Influence of Stellar Dynamics on Exoplanet Detectability in Multi-Star Systems

Carla Devnani, Kenneth Jenkins, Saurabh Saugar, Cameron Souza

Harvard DCE

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Abstract

This study investigates how the dynamical environment of multi-star systems influences the detectability of exoplanets through radial velocity and transit methods. By comparing planetary properties such as orbital periods, radii, and masses between multi-star and single-star systems, this research aims to understand the impact of stellar multiplicity on observational biases in exoplanet detection. The study utilizes a dataset provided by NASA characterized by confirmed planetary discoveries, employing statistical tests to quantify detectability variations.

Introduction

The motivation behind this project was fascination with astronomy, exoplanetology and space exploration. The NASA Exoplanet Archive provides numerous datasets on statistics of confirmed exoplanets associated with different methods of discovery. Exoplanets have been discovered in a variety of stellar environments, ranging from isolated single stars to complex multi-star systems. The detectability of these planets often depends on the method used, such as radial velocity or transit photometry, each sensitive to different planetary and stellar characteristics. In multi-star systems, gravitational interactions and the resultant stellar dynamics could significantly influence the orbital mechanics of planets, potentially affecting their detectability.

Hypothesis

Planets in multi-star systems exhibit statistically significant different mean values in detectable properties compared to those in single-star systems, influenced by their dynamic stellar environments.

Methods

We conducted a comprehensive analysis to understand how the dynamical environment in multi-star systems affects the detectability of exoplanets. We specifically compared these systems to single-star systems using the radial velocity and transit detection methods, which are the most common discovery methods in the dataset.

Data Source

We utilized a dataset of confirmed planets from NASA's Exoplanet Archive retrieved on March 13th, 2024. The dataset comprises observations from confirmed planetary discoveries published and categorized as "Published Confirmed" under the criteria of detection via radial velocity and transit methods totaling 5,180 planets. The dataset was filtered to include only those entries with a default flag of 1, signifying they are high-confidence measurements.

Data Preparation

Our initial task involved loading and cleaning the data to ensure accuracy and relevancy for this study. Using Python, we handled missing or improperly formatted data entries by skipping them and isolated our analysis records matching our study criteria. This process was critical to maintain the integrity of our analyses. Moving forward with exploring the data, we chose to include ten data parameters that had fewer than ten percent missing values. Additionally, we created a new variable (multi_star_flag) which had a value of ‘single-star’ or ‘multi-star’ if the system had more than one star (sy_snum).

Exploratory Analysis of Data

We started with exploring the skewness and variation in orbital period (pl_orbper) in days, planetary radius (pl_rade) in Earth radius, and mass (pl_bmasse) in Earth mass for both Radial and Transit Velocity methods, as shown in Figure 1. The Radial Velocity Method tends to detect planets with longer orbital periods and higher masses compared to the Transit Method, which might be due to its sensitivity to the gravitational effects of such planets. The Transit Method appears to identify a wider range of planet sizes as evidenced by the greater standard deviation in planet radii.

Both methods show right-skewed distributions for mass and orbital period, indicating the presence of outliers with high values in these measurements. These insights suggest that the Radial Velocity Method might be more effective at detecting larger, more massive planets that are farther from their stars, whereas the Transit Method may detect a broader variety of planet sizes, potentially closer to their stars. Analyzing the histograms provides valuable insights into the characteristics of exoplanets detected using Radial Velocity versus the Transit Method.

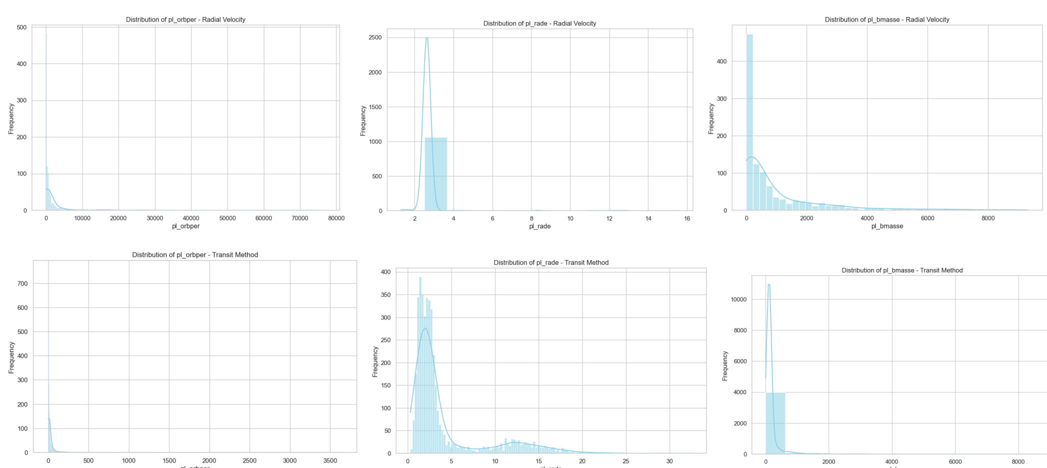

Figure 1: Histograms of Exoplanet characteristics

We also generated correlation matrices for both the Radial Velocity and Transit Methods to offer insights into the relationships between orbital period (pl_orbper), planet radius (pl_rade), and planet mass (pl_bmasse), as shown in Figure 2. The Radial Velocity Method shows a stronger correlation between mass and orbital period (0.480 versus 0.104 for transit velocity), which aligns with its sensitivity to gravitational effects from more massive planets that can induce detectable signals over longer periods. The lack of correlation between radius and mass in the Radial Velocity data (-0.004) might be due to this method's focus on gravitational effects rather than physical size. The Transit Method, which measures dips in starlight as a planet crosses in front of its star, shows a moderate correlation between planet size and mass (0.375), which could be due to the method's reliance on physical size for detection visibility.

```
Correlation Matrix for Radial Velocity Method:
           pl_orbper   pl_rade  pl_bmasse
pl_orbper   1.000000 -0.024407   0.479679
pl_rade    -0.024407  1.000000  -0.004042
pl_bmasse   0.479679 -0.004042   1.000000

Correlation Matrix for Transit Method:
           pl_orbper   pl_rade  pl_bmasse
pl_orbper   1.000000  0.027540   0.104414
pl_rade     0.027540  1.000000   0.374826
pl_bmasse   0.104414  0.374826   1.000000
```

Figure 2: Correlation Matrices for Radial Velocity and Transit Methods

We then expanded the analysis to various planetary and stellar parameters between single-star and multi-star systems including orbital period (pl_orbper) in days, planetary radius (pl_rade) in Earth radius, mass (pl_bmasse) in Earth mass, system brightness (sy_vmag, sy_kmag, sy_gaiamag), distance (sy_dist) in parsecs, stellar mass (st_mass) in Solar mass, and metallicity (st_met) in decimal exponent. We employed descriptive statistics to provide an initial overview of the data. See Appendix - Descriptive Statistics Results for the results of the analysis.

Figure 3 compares the means of each parameter between single-star and multi-star systems discovered by Radial Velocity method using bar plots. It is clear for orbital period (pl_orbper) and metallicity in decimal exponent (st_met) that there is a significant difference between the two groups. For other parameters, a t-test was needed to confirm whether the difference in means is statistically significant or not.

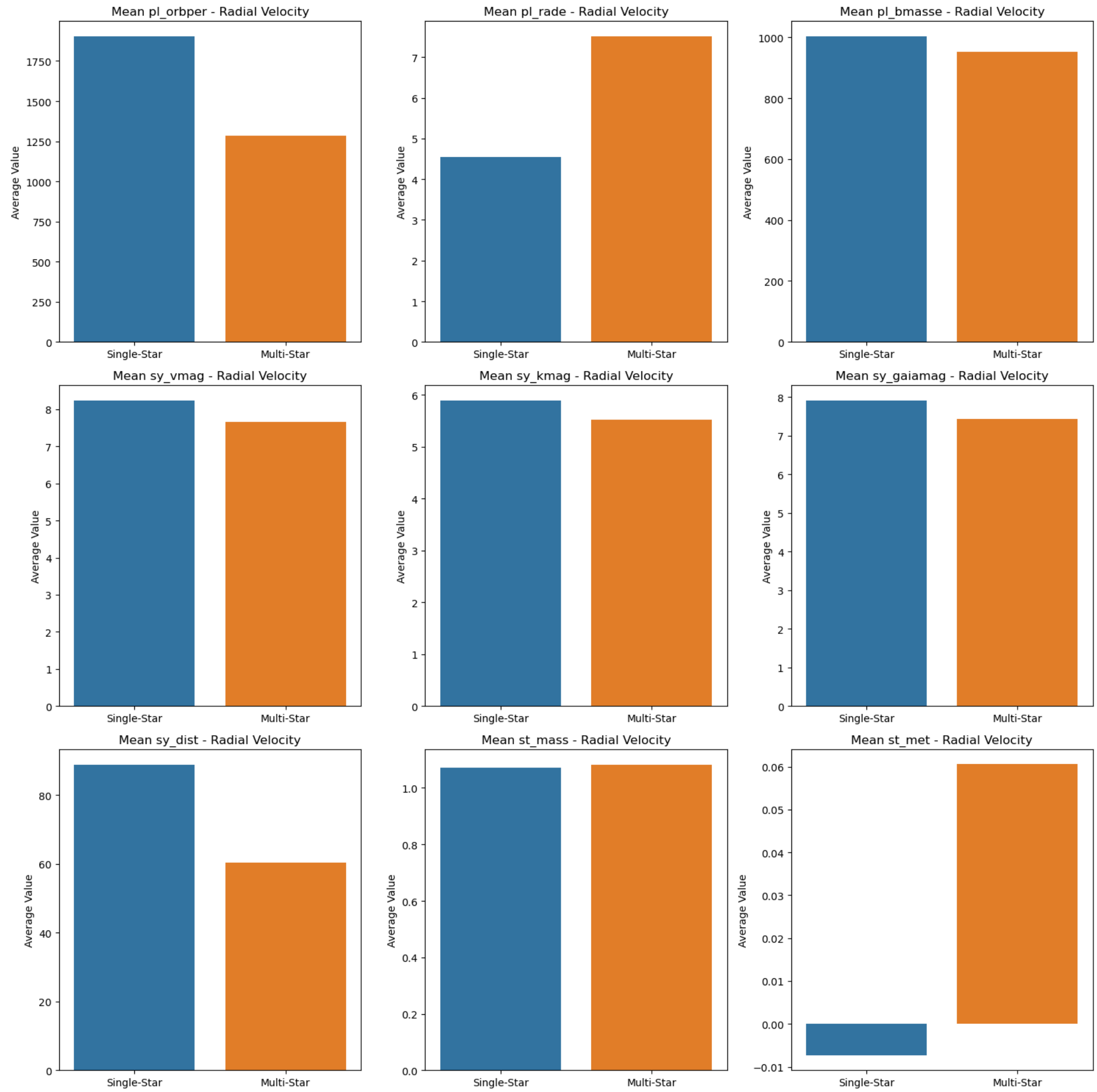

Figure 3: Visualizing Radial Velocity Data

Figure 4 compares the means of each parameter between single-star and multi-star systems discovered by the Transit method. Again, it is necessary to perform a t-test to confirm whether the difference in means is statistically significant or not.

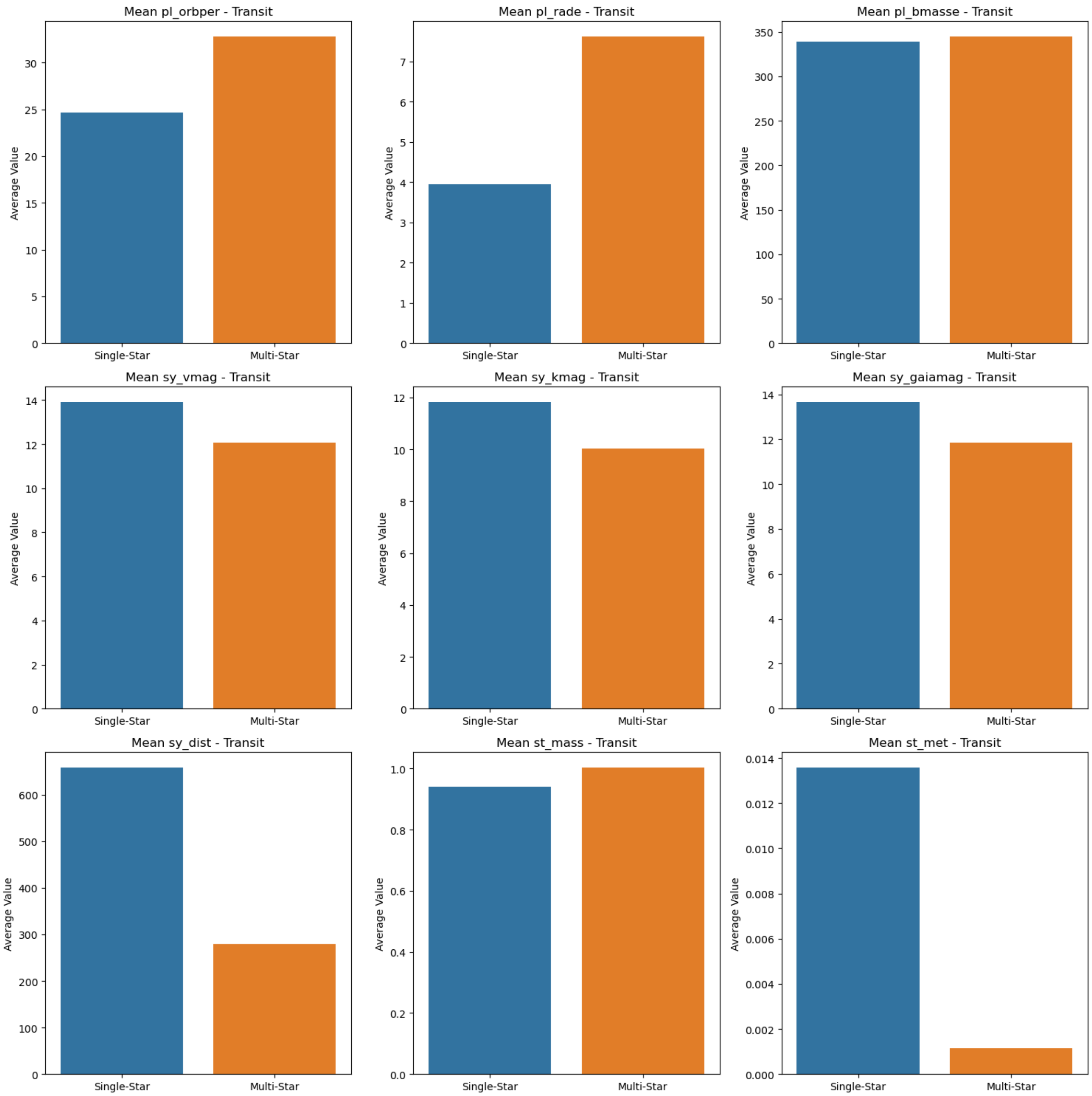

Figure 4: Visualizing Transit Data

There is a noteworthy difference in scale for some parameters such as orbital period (pl_orbper) and mass (pl_bmasse) between the Radial Velocity method (Figure 3) and the Transit method (Figure 4). Additionally, for some parameters the larger mean switches from single-star systems to multi-start systems between the two discovery methods (e.g. orbital period (pl_orbper) and metallicity (st_met)). We found existing research and data analysis on differences between discovery methods, which led us to focus on the single-star to multi-star differences for this project.

Statistical Approach

To determine the statistical significance of the observed differences, we performed t-tests to compare the mean values of these parameters between single-star and multi-star systems. These tests helped us understand if the mean differences in planetary characteristics like orbital periods and brightness were due to a random chance or influenced by the stellar multiplicity. By employing this method, we aimed to analyze how multi-star dynamics influence the detectability of exoplanets and to propose more effective detection techniques tailored to these complex environments. We used a cutoff value of 0.05 to determine if we reject the null hypothesis that means are equal between single-star and multi-star systems.

Parameter	**Radial Velocity p-value**	**Significant difference in means?**	**Transit p-value**	**Significant difference in means?**
Planetary Orbital Period	0.038	Yes	0.283	No
Planetary Radius	0.276	No	1.05e -18	Yes
Planetary Mass	0.664	No	0.903	No
System Visual Magnitude	0.001	Yes	1.06e-35	Yes
System K-band Magnitude	0.027	Yes	2.40e-45	Yes
Gaia Magnitude	0.003	Yes	5.34e-36	Yes
System Distance	0.0005	Yes	6.66e-77	Yes
Stellar Mass	0.804	No	0.010	Yes
Stellar Metallicity	0.005	Yes	0.338	No

Table 1: Results of t-tests for Radial Velocity and Transit methods

The visualizations of Figures 3 and 4 support the results shown in the table and offer a clearer comparison and highlight significant differences.

Results

The analysis highlighted significant differences in the properties of exoplanets orbiting within multi-star systems versus single-star systems, suggesting potential biases in detectability influenced by stellar dynamics across both Radial Velocity and Transit detection methods.

Notably, multi-star systems consistently exhibit more brightness (lower magnitude is associated with brighter objects) and larger planetary radii, suggesting that these systems may inherently favor the detectability of certain exoplanet types. In terms of the data points analyzed, there was a significant variation between system types and detection methods, which shows the robustness of the dataset. For the Radial Velocity method, 180 data points were analyzed for multi-star systems compared to 906 for single-star systems. In the Transit method, the figures were 286 for multi-star systems and 3,808 for single-star systems.

For planetary mass we are unable to reject the null hypothesis that mean planetary mass is equal across single-star and multi-star systems for both Radial Velocity and Transit methods. Overall, we can reject the null hypotheses that mean values of the detectable properties studied are equal. The following sections explain our results for each parameter studied and provide theories on differences between the two methods of discovery studied.

Orbital Periods

Orbital period is the time a planet takes to complete one orbit around its star, typically measured in days. For planets detected through the Radial Velocity method, multi-star systems exhibited a significantly shorter average orbital period of 1,286.93 days compared to 1,903.05 days for single-star systems, suggesting tighter orbits influenced by gravitational forces. This suggests that planets in multi-star systems might have tighter orbits due to complex gravitational interactions, and the result was statistically significant with a p-value of 0.038. Conversely, in the Transit method, the trend was reversed. Multi-star systems showed a higher average orbital period of 32.78 days compared to 24.64 days for single-star systems.

This difference starkly contrasts with the findings from the Radial Velocity method and highlights how detection methods can influence observed orbital dynamics. Additionally, the p-value for the orbital period in the Transit method was only 0.282, which is not statistically significant. This suggests that the differences observed in the Transit method might not be as reliable or pronounced as those observed in the Radial Velocity method, possibly due to the inherent detection sensitivities or biases of each method.

Planetary Radius

Exoplanet radii in terms of Earth radii in multi-star systems were larger on average across both detection methods. In the Radial Velocity method, the mean radius for multi-star systems was 7.51 Earth radii, significantly larger than the 4.54 Earth radii observed in single-star systems. This trend continued in the Transit method, with multi-star systems exhibiting a mean radius of 7.61 Earth radii compared to 3.94 for single-star systems. The differences in planetary radii are significantly emphasized in the Transit method with a p-value nearing 1.05e-18, indicating a strong statistical significance. However, the p-value for Radial Velocity was only 0.276, showing there is not a statistical significance.

Figure 5 showing the box plot comparison for the two methods provides additional insight on the results of the statistical test. The distribution of radii for single-star systems detected using the transit method is highly right skewed. In further studies, it may be prudent to confirm the higher radii detected by the transit method for single-star systems. Nonetheless, these findings across both detection methods suggest that the presence of multiple stars might influence the formation or migration patterns of larger exoplanets, thereby affecting their observable characteristics and detectability.

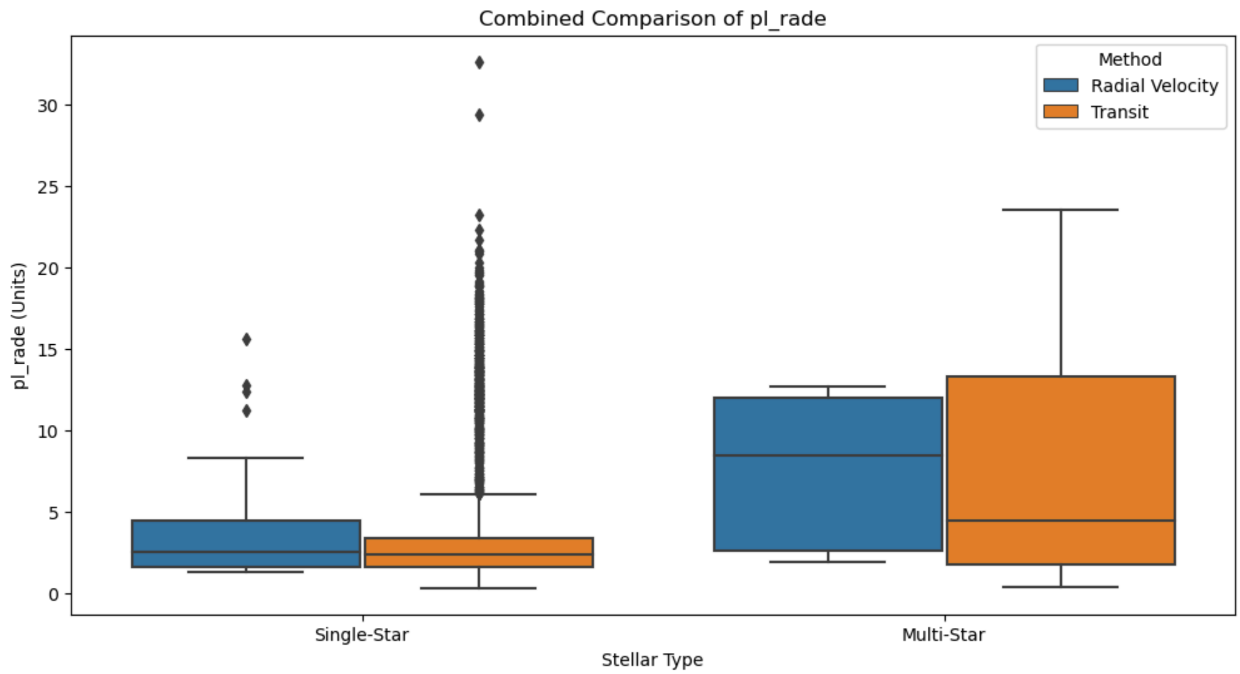

Figure 5: Planetary Radius for Radial Velocity and Transit Method

Planetary Mass

In the Radial Velocity method, multi-star systems exhibited a lower mean planetary mass of 952.60 Earth masses compared to 1003.10 Earth masses in single-star systems, however this difference was not statistically significant (p-value = 0.664). In the Transit method, the mean mass for multi-star systems was 344.57 Earth masses, which, while distinctively lower than the Radial Velocity method, also showed no significant statistical difference compared to the 338.64 Earth masses in single-star systems (p-value = 0.903). These findings indicate that while planetary mass varies between methods, the differences between multi-star and single-star systems within each method are not pronounced enough to be statistically significant.

System Brightness

Both detection methods showed that multi-star systems were generally brighter than single-star systems. In the Radial Velocity method, the mean system brightness values for vmag, kmag, and gaia mag were notably lower for multi-star systems (indicating brighter systems), with significant p-values: vmag (p-value = 0.001), kmag (p-value = 0.026), and gaiamag (p-value = 0.0028). The Transit method reinforced this trend with even stronger statistical support: vmag (p-value = 1.06e-35), kmag (p-value = 2.40e-45), and gaiamag (p-value = 5.34e-36). These results highlight a consistent pattern where multi-star systems are brighter across both Radial Velocity and Transit methods, influencing the detectability of exoplanets.

Distance

Significant differences were noted in the distances from Earth to multi-star systems versus Earth to single-star systems across both detection methods. In the Radial Velocity method, multi-star systems were closer, with a mean distance of 60.32 parsecs compared to 88.76 parsecs for single-star systems, a difference underscored by a p-value of 0.00045. The Transit method showed a similar pattern, with multi-star systems averaging 279.08 parsecs versus 657.69 parsecs for single-star systems, supported by an extremely low p-value of 6.66e-77. This suggests that closer stellar systems may be easier to study, particularly when they are part of multi-star configurations. Moreover, the highly significant distance results in the Transit method indicate its enhanced capability, compared to the Radial Velocity method, in detecting multi-star systems that are relatively farther away.

Stellar Mass

The analysis of stellar mass between multi and single-star systems revealed that there is relative similarity across both detection methods. In the Radial Velocity method, the mean stellar mass was 1.081 Solar mass for multi-star versus 1.071 for single-star systems, with a non-significant p-value of 0.804. In the Transit method, the mean stellar masses were also close, at 1.003 Solar mass for multi-star and 0.941 for single star systems, with a p-value of 0.010, suggesting a statistical significance in mean stellar mass using the Transit method but overall indicating minimal impact from detection method.

Stellar Metallicity

Stellar metallicity measures the proportion of heavier elements than hydrogen and helium within a star, serving as an indicator of its age and formation history. Metallicity differences were particularly notable in the Radial Velocity method, where multi-star systems showed a positive mean metallicity (0.061) compared to a slightly negative mean (-0.007) in single-star systems, with a significant p-value of 0.005. In contrast, the Transit method did not show statistically significant differences in metallicity, with a p-value of 0.338, indicating that metallicity effects might be more pronounced or detectable in the Radial Velocity environments.

Discussion

This research has delineated clear differences in the proportions of exoplanets found in multi-star versus single-star systems, shedding light on the significant role stellar dynamics play in the observability and characteristics of these exoplanets. The findings from both the Radial Velocity and Transit methods underscore the influence of multi-star environments on the detection and analysis of exoplanets. Multi-star systems exhibited shorter orbital periods in the Radial Velocity method and higher brightness levels across both detection methods, suggesting that gravitational interactions and luminosity are key factors in how these planets are detected and characterized.

Interestingly, while the Transit method showed a reversed trend in orbital periods, it also highlighted the method's sensitivity in detecting further and potentially fainter multi-star systems due to its capability to measure decreases in brightness caused by transiting planets. The significant differences in system brightness and the proximity of these systems point towards a possible observational bias, where brighter and closer systems are more likely to be studied and characterized. This bias could potentially overlook fainter or more distant multi-star systems unless specific observational strategies are adapted.

Conclusion

The analysis presented in this paper confirms that the dynamical environment of multi-star systems significantly affects the detectability of exoplanets. The variations in orbital periods, system brightness, and proximity suggest that current detection methods, while robust, may still be influenced by inherent stellar properties that could either enhance or obscure the detection of planets in these complex environments. The implications of these findings are broad for the field of exoplanet discovery. They emphasize the need for refined observational techniques that can adjust for the complex dynamics of multi-star systems. Enhancing our detection methods will not only increase the accuracy of our observations but also broaden our understanding of the diverse conditions under which planets can form and exist.

Moreover, the stark differences noted in metallicity between multi-star and single-star systems in the Radial Velocity method could point to interesting directions for future research, particularly in the study of how elemental composition affects planet formation. These insights could also be pivotal in guiding future telescopic and spectroscopic studies, focusing on the nuanced interactions within multi-star systems that influence planetary formation and stability. This study enriches our understanding of the discovery of stars and planets, highlighting the importance of gravitational forces and stellar evolution. It paves the way for future explorations that could redefine our knowledge of the universe's architectural complexity and the countless undiscovered worlds orbiting stars other than our own.

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Appendix

Partial Python Code for Project Execution

```
# Load and clean data
def load_and_clean_data(file_path, filter_method):
    try:
        df = pd.read_csv(file_path, comment='#', on_bad_lines='skip')
        df = df[(df['default_flag'] == 1) &
(df['discoverymethod'].str.contains(filter_method, case=False)) &
(df['soltype'] == 'Published Confirmed')]
        return df
    except Exception as e:
        print(f"Error loading data from {file_path}: {e}")
        return pd.DataFrame()

# Analyze data and compute means for visualization
def analyze_data_for_visualization(df, multi_star_flag, method_name):
    if df.empty:
        return "No data to analyze."

    df_filtered = df[df['sy_snum'] > 1] if multi_star_flag else
df[df['sy_snum'] == 1]
    print(f"Data points for {'multi-star' if multi_star_flag else
'single-star'} systems in {method_name} dataset: {len(df_filtered)}")

    mean_values = df_filtered.agg({
        'pl_orbper': 'mean',
        'pl_rade': 'mean',
        'pl_bmasse': 'mean',
        'sy_vmag': 'mean',
        'sy_kmag': 'mean',
        'sy_gaiamag': 'mean',
        'sy_dist': 'mean',
        'st_mass': 'mean',
        'st_met': 'mean'
    }).to_frame().T.rename(index={0: method_name})

    return mean_values
```

```python
# Descriptive statistics
def descriptive_statistics(df):
    if df.empty:
        return "No data to analyze."
    return df[['pl_orbper', 'pl_rade', 'pl_bmasse', 'sy_vmag',
'sy_kmag', 'sy_gaiamag', 'sy_dist', 'st_mass', 'st_met']].describe()

# Function to perform t-tests
def perform_t_tests(df_multi, df_single):
    parameters = ['pl_orbper', 'pl_rade', 'pl_bmasse', 'sy_vmag',
'sy_kmag', 'sy_gaiamag', 'sy_dist', 'st_mass', 'st_met']
    results = {}
    for param in parameters:
        if param in df_multi.columns and param in df_single.columns:
            multi_values = df_multi[param].dropna()
            single_values = df_single[param].dropna()
            if len(multi_values) >= 2 and len(single_values) >= 2:
                t_stat, p_val = ttest_ind(multi_values, single_values,
equal_var=False)
                results[param] = (t_stat, p_val)
            else:
                results[param] = ('Insufficient data', 'N/A')
    return results

# Visualize data
def visualize_data(multi_analysis, single_analysis, method_name):
    fig, axs = plt.subplots(1, 9, figsize=(45, 5))
    parameters = ['pl_orbper', 'pl_rade', 'pl_bmasse', 'sy_vmag',
'sy_kmag', 'sy_gaiamag', 'sy_dist', 'st_mass', 'st_met']

    for i, param in enumerate(parameters):
        ax = axs[i]
        sns.barplot(x=["Single-Star", "Multi-Star"],
y=[single_analysis[param][0], multi_analysis[param][0]], ax=ax)
        ax.set_title(f'Mean {param} - {method_name}')
        ax.set_ylabel('Average Value')
    plt.tight_layout()
    plt.show()
```

Descriptive Statistics Results

Data points for multi-star systems in Radial Velocity dataset: 180
Data points for single-star systems in Radial Velocity dataset: 906
Data points for multi-star systems in Transit dataset: 286
Data points for single-star systems in Transit dataset: 3808

Descriptive Statistics for Radial Velocity Multi-Star Systems:

	pl_orbper	pl_rade	pl_bmasse	sy_vmag	sy_kmag \
count	180.000000	5.000000	178.000000	179.000000	178.000000
mean	1286.929013	7.513000	952.598418	7.653799	5.517916
std	3090.163383	5.075684	1364.126849	2.115688	2.063047
min	0.736547	1.875000	1.070000	0.872000	-3.044000
25%	36.617420	2.630000	68.005750	6.273000	4.280500
50%	355.471975	8.400000	435.409500	7.880000	5.823500
75%	1257.939773	11.994000	1195.908840	8.608900	6.553000
max	27000.000000	12.666000	7977.493020	13.740000	10.871000

	sy_gaiamag	sy_dist	st_mass	st_met
count	175.000000	180.000000	178.000000	123.000000
mean	7.425822	60.317020	1.081798	0.060577
std	1.935555	81.085027	0.438155	0.243565
min	2.926270	1.301190	0.120000	-0.660000
25%	6.176735	18.262342	0.870000	-0.090000
50%	7.609090	40.921700	1.060000	0.110000
75%	8.275320	63.474025	1.277500	0.240000
max	12.465000	848.023000	3.500000	0.545000

Descriptive Statistics for Radial Velocity Single-Star Systems:

	pl_orbper	pl_rade	pl_bmasse	sy_vmag	sy_kmag \
count	906.000000	22.000000	905.000000	898.000000	894.000000
mean	1903.053259	4.540818	1003.100178	8.231856	5.888659
std	5616.052123	4.408263	1649.495933	2.187168	1.835076
min	1.220030	1.305000	0.700000	1.125120	-1.846000
25%	24.379450	1.604000	16.170000	7.012270	5.010000
50%	348.360000	2.526000	314.640000	8.000000	6.065000
75%	1153.649645	4.470000	1144.182270	9.370000	6.822000
max	77114.071580	15.581000	9333.031170	17.650000	13.105000

	sy_gaiamag	sy_dist	st_mass	st_met
count	894.000000	904.000000	898.000000	612.000000
mean	7.909862	88.758779	1.071726	-0.007408
std	1.961889	160.182922	0.717608	0.237857
min	2.364310	3.202600	0.100000	-1.000000
25%	6.843670	22.760925	0.790000	-0.160000
50%	7.802740	44.618850	1.010000	0.020000

75%	8.938923	79.183475	1.210000	0.170000
max	14.856100	1539.710000	10.940000	0.440000

Descriptive Statistics for Transit Multi-Star Systems:

	pl_orbper	pl_rade	pl_bmasse	sy_vmag	sy_kmag \
count	285.000000	285.000000	187.000000	283.000000	283.000000
mean	32.778926	7.613975	344.566497	12.080292	10.038654
std	125.518907	6.471741	578.610422	2.107001	1.742209
min	0.355007	0.403000	0.290130	6.380000	5.149000
25%	2.977641	1.773000	15.100000	10.800000	8.926000
50%	5.358760	4.450000	193.876300	11.922000	10.109000
75%	16.068190	13.260000	386.554600	13.193000	11.084500
max	1320.100000	23.539000	4386.054000	17.260000	15.548000

	sy_gaiamag	sy_dist	st_mass	st_met
count	275.000000	274.000000	259.000000	229.000000
mean	11.847962	279.077035	1.002973	0.001153
std	2.031915	242.580544	0.377606	0.185824
min	6.252760	6.869290	0.260000	-0.550000
25%	10.641100	123.739000	0.780000	-0.100000
50%	11.780000	247.976500	0.940000	0.010000
75%	12.989300	349.549000	1.170000	0.120000
max	16.958000	1819.170000	2.770000	0.514000

Descriptive Statistics for Transit Single-Star Systems:

	pl_orbper	pl_rade	pl_bmasse	sy_vmag	sy_kmag \
count	3805.000000	3792.000000	940.000000	3804.000000	3800.000000
mean	24.638383	3.939078	338.642469	13.907983	11.822367
std	85.582372	4.175913	728.628732	1.830316	1.715164
min	0.179719	0.310000	0.070000	5.650000	4.241000
25%	4.019752	1.581500	9.600000	12.813750	10.840750
50%	8.734858	2.340000	95.348760	14.231000	12.217500
75%	20.303005	3.401500	349.611688	15.289250	13.157250
max	3650.000000	23.203000	8654.150000	20.154400	15.271000

	sy_gaiamag	sy_dist	st_mass	st_met
count	3780.000000	3722.000000	3110.000000	2869.000000
mean	13.652983	657.691694	0.940572	0.013573
std	1.780593	478.843464	0.261378	0.218749
min	5.512800	9.412630	0.090000	-0.950000
25%	12.583200	285.193750	0.810000	-0.060000
50%	14.011850	579.034500	0.950000	0.010000
75%	15.036075	921.935500	1.080000	0.090000
max	19.879000	4483.050000	2.780000	7.790000

Radial Velocity Method Analysis:

```
Multi-Star Systems:
                 pl_orbper  pl_rade   pl_bmasse   sy_vmag   sy_kmag  \
Radial Velocity  1286.929013    7.513  952.598418  7.653799  5.517916

                 sy_gaiamag   sy_dist   st_mass    st_met
Radial Velocity    7.425822  60.31702  1.081798  0.060577
Single-Star Systems:
                 pl_orbper   pl_rade    pl_bmasse   sy_vmag   sy_kmag  \
Radial Velocity  1903.053259  4.540818  1003.100178  8.231856  5.888659

                 sy_gaiamag    sy_dist   st_mass    st_met
Radial Velocity    7.909862  88.758779  1.071726 -0.007408

Transit Method Analysis:
Multi-Star Systems:
         pl_orbper   pl_rade   pl_bmasse    sy_vmag    sy_kmag  sy_gaiamag  \
Transit  32.778926  7.613975  344.566497  12.080292  10.038654   11.847962

            sy_dist   st_mass    st_met
Transit  279.077035  1.002973  0.001153
Single-Star Systems:
         pl_orbper   pl_rade   pl_bmasse    sy_vmag    sy_kmag  sy_gaiamag  \
Transit  24.638383  3.939078  338.642469  13.907983  11.822367   13.652983

            sy_dist   st_mass    st_met
Transit  657.691694  0.940572  0.013573
```

```
T-test Results for Radial Velocity Method:
pl_orbper: t-statistic = -2.078572815477523, p-value = 0.03821959232449132
pl_rade: t-statistic = 1.2097821265230324, p-value = 0.276135107291644
pl_bmasse: t-statistic = -0.4352853039293037, p-value = 0.6636805101752394
sy_vmag: t-statistic = -3.3190214124769253, p-value = 0.001032767909619274
sy_kmag: t-statistic = -2.228472204717002, p-value = 0.026791824427465378
sy_gaiamag: t-statistic = -3.018581569269549, p-value = 0.0028033685488279775
sy_dist: t-statistic = -3.530212574278309, p-value = 0.00045322452919107286
st_mass: t-statistic = 0.24779849504413407, p-value = 0.8044196311413878
st_met: t-statistic = 2.8358067921813293, p-value = 0.00511952709816263

T-test Results for Transit Method:
pl_orbper: t-statistic = 1.0763017833400341, p-value = 0.28264545025164256
pl_rade: t-statistic = 9.439646284273037, p-value = 1.0526337452066623e-18
pl_bmasse: t-statistic = 0.12207077867738349, p-value = 0.902920644248511
sy_vmag: t-statistic = -14.199425902242329, p-value = 1.0607064194041972e-35
sy_kmag: t-statistic = -16.633523470643006, p-value = 2.399318992651873e-45
sy_gaiamag: t-statistic = -14.336333819693246, p-value = 5.338714620205982e-36
```

sy_dist: t-statistic = -22.774737801719464, p-value = 6.655606968338055e-77
st_mass: t-statistic = 2.607977902633926, p-value = 0.009598417377468912
st_met: t-statistic = -0.959761983279673, p-value = 0.3380002362633865