

Multiplicity of stars with planets in the solar neighbourhood

J. González-Payo^{1,2,*}, J. A. Caballero³, J. Gorgas¹, M. Cortés-Contreras¹,
M.-C. Gálvez-Ortiz³, and C. Cifuentes³

¹ Departamento de Física de la Tierra y Astrofísica & IPARCOS-UCM (Instituto de Física de Partículas y del Cosmos de la UCM), Facultad de Ciencias Físicas, Universidad Complutense de Madrid, 28040 Madrid, Spain

² UNIE Universidad, Departamento de Ciencia y Tecnología, c/ Arapiles 14, 28015 Madrid, Spain

³ Centro de Astrobiología (CSIC-INTA), European Space Astronomy Centre, Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain

Received 20 March 2024 / Accepted 26 July 2024

ABSTRACT

Aims. We intended to quantify the impact of stellar multiplicity on the presence and properties of exoplanets.

Methods. We investigated all exoplanet host stars at less than 100 pc using the latest astrometric data from *Gaia* DR3 and advanced statistical methodologies. We complemented our search for common proper motion and parallax companions with data from the Washington Double Star catalogue and the literature. After excluding a number of systems based on radial velocity data, and membership in clusters and open associations, or with resolved ultracool companions, we kept 215 exoplanet host stars in 212 multiple-star systems.

Results. We found 17 new companions in the systems of 15 known exoplanet host stars, and we measured precise angular and projected physical separations and position angles for 236 pairs of stars, compiled key parameters for 276 planets in multiple systems, and established a comparison sample comprising 687 single stars with exoplanets. With all of this, we statistically analysed a series of hypotheses regarding planets in multiple stellar systems. Although they are only statistically significant at a 2σ level, our analysis pointed to several interesting results on the comparison in the mean number of planets in multiple versus single stellar systems and the tendency of high-mass planets to be located in closer orbits in multiple systems. We confirm that planets in multiple systems tend to have orbits with larger eccentricities than those in single systems. In particular, we found a significant ($>4\sigma$) preference for planets to exhibit high orbital eccentricities at small ratios between star-star projected physical separations and star-planet semi-major axes.

Key words. astronomical databases: miscellaneous – virtual observatory tools – astrometry – binaries: general – binaries: visual – planetary systems

1. Introduction

After over 30 years since the discovery of the first exoplanets (Campbell et al. 1988; Wolszczan & Frail 1992; Mayor & Queloz 1995), almost 6000 exoplanet candidates have been reported. Except for a few ‘rogue’ planets (Caballero 2018, and references therein) and bodies of unknown nature found around compact objects such as white dwarfs and neutron stars (Bailes et al. 2011; Vanderburg et al. 2020), the majority of these exoplanet candidates orbit around main-sequence and giant stars. Planet occurrence rates determined with different techniques indicate that, on average, there are slightly more than one planet per star (Cassan et al. 2012; Dressing & Charbonneau 2015; Baron et al. 2019; Savel et al. 2020; Sabotta et al. 2021; Ribas et al. 2023). Additionally, a significant fraction of the stars in the Galaxy are part of stellar multiple systems, including double, triple, or higher-order systems (Abt & Levy 1976; Duchêne & Kraus 2013; Tokovinin 2008, and many others). As a consequence, many of the discovered exoplanet candidates are also part of stellar multiple systems.

Stellar multiplicity has been studied for centuries (Mayer 1778; Herschel 1802; Duquennoy & Mayor 1991; Jao et al. 2009; Duchêne & Kraus 2013). In our immediate vicinity, that is, in the 10 pc-radius volume centred on the Sun, Reylé et al. (2021) measured an overall multiplicity fraction (MF) of $27.4 \pm 2.3\%$. Actually, the MF decreases from the earliest to the latest spectral types: It varies from virtually 100% for O stars (except

for a few runaway stars; they are located in dense star-forming regions), to more than 70% for B and A stars (Kouwenhoven et al. 2007; Mason et al. 2009; Sana et al. 2013; Caballero 2014; Maíz Apellániz et al. 2019), 44–67% for solar-type stars (Duquennoy & Mayor 1991; Raghavan et al. 2010; Duchêne & Kraus 2013), 26–40% for M dwarfs (Fischer & Marcy 1992; Reid et al. 1997; Delfosse et al. 2004; Janson et al. 2012; Ward-Duong et al. 2015; Cortés-Contreras et al. 2017; Winters et al. 2019), and to below 20% for L, T, and Y ultracool dwarfs (Burgasser et al. 2003, 2005; Burgasser 2007; Fontanive et al. 2018). Since most of the reported exoplanet candidates orbit FGKM-type stars, several thousands of planetary systems would also be expected among multiple stellar systems. This fact is actually modulated by an observational bias in which many exoplanet surveys tend to discard close binaries in their input catalogues (e.g. Raghavan et al. 2006; Winn & Fabrycky 2015; Sebastian et al. 2021; Ribas et al. 2023). Currently, there are a few hundred multiple stellar systems with known exoplanet candidates (Eggenberger et al. 2004a; Konacki 2005; Furlan et al. 2017; Martin 2018; Bonavita & Desidera 2020, and many others).

The consequence of a star being in a multiple system is not only relevant for the formation and evolution of the star itself but also in the formation and evolution of planets, especially if the stellar companions are close to each other. Previous theoretical works predicted that nearby companion stars can significantly disrupt circumstellar discs and hinder the process of planetary formation (Lissauer 1987; Gladman 1993; Jensen et al. 1996; Artymowicz & Lubow 1996; Pichardo et al. 2005;

* Corresponding author; fcojgonz@ucm.es

Table 1. Observational works on multiplicity of stellar systems with planets.

Title	Reference	$N^{(a)}$	Methodology ^(b)
Multiplicity of stars with planets in the solar neighbourhood	This work	215	Misc.
An early catalog of planet-hosting multiple-star systems of order three...	Cuntz et al. (2022)	40	Misc.
Speckle observations of TESS exoplanet host stars. II. Stellar...	Lester et al. (2021)	102	SI
The census of exoplanets in visual binaries: population trends from a...	Fontanive & Bardalez Gagliuffi (2021)	218	Misc.
How many suns are in the sky? A SPHERE multiplicity... I. Four new ...	Ginski et al. (2021)	4	AO
Frequency of planets in binaries	Bonavita & Desidera (2020)	313	RV
Understanding the impacts of stellar companions on planet formation...	Hirsch et al. (2021)	109	AO, RV
Search for stellar companions of exoplanet host stars by exploring...	Mugrauer (2019)	204	WFI
The SEEDS high-contrast imaging survey of exoplanets around young...	Uyama et al. (2017)	68	AO
A lucky imaging multiplicity study of exoplanet host stars – II	Ginski et al. (2016)	60	LI
High-contrast imaging search for stellar and substellar companions of...	Mugrauer & Ginski (2015)	33	AO
A Lucky Imaging search for stellar companions to transiting planet host...	Wöllert et al. (2015)	49	LI
Binary frequency of planet-host stars at wide separations. A new brown...	Lodieu et al. (2014)	37	WFI
The multiplicity status of three exoplanet host stars	Ginski et al. (2013)	3	LI
Stellar companions to exoplanet host stars: lucky imaging of transiting...	Bergfors et al. (2013)	21	LI
Extrasolar planets in stellar multiple systems	Roell et al. (2012)	57	AO
Know the star, know the planet. I. Adaptive optics of exoplanet host...	Roberts et al. (2011)	62	AO
Know the star, know the planet. II. Speckle interferometry of exoplanet...	Mason et al. (2011)	118	SI
Binarity of transit host stars. Implications for planetary parameters	Daemgen et al. (2009)	14	LI
The frequency of planets in multiple systems	Bonavita & Desidera (2007)	202	Misc.
The multiplicity of exoplanet host stars. New low-mass stellar companions	Mugrauer & Neuhäuser (2009)	43	WFI
The multiplicity of planet host stars – new low-mass companions to planet...	Mugrauer et al. (2007b)	3	Misc.
The impact of stellar duplicity on planet occurrence and properties. I. ...	Eggenberger et al. (2007)	57	AO
A search for wide visual companions of exoplanet host stars: The Calar ...	Mugrauer et al. (2006)	44	WFI
Two suns in the sky: Stellar multiplicity in exoplanet systems	Raghavan et al. (2006)	36	Misc.
Detection and properties of extrasolar planets in double and multiple...	Eggenberger et al. (2004b)	15	AO
Planets in multiple-star systems: properties and detections	Udry et al. (2004)	15	Misc.
Stellar companions to stars with planets	Patience et al. (2002)	11	Misc.

Notes. ^(a) N : number of investigated multiple stellar systems with exoplanets. ^(b)AO: adaptive optics; LI: lucky imaging; RV: radial velocity; SI: speckle imaging; WFI: wide field imaging; Misc.: miscellanea.

Quintana & Lissauer 2006; Hamers et al. 2021; see also Thebault & Haghighipour 2015 and the series of papers initiated by Wang et al. 2014), while other theoretical works have focused on the long-term stability of planets in binary systems. For example, Holman & Wiegert (1999) were among the first to study such stability in great detail. A number of similar works on the long-term stability of S- (around one star) and P-type (around the two stars) systems were published afterwards by, for example, Pilat-Lohinger et al. (2003), Musielak et al. (2005), Mudryk & Wu (2006), and Doolin & Blundell (2011). There has also been theoretical work on the long-term stability of triple systems with planets (e.g. Buseti et al. 2018). Most of these publications, however, have focused on the eccentricity of stellar orbits rather than on the eccentricity of planet orbits. The relation between stellar multiplicity and planet eccentricity was first investigated by Mazeh et al. (1997), who analysed the stability of the 16 Cyg system. The system contains three stars (A: G1.5 V; B: G3 V; C: mid-M) and a $1.8 M_{\text{Jup}}$ -mass planet in an eccentric orbit ($e \approx 0.68$) around the secondary (Cochran et al. 1997; Turner et al. 2001; Rosenthal et al. 2021).

Likewise, there are a number of observational works on the multiplicity of stellar systems with planets. Table 1 enumerates many of the relevant observational publications on this topic. The authors have used a diversity of target stars with planets, methodologies, and even maximum distances (e.g. Hirsch et al. 2021: 25 pc; Eggenberger et al. 2007: 50 pc; Fontanive & Bardalez Gagliuffi 2021: 200 pc; Mugrauer 2019,

Lester et al. 2021: 500 pc). A wealth of results have been proposed after these observations. For example, Eggenberger et al. (2004b) and Udry et al. (2004) found that massive planets ($M \sin i > 2 M_{\text{Jup}}$) with moderately short periods ($P \leq 40\text{--}100$ d) in binaries tend to have low eccentricities, while Moutou et al. (2017b), with a more powerful facility (SPHERE at the Very Large Telescope), also concluded that the majority of high-eccentricity planets are ‘not embedded’ in multiple stellar systems. These results are rather inconsistent with those of Raghavan et al. (2006), who showed that planets in systems with confirmed stellar companions instead generally have higher eccentricities. The authors reasoned that companion stars would have a greater gravitational influence on the planets’ orbits and could shorten the periods of Kozai cycles (Innanen et al. 1997; Wu & Murray 2003; Tamuz et al. 2008; Naoz 2016). We finish this introduction with a sentence written by Eggenberger et al. (2004b) exactly two decades ago and that is still valid: “The studies [enumerated above] emphasise the importance of searching for planets in multiple star systems, even though it is more challenging to carry out than the search for planets around individual stars”.

In this work, we revisit the topic of multiplicity of stars with planets at less than 100 pc. After this introduction (Sect. 1), we describe our target sample in Sect. 2. Next, we detail in Sect. 3 our analysis, which consists of an individualised search for common proper-motion and parallax companions to exoplanet host stars with *Gaia* DR3 complemented with data from

the Washington Double Star catalogue and the literature. The results are presented in Sect. 4, where we report on new stellar systems with planets; the relationships between star-star separations, star-planet semi-major axes, and planet eccentricities; and the number and masses of planets in single and multiple systems, and we conclude with the properties of multiple star systems with planets. Finally, in Sects. 5 and 6 we discuss and summarise our results.

2. Sample

Our sample was built on the basis of the two most widely used exoplanet databases. We took all the host stars tabulated by either the Extrasolar Planets Encyclopaedia¹ (Schneider et al. 2011) or the NASA Exoplanet Archive² (Akeson et al. 2013). At the moment of downloading (3 January 2024), the first database contained 5576 planets in 4114 planetary systems, and the second one had 5566 planets in 4145 systems. We discarded all of the duplicate host stars in both databases. Sometimes the same star was tabulated with different names in each database, and did not always have the same exact coordinates. We finally obtained a set of 4612 non-duplicate host stars, all of which have an entry in the Simbad astronomical database (Wenger et al. 2000).

Secondly, we looked for the *Gaia* DR3 (Gaia Collaboration 2023b) counterpart of every host star. For some cases that required a visual inspection, we used the Aladin Sky Atlas (Bonnarel et al. 2000). Of the 4612 host stars, 339 do not have a *Gaia* DR3 entry. Of them, eight are just too bright for *Gaia*³, while the other 331 stars without a *Gaia* DR3 entry are distant microlensing objects from the OGLE⁴ (Udalski et al. 1992), KMT⁵ (Henderson et al. 2014), and MOA⁶ (Alcock et al. 1995, 1997) surveys, and some pulsars.

Of the 4273 stars with an entry in *Gaia* DR3, 4232 have a positive parallax value. For the remaining 41 stars (with a negative parallax or no parallax at all) plus the former 339 with no counterpart in *Gaia* DR3, we looked for their parallaxes or spectro-photometric distances in the HIPPARCOS (Perryman et al. 1997), *Gaia* DR2 (Gaia Collaboration 2018), *Gaia* EDR3 (Third Early Data Release – Gaia Collaboration 2021a), and UCAC4 (Fourth United States Naval Observatory CCD Astrograph Catalogues – Zacharias et al. 2013) catalogues and in the literature (e.g. Shkolnik et al. 2012; Gagné et al. 2015; Leggett et al. 2017; Finch et al. 2018; Winters et al. 2019). We were able to find a parallax or a distance for 351 of the mentioned 380 stars. To sum up, a total of 4583 exoplanet host stars in our sample have a tabulated distance and only 29 (0.63% of the 4612 non-duplicate host stars) do not. The distribution of distances of the 4583 stars is shown in the top panel of Fig. 1.

Next, we restricted the analysis to stars with distances less than 100 pc, which is the limit of the solar neighbourhood (Gaia Collaboration 2021b). There are many practical reasons behind this search limit selection, such as manageability of

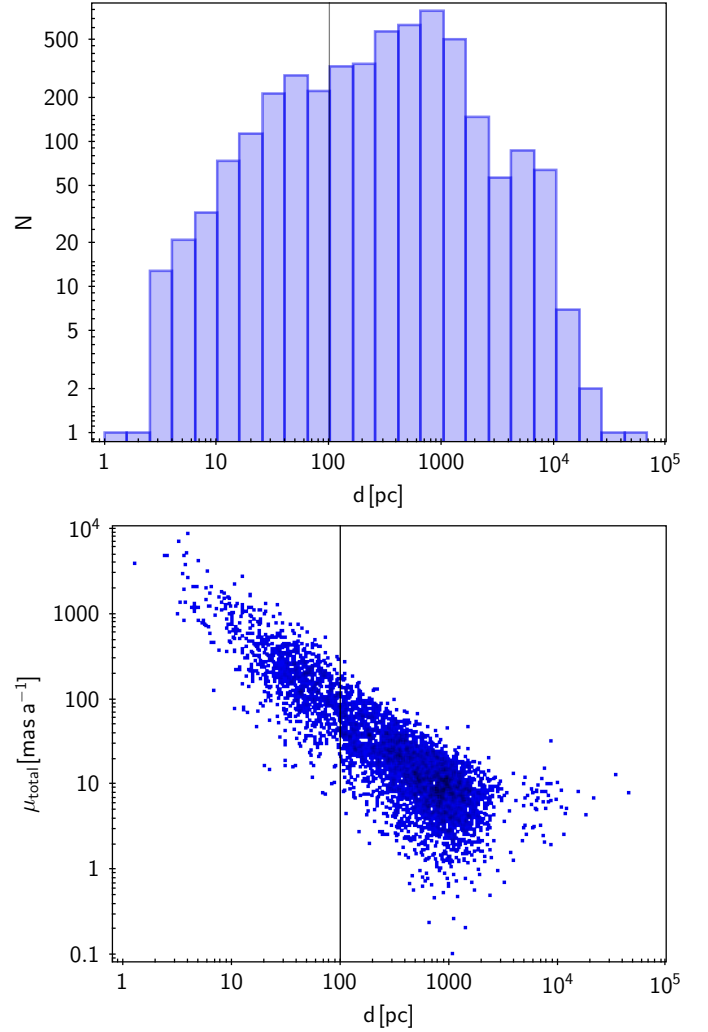


Fig. 1. Diagrams to determine the maximum distance of our analysis. *Top panel:* histogram of distances of the 4583 exoplanet host stars of the initial sample. *Bottom panel:* total proper motion as a function of distance for the same stars. The vertical line at $d = 100$ pc in both panels indicate the search limit.

the final sample for detailed analysis, increase of both the incompleteness of the exoplanet searches and of the astrometric uncertainty for the search for common proper motion companions at longer distances, as illustrated by the bottom panel of Fig. 1; and reliability of the parameters of the planetary systems, which have been mostly detected with the radial velocity and transit methods. Finally, 998 non-duplicate exoplanet host stars are located at less than 100 pc. They are listed in Table B.1.

3. Analysis

The flowchart in Fig. 2 summarises the sample preparation and the following analysis. In the diagram, the stadia indicate the beginning and ending, cylinders the databases, small circles the connectors, diamonds the decisions, rectangles the processes, stacks of rectangles the literature documents, rhomboids the inputting and outputting data, and flow lines (arrowheads) the processes' order of operation. Every flowline is labelled with the corresponding number of host stars.

¹ Now Encyclopaedia of Exoplanetary Systems, <http://exoplanet.eu/>

² <https://exoplanetarchive.ipac.caltech.edu/>

³ The eight very bright exoplanet host stars are: α PsA (Fomalhaut), α Ari (Hamal), α Tau (Aldebaran), β And (Mirach), β Gem (Pollux), β UMi (Kochab), γ Lib (Zubenelhakarabi), and γ^{01} Leo.

⁴ Optical Gravitational Lensing Experiment, <https://ogle.astrouw.edu.pl/>

⁵ Korea Microlensing Telescope Network, <https://kmtnet.kasi.re.kr/kmtnet/>

⁶ Microlensing Observations in Astrophysics, <http://www2.phys.canterbury.ac.nz/moa/>

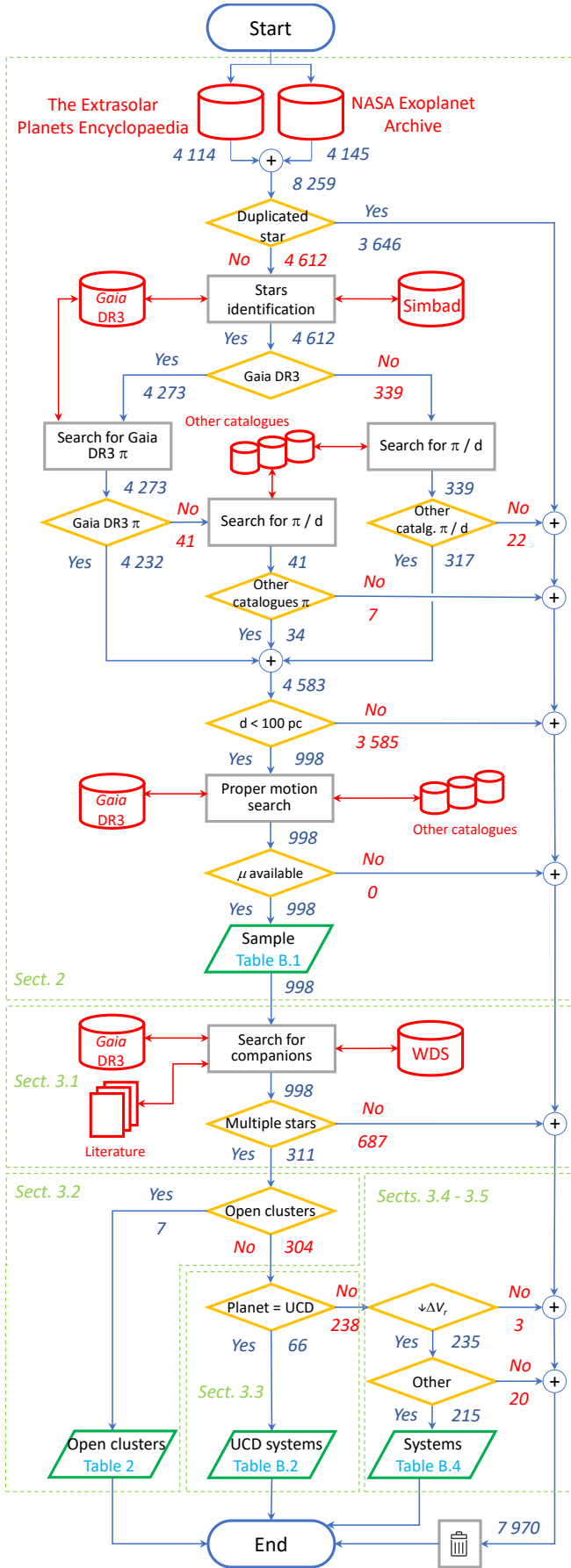


Fig. 2. Flowchart describing the sample preparation and following analysis.

3.1. Search for stellar companions

The first step of the analysis was to look for companions of common *Gaia* DR3 proper motion and parallax to our 998 non-duplicate exoplanet host stars at less than 100 pc. We used the same methodology as González-Payo et al. (2021) (their Sect. 3). In particular, we used Topcat (Tool for OPERations on Catalogues And Tables; Taylor 2005) with a customised code in ADQL (Astronomic Data Query Language; Yasuda et al. 2004) to search for companions at projected physical separations, $s = \rho \cdot d$, of up to 1 pc that satisfy the following criteria to distinguish between physical (bound) and optical (unbound) systems:

$$\mu_{\text{ratio}} = \sqrt{\frac{(\mu_{\alpha} \cos \delta_1 - \mu_{\alpha} \cos \delta_2)^2 + (\mu_{\delta_1} - \mu_{\delta_2})^2}{(\mu_{\alpha} \cos \delta_1)^2 + (\mu_{\delta_1})^2}} < 0.15, \quad (1)$$

$$\Delta \text{PA} = |\text{PA}_1 - \text{PA}_2| < 15 \text{ deg}, \quad (2)$$

and

$$\left| \frac{\pi_1^{-1} - \pi_2^{-1}}{\pi_1^{-1}} \right| < 0.15, \quad (3)$$

where PA_i is the angle between the proper motion vectors, with $i = 1$ for the primary star and $i = 2$ for the companion. The inverse of the parallax, π_i^{-1} , is the distance, which for $d < 100$ pc in general does not need any further correction (e.g. Bailer-Jones et al. 2018; Luri et al. 2018). The motivation of the 0.15 and 15 deg values by González-Payo et al. (2021) was justified by the dissimilarity of proper motions and parallaxes of bona fide physically bound stars of different *Gaia* colours in close resolved systems with astrometric solutions (i.e., we neither applied a colour-term parallax correction nor subtracted relative motions in systems with orbital periods of a few years). We found 230 pairs of stars that satisfy these criteria. While resolved binary systems are made of one pair of stars, resolved multiple systems are made of two (triple) or three (quadruple) pairs. See González-Payo et al. (2021) for further details on the search methodology.

Next, we complemented our *Gaia* DR3 search for companions with a cross match with data in the Washington Double Star catalogue (WDS; Mason et al. 2001). Currently, they tabulate angular separations and position angles for the first and last epochs of observation of about 156 000 multiple systems. While they also tabulate other parameters (e.g. equatorial coordinates, magnitudes, notes on systems), additional information can be obtained from the WDS team upon request.

There are 687 WDS pairs in 341 systems containing at least one of the 998 input stars or the 230 *Gaia* DR3 companions from our previous search. Since there are ultra-wide multiple systems with extremely large projected separations (Caballero 2009; Shaya & Olling 2011; González-Payo et al. 2023), we kept WDS systems with $s > 1$ pc if they satisfy the three astrometric criteria (Eqs. (1), (2), and (3)). The remaining stars, either host stars or *Gaia* companions, are not part of any WDS system.

Of the 687 WDS pairs, we rejected 417 because their stars have very different *Gaia* DR3 distances and proper motion moduli and direction (i.e. do not satisfy at least one of Eqs. (1), (2), and (3)). Generally, the discarded companions are further in the background and have lower proper motions than the planet host stars. Many of them have the WDS ‘U’ flag: ‘Proper motion or other technique indicates that this pair is non-physical’. The other 270 WDS pairs passed to the next step of our analysis.

Not all the WDS pairs were identified in the *Gaia* DR3 search, nor all the *Gaia* DR3 common μ and π companions were tabulated by WDS. Most, if not all, WDS companions not found in our *Gaia* DR3 search are in very close systems unresolvable by *Gaia*, have moderate angular separations but accompany very bright stars, or are very faint ultracool dwarfs beyond the *Gaia* limit at about $G \approx 20.3$ mag (Smart et al. 2017). Likewise, there are known WDS systems with additional *Gaia* DR3 common μ and π companions reported here for the first time (see below). As a result of our searches, we found companions to 311 of the 998 stars in the sample, including those in the 270 WDS pairs. Four representative examples of analysed systems are shown in Fig. 3.

We categorised the remaining 687 exoplanet host stars as single, either because WDS and the literature do not report any companions for them or because we were not able to find any common parallax and proper motion companion (by chance, there were also 687 WDS optical and physical pairs). The list of single stars may actually be shorter, as they may have faint companions beyond the *Gaia* magnitude limit, perhaps in the substellar domain (Smart et al. 2017, 2019; Marocco et al. 2020), or may be unidentified very close spectroscopic or astrometric binaries.

Finally, we also added five additional multiple systems with extremely close separations: the 3 circumbinary systems at less than 100 pc (RR Cae AB, Kepler-16 AB, and HD 202206 AB – Qian et al. 2012; Doyle et al. 2011; Benedict & Harrison 2017, respectively), 1 spectroscopic binary (HD 42936 AB – Barnes et al. 2020), and 1 very close pair (LP 413–32 AB – Feinstein et al. 2019). The five of them have been reported in the literature but not tabulated by WDS. We recovered them from an exhaustive object-by-object search thorough the literature. Fig. 4 summarises the casuistry of the different types of systems in the *Gaia*, WDS, and literature searches.

3.2. Wide pairs in open clusters and associations

There are reasonable doubts about the true binding of ultra-wide pairs of young stars, as they may actually be part of stellar kinematic groups and associations (Caballero 2010, and references therein). The doubts are more reasoned when the pairs belong to nearby open clusters and OB associations, and especially when the measured separation resembles the typical separation between cluster members. This is the case of seven of the 311 host stars with *Gaia* DR3 or WDS companions, shown in Table 2, which we excluded from our analysis. They belong to the nearby Hyades open cluster (Reid 1993; Perryman et al. 1998) and Lower Centaurus Crux OB association (de Zeeuw et al. 1999). As expected, all of them have a large number of common μ and π companions (and companions to companions) at wide projected physical separations, of up to 37 in the case of one of the Hyades (being the 37 companions known Hyades, too). The stars in Table 2 compose a complete volume-limited sample of exoplanet host stars in open clusters and dense OB associations, and could be used for chemical tagging studies linked to exoplanets (e.g. De Silva et al. 2006; Liu et al. 2019).

Table 2 does not include two close double candidates. We kept ϵ Tau as a single host star in the Hyades although WDS tabulates a very close companion (WSI 53 Ab) undetected by *Gaia*. For this pair, Mason et al. (2011) measured $\rho = 0.237$ arcsec and $\theta = 108.3$ deg on only one epoch (J2005.8687), and estimated $\Delta = 2.4$ mag from their speckle interferometric measurements in the optical. However, the companion candidate was not detected in an earlier speckle survey of the Hyades by Mason et al. (1993), nor has been detected yet by any other team. In particular,

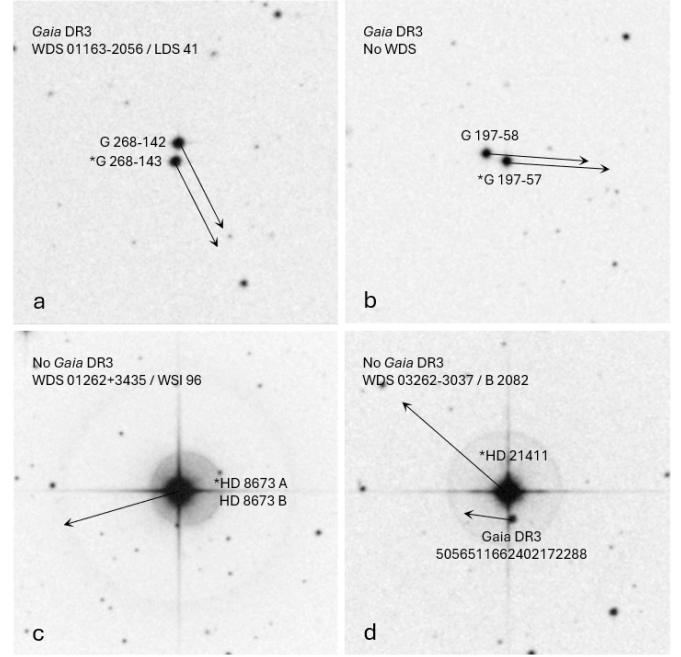


Fig. 3. European Southern Observatory Digital Sky Survey DDS2 Red images centred on four representative examples of analysed systems. The field of view is 5×5 arcmin, north is up and east is left. Stars are labelled, and exoplanet host names are preceded by an asterisk. Arrows indicate modulus and direction of *Gaia* proper motions. The four representative types are: (a) a resolved physical double identified in our *Gaia* search and with a WDS entry, (b) a resolved physical double found with *Gaia* and not in WDS (but reported by Gaia Collaboration 2021b), (c) a close physical double with a WDS entry ($\rho = 0.31$ arcsec) but not resolved by *Gaia*, and (d) an optical double in WDS but not identified in our *Gaia* search.

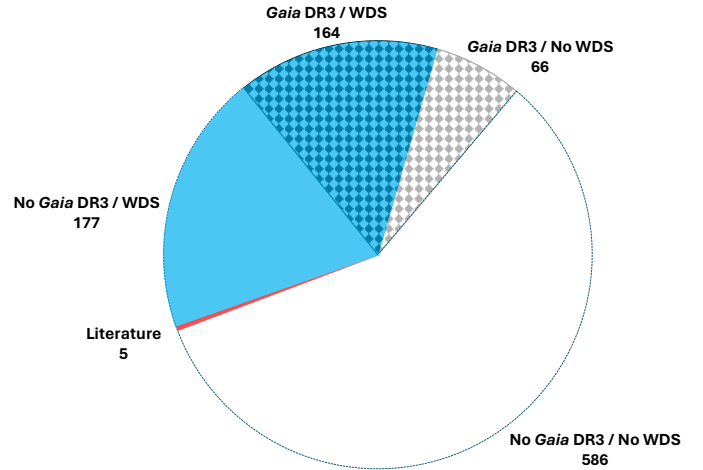


Fig. 4. Pie chart of *Gaia* (rhombus checked), WDS (blue), and literature (red) systems. Slices are labelled with the number of systems of each type.

there are no hints for any close companion beyond the $7.6 M_{\text{Jup}}$ -minimum-mass planet around ϵ Tau (Sato et al. 2007). The other close double is b Cen (AB), which is made of a B2.5 V star in the Upper Centaurus-Lupus OB association with a very close, later companion of uncertain properties and a wide-orbit substellar object detected in direct imaging (Janson et al. 2021); this system was, however, filtered in the following step.

Table 2. Host stars in open clusters and OB associations with discarded wide common μ and π companion candidates.

Star ^(a)	α (J2000) (hh:mm:ss.ss)	δ (J2000) (dd:mm:ss.s)	d (pc)	Open cluster ^(b)
HD 285507	04:07:01.23	+15:20:06.1	45.0	Hya
K2–25	04:13:05.61	+15:14:52.0	44.7	Hya
K2–136	04:29:38.99	+22:52:57.8	58.9	Hya
HD 28736	04:32:04.81	+05:24:36.1	43.3	Hya
HD 283869	04:47:41.80	+26:09:00.8	47.4	Hya
HD 95086	10:57:03.02	−68:40:02.4	86.5	LCC
HD 114082	13:09:16.19	−60:18:30.1	95.1	LCC

Notes. ^(a)The list does not contain ϵ Tau in the Hyades open cluster and b Cen (AB) in the Upper Centaurus-Lupus OB association. ^(b)Hya: Hyades open cluster; LCC: Lower Centaurus Crux OB association.

3.3. Ultracool dwarfs

In their desire to be as complete as possible, either the Extrasolar Planets Encyclopaedia, the NASA Exoplanet Archive, or both often tabulate exoplanet candidates that are far from being actual exoplanets according to the International Astronomical Union definition of a planet in the Solar System⁷. For example, although much has been written about the differences between brown dwarfs and substellar objects below the deuterium burning mass limit at about $13 M_{\text{Jup}}$ (Caballero 2018, and references therein), the Extrasolar Planets Encyclopaedia tabulates the first unambiguous brown dwarfs discovered, namely Teide 1 ($\sim 65 M_{\text{Jup}}$; Rebolo et al. 1995) and GJ 229 B ($\sim 35 M_{\text{Jup}}$; Nakajima et al. 1995), counting as exoplanets⁸, but not hundreds of other ultracool dwarfs (UCDs) with spectral type M7 V or later, *Gaia* parallax, and mass at or below the hydrogen burning limit (e.g. Basri 2000; Kirkpatrick 2005; Smart et al. 2019). Something similar happens to a few M-type companions to young stars in stellar kinematic groups and star-forming regions, and LTY-type companions to very nearby stars and brown dwarfs detected via direct imaging. These UCD companions, which are counted as exoplanets in one or the two catalogues, orbit at a few arcseconds from their primaries, comparable to the separations between stars in multiple systems, have been resolved from their stars and characterised photometrically and even spectroscopically, or have high-uncertainty model-dependent masses at or above the deuterium burning limit. Because of their extreme heterogeneity, we discarded a total of 66 stars in systems with UCDs discovered by direct imaging, which left us only exoplanet candidates in compact orbits detected with the RV and transit methods. The 66 stars with imaged UCD companions are collected in Table B.2 with their respective references. Actually, there are 65 systems because both young late M dwarfs 2MASS J14504216–7841413 and 2MASS J14504113–7841383, which form a common μ and π double, are each counted as exoplanet candidates. Among the 65 discarded systems, one can find cornerstone star-brown dwarf systems such as GJ 229 (HD 42581) itself (Nakajima et al. 1995), G 196–3 (Rebolo et al. 1998), η Tel (Lowrance et al. 2000), TWA 5 (CD–33 7795) (Macintosh et al. 2001), or CD–52 381 (Neuhäuser et al. 2003). We included here one of the three found systems with possible circumbinary planets, HD 202206,

because the planet is also a brown dwarf (Benedict & Harrison 2017). Most of the 66 discarded stars in 65 systems in Table B.2 have UCDs companions that are too faint (and, sometimes, too close) for *Gaia*.

3.4. Close binaries without *Gaia* astrometric solution

At this stage, we were back to the 238 multiple systems that remained from the original sample of 311 stars with companions after discarding the 7 stars in Table 2 and the 66 stars in Table B.2. All the 238 exoplanet host stars have both μ and π from *Gaia* DR3 except for 3 very bright stars (Aldebaran, Fomalhaut, and γ^{01} Leo), and LP 413–32 B, which was recovered (see above) from Feinstein et al. (2019). However, there are 79 companions without *Gaia* DR3 μ and π . Of them, 20 have a *Gaia* DR3 entry but not a five-parameter astrometric solution: one star that is the early K companion at 1.2 arcsec to the late-F planet-host star HD 176051; six fainter close companions with similar or slightly greater angular separations $\rho \sim 1.2$ –5.0 arcsec but much larger magnitude differences $\Delta G \sim 5.5$ –11.5 mag to their primaries (*Gaia* DR3 959971546241605120, *Gaia* DR3 1220404653532465536, *Gaia* DR3 5917231492302779776, *Gaia* DR3 4122133830617000320, *Gaia* DR3 4296208099223616640, and *Gaia* DR3 6407428994689762560); 12 stars that are wide companions to planet host stars and that are in turn part of close binaries tabulated by WDS ($\rho \approx 0.06$ –1.3 arcsec), namely ψ^{01} Aqr [BC]⁹, 94 Cet [BC] (both with very large uncertainties in *Gaia* equatorial coordinates for its magnitude), HD 178911 [AB], HD 222582 [BC] (LP 703–44 AB), BD–17 588 [BC], and LSPM J1301+6337 [AB] (a wide companion to HD 113337 with a bimodal distribution in its *G*-band light curve that depends on the scan direction across the source); and 1 wide companion that is also a close binary, namely L 72–1 [AB], but is presented here for the first time (WDS 15154–7032; Appendix A). The *Gaia* DR3 *G*-band light curve of L 72–1 [AB] displays the same bimodal distribution as LSPM J1301+6337 [AB], which, together with its missing *Gaia* astrometric solution, points towards a close binarity of the order of 0.2 arcsec.

The other 59 companions do not even have a *Gaia* DR3 entry. They include the three companions reported in the literature but not tabulated by WDS that were mentioned above (in two circumbinary systems and one spectroscopic binary) and 56 companions in very close WDS systems, usually resolved with adaptive optics and beyond *Gaia*’s capabilities (e.g. γ Cep AB; Neuhäuser et al. 2007), that are close to naked-eye stars with very bright haloes (τ Boo B, 26 Dra B, 54 Psc B) or that are very bright themselves (e.g. α Cen A and B, γ^{02} Leo). Although we could recover proper motions, parallaxes, or proper motions different from *Gaia* DR3 only for a small fraction of them, given the robust multiplicity classification in most cases, we kept all the known close companions in our analysis. Thanks to this analysis, though, we were able to add a new component to a system that was considered to be double and is instead triple (WDS 15154–7032; Appendix A).

3.5. Final cut

We went on with the revision of known exoplanet candidates, and discarded 18 additional systems from our analysis: one system, namely GJ 682, with a bright companion candidate at 0.17 arcsec reported by Ward-Duong et al. (2015) and discarded with deep

⁷ https://www.iau.org/static/resolutions/Resolution_GA26-5-6.pdf

⁸ <https://exoplanet.eu/catalog/#inclusion-criteria-section>

⁹ The square brackets indicate that we use these designations for the first time.

imaging by Desgrange et al. (2023); two systems, namely 14 Her and 70 Vir, with faint companion candidates ($\Delta I = 10.9\text{--}11.4$ mag, $\rho = 2.9\text{--}4.3$ arcsec and 42.8 arcsec) detected in imaging searches by Pinfield et al. (2006) and Roberts et al. (2011) on only one epoch that are background sources according to, for example, Patience et al. (2002), Grether & Lineweaver (2006), Carson et al. (2009), Leconte et al. (2010), Ginski et al. (2012), Durkan et al. (2016), and Fontanive & Bardalez Gagliuffi (2021) (see also Rodigas et al. 2011 and Dalba et al. 2021 for searches at even closer angular separations); two systems, namely HD 9578 and TOI-717, with planet candidates that have not undergone publication within a peer-reviewed journal yet¹⁰; one system, namely Fomalhaut (α PsA), with a planet candidate proposed by Kalas et al. (2005, 2008), considered to be the first candidate imaged at visible wavelengths, which is actually an expanding blob of debris from a massive planetesimal collision in the disc (Gáspár & Rieke 2020; Gáspár et al. 2023); one triple system, namely LP 563–38, with two M dwarfs and an eclipsing brown dwarf (Irwin et al. 2010); six systems, namely 11 Com, HD 26161, HD 77065, HD 109988, HD 127506, and BD+24 4697, with radial-velocity companions with minimum masses between $15.5 M_{\text{Jup}}$ and $53.0 M_{\text{Jup}}$ and therefore actual masses well above the deuterium burning mass limit; and five systems with exoplanet candidates with astrometric masses above the hydrogen burning mass limit, that is, in the stellar domain. The five discarded stellar companions are HD 184601 B ($M = 117^{+36}_{-32} M_{\text{Jup}}$; Xiao et al. 2023), HD 21847 B ($M = 148 \pm 5 M_{\text{Jup}}$; Philipot et al. 2023), HD 283668 B ($M = 319 \pm 19 M_{\text{Jup}}$; Xiao et al. 2023), HD 114762 B ($M = 210 \pm 10 M_{\text{Jup}}$; Gaia Collaboration 2023a), and BD-02 2198 B ($M = 196.9^{+5.0}_{-4.9} M_{\text{Jup}}$; Baroch et al. 2021 – see also Biller et al. 2022). Of them, HD 114762 B has received much attraction in the last decades (Latham et al. 1989; Patience et al. 2002; Bowler et al. 2009; Kane et al. 2011; Kiefer 2019 – See Latham 2012 for a historical review). On the contrary to the 66 discarded stars in Sect. 3.3, these 18 additional systems have companion candidates that have never been resolved from their host stars.

Including the new companion in the close binary with missing *Gaia* DR3 astrometric solution and bimodal distribution of *G*-band light curve (L 72–1 [AB]), we had a total of 64 companions found in our common μ and π search but not reported by WDS. We carefully investigated the literature associated with these 64 stars and found that 44 of them had already been proposed as companions to the exoplanet host stars by other authors (e.g. Fontanive & Bardalez Gagliuffi 2021; Gaia Collaboration 2021b). We looked for available *Gaia* (mean) absolute radial velocities for the remaining 20 stars (in 18 systems). Because of the typical faintness of the new companions reported here and the *Gaia* limit at $G \sim 16$ mag for radial velocities (Katz et al. 2023), there are measurements for both the exoplanet host star and companion candidates for only eight systems. RAVE and other radial-velocity surveys (Steinmetz et al. 2006; Kunder et al. 2017) did not provide with additional measurements of companions. Of the eight systems, three binary systems, namely those with exoplanet host stars HD 168009, HD 210193, and K2-137, have radial velocities that differ by 80.90 ± 0.27 , 32.55 ± 0.19 , and $34.4 \pm 2.9 \text{ km s}^{-1}$, respectively. Such differences may be difficult to ascribe to unknown close companions of the secondaries, as they may actually be happening to a lesser degree than to the M-dwarf companion to CD-24 12030, or among the G–K components of HD 222259. Therefore, the stars in the three pairs

do not have the same galactocentric velocities and are optical pairs. Hence, we discarded them from our analysis. This deletion left us with 17 genuinely new companions candidates, which are discussed in Sect. 4.1 and shown in Tables 3 and B.3. The former tabulates main derived data (stellar mass M_* , systemic radial velocity V_r , angular separation ρ , WDS identifier and discoverer code when available, a pictographical system schema, and reduced binding energy $|U_g^*|$ – see below), while the later tabulates the astrometric data (parallax, proper motion in right ascension and declination, μ_{ratio} , and ΔPA).

After all these considerations, we identified 215 exoplanet host stars in 212 multiple systems, of which 173 are binary, 39 are triple, and three are quadruple. The list of these multiple systems is shown in Table B.4. We tabulate only 212 entries because there are three binary systems with planets discovered around both stars. The three systems, accounting for six stars and ten planets, are also displayed in Table 4.

3.6. Planetary systems

For the 215 stars in 212 multiple systems, we compiled the main parameters of 276 of the 302 planets orbiting them from the Extrasolar Planets Encyclopaedia and NASA Exoplanet Archive. In particular, we retrieved their orbital periods, P , semi-major axes, a , eccentricities, e , and masses, M_{pl} , or minimum masses, $M_{\text{pl}} \sin i$, for transiting or radial-velocity planets, respectively. When exoplanets are common to both databases, we took the most recent parameters from the NASA Exoplanet Archive, except for very few cases with significantly smaller uncertainties that we took from the Extrasolar Planets Encyclopaedia. The remaining 26 planets miss at least one datum. The schematic configurations of the 212 systems with all their members (stars, white dwarfs, brown dwarfs, planets) are represented in Fig. 5. In occasions, the planet host star is not the brightest primary in the system (e.g. α Cen, 26 Dra, 83 Leo, GJ 667). A total of 32 of the investigated exoplanets orbit giant or subgiant stars and only one around a white dwarf (LP 141–14 b; Appendix A). The rest of the host stars are main-sequence stars (see Sect. 5 and Fig. 6).

Most exoplanet searches have focused on stars without close stellar companions. For example, the CARMENES survey for exoplanets around nearby M dwarfs (Quirrenbach et al. 2014) discarded from their guaranteed and legacy time observations target stars that have companions at less than 5 arcsec, including astrometric and spectroscopic binaries, but kept resolved stellar systems with wider separations (Caballero et al. 2016; Cortés-Contreras et al. 2017; Jeffers et al. 2018; Reinert et al. 2018b). Since the CARMENES survey is a prototypical radial-velocity exoplanet search and our sample is built upon a collection of results of searches, our target list of 212 systems is naturally biased against very close binary systems with planets. Acknowledging this bias prior to commencing any discussion is therefore mandatory. Furthermore, this deficit of close binary systems is also found in transit exoplanet searches, which are also partly affected by this bias (Ziegler et al. 2021).

For comparison purposes, we defined a control sample of single stars with exoplanets, but no known stellar or brown dwarf companion at any separation. For that, we took a few steps back in our sample definition and discarded multiple systems with planets (Table B.4), or with one or more ultracool dwarfs (Table B.2), and retained only single stars at $d < 100$ pc. For the 687 single stars with planets, we searched for P , a , e , and M_{pl} or $M_{\text{pl}} \sin i$ of their 1029 planets exactly as we did for the multiple systems with planets. From now on, we called this set of stars the “single star sample”.

¹⁰ HD 9578 was only announced in a press release in October 2009 during an international conference.

Table 3. Systems with new common μ and π companions.

Star	Spectral type		$M_\star$		V_r	ρ	WDS	Disc. code / Reference ^(a,b)	System schema ^(c)	$ U_g^* $ (10^{33} J)
	Value	Ref. ^(a)	($M_\odot$)	Ref. ^(a)	(km s^{-1})	(arcsec)				
* HD 1466 ^(d)	F8 V	Tor06	1.16	Des21	+6.53±0.16		...			...
UCAC3 52–533	M1.8 (V)	Kra14	0.45	Pec13	+5.97 ± 24.0	3023		This work		
UCAC3 53–724	M5.5 V	Kir11	0.12	Pec13	...	1817		Gai21		
2MASS J00191296–6226005	L1	Gag15	0.08	Pec13	...	3772		This work		
* HD 27196	K1–2 V	Ker22	0.90	Ker22	+0.41 ± 0.14		...			182
2MASS J04164536–2646205	~M4.5 V	This work	0.18	Pec13	...	28		This work		
* HD 30177	G8 V	Hou75	0.98	Fen22	+62.60 ± 0.12		...			3.8
<i>Gaia</i> DR3 4774292312023378816	M7 (V)	Rey18	0.10	Pec13	...	780		This work		
* HD 88072[A]	G3 V	Gra03	1.04	Fen22	−18.00 ± 0.13		...			1.3
HD 88072B	~M5 V	This work	0.14	Pec13	...	3.7		Gai21		
LP 609–39	~M5.5 V	This work	0.12	Pec13	...	4772		This work		
* HD 93396	G8/K0 IV	Hou99	1.46	Tur15	+35.00 ± 0.12		...			14
UCAC3 162–116679	~K6 V	This work	0.69	Pec13	+34.60 ± 0.71	1266		This work		
* HD 94834	K1 IV	Egg60	1.11	Luh19	+2.79 ± 0.12		...			1150
<i>Gaia</i> DR3 3995918691799173376	~M4 V	This work	0.23	Pec13	...	3.9		This work		
* HD 96700	G0 V	Gra06	0.99	Tur15	+12.80 ± 0.12		...			6.7
CD–27 7881	K6 V	Gra06	0.72	Pec13	...	6867		This work		
* CD–39 7945	~G8 V	This work	0.92	Fri20	−14.00 ± 0.16		...			2.9
<i>Gaia</i> DR3 6140359952471910272	~M5.5 V	This work	0.12	Pec13	...	726		This work		
* UPM J1349–4603	~M3 V	This work	0.39	Hob23	−15.00 ± 2.72		...			4.7
<i>Gaia</i> DR3 6107347154502415744	D:	Gen19	0.65	Gen19	...	1361		This work		
* HD 134606	G6 IV	Gra06	1.06	Luh19	+1.94 ± 0.12		15154–7032			1194
L 72–1[AB]	~M3+~M3	This work	0.74	Pec13	+8.54 ± 6.11	57		FMR 173/This work		
* HD 135872	G5 IV	Hou99	1.65	Fen22	−20.00 ± 0.13		...			61
<i>Gaia</i> DR3 6334935890969037696	~K4 V	This work	0.73	Pec13	−20.00 ± 0.48	423		This work		
* CD–24 12030	~K2.5 V	This work	0.80	Chr22	+5.17 ± 0.29		...			51
<i>Gaia</i> DR3 6214879765359934592	~M2 V	This work	0.45	Pec13	+8.78 ± 3.18	231		This work		
<i>Gaia</i> DR3 6214879769657777536	~M4 V	This work	0.25	Pec13	+42.30 ± 4.30	226		This work		
* HD 143361	G6 V	Hou78	0.95	Min09	−0.60 ± 0.16		...			2.3
<i>Gaia</i> DR3 5994315469412318848	~M4.5 V	This work	0.19	Pec13	...	1964		This work		
* TOI–1410	~K4 V	This work	0.71	Sta19	+2.46 ± 0.10		...			68
<i>Gaia</i> DR3 1958584427911285120	~M3 V	This work	0.36	Pec13	+3.38 ± 1.87	91		This work		
* HD 222259A	G6 V	Tor06	0.96	Ben19	+7.13 ± 0.28		23397–6912			4.6
HD 222259B	K3 V	Tor06	0.78	Pec13	+5.17 ± 0.42	5.4		R 348		
2MASS J23321028–6926537	M5.3 V	Ujj20	0.17	Pec13	...	2560		This work		

Notes. ^(a)References: Alo15: Alonso-Floriano et al. (2015); Ben19: Benatti et al. (2019); Chr22: Christiansen et al. (2022); Des21: Desidera et al. (2021); Egg60: Eggen (1960); Fen22: Feng et al. (2022); Fri20: Fridlund et al. (2020); Gag15: Gagné et al. (2015); Gai21: Gaia Collaboration (2021b); Gen19: Gentile Fusillo et al. (2019); Gra03: Gray et al. (2003); Gra06: Gray et al. (2006); Hob23: Hobson et al. (2023); Hou75: Houk & Cowley (1975); Hou78: Houk (1978); Hou99: Houk & Swift (1999); Ker22: Kervella et al. (2022); Kir11: Kirkpatrick et al. (2011); Kra14: Kraus et al. (2014); Lep13: Lépine et al. (2013); Low00: Lowrance et al. (2000); Luh19: Luhn et al. (2019); Min09: Minniti et al. (2009); Pec13: Pecaut & Mamajek (2013); Rey18: Reylé (2018); Rie17: Riedel et al. (2017a); Smi18: Smith et al. (2018); Sta19: Stassun et al. (2019); Tor06: Torres et al. (2006); Tur15: Turnbull (2015); Ujj20: Ujjwal et al. (2020). ^(b)WDS discoverer codes are written in uppercase, and literature references in lowercase. ^(c)Blue circles: already reported stars. Red circles: new stars in system. Stripped circles: exoplanet host stars. Symbol sizes are proportional to stellar masses. ^(d)The HD 1466 system is in the Tucana-Horologium association; we only tabulate *Gaia* DR3 companions at $s < 1$ pc.

4. Results

4.1. New stellar systems

Of the 17 genuinely new companions in Table 3, 12 are part of completely new systems, while the other five are additional companions to four systems tabulated by WDS (two) or reported in

the literature (two). In these four systems, the K- and M-dwarf companions had never been described in the literature and therefore, we tabulated their *Gaia* DR3 identifiers (the companion of HD 143361 was catalogued by Gaia Collaboration 2021b). On the other hand, the 17 companions are members of 15 systems, four of which are triple, and one is quadruple. The four known

Table 4. Binary systems with detected planets around both stars.

Star	Spectral type		α (J2000) (hh:mm:ss.ss)	δ (J2000) (dd:mm:ss.s)	d (pc)	Planets		s (au)
	Value	Reference ^(a)				Number	Reference ^(a)	
HD 20782	G1.5 V	Gra06	03:20:03.58	−28:51:14.7	35.9	1	Jon06	9 075
HD 20781	G9.5 V	Gra06	03:20:02.94	−28:47:01.8	36.0	4	May11, Udr19	
UCAC3 234–106607	M1.3 V	Bir20	12:58:23.27	+26:30:09.1	58.7	1	Lew22	909
Sand 178 ^(b)	M2.4 V	Bir20	12:58:22.24	+26:30:16.1	58.8	1	Lew22	
HD 133131A	G2.0 V	Sto72	15:03:35.45	−27:50:33.2	51.5	2	Tes16	379
HD 133131B	G2.0 V	Sto72	15:03:35.81	−27:50:27.6	51.5	1	Tes16	

Notes. ^(a)Bir20: Birky et al. (2020); Gra06: Gray et al. (2006); Jon06: Jones et al. (2006); Lew22: Lewis et al. (2022); May11: Mayor et al. (2011); Sto72: Stock & Wroblewski (1972); Tes16: Teske et al. (2016); Udr19: Udry et al. (2019). ^(b)Lewis et al. (2022) stated that “depending on the true period and eccentricity of the system, the minimum companion mass may fall in a range from $2 M_{\text{Jup}}$ to $50 M_{\text{Jup}}$, making it a possible brown dwarf candidate”.

systems with new additional companions and the new triple system are described in Appendix A. The remaining ten systems are new binaries, that were thought to be single.

As already noticed by Shaya & Olling (2011), Newton et al. (2019), or Gaia Collaboration (2021b), the very large projected physical separations between primary stars and companions casts doubts on the actual gravitational binding of some systems. In our sample, a few of the systems are very wide. In particular, there are at least two systems in young associations and separations greater than 1000 arcsec (HD 1466 with its M-L companions, and WDS 23397–6912), which make the multiple system classification even blurrier (Caballero 2010; Tokovinin & Lépine 2012; Duchêne & Kraus 2013).

To assess whether the 17 genuinely new companions in Table 3 are indeed bound or not, we calculated the reduced binding energy value by following the methodology outlined by Caballero (2009):

$$|U_g^*| = G \frac{M_{\star,1} M_{\star,2}}{s}, \quad (4)$$

where G is the gravitational constant, $M_{\star,1}$ and $M_{\star,2}$ are the masses of both stars, and s their projected physical separation. The asterisk in $|U_g^*|$ indicates that the absolute values of the “true” potential energies U_g using the physical separation r must be lower than in Table 3 (Caballero 2009). For the three triple systems, we used the combined masses of the close pairs in the calculus (e.g. at a large separation, LP 609–39 feels the gravitational attraction of HD 88072AB as if it were a single, more massive star). We refrained from using the $\bar{r} \approx 1.26 \bar{s}$ relation between projected and true separations determined by Fischer & Marcy (1992) to facilitate direct comparisons with certain other studies (Close et al. 2003; Burgasser et al. 2007; Radigan et al. 2009; Caballero 2010; Faherty et al. 2010).

We computed the projected physical separation from the angular separation and the (parallactic) distance to the primary and used the colour-magnitude diagram in Fig. 6 as a guide to determine stellar masses. For resolved stars in the main sequence, we used the conversion from Gaia G -band absolute magnitudes and $B_p - R_p$ colours to masses outlined in Table 5 of Pecaú & Mamajek (2013), which is available in an enhanced and updated version on line¹¹. For six stars out of the main sequence (e.g., four subgiants, one white dwarf, and one young

overluminous star), we took their masses from the literature (Turnbull 2015; Livingston et al. 2018; Gentile Fusillo et al. 2019; Luhn et al. 2019; Feng et al. 2022). For completeness, we also took spectral types from Simbad; when not available, we estimated them from photometry by relying on Pecaú & Mamajek (2013) and Cifuentes et al. (2020).

The names, spectral types (and references), stellar masses (and references), radial velocities for the 35 resolved stars, and angular separation, WDS identifier, pair discovery code or reference, and a schema of the 15 systems with new proper motion and parallax companions are displayed in Table 3, and their astrometric properties are shown in Table B.3. The asterisks denote the planet-host stars, which in all cases are the system primaries. We were able to compute $|U_g^*|$ values for all but one trapezoidal system, of which the host star is HD 1466 in Tucana-Horologium (González-Payo et al. 2023). The reduced binding energies vary from over 10^{36} J for the HD 94834 binary (K1 IV + ~M4 V) to merely a few 10^{33} J for the widest systems, with separations of up to 6900 arcsec. These small $|U_g^*|$ values are, however, slightly greater than 10^{33} J, which may represent the minimum threshold for binding gravitational energy before disruption by the galactic potential (Caballero 2010), as well as the minimum value of reduced binding energy of moderately separated binary systems of very low mass (Chauvin et al. 2004; Artigau et al. 2007; Caballero 2007; Radigan et al. 2009). Even for the system HD 88072 AB and LP 609–39, the lowest $|U_g^*|$ in Table 3 do not deviate from what is expected for gravitationally bound systems in the Milky Way (see Fig. 6 of González-Payo et al. 2023). Besides, the actual binding of HD 1466 and its companions in Tucana-Horologium and similar systems will be the subject of a forthcoming work, and it is out of the scope of this paper. Furthermore, we kept in Table B.4 two systems with ultra-wide separations greater than 6900 arcsec: WDS 14396–6050 (α Cen AB and Proxima, $\rho \sim 7960$ arcsec; Innes 1915) and WDS 08388–1315 (HD 73583 and BD–09 2535, $\rho \sim 14\,240$ arcsec; Shaya & Olling 2011). As a result, we maintained the 15 systems for the following analysis.

4.2. Semi-major axes and separations

As a first step of the analysis, we compared the projected physical separations between stars in multiple systems, s , and the exoplanet semi-major axes, a . In particular we compared the s between the exoplanet host star and the closest stellar (or white dwarf, or brown dwarf) companion in triple and quadruple

¹¹ https://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

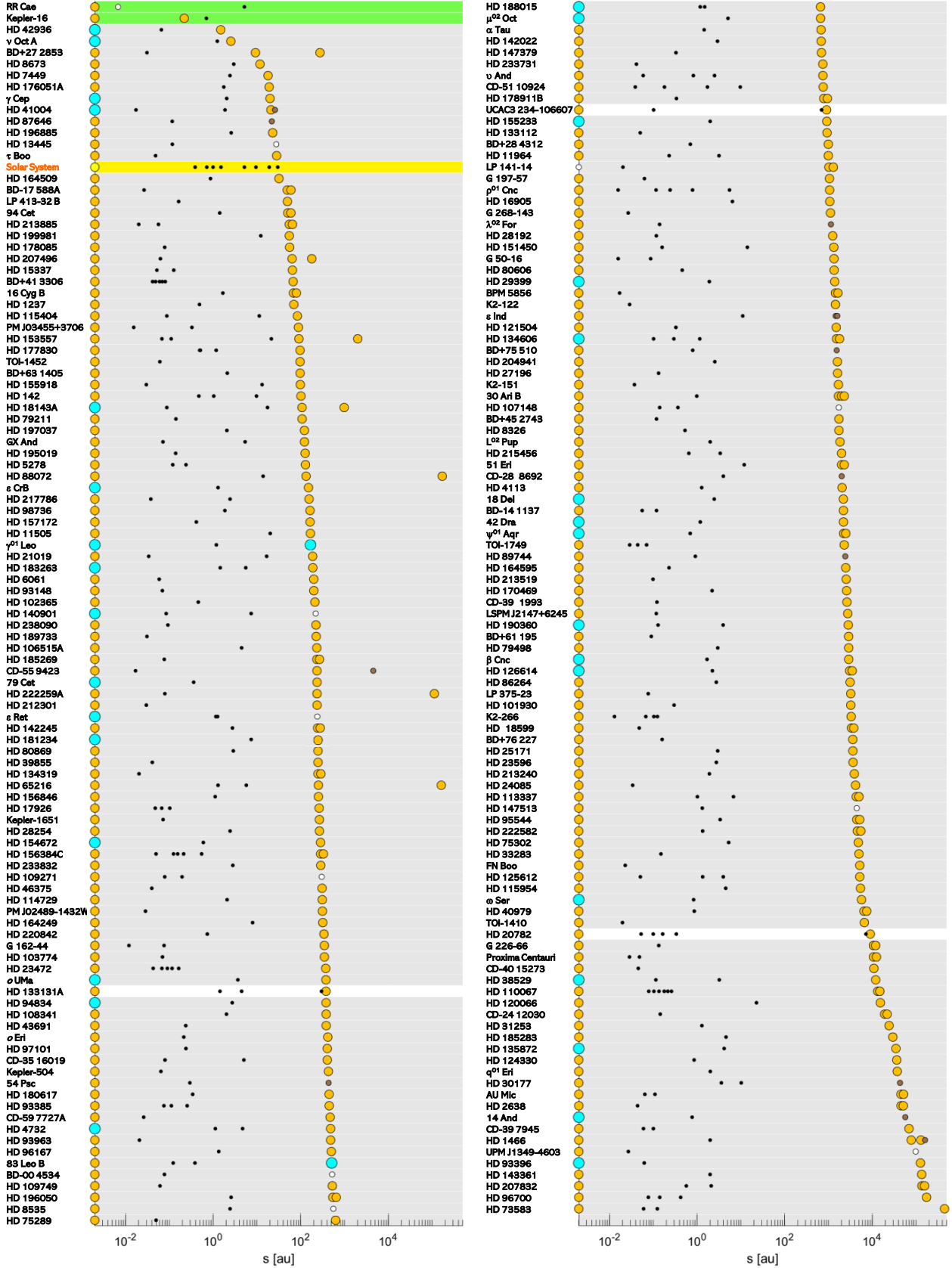


Fig. 5. Schematic configurations of multiple stellar systems with exoplanets. Orange circles are main-sequence stars, cyan circles are subgiant and giant stars, white circles are white dwarfs, small brown circles are brown dwarfs, and black dots are planets. We display our 212 systems with grey background, except for the two systems with circumbinary planets, namely RR Cae and Kepler-16, with green background, and the three systems from Table 4 with planets around both stars, with white background. The systems are sorted by increasing separation from the planet host star to the closest companion star. The abscissa is in logarithmic scale. We also display the Solar System in yellow as a comparison.

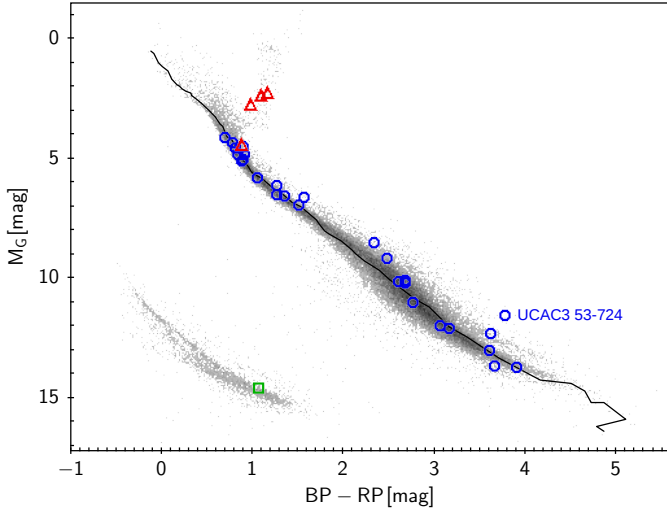


Fig. 6. *Gaia* colour-magnitude diagram of the systems with new common μ and π companions in Table 3. Blue circles, red triangles, and the green square stand for the main-sequence, subgiant, and white dwarf stars, while the small grey points are the over 50 000 random *Gaia* sources retrieved as Taylor (2021) did. The young overluminous star UCAC3 53–724 in Tucana-Horologium is labelled. The black solid line is the updated main sequence of Pecaut & Mamajek (2013). We did not apply any colour or magnitude correction for reddening.

systems, and the a of the most separated planet in multi-planet systems. This comparison is illustrated by Fig. 7. We mark the incompleteness areas in shadows of grey. The outer limit of the completeness area is defined by our maximum search s at 1 pc, while the approximate inner limit is set by $\bar{s} = \rho_{Gaia} \cdot \bar{d}$, where $\bar{s}$ and $\bar{d}$ are the median of the individual s and d , and ρ_{Gaia} is the critical value at 0.4 arcsec for spatial resolution of close binaries by *Gaia* (Lindgren et al. 2018, 2021). There have been, though, adaptive optics and speckle imaging searches that have explored inner regions ($\rho < 0.4$ arcsec). Besides, the investigated range of projected physical separations is directly proportional to the d , so the inner regions of nearby stars are in general better studied, and vice versa. Therefore, the darker the region, the more incomplete it is.

In Fig. 7, besides the two close binaries with circumbinary planets (RR Cae and Kepler–16), there is a number of remarkable systems that stand out because of their relatively small s/a ratios. They are relatively close binaries with planetary systems, some of which might challenge current exoplanet formation scenarios in truncated protoplanetary discs. About 25% of the displayed multiple systems have $s/a < 188$ (first quartile), and about 10% have $s/a < 34$ (first decile). We list in Table 5 the only 9 systems with $s/a < 20$, together with their corresponding references. The 9 systems represent about 8% of the systems (there is a gap in the s/a distribution at ~ 13 – 22). Most of the references, especially those presenting systems with the smallest s/a ratios, already made extensive discussion on the different formation, evolution, and stability mechanisms that gave rise to such peculiar systems (e.g. Neuhauser et al. 2007; Ramm et al. 2021; Feng et al. 2022). Some stellar parameter values may be biased due to companion blend (e.g. HD 176051 AB: Muterspaugh et al. 2010 did not know around which component the planet b, detected by astrometry, is orbiting). Actually, some stellar systems secondaries, marked with ‘[B]’ in Table 5, are so close to their primaries that they do not have an entry in Simbad and have only been resolved with high-resolution imagers. The non-tabulated system that stands

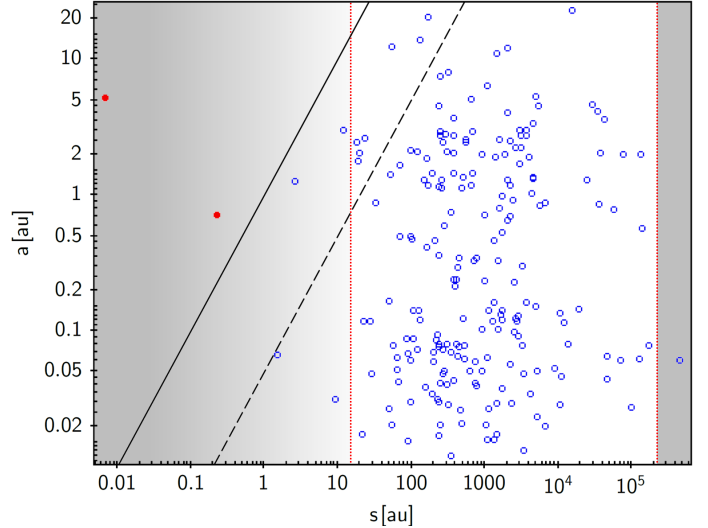


Fig. 7. Exoplanet semi-major axis versus star-projected physical separation. Solid and dashed black lines mark the $s:a$ relationships at 1:1 and 20:1, respectively. The two circumbinary systems are marked with red filled symbols. Grey regions delimited by red dotted lines (16.5 au and 1 pc = 648 000/π $\approx$ 206 264.81 au) indicate the approximate incompleteness areas (see main text).

out in Fig. 7 with $s \approx 1.5$ au and $a \approx 0.07$ au ($s/a \approx 22$) is HD 42936, which is made of a K0 IV primary orbited by a super-Earth at $P \approx 6.67$ d and a very low mass star at $P \approx 507$ d (Barnes et al. 2020).

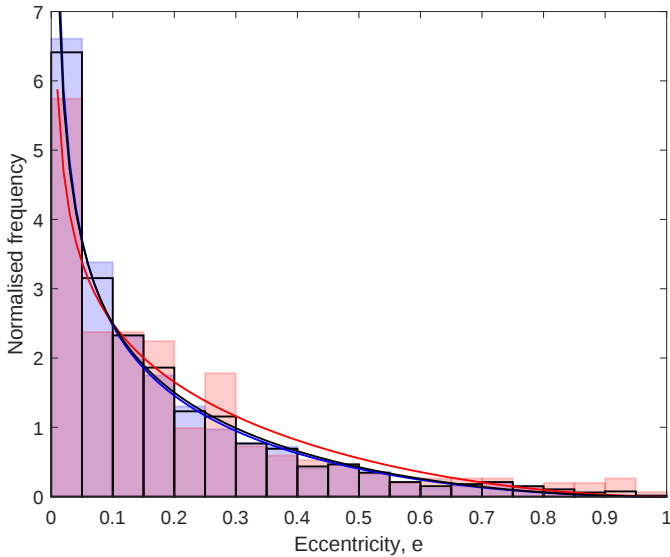
According to Winn & Fabrycky (2015), “the rough rule-of-thumb [for system stability is] that the planet’s period should differ by at least a factor of three from the binary’s period, even for a mass ratio as low as 0.1”. The three stars in Table 5 with the smallest s/a ratios are: HD 199981 (Feng et al. 2022, $s/a \approx 4.48$), HD 8673 (Hartmann et al. 2010; Feng et al. 2022, $s/a \approx 3.97$), and ν Oct (Ramm et al. 2021, $s/a \approx 2.04$). Their corresponding $P_{\text{star}}/P_{\text{planet}}$ ratios, after retrieving the stellar masses from the literature (e.g. Roberts et al. 2015) and applying Third Kepler’s Law, are about 8, 7, and 2.6, respectively. HD 199981 (a late-K primary and a mid-M secondary separated by 2.7 arcsec) and HD 8673 (a late-F primary and an early M secondary separated by 0.31 arcsec), both with massive substellar companions at the planet-brown dwarf boundary, seem to be stable systems in spite of their small s/a and $P_{\text{star}}/P_{\text{planet}}$ ratios (see again Feng et al. 2022). However, the ν Oct system (an early K giant with a $\sim 0.58 M_{\odot}$ companion separated by 0.11 arcsec and a planetary candidate in a retrograde orbit – Ramm et al. 2009, 2016, 2021; Ramm 2015), is catalogued in the Extrasolar Planets Encyclopaedia as “Unconfirmed” and is not catalogued at all by the NASA Exoplanet Archive. As a result, the hypothetical challenge for formation and stability scenarios may not apply in this particular case, nor in the other confirmed systems with larger s/a and $P_{\text{star}}/P_{\text{planet}}$ ratios.

4.3. Eccentricities

The previous section prepared the ground for this one where the inter-comparison of the planet eccentricity distributions gets more complicated and uses new tools introduced here. Except for the unconfirmed astrometric exoplanet candidate around one of the two stars in HD 176051 AB and for γ Cep Ab (which was originally discovered by Campbell et al. 1988 but confirmed 15 years later by Hatzes et al. 2003), all the planets in Table 5 have

Table 5. Multiple systems with planets and $s/a < 20$.

Host star	Companion star	Planet	s (au)	a (au)	e	References
HD 11505[A]	HD 11505B	b	167.19 ± 0.20	$20.2^{+4.8}_{-3.4}$	$0.144^{+0.011}_{-0.056}$	Feng et al. (2022)
HD 88072[A]	HD 88072B	b	132.77 ± 0.19	$13.9^{+4.1}_{-2.0}$	$0.16^{+0.14}_{-0.10}$	Feng et al. (2022)
HD 8673[A]	HD 8673[B]	b	11.8	$2.97^{+0.15}_{-0.17}$	$0.730^{+0.042}_{-0.026}$	Hartmann et al. (2010); Feng et al. (2022)
HD 196885	HD 196885B	b	23.0	2.6 ± 0.1	0.48 ± 0.02	Correia et al. (2008); Chauvin et al. (2011)
HD 7449[A]	HD 7449[B]	b	20.8 ± 0.3	$2.438^{+0.062}_{-0.063}$	$0.752^{+0.035}_{-0.032}$	Dumusque et al. (2011); Feng et al. (2022)
γ Cep [A]	γ Cep [B]	b	20.18 ± 0.66	2.05 ± 0.06	0.049 ± 0.034	Hatzes et al. (2003); Neuhäuser et al. (2007); Endl et al. (2011)
HD 176051A	HD 176051B	b	19.14 ± 0.04	1.76	0 (fixed)	Muterspaugh et al. (2010)
HD 199981[A]	HD 199981B	b	55.16 ± 0.03	$12.3^{+3.6}_{-2.2}$	$0.155^{+0.073}_{-0.041}$	Feng et al. (2022)
ν Oct [A]	ν Oct [B]	b	2.6	1.25 ± 0.05	0.11 ± 0.02	Ramm et al. (2016, 2021)

**Fig. 8.** Distributions of eccentricities of planetary orbits and fitted beta distributions. Black open bins: joint sample (1332 planets in single plus multiple stars); blue filled bins: single-star sample (1029 planets); red filled bins: multiple-star system sample (303 planets). The histograms are normalised to have a unit area. The three curve fittings (black for the joint sample, blue for single-star systems, and red for multiple-star systems) have beta distributions with different α and β parameters. See text for a description.

eccentricities e that are significantly different from null. Furthermore there are two planets with $e > 0.7$ and a third planet with $e \approx 0.48$. Therefore, we addressed the question of whether the multiplicity of the host stellar system has any effect on the eccentricities of the planetary orbits, as previously suggested by other authors (e.g. Eggenberger et al. 2004a; Raghavan et al. 2006; Lester et al. 2021). In Fig. 8, we show the distribution of eccentricities of our combined sample of planets around single and multiple stars. Apparently, there are more planets with low eccentricity in single systems and more planets with high eccentricities in multiple systems.

To assess the reliability of this possible effect, we first modelled the observed distribution of planet eccentricities in both single and multiple star samples using a unique probability distribution. We found that the beta distribution, the simplest distribution representing a continuum variable taking values

between 0 and 1, can indeed be used to model such a distribution. The likelihood can therefore be written as

$$P(e|\alpha, \beta) = \frac{e^{\alpha-1}(1-e)^{\beta-1}}{B(\alpha, \beta)}, \quad (5)$$

where $B(\alpha, \beta)$ is the beta function as a function of gamma functions:

$$B(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha + \beta)}. \quad (6)$$

In order to fit a beta distribution to these data, we constructed a Bayesian Markov chain Monte Carlo (MCMC) model written in Stan¹² (Carpenter et al. 2017). Stan is a programming language that makes use of the Hamiltonian Monte Carlo no U-turn sampler (HMC+NUTS) algorithm (Neal 2011; Hoffman & Gelman 2011) to perform Bayesian modelling and inference. This programming technique allowed us to introduce in the calculations the errors in the measured eccentricity, which are typically asymmetrical. In some cases, only an upper value for the eccentricity is available. This lack was solved by incorporating asymmetric Gaussian distributions in our Stan program. For the few planetary orbits without an estimation of the eccentricity error we assumed a typical value of 0.1.

Instead of working with the usual α and β parameters of the beta distribution, we parameterised it using the more intuitive parameters mean, $p = \alpha/(\alpha + \beta)$, and concentration, $\theta = \alpha + \beta$. First, for the joint sample of 1332 planetary orbits in 902 single and multiple systems (1029 planets around 687 single stars, 303 planets in 215 multiple systems, including the 3 binary systems with detected planets around both stars), we derived the posterior probability distributions for the parameters and obtained $p = 0.1719 \pm 0.0050$ and $\theta = 3.42 \pm 0.18$. The quoted errors are the standard deviation of these distributions, although they are not necessarily Gaussian. We did not fit the curve to the represented binned data, but to the original unbinned eccentricities using their measurement errors. The resulting beta distribution is plotted in black in Fig. 8.

To be able to assess the possible effect of the multiplicity of the host system on the eccentricity we fitted two additional models. In the second one we fitted the p and θ parameters separately for planets in single and multiple systems. The result was that there is no statistically significant difference in the θ

¹² <https://mc-stan.org>

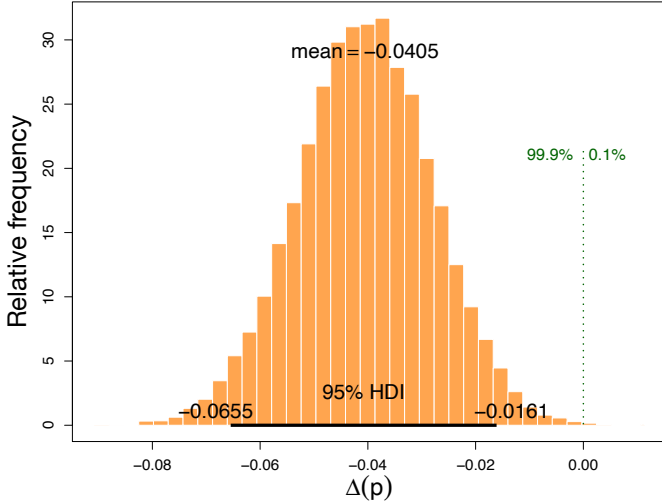


Fig. 9. Posterior probability distribution for the difference in the mean p parameter of the beta distributions fitted to the eccentricity distributions of planetary orbits in simple and multiple stars. Here $\Delta p = p_{\text{single}} - p_{\text{multiple}}$, and $\theta_{\text{single}} = \theta_{\text{multiple}}$. The thick horizontal black line represents the 95% HDI (see text), while the black labels indicate the upper and lower values of the 95% HDI and the mean Δp . The vertical green dotted line indicates the location of the null difference, while the percentages show the relative areas of the distribution at both sides of this line. This figure was created using a modified version of the software provided by Kruschke (2015).

values between both samples, with a mean difference of $\Delta\theta = |\theta_{\text{single}} - \theta_{\text{multiple}}| = 0.22 \pm 0.21$.

We finally fitted a third model in which the θ value was the same for both samples, whereas the p parameter was allowed to vary between them. The posterior parameters for this model were $\theta = 3.45 \pm 0.18$, $p_{\text{single}} = 0.1627 \pm 0.0058$, and $p_{\text{multiple}} = 0.203 \pm 0.012$. Fig. 8 also displays the distributions of eccentricities of planets in single and multiple systems and their corresponding beta fits (with $\theta_{\text{single}} = \theta_{\text{multiple}}$), in blue and red respectively.

To carry out an objective comparison among the three models, we applied an information criterion, namely the Watanabe-Akaike Information Criterion (WAIC; Watanabe 2013). The particular values obtained for the first (same p and θ parameters), second (different p and θ), and third (fixed θ , different p) were -2891.8 , -2908.2 , and -2909.3 , respectively. We obtained identical results with the Leave-One-Out Cross-Validation criterion (LOO-CV; Vehtari et al. 2017). Therefore, the third model, with shared θ and different p parameters, was indeed the best model representing the data according to this criterion. The analysis with the MCMC technique provides an estimate of the unknown parameters of the fitted model for each step of the Markov chains. In this case, we ran four separate chains with 12 500 points each and therefore obtained 50 000 estimates for the difference $\Delta p = p_{\text{single}} - p_{\text{multiple}}$. A histogram of these values is represented in Fig. 9. According to Gelman et al. (2014), who thoroughly discussed the Bayesian data analysis methods, this distribution is an unbiased true representation of the actual posterior distribution of the parameters. The thick horizontal line in the figure shows a 95% highest density interval (HDI). The HDI is the Bayesian counterpart of the classical confidence interval, and it is calculated as the narrowest interval that contains a certain percentage of the probability density. In other words, it encompasses the most credible values of the distribution though not necessarily symmetrical nor centred on the arithmetic mean

(see, for example, Kruschke 2015 for a definition and discussion of the HDI).

In our case, we obtained a posterior distribution that implies $\Delta p = -0.041 \pm 0.013$. In Fig. 9 we compare the extent of the 95% HDI bar with the position of the zero value. Only 0.1% of the posterior estimates are positive, and therefore our conclusion is that $\Delta p < 0$ with a significance level of 0.001 in conventional statistics. Thus, we concluded that planetary orbits in multiple stellar systems do exhibit significantly larger eccentricities than those around single stars. This result is expanded, nevertheless, in the next section.

4.4. Semi-major axes, separations, and eccentricities

Given the result obtained in Sect. 4.3, one would expect that the physical separation between the stars in the closest multiple systems may have an effect on the eccentricities of planetary orbits, though this effect is negligible for the widest pairs. To check and quantify this hypothesis, we fitted a model in which we allowed the mean p of the beta distribution of the eccentricities e to vary with the physical separation s between stars. For this purpose we constructed a generalised lineal model. This kind of models is useful to explore regressions with dependent variables not following a Gaussian distribution, such as the orbit eccentricities in our case, although its use in astrophysical research is limited. We refer the reader to de Souza et al. (2015a,b), Elliot et al. (2015), and Hilbe et al. (2017) for discussion of this statistical technique in the context of astrophysical problems, including some useful examples.

In our case, we fitted a generalised model in which the possible effect of physical separation in logarithmic units, $\log s$, was introduced by computing a linear predictor η :

$$\eta = \beta_1 + \beta_2 \log s, \quad (7)$$

which was related to the mean p of the beta distribution by a logit link function (Berkson 1944; McFadden 1973):

$$\eta \equiv \text{logit } p = \log \frac{p}{1-p} \quad (8)$$

We introduced the link function to transform from the unbounded scale of η to the bounded range of p between zero and one. The θ parameter of the beta distribution was not allowed to vary with the stellar separations, though. To perform the fit, we created another MCMC model in Stan to derive the posterior probability distributions for the three parameters θ , β_1 , and β_2 . These distributions can be summarised as $\theta = 1.981 \pm 0.160$, $\beta_1 = -1.034 \pm 0.226$, and $\beta_2 = -0.098 \pm 0.072$. It is already apparent from the estimate for β_2 that the effect of the stellar separation on the eccentricities is not statistically significant. This is more clearly seen in the left panel of Fig. 10, where we represent the prediction for the p parameter, and its 95% HDI in the e - $\log s$ plane. To guide the eye, and although they were not used in the fitting procedure, we included in Fig. 10 the mean eccentricities in bins of 1 dex.

The above result is not surprising since one would expect that the effect of star separation s on the orbit eccentricities should not depend just on the absolute value of s , but on its relative value compared to the star-planet separation. To confirm this hypothesis, we repeated the above analysis but replaced s by the ratio s/a between the separation between stars and the semi-major axis of the planetary orbit. As before, in the case of

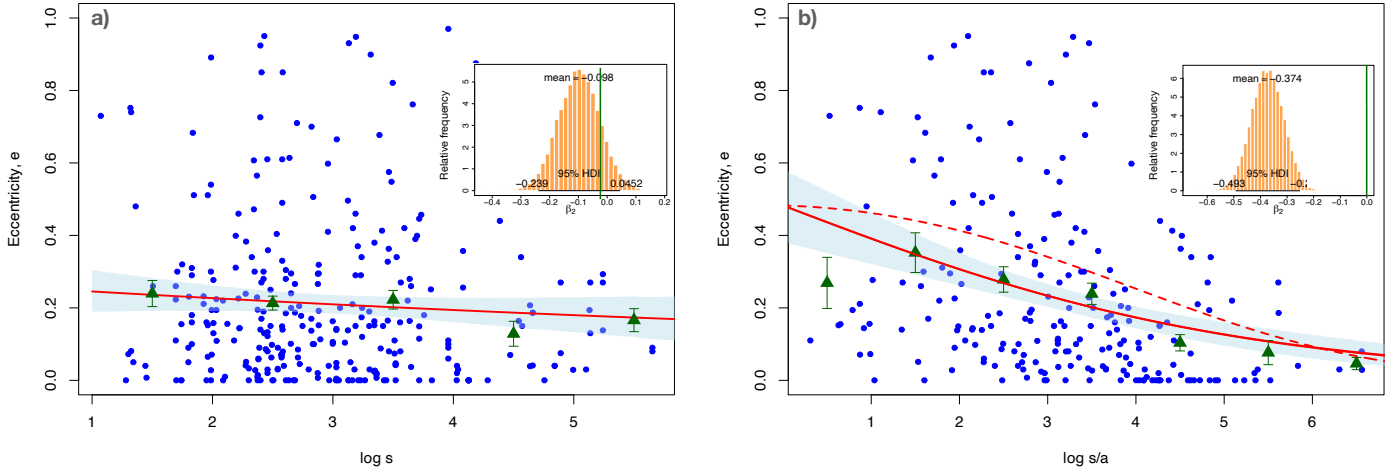


Fig. 10. Planet eccentricity as a function of star-star separation (panel a, *left*, in au) and of ratio between star-star separation and semi-major axis (panel b, *right*). The red lines show the predicted mean value p of the beta distributions as a function of the dependent variable, in logarithmic scale. The blue shades around these lines correspond to their 95% HDI. The insets show the corresponding posterior probability distribution of the β_2 parameters, and the vertical green lines mark $\beta_2 = 0$. Green triangles mark the mean eccentricities in bins of 1 dex, together with error bars for their formal errors. The dashed red line in panel b shows the result of a generalised model using a quadratic fit.

multiple planetary systems we used the a value of the outermost planet, and in the case of triple and quadruple systems we used the s value of the innermost star (or white dwarf or brown dwarf). The results are illustrated by the right panel of Fig. 10 and summarised by the following parameters: $\theta = 2.09 \pm 0.20$, $\beta_1 = -0.07 \pm 0.21$, and $\beta_2 = -0.374 \pm 0.062$. In the e - $\log s/a$ plane, the β_2 parameter is significantly different from zero; the equivalent significance level in conventional statistics is $< 2 \times 10^{-5}$ (i.e. beyond a 4σ effect). As a result, for a fixed semi-major axis a , planets in multiple systems with shorter star-star separations s tend to exhibit larger eccentricities e .

The mean binned eccentricities plotted in the right panel of Fig. 10 suggests a flattening of the relation for the lowest values of $\log(s/a)$. To assess the reliability of this effect we added a quadratic term to the relation between η and $\log(s/a)$, thus fitting the following relation:

$$\eta = \beta_1 + \beta_2 \log(s/a) + \beta_3 \log^2(s/a) \quad (9)$$

The result, which is also shown in the right panel of Fig. 10, confirms the suspected flattening. However, according to the values of the WAIC information criterion, this expanded model does not improve the linear one, which we kept afterwards.

4.5. Number of planets in single and multiple systems

We also investigated the planet rate in single (with one star) and multiple systems (with two, three, or four stars). The arithmetic mean numbers of planets around the 687 single and 215 multiple stars in our two samples are 1.51 and 1.41, respectively, which suggest that single stars tend to host slightly more planets. To test whether this measured difference is statistically significant, we applied the MCMC technique, programmed in Stan, to fit Poisson distributions to the detected number of planets in each sample. Since the two samples do not include cases with no planets orbiting the host star, we used a zero-truncated Poisson (ZTP) distribution (Hilbe et al. 2017), which corrects the classical Poisson model to exclude the possibility of observations with zero counts. In particular, if N denotes the random variable representing the number of planets, and λ is the parameter of the Poisson

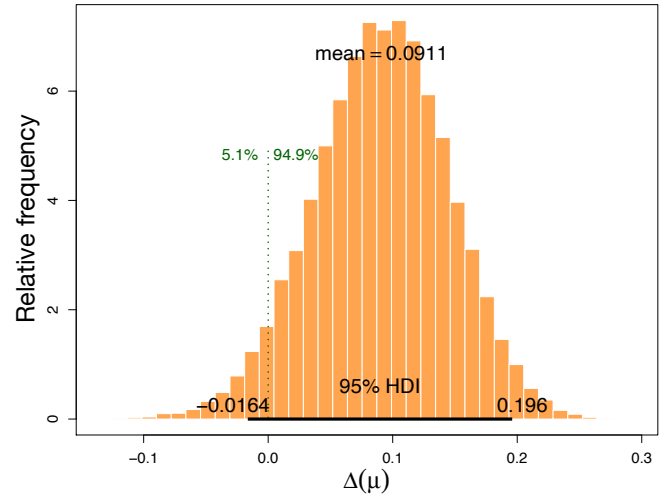


Fig. 11. Same as Fig. 9 but for the difference in the number of planets in single and multiple systems, $\Delta\mu = \mu_{\text{single}} - \mu_{\text{multiple}}$.

distribution, the ZTP probability distribution function takes the form:

$$P(N = k) = \frac{\lambda^k e^{-\lambda}}{k! (1 - e^{-\lambda})}, \quad (10)$$

where the corrected mean number of planets μ is:

$$\mu = \frac{\lambda}{1 - e^{-\lambda}}. \quad (11)$$

Here $e^{-\lambda}$ is the expected number of zeroes in a Poisson distribution with parameter λ .

The corresponding means of planets per host star are $\mu_{\text{single}} = 1.508 \pm 0.029$ and $\mu_{\text{multiple}} = 1.416 \pm 0.046$, virtually identical to the arithmetic means. The posterior probability distribution of the difference of the two means is represented in Fig. 11, which displays a mean offset of $\Delta\mu = 0.091 \pm 0.054$. This difference is only marginally significant and hovers at the edge of the 95% confidence interval. As a conclusion, although

the data suggest a larger number of planets around single stars when compared to multiple systems, the statistical significance of this effect is weak and we could not derive a firm conclusion.

One caveat of the previous analysis is that the applied ZTP distribution is not completely appropriate since, as it is often the case in real observational data, the observed dispersion in N is larger than the one expected from a Poisson distribution (i.e. $\sigma > \sqrt{\lambda}$). To solve this problem, we used an alternative probability distribution, namely the negative binomial, which is similar to the Poisson distribution but with one more parameter to account for a possible overdispersion. We again refer the reader to [de Souza et al. \(2015b\)](#) and [Hilbe et al. \(2017\)](#) for descriptions of the use of the negative binomial distribution in astrophysical contexts. To analyse the possible effects of this more reliable distribution, we constructed an MCMC model introducing a zero-truncated negative binomial distribution and applied it to our data. The result is that the mean offset in the number of planets between both samples becomes $\Delta\mu = 0.088 \pm 0.066$. This difference from zero is even less significant than our estimate with the Poisson distribution and therefore we reinforce our previous conclusion of a non-significant effect of the stellar multiplicity on the number of planets per star.

Given the results of Sect. 4.4, in which we showed how the increase of eccentricities is more apparent in low- s/a systems (i.e. systems in which the star-star separation is not much wider than the size of the planetary orbit), a possible effect of a lower number of planets for multiple systems could be hindered by the inclusion of high- s/a systems, which could be more similar to single systems. To check this hypothesis, we constructed a generalised linear model in which the mean parameter of the Poisson distribution was allowed to vary with $\log(s/a)$. As in Sect. 4.2, in the case of multi-planet systems, we used the a value of the outermost planet and s of the closest stellar companion, so s/a should be read as $\min(s/a)$. In particular, we used an exponential link function to go from the unbounded scale of a linear relation to the positive scale of the parameter of the Poisson distribution, that is:

$$\lambda = e^{\beta_1 + \beta_2 \log(s/a)} \quad (12)$$

The result for the slope parameter of the linear relation is $\beta_2 = -0.015 \pm 0.080$. Therefore, it is not significantly different from zero, and we concluded that there is no apparent effect of s/a on the observed number of planets. A computation of the corresponding WAICs also indicates that this model is worst than the constant λ model.

4.6. Planet masses in single and multiple systems

In this section, we explore whether stellar multiplicity has an impact on the locus of planets in the orbital period-planetary mass diagram. For example, [Fontanive et al. \(2019\)](#) and [Fontanive & Bardalez Gagliuffi \(2021\)](#), while not offering specific statistics, suggested that the separation of high-mass planets is influenced by stellar multiplicity. With the expanded and enhanced sample presented in our work, we can address these concerns with greater confidence. In Fig. 12 we display the period-mass diagram where we discriminate between planets in single and multiple systems. As shown in the plot, our sample comprises 850 planets around single stars and 276 in multiple systems with all data, which account for a 25% of the total sample. At a first glance, Fig. 12 suggests that high-mass planets with short periods may be relatively more frequent in multiple systems. To verify this hypothesis, we divided the

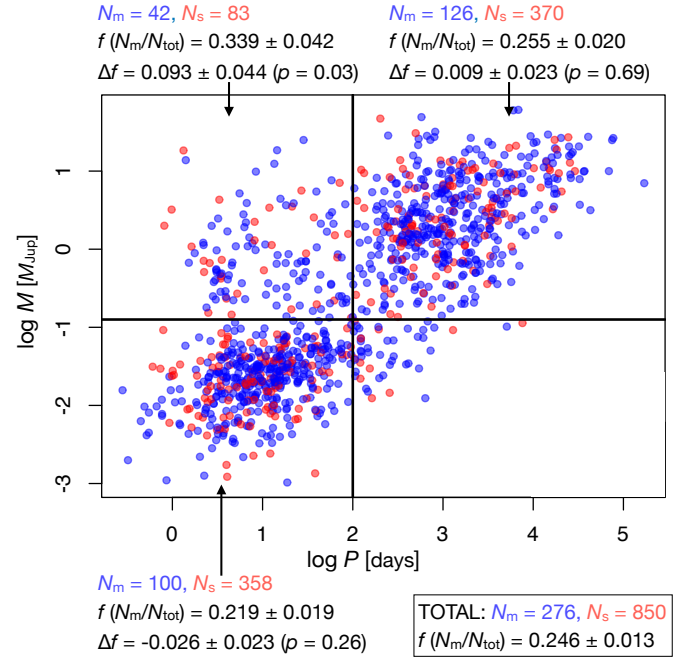


Fig. 12. Period-mass diagram for planets in single (red circles) and multiple systems (blue circles). The horizontal black line divides the sample into high- and low-mass regimes using a cutoff of $0.1258 M_{\text{Jup}}$ ($40 M_{\oplus}$), while the vertical black line at $P = 100$ d marks the position of the arithmetic mean of the distribution in orbital periods. The information showed for each quadrant is the number of planets in multiple, N_m , and single systems, N_s , the fraction of planets in multiple systems with respect to the whole sample, $f = N_m/(N_m + N_s)$, the difference Δf between this ratio and the value computed for the total sample ($f_{\text{tot}} = 0.246$), and, in parenthesis, the statistical significance p of the differences. No information is offered for the bottom-right quadrant due to the insufficient number of planets.

plane into four quadrants, as depicted in Fig. 12, and determined a number of parameters, together with their errors, by fitting binomial distributions using the MCMC technique. We found a marginally significant difference only in the upper-left quadrant, which suggested that high-mass planets ($M > 40 M_{\oplus}$) in close orbits ($P < 100$ d) appear to be relatively more frequent in multiple systems than around single stars. Other authors, such as [Eggenberger et al. \(2004b\)](#) and [Fontanive & Bardalez Gagliuffi \(2021\)](#), have also concluded that the most massive short-period planets (with masses greater than $2 M_{\text{Jup}}$) also tend to orbit in multiple star systems.

To delve deeper into these potential findings, in Fig. 13 we present histograms illustrating the distribution of orbital periods for high-mass ($M > 40 M_{\oplus}$) planets in both single and multiple systems. The relative increase in the proportion of planets with low orbital periods in the latter systems becomes apparent, as suggested by the previous quadrant analysis. To assess the reliability of this observation, we compared the cumulative distribution functions of both subsamples, as depicted in the inset of Fig. 13. For this purpose, we conducted an Anderson-Darling test ([Anderson & Darling 1952](#)), which is a modification of the Kolmogorov-Smirnov test, but more suitable for situations where greater emphasis must be placed on the tails of the distribution¹³, as it is the case with our data. The outcome of this test indicates that the statistical significance of the difference between

¹³ <https://asaip.psu.edu/Articles/beware-the-kolmogorov-smirnov-test>

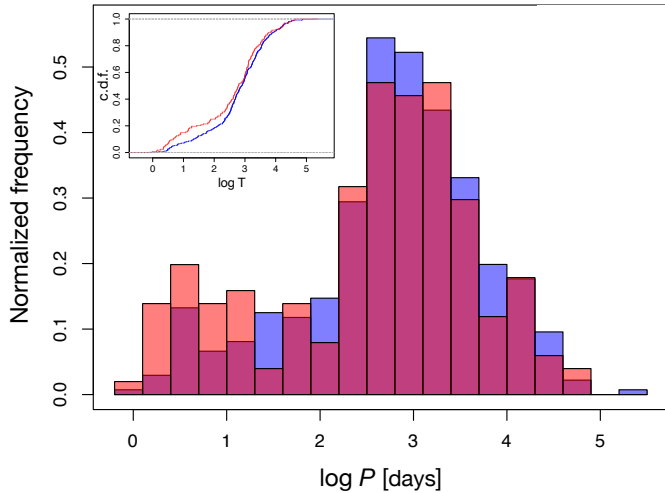


Fig. 13. Histogram of the distributions of orbital periods for high-mass ($M > 40 M_{\text{Jup}}$) planets in single (blue bars) and multiple (orange bars) systems. The inset of the figure compares the cumulative distribution functions of both subsamples.

both distributions is $p = 0.054$. Consequently, we cannot draw a definitive conclusion, and larger samples are evidently required to evaluate the reliability of this trend.

5. Discussion

5.1. Missing multiple systems

We evaluated the existence of unidentified multiple systems in our sample. First, our common proper motion and parallax search was limited by the *Gaia* completeness at $G \sim 20.3$ mag. According to Table 7 of [Smart et al. \(2019\)](#), our *Gaia* search was complete down to spectral type $M8 \pm 1$ V up to 100 pc, and $L8 \pm 1$ up to 10 pc. As a result, we were expected not to be able to detect ultracool dwarfs M9 V and later in the whole surveyed volume, nor T- and Y-type brown dwarfs just beyond 10 pc. Actually, we identified an L1 ultracool dwarf as a wide companion to HD 1466 in Tucana-Horologium, but it is overluminous because of its youth (Appendix A). While we might have conservatively stated that our *Gaia* search for resolved companions was virtually complete in the stellar domain down to about $0.1 M_{\odot}$ ([Cifuentes et al. 2020](#)), it was far from being complete for the least massive stars and the whole substellar domain. Furthermore, most of the brown dwarf companions analysed here came from WDS or literature works that employed deep adaptive optics imaging (e.g. GJ 229 B; [Nakajima et al. 1995](#)). Additional wide stellar companions with spectral types earlier than M8 V might have also been uncatalogued by *Gaia* in crowded regions at low galactic latitudes ([Reylé et al. 2021](#)).

Second, there may be more unidentified multiple systems, although hidden in plain sight. Exoplanet-host stars have naturally been monitored and validated with high-resolution spectroscopy in search for close unresolved binaries. Except for a few cases with long-term radial-velocity trends superimposed on short-term exoplanetary signals (e.g. 51 Peg itself), most host stars are known to have only exoplanetary companions at close separations. However, their resolved companions, usually fainter and with later spectral types, have in general not been analysed so thoroughly, so it may happen that some of the identified double systems actually are triple systems (and triple systems are quadruple systems, and so on). Furthermore, the proverb “these

things always come in threes” seems to apply well to multiple stellar systems through a major prevalence of wide triples over wide binaries ([Basri & Reiners 2006](#); [Tokovinin et al. 2006](#); [Caballero 2007](#); [Cifuentes et al. 2021](#)).

There have been only a few papers with exhaustive searches for companions of very different masses and at very different projected separations from the primary stars. For example, [Caballero et al. \(2022\)](#) compiled CHARA interferometry, NICMOS/*Hubble* Space Telescope and PUEO/Canada-France-Hawai’i Telescope high-resolution imaging, CARMENES/3.5 m Calar Alto and MAROON-X/Gemini high-resolution spectroscopy, and *Gaia* spectrophotometry, and ruled out the presence of stellar and high-mass brown-dwarf companions to the exoplanet-host star Gliese 486 from the limit of the *Hubble* observations at 24–32 au up to 100 000 au and of planets with minimum masses of $\sim 30 M_{\text{Jup}}$ with periods up to 20 000 days (~ 11 au). Other planetary systems have not been the subject of such a massive observational effort, but reasonable upper limits to the presence of additional companions exist for many of them. As a result, some of the 687 single stars with planets may not be single, but there are high chances that the great majority of them, especially those at the closest distances, do not have stellar companions at close or wide separations.

5.2. Eccentricity: Nature or nurture

One of the main results of our work is that the orbital eccentricity, e , of known planets in multiple stellar systems does not depend on the projected physical separation between component stars, s , but on the ratio between this separation and the planet semi-major axis, a . Therefore, the smaller the s/a ratio, the more probable the planet e is significantly larger than zero. However, in spite of this significant result after so many previous searches and analyses, we are still far from understanding the nature-nurture dilemma of eccentric planets in close multiple stellar systems (Sect. 1) or the role of the modulation of the orbital eccentricity, which strongly depends on the relative inclination between the plane of motion of the planet and that of the binary ([Mazeh et al. 1997](#)). This relative inclination is known for very few systems, if any, as the planet must (in general) transit and the stellar binary orbit must have an astrometric solution. The collection of multiple stellar systems with exoplanets in Table B.4, especially those with short projected angular separations, is an excellent input for forthcoming determinations of astrometric orbit parameters with periods of a few years. Such determinations will open the door to further dynamical analyses of systems with stellar and planetary companions orbiting primary stars at different angles, from which to extract conclusions on their formation, evolution, and stability.

We also made a visual inspection of planet e as a function of total mass of the system, and did not find any hint of relation that could be statistically analysed. It happened the same when we inspected the exoplanets orbital periods and the number of planets in system as a function of total mass. However, trying to analyse the detectability of exoplanets and therefore the number and (minimum) mass of exoplanets per system as a function of parameters of only the planet-host stars, such as their mass, spectral type, and degree of activity, is beyond the scope of this work (e.g. [Sabotta et al. 2021](#)).

5.3. Multiplicity function and future exoplanets surveys

We went on by comparing our results with those from the literature. The stellar MF of exoplanet systems (i.e. the fraction

of exoplanet systems with stellar companions) has been determined since the very beginning of exoplanetology at about 20% (Bakos et al. 2006; Bonavita & Desidera 2007; Mugrauer et al. 2007b). More precise determinations have varied around the narrow interval of 23% (30 multiple systems in 131 planetary systems; Raghavan et al. 2006) and $23.2 \pm 1.6\%$ (218 multiple systems in 938 planetary systems; Fontanive & Bardalez Gagliuffi 2021), compatible with the value of at least 12% proposed by Roell et al. (2012). In our case, after discarding pairs in open clusters and associations and with ultracool dwarf companions, we determined an MF of exoplanet systems of $21.6 \pm 2.9\%$ (212 multiple systems in 899 planetary systems). We stress on three issues in the comparison with the recent value of Fontanive & Bardalez Gagliuffi (2021): (i) the actual MF of exoplanet systems must be slightly larger because all searches, including ours, are incomplete at the latest spectral types (Sect. 5.1); (ii) the identical value but the larger uncertainty of our measurement in spite of the similar numbers. In particular, we used the Wald interval (Agresti & Coull 1998) assuming Poisson statistics for computing our uncertainties with a Wald 95% confidence interval (Wald interval = $(\lambda - 1.96 \sqrt{\lambda/n}, \lambda + 1.96 \sqrt{\lambda/n})$, where λ is the number of successes in n trials); and (iii) they explored a volume eight times larger than us, since they studied systems up to 200 pc, and we did it up to 100 pc. Our value of $21.6 \pm 2.9\%$ must necessarily be compared with MFs of nearby stars regardless planet presence. Since the MF depends on spectral type, the comparison should be done with that of field stars of spectral types between late F and mid M, as most radial-velocity and transit surveys during the last three decades have focused on them. All reference MF values enumerated in Sect. 1 are larger than our MF. Although there have been claims establishing that the influence of a companion star results in the system's stars being unable to host planets, whether due to formation or stellar evolution, (e.g. Wang et al. 2014; Kraus et al. 2016), we instead ascribe our lower multiplicity fraction to the aforementioned exoplanet survey bias (Winn & Fabrycky 2015 and the CARMENES examples; Sect. 3.6).

There is no exoplanet survey free of multiplicity bias, unless especially designed to overcome it. For example, one could envisage a search for smaller-amplitude signals in radial-velocity and light curves of known spectroscopic and eclipsing binaries, which are generally discarded in the first stages of exoplanet surveys (García-Melendo & López-Morales 2011; Gillon et al. 2017; Jeffers et al. 2018; Tal-Or et al. 2018; Parviainen et al. 2019; Kristiansen et al. 2022). Although several major transiting surveys are or will be greatly affected by multiplicity because of their poor spatial resolution, such as TESS (Ricker et al. 2015) and PLATO (Rauer et al. 2024), wide multiplicity barely affects radial-velocity exoplanet searches. Actually, some of the stars in wide multiple systems monitored by CARMENES, with companions at more than 5 arcsec, eventually turned out to host new exoplanets (e.g. Trifonov et al. 2018; Reiniers et al. 2018a; Kaminski et al. 2018; González-Álvarez et al. 2020; Kossakowski et al. 2021). The CARMENES limit at 5 arcsec was defined from the size of the spectrograph's optical fibre projected on the sky, 1.5 arcsec, the typical seeing at the Calar Alto observatory, and the maximum allowed spectral contamination by a close companion (Quirrenbach et al. 2014; Cortés-Contreras et al. 2017). Similar minimum separations have been defined for other radial velocity searches with HARPS (Bonfils et al. 2013) or SPIRou (Moutou et al. 2017a; Fouqué et al. 2018), just too put two comparable examples. A separation of 5 arcsec is, however, too short for TESS and PLATO, which have pixel sizes of 15.6–21.0 arcsec, and therefore they need compulsory

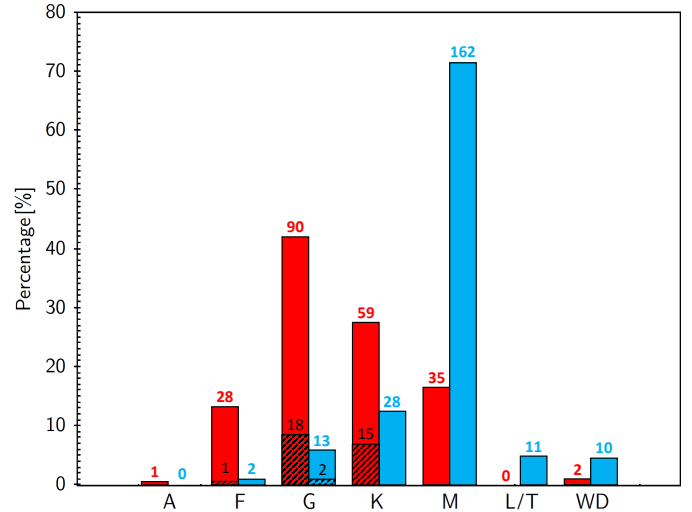


Fig. 14. Relative distribution of host stars (red) and companion stars (blue) per spectral type. Each bar is labelled with the absolute number of stars per bin. The black striped area represents the number of subgiant and giant stars in each spectral type. Compare with Fig. 3 of Fontanive & Bardalez Gagliuffi (2021).

Gaia, lucky imaging, or adaptive optics data in order to validate transiting targets or even pre-launch scientific prioritising targets (Collins et al. 2018; Clark et al. 2022; Nascimbeni et al. 2022). As a result, the crux of the matter is perhaps the definition of a boundary between ‘wide’ and ‘close’ multiples, which depends on the exoplanet survey. For example, one of the key exoplanet surveys of the next decades will be the Habitable Worlds Observatory¹⁴ (HWO; Clery 2023), for which preliminary target lists are currently starting to be defined (Tuchow et al. 2024; Harada et al. 2024). Although the HWO scientific requirements and therefore the mission specifications are far from being fixed, a wide multiple stellar system (i.e. one in which a stellar companion does not affect observations of host stars) must necessarily be less than 1 arcsec for HWO. The same shall happen to the Large Interferometer For Exoplanets¹⁵ (LIFE; Quanz et al. 2022). The bulk of the resolved stellar systems have angular separations greater than that value (there is a recent Öpik diagram in Fig. 1 of González-Payo et al. 2023). However, the astronomical community must make a joint effort to complement the forthcoming *Gaia* DR4 data in order to analyse in great detail the innermost arcsecond of the nearest stars regardless their age, using high-resolution spectroscopy, searching for new spectroscopic multiples, or obtaining deep imaging (e.g. Oppenheimer et al. 2001; McCarthy & Zuckerman 2004; Dieterich et al. 2012; Gauza et al. 2021).

5.4. Spectral types and hierarchy

Following the comparison with previous works, we also studied the relative distribution of spectral types of all the stars considered in our sample, distinguishing between host and companion stars, as illustrated by Fig. 14. Our sample contains stars (and brown dwarfs) from types A, F, G, M, L, T, and white dwarfs (WD). As already noticed by Fontanive & Bardalez Gagliuffi (2021), most host stars are obviously G- and K-type stars, while most companions are M-type stars (see also Mugrauer et al. 2007b).

¹⁴ <https://habitableworldsobservatory.org>

¹⁵ <https://life-space-mission.com>

However, we found a larger proportion of late spectral types as companions, with higher proportion of M stars (71.7%), and of L and T ultracool dwarfs (4.9%). Many of them were missing in Fontanive & Bardalez Gagliuffi (2021)’s work. Here the effect of the different maximum survey distances and Malmquist bias played a role.

Finally, we devote the last part of our discussion to systems hierarchy. As already mentioned, we found 40 triple and three quadruple stellar systems with exoplanets. Accounting for the 172 binaries with exoplanets, this means that 18.9% and 1.4% of the multiple systems are triple and quadruple, respectively. The values reasonably match those reported by Duchêne & Kraus (2013) and Reylé et al. (2021) for field stars in general, regardless they have planets or not. For example, Reylé et al. (2021) found that ~20% and ~5% of the multiple systems in the 10 pc neighbourhood are triple and quadruple+quintuple, respectively. In the case of quadruple systems, Cuntz et al. (2022) concluded that they are in general made of two groups of binary stars. This is indeed the case for two of our three quadruples, namely 30 Ari and HD 18599, but not for the third one centred on HD 1466 (Table 3). This is, however, a young system in Tucana-Horologium (Riedel et al. 2017b; Gagné et al. 2018) that will likely be disrupted in a few tens of millions of years (Caballero 2009). In the case of the triple systems, the 40 of them are made of a close pair plus a separated companion (i.e. AB–C or A–BC), in line with what was already presented by Mugrauer et al. (2007a), but with a much poorer statistics of just five triple systems. As in the case of Cuntz et al. (2022), we did not find any system of higher order (i.e. quintuple or higher).

6. Summary

In this study, we have compiled all stars with reported planets from the Extrasolar Planets Encyclopaedia and the NASA Exoplanet Archive at less than 100 pc. Employing primarily *Gaia* DR3 data supplemented by searches in the Washington Double Star catalogue and the available literature, we identified 215 exoplanet host stars in 212 multiple-star systems with common parallax and proper motion. During the analysis, we rejected stellar systems that are part of open clusters (Hyades) or OB associations (Lower Centaurus Crux), and planetary systems that have controversial planet candidates (e.g. with minimum masses above the hydrogen burning limit). Of the 212 multiple-star systems, 173 are binary (including two systems with circumbinary planets), 39 are triple, and three are quadruple, as expected from the rate of triple or higher-order multiples of field systems. There are three binary systems with detected planets around both stars.

We identified 17 new companions in 15 systems (ten binaries, four triples, one quadruple) with known planet host stars. All the new physically bound companions have spectral types, either determined by other teams or estimated by us, between K4 V and L1, except for a white dwarf candidate companion. Some of the components in the widest systems have been reported to belong to very young stellar kinematic groups, such as Tucana-Horologium, which may indicate that they are currently in the process of disruption by the galactic gravitational potential.

We were able to measure projected physical separations between stars with *Gaia* data in most cases, and to compile key parameters for 276 planets in multiple systems, with which we statistically analysed a series of hypotheses. First, we computed the ratio between separations and semi-major axes for all multiple systems and identified the nine of them with the smallest ratio, $s/a < 20$. Only one controversial planet candidate, namely ν Oct b, poses a challenge to current planet formation

and evolution models. Next, we constructed a single planet-host star sample for comparison purposes and found a significant difference between the eccentricities of planets in multiple systems and those of planets around single stars. In particular, planets in multiples systems with small s/a ratios have eccentricities that are significantly larger than those of planets with larger s/a ratios. This result is in line with a number of theoretical predictions; however, our sample is more complete, and our statistical tools are more advanced than most previous observational studies. Actually, we have a higher proportion of faint M, L, and T companions than previous searches, which provides more statistical robustness to our findings.

Concerning the comparison in the number of planets around multiple and single systems, we found a possible trend in the sense that the former tend to host a smaller number of planets, although the significance level of this result (around 0.05) precludes us from reaching a firm conclusion. Also, we detected a greater frequency of high-mass planets in close orbits in multiple systems compared to single ones but again, this result is on the verge of being statistically significant. Finally, we estimated a multiplicity fraction of stars with planets of $21.6 \pm 2.9\%$, a value close to what has been reported by similar studies but also smaller than the multiplicity fraction of field stars, regardless of whether they have planets. We ascribed this difference not to a different formation or evolution mechanism, but to a well-known observational bias in exoplanet searches, especially in radial-velocity surveys.

One may speculate on extending the survey limit up to 200 pc or beyond as a future work. Nonetheless, we must acknowledge the considerable time invested in the individualised analysis of thousands of planetary system candidates, some of which we had to discard. We instead propose prioritising the continued investigation of stellar multiplicity with planets with a previous work aimed at confirming and characterising the myriad of controversial planetary systems that have polluted past and current analyses. Eventually, we can leverage *Gaia* DR4 for this purpose.

Data availability

Tables B.1, B.2, B.3, and B.4 are available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/689/A302>

Acknowledgements. We thank the anonymous reviewer for their comprehensive report, and F. M. Rica and M. R. Zapatero Osorio for helpful comments. We acknowledge financial support from the Agencia Estatal de Investigación of the Ministerio de Ciencia e Innovación and the ERDF “A way of making Europe” through projects PID2022-138855NB-C31, PID2022-137241NB-C4[1:2], and PID2020-112949GB-I00, and from the European Commission Framework Programme Horizon 2020 Research and Innovation through the ESCAPE project under grant agreement no. 824064. This research made use of the NASA’s Astrophysics Data System Bibliographic Services and the Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program, the Washington Double Star catalogue maintained at the U.S. Naval Observatory, the Simbad database (Wenger et al. 2000), the VizieR (Ochsenbein et al. 2000) catalogue access tool, and the Aladin sky atlas (Bonnarel et al. 2000) at the Centre de données astronomiques de Strasbourg (France).

Note added in proof. P. Thebault kindly communicated us that Michel & Mugrauer (2024, MNRAS, 527, 3183) actually discovered the binary with primary HD 94834, not us.

References

- Abt, H. A., & Levy, S. G. 1976, *ApJS*, 30, 273
- Agresti, A., & Coull, B. 1998, *Am. Stat.*, 52, 119

- Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, *PASP*, **125**, 989
- Alcock, C., Allsman, R. A., Alves, D., et al. 1995, *ApJ*, **454**, L125
- Alcock, C., Allen, W. H., Allsman, R. A., et al. 1997, *ApJ*, **491**, 436
- Alonso-Floriano, F. J., Morales, J. C., Caballero, J. A., et al. 2015, *A&A*, **577**, A128
- Anderson, T. W., & Darling, D. A. 1952, *Ann. Math. Statist.*, **469**, 193
- Artigau, É., Lafrenière, D., Doyon, R., et al. 2007, *ApJ*, **659**, L49
- Artymowicz, P., & Lubow, S. H. 1996, *ApJ*, **467**, L77
- Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, *AJ*, **156**, 58
- Bailes, M., Bates, S. D., Bhalerao, V., et al. 2011, *Science*, **333**, 1717
- Bakos, G. Á., Pál, A., Latham, D. W., Noyes, R. W., & Stefanik, R. P. 2006, *ApJ*, **641**, L57
- Barnes, J. R., Haswell, C. A., Staab, D., et al. 2020, *Nat. Astron.*, **4**, 419
- Baroch, D., Morales, J. C., Ribas, I., et al. 2021, *A&A*, **653**, A49
- Baron, F., Lafrenière, D., Artigau, É., et al. 2019, *AJ*, **158**, 187
- Basri, G. 2000, *ARA&A*, **38**, 485
- Basri, G., & Reiners, A. 2006, *AJ*, **132**, 663
- Benatti, S., Nardiello, D., Malavolta, L., et al. 2019, *A&A*, **630**, A81
- Benedict, G. F., & Harrison, T. E. 2017, *AJ*, **153**, 258
- Bergfors, C., Brandner, W., Daemgen, S., et al. 2013, *MNRAS*, **428**, 182
- Berkson, J. 1944, *J. Am. Stat. Assoc.*, **39**, 357
- Biller, B. A., Grandjean, A., Messina, S., et al. 2022, *A&A*, **658**, A145
- Birky, J., Hogg, D. W., Mann, A. W., & Burgasser, A. 2020, *ApJ*, **892**, 31
- Bonavita, M., & Desidera, S. 2007, *A&A*, **468**, 721
- Bonavita, M., & Desidera, S. 2020, *Galaxies*, **8**, 16
- Bonfils, X., Delfosse, X., Udry, S., et al. 2013, *A&A*, **549**, A109
- Bonnarel, F., Fernique, P., Bienaymé, O., et al. 2000, *A&AS*, **143**, 33
- Bowler, B. P., Liu, M. C., & Cushing, M. C. 2009, *ApJ*, **706**, 1114
- Burgasser, A. J. 2007, *ApJ*, **659**, 655
- Burgasser, A. J., Kirkpatrick, J. D., Reid, I. N., et al. 2003, *ApJ*, **586**, 512
- Burgasser, A. J., Kirkpatrick, J. D., & Lowrance, P. J. 2005, *AJ*, **129**, 2849
- Burgasser, A. J., Reid, I. N., Siegler, N., et al. 2007, in *Protostars and Planets V*, eds. B. Reipurth, D. Jewitt, & K. Keil, 427
- Busetti, F., Beust, H., & Harley, C. 2018, *A&A*, **619**, A91
- Caballero, J. A. 2007, *A&A*, **462**, L61
- Caballero, J. A. 2009, *A&A*, **507**, 251
- Caballero, J. A. 2010, *A&A*, **514**, A98
- Caballero, J. A. 2014, *The Observatory*, **134**, 273
- Caballero, J. A. 2018, *Geosciences*, **8**, 362
- Caballero, J. A., Cortés-Contreras, M., Alonso-Floriano, F. J., et al. 2016, in *19th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (CS19)*, 148
- Caballero, J. A., González-Álvarez, E., Brady, M., et al. 2022, *A&A*, **665**, A120
- Campbell, B., Walker, G. A. H., & Yang, S. 1988, *ApJ*, **331**, 902
- Carpenter, B., Gelman, A., Hoffman, M. D., et al. 2017, *J. Stat. Softw.*, **76**, 1
- Carson, J. C., Hiner, K. D., Villar, Gregorio G., I., et al. 2009, *AJ*, **137**, 218
- Cassan, A., Kubas, D., Beaulieu, J. P., et al. 2012, *Nature*, **481**, 167
- Chauvin, G., Lagrange, A. M., Dumas, C., et al. 2004, *A&A*, **425**, L29
- Chauvin, G., Beust, H., Lagrange, A. M., & Eggenberger, A. 2011, *A&A*, **528**, A8
- Christiansen, J. L., Bhure, S., Zink, J. K., et al. 2022, *AJ*, **163**, 244
- Cifuentes, C., Caballero, J. A., Cortés-Contreras, M., et al. 2020, *A&A*, **642**, A115
- Cifuentes, C., Caballero, J. A., & Agustí, S. 2021, *RNAAS*, **5**, 129
- Clark, C. A., van Belle, G. T., Ciardi, D. R., et al. 2022, *AJ*, **163**, 232
- Clery, D. 2023, *Science*, **379**, 123
- Close, L. M., Siegler, N., Freed, M., & Biller, B. 2003, *ApJ*, **587**, 407
- Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G. W. 1997, *ApJ*, **483**, 457
- Collins, K., Quinn, S. N., Latham, D. W., et al. 2018, in *American Astronomical Society Meeting Abstracts*, 231, 439.08
- Correia, A. C. M., Udry, S., Mayor, M., et al. 2008, *A&A*, **479**, 271
- Cortés-Contreras, M., Béjar, V. J. S., Caballero, J. A., et al. 2017, *A&A*, **597**, A47
- Cruzalèbes, P., Petrov, R. G., Robbe-Dubois, S., et al. 2019, *MNRAS*, **490**, 3158
- Cuntz, M., Luke, G. E., Millard, M. J., Boyle, L., & Patel, S. D. 2022, *ApJS*, **263**, 33
- Daemgen, S., Hormuth, F., Brandner, W., et al. 2009, *A&A*, **498**, 567
- Dalba, P. A., Kane, S. R., Howell, S. B., et al. 2021, *AJ*, **161**, 123
- de Geus, E. J., Lub, J., & van de Grift, E. 1990, *A&AS*, **85**, 915
- De Silva, G. M., Sneden, C., Paulson, D. B., et al. 2006, *AJ*, **131**, 455
- de Souza, R. S., Cameron, E., Killedar, M., et al. 2015a, *Astron. Comput.*, **12**, 21
- de Souza, R. S., Hilbe, J. M., Buelens, B., et al. 2015b, *MNRAS*, **453**, 1928
- de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, *AJ*, **117**, 354
- Delfosse, X., Beuzit, J., Marchal, L., et al. 2004, in *ASPCS*, 318, Spectroscopically and Spatially Resolving the Components of the Close Binary Stars, eds. R. W. Hilditch, H. Hensberge, & K. Pavlovski, 166
- Desgrange, C., Milli, J., Chauvin, G., et al. 2023, *A&A*, **680**, A64
- Desidera, S., Chauvin, G., Bonavita, M., et al. 2021, *A&A*, **651**, A70
- Dieterich, S. B., Henry, T. J., Golimowski, D. A., Krist, J. E., & Tanner, A. M. 2012, *AJ*, **144**, 64
- Doolin, S., & Blundell, K. M. 2011, *MNRAS*, **418**, 2656
- Doyle, L. R., Carter, J. A., Fabrycky, D. C., et al. 2011, *Science*, **333**, 1602
- Dressing, C. D., & Charbonneau, D. 2015, *ApJ*, **807**, 45
- Duchêne, G., & Kraus, A. 2013, *ARA&A*, **51**, 269
- Dumusque, X., Lovis, C., Ségransan, D., et al. 2011, *A&A*, **535**, A55
- Dupuis, J., Vennes, S., Bowyer, S., Pradhan, A. K., & Thejll, P. 1994, in *American Astronomical Society Meeting Abstracts*, 184, 29.01
- Duquenooy, A., & Mayor, M. 1991, *A&A*, **248**, 485
- Durkan, S., Janson, M., & Carson, J. C. 2016, *ApJ*, **824**, 58
- Eggen, O. J. 1960, *MNRAS*, **120**, 430
- Eggenberger, A., Udry, S., & Mayor, M. 2004a, *A&A*, **417**, 353
- Eggenberger, A., Udry, S., Mayor, M., et al. 2004b, in *Astronomical Society of the Pacific Conference Series*, 321, Extrasolar Planets: Today and Tomorrow, eds. J. Beaulieu, A. Lecavelier Des Etangs, & C. Terquem, 93
- Eggenberger, A., Udry, S., Chauvin, G., et al. 2007, *A&A*, **474**, 273
- Elliot, J., de Souza, R. S., Krone-Martins, A., et al. 2015, *Astron. Comput.*, **10**, 61
- Endl, M., Cochran, W. D., Hatzes, A. P., & Wittenmyer, R. A. 2011, in *American Institute of Physics Conference Series*, 1331, Planetary Systems Beyond the Main Sequence, eds. S. Schuh, H. Drechsel, & U. Heber, 88
- Faherty, J. K., Burgasser, A. J., West, A. A., et al. 2010, *AJ*, **139**, 176
- Feinstein, A. D., Schlieder, J. E., Livingston, J. H., et al. 2019, *AJ*, **157**, 40
- Feng, F., Butler, R. P., Vogt, S. S., et al. 2022, *ApJS*, **262**, 21
- Finch, C. T., Zacharias, N., & Jao, W.-C. 2018, *AJ*, **155**, 176
- Fischer, D. A., & Marcy, G. W. 1992, *ApJ*, **396**, 178
- Fontanive, C., & Bardalez Gagliuffi, D. 2021, *Front. Astron. Space Sci.*, **8**, 16
- Fontanive, C., Biller, B., Bonavita, M., & Allers, K. 2018, *MNRAS*, **479**, 2702
- Fontanive, C., Rice, K., Bonavita, M., et al. 2019, *MNRAS*, **485**, 4967
- Fouqué, P., Moutou, C., Malo, L., et al. 2018, *MNRAS*, **475**, 1960
- Fridlund, M., Livingston, J., Gandolfi, D., et al. 2020, *MNRAS*, **498**, 4503
- Furlan, E., Ciardi, D. R., Everett, M. E., et al. 2017, *AJ*, **153**, 71
- Gagné, J., Lafrenière, D., Doyon, R., Malo, L., & Artigau, É. 2015, *ApJ*, **798**, 73
- Gagné, J., Mamajek, E. E., Malo, L., et al. 2018, *ApJ*, **856**, 23
- Gaia Collaboration (Brown, A. G. A., et al.) 2018, *A&A*, **616**, A1
- Gaia Collaboration (Brown, A. G. A., et al.) 2021a, *A&A*, **649**, A1
- Gaia Collaboration (Smart, R. L., et al.) 2021b, *A&A*, **649**, A6
- Gaia Collaboration (Arenou, F., et al.) 2023a, *A&A*, **674**, A34
- Gaia Collaboration (Vallenari, A., et al.) 2023b, *A&A*, **674**, A1
- García-Melendo, E., & López-Morales, M. 2011, *MNRAS*, **417**, L16
- Gáspár, A., & Rieke, G. 2020, *PNAS*, **117**, 9712
- Gáspár, A., Wolff, S. G., Rieke, G. H., et al. 2023, *Nat. Astron.*, **7**, 790
- Gauza, B., Béjar, V. J. S., Rebolo, R., et al. 2021, *ApJ*, **923**, 119
- Gelman, A., Carlin, J. B., Stern, H. S., et al. 2014, *Bayesian Data Analysis*, 3rd edn. (CRC Press)
- Gentile Fusillo, N. P., Tremblay, P.-E., Gänsicke, B. T., et al. 2019, *MNRAS*, **482**, 4570
- Gillon, M., Demory, B. O., Lovis, C., et al. 2017, *A&A*, **601**, A117
- Ginski, C., Mugrauer, M., Seeliger, M., & Eisenbeiss, T. 2012, *MNRAS*, **421**, 2498
- Ginski, C., Mugrauer, M., Seeliger, M., & Löhne, T. 2013, *A&A*, **559**, A71
- Ginski, C., Mugrauer, M., Seeliger, M., et al. 2016, *MNRAS*, **457**, 2173
- Ginski, C., Mugrauer, M., Adam, C., Vogt, N., & van Holstein, R. G. 2021, *A&A*, **649**, A156
- Gladman, B. 1993, *Icarus*, **106**, 247
- González-Álvarez, E., Zapatero Osorio, M. R., Caballero, J. A., et al. 2020, *A&A*, **637**, A93
- González-Payo, J., Cortés-Contreras, M., Lodieu, N., et al. 2021, *A&A*, **650**, A190
- González-Payo, J., Caballero, J. A., & Cortés-Contreras, M. 2023, *A&A*, **670**, A102
- Gray, R. O., Corbally, C. J., Garrison, R. F., McFadden, M. T., & Robinson, P. E. 2003, *AJ*, **126**, 2048
- Gray, R. O., Corbally, C. J., Garrison, R. F., et al. 2006, *AJ*, **132**, 161
- Grether, D., & Lineweaver, C. H. 2006, *ApJ*, **640**, 1051
- Hamers, A. S., Rantala, A., Neunteufel, P., Preece, H., & Vynatheya, P. 2021, *MNRAS*, **502**, 4479
- Harada, C. K., Dressing, C. D., Kane, S. R., & Ardestani, B. A. 2024, *ApJS*, **272**, 30
- Hartmann, M., Guenther, E. W., & Hatzes, A. P. 2010, *ApJ*, **717**, 348
- Hatzes, A. P., Cochran, W. D., Endl, M., et al. 2003, *ApJ*, **599**, 1383
- Henderson, C. B., Gaudi, B. S., Han, C., et al. 2014, *ApJ*, **794**, 52
- Herschel, W. 1802, *Philos. Trans. Roy. Soc. Lond.*, **92**, 213
- Hilbe, J. M., de Souza, R. S., & Ishida, E. E. O. 2017, *Bayesian Models for Astrophysical Data Using R, JAGS, Python, and Stan* (Cambridge University Press)

- Hirsch, L. A., Rosenthal, L., Fulton, B. J., et al. 2021, *AJ*, **161**, 134
- Hobson, M. J., Jordán, A., Bryant, E. M., et al. 2023, *ApJ*, **946**, L4
- Holman, M. J., & Wiegert, P. A. 1999, *AJ*, **117**, 621
- Hoffman, M. D., & Gelman, A. 2011, arXiv e-prints [arXiv:1111.4246]
- Houk, N. 1978, *Michigan Catalogue of Two-dimensional Spectral Types for the HD Stars* (Ann Arbor, MI, USA: Department of Astronomy, University of Michigan)
- Houk, N., & Cowley, A. P. 1975, *University of Michigan Catalogue of Two-dimensional Spectral Types for the HD Stars. Volume I. Declinations –90 deg to –53 deg.* (Ann Arbor, MI, USA: Department of Astronomy, University of Michigan)
- Houk, N., & Swift, C. 1999, *Michigan Spectral Survey*, **5**, 0
- Innanen, K. A., Zheng, J. Q., Mikkola, S., & Valtonen, M. J. 1997, *AJ*, **113**, 1915
- Innes, H. R. A. 1915, *Circ. Union Observatory Johannesburg*, **30**, 235
- Irwin, J., Buchhave, L., Berta, Z. K., et al. 2010, *ApJ*, **718**, 1353
- Janson, M., Hormuth, F., Bergfors, C., et al. 2012, *ApJ*, **754**, 44
- Janson, M., Gratton, R., Rodet, L., et al. 2021, *Nature*, **600**, 231
- Jao, W.-C., Mason, B. D., Hartkopf, W. I., Henry, T. J., & Ramos, S. N. 2009, *AJ*, **137**, 3800
- Jeffers, S. V., Schöfer, P., Lamert, A., et al. 2018, *A&A*, **614**, A76
- Jensen, E. L. N., Mathieu, R. D., & Fuller, G. A. 1996, *ApJ*, **458**, 312
- Jones, H. R. A., Butler, R. P., Tinney, C. G., et al. 2006, *MNRAS*, **369**, 249
- Kalas, P., Graham, J. R., & Clampin, M. 2005, *Nature*, **435**, 1067
- Kalas, P., Graham, J. R., Chiang, E., et al. 2008, *Science*, **322**, 1345
- Kaminski, A., Trifonov, T., Caballero, J. A., et al. 2018, *A&A*, **618**, A115
- Kane, S. R., Henry, G. W., Dragomir, D., et al. 2011, *ApJ*, **735**, L41
- Katz, D., Sartoretti, P., Guerrier, A., et al. 2023, *A&A*, **674**, A5
- Kervella, P., Arenou, F., & Thévenin, F. 2022, *A&A*, **657**, A7
- Kiefer, F. 2019, *A&A*, **632**, L9
- Kirkpatrick, J. D. 2005, *ARA&A*, **43**, 195
- Kirkpatrick, J. D., Cushing, M. C., Gelino, C. R., et al. 2011, *ApJS*, **197**, 19
- Konacki, M. 2005, *Nature*, **436**, 230
- Kossakowski, D., Kemmer, J., Bluhm, P., et al. 2021, *A&A*, **656**, A124
- Kouwenhoven, M. B. N., Brown, A. G. A., Portegies Zwart, S. F., & Kaper, L. 2007, *A&A*, **474**, 77
- Kraus, A. L., Shkolnik, E. L., Allers, K. N., & Liu, M. C. 2014, *AJ*, **147**, 146
- Kraus, A. L., Ireland, M. J., Huber, D., Mann, A. W., & Dupuy, T. J. 2016, *AJ*, **152**, 8
- Kristiansen, M. H. K., Rappaport, S. A., Vanderburg, A. M., et al. 2022, *PASP*, **134**, 074401
- Kruschke, J. 2015, *Doing Bayesian Data Analysis: A Tutorial with R, JAGS, and Stan* (Academic Press)
- Kunder, A., Kordopatis, G., Steinmetz, M., et al. 2017, *AJ*, **153**, 75
- Latham, D. W. 2012, *New Astron. Rev.*, **56**, 16
- Latham, D. W., Mazeh, T., Stefanik, R. P., Mayor, M., & Burki, G. 1989, *Nature*, **339**, 38
- Leconte, J., Soummer, R., Hinkley, S., et al. 2010, *ApJ*, **716**, 1551
- Leggett, S. K., Tremblin, P., Esplin, T. L., Luhman, K. L., & Morley, C. V. 2017, *ApJ*, **842**, 118
- Lépine, S., Hilton, E. J., Mann, A. W., et al. 2013, *AJ*, **145**, 102
- Lester, K. V., Matson, R. A., Howell, S. B., et al. 2021, *AJ*, **162**, 75
- Lewis, H. M., Anguiano, B., Majewski, S. R., et al. 2022, *MNRAS*, **509**, 3355
- Lindgren, L., Hernández, J., Bombrun, A., et al. 2018, *A&A*, **616**, A2
- Lindgren, L., Klioner, S. A., Hernández, J., et al. 2021, *A&A*, **649**, A2
- Lissauer, J. J. 1987, *Icarus*, **69**, 249
- Liu, F., Asplund, M., Yong, D., et al. 2019, *A&A*, **627**, A117
- Livingston, J. H., Endl, M., Dai, F., et al. 2018, *AJ*, **156**, 78
- Lodieu, N., Pérez-Garrido, A., Béjar, V. J. S., et al. 2014, *A&A*, **569**, A120
- Lowrance, P. J., Schneider, G., Kirkpatrick, J. D., et al. 2000, *ApJ*, **541**, 390
- Luhn, J. K., Bastien, F. A., Wright, J. T., et al. 2019, *AJ*, **157**, 149
- Luri, X., Brown, A. G. A., Sarro, L. M., et al. 2018, *A&A*, **616**, A9
- Macintosh, B., Max, C., Zuckerman, M., et al. 2001, in *ASP Conf. Ser.*, **244**, Young Stars Near Earth: Progress and Prospects, ed. R. Jayawardhana & T. Greene, 309
- Maíz Apellániz, J., Trigueros Páez, E., Negueruela, I., et al. 2019, *A&A*, **626**, A20
- Marocco, F., Smart, R. L., Mamajek, E. E., et al. 2020, *MNRAS*, **494**, 4891
- Martin, D. V. 2018, in *Handbook of Exoplanets*, eds. H. J. Deeg, & J. A. Belmonte, 156
- Mason, B. D., McAlister, H. A., Hartkopf, W. I., & Bagnuolo, W. G. J. 1993, *AJ*, **105**, 220
- Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, *AJ*, **122**, 3466
- Mason, B. D., Hartkopf, W. I., Gies, D. R., Henry, T. J., & Helsel, J. W. 2009, *AJ*, **137**, 3358
- Mason, B. D., Hartkopf, W. I., Raghavan, D., et al. 2011, *AJ*, **142**, 176
- Mayer, C. 1778, *Gründliche Vertheidigung neuer Beobachtungen von Sternwarte entdeckt worden sind Fixsterntabanten, welche zu Mannheim auf der kurfürstlichen* (Mannheim)
- A302, page 20 of 22
- Mayor, M., & Queloz, D. 1995, *Nature*, **378**, 355
- Mayor, M., Marmier, M., Lovis, C., et al. 2011, arXiv e-prints [arXiv:1109.2497]
- Mazeh, T., Krymowski, Y., & Rosenfeld, G. 1997, *ApJ*, **477**, L103
- McCarthy, C., & Zuckerman, B. 2004, *AJ*, **127**, 2871
- McFadden, D. 1973, in *Frontiers in Econometrics*, eds. P. Zarembka (New York, NY, USA: Academic Press New York), 105
- Mesa, D., Bonavita, M., Benatti, S., et al. 2022, *A&A*, **665**, A73
- Minniti, D., Butler, R. P., López-Morales, M., et al. 2009, *ApJ*, **693**, 1424
- Moutou, C., Hébrard, E. M., Morin, J., et al. 2017a, *MNRAS*, **472**, 4563
- Moutou, C., Vigan, A., Mesa, D., et al. 2017b, *A&A*, **602**, A87
- Mudryk, L. R., & Wu, Y. 2006, *ApJ*, **639**, 423
- Mugrauer, M. 2019, *MNRAS*, **490**, 5088
- Mugrauer, M., & Ginski, C. 2015, *MNRAS*, **450**, 3127
- Mugrauer, M., & Neuhäuser, R. 2009, *A&A*, **494**, 373
- Mugrauer, M., Neuhäuser, R., Mazeh, T., et al. 2006, *Astron. Nachr.*, **327**, 321
- Mugrauer, M., Neuhäuser, R., & Mazeh, T. 2007a, *A&A*, **469**, 755
- Mugrauer, M., Seifahrt, A., & Neuhäuser, R. 2007b, *MNRAS*, **378**, 1328
- Musielak, Z. E., Cuntz, M., Marshall, E. A., & Stuit, T. D. 2005, *A&A*, **434**, 355
- Muterspaugh, M. W., Lane, B. F., Kulkarni, S. R., et al. 2010, *AJ*, **140**, 1657
- Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. 1995, *Nature*, **378**, 463
- Naoz, S. 2016, *ARA&A*, **54**, 441
- Nascimbeni, V., Piotto, G., Börner, A., et al. 2022, *A&A*, **658**, A31
- Neal, R. 2011, in *Handbook of Markov Chain Monte Carlo*, 113
- Neuhäuser, R., Guenther, E. W., Alves, J., et al. 2003, *Astron. Nachr.*, **324**, 535
- Neuhäuser, R., Mugrauer, M., Fukagawa, M., Torres, G., & Schmidt, T. 2007, *A&A*, **462**, 777
- Newton, E. R., Mann, A. W., Tofflemire, B. M., et al. 2019, *ApJ*, **880**, L17
- Ochsenbein, F., Bauer, P., & Marcout, J. 2000, *A&AS*, **143**, 23
- Oppenheimer, B. R., Golimowski, D. A., Kulkarni, S. R., et al. 2001, *AJ*, **121**, 2189
- Parviainen, H., Tingley, B., Deeg, H. J., et al. 2019, *A&A*, **630**, A89
- Patience, J., White, R. J., Ghez, A. M., et al. 2002, *ApJ*, **581**, 654
- Pecat, M. J., & Mamajek, E. E. 2013, *ApJS*, **208**, 9
- Perryman, M. A. C., Lindegren, L., Kovalevsky, J., et al. 1997, *A&A*, **323**, 49
- Perryman, M. A. C., Brown, A. G. A., Lebreton, Y., et al. 1998, *A&A*, **331**, 81
- Philpot, F., Lagrange, A. M., Rubini, P., Kiefer, F., & Chomez, A. 2023, *A&A*, **670**, A65
- Pichardo, B., Sparke, L. S., & Aguilar, L. A. 2005, *MNRAS*, **359**, 521
- Pilat-Lohinger, E., Funk, B., & Dvorak, R. 2003, *A&A*, **400**, 1085
- Pinfild, D. J., Jones, H. R. A., Lucas, P. W., et al. 2006, *MNRAS*, **368**, 1281
- Qian, S. B., Liu, L., Zhu, L. Y., et al. 2012, *MNRAS*, **422**, L24
- Quanz, S. P., Ottiger, M., Fontanet, E., et al. 2022, *A&A*, **664**, A21
- Quintana, E. V., & Lissauer, J. J. 2006, *Icarus*, **185**, 1
- Quirrenbach, A., Amado, P. J., Caballero, J. A., et al. 2014, *SPIE Conf. Ser.*, **9147**, 91471F
- Radigan, J., Lafrenière, D., Jayawardhana, R., & Doyon, R. 2009, *ApJ*, **698**, 405
- Raghavan, D., Henry, T. J., Mason, B. D., et al. 2006, *ApJ*, **646**, 523
- Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, *ApJS*, **190**, 1
- Ramm, D. J. 2015, *MNRAS*, **449**, 4428
- Ramm, D. J., Pourbaix, D., Hearnshaw, J. B., & Komonjinda, S. 2009, *MNRAS*, **394**, 1695
- Ramm, D. J., Nelson, B. E., Endl, M., et al. 2016, *MNRAS*, **460**, 3706
- Ramm, D. J., Robertson, P., Reffert, S., et al. 2021, *MNRAS*, **502**, 2793
- Rauer, H., Aerts, C., Cabrera, J., et al. 2024, arXiv e-prints [arXiv:2406.05447]
- Rebolo, R., Zapatero Osorio, M. R., & Martín, E. L. 1995, *Nature*, **377**, 129
- Rebolo, R., Zapatero Osorio, M. R., Madrugá, S., et al. 1998, *Science*, **282**, 1309
- Reid, N. 1993, *MNRAS*, **265**, 785
- Reid, I. N., Gizis, J. E., Cohen, J. G., et al. 1997, *PASP*, **109**, 559
- Reiners, A., Ribas, I., Zechmeister, M., et al. 2018a, *A&A*, **609**, L5
- Reiners, A., Zechmeister, M., Caballero, J. A., et al. 2018b, *A&A*, **612**, A49
- Reylé, C. 2018, *A&A*, **619**, A8
- Reylé, C., Jardine, K., Fouqué, P., et al. 2021, *A&A*, **650**, A201
- Ribas, I., Reiners, A., Zechmeister, M., et al. 2023, *A&A*, **670**, A139
- Rica, F. M. 2012, *IAU Commission 26 (Double Stars)*, Information Circular 176, 6
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *JATIS*, **1**, 014003
- Riedel, A. R., Alam, M. K., Rice, E. L., Cruz, K. L., & Henry, T. J. 2017a, *ApJ*, **840**, 87
- Riedel, A. R., Blunt, S. C., Lambrides, E. L., et al. 2017b, *AJ*, **153**, 95
- Roberts, L. C. J., Turner, N. H., ten Brummelaar, T. A., Mason, B. D., & Hartkopf, W. I. 2011, *AJ*, **142**, 175
- Roberts, L. C. J., Mason, B. D., Neyman, C. R., et al. 2015, *AJ*, **149**, 144
- Rodigas, T. J., Males, J. R., Hinz, P. M., Mamajek, E. E., & Knox, R. P. 2011, *ApJ*, **732**, 10
- Roell, T., Neuhäuser, R., Seifahrt, A., & Mugrauer, M. 2012, *A&A*, **542**, A92
- Rosenthal, L. J., Fulton, B. J., Hirsch, L. A., et al. 2021, *ApJS*, **255**, 8
- Sabotta, S., Schlecker, M., Chaturvedi, P., et al. 2021, *A&A*, **653**, A114
- Sana, H., de Koter, A., de Mink, S. E., et al. 2013, *A&A*, **550**, A107

- Sato, B., Izumiura, H., Toyota, E., et al. 2007, *ApJ*, **661**, 527
- Savel, A. B., Dressing, C. D., Hirsch, L. A., et al. 2020, *AJ*, **160**, 287
- Schneider, J., Dedieu, C., Le Sidaner, P., Savalle, R., & Zolotukhin, I. 2011, *A&A*, **532**, A79
- Sebastian, D., Gillon, M., Ducrot, E., et al. 2021, *A&A*, **645**, A100
- Shaya, E. J., & Olling, R. P. 2011, *ApJS*, **192**, 2
- Shkolnik, E. L., Anglada-Escudé, G., Liu, M. C., et al. 2012, *ApJ*, **758**, 56
- Smart, R. L., Marocco, F., Caballero, J. A., et al. 2017, *MNRAS*, **469**, 401
- Smart, R. L., Marocco, F., Sarro, L. M., et al. 2019, *MNRAS*, **485**, 4423
- Smith, A. M. S., Cabrera, J., Csizmadia, S., et al. 2018, *MNRAS*, **474**, 5523
- Stassun, K. G., Oelkers, R. J., Paegert, M., et al. 2019, *AJ*, **158**, 138
- Steinmetz, M., Zwitter, T., Siebert, A., et al. 2006, *AJ*, **132**, 1645
- Stephan, A. P., Naoz, S., & Gaudi, B. S. 2021, *ApJ*, **922**, 4
- Stock, J., & Wroblewski, H. 1972, *A&A*, **18**, 341
- Tal-Or, L., Zechmeister, M., Reiners, A., et al. 2018, *A&A*, **614**, A122
- Tamuz, O., Ségransan, D., Udry, S., et al. 2008, *A&A*, **480**, L33
- Taylor, M. B. 2005, in *ASP Conf. Ser.*, 347, Astronomical Data Analysis Software and Systems XIV, eds. P. Shopbell, M. Britton, & R. Ebert, 29
- Taylor, M. B. 2021, *Tutorial #4: Exploring Gaia data with TOPCAT and STILTS*, Tech. Rep. Revision a36031a, University of Bristol
- Teske, J. K., Shectman, S. A., Vogt, S. S., et al. 2016, *AJ*, **152**, 167
- Thebault, P., & Haghighipour, N. 2015, in *Planetary Exploration and Science: Recent Results and Advances*, 309
- Thome, J. M. 1892, *Resultados Observatorio Nacional Argentino*, **16**, 1
- Tokovinin, A. 2008, *MNRAS*, **389**, 925
- Tokovinin, A., & Lépine, S. 2012, *AJ*, **144**, 102
- Tokovinin, A., Thomas, S., Sterzik, M., & Udry, S. 2006, *A&A*, **450**, 681
- Torres, C. A. O., Quast, G. R., da Silva, L., et al. 2006, *A&A*, **460**, 695
- Trifonov, T., Kürster, M., Zechmeister, M., et al. 2018, *A&A*, **609**, A117
- Trifonov, T., Tal-Or, L., Zechmeister, M., et al. 2020, *A&A*, **636**, A74
- Tuchow, N. W., Stark, C. C., & Mamajek, E. 2024, *AJ*, **167**, 139
- Turnbull, M. C. 2015, arXiv e-prints [arXiv:1510.01731]
- Turner, N. H., ten Brummelaar, T. A., McAlister, H. A., et al. 2001, *AJ*, **121**, 3254
- Udalski, A., Szymanski, M., Kaluzny, J., Kubiak, M., & Mateo, M. 1992, *Acta Astron.*, **42**, 253
- Udry, S., Eggenberger, A., Mayor, M., Mazeh, T., & Zucker, S. 2004, in *Rev. Mex. Astron. Astrofis. Conf. Ser.*, 21, eds. C. Allen, & C. Scarfe, 207
- Udry, S., Dumusque, X., Lovis, C., et al. 2019, *A&A*, **622**, A37
- Ujjwal, K., Kartha, S. S., Mathew, B., Manoj, P., & Narang, M. 2020, *AJ*, **159**, 166
- Uyama, T., Hashimoto, J., Kuzuhara, M., et al. 2017, *AJ*, **153**, 106
- Vanderburg, A., Rappaport, S. A., Xu, S., et al. 2020, *Nature*, **585**, 363
- Vehtari, A., Gelman, A., & Gabry, J. 2017, *Stat. Comput.*, **27**, 1413
- Wang, J., Xie, J.-W., Barclay, T., & Fischer, D. A. 2014, *ApJ*, **783**, 4
- Ward-Duong, K., Patience, J., De Rosa, R. J., et al. 2015, *MNRAS*, **449**, 2618
- Watanabe, S. 2013, *JMLR*, **14**, 867
- Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, *A&AS*, **143**, 9
- Winn, J. N., & Fabrycky, D. C. 2015, *ARA&A*, **53**, 409
- Winters, J. G., Henry, T. J., Jao, W.-C., et al. 2019, *AJ*, **157**, 216
- Wöllert, M., Brandner, W., Bergfors, C., & Henning, T. 2015, *A&A*, **575**, A23
- Wolszczan, A., & Frail, D. A. 1992, *Nature*, **355**, 145
- Wu, Y., & Murray, N. 2003, *ApJ*, **589**, 605
- Xiao, G.-Y., Liu, Y.-J., Teng, H.-Y., et al. 2023, *Res. Astron. Astrophys.*, **23**, 055022
- Yasuda, N., Mizumoto, Y., Ohishi, M., et al. 2004, in *ASP Conf. Ser.*, 314, Astronomical Data Analysis Software and Systems (ADASS) XIII, eds. F. Ochsenbein, M. G. Allen, & D. Egret, 293
- Zacharias, N., Finch, C. T., Girard, T. M., et al. 2013, *AJ*, **145**, 44
- Ziegler, C., Tokovinin, A., Latiolais, M., et al. 2021, *AJ*, **162**, 192
- Zink, J. K., Hardegree-Ullman, K. K., Christiansen, J. L., et al. 2021, *AJ*, **162**, 259

Appendix A: Remarkable systems

HD 1466, two M dwarfs, and an early L ultracool dwarf. Before our analysis, this system was made of the young late F-type star HD 1466, which hosts an astrometrically inferred Jovian exoplanet (Mesa et al. 2022), in the Tucana-Horologium association and a wide M5.5 V companion at about 30 arcmin (Gaia Collaboration 2021b). We added to the system, which became quadruple, an early M dwarf and an L1 ultracool dwarf already reported as members of the Tucana-Horologium association (Kraus et al. 2014; Gagné et al. 2015) at about twice the projected angular separation of the wide M5.5 V companion. The ultracool dwarf is the latest, least massive system component reported in this work.

HD 88072 AB and LP 609–39. The bright, close ($\rho \sim 3.7$ arcsec) pair HD 88072 AB was reported by Gaia Collaboration (2021b), while the planet ($\rho_{\text{planet}} \sim 0.39$ arcsec calculated from the semi-major axis a and distance d) was reported by Feng et al. (2022). To this compact, relatively new system we added another new component, namely LP 609–39, which is a poorly investigated $\sim$ M5.5 V companion at an extremely wide separation of about 80 arcmin.

HD 134606 and L 72–1 [AB] (WDS 15154–7032). It was made of the three-exoplanet host star HD 134606 (Mayor et al. 2011) and an $\sim$ M3.5 V companion at about 1 arcmin, namely L 72–1. Interestingly, the wide pair was discovered by an amateur astronomer (Rica 2012). As discussed in Sect. 3.4, L 72–1 [AB] displays a bimodal distribution of the Gaia DR3 G -band light curve, which is indicative of a close binarity of the order of 0.2 arcsec. Furthermore, in his personal notes, F. M. Rica also annotated a possible close binarity of L 72–1 based on the difference between its V -band absolute and apparent magnitudes. Furthermore, the Gaia DR3 d value of L 72–1 [AB] by Finch et al. (2018) in Table B.4 is affected by close multiplicity.

CD–24 12030 and two M-dwarf companions. The K2.5 V-type primary star has received little attention since the tabulation by Thome (1892) in his Cordoba Durchmusterung (e.g. de Geus et al. 1990; Cruzalèbes et al. 2019; Trifonov et al. 2020). It hosts a transiting planet discovered by K2 (Zink et al. 2021; Christiansen et al. 2022). The two co-moving companions at about 3.7 arcmin, which are separated by 10.2 arcsec between them (and 46.6 deg of position angle), have not been previously discussed in the literature. The abnormal radial velocity of the faintest component is probably due to the orbital effect of the close binary.

HD 222259 AB and 2MASS J23321028–6926537 (WDS 23397–6912). The system was originally made of the bright, close binary system HD 222259 A and B, which are late G and early K dwarfs, respectively. The pair, separated by about 5 arcmin, was resolved for the first time by H. C. Russell at the end of the 19th century, and is best known in the literature as DS Tuc AB. The primary, DS Tuc A, hosts an inflated transiting planet (Newton et al. 2019; Benatti et al. 2019). We added a $\sim$ M5 V wide companion at about 43 arcmin, namely 2MASS J23321028–6926537, which is also a member of Tucana-Horologium (Gagné et al. 2015; Ujjwal et al. 2020). Actually, Newton et al. (2019) noticed the co-moving, co-distant candidate companion, but given its very wide separation they

classified it as “likely [...] unbound member of Tuc-Hor and not a bound companion of DS Tuc”. Its binding energy is $|U_g| \sim 4.6 \cdot 10^{33}$ J, comparable to other wide binaries reported in the literature.

LP 141–14 and two M-dwarf companions. LP 141–14 is a white dwarf (spectral type DC D, Dupuis et al. 1994) located in a triple system, along with stars G 229–20A and G 229–20B, which are two M dwarfs with very similar individual masses and a combined mass of about $0.65 M_{\odot}$ (Stephan et al. 2021). The separation of LP 141–14 with the two close M dwarfs is 43.7 arcsec (1082 au), while the separation between the planet (LP 141–14 b, Vanderburg et al. 2020) and the white dwarf it is orbiting around is 0.0204 au. Together with the circumbinary planet RR Cae b, LP 141–14 b is the only planet orbiting a white dwarf in our sample.