and planar triples represent two extremes in one common population.

The angle Φ between inner and outer angular momenta (orbital spins) can vary between 0 and 180° . For un-

correlated spin directions, $\cos \Phi$ is distributed uniformly between -1 and 1 , hence $f(\Phi) \propto \sin \Phi$, making $\Phi \approx 90^\circ$ the most likely angle. In such case, 78% of triples have $39^\circ < \Phi < 141^\circ$ and their relative inclination and inner eccentricity change periodically in the Kozai-Lidov cycles (see the references in Antognini & Thompson 2016). In these cycles, the inner eccentricity can reach high values. When two stars on eccentric orbit approach each other within a few stellar radii, tidal forces come into play and shorten the inner period, creating a close binary (Kiseleva et al. 1998). Statistical study of this mechanism by Fabrycky & Tremaine (2007) assumed initial triples with randomly aligned orbits; the final inclinations concentrate around $\Phi \approx 40^\circ$ and $\Phi \approx 140^\circ$, i.e. half of the close binaries are counter-rotating, while the frequency of $\Phi \sim 90^\circ$ is reduced. In reality, counter-rotation is rare (Borkovits et al. 2016), implying that the initial distribution of Φ was not random. If triple systems are approximately aligned at birth, as in (Bate 2014), formation of close binaries by the Kozai mechanism becomes much less frequent than surmized by Fabrycky & Tremaine (2007).

The angle Φ can be measured directly only in a small number of resolved hierarchical systems. The statistics of Φ is best studied by indirect techniques relating some observable quantity to the distribution of Φ . The general trend of orbit alignment in triple systems has been demonstrated for the first time by Worley (1967). He compared the numbers of apparently co- and counter-rotating visual triples and interpreted their relative frequency in terms of the average angle $\langle \Phi \rangle$, which he found to be about 50° . This simple yet powerful method has been used in the following studies of orbit alignment, including this one. Tokovinin (1993) applied several statistical methods to different subsets of triple systems. His results were updated by Sterzik & Tokovinin (2002) who attempted to match the observed partial alignment by dynamical simulations of small decaying clusters.

The present study takes advantage of the increased number of multiple systems with known orbits, allow-

ing us for the first time to probe orbit alignment as a function of component’s mass and separation. Indeed, considering all triple stars as one population is a crude assumption adopted in earlier works out of necessity, because of the small samples; it can be dropped now. The sign correlation pioneered by Worley is the main method used here (Section 3). It is supplemented by the study of triple systems with known outer and inner orbits (Section 4) and by the analysis of apparent configurations of triples (Section 5). The results are discussed in Section 6 and compared to the studies of disk alignment in young binaries and to the recent work by Borkovits et al. (2016) on compact triples.

2. DATA

The data on hierarchical systems are extracted from the Multiple Star Catalog, MSC (Tokovinin 1997). Its latest (2010) on-line version¹ has been augmented by adding new multiples from the 67-pc sample (Tokovinin 2014), results of speckle interferometry (e.g. Tokovinin et al. 2015b), and the literature. The latest version of the visual orbit catalog VB6 (Hartkopf et al. 2001) was queried to add new orbits. The preliminary version of the updated MSC is posted online.²

We extracted from the MSC triple systems with known visual or astrometric inner orbits (types V or A) and a distant tertiary component. For the purpose of this study, we ignore additional outer and inner subsystems, i.e. consider higher-order hierarchies as simple “triples”. The sample contains 274 triples and 138 systems of four or more stars. Each of the 19 2+2 quadruples with both inner orbits known is listed as two triples with the same outer separation.

Table 1 contains the WDS code of the system, its parallax π_{HIP} (in mas), the mass of the primary component in the inner subsystem M_1 , five elements of the inner visual orbit $P_1, a_1, e_1, \Omega_1, i_1$, separation ρ and position angle θ of the outer companion, its direction of the angular motion (1 for direct, -1 for retrograde, 0 for unknown), and the apparent rotation sense (1 for co-rotating, -1 for counter-rotating). The sense of angular motion is considered known if the position angle of the outer component, corrected for precession, has changed by no less than 2° between its first and last observations reported in the Washington Double Star Catalog, WDS (Mason et al. 2001). However, the first measures in the WDS are not always accurate, especially those made in the 18th century. Some genuine tertiary companions confirmed by common radial velocity or by the large common proper motion may appear to move faster than the escape velocity because of inaccurate positions. We consider the first-epoch measurements of those wide pairs as unreliable and assume that their revolution direction is unknown. Table 1 contains 443 systems, of which 216 have known revolution direction of the outer pair, including six 2+2 systems with both inner orbits known.

For the sign correlation, there is no need to know the inner orbit, only the sense of rotation. About a hundred additional triples with known sense of inner and outer rotation can be found in the MSC. Such increment of the sample size is not critical, so we decided not to con-

sider those additional objects. Inner orbital elements are useful for comparison of eccentricities and for the analysis of configurations in Section 5.

Orbital motion in the inner subsystem introduces some modulation (wobble) in the angular motion of the outer pair. The average effect of this modulation is zero, so it is irrelevant when the observations cover more than one inner period. We neglect this complication, which might distort the measured direction of motion in a few systems, if at all. When accurate *instantaneous* proper motions are available from *Gaia*, their distortion by the inner subsystems will need to be addressed carefully.

The sample of triple systems used here is based on the compilative MSC catalog affected by various poorly known selection biases. It is not representative of the real population of hierarchical systems in the field. Additional selection effects are caused by the need to get measurable revolution direction of the outer system (this favors smaller outer separations). Yet, the selection filters do not depend on the *sense* of rotation. Similarly, the measured rotation direction and eccentricity of the inner orbit should not depend on the rotation direction of the outer orbit. So, the results of this study are reasonably immune to the selection and are valid for the actual population of hierarchical systems.

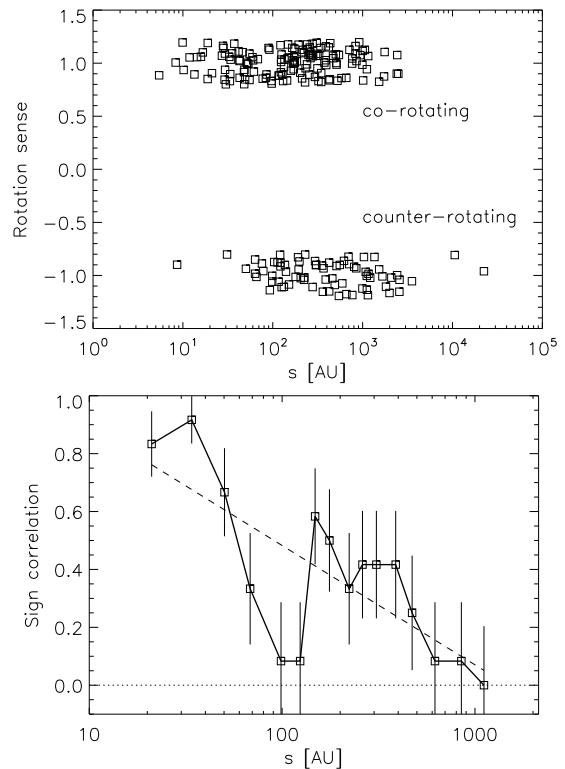


FIG. 1.— Sign correlation C vs. outer projected separation s . Top: relative revolution sense (1 for co-rotating, -1 for counter-rotating) vs. projected separation s (random vertical spread is introduced to avoid overlap). Bottom: average C and its error as a function of separation, computed in sub-samples of 24 systems as a running mean and plotted against the median separation in each sub-sample. The dashed line is a linear fit.

3. SIGN CORRELATION

3.1. Definition

¹ <http://www.ctio.noao.edu/~atokovin/stars/index.php>

² <http://www.ctio.noao.edu/~atokovin/newmsc.tgz>

TABLE 1
HIERARCHICAL SYSTEMS WITH RESOLVED INNER ORBIT (FRAGMENT)

WDS	π_{HIP} (mas)	M_1 (M_\odot)	P_1 (yr)	e_1	a_1 ($''$)	Ω_1 ($^\circ$)	i_1 ($^\circ$)	ρ ($''$)	θ ($^\circ$)	Revolution Direction	Sign
00024+1047	11.4	1.04	129.7	0.046	0.366	59.4	97.2	63.20	301.0	0	0
00046+4206	6.7	3.05	70.1	0.515	0.165	100.6	104.8	5.35	169.8	0	0
00047+3416	5.6	2.50	545.0	0.670	0.623	136.4	99.4	95.30	238.0	0	0
00057+4549	88.3	0.63	509.6	0.220	6.210	13.5	54.9	328.00	254.0	0	0
00084+2905	33.6	3.37	0.3	0.535	0.024	284.4	105.6	6.70	5.0	0	0
00093+2517	19.5	1.13	1.3	0.220	0.025	169.0	74.0	29.50	237.0	0	0
00134+2659	7.0	2.42	422.0	0.720	0.641	193.0	124.1	18.01	223.7	1	-1
00174+0853	15.3	1.25	35.7	0.002	0.189	124.1	95.4	3.94	234.2	-1	1

The sign correlation C is based on counting the number of triples with coincident revolution directions n_+ and the number of apparently counter-rotating triples n_- . Then

$$C = (n_+ - n_-)/(n_+ + n_-) = 2n_+/n - 1. \quad (1)$$

It can be inferred from the properties of the binomial distribution that the rms error of this estimate is $\sigma_C = \sqrt{(1+C)(1-C)/n}$, where $n = n_+ + n_-$ is the sample size. It is easy to show that for random orbit orientation relative to the observer, the average angle between angular momentum vectors Φ is related to C , $\langle\Phi\rangle = \pi/2(1-C)$ (Worley 1967). The revolution direction of the inner subsystems is securely measured from the inclination i of their orbits: direct if $i < 90^\circ$, retrograde otherwise. The full sample of 216 triples yields $C = 0.324 \pm 0.064$, or $\langle\Phi\rangle = 60^\circ.8$, in agreement with Sterzik & Tokovinin (2002) and earlier works.

The relation between sign correlation and $\langle\Phi\rangle$ is valid for random orientation with respect to the observer. In the present sample is not quite random for two reasons. First, the computation of visual orbits is difficult for large inclinations and such orbits are under-represented in VB6, despite the fact that $i = 90^\circ$ is the most probable inclination of randomly oriented orbits. Second, the projected angular velocity of the outer component also depends on the inclination, favoring smaller i (see Sterzik & Tokovinin 2002). However, all biases are symmetric with respect to the revolution direction, so the parameter C is a very robust diagnostic of the relative orbit alignment.

3.2. Dependence of orbit alignment on separation

It has been noted by Sterzik & Tokovinin (2002) that the orbit alignment depends on the degree of hierarchy, being stronger for systems with comparable inner and outer periods or separations. This result is confirmed by the new, larger sample. An even stronger dependence of orbit alignment on the projected outer separation $s = \rho/\pi_{\text{HIP}}$ is found here. The sample has been sorted on s and the sign correlation C was computed for groups of 24 triples with increasing separation, as a running mean. Figure 1 shows the dependence of the sign correlation on the outer separation. The linear fit $C = 1.31 - 0.41 \log s$ is an adequate representation of the trend. The local minimum at $s \sim 100$ AU is most likely a statistical fluctuation. Relatively tight triples with $s < 50$ AU are strongly aligned, with C exceeding 0.8 or $\langle\Phi\rangle < 18^\circ$. The top panel of Figure 1 shows the raw data without any binning in separation.

TABLE 2
DEPENDENCE OF ORBIT ALIGNMENT ON MASS

M_1 (M_\odot)	$\langle M_1 \rangle$ (M_\odot)	N	C	$\langle s \rangle$ (AU)	e_+	e_-
<1	0.80	62	0.61 ± 0.10	128	0.36	0.61
1 to 2	1.33	83	0.23 ± 0.11	255	0.40	0.47
>2	3.46	71	0.18 ± 0.12	315	0.50	0.47
All	1.39	216	0.32 ± 0.06	222	0.42	0.49

3.3. Dependence of orbit alignment on mass

The multiplicity fraction and companion fraction strongly depend on stellar mass, being larger for massive stars. The orbit alignment also depends on mass, but in the opposite sense, with low-mass stars having stronger alignment. The sample has been subdivided into three approximately equal parts based on the primary mass in the inner subsystem M_1 (when the primary component is itself a binary, its total mass is considered). Table 2 indicates that the orbit alignment decreases with mass. Its columns contain the mass range, the median mass, the number of systems N , the sign correlation C and its error, median outer separation, and average inner orbital eccentricities for co- and counter-rotating systems. Figure 2 shows the mass dependence graphically.

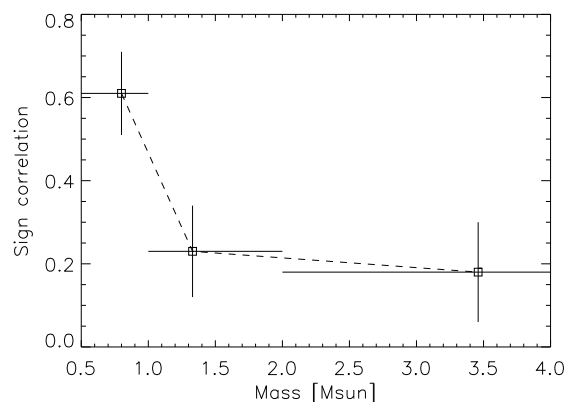


FIG. 2.— Dependence of the sign correlation C on the mass. The vertical bars depict formal errors of C , the horizontal bars show the mass range of each group.

The separations of low-mass triples are, on average, smaller compared to the more massive ones. Given the dependence of orbit alignment on the outer separation, one might wonder whether the mass dependence is not caused only by the difference in separations. Figure 3 shows the dependence of orbital alignment on the outer separation in the two mass regimes. The different degree

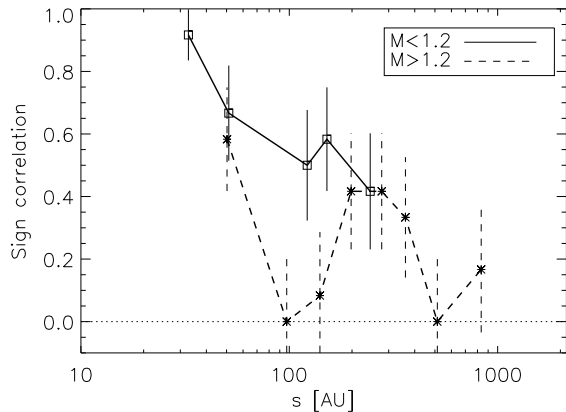


FIG. 3.— Sign correlation vs. projected separation s . The full line corresponds to 88 systems with $M_1 < 1.2M_\odot$, the dashed line corresponds to 128 systems with $M_1 > 1.2M_\odot$.

of orbit alignment *at comparable outer separation* tells us that the mass dependence is genuine.

The last two columns of Table 2 contain the mean eccentricity of the inner orbits computed for the triples with coincident and opposite sense of rotation, e_+ and e_- respectively. When there is an orbit alignment (large C), we find that $e_+ < e_-$, meaning that the inner orbits in aligned triples are, on average, less eccentric.

4. TRIPLE SYSTEMS WITH TWO KNOWN ORBITS

The sign correlation constrains the average angle $\langle\Phi\rangle$, but not its distribution. A mixture of well-aligned and randomly aligned systems or a single population of loosely aligned systems can have the same $\langle\Phi\rangle$. Additional information on the distribution of Φ can be obtained from triple stars with known inner and outer orbits studied in this Section and from the apparent configurations of triples studied in Section 5.

The angle Φ between the angular momentum vectors, sometimes called mutual inclination, is computed as

$$\cos \Phi = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Omega_1 - \Omega_2), \quad (2)$$

where i and Ω are the inclinations and position angles of the node in the inner and outer orbits.

Visual orbits do not distinguish between the two orbital nodes, leaving a 180° ambiguity in the element Ω . To determine the angle Φ , we thus need to identify the correct ascending nodes in both inner and outer orbits from radial velocities. This is done only for a small number of systems. The ambiguity in Ω is equivalent to the \pm sign of the second term in equation 2. So, for each system the two angles Φ_1 and Φ_2 are computed and we do not know which of those is the correct one. The work around consists in simulating the effect of this ambiguity numerically.

In the above sample, 54 triples have known outer visual orbits. The actual number is larger, but we discarded poorly defined outer orbits with very long periods above 1000 yr and inner orbits with incomplete parameters (e.g. the missing angle Ω). Many orbits in the VB6 are preliminary or uncertain, being based on incomplete coverage and/or on noisy position measurements. However, discarding those orbits would dramatically reduce the sample size. The uncertainty of Φ computed from the visual orbits is difficult to quantify in most cases.

Table 3 lists relevant data for this sub-sample, two lines per system. The first line gives the orbital parameters of

the inner binary ('I' in the 2nd column): its period P , eccentricity e , semimajor axis a , position angle of node Ω and inclination i , the grade of the orbit, from 1 (best) to 5 (tentative), 8 and 9 (astrometric), and the bibliographic reference code adopted in the VB6. The last column gives the angle Φ_1 . The following O-line contains the orbital parameters of the outer binary, while the angle Φ_2 is given in the last column. Some orbits in Table 3 were determined or refined by the author and are still unpublished.

For this sample, we find $C = 0.48 \pm 0.12$, or $\langle\Phi\rangle = 47^\circ$. These systems are closer than in the main sample; the average outer semimajor axis is only 75 AU.

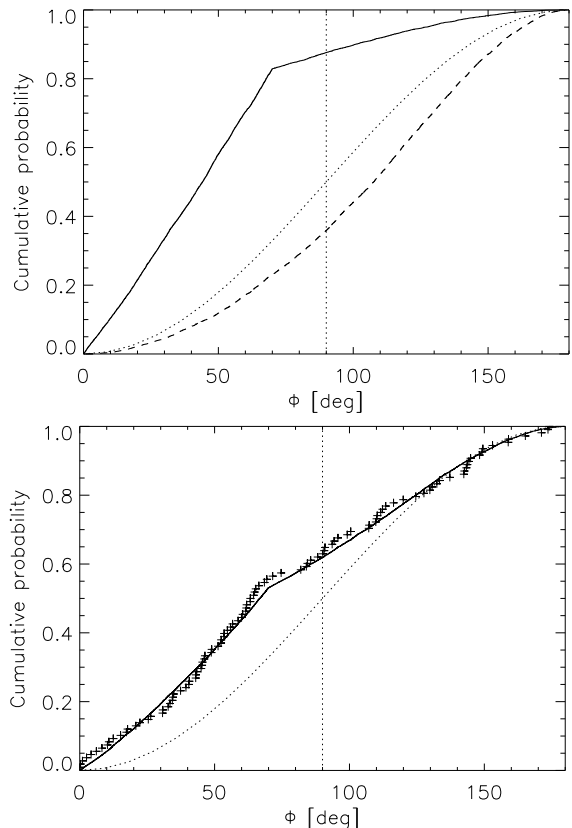


FIG. 4.— Top: cumulative distribution of the angles Φ_1 and Φ_2 (full and dashed lines, respectively) in simulated triple stars. Bottom: joint cumulative distributions of both angles in the real sample (crosses) and in simulations (full line). In both plots, the dotted line corresponds to the uncorrelated orbit orientation.

When the orbits are aligned randomly, both $\cos \Phi_1$ and $\cos \Phi_2$ are distributed uniformly, and these two angles are slightly anti-correlated with each other. When the orbital spins are partially aligned, the cumulative distribution of the true angle Φ_1 is above the random one, while the cumulative distribution of Φ_2 is below. The statement of Sterzik & Tokovinin (2002) that for partially correlated spins the distribution of Φ_2 is random is incorrect.

We simulated triple systems with some assumed distribution of Φ and random orientation with respect to the observer. A simple model is adopted, where Φ is distributed uniformly in the interval $(0, \Phi_0)$ for a fraction f of the triples and is random for the remaining $1 - f$ fraction. After a few trials, the parameters $\Phi_0 = 70^\circ$

TABLE 3
HIERARCHICAL SYSTEMS WITH TWO KNOWN VISUAL ORBITS (FRAGMENT)

WDS	In/Out	P (yr)	e	a ($''$)	Ω ($^\circ$)	i ($^\circ$)	Orbit Grade	Reference Code	Φ ($^\circ$)
00247–2653	I	17.25	0.017	0.460	14.8	62.0	2	Tok2017b	1.0
00247–2653	O	77.47	0.026	1.531	13.9	62.6	4	Tok2017b	124.6
00321+6715	I	15.00	0.083	0.348	175.0	47.0	9	Ana2011	0.3
00321+6715	O	222.30	0.293	3.322	174.9	47.3	5	Doc2008d	94.3
00335+4006	I	4.72	0.076	0.058	96.1	97.1	4	Tok2017a	142.6
00335+4006	O	69.37	0.329	0.389	299.0	112.8	2	Tok2017a	27.1
00568+6022	I	4.85	0.224	0.032	149.9	47.6	4	Doc2006c	20.8
00568+6022	O	83.10	0.241	0.245	175.0	54.9	2	CWA1992	99.2

and $f = 0.8$ were chosen to match the combined distribution of both angles in the real sample (Figure 4, bottom). This model has $\langle \Phi \rangle = 46^\circ$. The top panel shows the separate cumulative distributions of Φ_1 and Φ_2 in the simulated triples. The distribution of Φ_1 , as well as the merged distribution, have a characteristic break at $\Phi \approx \Phi_0$, and the merged cumulative distribution of Φ is almost (but not exactly) linear at $\Phi < \Phi_0$, reflecting the true input distribution of Φ_1 . A population of well-aligned (nearly coplanar) triples would manifest itself by a peak at small Φ in the merged distribution, which is not present. However, the empirical distribution of Φ is broadened by the errors of visual orbits.

We see that despite the uncertainty associated with unknown orbit nodes, the merged distribution of both angles Φ contains information on the distribution of the true angles Φ_1 . The observed distribution matches the model where 80% of visual triples are aligned within 70° .

5. PROJECTED CONFIGURATIONS

Another method of checking orbital alignment in triple stars is based on their apparent (projected) configurations. It does not require the knowledge of rotation sense and can be applied even to very wide triples. Suppose that a coplanar triple system is seen edge-on. Then the position angles of the inner and outer pairs will be either equal or will differ by 180° . When such system is viewed from an arbitrary direction and at arbitrary phases of both orbits, the correlation between the position angles is reduced, but does not vanish completely. Our simulations show that orbit alignment can be detected from apparent configurations in a large (on the order of 1000 or more) sample of triple stars with strong coplanarity, otherwise the effect is washed out by the randomness of projections and orbital phases. Therefore, we do not study here the difference between position angles of the inner and outer pairs.

A better option is to compare the angle α between the line of nodes in the inner orbit and the direction toward the tertiary component (Figure 5). This approach requires the knowledge of the inner orbit, but eliminates one random factor (position of the inner binary on its orbit). The angle α is defined modulo 90° . The line of nodes is perpendicular to the projection of the orbital spin vector on the sky. As the tertiary component C spends more time at large separations, the chance of obtaining small α for a nearly coplanar triple is high. However, when the tertiary is found at another position C', the angle α can be close to 90° even in a perfectly coplanar triple. The method works only in the statistical sense, through the analysis of the distribution of α . This

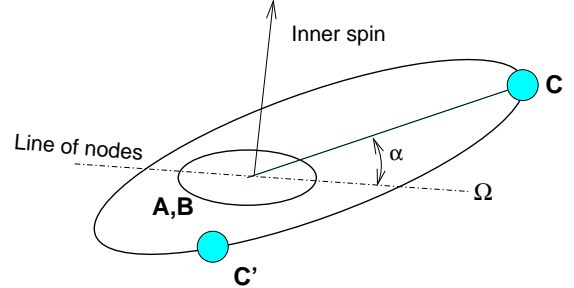


FIG. 5.— Definition of the angle α between the inner line of nodes in the subsystem A,B and the position angle of the tertiary component C.

approach has been used by Wheelwright et al. (2011) to study alignment between dust disk and orbital plane in 20 young wide binaries.

In the pre-computer era, Agekyan (1952) proposed this method for evaluating coplanarity of triple stars from their apparent configurations. He demonstrated analytically that the average quantity $A = \langle \cos^2 \alpha \rangle$ equals 0.6932 in the case of coplanar orbits, while it is 0.5 for uncorrelated orbital planes. In other words, small values of α dominate in the coplanar case, but for the random relative orientation α is distributed uniformly between 0 and 90° . Neither Agekyan nor Tokovinin (1993) had detected any significant deviations of A from 0.5 in small samples of visual triple stars. Here we study the distribution of α rather than the average diagnostic A .

The distribution of α was calculated by numerical simulation. A large number of triple systems with random relative orientation have been generated. The distribution of α for the full simulated sample is uniform, as expected. When only the aligned part of the sample with $\Phi < \Phi_0$ is selected, small α become more probable and the distribution deviates from uniformity (Figure 6, top). For three values of $\Phi_0 = 30^\circ, 60^\circ, 90^\circ$, the average angle between the orbital spins is $\langle \Phi \rangle = 20.4, 39.5, 57.1$. With $\Phi_0 = 90^\circ$, the average Φ is similar to the one actually observed, the orbital spins are partially correlated. However, the distribution of α is practically indistinguishable from the uniform one. So, this method can detect only a relatively well-aligned population of multiples. Even in this case (e.g. $\Phi < 30^\circ$), the α -distribution is strongly broadened by random projection and orbital phase (see also Figures 2 and 3 in Wheelwright et al. 2011).

The angles α were computed for all 443 triples in our sample (there is no need to know the revolution direction of the outer component). Their distribution only barely differs from the uniform one. This difference is enhanced in the sub-sample of 140 close triples with outer

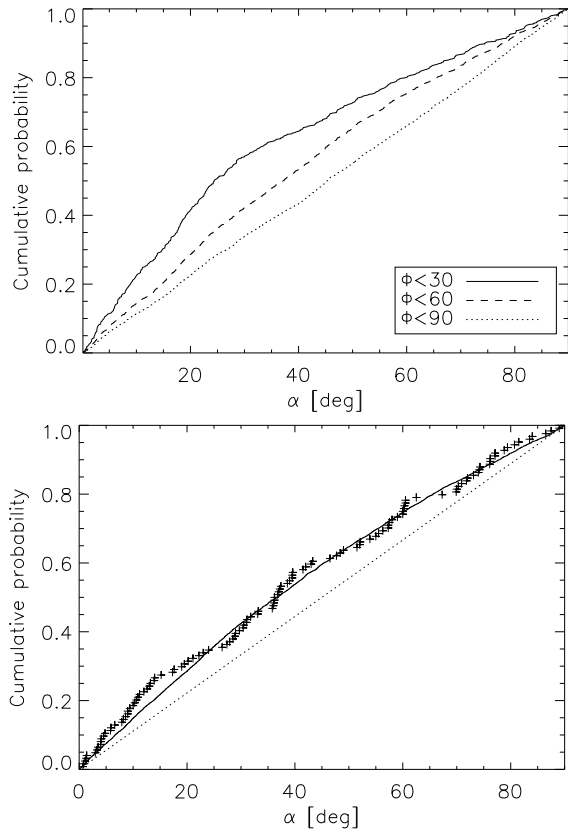


FIG. 6.— Cumulative distributions of the angle α . The upper plot shows the results of numerical simulation. The bottom plot shows the actual distribution in the subset of 124 systems with $M_1 < 1M_\odot$ (crosses) compared to the simulated distribution (full line). The dotted line marks the uniform distribution corresponding to the uncorrelated orbit orientation.

separation $s < 300$ AU, in agreement with the previous finding that such triples are better aligned (they have $C \approx 0.6$ and $\langle \Phi \rangle \approx 36^\circ$). The effect is even larger for the sub-sample of 124 low-mass triples with $M_1 < 1M_\odot$. The maximum deviation of the cumulative histogram of α from the linear (uniform) distribution in the low-mass sample is 0.13 and corresponds to the Kolmogorov-Smirnov significance level of 0.02. Figure 6 compares the observed distribution of α in low-mass triples with simulations of partially aligned triples presented above in Section 4 ($\Phi_0 = 70^\circ$, $f = 0.8$). The agreement is satisfactory, thus favoring the simulated distribution of Φ .

6. DISCUSSION

We found a strong tendency of orbit alignment in triple stars with outer separations less than ~ 50 AU. This roughly matches the scale of circumstellar disks. Formation and/or dynamical evolution of those close triples should have been influenced by the disk. Additional evidence of the importance of dissipative dynamical interactions with gas is furnished by the statistically smaller eccentricity of inner orbits in the co-aligned triples, compared to the average eccentricity. The quadruple system HD 91962 (Tokovinin et al. 2015a) with nearly coplanar orbits of small eccentricity is thus representative of the class of low-mass hierarchies with a planar, planetary-like architecture. There exist other low-mass multiples with similar properties (Tokovinin & Latham 2017).

We also found that the orbit alignment is stronger in triple stars with low-mass primaries, compared to more massive triples. Compact ($s < 50$ AU) low-mass triples have $C \approx 0.8$, or $\langle \Phi \rangle \approx 18^\circ$, while more massive triples are less well aligned.

Dynamical interactions in unstable multiples should leave residual misaligned triples, often with highly eccentric orbits (Antognini & Thompson 2016). It seems that chaotic stellar dynamics played a larger role in the formation of massive stars. Another process that can create misaligned triples is the accretion of gas with randomly aligned angular momentum at the epoch of star formation. Massive stars form in clusters and accrete misaligned gas from the cluster volume, not just from the parent core. Misaligned gas changes the orientation of the outer orbit and, even more importantly, causes its rapid inward migration. Shrinking of the outer orbit can destabilize a multiple system (Smith et al. 1997), leading to violent interactions and ejections of some members at high velocity (runaway stars). These internal dynamical interactions operate even on small scale. In contrast, dynamical interactions with other cluster members are relevant on the spatial scale of thousands of AU (depending on the cluster density) and are associated with moderate ejection velocities.

Alignment in triple systems is related to the alignment between disks and stellar spins in binaries, being influenced by the same phenomena. Monin et al. (2006) estimated from polarization the relative alignment between two disks in young wide binaries. They found a clear evidence of disk alignment between binary components and a hint on stronger alignment in closer binaries. Echoing this result, Wheelwright et al. (2011) established that resolved disks are aligned with the binary orbit. Recently, angles between projected spins of young stars (traced by the outflow direction) paired in wide ($s > 1000$ AU) binaries have been studied by Lee et al. (2016) and Offner et al. (2016).³ This technique is similar to the α -statistics for triple stars, but it eliminates one random factor (the phase of the outer orbit), being affected only by random projections. Both triple-star configurations and the distribution of projected spin angles are not sensitive to the spin direction. This is the weakness of this method, compared to the sign correlation. Unlike Monin et al., Offner et al. (2016) conclude that the spin directions of components in wide binaries are not mutually correlated. Their sample is small (26 spin pairs) and the significance of this result is marginal. It matches however the lack of alignment between outer and inner orbits in triple systems with outer separations above 1000 AU, found here.

On the other hand, orbit alignment is strong in very compact multiple systems. Borkovits et al. (2016) studied relative orbit orientation in close triple systems containing eclipsing binaries, using *Kepler* photometry in combination with dynamical analysis. This method is indirect because the systems are not spatially resolved. The outer periods of those triples are of the order of a year, their masses of the order of one solar mass. For 62 systems the authors were able to estimate the angles Φ . Borkovits (2017, private communication) cautioned how-

³ Misleadingly, these authors call orthogonal directions “anti-aligned”, while here and generally anti-alignment means oppositely directed parallel spins.

ever that the sign of $\cos \Phi$ depends on the higher order perturbation terms and is determined by this method less reliably than $\sin \Phi$. Only one triple out of 62 has $\Phi = 147^\circ$ (counter-rotating), all remaining triples have $\Phi < 60^\circ$. The average $\langle \Phi \rangle = 21^\circ$ computed from their data implies $C = 0.77$ and matches the large values of C found here for compact triples.

Figure 15 of Borkovits et al. (2016) presents the bimodal distribution of the angle Φ , with a strong peak of 29 nearly coplanar ($\Phi < 10^\circ$) triples and the second peak at $\Phi \approx 40^\circ$, presumably matching the outcome of the Kozai mechanism. These authors note, however, that the inner periods of eclipsing binaries show neither correlation with Φ nor the clustering between 3 and 10 days expected from the tidal circularization. This contradicts the predictions of Fabrycky & Tremaine (2007), unless the inner periods were shortened by other mechanisms such as magnetic braking. If some co-rotating inner binaries with $\Phi \approx 40^\circ$ indeed resulted from the Kozai cycles with tidal circularization, their progenitors had $\Phi < 90^\circ$, i.e. had correlated rather than random orbital spins. Overall, $43/62=0.69$ fraction of compact triples in Borkovits et al. (2016) have $\Phi < 30^\circ$, too small to result from the Kozai mechanism. Instead, gas friction in a disk could be the dominant formation channel of close binaries and compact triples.

The spin-orbit angle and the sense of rotation can be established for transiting exoplanets, informing us on the primordial disk alignment. Fielding et al. (2015) found from their simulations of turbulent fragmentation typical

spin-orbit angles $\Phi \sim 40^\circ$, in agreement with observations of exoplanets and similar to the orbit alignment in close triple systems.

Although the sample of triple stars with known inner orbits and known sense of revolution of the third components has increased substantially since the work of Sterzik & Tokovinin (2002), from 135 to 216, the progress remains slow, being paced by the long orbital periods and the slow accumulation of data. Continued monitoring of triple stars by means of speckle interferometry is needed to determine more orbits and to reach closer, more interesting triples. Long-baseline interferometry has begun to make its contribution in this area (e.g. Schaefer et al. 2016) and will hopefully continue doing so, especially if fainter stars can be observed by interferometers. *Gaia* might determine astrometric orbits in inner subsystems of resolved binaries by very accurate monitoring of positions during its 5-year mission. Complementary accurate radial velocities will be needed to strengthen astrometric and visual orbits and to resolve the ambiguity of their nodes.

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