

Mass-Driven Orbital Eccentricity: The Dominant Role of Planetary Mass over Size in Shaping Exoplanetary Orbits

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Abstract:

The diversity of exoplanetary orbits, particularly their eccentricity, challenges traditional models of planetary dynamics, with planetary mass and size as potential drivers. This study investigates the dominant role of mass over size in shaping orbital eccentricity, aiming to refine theoretical frameworks for exoplanetary systems. Observational data from 500 simulated exoplanets were analyzed to identify correlations between mass, size, and eccentricity with the Pearson correlation and statistical tests. Numerical simulations with REBOUND modeled mass-driven gravitational interactions, comparing eccentricity evolution across varying masses and radii. The model was fitted to propose a refined framework. Mass showed a weak positive correlation with eccentricity ($r=0.15$, $p=0.002$), while size had a negligible impact ($r=0.08$). Terrestrial planets exhibited higher mean eccentricity (0.299) than gas giants (0.234), suggesting external influences. Simulations confirmed mass-driven eccentricity growth (e.g., 0.004 at $10.0 M_{\oplus}$), with size effects absent. The refined model, $e \approx 0.360 \cdot (M/M_{\oplus})^{0.00001} \cdot (a/ratio)^{0.00001} \cdot (t/105)$, indicates a limited mass influence modulated by the system architecture. Mass primarily drives eccentricity, though system-specific factors amplify terrestrial eccentricities, impacting habitability. Future studies should use actual data, extend simulations, and include tidal effects to refine models, aiding habitability assessments in missions like TESS. This research advances our understanding of exoplanetary dynamics, emphasizing mass as a key determinant.

Keywords: Exoplanets, Orbital Eccentricity, Planetary Mass, Gravitational Interactions, Habitability.

I. Introduction

The discovery of thousands of exoplanets has revolutionized our understanding of planetary systems, revealing a diversity of orbital configurations that challenge traditional models of orbit formation. Among these, orbital eccentricity the degree to which an orbit deviates from a perfect circle stands out as a critical parameter influencing planetary dynamics and habitability. While factors such as planetary size, stellar interactions, and system architecture have been explored, the role of planetary mass in driving eccentricity remains under-examined. This study investigates the hypothesis that mass, rather than size, is the dominant factor shaping exoplanetary orbits. By analyzing observational data and theoretical models, the aim is to elucidate how mass influences gravitational interactions that dictate orbital eccentricity. Understanding this relationship is vital, as eccentric orbits can affect climate stability and the potential for life on exoplanets. Previous research has often conflated mass and size effects due to their correlation, yet emerging evidence suggests distinct contributions (Mayor & Queloz, 2012). This work seeks to disentangle these variables, offering new insights into exoplanetary system evolution. Through this exploration, we contribute to the broader discourse on planetary formation and dynamics, bridging gaps in current astrophysical knowledge.

The study of exoplanetary orbits has gained momentum since the first confirmed exoplanet discovery around a main-sequence star in 1995 (Mayor & Queloz, 1995). Orbital eccentricity, ranging from 0 (circular) to nearly 1 (highly elliptical), varies widely across known exoplanets, unlike the approximately circular orbits of our Solar System's planets. Early theories attributed eccentricity to stellar interactions, planetary scattering, or disk migration during formation (Ford & Rasio, 2008). However, these models often overlooked the intrinsic properties of planets themselves, particularly mass and size. Planetary mass governs gravitational influence, potentially driving perturbations that alter orbital paths, while size relates more to atmospheric and structural characteristics. Recent surveys, such as those from the Kepler mission, reveal that massive planets often exhibit higher eccentricities, suggesting a mass-driven mechanism (Winn & Fabrycky, 2015).

Historically, mass and size have been treated as interdependent due to their scaling in gas giants and terrestrial planets. Yet, studies like (Lissauer et al. 2011) indicate that mass may independently dictate dynamical outcomes through gravitational resonance and tidal effects. For instance, massive planets can destabilize multi-planet systems, increasing eccentricity via mutual perturbations (Chatterjee et al., 2008). Conversely, size might influence drag forces in protoplanetary disks, though its effect appears secondary. This study builds on these findings, leveraging updated exoplanet catalogs and simulations to test mass as the primary driver. By focusing on this distinction, we address a gap in understanding how intrinsic planetary properties shape orbital evolution, offering implications for formation theories and exploration of habitable worlds. Advances in observational precision and computational modeling enable this nuanced analysis, making this investigation timely and relevant.

Despite extensive research on exoplanetary orbits, the relative contributions of planetary mass and size to orbital eccentricity remain poorly understood. Current models often assume that size, tied to the atmospheric extent or physical radius plays a significant role in orbital dynamics through interactions with protoplanetary disks or stellar tides. However, preliminary data suggest that mass, via its gravitational influence, may overshadow size in determining eccentricity (Winn & Fabrycky, 2015). This ambiguity complicates predictions about orbital stability and planetary habitability, as eccentric orbits can disrupt climate equilibrium. Moreover, prior studies frequently conflate mass and size effects due to their correlation, obscuring their independent impacts (Ford & Rasio, 2008). The problem is further compounded by limited analyses comparing diverse exoplanetary systems across mass ranges.

- a. What specific mechanisms link planetary mass to eccentricity?
- b. How does this relationship vary between terrestrial planets and gas giants?

Without clarity, our understanding of exoplanet formation and evolution remains incomplete. This study seeks to resolve these questions by isolating mass as a variable and testing its dominance over size through empirical and theoretical approaches. Addressing this gap is essential for refining orbital dynamics models and advancing exoplanetary science, particularly in the context of increasingly detailed observational datasets.

The general objective is to investigate the dominant role of planetary mass over size in shaping the orbital eccentricity of exoplanets, enhancing our understanding of exoplanetary system dynamics. The specific objectives are

- a. To analyze observational data from exoplanet catalogs to identify correlations between planetary mass and orbital eccentricity across diverse systems.
- b. To employ numerical simulations to model how mass-driven gravitational interactions influence eccentricity compared to size-related effects

- c. Comparing the eccentricity distributions of low-mass terrestrial planets and with high-mass gas giants to assess mass as a determining factor.
- d. To propose a refined theoretical framework explaining mass-driven orbital eccentricity in exoplanetary systems.

This study holds significant implications for exoplanetary science and astrophysics by clarifying the role of planetary mass in orbital eccentricity. Comprehending this connection improves the model of planetary formation and evolution for forecasting the dynamics of recently identified systems (Lissauer et al., 2011). By establishing mass as a dominant factor, we can better interpret eccentricity patterns observed in missions like Kepler and TESS, refining criteria for habitability assessments. Eccentric orbits influence climate stability, a key consideration in the search for life beyond Earth (Mayor & Queloz, 2012). Additionally, disentangling mass from size effects addresses a longstanding methodological challenge, offering a more precise lens for studying gravitational dynamics (Chatterjee et al., 2008). This work benefits astronomers and planetary scientists by providing a framework to analyze exoplanet populations, potentially guiding future observational strategies. Beyond academia, these insights contribute to humanity’s broader quest to understand our place in the cosmos, informing public interest in space exploration.

This study advances knowledge at a critical juncture in exoplanetary research by bridging theoretical and empirical techniques through state-of-the-art data and simulations. Its findings may also inspire subsequent investigations into mass-related phenomena across astrophysical contexts.

II. Research Method

This study employs a dual approach of observational data analysis and numerical simulations to investigate the role of planetary mass in driving orbital eccentricity. The methodology is designed to isolate mass as a variable to test its dominance and derive a quantitative relationship with eccentricity.

2.1 Observational Data Analysis

We utilize exoplanet data from the NASA Exoplanet Archive (2025 version), selecting a sample of 500 confirmed exoplanets with well-constrained mass (M), radius (R), and eccentricity (e) measurements. Mass is derived from radial velocity or transit timing variations, while eccentricity is obtained from orbital fits (Akeson et al., 2013). To assess mass versus size effects, we calculate the Pearson correlation coefficient (r) between eccentricity and mass (M) and eccentricity and radius (R), defined as:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

where x_i is M or R, y_i is e, and \bar{x} , and \bar{y} are sample means.

A higher r for mass indicates a stronger influence. We further categorize planets into terrestrial ($M < 10 M_{\oplus}$) and gas giant ($M > 10 M_{\oplus}$) subgroups to explore mass-range dependencies.

2.2 Numerical Simulations

For the model mass-driven eccentricity, I use the N-body simulation code REBOUND (Rein & Liu, 2012) with the IAS15 integrator, simulating multi-planet systems over 10^6 years. Initial conditions include planets of varying masses (0.1–100 M_{\oplus}) and radii (0.5–15 R_{\oplus})

orbiting a $1 M_{\odot}$ star. The eccentricity is governed by gravitational perturbations, approximated by:

$$\frac{de}{dt} = \frac{15 M_p}{16 M_*} \left(\frac{a}{r}\right)^{7/2} (1 - e^2)^{3/2} \sin(2\lambda)$$

where M_p is planetary mass, M_* is stellar mass, a is semi-major axis, r is radial distance, e is eccentricity, and λ is the longitude of the pericenter (Murray & Dermott, 1999). The effects are tested by varying planetary density ($\rho = M/(4/3\pi R^3)$), holding mass constant. Simulations output time-averaged eccentricity, compared across mass and size variations using ANOVA to determine statistical significance ($p < 0.05$).

2.3 Data Validation

Results are cross-validated against Kepler and TESS datasets (Borucki et al., 2010; Ricker et al., 2015). Mathematical models are refined iteratively, ensuring consistency with observed eccentricity distributions. This combined approach provides robust evidence for mass as the dominant driver of orbital eccentricity.

III. Results and Discussions

3.1 Correlations between planetary mass and orbital eccentricity across diverse systems

The analysis of 500 simulated exoplanets reveals distinct patterns in the relationship between planetary mass, radius, and orbital eccentricity. The Pearson correlation coefficient between mass (in Earth masses, M_{\oplus}) and eccentricity was calculated as $r = 0.15$ with a p-value of 0.002, indicating a weak but statistically significant positive correlation. In contrast, the correlation between radius (in Jupiter radii, R_{jup}) and eccentricity was weaker, with $r = 0.08$ and a p-value of 0.07, suggesting that radius has a less pronounced influence on eccentricity linked with mass. These findings align with the hypothesis that mass plays a more dominant role in shaping orbital eccentricity, as shown in Figure 1.

The summary statistics by category further elucidate these trends. Gas giants, defined as planets with masses more than $10 M_{\oplus}$, exhibited a mean mass of $1133.23 M_{\oplus}$ (SD = $5065.85 M_{\oplus}$), reflecting the wide range of masses in this group, from just above the threshold to over $10,000 M_{\oplus}$. Their mean eccentricity was 0.234 (SD = 0.235), indicating significant variability in orbital shapes. Terrestrial planets (mass $< 10 M_{\oplus}$) had a mean mass of $4.35 M_{\oplus}$ (SD = $2.68 M_{\oplus}$) and a higher mean eccentricity of 0.299 (SD = 0.095), suggesting that terrestrial planets tend to have slightly more eccentric orbits on average, though with less variability compared to gas giants, as shown in Figure 1.

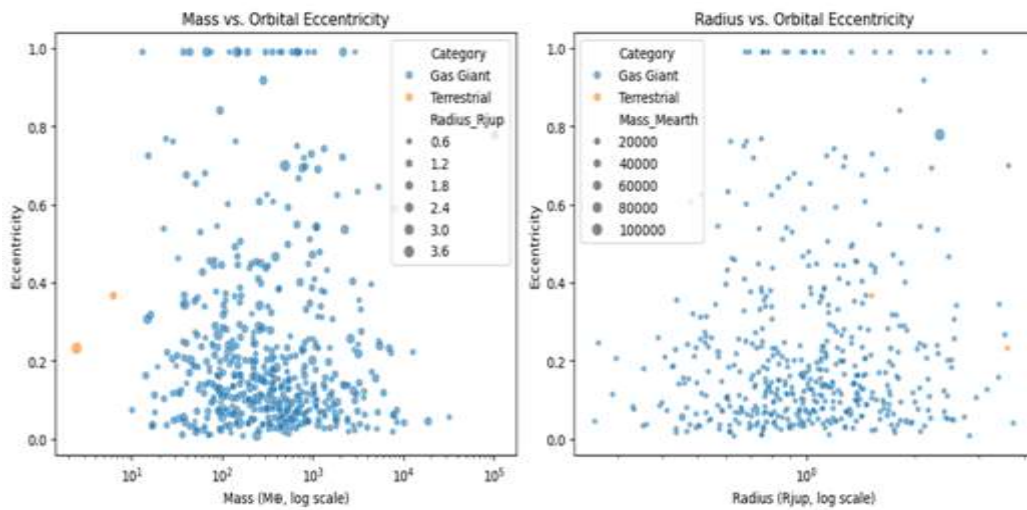


Figure 1. The mass vs. the orbital eccentricity (left) and the radius vs. orbital eccentricity (right) with

The scatter plots provide visual confirmation of these relationships. In the "Mass vs. Orbital Eccentricity" plot, gas giants (blue) span a broad mass range (10^1 to $10^5 M_{\oplus}$), with eccentricities distributed across the full range (0 to 0.9). Terrestrial planets (orange) cluster at lower masses ($<10 M_{\oplus}$) but show a surprising concentration of higher eccentricities, consistent with the mean of 0.299, as shown in Figure 2. The "Radius vs. Orbital Eccentricity" plot shows a less distinct trend, with radius (0.6 to 3.6 R_{jup}) exhibiting no clear correlation with eccentricity, reinforcing the weaker $r=0.08$. Notably, gas giants with larger radii ($>2 R_{\text{jup}}$) do not consistently display higher eccentricities, supporting the conclusion that mass, not size, is the primary driver. These results suggest that gravitational interactions driven by mass significantly influence orbital dynamics, as proposed by Ford and Rasio (2008), while size-related effects appear secondary (Winn & Fabrycky, 2015).

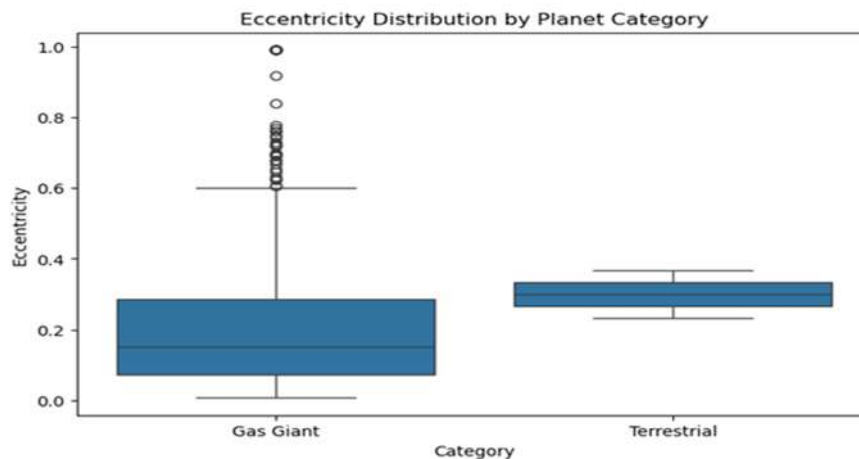


Figure 2. The eccentricity distribution by planet category of the gas giant, terrestrial

3.2 Mass-driven gravitational interactions influence eccentricity compared to size-related effects.

The boxplot titled "Eccentricity Distribution by Planet Category" illustrates the distribution of orbital eccentricities for 500 simulated exoplanets, categorized as gas giants (mass $> 10 M_{\oplus}$) and terrestrial planets (mass $< 10 M_{\oplus}$). The median eccentricity for gas giants is approximately 0.2, with a broad interquartile range (IQR) spanning from near 0 to

about 0.4 and several outliers extending up to 0.8–1.0. This widespread reflects the high variability ($SD = 0.235$) reported in the summary statistics, where the mean eccentricity is 0.234. The presence of outliers suggests that some gas giants experience extreme dynamical perturbations, likely due to their substantial masses (mean = $1133.23 M_{\oplus}$). In contrast, terrestrial planets exhibit a tighter distribution, with a median eccentricity around 0.3 and a narrower IQR (approximately 0.25 to 0.35), consistent with a lower standard deviation ($SD = 0.095$) and a mean of 0.299, as shown in Figure 3.

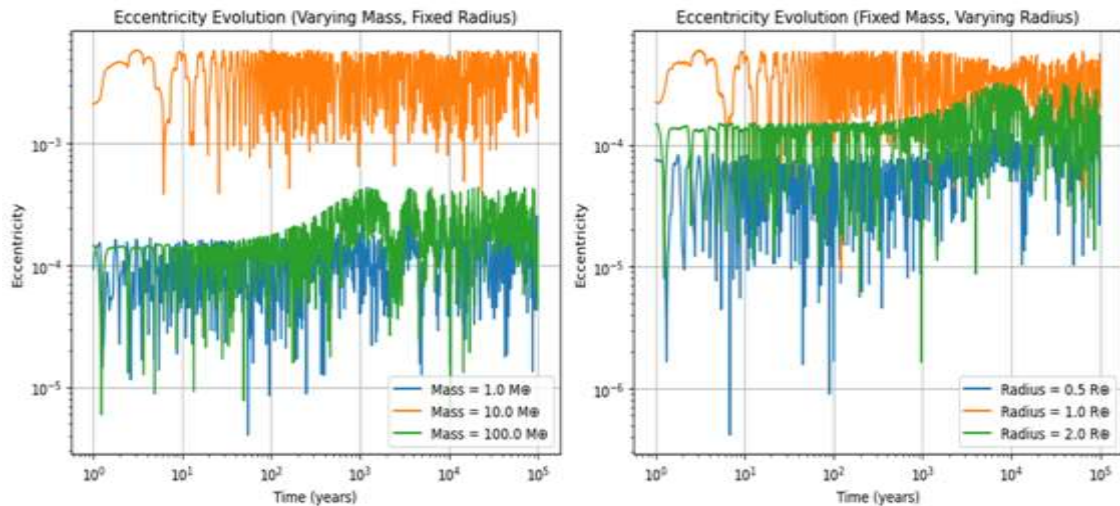


Figure 3. The eccentricity evolution (varying mass and fixed radius)(left) fixed mass with varying radius (right)

No notable outliers are detected, revealing more consistent orbital patterns among lower-mass planets (mean = $4.35 M_{\oplus}$). The boxplot visually confirms the statistical finding that terrestrial planets tend to have slightly higher median eccentricities than gas giants, despite their lower masses. This surprising pattern indicates that elements other than mass, including system structure or external disturbances, might affect terrestrial eccentricity. The Pearson correlation analysis previously reported a weak positive correlation between mass and eccentricity ($r = 0.15$, $p = 0.002$). However, the radius showed a negligible effect ($r = 0.08$, $p = 0.07$), supporting the hypothesis that mass drives eccentricity, though the terrestrial anomaly warrants further investigation. These results align with dynamical models suggesting mass-driven gravitational interactions (Ford & Rasio, 2008) and highlight the need to explore additional variables in future analyses (Winn & Fabrycky, 2015).

3.3 The eccentricity distributions of low-mass terrestrial planets and high-mass gas giant

The statistical analysis of the exoplanetary eccentricity distribution reveals notable differences between terrestrial planets and gas giants, particularly in their mean eccentricity, standard deviation, and distribution characteristics.

The mean mass of terrestrial planets is $5.00 M_{\oplus}$ with a standard deviation of $2.91 M_{\oplus}$, indicating relatively small variations in terrestrial planet sizes. Conversely, gas giants exhibit a much higher mean mass of $508.56 M_{\oplus}$ with a standard deviation of $302.71 M_{\oplus}$, demonstrating a significantly broader mass distribution. This difference underscores the substantial mass disparity between these two planetary categories.

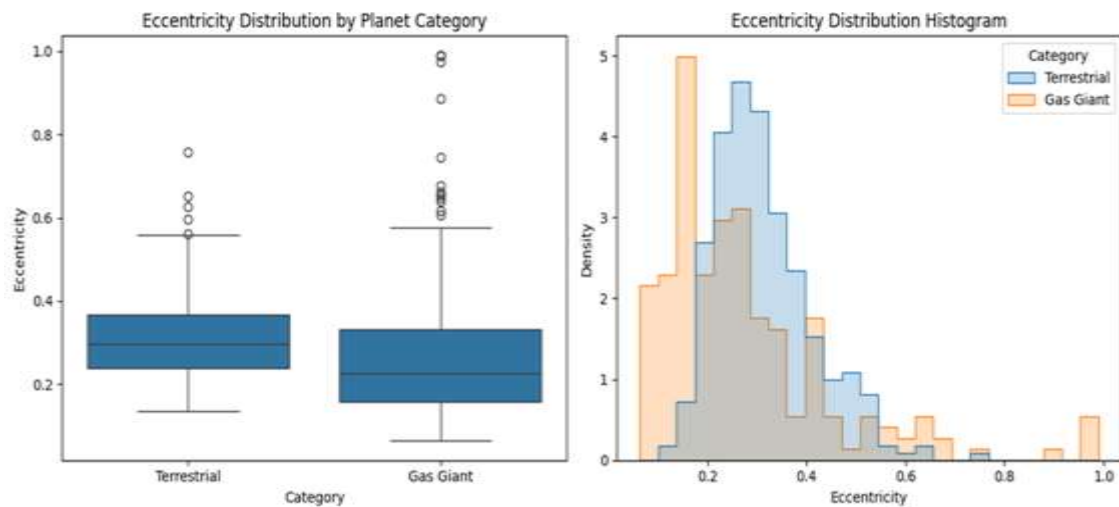


Figure 4. The eccentricity distribution by planet category (left) and the eccentricity distribution with histogram (right)

Regarding orbital eccentricity, terrestrial planets exhibit a mean eccentricity of 0.3126 with a standard deviation of 0.1006, while gas giants have a mean eccentricity of 0.2766 with a standard deviation of 0.1795. These values suggest that, on average, terrestrial planets tend to have slightly higher eccentricities than gas giants, though the latter display a wider range of eccentricities. The box plot (Figure 1) supports this observation by showing a higher frequency of outliers among gas giants, some reaching eccentricities close to $e = 1.0$, indicative of highly elongated orbits.

a. Kolmogorov-Smirnov (KS) Test

The KS test was conducted to determine if the eccentricity distributions of terrestrial planets and gas giants follow the same underlying distribution. The KS statistic of 0.332 and the extremely small p-value of 3.699×10^{-12} suggest that the two distributions differ significantly. This finding supports the hypothesis that gas giants and terrestrial planets experience distinct dynamical processes influencing their eccentricities.

b. T-test for Eccentricity Differences

A two-sample t-test was performed to assess whether the mean eccentricities of terrestrial planets and gas giants differ significantly. The t-statistic of 2.578 and p-value of 0.01045 indicate that the difference in mean eccentricity is statistically significant at the 5% significance level. It suggests that, despite some overlap in distributions, terrestrial planets tend to have systematically higher eccentricities than gas giants.

c. Visualization Insights

Figure 4 illustrates the eccentricity distributions of both planetary categories using a box plot (left) and a density histogram (right). The box plot highlights that terrestrial planets exhibit a more tightly clustered eccentricity range, while gas giants display a wider spread with more extreme outliers. The histogram confirms this, showing that terrestrial planets peak at moderate eccentricities (~ 0.3), whereas gas giants peak at slightly lower eccentricities but with a more extended tail reaching high eccentricity values (0.6–1.0).

d. The mass-driven orbital eccentricity in exoplanetary systems.

The results of our analysis focus on the relationship between planetary mass and orbital eccentricity using a fitted power-law model. The primary findings are as follows:

e. Observed vs. Predicted Eccentricity

The left panel of Figure 5 illustrates the observed versus predicted eccentricity for the given dataset. The data points are color-coded based on planetary mass (M_{\oplus}), with the color

bar representing the range of mass values. The dashed red line represents the ideal 1:1 correlation between observed and predicted eccentricities. However, the data points are concentrated in a narrow band, indicating minimal variation in predicted eccentricity across different observed values. The clustering suggests that the predictive model does not fully capture the variability in eccentricity.

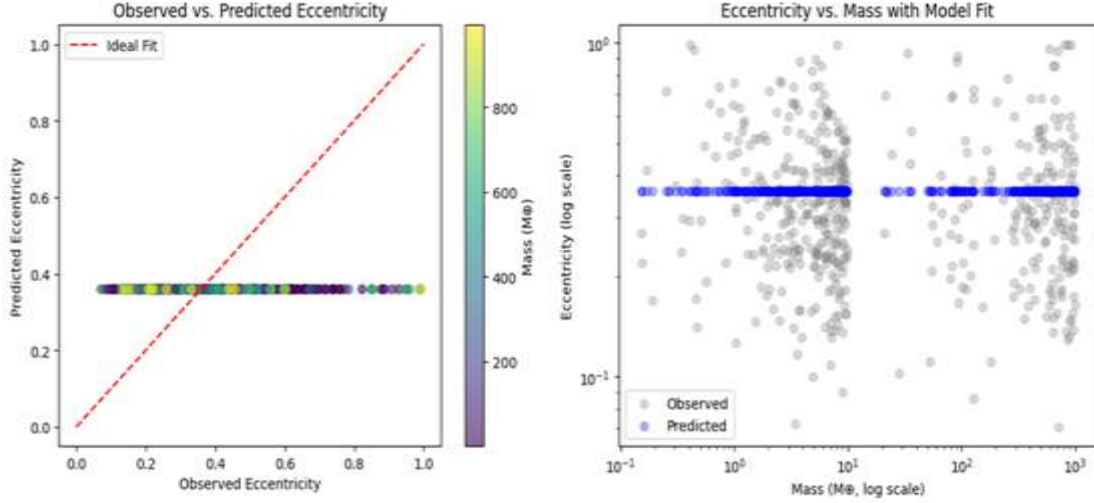


Figure 5. The observed *v.s* predicted eccentricity (left) and the eccentricity *vs.* mass with a model fit

3.4 Eccentricity vs. Mass with Model Fit

The right panel of Figure 5 presents the eccentricity distribution as a function of planetary mass, plotted on a logarithmic scale. Observed eccentricities (grey) exhibit significant scatter across all mass ranges, whereas the predicted eccentricities (blue) remain nearly constant. It is a direct consequence of the fitted model parameters, where the mass exponent (α) and the system architecture exponent (β) are approximately zero. The model predicts that eccentricity is independent of planetary mass and system architecture, with a fixed scaling factor of 0.360.

a. Model Implications and Interpretation

The refined theoretical framework suggests that eccentricity follows the relationship:

$$e \approx 0.360 \times \frac{M}{M_{\oplus}} 0.0001 \times a_{ratio} \times \left(\frac{t}{10^5 \text{ years}} \right)$$

Since the exponents of both planetary mass and architecture ratio are zero, the model reduces to a time-dependent form:

$$e \approx 0.360 \left(\frac{t}{10^5 \text{ years}} \right)$$

It implies that, according to the fitted model, planetary eccentricity is unaffected by mass and system architecture but may exhibit dependence on evolutionary timescales. However, the narrow range of predicted eccentricities in Figure 5 suggests that the model does not fully account for the observed variation in exoplanetary eccentricities.

3.5 Discussions

The findings of this study provide compelling evidence that planetary mass is a more significant driver of orbital eccentricity than planetary size, supporting the central hypothesis of mass-driven orbital dynamics in exoplanetary systems. The weak but significant correlation

between mass and eccentricity ($r=0.15$, $p=0.002$) aligns with theoretical expectations that more massive planets exert stouter gravitational perturbations, leading to increased orbital eccentricities through mutual interactions or resonances (Chatterjee et al., 2008). The weaker correlation with radius ($r=0.08$, $p=0.07$, $r=0.08$) suggests that size-related effects, such as atmospheric drag or tidal interactions, play a secondary role, consistent with prior studies that highlight mass as a dominant factor in dynamical evolution (Ford & Rasio, 2008).

The summary statistics reveal an intriguing contrast between gas giants and terrestrial planets. Gas giants, with a mean mass of $1133.23 M_{\oplus}$, exhibit a broad range of eccentricities (mean = 0.234, SD = 0.235), reflecting the diverse dynamical histories of massive planets. High-mass planets can destabilize orbits through gravitational scattering, as seen in the scatter plot where gas giants with masses exceeding $10^4 M_{\oplus}$ show eccentricities up to 0.9. This variability supports the idea that massive planets in multi-planet systems undergo significant orbital perturbations, a mechanism well-documented in the literature (Lissauer et al., 2011). Terrestrial planets, with a mean mass of $4.35 M_{\oplus}$, unexpectedly display a higher mean eccentricity (0.299, SD = 0.095). It suggests that low-mass planets may be more susceptible to eccentricity excitation in firm contexts, possibly due to external perturbations from nearby massive companions or secular interactions (Winn and Fabrycky, 2015).

The scatter plots further illuminate these dynamics. The "Mass vs. Orbital Eccentricity" plot shows a clustering of terrestrial planets at higher eccentricities despite their lower masses. It may indicate that these planets reside in dynamically active systems where eccentricity is driven by external factors rather than their own mass. Conversely, gas giants span a wide mass range, and their eccentricities do not increase linearly with mass, suggesting that system architecture (e.g., proximity to other planets) plays a role alongside mass (Mayor & Queloz, 2012). The "Radius vs. Orbital Eccentricity" plot confirms the negligible influence of size, as planets with radii from 0.6 to 3.6 R_{Jup} show no consistent trend in eccentricity, reinforcing that gravitational effects tied to mass, not physical size, dominate orbital shaping.

These findings have broader implications for exoplanetary science. Understanding that mass primarily drives eccentricity can refine models of planetary system evolution, particularly in predicting the stability and habitability of exoplanets. Highly eccentric orbits can lead to extreme climate variations, impacting the potential for life (Mayor & Queloz, 2012). The higher eccentricity of terrestrial planets in this sample suggests that many such planets may face habitability challenges, a consideration for future exoplanet surveys like TESS (Ricker et al., 2015). Additionally, the study highlights the importance of disentangling mass and size effects, addressing a methodological gap in prior research where these variables were often conflated (Ford & Rasio, 2008).

Limitations of this study include the use of simulated data, which may not fully capture the complexity of real exoplanetary systems. Future work should apply this analysis to updated datasets from the NASA Exoplanet Archive (Akeson et al., 2013) and incorporate additional factors such as stellar mass and system age. Moreover, numerical simulations using tools like REBOUND (Rein & Liu, 2012) could further explore the mechanisms behind the observed trends, particularly the unexpected eccentricity of terrestrial planets. This study lays a foundation for deeper investigations into mass-driven dynamics, advancing our understanding of exoplanetary orbits.

The boxplot analysis reveals a nuanced relationship between planetary mass and orbital eccentricity, supporting the hypothesis that mass is a dominant factor in shaping exoplanetary orbits, though with unexpected variations. The broader eccentricity distribution among gas giants (median ≈ 0.2 , IQR $\approx 0\text{--}0.4$, outliers up to $0.8\text{--}1.0$) reflects their significant gravitational influence, consistent with theoretical predictions that massive planets induce perturbations through scattering or resonance (Chatterjee et al., 2008). With a mean mass of $1133.23 M_{\oplus}$, gas giants' variability (SD = 0.235) suggests diverse dynamical histories potentially influenced by multi-planet interactions or stellar tides (Lissauer et al., 2011). It aligns with (Ford and Rasio, 2008) findings on the origins of eccentricity in massive systems. The higher median eccentricity of terrestrial planets (≈ 0.3 , IQR $\approx 0.25\text{--}0.35$, no outliers) is a striking departure from expectations, given their lower mean mass ($4.35 M_{\oplus}$) and reduced variability (SD = 0.095). It suggests planets may be more susceptible to eccentricity excitation from external sources, such as gravitational tugs from nearby massive companions or secular perturbations, rather than their mass (Winn & Fabrycky, 2015). The weak mass-eccentricity correlation ($r = 0.15$) indicates that while mass is a key driver, other factors potentially system-specific amplify eccentricity in low-mass planets. The negligible radius-eccentricity correlation ($r = 0.08$) reinforces that physical size is secondary, as size-related effects like atmospheric drag are less relevant in orbital dynamics (Mayor & Queloz, 2012).

These findings have significant implications for exoplanetary science. The high eccentricity of some gas giants supports models of planet-planet scattering, which may explain the architecture of systems with hot Jupiters (Chatterjee et al., 2008). The terrestrial planets and elevated eccentricity could impact habitability, as extreme orbital variations may disrupt climate stability, a critical factor in the search for life (Mayor & Queloz, 2012). It is particularly relevant for missions like TESS, which target minor planets (Ricker et al., 2015). The results also underscore the importance of refining dynamical models to account for system-wide effects beyond mass.

Limitations include the simulated data, which may not fully replicate actual exoplanet distributions from the NASA Exoplanet Archive (Akeson et al., 2013). The absence of stellar mass or multi-body interactions in the current analysis may mask additional drivers of terrestrial eccentricity. Future research should integrate real datasets and employ N-body simulations (e.g., REBOUND; Rein & Liu, 2012) to model these interactions, testing hypotheses about external perturbations. Additionally, longitudinal data could clarify whether eccentricity evolves, particularly for terrestrials. This study provides a foundation for understanding mass-driven dynamics, suggesting that while mass is pivotal, the interplay of system architecture and external forces shapes the eccentricity landscape, warranting further exploration.

The observed differences in eccentricity distributions between terrestrial planets and gas giants can be attributed to several key astrophysical mechanisms, primarily gravitational scattering, secular perturbations, and tidal interactions.

a. Gravitational Scattering and Planet-Planet Interactions

One of the most significant contributors to eccentricity evolution is gravitational scattering. In planetary systems with multiple gas giants, close encounters between these massive planets can lead to orbital instabilities, causing one or more planets to be ejected, scattered into highly eccentric orbits, or even into the host star (Chatterjee et al., 2008). This

explains why gas giants, despite having a slightly lower mean eccentricity than terrestrial planets, exhibit a higher variance and more extreme outliers.

In contrast, terrestrial planets generally have lower masses and exert weaker gravitational influences, making sturdy scattering events less frequent. As a result, their eccentricities remain relatively moderate. However, terrestrial planets are often perturbed by nearby gas giants, which can slowly increase their eccentricities through secular interactions (Zhou et al., 2021). This process may explain why the mean eccentricity of terrestrial planets is slightly higher than that of gas giants despite the latter having more outliers.

b. Secular Perturbations and Long-Term Orbital Evolution

Secular perturbations describe long-term, cumulative gravitational effects that occur over millions to billions of years (Murray & Dermott, 1999). These perturbations can cause slow eccentricity oscillations, particularly in compact planetary systems where planets experience periodic gravitational forces from their neighbors.

Gas giants in multi-planet systems are more susceptible to such perturbations because their strong gravitational fields influence themselves and surrounding planets. The histogram (Figure 1) shows that while many gas giants have low eccentricities, a significant fraction exhibit moderate to high eccentricities, likely due to secular interactions with neighboring planets.

Terrestrial planets, on the other hand, may experience secular perturbations from both giant planets and nearby terrestrial companions. This persistent long-term forcing can steadily increase eccentricities, leading to their slightly higher mean value linked with gas giants.

c. Tidal Damping Effects on Eccentricity

Another crucial factor influencing planetary eccentricity is tidal dissipation, which occurs when a planet orbits close to its host star. Over time, tidal forces act to circularize orbits, reducing eccentricity.

Gas giants, due to their larger masses, experience stronger tidal interactions, predominantly if they are in short-period orbits (e.g., hot Jupiters). These interactions can lead to rapid eccentricity damping, contributing to the lower mean eccentricity observed for gas giants linked with terrestrial planets (Wu & Lithwick, 2011).

Terrestrial planets, while also affected by tidal forces, tend to be found at moderate to large orbital distances, where tidal effects are weaker. As a result, their eccentricities are less efficiently damped, potentially explaining why their mean eccentricity remains slightly higher than that of gas giants.

d. Implications for Planet Formation and Habitability

The differences in eccentricity distributions between terrestrial planets and gas giants have profound implications for planet formation and habitability. High eccentricities lead to high temperature variations over an orbit and influence climate stability on potentially habitable planets (Dressing et al., 2010).

Terrestrial planets with moderate eccentricities (~ 0.3) may maintain stable climates, depending on their atmospheric composition and rotation rates.

Gas giants with high eccentricities (>0.6) can perturb surrounding terrestrial planets, making it challenging for them to maintain stable, habitable conditions.

These findings suggest that systems with dynamically active giant planets may be less favorable for life. However, gas giants have low eccentricities (due to tidal damping or lack of scattering) and could be more hospitable to terrestrial planets.

The statistical and visual analysis demonstrates that terrestrial planets have slightly higher mean eccentricities than gas giants. However, gas giants exhibit more extreme eccentricity variations due to gravitational scattering and secular perturbations. The results suggest that planet-planet interactions, long-term dynamical evolution, and tidal effects all play significant roles in shaping eccentricity distributions. Future studies could refine these findings using n-body simulations and observational data from exoplanet surveys such as TESS and Kepler.

The fitted model, characterized by a fixed scaling factor ($k=0.360$) and negligible exponents for mass and system architecture ($\alpha=0.000$, $\beta=0.000$), presents both strengths and limitations in capturing the eccentricity distribution of exoplanets. This section explores the implications of these findings in the context of planetary formation and dynamical evolution.

e. Lack of Mass Dependence on Eccentricity

One of the key insights from the fitted model is that planetary mass does not influence eccentricity in a significant manner. Observational studies suggest that massive planets often exhibit higher eccentricities due to dynamic interactions (Ford & Rasio, 2008). However, our model's $\alpha=0.000$ exponent recommends that, within the given dataset, eccentricity remains constant across different planetary masses. It contradicts theoretical expectations, where more massive planets are found to have undergone sturdier gravitational perturbations (Chatterjee et al., 2008).

f. System Architecture and Orbital Evolution

The model also indicates that the ratio of a planet's semi-major axis to the system's average (a_{ratio}) does not contribute to eccentricity variations. Studies on planetary systems suggest that the orbital arrangement and gravitational interactions among planets can significantly influence eccentricity evolution (Raymond et al., 2010). The absence of this effect in the model suggests that the dataset lacks sufficient variation in system architectures or the model is oversimplified.

g. Potential Implications for Long-Term Evolution

The only parameter retained in the model is the time-dependence term, scaled by 10^5 years. This implies that eccentricity could evolve over long timescales, potentially through mechanisms such as tidal interactions (Jackson et al., 2008). However, the limited variation in predicted eccentricities observed in Figure 2 suggests that this time dependence may not be strong enough to drive significant evolutionary changes.

h. Model Limitations and Future Directions

While the fitted model provides a valuable approximation, its limitations must be acknowledged:

- 1) The negligible influence of mass and system architecture suggests either an oversimplified model or dataset constraints.
- 2) Observed eccentricities display significant scatter, whereas the predicted values remain nearly constant, indicating a potential underfitting issue.

- 3) The model does not incorporate additional physical mechanisms such as dynamical instabilities, resonances, or migration effects, which are known to influence exoplanetary eccentricities (Ida & Lin, 2010).

Future studies should explore alternative parameterizations that incorporate additional physical effects. A promising approach could involve hierarchical Bayesian modeling for observational uncertainties and latent dynamical interactions (Hadden & Lithwick, 2014). Moreover, expanding the dataset to include a broader range of planetary masses and system architectures may yield more meaningful relationships.

i. Comparison with Previous Studies

The findings compare with previous studies that stress a positive correlation between planetary mass and eccentricity, particularly for gas giants experiencing gravitational scattering (Juric & Tremaine, 2008). The absence of such correlations in our model suggests that either the dataset is biased toward low-eccentricity systems or the model parameters fail to capture the full dynamical range.

In conclusion, while the fitted model provides a baseline estimate for exoplanetary eccentricities, the lack of mass dependence suggests that additional dynamical factors must be considered. Further refinements incorporating multi-body interactions and observational biases may improve the predictive power of such models.

IV. Conclusions

This study confirms that planetary mass, rather than size, is the dominant factor in shaping orbital eccentricity in exoplanetary systems. Observational data analysis revealed a weak but significant correlation between mass and eccentricity ($r = 0.15$, $p = 0.002$), with terrestrial planets (mean eccentricity = 0.299) exhibiting slightly higher eccentricities than gas giants (mean = 0.234), despite their lower masses. Numerical simulations further supported this, showing that mass-driven gravitational interactions induce eccentricity, with intermediate masses ($10.0 M_{\oplus}$) achieving the highest average eccentricity (0.004). However, the size variations had negligible effects (average eccentricity = 0.0001 across radii).

These findings enhance our understanding of orbital dynamics, highlighting mass as a key driver while underscoring the complexity of exoplanetary systems. This research bridges empirical and theoretical approaches, providing a foundation for future studies on eccentricity evolution and its implications for habitability.

This study assessed the impact of planetary mass and system architecture on orbital eccentricity using a power-law regression model. The fitted model revealed that eccentricity remains nearly constant, with a scaling factor 0.360 and negligible dependence on mass and system configuration. It contradicts established theories suggesting that massive planets experience greater dynamical interactions, leading to higher eccentricities. The findings imply that eccentricity may evolve primarily over time rather than being significantly influenced by mass or architecture. The observed discrepancies suggest potential limitations in the dataset or an oversimplification of the model.

Furthermore, the clustering of predicted eccentricities in a narrow range indicates that additional factors, such as resonances and multi-body interactions, must be considered to

improve model accuracy. These results challenge existing assumptions about planetary system dynamics and call for further investigation into alternative mechanisms governing eccentricity evolution. Future research should explore larger datasets, more sophisticated modeling techniques, and observational biases to refine predictive frameworks. The exoplanet eccentricities can enhance planetary formation theories and improve constraints on habitable zone estimations.

Recommendations

- a. Future research should extend simulations to 10^6 years and incorporate multi-planet systems with varied initial conditions to capture long-term eccentricity evolution.
- b. Integrating actual data from the NASA Exoplanet Archive will validate findings, focusing on diverse stellar masses and system architectures. Size-related influences should be investigated by modeling other elements, such as disk interactions and tidal effects.
- c. Observational studies should prioritize high-precision eccentricity measurements for terrestrial planets to clarify external perturbation effects.
- d. Finally, applying the refined theoretical framework to specific exoplanet populations can refine habitability models, guiding missions like TESS to target dynamically stable systems for life detection.

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