A Hunting Expedition for High-Order Hierarchies

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ABSTRACT
Stellar hierarchical systems of high order containing more than three stars are rare and fascinating objects; their discovery and study highlights still unknown aspects of star formation and early evolution. We matched eclipsing binaries discovered by *TESS* with a Gaia catalog of wide binaries and selected candidate quadruple (or higher-order) systems based on excessive astrometric noise. A subset of 192 southern candidates located within 500 pc were observed by speckle interferometry, and we resolved for the first time 50 close pairs, confirming their high-order (from four to five components) multiplicity. These observations are reported, and some remarkable hierarchical systems are discussed.

Key words: (stars:) binaries: eclipsing – (stars:) binaries (including multiple): close – methods: analytical

1 INTRODUCTION

Close binaries play an important role in the study of stellar evolution and such physical processes as mass transfer, accretion, compact objects, supernovae, etc. Individual stars form by compressing and accreting gas from a large volume, so two stars cannot be born in close proximity as they have to approach each other somehow to make a tight binary. Observers noted a long time ago that close binaries are often found as inner components of hierarchical systems (e.g. Tokovinin et al. 2006; Hwang 2023a), but reasons of this empirical connection are still elusive, as discussed by Moe & Kratter (2018).

Although a tertiary companion can help in forming a close pair by extracting its angular momentum, some tertiaries are too wide (hundreds and thousands of au) to exert any dynamical influence on the inner pair. But perhaps such hierarchies host an intermediate, closer satellite of the inner binaries, such that the presumed tertiaries are in fact outermost bodies in quadruple systems of 3+1 hierarchy. This hypothesis can be tested using modern space missions such as *Gaia* (Gaia Collaboration et al. 2021) and the Transiting Exoplanet Survey Satellite (*TESS*) mission (Ricker et al. 2015). These missions, however, have been designed to pursue other goals (e.g. Galactic structure, exoplanets), and use of their data for multiplicity studies can be greatly enhanced by combination with ground-based follow-up. A pilot search for new 3+1 quadruples exploiting this idea is the subject of this paper.

Photometric precision and time coverage provided by *TESS* has already enabled discovery of interesting hierarchical systems based exclusively on photometry. Study of the extraordinary sextuple system TIC 168789840 which contains three very similar eclipsing binaries (EBs) (Powell et al. 2021) has been particularly motivating for the present project. More recently, the system V994 Herculis, previously identified as a quadruple (Lee et al. 2008), has also been shown to be a sextuple system consisting of three eclipsing binaries (Zasche et al. 2023). Other recent related works are those by Rappaport et al. (2022, 2023) and Czavalinga et al. (2023); the latter authors combined *TESS* data on EBs with the Gaia catalog of orbits (Gaia Collaboration et al. 2022) to find interesting compact triples. A sample of 97 doubly eclipsing quadruple stars has been identified through a combination of machine learning methods and visual survey from the *TESS* data by Kostov et al. (2022). Another similar catalog was published by Zasche et al. (2022), where the authors examined the *TESS* light curves of known eclipsing system from the Variable Star Index (Watson et al. 2006).

A close tertiary companion of an EB can be discovered photometrically by the eclipse time variation (ETV) due to the light-time effect and mutual dynamics (the latter is also manifested by variable eclipse amplitudes in precessing EBs). Long-duration photometric data needed for such analysis may be available for some EBs in our sample.

Traditionally, high-order hierarchies are discovered by finding new components in known systems, e.g. tertiary bodies in binaries, fourth companions to triples, etc. Here we start with a sample of triple candidates — wide Gaia pairs from El-Badry et al. (2019) containing *TESS* EBs. That is, one of the two components in the pair noted by El-Badry et al. (2019) is actually an eclipsing binary when examined in *TESS* data, making the system at least a triple. Furthermore, one or both components of the wide pairs have signs of inner subsystems according to Gaia, namely the increased astrometric noise. We probed a subset of 192 such candidates with high-resolution imaging and were able to resolve a subsystem in 50 cases. Apart from proving the existence of additional subsystems, these resolutions enable estimation of their periods and mass ratios.

Our pilot project thus explores a new strategy for finding high-order hierarchies by combining *TESS*, Gaia, and speckle interferometry. It is complementary to other approaches mentioned above. Each approach has its own shortfalls and limitations, and this one is not an exception.

In Section 2 we will discuss our selection criteria for systems to

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examine with speckle interferometry, followed by an explanation of the observation method in Section 3. We will discuss new hierarchies discovered by our process in Section 4, then summarize our findings in Section 5.

2 SELECTION OF HIGH-ORDER MULTIPLE CANDIDATES

We began our selection process with EBs found in the *TESS* data using a machine learning approach further described by Powell et al. (2021). We cross referenced our list against binaries from El-Badry et al. (2019). The *TESS* EBs tend to have short periods, whereas wide pairs from El-Badry et al. (2019) have very long periods. Combination of the two sets allows for the identification of bound systems where one of the two components in a wide pair is indeed a close binary in itself (the short-period *TESS* EB), and therefore the system is at least a triple.

We further narrowed the systems selected by this criteria by applying the criteria of a Renormalized Unit Weight Error (RUWE) > 1.4 for either of the components, as Stassun & Torres (2021) found this criteria was indicative of a subsystem. In order to select systems viable for speckle imaging, we also reduced our data set to those nearer than 500 pc. Finally, we conducted a photocenter analysis of the EB to confirm the eclipses were on target with the corresponding system from (El-Badry et al. 2019), resulting in a total of 221 candidates for speckle imaging, of which 192 were observed.

EBs have short periods. The frequency of close binaries depends strongly on the mass (Moe & Di Stefano 2017), favoring massive primaries. On the other hand, massive stars are rare and short-lived, while solar-type EBs are numerous; their formation is helped by magnetic braking of close pairs containing stars with convective zones. Combination of these selection effects leaves in our sample mostly stars with masses from 1 to 2 $M_\odot$. The absolute magnitudes of our primaries are concentrated in the M_G interval from 1.5 to 5 mag. Statistically, massive stars are more distant than nearby low-mass dwarfs, biasing our candidate sample to smaller parallaxes in comparison with typical wide binaries in El-Badry et al. (2019).

For the high-resolution imaging, we trimmed our candidate list to systems within 500 pc. The resolution limit of 40 mas (see Section 3) corresponds to a separation of 20 au at this distance, enabling us to probe the peak of binary separation distribution at ~50 au. There were 221 candidates with ϖ > 2 mas, and their median parallax is 3.54 mas. We observed 192 candidates from this reduced list. The median period of these EBs is 0.86 days, and the minimum period is 0.13 days. Natural preference of short periods, inherent to all EB samples, is further enhanced here by including small-amplitude ellipsoidal variables, detected by *TESS* owing to its precise photometry. High precision also helps to detect shallow eclipses whose amplitude is reduced (diluted) by the light of other components in multiple systems.

Candidates where the subsystems were resolved previously, as reported in the Washington Double Star Catalog (WDS; Mason et al. 2001) and in the Multiple Star Catalog (MSC; Tokovinin 2018b), were removed from the observing program. Some wide Gaia binaries are known pairs listed in the WDS (we provide below their discoverer codes). Similarly, some *TESS* EBs were previously identified from ground-based photometry and have variable-star designations.

The increased astrometric noise in Gaia, quantified by the RUWE parameter, can have diverse causes. Non-linear motion of the photocenter due to a close unresolved binary is an obvious reason for a high RUWE (Penoyre et al. 2022). However, a binary companion on a long-period (centuries and millenia) orbit can also produce an increased RUWE by influencing Gaia measurements, especially when it is not identified in Gaia as a distinct source. Some pairs in our sample with separations of ~1″ could have a large RUWE for this reason. On the other hand, the EBs themselves also can increase the astrometric noise either by their orbital motion or by the changing flux that displaces the photocenter of an unresolved binary (variability-induced motion). As a result, our list of candidate quadruples needs additional vetting to establish their true nature.

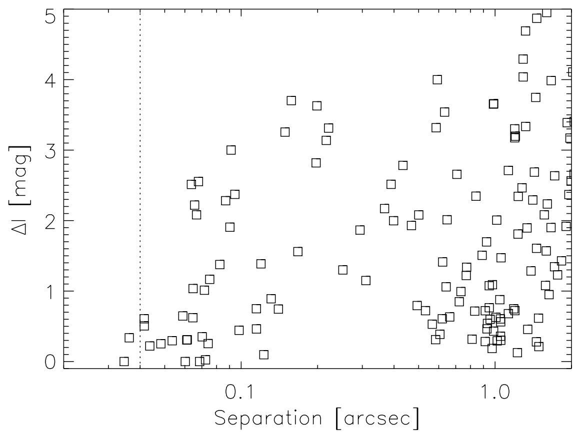

Figure 1. Separation and magnitude difference ΔI of resolved pairs. The vertical dotted line indicates the nominal diffraction limit of 40 mas.

3 SPECKLE INTERFEROMETRY AT SOAR

The high-resolution camera (HRCam) at the 4.1-m Southern Astrophysical research (SOAR) telescope in Chile has been used for imaging selected candidates. The instrument and data processing are covered in (Tokovinin 2018a) and in several papers reporting the results (Tokovinin et al. 2022, latest in series). Briefly, image cubes with a short exposure time of 25 ms and a fine pixel scale of 15 mas are recorded and processed by the standard speckle interferometry pipeline.

Candidates from our list were merged with the general HRCam program and observed at low priority (as fillers) in 2021–2023. The *I*-band filter (824/170nm) was used to reach fainter stars and to maximize the contrast of faint, red companions. The diffraction-limited resolution was about 40 mas. The 3.″15 field of view enables discovery and measurement of companions up to 1.″5 separation (for wider pairs, we took images of larger size). Figure 1 illustrates the resolution and contrast limits of this program by plotting parameters of resolved pairs, both known and new. Absence of pairs with small ΔI and intermediate separations reflects the lack of their Gaia astrometry, hence their absence in the catalog of El-Badry et al. (2019) and in our sample. Pairs wider than ~0.″8 are recognized as distinct sources in Gaia. They were also measured by HRCam, and in some of them inner subsystems were resolved. There was a modest overlap between this and other programs, and some observations reported below appear in the published HRCam data (Tokovinin et al. 2022); they are duplicated here for completeness.

The results of HRCam observations are assembled in Table 1. Each system is labeled by a unique 10-character code based in the J2000 coordinates, as in the WDS and MSC. The second column contains

Table 1. Results of the HRCam Observations (Fragment, full table is available online)

WDS (J2000)	Name	R.A. (deg)	Dec. (deg)	Date (JY-2000)	θ (deg)	ρ ($''$)	ΔI (mag)	Flag	$\rho_{\rm min}$ ($''$)	$\Delta I_{0.15}$ (mag)	ΔI_1 (mag)
00494−3853	TDS1631	12.340231	−38.885699	21.7322	266.2	0.4933	0.8	q	0.048	2.43	3.43
01115−2842	AB	17.867231	−28.697093	21.7538	18.2	1.3202	3.3	*	0.046	2.68	4.35
01135−3821	BRG 4	18.367253	−38.350854	21.7322	24.9	1.4834	0.6	*	0.064	2.36	3.03
01359−5229	Aa,Ab	23.984338	−52.477317	21.7295	205.0	0.0415	0.5		0.054	2.15	3.28
01359−5229	Aa,B	23.984338	−52.477317	21.7295	85.7	0.6629	0.6		0.054	2.15	3.28
01429−2007	Aa,Ab	25.728319	−20.124463	21.7322	173.6	0.3985	2.0	q	0.050	2.45	3.82
01496−1937	A	27.390387	−19.624787	21.7322	0.0	0.0000	0.0		0.052	2.47	3.71

system names adopted in the WDS, if present, or just indication of pairings between components. For example, in 01359−5229 the wide 0.″66 pair Aa,B is present in Gaia (but not listed in the main WDS catalog), while the 0.″04 pair Aa,Ab is resolved for the first time here. The following columns of Table 1 contain the results in the standard form: equatorial coordinates for J2000 (for identification and cross-reference), Julian date of the observation, position angle θ, separation ρ, and magnitude difference ΔI; for unresolved targets all these numbers are zero. Flag (*) indicates that ΔI of a wide pair was determined by alternative method that avoids speckle anisoplanatism, flag (q) means that the quadrant is determined without the 180° ambiguity, (:) marks noisy or uncertain measurements. The last three columns contain the resolution limit $\rho_{\rm min}$ (it is larger than the diffraction limit for faint targets and/or under poor observing conditions) and the maximum detectable contrasts $\Delta I_{0.15}$ and ΔI_1 at separations of 0.″15 and 1″, respectively, estimated by the speckle pipeline.

To illustrate the results, speckle autocorrelation functions (ACFs) of six targets are shown in Figure 2. The wide pairs were known from Gaia or ground-based data, while close inner subsystems are resolved here (with the exception of 02578−2614, where the faint Gaia companion B and the new, brighter companion Ab are at comparable separations). The ACF of a triple star has, in general, six peaks plus the strong peak at the center. However, some peaks may be blended or too faint, depending on the separations and contrast. Close subsystems have overlapping ACF peaks, but they are securely detected by fringes in the speckle power spectrum. Some new close pairs were reobserved for confirmation and orbital motion monitoring.

4 NEW HIERARCHIES

In this section, we focus on the 50 hierarchies where inner subsystems were resolved at SOAR, making them confirmed quadruples. In fact, two of those hierarchies are quintuple (see below).

The large pixel size of *TESS* (27″) does not allow identification of an EB with particular components of the multiple systems studied here. A default assumption that the EBs are associated with the brightest stars is made, justified by a larger amplitude of eclipses in the combined light curve in such cases. This cannot be true for all systems, but is very likely for wide binaries with a large magnitude difference (e.g. >5 mag), because if the EB were hosted by the faint secondary, it would not be detectable owing to its strongly reduced eclipse amplitude. These likely 3+1 quadruple systems are 01429−2007, 04014−4043, 04461−3037, 07127−1202, 07346−6457, 08343−0707, 08413+0507, 08500−4139, 08572−5760, 09059−2248, 09063−1548, 09487−5058, 10353−7511, 10486−0337, 11015−3701, 11121−3735, 13493−6808, 17027+1522, 18387−6306, and 20505−2901 (20 in total). On the contrary, when the components of a wide pair have comparable magnitude, it is plausible that the resolved and eclipsing subsystems are hosted by different stars, and this could be a 2+2 quadruple.

Information on new hierarchies with resolved subsystems was entered in the MSC and will become public after its next update.[1] A subset of the catalog on the 50 hierarchies with resolved subsystems is reproduced here for consistency. The content and format are similar to those of MSC, but a few less significant fields are omitted for brevity. Table 2 lists basic data on the individual components, identified with resolved Gaia sources and designated by capital letters. All astrometric data (positions, proper motions, parallax) come from Gaia DR3, the V-band magnitudes are computed from G magnitudes and BP−RP colors as prescribed in the Gaia documentation. Table 3 gives data on individual subsystems, linked by the common 10-letter MSC code. The content and notation are same as used in the MSC. The hierachy is coded by the triads (primary, secondary, parent), where * stands for the root (upper level) system, in our case the wide Gaia binary. Types of the systems correspond to observing methods (C – common proper motion, v – visual, E – eclipsing, etc.). The units of period (d – days, y – years, k – kiloyears) and separation (m – mas, ″ – arcseconds) are placed together with the values in the period and separation columns, respectively. Then follow the visual magnitudes V and the estimated masses M of the components. The mass codes specify method of estimation (v – from absolute magnitude, s – sum of masses in the inner subsystem). Missing or unknown values are replaced by zero. Each quadruple system has three lines in Table 3.

Below we comment on selected hierarchies of particular interest from our set of 50. Diagrams illustrating the structure of two quintuple systems (05529−1103 and 08002+0707) are shown in Figure 3.

- 01429−2007. The eclipsing subsystem was also discovered by ASAS (Kiraga 2012). Considering the faintness of B (20 mag), the close binary belongs to Aa or Ab.
- 01576−1234. Parallax 13 mas, expected period of Aa,Ab is 11 yr.
- 02578−2614. The new 0.″65 par of similar stars Aa,Ab is totally unexpected, while the much fainter star B at 1.″66 is found in Gaia. The sky is not crowded, all three resolved components are likely related. The non-hierarchical configuration could be a result of projection on the sky.
- 03230−7047. It is likely a 2+2 quadruple, where Aa,Ab is eclipsing and Ba,Bb is resolved at SOAR (0.″11, RUWE 24.4).
- 03442−2727. The 18 day eclipsing subsystem Aa,Ab has a

[1] See http://www.ctio.noirlab.edu/~atokovin/stars/index.html

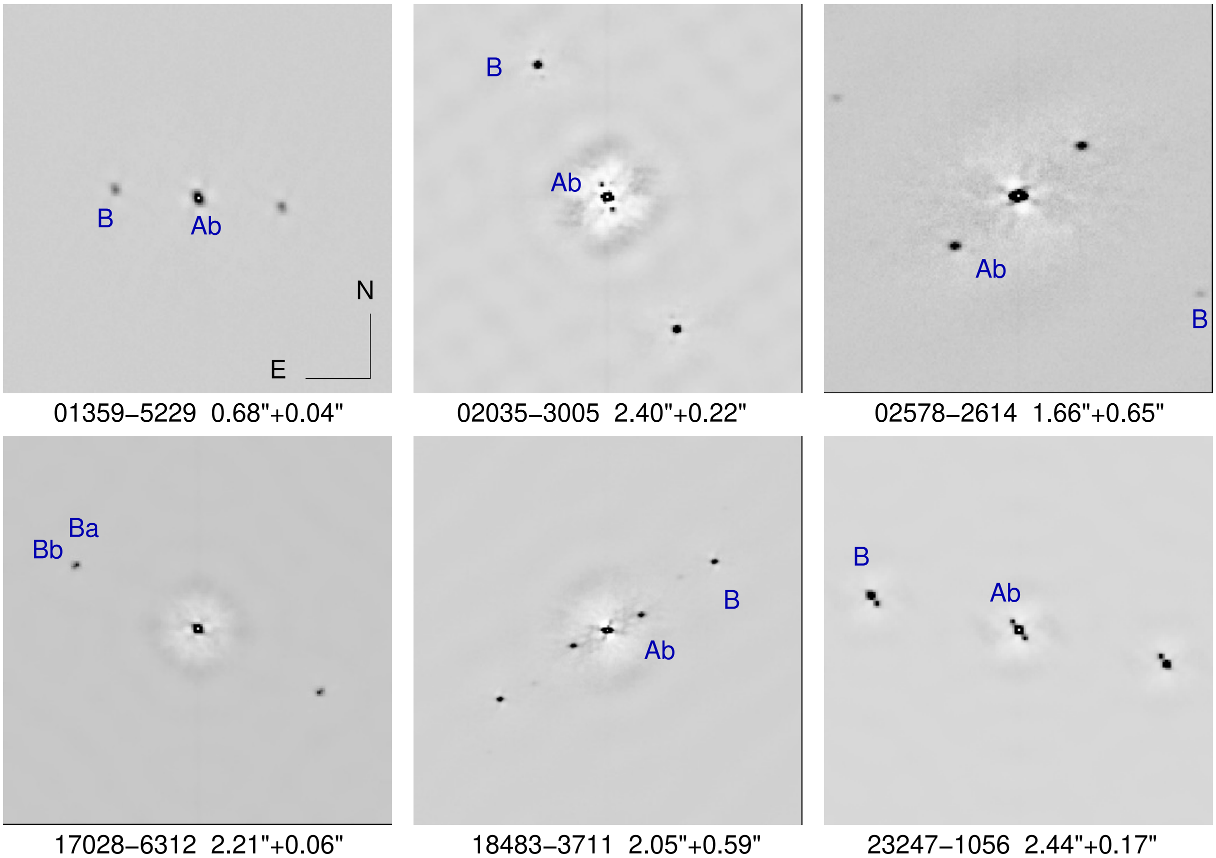

Figure 2. Speckle ACFs of some Gaia binaries with newly resolved subsystems. Secondary peaks corresponding to true orientation of companions are marked on the images, the WDS identifiers and separations are given below each image. Negative intensity stretch and standard orientation (north up, east left). The white dot marks the center of the ACF.

Table 2. Components of New Hierarchies (Fragment, full table is available online)

MSC (J2000)	Comp.	R.A. (deg)	Dec. deg)	ϖ (mas)	μ^*_α (mas yr^{-1})	μ_δ (mas yr^{-1})	V (mag)
01359-5229	A	23.984338	-52.477317	3.89	68.1	31.8	11.40
01359-5229	B	23.984673	-52.477303	3.59	64.5	32.6	12.73
02035-3005	A	30.882374	-30.084916	4.01	-15.8	-1.9	10.80
02035-3005	B	30.882744	-30.084329	3.78	-16.2	-2.3	13.28
05529-1103	A	88.214650	-11.053158	2.71	-13.7	13.7	11.37
05529-1103	B	88.216242	-11.058290	2.10	-13.0	14.0	11.55
08002+0707	A	120.058429	7.110688	6.13	-19.3	-1.2	11.27
08002+0707	B	120.062694	7.113729	6.14	-19.7	-2.3	11.66

Table 3. Parameters of Subsystems (Fragment, full table is available online)

MSC (J2000)	Comp.	Type	P	Sep.	V_1 (mag)	V_2 (mag)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	Note
01359-5229	A,B,*	Cmp	1.4073 k	0.680 "	11.80	12.73	1.81 s	0.88 v	Gaia
01359-5229	Aa,Ab,A	v	26.3337 y	0.042 "	12.33	12.83	0.95 s	0.87 v	SOAR dI=0.5
01359-5229	Aa1,Aa2,Aa	E	0.2460 d	0.029 m	12.33	0.00	0.95 v	0.00	TESS, Ell
02035-3005	A,B,*	Cmp	8.7969 k	2.400 "	10.77	13.28	1.96 s	0.81 v	RST 2270 EDR3 pos.
02035-3005	Aa,Ab,A	v,a	286.1729 y	0.218 "	10.83	13.93	1.22 s	0.74 v	SOAR dI=3.1 RUWE
02035-3005	Aa1,Aa2,Aa	E	0.3681 d	0.043 m	10.80	0.00	1.22 v	0.00	TESS EB

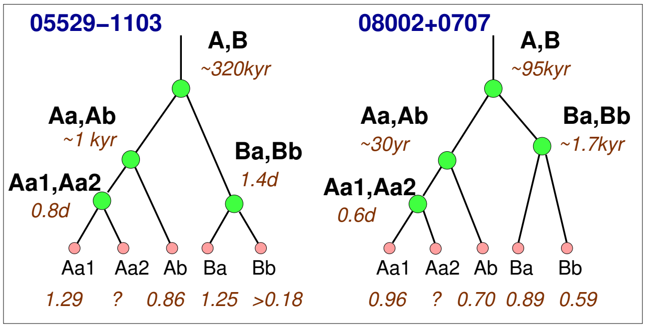

Figure 3. Hierarchical structure of two quintuple systems. Green circles denote subsystems, smaller pink circles — stars. Their estimated masses in solar units are indicated below. Periods of resolved subsystems are estimated from their projected separations.

double-lined spectroscopic orbit in Gaia DR3, while B is resolved at SOAR (0.″60, RUWE 2.4).

• 05529−1103. A quintuple system. The component A is resolved at SOAR (0.″37) and contains a 0.806 day EB. Star B, at 19″ from A, has a single-lined spectroscopic orbit with $P = 1.437$ days in Gaia. The period ratio of Aa,Ab and Ba,Bb differs from 1:2, so the two inner binaries are distinct (not the same system with a wrong photometric period).

• 06471+1539. The 0.46 day eclipsing subsystem is known as V405 Gem. If it belongs to the primary star A (resolved at 0.″07), this is a 3+1 quadruple, otherwise the hierarchy is 2+2.

• 07550−6830. The 0.″63 subsystem A,C has comparable separation with the outer binary A,B (2.″19). It is not known which star hosts the 2 day EB.

• 08002+0707. A quintuple system. Both components of the 18.″7 Gaia pair are resolved at SOAR (separations 0.″07 and 0.″99), and one of them contains the 0.635 day eclipsing subsystem.

• 08343−0707. Contains three Gaia sources A, B, and C at separations of 1.″07 and 19.″55. Star A is resolved at 0.″08 (RUWE 3.6). The system contains a suspected but unconfirmed *TESS* EB with unknown period, making it quintuple.

• 09046−4104. The 10.3 day eclipsing pair V405 Vel belongs to the resolved star A (0.″06), so it is a 3+1 quadruple. The subsystem Aa,Ab was observed four times between 2021.16 and 2022.86 and turned by 41°; its estimated period is ~20 yr or less. Detection of the ETV is likely.

• 10353−7511 contains three Gaia sources A, B, C, and the inner pair A,B (0.″81) is resolved at SOAR; it hosts a 0.189 day contact pair.

• 10486−0337. The eclipsing pair DE Sex (0.368 days) belongs to star A, resolved at 0.″29 separation.

• 11121−3735. The eclipsing pair V1071 Cen is hosted by star A, also resolved at 0.″09.

• 11195−3951. Three Gaia sources, where the inner 0.″76 pair A,C is also resolved at SOAR. The 0.22 day eclipsing pair is V1407 Cen. A young system in Centaurus, parallax 6.2 mas.

• 11442−1815. Eclipses are suspected, but no period is known, so the system is listed in the MSC as triple.

• 17003−7612. Star B is resolved at 0.″07 (RUWE 2.8). If the 1.5 day EB belongs to A, this is a 2+2 quadruple.

• 17027+1522. Triple lines in the spectrum were found by Guillout et al. (2009). Eclipses with a period of 1.472 days were detected by ASAS (Kiraga 2012) and confirmed by *TESS* (the *TESS* period of 0.736 days is half of the true period). So, this is a genuine 3+1 quadruple, where three solar-type stars belong to the inner triple resolved at SOAR (0.″09, estimated period 50 yr), and the Gaia companion B at 3″ is smaller, about 0.6 $M_\odot$.

• 18541−5131. Parallax 5.9 mas, estimated period of Aa,Ab (0.″07) 26 yr. If the 0.60 day eclipsing pair V362 Tel belongs to star A, an ETV is expected.

• 19220+1621. The 0.″7 pair Aa,Ab resolved at SOAR may be optical because the sky is crowded. This will become clear after its re-observation in a few years because the proper motion is fast, 107 mas yr^{-1}.

• 22378−3951. The inner binary is ellipsoidal variable CX Cru (period 1.742 days). It likely belongs to the main component A, while B, at 3.″25, is resolved at 0.″15. Estimated period of Ba,Bb is 50 yr (parallax 10.3 mas).

5 SUMMARY

In this work, we explored a new approach for detection and confirmation of hierarchical systems containing at least four stars using combination of Gaia astrometry, *TESS* photometry, and high-resolution ground-based imaging. Several alternative strategies proposed by other teams, such as combination of Gaia orbits with wide binaries (Hwang 2023b) or Gaia orbits with eclipsing binaries (Czavalinga et al. 2023), deliver candidate triples rather than quadruples, with the exception of doubly eclipsing stars in (Kostov et al. 2022). A quarter of our candidates have been resolved, confirming their quadruple nature, and a substantial fraction of those (0.4 or more) have a 3+1 hierarchy, as anticipated.

Our sample is opportunistic, being driven by the available data rather than by a targeted choice of parent population (e.g. volume- or mass-limited). Only a minute fraction of 3+1 quadruples in the 500 pc volume have been explored here, and these random discoveries probably have little statistical significance. Instead, we hoped to find rare and unusual hierarchies worth of further study, like the sextuple system TIC 168789840. As indicated in the notes above, some of these systems indeed merit additional investigation.

Newly resolved close subsystems with estimated periods shorter than ~50 yr are interesting candidates for follow-up speckle observations. Their orbital motion can be detected within a few years (in 09046−4104, the subsystem Aa,Ab turned by 41° in 1.7 yr; its estimated period is 20 yr or less). The EBs in these systems are expected to have ETV or signs of dynamical interaction (e.g. precession) which can be looked for via analysis of archival and new ground-based photometry.

Detection of an ETV would securely associate the EB with the intermediate subsystem. Other means to link the EB to a specific star in a resolved multiple system are targeted differential photometry or measurement of centroid displacement during eclipses. Chances of success depend on the eclipse amplitude. Spectroscopic follow-up can help by detecting multiple lines and following their variation with time; the triple-lined system 17027+1522 is the first candidate.

Our work gives some suport to the idea that wide tertiary companions to close binaries (either eclipsing or spectroscopic) are not directly responsible for their formation, but rather signal the presence of intermediate, closer subsystems in 3+1 hierarchies. This finding adds another piece of evidence to the still mysterious relation between close binaries and hierarchies. Speculation on the nature of this relation is beyond the scope of our purely observational work.

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DATA AVAILABILITY

Full electronic versions of Tables 1–3 are available as Supplementary Data.

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