Newly identified compact hierarchical triple system candidates using *Gaia* DR3

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Hierarchical triple systems

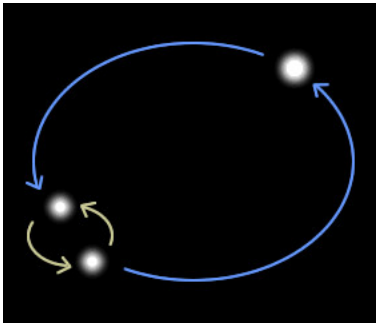


Figure 1: Configuration of hierarchical triple systems

Hierarchical triple systems

- contain 3 stars
- bound by gravitational force
- for long-term stability it is important to orbit in hierarchical configuration
- hierarchical configuration: one of the stars is far away from the other two

Importance in astrophysics

Highly accurate parameters can be used to refine stellar evolutionary models and to study the formation and evolution of such systems.
Possible progenitors of:

- Type Ia supernovae
- compact binary objects

Compact hierarchical triple systems (CHTs)

The outer period of CHT systems is below $\sim$ 1000 days
The dynamical perturbations can be strong in these systems, they can make a significant changes in short timescales
We only knew a relatively small amount of these systems (roughly 500) before this study

How can we search for compact hierarchical triple systems?

Detection

Similar methods can be used to detect triple systems as binary stars. The inner binary and the third component can be detected by several methods.

Astrometric

The motion of a star around its centre of mass is detected using astrometric methods. Typically, it is possible to detect the outer, wide orbit.

Spectroscopic

It is detected by the shift of the spectral lines in the spectrum of an unresolved binary.

Photometric

Detect changes in the brightness of unresolved stars due to eclipse and/or ellipsoidal variations.
For triple systems: Light Travel Time Effect (LTTE) or dynamical effect in Eclipse Timing Variations (ETVs) on the O-C diagram

Gaia Data Release 3

The Data Release 3 (DR3) was published on 13 June 2022, covering about 34 months of data from 15 July 2014 to 28 May 2017. DR3 contains:

- full astrometric solutions for 1,46 billion objects
- photometric measurements for 1 billion objects
- median radial velocity measurements for 33 million stars
- non-single star [NSS] solutions

In previous data releases, each point source was treated as an individual star, but even for Gaia DR3, only binary star solutions have been developed.

NSS solutions

Astrometric

The periodic oscillation of the photocenter was used to detect the binarity.
known parameters: period, eccentricity, inclination, angular distance of the photocenter from the center of mass, ω, Ω

Spectroscopic

The shift of the spectral lines in the spectrum of an unresolved binary
known parameters: period, eccentricity, K_1, ω

Eclipse

Changes in the brightness of unresolved stars due to eclipses
known parameters: period, inclination, $e \cdot sin(\omega)$

More than one solution is possible for an object. In all cases, the binary appears only as a point source in Gaia images.

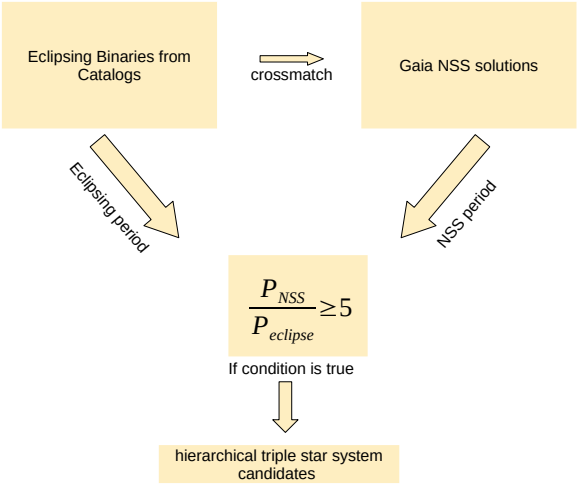
Catalogs

Number of eclipsing binaries (EBs) in different catalogs:

- AAVSO Photometric All Sky Survey
- All-Sky Automated Survey for Supernovae
- General Catalog of Variable Stars
- *Kepler* Eclipsing Binary Stars
- *TESS* Eclipsing Binary Stars
- The International Variable Star Index

Catalogs	Number of EBs
APASS	4 516
ASAS-SN	35 464
GCVS	6 849
Kepler EBs	2 876
TESS EBs	4 584
VSX	971 757
Total	1 026 046

Identification of candidates

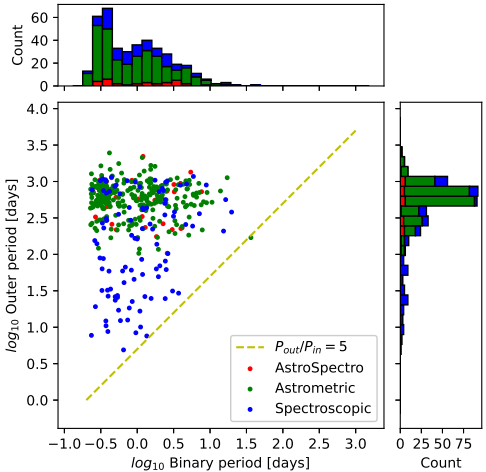


Results

We have identified 403 hierarchical triple candidates among formerly known EBs from the literature based on the periods of their Gaia NSS orbital solutions.

- 100 spectroscopic solutions
- 267 astrometric solutions
- 31 combined solutions
- 5 independent solutions from different methods

Distribution of inner binary periods and the corresponding outer orbital periods (Czavalinga+23)



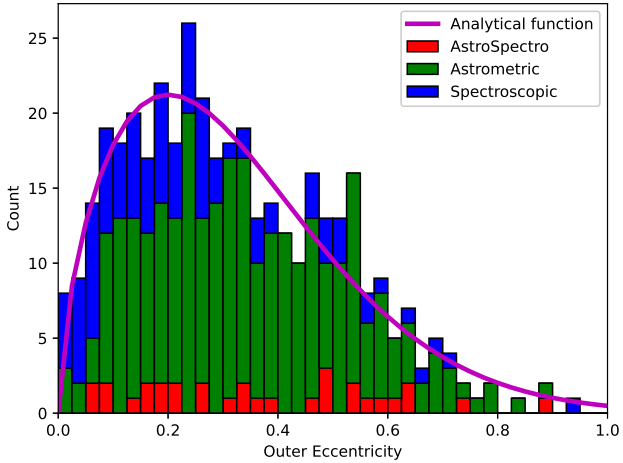


Figure 3: Differential probability distribution of the outer orbit eccentricities (Czavalinga+23)

Analytical expression (Czavalinga+23)

$$\frac{dN}{de} \simeq 8.34\, e^{0.618} \exp[-5.15 e^{1.618}]$$

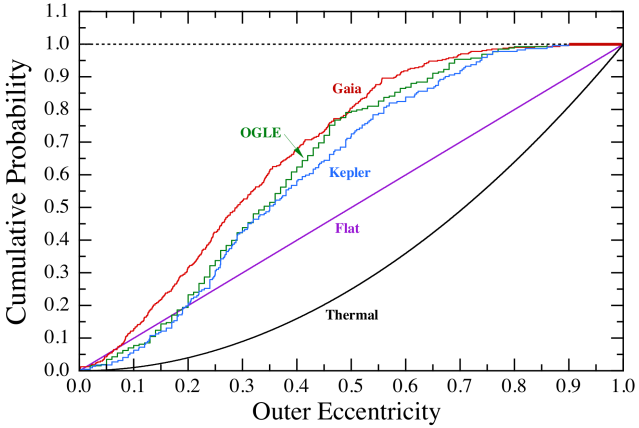


Figure 4: Cumulative eccentricity distribution of the outer orbit (Czavalinga+23)

Validation

- In order to confirm the Gaia NSS solutions, we first checked whether any of the 403 systems are known in the literature
  We found 27 systems
- Determination of eclipse minima times with the TESS space telescope and search for LTTE or dynamical effects

Number	Category
403	Total number of candidates
27	Previously known triples
22	Sufficient *TESS* ETV points to directly confirm outer orbit
192	Significant non-linear behavior in *TESS* ETV points
4	Exhibit third body eclipses, i.e., they are triply eclipsing triples
4	Probable quadruple system with 2+2 configuration
245	Total confirmed triples
217	Total confirmed new triples
158	Insufficient supplementary data to independently confirm triple nature

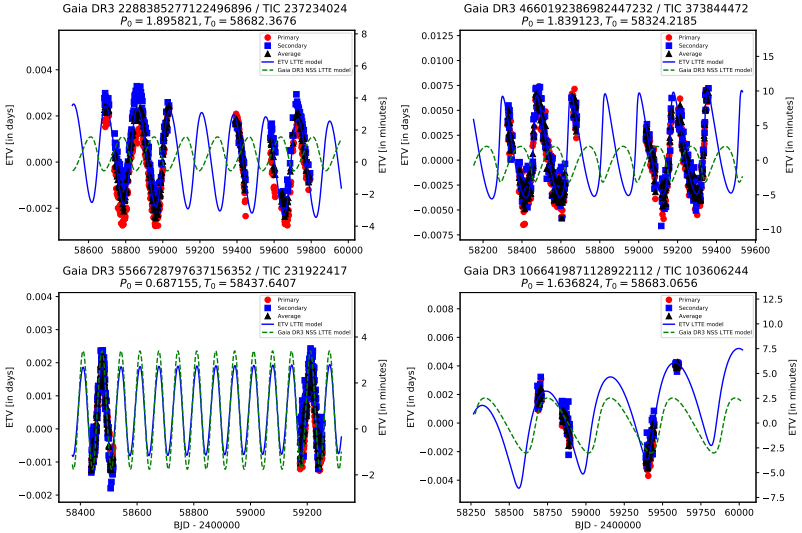
Validation of parameters

In the case of 22 triple systems, the good coverage of the TESS data series allowed us to investigate the outer orbital parameters using the O-C diagram.

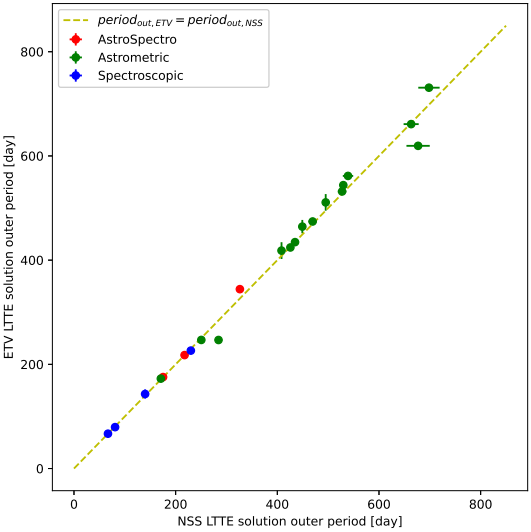
Analytical LTTE

$$\Delta_{\mathrm{LTTE}} = -\frac{a_{\mathrm{AB}} \sin i_2}{c} \frac{(1 - e_2^2) \sin(\nu_2 + \omega_2)}{1 + e_2 \cos \nu_2}$$

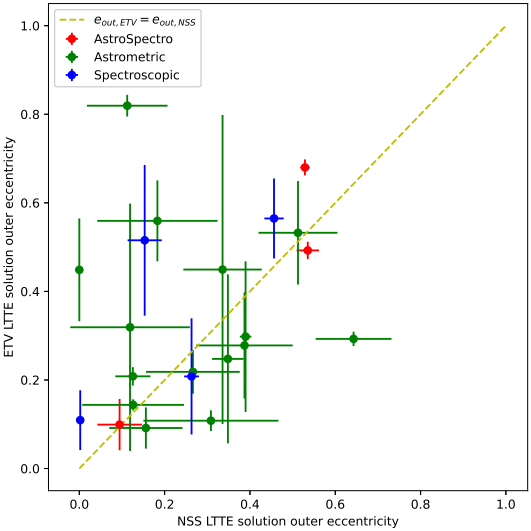
a_{AB} is the semi-major axis of the orbit of the inner binary component around the center of mass of the system, i_2 is the inclination, e_2 is the eccentricity, ω_2 is the argument of periastron of the outer orbit ν_2 is the true anomaly of the outer orbit and c is the velocity of light.


Gaia DR3 2288385277122496896 / TIC 237234024
$P_0 = 1.895821, T_0 = 58682.3676$
Gaia DR3 4660192386982447232 / TIC 373844472
$P_0 = 1.839123, T_0 = 58324.2185$
Gaia DR3 5566728797637156352 / TIC 231922417
$P_0 = 0.687155, T_0 = 58437.6407$
Gaia DR3 1066419871128922112 / TIC 103606244
$P_0 = 1.636824, T_0 = 58683.0656$
Primary
Secondary
Average
ETV LTTE model
Gaia DR3 NSS LTTE model
ETV [in days]
ETV [in minutes]
BJD - 2400000

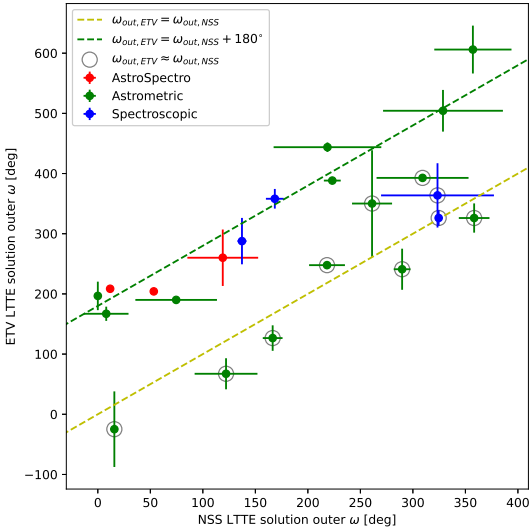
Period (Czavalinga+23)



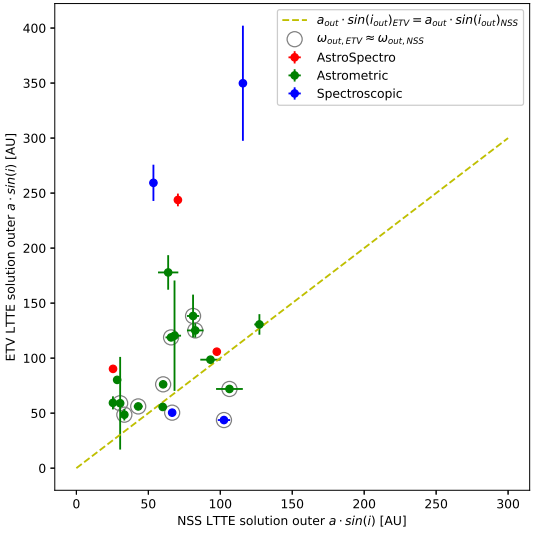
Eccentricity (Czavalinga+23)



Argument of periastron (Czavalinga+23)



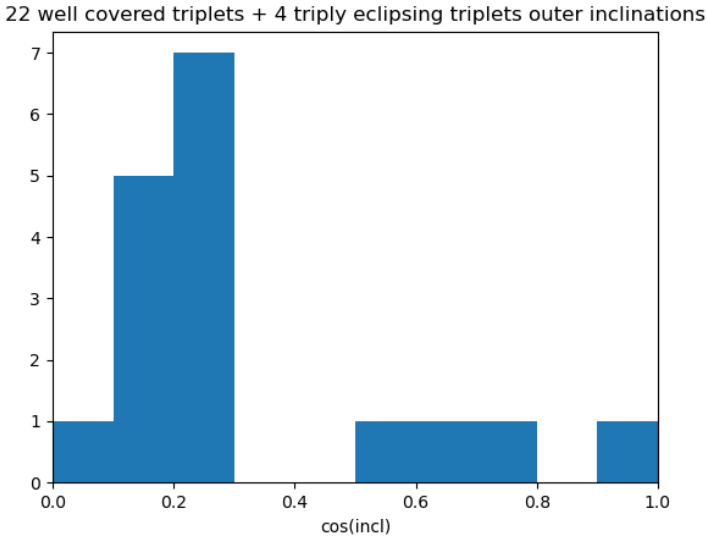
Projected semi-major axis (Czavalinga+23)

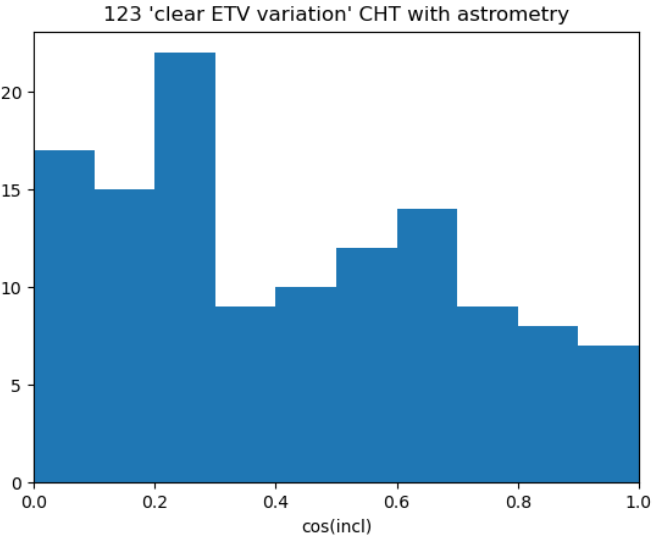


Summary

- We found 403 compact hierarchical triple system candidates
- 376 are newly proposed objects
- From TESS measurements, 218 compact triple systems were confirmed, more than half of the compact triple systems known before this study
- We found four triply eclipsing triple stars unknown in literature
- We used an independent and fundamentally different method to test the orbital parameters of the Gaia NSS solutions

Thank you for your attention!


22 well covered triplets + 4 triply eclipsing triplets outer inclinations
0
1
2
3
4
5
6
7
0.0
0.2
0.4
0.6
0.8
1.0
cos(incl)


123 'clear ETV variation' CHT with astrometry
20
15
10
5
0
0.0
0.2
0.4
0.6
0.8
1.0
cos(incl)