An Early Catalog of Planet-hosting Multiple-star Systems of Order Three and Higher

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Abstract

We present a catalog (status 2022 July 1) of triple and higher-order systems identified containing exoplanets based on data from the literature, including various analyses. We explore statistical properties of the systems with a focus on both the stars and the planets. So far, about 30 triple systems and one to three quadruple systems, including (mildly) controversial cases, have been found. The total number of planets is close to 40. All planet-hosting triple-star systems are highly hierarchic, consisting of a quasi-binary complemented by a distant stellar component, which is in orbit about the common center of mass. Furthermore, the quadruple systems are in fact pairs of close binaries (“double–double”), with one binary harboring a planet. For the different types of star–planet systems, we introduce a template for the classifications of planetary orbital configurations in correspondence to the hierarchy of the system and the planetary host. The data show that almost all stars are main-sequence stars, as expected. However, the stellar primaries tend to be more massive (i.e., corresponding to spectral types A, F, and G) than expected from single-star statistics, a finding also valid for stellar secondaries but less pronounced. Tertiary stellar components are almost exclusively low-mass stars of spectral type M. Almost all planets have been discovered based on either the Radial Velocity method or the Transit method. Both gas giants (the dominant type) and terrestrial planets (including super-Earths) have been identified. We anticipate the expansion of this database in the light of future planetary search missions.

Unified Astronomy Thesaurus concepts: Catalogs (205); Exoplanets (498); Exoplanet systems (484); Stellar types (1634); Interstellar dynamics (839); Stellar physics (1621); Exoplanet catalogs (488); Stellar astronomy (1583); Exoplanet astronomy (486)

1. Introduction

Comprehensive studies of star–planet systems have become a main segment of contemporaneous astronomy, astrophysics, and astrobio. Since the first detection of a planet beyond the solar system in orbit about a solar-type star (Mayor & Queloz 1995), the number of confirmed exoplanets1 is currently exceeding 5000. Note that most planets are hosted by single stars, although there are a notable number of planets (which is about 100, in part depending on the cutoff regarding the stellar separation distance) that are members of stellar binary systems (e.g., Duquennoy & Mayor 1991; Patience et al. 2002; Eggenberger et al. 2004; Lada 2006; Raghavan et al. 2006, 2010; Roell et al. 2012; Wang et al. 2015a, 2015b; Pilat-Lohinger et al. 2019). However, the number of planets found to be hosted by higher-order systems is relatively small, i.e., about 40 for triple and quadruple systems combined, with the exact number depending on whether some controversial or unconfirmed cases are included. These kinds of systems are the focus of the present study.

Note that a considerable fraction of stellar systems is composed of multiple stars, which have previously been the topic of intense research, encompassing stellar structure analyses, orbital stability studies, and research devoted to evolution (see below). Following Tokovinin (2014a, 2014b), single stars account for approximately half, binaries a third, and triples less than a tenth. Comparable statistics, including studies on the origin of triple and quadruple stellar systems, have been given by Tokovinin (2008) and Eggleton & Tokovinin (2008). Previous studies about the stability of planets in triple and higher-order stellar systems have been given by Ford et al. (2000), Mardling & Aarseth (2001), Verrier & Evans (2007), Hamers et al. (2015), Correia et al. (2016), Bussetti et al. (2018), and Mylläri et al. (2018).

Regarding planets in binary systems, two different kinds of cases have been identified (Dvorak 1982). First, planets may orbit one of the binary components; those are categorized as planets in an S-type orbit (see Figure 1). In those systems the other stellar component is at a notable distance; however, it may act as a perturbator. Second, planets may orbit both binary components; those are said to be in P-type orbits. This type of nomenclature has also been adopted by, e.g., Bussetti et al. (2018) for triple stellar systems; it will be applied and augmented in this study. Previously, hierarchical triple-star systems have also been studied by Verrier & Evans (2007) with a focus on single planets in orbit about inner binaries. For studies of possible habitability for planets in S-type and P-type orbits see, e.g., Cuntz (2014) and references therein.

Tokovinin (2008) conveyed comparative statistics and comments on the origin of triple and quadruple stellar systems. For triple and quadruple systems, they found notably different statistics for the orbital periods and mass ratios. Regarding the quadruple systems, they identified a relatively high abundance of ε-Lyrae-type systems (double binaries, also called “double–double”) with similar masses and inner periods. However, the outer and inner mass ratios in triple and quadruple stars were not mutually correlated. They also argue that the origin of

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1 For updated information see, e.g., http://exoplanet.eu and http://exoplanets.org.
Figure 1. Possible orbits of a planet in a hierarchical triple-star system. Note that \( m_1, m_2, \) and \( m_3 \) do not necessarily agree.

triple- and quadruple-star systems could perhaps be explained via rotationally driven (cascade) fragmentation possibly followed by migration of inner and/or outer orbits to shorter periods.

Besides observational verifications indicating that planets are able to exist in binaries and multiple stellar systems, additional support about the abundance and significance of those planets stems from the discovery of protoplanetary disks in those systems. Besides the plethora of results on binaries (see, e.g., Rodríguez et al. 1998; Jenson & Akeson 2014; Czekala et al. 2019, and references therein)—encompassing different aspects such as planet formation, disk alignment, and evolution—a rare example of a disk in a triple-star system was recently identified as well. Bi et al. (2020) found that GW Ori, a hierarchical triple system, possesses a rare circumtriple disk. The authors noted three dust rings in the GW Ori disk at \( \sim 46, 188, \) and 338 au, with an estimated dust mass of 74, 168, and 245 \( M_\oplus \), respectively. The data also indicate complex disk dynamics initiated by the various stellar components. Subsequent work by Smallwood et al. (2021) conveyed evidence of disk breaking that, according to the authors, is likely caused by undetected planets, which, if confirmed, would constitute the first planet(s) identified in a circumtriple orbit.

The present-day record regarding stellar multiplicities are the currently known two septicule systems AR Cassiopeiae and \( \nu \) Scorpii (see Tokovinin 1997; Eggleton & Tokovinin 2008, and references therein). Both systems are highly hierarchical, with both containing different types of stars (although the properties of many components still await classification), including main-sequence stars. Higher multiplicities may in fact be possible; in fact, there may be a smooth transition to (though perhaps loosely) gravitationally bound “open clusters.”

Due to the complex patterns of gravitation interaction in those systems, possible exoplanets hosted in high-order systems may be restricted to (probably tight) S-type configurations and to P-type configuration with respect to quasi-binaries. However, no detections have been made.

More recently, work pertaining to planet-hosting star systems has been done by, e.g., Mugrauer (2019) and Lester et al. (2021). Mugrauer (2019) presented a new survey that explores the second data release of the ESA Gaia mission, in order to search for stellar companions of exoplanet host stars, located at distances closer than about 500 pc around the Sun. In total, 176 binaries, 27 hierarchical triples, and 1 hierarchical quadruple system have been detected among more than 1300 exoplanet host stars. As part of their study, they examined dynamical aspects of the systems, as well as the associated mass distribution. Lester et al. (2021) reported speckle observations of TESS exoplanet host stars, with a focus on stellar companions at 1–1000 au, including implications for small-planet detection.

The purpose of this work is to provide a repository of data for triple- and quadruple-star–planet systems as known to date, together with elements of analysis and interpretation. In Section 2, we report on the data acquisition for the various star–planet systems. We also offer a template of system classification, which particularly considers the various types of planetary orbits. Additionally, we discuss cases of controversies and planet rejections as reported in the literature. In Section 3, we provide selected statistical analyses and interpretation, encompassing both the planets and the host stars. As a case study, detailed information about the Alpha and Proxima Centauri system, including aspects of orbital stability and habitability, is presented in Section 4. Additional analyses are given in Section 5, whereas Section 6 conveys our summary and conclusions. See the Appendix, Table A1, for the list of acronyms.

2. Data Acquisition

2.1. Approach and Attributes

The aim of this study is to present a catalog of planet-hosting multiple-star systems identified to contain exoplanets (see Table 1). The underlying data have been obtained from the literature. They include data on the planets and the stellar components, especially the planetary host stars, as well as information on the stellar distances and the composition of the stellar systems. For star–planet systems that are outside of the scientific community’s main focus, thus lacking notable updates, the original data provided at the time of discovery have been used. In other cases, such as the Alpha Centauri system, updates became available when additional system planets have been discovered, often leading to the refinement of the data of previously discovered planets.

Figures 2 and 3 depict the distribution of currently known planets in triple and quadruple stellar systems in the two celestial hemispheres. Certain (the overwhelming majority) and uncertain detections are identified as such. The images were produced using the StarChart software. Each image is a chart of all of the stars, above a threshold magnitude, and constellations from its database. Each image also plots the path of the celestial equator, ecliptic plane, and galactic plane. Planetary detections, including the small number of unconfirmed cases, at present occur in 22 out of the 88 constellations. Unsurprisingly, a high accumulation of systems takes place at the Summer Triangle, a consequence of the multiyear contributions by the Kepler mission. Information about the system coordinates is given in Table 2.

\[ \text{Source of data: https://github.com/dfc21/star-charter.} \]

\[ \text{Source of data: https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/convcoord/convcoord.pl.} \]
Table 1
Triple and Quadruple Systems, Overview

| System Name     | Type | Planets | Constellation | Distance (pc) | Discovery |
|-----------------|------|---------|---------------|---------------|-----------|
| 16 Cygni        | 3    | 1       | Cygnus        | 21.1          | COC–97    |
| 2M J0441+2301   | 3    | 0 (1)   | Taurus        | 120           | TOD–10    |
| 30 Arietis      | 4    | 0 (1)   | Aries         | 44.7          | GUE–09    |
| 40 Eridani      | 3    | 0 (1)   | Eridanus      | 5.04          | MA–18     |
| 51 Eridani      | 3    | 1       | Eridanus      | 29.8          | MAC–15    |
| 91 Aquarii      | 3    | 1       | Aquarius      | 44.0          | MIT–03    |
| 94 Ceti         | 3    | 1       | Cetus         | 22.5          | MAY–04    |
| Alpha Centauri  | 3    | 3 (1)   | Centaurus     | 1.302         | ANG–16, DAM–20, FAR–22 |
| Epsilon Indi    | 3    | 1       | Indus         | 6.64          | FEN–19    |
| Giese 667       | 3    | 2 (1)   | Scorpius      | 7.24          | ANG–12    |
| HAT-P-8         | 3    | 1       | Pegasus       | 212           | LAT–09    |
| HAT-P-57        | 3    | 1       | Aquila        | 280           | HAR–15    |
| HD 126614       | 3    | 1       | Virgo         | 73.1          | HOW–10    |
| HD 132563       | 3    | 1       | Boötes       | 105           | DES–11    |
| HD 178911       | 3    | 1       | Lyra          | 41.0          | ZUC–02    |
| HD 185269       | 3    | 1       | Cygnus        | 52.0          | MOU–06    |
| HD 188753       | 3    | 0 (1)   | Cygnus        | 48.1          | KON–05    |
| HD 196050       | 3    | 1       | Pavo          | 50.7          | JON–02    |
| HD 2638 / HD 2567 | 3  | 1       | Cetus         | 55.0          | MOU–05    |
| HD 40979        | 3    | 1       | Auriga        | 34.1          | FIS–03    |
| HD 41004        | 3    | 1       | Pictor        | 41.6          | ZUC–04    |
| HD 41113        | 3    | 1       | Sculptor      | 41.9          | TAM–08    |
| HD 65216        | 3    | 2       | Carina        | 35.1          | MAY–04, WIT–19 |
| HW Virginis     | 3    | 0 (1)   | Virgo         | 172           | LEE–09    |
| K2-290          | 3    | 2       | Libra         | 273           | HJO–19    |
| Kelt-4          | 3    | 1       | Leo           | 218           | EAS–16    |
| Kepler-13       | 3    | 1       | Lyra          | 519           | SHP–11    |
| Kepler-64       | 4    | 1       | Cygnus        | 1033          | SCH–13    |
| Kepler-444      | 3    | 5       | Lyra          | 36.4          | CAM–15    |
| KIC 7177553     | 4    | 0 (1)   | Lyra          | 406           | LEH–16    |
| KOI-5 = TOI-1241| 3    | 1       | Cygnus        | 547           | CIA–21    |
| LTT 1445        | 3    | 2       | Eridanus      | 6.87          | WIN–19, WIN–22 |
| Ps1 Draconis    | 3    | 1       | Draco         | 22.7          | END–16    |
| WASP-8          | 3    | 2       | Sculptor      | 90.0          | QUE–10, KNU–14 |
| WASP-12         | 3    | 1       | Auriga        | 427           | HEB–09    |

Note. See the main text for information on the distance measurements, including references. Values of higher precision are available for most systems, as well as uncertainty information. The number of unconfirmed planets is given in parentheses (see Table 5 for details).

Figure 4 conveys information on the year of discovery4 for planets hosted by triple- or quadruple-star systems. The first confirmed discovery has been 16 Cygni Bb (Cochran et al. 1997), a planet in a highly elliptical orbit hosted by a solar-type star being part of a triple-star system. In total, there are 27 confirmed triple stellar systems with planets and one confirmed planet-hosting quadruple stellar system, which is Kepler-64 (Schwamb et al. 2013), amounting to 39 confirmed planets in multiple stellar systems. In fact, there are seven multiplanetary systems; the total number of planets in those systems is 18. Both the confirmed and nonconfirmed planet-hosting quadruple stellar systems are so-called “double–doubles,” i.e., pairs of stellar binaries, with one of them hosting a planet. Regarding the triple-star systems, the current record indicates about one discovery per year over a time span of 25 yr, with a notable increase within the past 5 yr. Actually, two discoveries have already occurred in the first few months of 2022: Proxima Centauri d and LTT 1445Ac; see Faria et al. (2022) and Winters et al. (2022) for details.

Furthermore, we provide a list of the distances to each planet-hosting star system (see Table 1 and Figure 5). The distance data mostly originate from the NASA Exoplanet Archive. This archive relies on data from the TESS Input Catalog (TIC), Version 8. The TIC uses parallax measurements from Gaia to estimate the distance to the star systems; see Stassun et al. (2019). However, there are a few systems, i.e., HD 188753, KOI-5, and KIC 7177553, where no information could be located in the archive. Thus, for HD 188753 and KOI-5, the distance reference of Bailer-Jones et al. (2018) was used by utilizing their VizieR Catalogue. KIC 7177553 appears to be unavailable in both the NASA Exoplanet Archive and the VizieR Catalogue. In this case, we quote the distance value given by Lehmann et al. (2016).

The closest planet-hosting multiple-star system is Alpha and Proxima Centauri at a distance of 1.302 pc (Brown et al. 2018)—a finding that will continue to persist considering that this system is closest to Sun–Earth. However, various planet-

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4 The year of discovery is set as the year of publication concerning the respective planet.

5 Source of data: http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=I/347.

6 Gaia Data Release 2; see http://gea.esac.esa.int/archive/documentation/GDR2/index.html.
hosting triple-star systems (certain detections), such as WASP-12, Kepler-13, and KOI-5, were also discovered at relatively large distances; they are located at distances of 427, 519, and 547 pc, respectively (see Table 1). For KOI-5, the existence of the planet was suggested by Hirsch et al. (2017) and confirmed by Ciardi (2021). A statistical analysis indicates that the mean and median values for the distances of these kinds of systems are given as 45 and 120 pc, respectively. Note that the significant skewness of that distribution is due to a small number of large-distance outliers associated with successful detections by SuperWASP and Kepler.

Table 3 and Figure 6 give information on the method of discovery for the various exoplanets, as well as the primary astronomical facility. Regarding the latter, major contributions have been made by the La Silla, Keck, Lick, and McDonald Observatories, as well as the Kepler mission. Most recently, contributions were also made by K2 and TESS. Concerning planetary discoveries, the dominant method has been the Radial Velocity method, prevalent especially during the early phases of the planet discovery history and thus yielding 21 confirmed planets in triple systems. The second most important method has been the Transit method, also utilized by Kepler, with an output of 16 confirmed planets in triple systems. Minor contributions have been made through direct imaging and by astrometry and eclipse timing.

Both gas giants (the dominant type) and terrestrial planets (including super-Earths) have been identified (see Figure 7). The Radial Velocity method led to the discovery of many Jupiter-type planets, noting that with respect to triple-star systems, 24 Jupiter-type planets have been found. However, in the absence of alternate methods, only minimum values for the masses could be ascertained. Earth-mass and sub-Earth-mass planets have been detected in the systems of Alpha Centauri (see Section 4), Kepler-444, and LTT 1445; see
2.2. System Templates and Classifications

2.2.1. General Remarks

This work is aimed at presenting and evaluating planet-hosting triple and quadruple stellar systems. A careful review of the data and literature shows that most of those systems are genuine, which means that both the proposed planet(s) and the respective stellar components can be assumed as confirmed; see Tables 4 and 5. In those cases, there is no sincere controversy on the existence of the various system components (OK case). However, there are some systems where this is not the case, referred to as Cases 1, 2, and 3, respectively. In that regard, the following nomenclature is used.

Case 1 means that all stars have been confirmed and at least one exoplanet has been confirmed; however, there is at least one other unconfirmed system planet or stellar component. Case 2 means that there is an unconfirmed stellar component besides (at least) one confirmed exoplanet. Thus, the system may instead be a planet-hosting binary (if a suggested triple-star system) or a planet-hosting triple-star system (if a suggested quadruple-star system). Finally, Case 3 means that all stellar components are confirmed; however, the proposed exoplanet is still unconfirmed. This kind of nomenclature is consistently used throughout this work, including the various statistical analyses.

It is also found that all triple-star systems as considered are hierarchical in nature. In those systems, like any other kinds of systems, each star orbits the system’s center of mass. However, in a hierarchical triple-star system (see Figure 1), two of the stars form a close binary, and the third orbits this pair at a distance.

Figure 3. Same as Figure 2, but for R.A. between 12 and 24 hr. Some of the system names for objects at or near the Summer Triangle have been omitted owing to overcrowding.

Faria et al. (2022), Campante et al. (2015), and Winters et al. (2019) for details and results.
distance much larger than the distance of binary separation; see, e.g., Eggleton & Kiseleva (1995) and subsequent work for the examinations of triple system stability and related topics. Table 6 provides information on the configuration of the triple stellar systems as discussed in this study, as well as on the stellar spectral types. References of the latter are typically included in the publication of the planetary discovery (see Table 1) or available through SIMBAD.\footnote{See \url{http://simbad.u-strasbg.fr/simbad/}.} We also give information on small and large separation distances of the stellar components, given as $a_{\text{bin}}^{(1)}$ and $a_{\text{bin}}^{(2)}$ as obtained from the literature (see Section 2.2.3).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Year of discovery for the planet-hosting triple- and quadruple-star systems, as gauged by the year of publication pertaining to the planet(s); see main text for references. C-TSy and UC-TSy denote certain and uncertain planet-hosting triple-star systems, respectively, whereas C-QSy and UC-QSy denote certain and uncertain planet-hosting quadruple-star systems, respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Distance for the various planet-hosting star systems; see main text for references. See Figure 4 for the definitions of the acronyms.}
\end{figure}
2.2. Comments on Planetary Orbits

When attempting to identify and analyze systems containing an abundant number of stellar and/or planetary components, especially those identified by different groups or individuals, their identity can be difficult to distinguish. For instance, an AC-B system—assumed as hierarchical—is named that way because the C component has been found to orbit component A (the primary), but this discovery took place after the confirmed existence of the distant component B. Thus, the C component would constitute the second stellar component in that system irrespectively of the star’s discovery history. Regarding our study, we have adopted this terminology focusing on the order of the stellar components rather than the name given to them. Consequently, for the case of planetary orbits in an AC-B system, if a planet orbited A, it would be S1; if it orbited C, it would be S2; and if it orbited B, it would be S3. Equivalent terminology applies to any variation of the traditional AB-C or A-BC system. Here, a planet in orbit about the B and C component would be referred to as S2 and S3, respectively.

A planet in a quasi-circumbinary orbit about components A and C in an AC-B system is referred to as P12. However, due to the lack of orbital stability, P13 and P23 planets in an AC-B system, in orbit about AB and CB, respectively, would be impossible in this kind of hierarchical triple system. In the case of nonhierarchical triple systems, P13 and P23 planets may be possible, although detailed stability analyses would be required to verify their existence. Planets orbiting all three stellar components at once, expected to require wide orbits, may occur in nonhierarchical and mildly hierarchical triple stellar systems; they would be referred to as T123 planets (“circumtrinary” planets). However, those cases still await observational verification.

Information regarding the triple-star systems considered in this study is given in Table 7. It is found that for both confirmed and unconfirmed systems the overwhelming case is that of S1 with 28 and 4 identifications, respectively; see Table 7. For confirmed cases, the second most common case is S3, followed by S2, with seven and three identifications, respectively. For confirmed systems, no P12 case is found; however, there is one unconfirmed P12 case, which is HW Virginis.

The terminology used in this work bears some similarities to that previously adopted by Busetti et al. (2018), although some notable differences exist. They use very similar definitions for their planet orbits; however, their paper focuses on studying one kind of configuration for triple systems, which is hierarchical in a particular manner. Thus, the inner binary is orbited by a third component outside of the quasi-binary. Here we adopt a different kind of P-type orbital definition, as we account for both inner and outer binary pairs as seen in a possible AB-C or A-BC system. Moreover, Busetti et al. (2018) do not distinguish whether they are tracking all planets located within a system or simply noting the orbital type of a confirmed planet in the system. In contrast, our study focuses on a more comprehensive picture of possible triple stellar system configurations instead of a single setup.

2.2.3. Validation of the Stellar Components

A crucial aspect of this study is to corroborate the existence of the previously identified stellar system components. Hence,
Table 2

| System                  | R.A.     | Decl.    |
|-------------------------|----------|----------|
| 16 Cygni                | 295.454540 | +50.525440 |
| 2M0441+2301             | 70.430766  | +39.030947 |
| 30 Arietis              | 39.252181  | −24.647219 |
| 40 Eridani              | 63.817999  | −7.652872  |
| 51 Eridani              | 69.400551  | −2.473550  |
| 91 Aquarui              | 348.972897 | −9.087734  |
| 94 Ceti                 | 48.193487  | −1.906972  |
| Alpha Centauri          | 219.873833 | −60.832222 |
| Epsilon Indi            | 330.840226 | −56.785983 |
| Gliese 667              | 259.738187 | −34.989762 |
| HAT-P-8                 | 343.041098 | +35.447113 |
| HAT-P-5                 | 274.743438 | +10.597258 |
| HD 126614               | 216.701165 | −5.177781  |
| HD 132563               | 224.589654 | +44.031416 |
| HD 178911               | 287.268133 | +34.600345 |
| HD 185269               | 294.298921 | +28.499862 |
| HD 188753               | 298.743216 | +41.871536 |
| HD 196050               | 309.465458 | −60.634885 |
| HD 2638 / HD 2567       | 7.317127   | −5.910490  |
| HD 40979                | 91.124762  | +44.260444 |
| HD 41004                | 89.956864  | −48.239668 |
| HD 4113                 | 10.802482  | −37.982633 |
| HD 65216                | 118.422164 | −63.647320 |
| HW Virginis             | 191.084328 | −8.671347  |
| K2-290                  | 234.857760 | −20.198825 |
| Kelt-4                  | 157.062546 | +25.573187 |
| Kepler-13               | 286.971271 | +46.683353 |
| Kepler-64               | 298.215071 | +39.955103 |
| Kepler-444              | 289.752288 | +41.634602 |
| KIC 7177553             | 283.012120 | +42.712159 |
| KOI-5:TOI-1241          | 289.739713 | +44.674394 |
| LTT 1445                | 45.462500  | −16.593364 |
| Pal Draconis            | 265.484625 | +72.149500 |
| WASP-8                  | 359.900297  | −35.031368  |
| WASP-12                 | 97.636653   | +29.672296  |

Note. Values are for J2000. The R.A. is given in units of degrees rather than hours.

Table 2 shows the System Coordinates for various systems, including HD 188753, Gliese 667, and Alpha Centauri. The table lists the right ascension (R.A.) and declination (Decl.) for each system.

For some of the triple and quadruple systems, as listed in Table 5, ongoing controversies exist about the reality and properties of the respective planets. Some of those systems require further studies on their composition and the properties of the various components. In general, the identified systems may host additional planets, noting that for some of those systems, such as the Alpha Centauri system, evidence of still-unconfirmed planets has already surfaced (e.g., Wagner et al. 2021). In the case of 2M0441+2301, it is still unclear whether one of the system components is a low-mass brown dwarf or a giant planet (Todorov et al. 2010; Bowler & Hillenbrand 2015). Other objects of interest include HD 188753 and Gliese 667. Regarding the systems Fomalhaut and HD 131399, solid evidence has been provided that the previously proposed planets do not exist. Therefore, in the context of this study, these systems are considered as retracted and are thus not listed as controversial.

Following Konacki (2005), the system of HD 188753 contains a solar-type star (with a temperature and mass akin to the Sun) that is host to a hot Jupiter and a close binary, hence the classification as a planet-hosting triple stellar system. However, follow-up observations by Eggenberger et al. (2007) based on Doppler measurements did not confirm the planet’s existence; therefore, we listed this system as controversial. Gliese 667 (or GJ 667) is another case of a long-standing controversy. GJ 667 is a planet-hosting triple-star system, but note that GJ 667C, the least massive of the three components, is
### Table 3
Method of Planet Discovery and Facility

| System Name | Type | Planets | Method | Facility |
|-------------|------|---------|--------|----------|
| 16 Cygni    | 3    | 1       | RV     | McDonald Obs., Lick Obs. |
| 2M J0441+2301 | 3     | 0 (1)   | Astrometry | HST, Gemini Obs. |
| 30 Arietis  | 4    | 0 (1)   | RV     | Karl Schwarzschild Obs. |
| 40 Eridani  | 3    | 0 (1)   | RV     | Keck Obs., Dharma Planet Imager |
| 51 Eridani  | 3    | 1       | Imaging | Gemini Obs. |
| 91 Aquarrii | 3    | 1       | RV     | Lick Obs. |
| 94 Ceti     | 3    | 1       | RV     | La Silla Obs. |
| Alpha Centauriaa | 3     | 3 (1)   | ...    | ... |
| Epsilon Indi | 3    | 1       | RV, Astrometry | La Silla Obs., Gaia |
| Gliese 667  | 3    | 2 (1)   | RV     | La Silla Obs. |
| HAT-P-8     | 3    | 1       | Transit | Keck Obs. |
| HAT-P-57    | 3    | 1       | Transit | Keck Obs. |
| HD 126614   | 3    | 1       | RV     | Keck Obs. |
| HD 132563   | 3    | 1       | RV     | Galileo Nat’l Telescope |
| HD 178931   | 3    | 1       | RV     | Keck Obs., Obs. de Haute-Provence |
| HD 185269   | 3    | 1       | RV     | Obs. de Haute-Provence |
| HD 188753   | 3    | 0 (1)   | RV     | Keck Obs. |
| HD 196050   | 3    | 1       | RV     | La Silla Obs. |
| HD 2638 / HD 2567 | 3 | 1 | RV | La Silla Obs. |
| HD 40979    | 3    | 1       | RV     | La Silla Obs., Keck Obs. |
| HD 41004    | 3    | 1       | RV     | La Silla Obs. |
| HD 4113     | 3    | 1       | RV     | La Silla Obs. |
| HD 65216    | 3    | 2       | RV     | La Silla Obs. |
| HW Virginis | 3    | 0 (1)   | Eclipse Timing | SOAO, CNUO |
| K2-290      | 3    | 2       | Transit | K2 |
| Kelt-4      | 3    | 1       | Transit | SuperWASP |
| Kepler-13   | 3    | 1       | Transit | Kepler |
| Kepler-64   | 4    | 1       | Transit | Kepler |
| Kepler-444  | 3    | 5       | Transit | Kepler |
| KIC 7177553 | 4    | 0 (1)   | Eclipse Timing | Kepler, Karl Schwarzschild Obs. |
| KOI-5=TOI-1241 | 3 | 1 | Transit / Imaging | Kepler, TESS |
| LTT 1445    | 3    | 2       | Transit | TESSb |
| Psi1 Draconis | 3 | 1 | RV | McDonald Obs. |
| WASP-8      | 3    | 2       | Transit / RV | SuperWASP, Keck Obs. |
| WASP-12     | 3    | 1       | Transit | SuperWASP |

**Notes.** See Table 1 for further information, including references. Besides the facilities as indicated, other sites have typically been highly relevant as well, especially for the establishment and confirmation of the system’s multiplicity and the properties of the system’s components.

a The three confirmed planets have been identified through the RV method, except Proxima Centauri b, where astrometry contributed as well. Relevant facilities included La Silla, VLT, and HST.

b For LTT 1445Ac, additional data from five spectrographs have been used to established the planet’s existence.

c SuperWASP consists of two robotic telescopes, located on the island of La Palma and at the site of the South African Astronomical Observatory.

### Table 4
Case Legend for the Star–Planet Systems

| Type          | Color  | Definition                                      |
|---------------|--------|------------------------------------------------|
| OK Case       | Green  | No noted controversy about the existence of the stellar components or the planet(s). |
| Case 1        | Blue   | The stellar components are confirmed and at least one exoplanet is confirmed; however, there may be another unconfirmed exoplanet or stellar component. |
| Case 2        | Red    | There is an unconfirmed stellar component, with one or more confirmed exoplanets. |
| Case 3        | Purple | The stellar components are confirmed; however, the exoplanet is unconfirmed. |

**Note.** The denoted color scheme has been used in Figures 2 and 3.
homestead to two confirmed super-Earth planets (Feroz & Hobson 2014; Robertson & Mahadevan 2014). Previously, it was argued that GJ 667 would host several additional planets, including three planets in its HZ (Anglada-Escudé et al. 2012, 2013; Delfosse et al. 2013). Subsequent estimates based on the Bayesian analysis of radial velocity data (Feroz & Hobson 2014) reduced that number to two (or, less likely, three). A key aspect in the determination of the correct number of planets hosted by M dwarfs such as GJ 667C is the adequate analysis of stellar activity, which is particularly challenging (e.g., Tuomi et al. 2019; Lafarga et al. 2021, and references therein).

Other cases of ongoing discussions and controversies include the systems of HD 4113, HW Virginis, KIC 7177553, and 40 Eridani. According to Cheetham et al. (2018), HD 4113 is a complex dynamical system consisting of a giant planet, a stellar host, and a known M-dwarf companion; see also Mugrauer et al. (2014) and Mugrauer (2019) for additional results. The system also contains an ultracool substellar companion of late T spectral type; its estimated mass, given as about 66 M_J, is evidently beyond the Jovian planet limit. Evidence of the planet Ab has been reported by Tamuz et al. (2008). However, open questions about the system’s composition remain, as the memberships of some components are not fully established. In fact, one of the system components is situated at an angular separation of 43″, corresponding to a projected separation of 2000 au.10

HW Virginis is a system that is considered potentially unstable; it appears to consist of two stars, a Jupiter-type planet and a brown dwarf, and thus is a triple-star system. Previous work on the stability of that system was pursued by Beuermann et al. (2012) and Horner et al. (2012). KIC 7177553 is a young system observed by the Kepler satellite (Lehmann et al. 2016). It consists of a pair of binary stars; hence, it is a quadruple system. The system also contains a supermassive Jupiter-type planet (but below the brown dwarf mass limit). However, considering the system’s complexity and dynamics, there is a need for additional transit data to ultimately confirm the planet’s existence.

For 40 Eridani, Ma et al. (2018) reported a super-Earth in a 42.4-day orbit, using data sets taken by multiple spectrographs, including HIRES. Considering the close proximity of this system to Earth, given as 5.04 pc (see Table 1), this would have made that planet-hosting triple-star system the second closest to Earth known to date, only topped by Proxima Centauri. However, Rosenthal et al. (2021) determined a significant periodicity at 42 days in the HIRES S-value measurements, thus concluding that 42 days is the likely rotation period of that star. Moreover, Rosenthal et al. (2021) identified evidence of a long-period magnetic activity cycle with nearly the same period. Hence, the previously acclaimed planet is most likely a false positive.

2.4. Refutations and Retractions

2.4.1. Fomalhaut b

Following Kalas et al. (2008) and references therein, Fomalhaut (α PsA) is a triple stellar system, with its main component, an A-type star, shrouded by an extended disk structure, indicating ongoing planet formation. According to this study, optical observations point to an exoplanet candidate, Fomalhaut b. Moreover, optical dynamical models of the interaction between the putative planet and the gas and dust belt indicate that Fomalhaut b’s mass is at most 3 times that of Jupiter. However, open questions about observational features at different wavelengths (millimeter regime), including variabilities,
Table 5

| System             | Type | Uncertainty | Orbit Type |
|--------------------|------|-------------|------------|
|                    |      |             | Confirmed  | Unconfirmed|
| 16 Cygni           | 3    | ...         | S2         | ...        |
| 2M J0441+2301       | 3    | Case 2      | S2         | ...        |
| 30 Arietis         | 4    | Case 3      | S1         | ...        |
| 40 Eridani          | 3    | Case 3      | S1         | ...        |
| 51 Eridani          | 3    | ...         | S1         | ...        |
| 91 Aquarii          | 3    | ...         | S1         | ...        |
| 94 Ceti             | 3    | ...         | S1         | ...        |
| Alpha Centauri      | 3    | Case 1      | S1, S2     | ...        |
| Epsilon Indi       | 3    | S1          | ...        |            |
| Gliese 667         | 3    | Case 1      | S3 (2 ×)   | S1, S2     |
| HAT-P-8             | 3    | ...         | S1         | ...        |
| HAT-P-57            | 3    | ...         | S1         | ...        |
| HD 126614           | 3    | ...         | S1         | ...        |
| HD 132563           | 3    | ...         | S3         | ...        |
| HD 178911           | 3    | ...         | S3         | ...        |
| HD 185269           | 3    | ...         | S1         | ...        |
| HD 188753           | 3    | Case 3      | S1         | ...        |
| HD 196050           | 3    | ...         | S1         | ...        |
| HD 2638 / HD 2567   | 3    | ...         | S2         | ...        |
| HD 40979            | 3    | ...         | S1         | ...        |
| HD 41004            | 3    | ...         | S1         | ...        |
| HD 4113            | 3    | Case 2      | S1         | ...        |
| HD 65216            | 3    | ...         | S1 (2 ×)   | ...        |
| HW Virginis        | 3    | Case 3      | P12        | ...        |
| K2-290             | 3    | ...         | S1 (2 ×)   | ...        |
| Kelt-4             | 3    | ...         | S1         | ...        |
| Kepler-13          | 3    | ...         | S1         | ...        |
| Kepler-64          | 4    | ...         | P12        | ...        |
| Kepler-444         | 3    | ...         | S1 (5 ×)   | ...        |
| KIC 717753         | 4    | Case 3      | P12        | ...        |
| KOI-5=TOI-1241     | 3    | ...         | S1         | ...        |
| LTT 1445           | 3    | ...         | S1 (2 ×)   | ...        |
| Ps1 Dracois        | 3    | ...         | S2         | ...        |
| WASP-8             | 3    | ...         | S1 (2 ×)   | ...        |
| WASP-12            | 3    | ...         | S1         | ...        |

Notes. See Table 4 for information on the definition of Cases 1–3.

1 Unclear whether one of the system components is a low-mass brown dwarf or a giant planet.
2 The suspected planet may in fact be a brown dwarf or red dwarf. In this case, the system would thus be a quintuple system without a planet instead of a planet-hosting quadruple system (see Section 3.2).
3 There is evidence that the previously reported planet is a false positive.
4 There are claims of additional planets regarding all three stellar components.
5 Two planets are confirmed; however, there are claims of at least one additional planet orbiting the same component.
6 Follow-up observations did not confirm the planet’s existence, which may, however, be due to the limited precession of that measurement.
7 Some members of the system are not fully established; hence, HD 4113 may be a planet-hosting binary system.
8 The system is potentially dynamically unstable. Apparently, it consists of two stars, a Jupiter-type planet, and a brown dwarf; thus, it is a triple-star system.
9 More transit data are needed to ultimately confirm the planet’s existence.

indicating that the existence of Fomalhaut b is not consistent with the system’s eccentric debris ring. Hence, an irregular satellite swarm around a super-Earth is proposed instead. Lawler et al. (2015) also predicted that the feature mimicking the existence of Fomalhaut b is expected to expand until it either dissolves or becomes too faint to be seen.

This view is in alignment with a recent study by Gáspár & Rieke (2020), based on HST observations, which arrived at a different conclusion than previously conveyed by Kalas et al. (2008). Gáspár & Rieke (2020) revisited published data, together with more recent HST data, concluding that the source is likely on a radial trajectory, evidently related to a collision between two large planetesimals, and has started to fade away. Apparently, we are witnessing the effects of gravitational stirring due to the orbital evolution of hypothetical planet(s), which may still exist in that system. However, the exoplanet Fomalhaut b does not exist.

2.4.2. HD 131399 Ab

HD 131399, located in the constellation of Centaurus, was previously classified as a planet-hosting multiple stellar system. However, this assessment has changed. As a consequence, HD 131399 is not considered any further in this study. Earlier, Wagner et al. (2016) reported the discovery of a Jovian exoplanet, named HD 131399 Ab, in that system based on direct imaging. They classified HD 131399 Ab as a Jovian planet of $4 \pm 1 M_J$ with a relatively wide orbit situated in a hierarchical triple-star system. Wagner et al. (2016) already pointed out that the planetary orbit is potentially unstable. Additional details about the system were given by Lagrange et al. (2017), who also noted that the planet’s existence challenges conventional planet formation theories. The object was originally recorded using the SPHERE imager at ESA’s Very Large Telescope.

However, a follow-up study by Nielsen et al. (2017) indicated that the candidate planet is, in actuality, a background star instead. The authors conveyed results from JHKIL’ photometry and spectroscopy obtained with the Gemini Planet Imager, VLTI/SPHERE, and Keck/NIRC2, as well as a reanalysis of the previous analysis data. This finding is also consistent with the object’s proper motion. Furthermore, as discussed by Nielsen et al. (2017), if HD 131399 Ab were a physically associated object, its projected velocity would exceed the escape velocity given the mass and distance to HD 131399 A. Hence, the putative exoplanet is most likely a background K or M dwarf instead. Wagner et al. now concur with most if not all of these findings, and on 2022 April 14 they retracted their article.

3. Statistical Analysis and Interpretation

3.1. Triple Systems

3.1.1. Stellar Components

Table 8 provides information on the planet host stars of confirmed triple stellar systems; see also Figure 8 for additional information. There is a notable range regarding spectral type, with the upper end given by Kepler-13A, an A-type star (Shporer et al. 2014). Based on their report, the main stellar parameters are given as $T_{\text{eff}} = 7650 \pm 250$ K, $M_*=1.72 \pm 0.10 M_\odot$, and $R_*=1.71 \pm 0.40 R_\odot$. In fact, the majority of planet host stars are G dwarf, noting that 16 Cygni B most closely

remained—although work by Currie et al. (2012) provided support for the interpretation of Kalas et al.

In a follow-up study, Lawler et al. (2015) pointed out that although the planet candidate Fomalhaut b is bright in optical light but undetected in longer wavelengths, a large, reflective dust cloud is implied. According to the authors, the new observations point to an extremely eccentric orbit ($e \approx 0.8$),
Table 6
Triple System Configurations

| System Name | Status | Star 1 | Star 2 | Star 3 | \(a_{\text{in}}^{(1)}\) (au) | \(a_{\text{in}}^{(2)}\) (au) | Configuration | Reference |
|-------------|--------|--------|--------|--------|-----------------|-----------------|--------------|-----------|
| 16 Cygni    | UC     | G1.5 V | M      | G2.5 V | 73              | 860             | AC-B, 2-1    | RAG-06    |
| 2M J0441+2301 | UC | M8.5 V | ...   | M3.5 V | ...            | ...            | A-BaBb, 1-2 | RAG-06    |
| 40 Eridani  | UC     | K0 V   | DA2.9  | M4.5 V | 35              | 400             | A-BaBb, 1-2 | FEI-06, MON-15 |
| 51 Eridani  |        | F0 V   | M      | M      | 9.8             | 2000            | A-BaBb, 1-2 | RAG-06, ZIR-07 |
| 91 Aquarii  |        | K1 III | K      | K      | 21.5            | 2248            | A-BaBb, 1-2 | ROE-12    |
| 94 Ceti     |        | F8 V   | M0 V   | M3 V   | 0.98            | 220             | A-BaBb, 1-2 | ROE-11, ROE-12 |
| Alpha Centauri |     | G2 V   | K1 V   | M5.5 Ve| 17.5            | 8200            | AB-C, 2-1   | AKE-21    |
| Epsilon Indi |   | K5 V   | T1–1.5 | T6     | 2.6             | 1459            | A-BaBb, 1-2 | SCH-03, DIE-18 |
| Gliese 667  |        | K3 V   | K5 V   | M1.5 V | 1.82            | 300             | AB-C, 2-1   | FER-14    |
| HAT-P-8     |        | F5 V   | M5 V   | M6 V   | 15              | ...            | A-BaBb, 1-2 | BEC-14    |
| HAT-P-57    |        | A8 V   | ...    | ...    | 68              | 800             | A-BaBb, 1-2 | HAR-15    |
| HD 126614   |        | K0 V   | M      | M5.5 V | 36              | 3040            | AB-C, 2-1   | DEA-14, LOD-14 |
| HD 132563   |        | F8 V   | M      | G0 V   | 40              | 400             | AaAb-B, 2-1 | DES-11    |
| HD 178911   |        | G1 V   | K1 V   | G5 V   | 4.9             | 789             | AaAb-B, 2-1 | RAG-06    |
| HD 185269   |        | G0 IV  | ...    | ...    | 5               | ...            | A-BaBb, 1-2 | GIN-16    |
| HD 188753   | UC     | G8 V   | K0 V   | ...    | 0.67            | 12.3            | A-BaBb, 1-2 | POR-05    |
| HD 196050   |        | G3 V   | M1.5–4.5 V | M2.5–4.5 V | 28            | 7511            | A-BaBb, 1-2 | MAS-01, MUG-05 |
| HD 2638 / HD 2567 | | G0 V   | G8 V   | M1 V   | ...            | 25.5            | A-BaBb, 1-2 | ROB-15    |
| HD 40979    |        | F8 V   | K3 V   | M3 V   | 129             | 6416            | A-BaBb, 1-2 | MUG-07    |
| HD 41004    |        | K1 V   | M2 V   | ...    | 0.017           | 21              | A-BBb, 1-2 | SAN-02    |
| HD 4113     | UC     | G5 V   | T9     | M0–1 V | 23              | 2000            | A-BaBb, 1-2 | CHE-18    |
| HD 65216    |        | G5 V   | M7–8 V | L2–3   | 6               | 253             | A-BaBb, 1-2 | MUG-07    |
| HW Virginis | UC     | sdB    | M6–7 V | ...    | 0.86            | ...            | AB-C, 2-1   | LEE-09    |
| Kelt-4      |        | F      | K      | K      | 10.3            | 328             | A-BaBb, 1-2 | EAS-16    |
| Kepler-13   |        | A0 V   | A      | G      | ...            | 610             | A-BaBb, 1-2 | SHP-14    |
| Kepler-444  |        | KO0 V  | M      | M      | 0.3             | 367             | A-BaBb, 1-2 | DUP-16    |
| KOI-5=TOI-1241 | UC | G      | ...    | ...    | ...            | ...            | AB-C, 2-1   | ...       |
| K2-290      |        | F8 V   | M      | M      | 113             | 2467            | AB-C, 2-1   | HJO-19    |
| LTT 1445    |        | M2.5 V | M3 V   | M      | 1.2             | 34              | A-BaBb, 1-2 | WIN-19    |
| PS' Draconis |      | M5 IV-V | ...    | F8 V   | ...            | 680             | AB-C, 2-1   | GUL-15    |
| WASP-8      |        | G6 V   | M      | ...    | 408             | ...            | AB-C, 2-1   | BOF-20    |
| WASP-12     |        | F      | M3 V   | M3 V   | 21              | ...            | A-BaBb, 1-2 | BEC-14    |

Note. UC indicates that the status of the system is unconfirmed (i.e., Case 2 or 3). Stars with the luminosity class omitted are almost certainly main-sequence stars. Configuration information employs the acronyms of the stellar components readily used in the literature. Background information and additional references, including those pertaining to spectral types, can be found in the articles reporting the respective planet discoveries (see Table 1), as well as in the main text, especially Sections 2.3 and 3.1. As all triple-star systems are hierarchic, \(a_{\text{in}}^{(1)}\) and \(a_{\text{in}}^{(2)}\) denote the small and large separation distances of the stellar components (which are both often \textit{relatively uncertain} and may also be affected by \textit{projection effects}), respectively; see Section 2.2.3 for additional comments. The references pertain to the system’s composition, including \(a_{\text{in}}^{(1)}\) and \(a_{\text{in}}^{(2)}\).

Table 7
Planetary Orbital Classification, Triple Systems

| Type | Confirmed | Unconfirmed |
|------|-----------|------------|
| S1   | 28        | 4          |
| S2   | 3         | 2          |
| S3   | 7         | 1          |
| P12  | 0         | 1          |
| P13  | 0         | 0          |
| P23  | 0         | 0          |
| T123 | 0         | 0          |

Note. S1, S2, S3: Stellar mass range: 0.12–1.72 \(M_\odot\) (Section 4). P12, P13, P23: Planet mass range: 1–10 \(M_{\text{Jup}}\) (Section 4). T123: Total mass range: 0.12–1.72 \(M_\odot\) (Section 4).}

resembles the Sun (e.g., Metcalfe et al. 2015). The least massive star is Proxima Centauri with a mass of 0.12 \(M_\odot\) (see Section 4 for details). In Table 8, for each host star information is given about the respective stellar effective temperature, mass, radius, and luminosity as obtained from the literature.

Various kinds of techniques have been employed for deriving the acquired information, which in regard to the mass also considered stellar evolution scenarios. Stellar surface temperatures have typically been deduced spectroscopically. Since the stellar effective temperature, radius, and stellar luminosity are not independent of one another, extra opportunities exist for deriving the missing parameter. In the case of the systems HAT-P-8, K2-290, Kepler-444, and KOI-5, the star’s luminosity value has been deduced from the stellar effective temperature and radius. For some main-sequence stars, the mass–luminosity relation proved useful as well; see, e.g., Cuntz & Wang (2018) for information on the \(M–L\) relationship for K dwarfs.

The masses of the planet host stars of confirmed triple stellar systems range from 0.12 \(M_\odot\) (Proxima Centauri) to 1.72 \(M_\odot\) (Kepler-13A). Regarding the Kepler-13AB system, valuable information has been obtained by Howell et al. (2019) based on the high-resolution imaging instrument, Álopeke, at the Gemini-N telescope indicating that Kepler-13b is a highly irradiated gas giant with a bloated atmosphere. The denoted mass range can be compared to previous work by, e.g., Mugrauer (2019), who studied the properties of planet host stars, which are typically not members of multiple stellar systems, while also using information provided by Gaia astrometry. They found that those stars
exhibit masses in the range between about 0.078 and 1.4 $M_\odot$ with a peak in their mass distribution between 0.15 and 0.3 $M_\odot$. However, the planet host stars in triple systems are identified to be more massive; see Section 5 for further comments.

Important sources for accurate information about stellar diameters and temperatures of the various stellar components have been given by Boyajian et al. (2012), Boyajian et al. (2013), and White et al. (2013). They conveyed interferometric
Table 9
Triple Systems, Confirmed—Planetary Data, Single Planets

| System Name | Planet Name | Planet Type | Mass (M$_J$) | Radius (R$_J$) | Semimajor Axis (au) | Orbital Period (days) | Eccentricity | Reference |
|-------------|-------------|-------------|-------------|---------------|---------------------|-----------------------|--------------|-----------|
| 16 Cygni    | 16 Cygni Bb | Jupiter-type | 2.38        | ...           | 1.693               | 799.5                 | 0.089        | PLA–13    |
| 51 Eridani  | 51 Eridani b| Jupiter-type | 2.6         | 1.11          | 11.1                | 28.1                  | 0.53         | ROS–20    |
| 91 Aquarii  | 91 Aquarii Ab| Jupiter-type | >3.20       | ...           | 0.70                | 181.4                 | 0.027        | MIT–13    |
| 94 Ceti     | 94 Ceti Ab  | Jupiter-type | 1.86        | ...           | 1.427               | 535.7                 | 0.30         | PLA–13    |
| Epsilon Indi| Epsilon Indi Ab| Jupiter-type | 3.25        | ...           | 11.55               | 16510                 | 0.26         | FEN–19    |
| HAT-P-8     | HAT-P-8 Ab  | Jupiter-type | 1.275       | 1.32          | 0.04387             | 30706                 | 0.0          | MAN–13    |
| HAT-P-57    | HAT-P-57 Ab | Jupiter-type | <1.85       | 1.41          | 0.004060            | 2.4653                | 0.0          | HAR–15    |
| HD 126614   | HD 126614 Ab| Jupiter-type | >0.38       | ...           | 2.35                | 1244                  | 0.41         | HOW–10    |
| HD 132563   | HD 132563 Ab| Jupiter-type | >1.49       | ...           | 2.62                | 1544                  | 0.22         | DES–11    |
| HD 178911   | HD 178911 Ab| Jupiter-type | >7.35       | ...           | 0.345               | 71.51                 | 0.139        | BUT–06    |
| HD 185269   | HD 185269 Ab| Jupiter-type | >1.01       | 1.26          | 0.077               | 68378                 | 0.229        | LUH–19    |
| HD 196050   | HD 196050 Ab| Jupiter-type | >2.90       | ...           | 2.54                | 1378                  | 0.228        | BUT–06    |
| HD 2638 / HD 2567 | HD 2638 Ab| Jupiter-type | >0.48       | ...           | 0.044               | 34442                 | 0.041        | MOU–05    |
| HD 40979   | HD 40979 Ab  | Jupiter-type | >3.83       | ...           | 0.855               | 263.8                 | 0.269        | BUT–06    |
| HD 41004   | HD 41004 Ab  | Jupiter-type | >2.56       | ...           | 1.70                | 963                   | 0.74         | ZUC–04    |
| Kelt-4     | Kelt-4 Ab   | Jupiter-type | 0.878       | 1.71          | 0.04321             | 2.9896                | 0.03         | EAS–16    |
| Kepler-13  | Kepler-13 Ab| Jupiter-type | ~6.5        | 1.41          | 0.03641             | 1.7636                | 0.0          | SHP–14    |
| KOI-5=TOI-1241 | KOI-5 Ab | Neptune-type | 0.179       | 0.63          | 0.05961             | ~5                    | 0.0 [set]    | HIR–17    |
| Ps¹ Draconis | Ps¹ Draconis Bb| Jupiter-type | >1.53       | ...           | 4.43                | 3117                  | 0.40         | END–16    |
| WASP-12    | WASP-12 Ab  | Jupiter-type | 1.47        | 1.90          | 0.02340             | 1.0914                | 0.0 [set]    | COL–17    |

Note. See references for details, including information about data uncertainties. In some cases, alternate references are available yielding similar results.

Table 10
Triple Systems, Confirmed—Planetary Data, Multiple Planets

| System Name | Planet Name | Planet Type | Mass (M$_J$) | Radius (R$_J$) | Semimajor Axis (au) | Orbital Period (days) | Eccentricity | Reference |
|-------------|-------------|-------------|-------------|---------------|---------------------|-----------------------|--------------|-----------|
| Alpha Centauri | Proxima Centauri b | Earth-type/super-Earth | 1.63 M$_J$ | 1.30 R$_J$ | 0.04856 | 11.18 | 0.109 | ANG–16 |
| Alpha Centauri | Proxima Centauri c | super-Earth/mini-Neptune | 7.0 M$_J$ | ... | 1.489 | 1928 | 0.04 | DAM–20 |
| Alpha Centauri | Proxima Centauri d | sub-Earth | >0.26 M$_J$ | 0.81 R$_J$ | 0.02885 | 5.122 | 0.04 | FAR–22 |
| Gliese 667 | Gliese 667Cb | super-Earth | >5.6 M$_J$ | ... | 0.05043 | 7.1999 | 0.15 | ... |
| Gliese 667 | Gliese 667Cc | super-Earth | >4.1 M$_J$ | ... | 0.12501 | 28.10 | 0.27 | ... |
| HD 65216 | HD 65216 Ab | Jupiter-type | >1.295 M$_J$ | ... | 1.301 | 577.6 | 0.27 | MAY–04 |
| HD 65216 | HD 65216 Ac | Jupiter-type | >2.03 M$_J$ | ... | 5.75 | 5370 | 0.17 | WIT–19 |
| K2-290 | K2-290 Ab | mini-Neptune | <2.11 M$_J$ | 3.06 R$_J$ | 0.0923 | 9.212 | 0 [set] | HJO–19 |
| K2-290 | K2-290 Ac | Jupiter-type | 0.774 M$_J$ | 1.01 R$_J$ | 0.305 | 48.367 | 0 [set] | HJO–19 |
| Kepler-444 | Kepler-444 Ab | sub-Earth | ... | 0.41 R$_J$ | ... | 3.600 | ... | MIL–17 |
| Kepler-444 | Kepler-444 Ac | sub-Earth | ... | 0.52 R$_J$ | ... | 4.546 | ... | MIL–17 |
| Kepler-444 | Kepler-444 Ad | sub-Earth | 0.036 M$_J$ | 0.54 R$_J$ | 0.0600 | 6.189 | 0.18 | MIL–17 |
| Kepler-444 | Kepler-444 Ae | sub-Earth | 0.034 M$_J$ | 0.55 R$_J$ | 0.0696 | 7.743 | 0.10 | MIL–17 |
| Kepler-444 | Kepler-444 Af | sub-Earth | ... | 0.77 R$_J$ | ... | 9.741 | ... | MIL–17 |
| LTT 1445 | LTT 1445 Ab | Earth-type/super-Earth | 2.87 M$_J$ | 1.305 R$_J$ | 0.03813 | 5.3588 | 0.110 | WIN–22 |
| LTT 1445 | LTT 1445 Ac | Earth-type/super-Earth | 1.54 M$_J$ | 1.15 R$_J$ | 0.02661 | 3.1239 | 0.223 | WIN–22 |
| WASP-8 | WASP-8 Ab | Jupiter-type | 2.216 M$_J$ | 1.165 R$_J$ | 0.08170 | 8.1587 | 0.310 | SOU–20 |
| WASP-8 | WASP-8 Ac | Jupiter-type | >9.45 M$_J$ | ... | 5.28 | 4323 | 0 [set] | KNU–14 |

Note. * ANG–12, ANG–13, FER–14, ROB–14. See references for details, including information about data uncertainties. In some cases, alternate references are available yielding similar results. For planets, referred to as Earth-type/super-Earth, their final classification needs to await improved mass measurements, as well as the consensus of the scientific community about the lower mass limit of super-Earth planets.

angular diameter measurements made with the CHARA Array for a notable range of main-sequence stars. These data were used in combination with the Hipparcos parallaxes and new measurements of the stellar bolometric fluxes to compute absolute luminosities, linear radii, and stellar effective temperatures. Previously, van Belle & von Braun (2009) determined linear radii and effective temperatures for numerous exoplanet host stars based, in part, on qualified estimates of bolometric fluxes and redenning through spectral energy distribution fits. Improved spectroscopic parameters for various transiting planet host stars have been given by Torres et al. (2012). Relevant information for most objects has also been obtained through the Gaia data release (Brown et al. 2018).

In the case of late K and M dwarfs, detailed studies by Mann et al. (2015) led to improved empirical measurements of the stellar effective temperatures, bolometric luminosities, masses, and radii. Another important contribution has been made by Baines et al. (2018), who derived fundamental properties of
Figure 9. Display of the planetary eccentricity as a function of the semimajor axis pertaining to confirmed planet-hosting triple-star systems. Planets of single and multiple planetary systems are depicted by blue and red data points, respectively. If the eccentricity is assumed to be zero (instead of measured), a triangle is used. Despite the fact that the total number of planets hosted by triple-star systems is relatively small, an attempt can be made to identify some general trends. In Figure 9, we display the planetary eccentricity $e_p$ as a function of the semimajor axis $a_p$; here we also distinguish between planets of single and multiple planetary systems. Furthermore, in Figure 10 we report the planetary masses $M_p$, again as a function of the semimajor axis $a_p$. Note that an arrow was used when only the planet’s minimum or maximum mass is known. (The former case typically occurs when a planet has been identified through the Radial Velocity method.)

Both Figures 9 and 10 are, in essence, scatter plots with no discernible trend information. Most planets have low or moderately high eccentricities, and there are two planets, 16 Cygni Bb and HD 41004Ab, with eccentricities exceeding 0.65. Very small eccentricities (i.e., close to or indistinguishable from zero) can be found for close-in planets, a result also known from previous studies. Examples of early work include contributions by Marcy et al. (2004) and Butler et al. (2006), with the former being a Doppler planet survey of 1330 FGKM stars. By making use of Lick, Keck, and ATT, 75 planets have been found that, broadly speaking, exhibit a very similar $e_p - d_p$ distribution to that depicted in Figure 9.

Similar results have been found by Butler et al. (2006), who presented a catalog of nearby exoplanets. They examined 168 planets regarding their $e_p$ and $d_p$ properties; in this case, 11 planets have been identified with eccentricities in excess of 0.65. However, no viable conclusion about the abundance of high-eccentricity planets in triple stellar systems can be conveyed considering the inherent limitations of small number statistics. Our results are also consistent with work by Kane et al. (2012), who studied the exoplanet eccentricity distribution from Kepler planet candidates. Among other results, they found that the mean eccentricity of the Kepler candidates decreases with decreasing planet size, indicating that smaller

3.1.2. Planetary Components

As conveyed in Tables 1, 3, and 5, a total of 27 confirmed planet-hosting triple-star systems has been identified, and the total number of confirmed planets is 38. Various detection methods have been utilized, while noting that the most successful method has been the Radial Velocity method, yielding 21 planets, followed by the Transit method, utilized by Kepler. Minor contributions were made through direct imaging and by astrometry and eclipse timing. Both gas giants (the dominant type) and terrestrial planets (including super-Earths) have been identified. Thanks to the Radial Velocity method, 24 Jupiter-type planets have been discovered.

In addition, a small number of Earth-mass and sub-Earth-mass planets have been found as well, located in the systems of Alpha Centauri, Kepler-444, and LTT 1445; see Faria et al. (2022), Campante et al. (2015), and Winters et al. (2019), respectively; see Tables 9 and 10 for details and further information. The exoplanet of lowest mass, which is 0.034 $M_{\oplus}$, has been found within the multiple planetary system hosted by Kepler-444 (Campante et al. 2015). Kepler-444 is identified as a metal-poor Sun-like star from the old population of the Galactic thick disk.

Despite the fact that the total number of planets hosted by triple-star systems is relatively small, an attempt can be made to identify some general trends. In Figure 9, we display the planetary eccentricity $e_p$ as a function of the semimajor axis $a_p$; here we also distinguish between planets of single and multiple planetary systems. Furthermore, in Figure 10 we report the planetary masses $M_p$, again as a function of the semimajor axis $a_p$. Note that an arrow was used when only the planet’s minimum or maximum mass is known. (The former case typically occurs when a planet has been identified through the Radial Velocity method.)

Both Figures 9 and 10 are, in essence, scatter plots with no discernible trend information. Most planets have low or moderately high eccentricities, and there are two planets, 16 Cygni Bb and HD 41004Ab, with eccentricities exceeding 0.65. Very small eccentricities (i.e., close to or indistinguishable from zero) can be found for close-in planets, a result also known from previous studies. Examples of early work include contributions by Marcy et al. (2004) and Butler et al. (2006), with the former being a Doppler planet survey of 1330 FGKM stars. By making use of Lick, Keck, and ATT, 75 planets have been found that, broadly speaking, exhibit a very similar $e_p - d_p$ distribution to that depicted in Figure 9.

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planets are preferentially found in low-eccentricity orbits. In our case, those planets happen to be close-in planets.

In Figure 11, we relate the planetary mass to the mass of the planet host star. Here it is found that planets with small masses, i.e., Earth-mass and sub-Earth-mass planets, are preferably found in the environments of low-mass stars, i.e., K and M dwarfs. Those planets also occur within multiple planetary systems, notably the systems hosted by Proxima Centauri and Kepler-444A; however, additional observations of planets in tertiary stellar systems would be required to allow conclusions of statistical significance. Previous results on the occurrence and mass distributions of close-in super-Earths, Neptunes, and Jupiters have been given by Howard et al. (2010) and others, which should be considered as part of future analyses.

3.2. Quadruple Systems

So far, three systems with (at least) four stellar components have been identified that are hosts to confirmed or suspected exoplanets. They are 30 Arietis, Kepler-64, and KIC 7177553.
The most convincing case is Kepler-64, whereas for the systems of 30 Arietis and KIC 7177553 notable uncertainties exist.

Regarding Kepler-64, a planet has been found by Schwamb et al. (2013) constituting a transiting circumbinary planet around an eclipsing binary in the Kepler field. According to that report, the planet was discovered by volunteers as part of the Planet Hunters citizen science project. The physical and orbital parameters of both the host stars and planet were obtained via a photometric-dynamical model, simultaneously fitting both the measured radial velocities and the Kepler light curve of the host objects. According to Schwamb et al. (2013), the 6.18 ± 0.17 R_\odot planet orbits outside the 20-day orbit of an eclipsing binary consisting of an F dwarf (1.734 ± 0.044 R_\odot, 1.528 ± 0.087 M_\odot) and an M dwarf (0.378 ± 0.023 R_\odot, 0.408 ± 0.024 M_\odot). The authors report an upper planetary mass limit of 0.531 M_\oplus. Outside the planet’s orbit, at ~1000 au, a previously unknown visual binary has been identified (Schwamb et al. 2013) that is likely bound to the planetary system, making this the first known case of a planet-hosting quadruple-star system, a so-called “double–double.”

30 Arietis and KIC 7177553 are two uncertain cases of planet-hosting quadruple systems; the putative planets have been identified by Guenther et al. (2009) and Lehmann et al. (2016), respectively. 30 Arietis constitutes either a planet-hosting stellar quadruple system or a quintuple stellar system without a confirmed planet. According to Roberts et al. (2015), 30 Arietis A and B are separated by 1500 au. The two stellar components are at almost the same distance and have very similar proper motions; thus, they are almost certainly gravitationally bound. Furthermore, the main components of both systems are both binaries with a composite spectra indicative of F-type stars. Following Morbey & Brosterhus (1974), 30 Arietis A is a spectroscopic binary with an orbital period of 1.1 days. Based on work by Roberts et al. (2015), there is also a red dwarf component commonly referred to as 30 Arietis C. According to Guenther et al. (2009), 30 Arietis B is hosting another object, denoted as Bb, at about 1 au. Guenther et al. (2009) previously identified 30 Arietis Bb as a planet. However, recent measurements of the planetary orbit by Kiefer et al. (2021) led to evidence that the object might fall in the mass range of a brown dwarf or red dwarf instead.

According to Lehmann et al. (2016), KIC 7177553 is a system previously observed by the Kepler satellite. It consists of a pair of binary stars; hence, it is a quadruple system. The system also contains a supermassive Jupiter-type planet, but apparently below the brown dwarf mass limit. The latter object was revealed through eclipse timing variations; it has a period of approximately 529 days. Based on the work by Lehmann et al. (2016) employing RV measurements, it became obvious that the same Kepler target contains another eccentric binary, which is on a 16.5-day orbital period. Lehmann et al. (2016) also pointed out that the separation distance of the two binaries is about 167 au and that they have nearly the same magnitude (to within 2%). In addition, the close angular proximity of the two binaries and very similar γ-velocities strongly suggest that KIC 7177553 is one of the rare planet-hosting double–double systems where at least one system is eclipsing. Moreover, both systems consist of slowly rotating, nonevolved, solar-like stars of comparable masses. However, considering the system’s complexity and dynamics, there is a need for additional transit data to ultimately confirm the planet’s existence.

4. Case Study: The Alpha and Proxima Centauri System

4.1. Basic Properties

Alpha Centauri is the closest star (if reduced to one component) and the closest stellar system to Sun–Earth. Hence, any planet hosted by that system constitutes the closest exoplanet to Earth, regardless of any future planet detections. Alpha Centauri is a hierarchical triple stellar system, consisting of a quasi-binary, i.e., stars A and B, of spectral type G2 V and K1 V, respectively (Torres et al. 2006), and a distant component, which is Proxima Centauri, an M dwarf. Alpha Centauri A and B have effective temperatures of 5790 and 5260 K and masses of 1.13 and 0.97 M_\odot, respectively; see Thévenin et al. (2002) and Pourbaix & Boffin (2016). For additional information on stellar parameters see, e.g., Boyajian et al. (2013), Kervella et al. (2017), and Akesson et al. (2021).

Alpha Cent A and B are at a distance of 1.339 pc from the Sun, whereas Proxima Cen is at a distance of 1.302 pc (Brown et al. 2018); these values have been obtained by Gaia. The pair Alpha Cent A and B is in a highly eccentric orbit, with their relative distance changing between 11.2 and 35.6 au; the orbital period is given as 79.91 yr (Hartkopf et al. 2008). The system’s age has been determined as 5.3 ± 0.3 Gyr (Joyce & Chaboyer 2018) based on classically and asteroseismologically constrained stellar evolution models.

Proxima Centauri, also known as Alpha Centauri C or GJ 551, is 8200±300 au apart (semimajor axis) from Alpha Cen A and B. It has an orbital period of 511,000±14,000 yr (Akesson et al. 2021; see also Kervella et al. 2017). Furthermore, Proxima Cen is on a highly eccentric orbit; its current distance from Alpha Cen AB is 12,950 au—a number that is poised to change as time progresses. Proxima Cen is a red dwarf of spectral type M5.5 Ve (Bessel 1991). Its stellar effective temperature is about 3000 K; moreover, its stellar mass and radius are given as about 0.12 M_\odot and 0.15 R_\odot (Delfosse et al. 2000; Ségransan et al. 2003; Boyajian et al. 2012; Mann et al. 2015; Ribas et al. 2017), respectively. Proxima Cen also exhibits significant amounts of stellar activity—composed of emission, flares, and outflows detectable in different wavelength regimes (e.g., Fuhrmeister et al. 2011; Ayres 2014; Robertson et al. 2016; Pavlenko et al. 2017; Howard et al. 2018). Note that these features are highly relevant for its prospects of circumstellar habitability.

4.2. Planet Detections

For Alpha Centauri A and B, there are no confirmed planet detections—yet, regarding Alpha Cen A, there is tentative evidence in favor of a possible planet or exozodiakal disk as discussed by Wagner et al. (2021); see, e.g., Wang et al. (2022) for additional analyses. A previous report about an Earth-mass planet hosted by Alpha Cen B by Dumusque et al. (2012) has been superseded by Rajpaul et al. (2016), who demonstrated that this earlier detection was a false positive. On the other hand, Proxima Centauri is known to harbor three planets, discovered between 2016 and 2022 by Anglada-Escudé et al. (2016), Damasso et al. (2020), and Faria et al. (2022), respectively. Facilities that made these observations possible include La Silla, VLT, and HST. Theoretical results indicating the possible existence of planets in the Alpha Cen system have been obtained by Quintana et al. (2002), who examined terrestrial planet formation for different dynamic scenarios.
General studies on planet detectability in the Alpha Cen system have been published by Zhao et al. (2018).

Anglada-Escudé et al. (2016) identified an Earth-mass planet (minimum mass 1.3 $M_{\oplus}$) in orbit about Proxima Cen with a period of about 11.2 days at a semimajor-axis distance of close to 0.029 au from its host. Following Faria et al. (2018), due to the highly hierarchical nature of the triple-star systems studied here, general studies on planet detectability in the Alpha Cen system have been published by Zhao et al. (2018).

In Table 5 and 6, Table 8 shows that those stars encompass a large range of masses, including M dwarfs such as Proxima Centauri, Gliese 667C, and LTT 1445A with masses as low as 0.12 $M_{\odot}$; see Ribas et al. (2017), Tokovinin (2008), and Winters et al. (2022), respectively. On the other hand, planet-hosting stars of higher mass have been identified as well, with 51 Eri A, an F-type star of mass 1.75 ± 0.05 $M_{\odot}$ (Simon & Schaefer 2011), as the current number one.

Next, we focus on the distribution of stellar spectral types (see Figure 8 and Tables 6 and 11). It is found that the system’s main components are relatively more massive compared to main-sequence stars on average. Specifically, stellar primaries tend to be more massive than typical main-sequence single stars, a finding also valid for stellar secondaries though less pronounced. Tertiary stellar components are almost exclusively low-mass stars of spectral type M. Hence, in regard to planetary host stars, there is an increased abundance of A-, F-, and G-type stars.

In Table 12, we offer more detailed statistics for stellar spectral types using a number scheme such as that A0, F0, G0, K0, and M0 stars are denoted as 1.0, 2.0, 3.0, 4.0, and 5.0, respectively. Stars of intermediate spectral types are denoted accordingly. Furthermore, we refrain from considering non-main-sequence stars, which led to the dismissal of 91 Aqr A, according to the authors, as the current number one.

4.3. Orbital Stability and Habitability

There is little doubt about the orbital stability of the stellar components and the Alpha Centauri system planets. This view has been confirmed by Boyle & Cuntz (2021), who investigated the orbital stability\(^{11}\) of the outlying stellar component and the two heretofore-identified exoplanets based on the Hill stability criterion. Examples of previous work on planetary habitability for the Alpha Centauri system, such as the circumstellar environment of Proxima Centauri, include the studies by Barnes et al. (2016) and Meadows et al. (2018).

Meadows et al. (2018) used 1D coupled climate-photochemical models to generate self-consistent atmospheres for several evolutionary scenarios, including Earthlike atmospheres, with both oxic and anoxic compositions. They showed that these modeled environments can be habitable or uninhabitable at Proxima Cen b’s position in the habitable zone. These results (according to the authors) are applicable not only to Proxima Cen b but to other terrestrial planets orbiting M dwarfs as well—especially considering that M dwarfs are disadvantageous for hosting planets with life compared to, e.g., K dwarfs (e.g., Cuntz & Guinan 2016). On a perhaps less serious note, Marin & Beluffi (2018) calculated, through employing multiparameter Monte Carlo simulations, the minimal crew for a multigenerational space journey toward Proxima b, estimated to last about 6300 yr (their primary model). This work reemphasizes the impossibility of interstellar travel under realistic assumptions based on current technology.

5. Additional Analyses

Another item of interest is the statistical analysis of the planet host stars in triple stellar systems. Thus, we focus on the 27 confirmed systems, defined as that all three stellar system components and at least one planet have been verified (see Tables 5 and 6). Table 8 shows that those stars encompass a large range of masses, including M dwarfs such as Proxima Centauri, Gliese 667C, and LTT 1445A with masses as low as 0.12 $M_{\odot}$; see Ribas et al. (2017), Tokovinin (2008), and Winters et al. (2022), respectively. On the other hand, planet-hosting stars of higher mass have been identified as well, with 51 Eri A, an F-type star of mass 1.75 ± 0.05 $M_{\odot}$ (Simon & Schaefer 2011), as the current number one.

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In Table 12, we offer more detailed statistics for stellar spectral types using a number scheme such as that A0, F0, G0, K0, and M0 stars are denoted as 1.0, 2.0, 3.0, 4.0, and 5.0, respectively. Stars of intermediate spectral types are denoted accordingly. Furthermore, we refrain from considering non-main-sequence stars, which led to the dismissal of 91 Aqr A, according to the authors, as the current number one.

Our analysis shows that at present the average spectral type of planet host stars in triple stellar systems is given as G3 V. Furthermore, there is no statistically significant difference whether or not the system harbors close-in planets or the planets are situated farther out; here a divider at 0.1 au (semimajor axis) is used. We also compared this result to planet-hosting binaries, applied to S-type systems, where the planet is in orbit about one stellar component—instead of both, with the latter case referred to as a P-type system; see, e.g., Dvorak (1982). The data for the binary systems as considered are taken from Pilat-Lohinger et al. (2019). In this case, the average spectral type of planet host stars is given as G8 V. Evidently, those stars are of later type; however, the difference to planet-hosting stars situated in triple-star systems is about one standard deviation. Hence, a larger database, particularly

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\(^{11}\) Due to the highly hierarchical nature of the triple-star systems studied here, including Alpha Centauri, the binary approximation in orbital stability simulations is often appropriate; see work by, e.g., Holman & Wiegert (1999), Fatuzzo et al. (2006), and Cuntz et al. (2007), among other contributions.
concerning triple-star systems, would be advantageous to further explore that statistical trend. This statistical outcome can also be compared with the general spectral distribution for main-sequence stars; the latter is in part informed by Kroupa (2001, 2002) and Chabrier (2003), who pursued detailed analyses of the universal stellar initial mass function for the various components of the Milky Way. These studies reconfirmed that the mass function is heavily skewed toward the low end of the main sequence. Previous work by Ledrew (2001) for the spectral types of main-sequence stars located in the solar neighborhood identified the following distribution: $A - 0.6\%; F - 3.0\%; G - 7.6\%; K - 12.1\%; M - 76.5\%$. (This also means that the Sun constitutes a high-mass star, although this attribution is barely made.) These percentages are strikingly similar to the result obtained by E. Mamajek in 2016 (unpublished; used with permission),\footnote{https://figshare.com/articles/figure/Fraction_of_Stars_by_Spectral_Type_in_the_Solar_Vicinity/3206527} which for the various spectral types reads as follows: $A - 0.6\%; F - 3\%; G - 6\%; K - 13\%; M - 72\%$ (while ignoring a normalization factor of 1.057). Hence, the typical spectral type of general main-sequence stars is about M3 (the median), which is much closer to the lower end of the main sequence than found for planet host stars in triple stellar systems. Consequently, from a statistical point of view, the latter types of stars are more massive, concurrent with a notably higher surface temperature and luminosity, than main-sequence stars in the solar neighborhood.

### 6. Summary and Conclusions

The focus of this study is to present a catalog, including background information and associated interpretation, of planet-hosting triple- and quadruple-star systems by making use of observations and data available in the literature. We explored statistical properties of those kinds of systems with a focus on both the stars and the planets. So far, about 30 triple systems and one confirmed quadruple system have been identified. Regarding both the triple and quadruple systems, there is also a small number of controversial cases, which have been discussed as well.

The total number of planets identified in planet-hosting triple and quadruple stellar systems is close to 40. All triple-star systems are highly hierarchic, consisting of a quasi-binary complemented by a distant stellar component, which is in orbit about the common center of mass. Furthermore, the confirmed and unconfirmed planet-hosting quadruple systems are, in fact, pairs of close binaries (“double-doubles”), with one of the binaries harboring an exoplanet. We acknowledge that planet-hosting systems of higher multiplicity are expected as well. Actually, there may be a smooth transition between high-order multiple stellar systems and gravitationally bound open clusters containing a high number of stellar components. Due to the complex patterns of gravitation interaction in those systems, possible exoplanets hosted in high-order systems may, however, be restricted to relatively tight S-type configurations and P-type configurations pertaining to quasi-binaries. But so far no detections for systems of five or more stars have been obtained. We identified the following properties regarding planet-hosting triple-star systems:

1. The closest planet-hosting multiple-star system is Alpha and Proxima Centauri at a distance of 1.302 pc. Previously, this system has received heightened attention regarding both orbital stability and habitability; some of these aspects are discussed in this study.

2. Planet-hosting multiple-star systems, including a small number of unconfirmed cases, are at present found in 22

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**Table 11**

| Spectral Type | Total Number of Stars | FMS | Expected Value (MS) |
|---------------|-----------------------|-----|---------------------|
| A             | 3                     | 0.6 | 0.4                 |
| F             | 10                    | 3.0 | 1.9                 |
| G             | 14                    | 7.6 | 4.9                 |
| K             | 14                    | 12.1| 7.7                 |
| M             | 27                    | 76.5| 48.9                |
| Substellar    | 3                     | 0.6 | 0.4                 |

**Note.** Total (MS) refers to the combined number of main-sequence stars, noting that stars with no reported luminosity class are assumed to be main-sequence stars as well. Total refers to all stars considering that, regarding the main component, there are also four evolved stars, i.e., three subgiants and one giant, that are also included. Unconfirmed systems (status UC) have been disregarded. FMS indicates the observed frequency of main-sequence stars in the solar neighborhood; see text for details.

**Table 12**

| Case                        | Spectral Code | Standard Dev. | Spectral Type |
|-----------------------------|---------------|---------------|---------------|
| Main-sequence stars (general) | 5.3           | ...           | ~M3 V         |
| Binary S-type planet host stars ($d < 500$ au) | 3.7 | 0.8 | ~G7 V |
| Binary S-type planet host stars ($d < 100$ au) | 4.0 | 0.9 | ~K0 V |
| Triple-star systems, planet host stars | 3.3 | 1.0 | ~G3 V |
| Triple-star systems, planet host stars ($t_p < 0.1$ au) | 3.4 | 1.3 | ~G4 V |
| Triple-star systems, planet host stars ($t_p > 0.1$ au) | 3.3 | 0.7 | ~G3 V |

**Note.** Data for the binary systems are based on Pilat-Lohinger et al. (2019).
of the 88 constellations. As expected, a high number of systems exist at or near the Summer Triangle, largely due to the contributions from the Kepler mission.

3. All or almost all planets are found to be in orbit about single stars rather than pairs of stars; these settings are readily referred to as S-type orbits. So far, no planets have been identified that are in orbit about three stars at once (“circumtrinary” planets). The presence of those planets is incompatible with highly hierarchical triple-star configurations.

4. Besides the various systems with one identified planet, there are at present seven multiplanetary systems hosted by triple-star systems; the total number of planets in those systems is 18. The highest number of planets has been found in the system of Kepler-444, which are all identified as sub-Earth-type planets.

5. The dominant method of planet detections has been the Radial Velocity method, yielding 21 confirmed planets in triple-star systems. The second most important method has been the Transit method, utilized by Kepler. Minor contributions were made through direct imaging and by astrometry and eclipse timing.

6. Both gas giants (the dominant type) and terrestrial planets (including super-Earths) have been identified. Thanks to the Radial Velocity method, 24 Jupiter-type planets were discovered in triple stellar systems. Moreover, a small number of Earth-mass and sub-Earth-mass planets have been detected as well—including planets hosted by Proxima Centauri prompting a considerable array of studies about planetary formation, orbital stability, and habitability.

7. The data show that almost all stars are main-sequence stars, as expected. However, the stellar primaries tend to be more massive (i.e., corresponding to spectral types A, F, and G) than expected from single-star statistics, a finding also valid for stellar secondaries but less pronounced. Furthermore, tertiary stellar components are almost exclusively M dwarfs—a finding also mirrored by the statistical distribution of stellar spectral types in the solar neighborhood (e.g., Kroupa 2001, 2002; Chabrier 2003).

8. Our analysis also shows that the average spectral type of planet host stars in triple stellar systems is given as G3 V and, furthermore, there is no identifiable difference whether or not the system harbors close-in or far-away planets. Thus, planet host stars tend to be more massive and, consequently, have a notably higher surface temperature and luminosity than typical main-sequence stars (as defined by the median of the stellar mass sequence).

Topics of future studies pertaining to planets in higher-order systems are expected to include studies of orbital stability, history of formation, and habitability—particularly regarding Earth-type planets and super-Earths. Previous studies about the influence of stellar multiplicity on planet formation have been given by, e.g., Wang et al. (2014), Dutrey et al. (2014), and subsequent work, indicating that planet formation due to stellar companions is noticeably reduced but nonetheless substantial. It would be of great interest to expand these investigations while taking into account expanded parameter domains, including effects associated with various types of outside forcings.

Previous work about the stability of planets in triple and higher-order stellar systems has been done by, e.g., Verrier & Evans (2007), Hamers et al. (2015), Correia et al. (2016), Busetti et al. (2018), and Mylläri et al. (2018). However, these studies are typically limited to triple stellar systems, especially to those of highly hierarchical nature—an approach well motivated by the current observations. On the other hand, in consideration of ongoing and future observational campaigns, more intricate compositional and dynamical star–planet structures are expected to be found. Those findings are expected to inform future studies of orbital stability and habitability. The latter will need to take into account both gravitational and radiative boundary conditions imposed by the various system components, which in turn will require additional observational and theoretical studies. Other contributions are expected to arise from the development of future space mission concepts such as LUVOIR (The LUVOIR Team 2019), HabEx (Gaudi et al. 2020), and LIFE (Quanz et al. 2022), which are poised to provide additional crucial insights into the physics of multiple stellar and multiple planetary systems.

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Appendix

Summary of Acronyms

Table A1 provides a summary of the acronyms used.

Table A1
