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Multiplicity of stars with planets

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Abstract

We aimed to assess how stellar multiplicity affects exoplanets' presence and properties. We analysed all exoplanet host stars within 100 pc using *Gaia* DR3 data, advanced statistical methods, and additional information from the Washington Double Star catalogue and literature. Identified 215 exoplanet host stars in 212 multi-star systems, discovering 17 new companions in 15 known systems. Our findings showed differences in the average number of planets in multiple versus single systems and a tendency for high-mass planets to orbit closer in multiple systems. We confirmed that planets in multiple systems generally have higher orbital eccentricities, with a significant trend towards high eccentricities when star-star separations are small compared to star-planet distances.

1 Introduction

Many relevant observational works about the multiplicity of stellar systems with planets have been published. The authors have used a diversity of target stars with planets, methodologies, and even maximum distances (e.g. [1]: 25 pc; [2]: 50 pc; [3]: 200 pc; [4, 5]: 500 pc). A wealth of results have been proposed after these observations, and all of these studies 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.

2 Sample

Our sample was built using the two most commonly referenced exoplanet databases. We included all host stars listed in either the Extrasolar Planets Encyclopaedia [6] or the NASA Exoplanet Archive [7]. As of our download date (3 January 2024), the first database contained 5,576 planets in 4,114 planetary systems, while the second had 5,566 planets in 4,145 systems. We removed all duplicate host stars from the two databases, accounting for cases where the same star was listed under different names or with slightly different coordinates. This process resulted in a set of 4,612 unique host stars. Next, we searched for the *Gaia* DR3 [8] counterpart for each host star. After restricting the analysis to stars with distances less than 100 pc, we obtained a work sample of 998 exoplanet host stars.

3 Analysis

The flowchart in Figure 1 summarises the sample preparation and the following analysis.

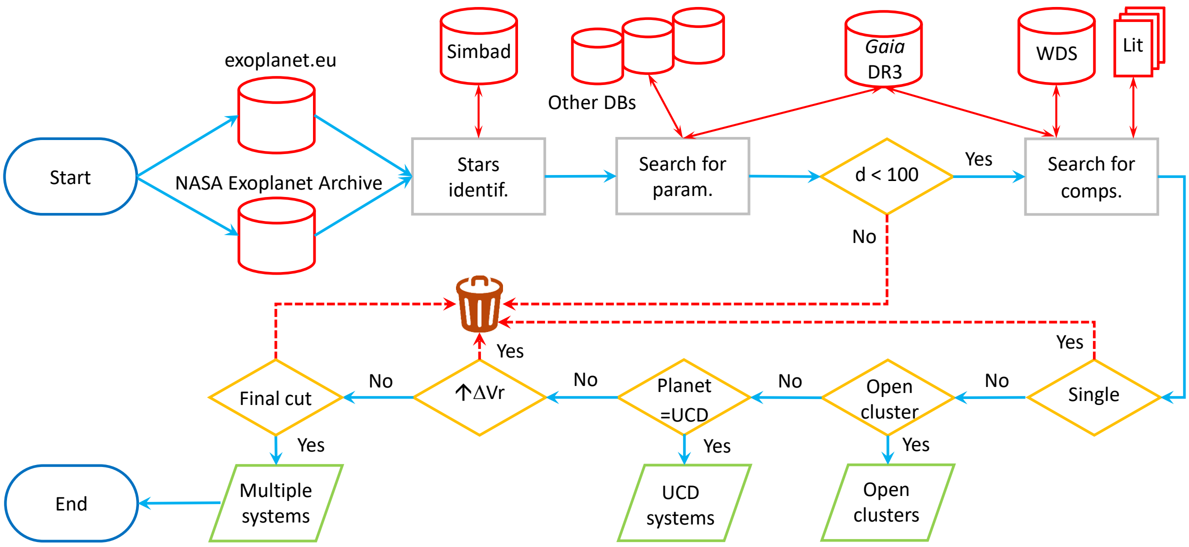

Figure 1: Flowchart describing the sample preparation and following analysis.

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 [9] (their Sect. 3). In particular, we searched 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:

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

$$\Delta{\rm PA} = |{\rm PA}_1 - {\rm PA}_2| < 15\,{\rm deg}, \tag{2}$$

and

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

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.

We further enhanced our *Gaia* DR3 search for companions by cross-referencing with the Washington Double Star catalogue (WDS) [10]. This catalogue currently lists angular separations and position angles for the initial and most recent observation epochs of approximately 156,000 multiple systems. In addition to these measurements, the WDS includes other details like equatorial coordinates, magnitudes, and system notes.

3.2 Multiple star systems candidates filtering

Not all of the candidates are valid for different reasons, and we performed a filtering to discard some of the systems.

The first step was with those stellar systems than can be wide pairs in open clusters and associations. There are valid concerns about the true gravitational binding of very wide pairs of young stars, as they might actually be part of stellar kinematic groups or associations [11]. These doubts are particularly justified when the pairs are associated with nearby open clusters or OB associations, especially if the separation between them is similar to the typical distances between cluster members. This is the situation for a set of stars that we excluded from our analysis. These stars belong to the nearby Hyades open cluster [12] and the Lower Centaurus Crux OB association [13].

The second step in the filtering was the discarding of those planets that were in fact ultracool dwarfs. In their effort to be as complete as possible, both the Extrasolar Planets Encyclopaedia and the NASA Exoplanet Archive frequently include exoplanet candidates that do not meet the International Astronomical Union's criteria for a true planet within the Solar System. There are differences between brown dwarfs and substellar objects below the deuterium burning mass limit at about $13\,\mathrm{M_{Jup}}$ [14]. A similar situation arises with some M-type companions to young stars in stellar kinematic groups and star-forming regions, as well as with LTY-type companions to nearby stars and brown dwarfs detected through direct imaging.

These ultracool dwarf companions, which are sometimes classified as exoplanets in one or both catalogues, orbit at separations of a few arcseconds from their primaries, similar

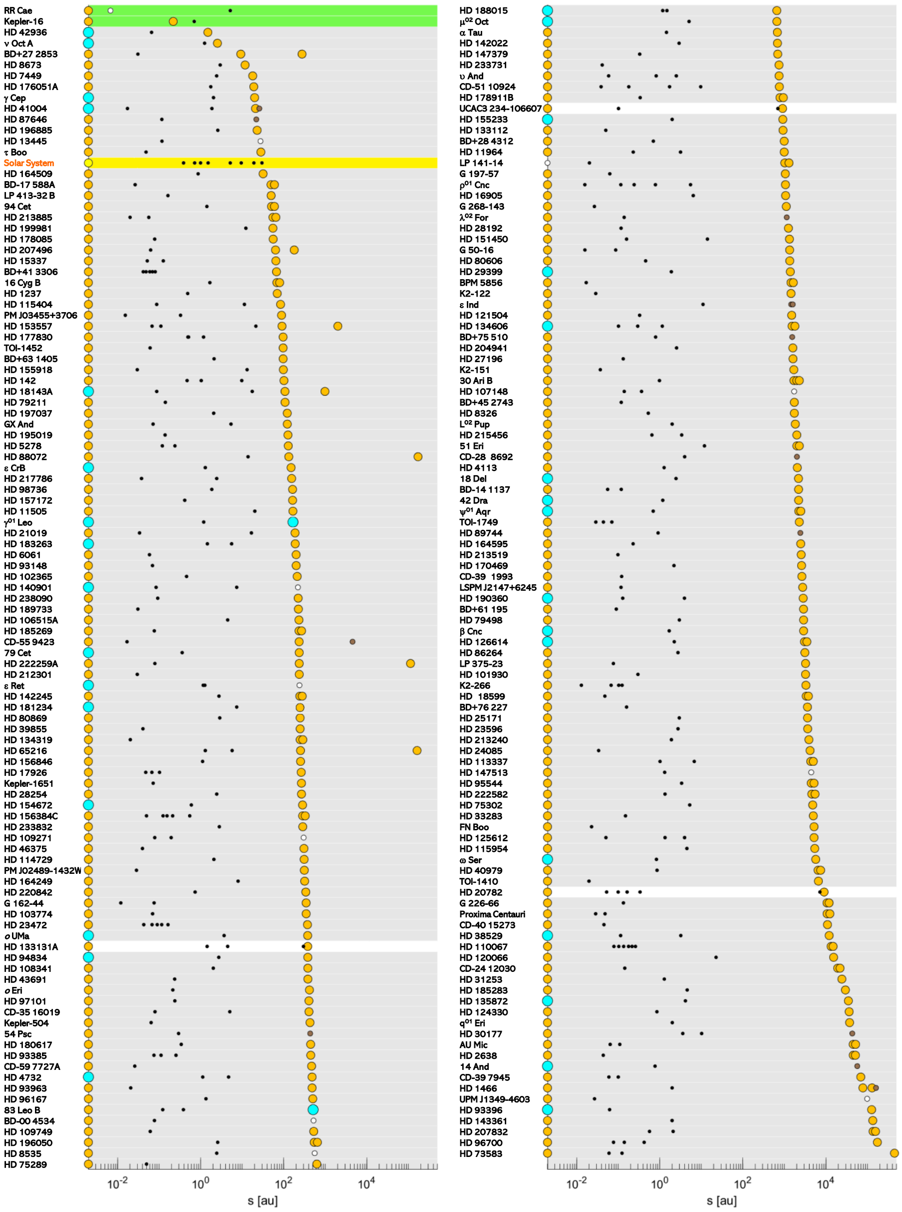

Figure 2: Schematic configurations of multiple stellar systems with exoplanets. Orange circles are main-sequence stars, cyan circles are subgiant and giant stars, white circles are white dwarfs, small brown circles are brown dwarfs, and black dots are planets. We display our 212 systems with grey background, except for the two systems with circumbinary planets, namely RR Cae and Kepler-16, with green background, and the three systems 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.

to separations in multiple-star systems. They have been resolved from their host stars and characterized through photometric or even spectroscopic methods, or they possess model-dependent masses with high uncertainties, often at or above the deuterium-burning threshold. Due to this diversity, we excluded many stars in systems containing directly imaged UCDs, focusing only on exoplanet candidates in compact orbits detected through radial velocity and transit methods.

The last step was to a final discarding of other candidates for different reasons, such as the lack of official confirmation of the existence of the planet, or because of the radial velocity was really different between companion stars.

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. We tabulate only 212 entries because there are three binary systems with planets discovered around both stars

4 Results

We identified 17 genuinely new companion stars. Twelve of these belong to entirely new systems, while the remaining five are additional companions to four systems already catalogued by the WDS or noted in the literature. In these four systems, the K- and M-dwarf companions had not previously been documented, so we recorded their *Gaia* DR3 identifiers. In total, the 17 new companions are part of 15 systems, of which four are triple systems and one is a quadruple system. To determine if the 17 new companions are truly gravitationally bound, we calculated their reduced binding energy using the method described by [15], and found that they are all indeed bound.

Using powerful statistical tools, we have examined the behavior and existence of planets in relation to the projected physical separation between host stars and their companions, as well as the semi-major axis and eccentricities of the planets' orbits.

Firstly, we compared the projected physical separations, s, between the exoplanet host star and the nearest companion—whether it's a star, white dwarf, or brown dwarf—in triple and quadruple systems between stars in multiple systems and the semi-major axes, as well as the semi-major axis a, of exoplanets of the most distant planet in multi-planet systems. According to [16], a general guideline for system stability is that the planet's orbital period should be at least three times different from the binary's period, even when the mass ratio is as low as 0.1. 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 $P_{\rm star}/P_{\rm planet}$ ratios.

In terms of eccentricities, we concluded that planetary orbits in multiple stellar systems do exhibit significantly larger eccentricities than those around single stars. So, 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. 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, as we could demonstrate.

Another key finding was that we could not draw any definitive conclusions about the relationship between the number of planets in single versus multiple systems. Similarly, there was insufficient evidence to claim that planet masses differ between single and multiple systems. Additionally, several studies, such as [3], have examined the relative distribution of host and companion stars by spectral type. Our results align with most of these previous findings.

Future work could be extending the survey to 200 pc, but given the effort required for analysing numerous candidates, we recommend focusing on confirming and characterizing disputed planetary systems. *Gaia* DR4 will aid in this process.

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Our presentation in zenodo.org can be found here