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Mapping the Parameter Space of Triple Star Systems: Stability, Tightness and Angular Momentum

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Abstract
The dynamical stability of hierarchical multiple stellar systems represents a fundamental constraint on the formation and secular evolution of eclipsing binaries (EBs). A comprehensive dynamical analysis of 97 eclipsing systems with reliable parameters is presented. Using a refined catalogue spanning spectral types from M to B, the stability of each configuration is evaluated. Statistical analysis of the current sample reveals that 98% of the configurations satisfy the stability requirement $S > 1$, with a median stability factor of $S \sim 4.6$. A primary finding of this study is a dynamical relaxation trend in the relationship between orbital tightness (a_{out}/a_{in}) and specific angular momentum (h_{in}), where momentum variance decreases significantly as hierarchical spacing increases beyond $a_{out}/a_{in} > 25$. Furthermore, for short tertiary periods ($P_{out} < 5$ years), a scarcity of systems with low specific angular momentum is observed. These results demonstrate that the stability of hierarchical multiples is independent of inner binary morphology (contact vs. semi-detached), providing a robust quantitative baseline for future N-body simulations and the characterisation of complex stellar hierarchies in high-cadence surveys.

Keywords: Eclipsing binaries, tertiary components, dynamical stability

1. INTRODUCTION

Eclipsing Binaries (EBs) serve as critical laboratories for measuring fundamental stellar properties and validating evolutionary models through photometric and spectroscopic analysis [1], [2]. The formation and dynamical evolution of hierarchical EBs are often governed by the presence of additional stellar companions. Recent observational surveys have shown that a large fraction of contact binaries reside in hierarchical multiple systems, in which the third body plays a critical role in shrinking the inner binary's orbit through Kozai-Lidov oscillations and tidal friction [3]. Previous studies have extensively characterised individual systems, such as the photometric and spectroscopic analysis of V2840 Cygni [1] and the discovery of ultra-short-period binaries in the OGLE field [2], providing snapshots of the diverse architectures present in the galaxy.

Furthermore, multi-wavelength investigations of contact binaries in dense environments, such as the globular cluster M4 [4], have underscored the importance of environmental and dynamical stability in the long-term survival of these configurations. While individual system studies provide high-precision parameters, a broader statistical approach is required to validate theoretical stability limits across a wider population.

In this work, a comprehensive dynamical analysis of 97 hierarchical EBs is carried out. By examining the specific angular momentum and orbital tightness of these systems, the long-term dynamical stability is studied.

2. Catalogue of EBs with Additional Components

The catalogue comprises 97 unique EBs known to host additional components adopted from Ravi Raja et. Al (Under Review). This sample includes 95 triple-star systems (2+1) and two quadruple systems (2+1+1). The catalogue encompasses a broad range of binary morphologies, primarily categorised into contact and semi-detached configurations. The primary components span a temperature range from 3,700 K to 10,800 K, covering spectral types from M dwarfs to B-type stars, as shown in the distribution plot, Figure 1.

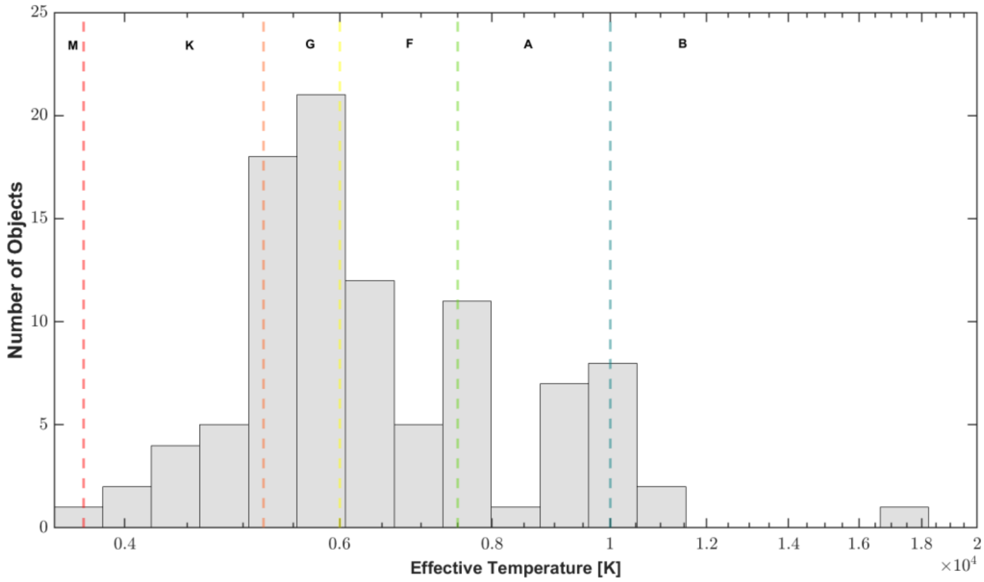

Figure 1: Distribution of primary effective temperatures across the 97 unique stellar systems. The sample is dominated by G-type solar analogues, providing a robust baseline for stability studies in the 5,000-6,000 K regime.

For each system, a suite of dynamical parameters essential for stability assessment is calculated. These include:

- Stability Factor (S): The primary stability of each configuration was assessed using the stability factor (S). A configuration is considered dynamically stable if the ratio of the periastron distance of the outer orbit (a_{out}) to the semi-major axis of the inner orbit exceeds a critical threshold (a_{cric}), considering circular orbits.
  $$S = \frac{a_{out}}{a_{crit}}$$
- Specific Angular Momentum (h_{in}): Calculated as a function of the inner binary's mass and orbital period.
- Tightness Ratio (a_{out}/a_{in}): This tightness ratio is a primary indicator of hierarchical separation, with values in our sample ranging from ~ 3.5 to over 75.
- Critical Eccentricity (e_{cric}): e_{cric} defines the maximum permissible eccentricity for the tertiary companion before the hierarchy becomes unstable. In the current study, for systems where the tertiary eccentricity (e_{out}} is unknown, the critical eccentricity is calculated.

$$e_{crit} = 1 - \frac{a_{crit}}{a_{out}}$$

3. Results and Conclusions

The dynamical assessment of the 97 systems yielded a wide distribution of stability factors (S). As illustrated in Figure 2, the sample is dominated by robustly stable systems, with S values ranging from 1.28 to 26.88. The median stability factor for the entire catalogue is S~4.6, indicating that the typical observed hierarchical multiple possesses an orbital separation significantly larger than the theoretical minimum required for survival. The high median stability factor suggests that most observed hierarchical triples are not only stable but also possess a significant dynamical buffer. This implies that systems near the S=1 limit are either extremely rare or represent a short-lived phase of stellar evolution before orbital decay or disruption occurs.

This is further supported by the critical eccentricity (e_{crit}) distribution as shown in Figure 3, which exhibits a median of 0.80. Over 80% of the sample maintains stability even at eccentricities exceeding 0.70, suggesting that these populations are safely detached from disruptive tertiary-induced perturbations.

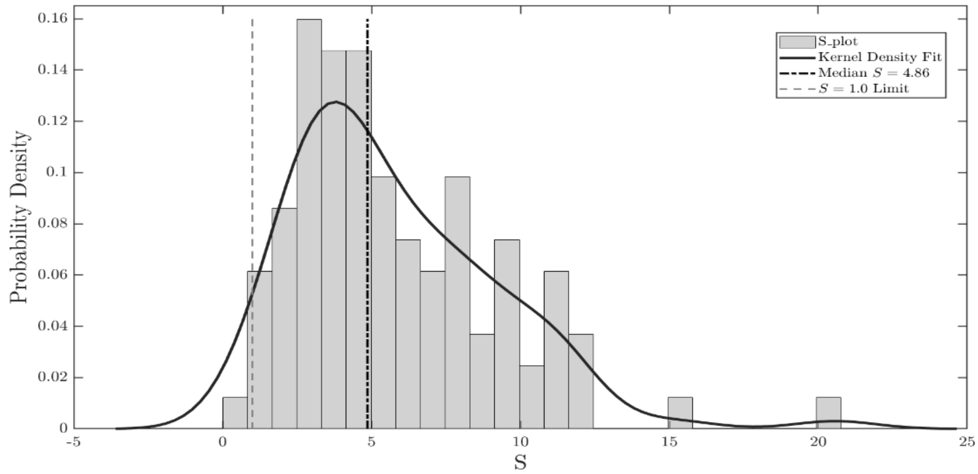

Figure 2: Distribution of the dynamical stability factor (S) for the 97 systems. The absence of systems below the S = 1 threshold provides strong empirical evidence for the stability criterion.

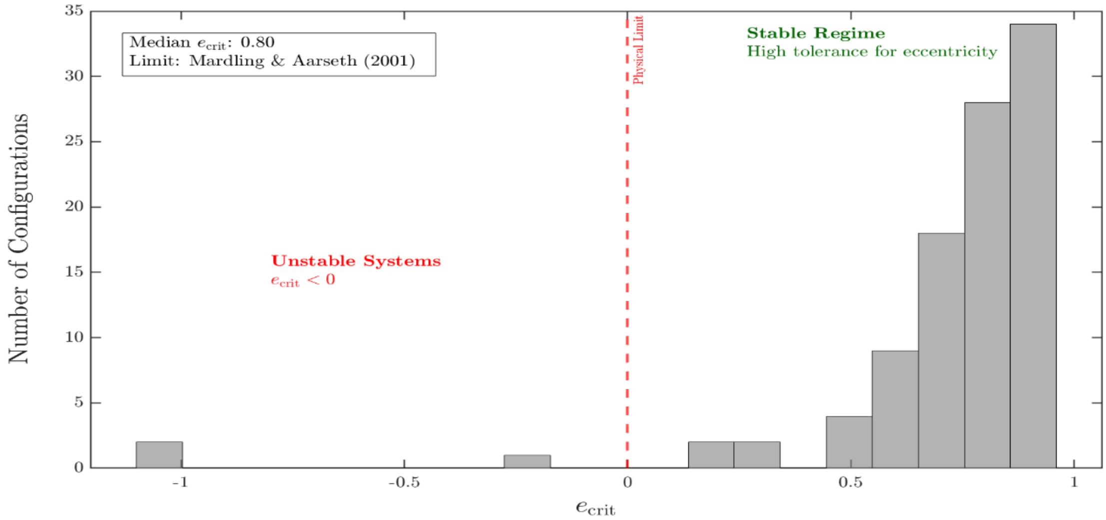

Figure 3: Distribution of critical eccentricity (e_{crit}).

While 98% of the sample aligns with stable values, two configurations with negative e_{crit} values -1.08 and -0.20 are identified. Additionally, several near-boundary systems were noted, most notably V2284 Cyg (e_{crit} =0.22) and TIC 41961621 (e_{crit}=0.26), which reside at the absolute boundary of the stable regime.

The relationship between orbital tightness and angular momentum provides further evidence of dynamical relaxation. In Figure 4, the significant decrease in angular momentum variance beyond a_{out}/a_{in} ~25 suggests that as hierarchical spacing increases, the inner binary becomes increasingly decoupled from secular perturbations. Conversely, the negative e_{crit} outliers and near-boundary systems like V2284 Cyg represent the absolute limits of hierarchical survival. The negative values (e.g. -1.08) provide a quantitative measure of how far a system has penetrated the unstable regime, likely indicating transient dynamical states or high-inclination hierarchies where Kozai-Lidov cycles have temporarily pushed the system into configurations captured as momentarily unstable by photometric modelling.

The 2+1+1 quadruple systems, CC Com and TIC 8677671, exhibit exceptionally high stability factors (S>20) at their outermost levels. Such extreme stability is likely a prerequisite for the survival of the inner triple structure against the cumulative long-term tidal perturbations of a fourth body.

The scarcity of systems with low specific angular momentum at short tertiary periods (P_{out}< 5 years) provides indirect empirical support for the Kozai-Lidov (KL) mechanism combined with tidal friction. It suggests that systems born with certain configurations are rapidly pushed into the tighter, more stable orbits as observed today, effectively clearing out the low-momentum parameter space.

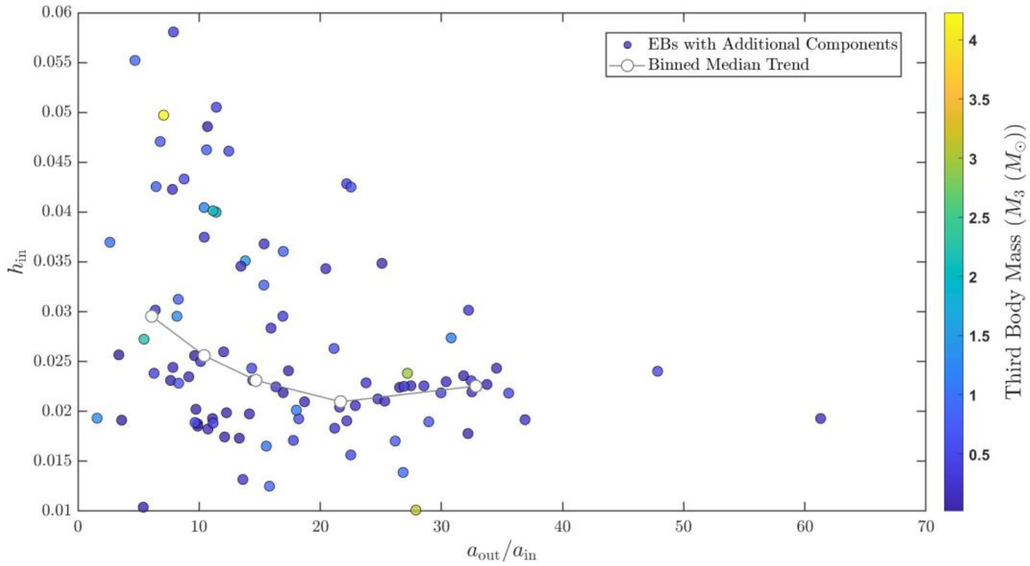

Figure 4: Orbital tightness ratio (a_{out}/a_{in}) vs. h_{in}. The black line represents the binned median trend. We observe a clear dynamical relaxation, where the variance in angular momentum decreases significantly as the hierarchical spacing increases beyond a_{out}/a_{in} > 25.

Measurement	Result	Implication
S Median	4.6	Robust survival far from the unstable limit.
e_{crit} Median	0.80	High tolerance for eccentric third bodies.
Relaxation Point	a_{out}/a_{in} >25	The point where the inner binary decouples from the third body.
Outlier Rate	~2%	Potential transient or unstable configurations.

Table 1: Summary of Statistical Findings.

In summary, as presented in Table 1, this study confirms that 98% of hierarchical multiples in the current sample maintain a significant safety buffer, proving that dynamical stability limits strictly dictate the observed architecture of close eclipsing binaries. This study also provides a quantitative framework for future investigations into the formation and tidal evolution of multiple star systems. By demonstrating that morphological independence exists within these stability boundaries, this work bridges the gap between photometric observation and hierarchical N-body dynamics.

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