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Disruption of Planetary System Architectures by Stellar Flybys

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Abstract

We investigate the survivability of solar system-like planetary systems during close encounters in stellar associations using a suite of 1980 N-body simulations. Each system is based on one of the possible five-planet resonant configurations proposed to represent the initial solar system architecture and is systematically scaled in both planetary mass and orbital compactness to explore the parameter space of observed exoplanetary architectures. Simulations explore a range of stellar encounter scenarios drawn from four distinct cluster environments. Our results show that system survival depends critically on the interplay between planetary mass and orbital scale: compact configurations are more resistant to external perturbations, while increased planetary mass improves resilience only up to a threshold, beyond which internal instabilities dominate. No system whose planets are twice as massive as the ones in the solar system survives stellar encounters. Systems that are at least an order of magnitude more compact than the solar system remain stable under typical encounter conditions. These findings place strong constraints on the initial architectures of planetary systems that can endure stellar-dense birth environments.

Keywords: planetary systems; N-body simulations; stellar encounters; stability; planets; solar system; chaos

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1. Introduction

Studies on the dynamical stability of the solar system have long revealed its partly chaotic nature [1]. In particular, for the terrestrial planets, this chaos drives a slow diffusion of their eccentricity oscillations, threatening Mercury's existence on gigayear timescales. In a recent paper, Ref. [2] showed that the occasional occurrence of extremely close encounters with galactic field stars holds the potential for even more far-reaching breakdowns of our planetary system. Soon after the first discoveries of exoplanets and the discovery of unexpected orbital properties, numerical explorations were performed to study internal instabilities of planetary systems [3,4] and instabilities due to the dynamical environment [5]. Moreover, in the last decade, exoplanet research has opened up new possibilities to better explore the topic, as many extrasolar planetary systems tend to bear evidence of a violent past quite different from that of our solar system [6–11].

Planetary systems may be broken down through both internal and external processes. Internal disruptions are related to the mutual interactions between the objects contained within the system. Studies on internally triggered disruptions require a focus on interactions between planets, planetesimals, and the gaseous disk of a young system, and they have been performed in the past [12–14]. These studies highlight that the dispersal of the native gas disk represents a critical transition for infant systems of giant planets, as the disappearance of the stabilizing effect of the disk gas can lead to instabilities and the disruption of such systems. On the other hand, instabilities may also arise due to other stellar systems passing close by the planetary system. Perturbations caused by such conditions are considered external. Studies focusing on external perturbations in a stellar cluster environment have been performed by [15] concerning open clusters and [16] concerning embedded clusters.

While close encounters (henceforth CEs) between stars can dramatically affect planetary systems, their relevance depends strongly on the stellar birth environment. In the solar neighborhood, the vast majority of stars (90–95%) form in unbound associations rather than in gravitationally bound clusters [17,18]. The lifetime of these is always shorter than their crossing time [19], and therefore, they do not undergo the kinds of dynamical interactions that lead to disruptive CEs. Dynamical encounters capable of affecting planetary systems are thus rare during the formation of most stars in the present-day universe. However, the fraction of stars forming in bound clusters was likely higher in the past, reaching 30% on average over cosmic time [18]. As such, while not the dominant mode of star formation today, CEs may have played a more significant role in earlier epochs, when most of the extant planetary systems formed, motivating the study of their long-term dynamical consequences for planetary system evolution.

Planetary systems may stochastically experience CEs with other stars while in the embedded cluster. Different stars in the same cluster can follow drastically different trajectories, either frequently visiting the dense inner regions or staying all the time in the low-density outskirts. In our previous research [20], we investigated four embedded clusters with different initial conditions. We found that even though planetary systems in more compact clusters tend to experience larger numbers of CEs, this is not true for all stars, and systems born in such clusters may experience the entirety of their infancy without undergoing any such event [21]. The only external perturbations experienced by these systems are tidal forces coming from the global gravitational potential of the clusters. However, Ref. [20] also showed that such forces are insufficient to excite the systems enough to trigger instabilities and can be neglected.

In this work, we focus solely on the external triggers caused by CEs with other stars in the same association as the planetary host star, which we refer to as intruders in this work. This paper is structured as follows. Section 2.1 describes the selection of encounter scenarios for this research. Section 2.2 briefly describes the scaling approach for the simulations. The general results of the study are described in Section 3.1, while Section 3.2 describes a single case of Uranus's and Neptune's orbit swap.

2. Methods

2.1. Planetary System Models

This research aimed to assess the survivability of planetary systems during stellar CEs based on the system's size and mass scales. The end states of systems undergoing

CEs depend on a few different factors. Besides an intuitive conclusion that the mass of the intruder star and the miss distance of the CE shape the effects of the CE on the system, preliminary simulations performed in [20] showed that more compact and less massive planetary systems are more likely to survive CEs. As such, we explored the effect of stellar intruders on planetary systems across a range of radial extensions and total masses. We consider a planet extracted if its semi-major axis is increased to more than 100 au after the CE, but the planet is still gravitationally bound to its host star. If the planet enters a hyperbolic orbit after the CE, we consider such a planet ejected [20]. The perturbation experienced by the system can either only moderately excite planetary orbits or trigger dynamic chaos directly or indirectly. By indirect dynamic chaos, we mean situations where there is no ejection or extraction of any planet, but the eccentricities of two planets are increased enough to make the planets' perihelia q and aphelia Q overlap:

$$Q_{planet\,n} \geq q_{planet\,n+1}, \tag{1}$$

where the planets n and $n+1$ are ordered from the inside out. Although such a system may initially behave as stable, it is bound to break down at some point, even long after the CE, because of the crossing of the orbits [8]. In such a scenario, the only chance of survival on Gyr time scales is a stable mean motion resonance like that of Pluto with respect to Neptune. However, this was likely established by the capture of Pluto during Neptune's outward migration [22]. Such a capture seems unlikely following orbital changes triggered by a passing star.

The cluster simulations are adopted from a previous investigation of the formation of the Oort Cloud and Sednoid populations in the outer parts of the solar system [23]. We simulated four embedded clusters with different initial conditions, as shown in Table 1.

Table 1. Initial conditions for the four simulated embedded clusters.

Cluster ID	Number of Stars	Star Formation Efficiency	Plummer Radius (pc)	Gas Expulsion Delay Time (Myr)	Virial Ratio (Target)	Binary Fraction	Mass Segregation Strength
A	1000	0.33	1.17	0.077	0.15	0.3	0.5
B	1000	0.33	1.17	0.153	0.15	0.3	0.5
C	1000	0.33	0.585	0.077	0.15	0.3	0.5
D	1000	0.33	0.585	0.153	0.15	0.3	0.5

The initial conditions for the cluster simulations were specified using the McLuster code [24], with values for the structural parameters chosen to focus on studying the influence of the concentration factor (ratio of tidal to Plummer radius) and the lifetime of the residual gas (delay time before the gas dispersal sets in). Each embedded cluster was simulated three times. The cluster models were integrated using NBODY6++GPU [25] over a time frame of 10 Myr, and the solar system integrations were made using relevant software like RA15 [26] or IAS15 [27]. Each of the four clusters was simulated three times. From each simulation, we randomly picked six stars with masses of 0.95–1.05$M_\odot$, resulting in a total number of 72 stars, each with its own intruder trajectories. These stars are referred to as sun templates, and the intruders' trajectories are referred to as scenarios. Each sun template was host to a resonant planetary system based on the architecture simulated by [12], henceforth referred to as the NMS system, and consisted of five giant planets—Jupiter, Saturn, Planet 5, Uranus, and Neptune. The chosen initial conditions correspond to one of many cases of Nice model realization performed by [12]. For this research, we selected the one that gave the best fit to the present system of giant planets in the solar system, and the initial orbits of the planets are presented in Table 2. This system was found to be internally stable on a timescale of 10 Gyr in the absence of stellar encounters, in agreement with the long-term stability found for the solar system by [12].

Table 2. Initial orbital elements of the NMS system.

Planet	**R (AU)**	**M (M_{Jup})**	**a (AU)**	**e**	**i (rad)**
Jupiter	0.0004778945	1	5.71	0.00339	0.00022
Saturn	0.0004028667	0.3	7.78	0.01148	0.00108
Planet 5	0.0001708514	0.045	10.51	0.00365	0.00158
Uranus	0.0001708514	0.045	17.62	0.00221	0.00057
Neptune	0.0001655371	0.053	23.34	0.00182	0.00117

The wide architecture of the original NMS system is good for stability because wide orbits help avoid the chaos triggered by encounters between Uranus and Neptune. On the other hand, its wide orbits increase the differential gravity of the intruder on the Sun and the planet, so the perturbation grows with respect to the gravitational pull of the Sun. Scaling down the system decreases the perturbations caused by the intruder stars for the same reason, but there is a risk of internal instability if the planets become too close to each other's orbits.

Scaling up the mass of the NMS system increases the risk of internal instability due to the stronger gravitational interactions between the planets. Scaling the mass of the NMS system in the opposite direction naturally has the opposite consequence: a decrease in the risk of internal instability. N-body simulations can map out the net effects of scaling the NMS system in both size and mass. Thus, we simulated all possible combinations of scenarios to verify which scaling approaches result in stable architectures.

Our first step was to introduce cluster effects to the NMS system to determine whether external forces could lead to close encounters of planets and destabilize the system. We selected 72 scenarios, each with different tides and intruders, and performed 10 Myr simulations using the IAS15 integrator [27], included in the REBOUND package [28]. After the initial simulations, we repeated the simulations for the same cluster effects, but we scaled down the semi-major axes of the planetary system to see if the instabilities would occur for a more compact architecture as well.

Apart from the original NMS, we considered two increasingly compact architectures for each system:

- 72 simulations of NMS;
- 72 simulations of compact NMS, where we scaled down the semi-major axes of all planets by a factor of 5;
- 72 simulations of ultra-compact NMS with semi-major axes scaled down by a factor of 20, while the masses of planets were scaled down by a factor of 5.

Out of all 72 scenarios, 9 cases were unstable for all three starting architectures. These nine scenarios were then subject to multiple simulations with the same intruders while using a grid of scaling factors for the orbital sizes and masses of the planets.

2.2. Initial Conditions

Our first goal was to make sure that the scaling of the planets' masses and orbits does not make them internally unstable. The original system becomes internally unstable upon increasing the planetary masses fourfold. Scaling down the semi-major axes and masses of the planets does not have the same effect. Finally, we simulated the nine aforementioned systems 110 times each, with each simulation having a unique combination of scaling factors. The masses of planets in these simulations were divided by factors of 6, 4, and

2, kept in the original way, or multiplied by 2. Semi-major axes were scaled down by factors up to 50. Up to the factor 15, the scaling step was 1 (e.g., 1, 2, . . ., 14, 15). From 15 to 50, the step was 5 (e.g., 15, 20, . . ., 45, 50). This resulted in a grid of 110 possible combinations of mass and semi-major axis scaling factors. The radii of the planets were not scaled, assuming that smaller planets would be more inflated than their more massive counterparts. This is consistent with the observational data on the range of planetary densities for any given exoplanetary mass (https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/nea_scatter_PS_output_pl_massj_pl_dens_pres.png, (accessed on 10 July 2025)), with the results of interior models for gas-rich planets from [29], and with the more compact nature of their orbits, which translates into higher stellar irradiation and more inflated envelopes. This choice is also equivalent to adopting a stricter stability criterion, as larger planetary radii imply larger impact probabilities and therefore lead to systems undergoing collisions more easily. It is important to emphasize that the mass scaling factor is applied only to the planets. Regardless of the scale of the system, the central star always has a mass of one solar mass.

We observed that, in order to accurately reproduce the dynamical evolution of the most compact systems, the adaptive timestep of the IAS15 integrator caused the simulations to cease to proceed for more compact systems. The timestep of the most compact system simulations (i.e., with semi-major axes scaled down more than 30 times) was diminished to the point that no further progress was recorded. Therefore, we defined a wall time of 240 h for the simulations to avoid wasting the available computational resources, as for such tightly bound systems, we expect the majority of the cases to prove stable (as shown in Figure 1). For such systems, we performed all the simulations once more, using the fixed-timestep MERCURIUS integrator [30]. MERCURIUS is based on the Wisdom–Holman integrator [31] but switches to the adaptive IAS15 integrator in cases of close encounters, following the hybrid sympletic scheme from [32]. This approach not only allowed us to finish all the simulations in a reasonable computing time but was also used as a confirmation for the stability acquired using the IAS15 integrator, as divergent solutions between the two integrators would provide an indication of possible chaotic behaviors.

The general initial conditions of the simulation were the same as in our previous research [20]. As intruder stars destabilize the systems, two types of collisions between the system's objects may occur: planetary collisions or engulfments by the star. We decided that only collisions between planets should cease the simulation, as our implementation of the integrator was not designed to resolve the geometry of these collisions. Such collisions could either create multiple smaller objects with various sizes, masses, and trajectories; create a merged, larger one; or evolve into a hit-and-run encounter, which would alter the orbits of the two objects without changing their number or masses. An analysis of such a collision's aftermath is beyond the scope of our work, which is focused solely on a system scaling–stability relation. In cases of engulfment and ejection, we continue the simulations, as the outcomes of these events are fully resolved by the code. Moreover, in cases of engulfment, the increase in the stellar mass is negligible and therefore ignored in our simulations. The simulations were set to run for 10 Myr, which is the full extent of the embedded cluster simulation, or until the sun template leaves the cluster on its own earlier. The parameters of the CEs are presented in Table 3.

Table 3. Parameters of the intruders. The velocity is given for the point of minimum distance between the intruder and the Sun.

Scenario	Mass (M_{Sun})	Velocity ($\frac{km}{s}$)	Minimum Distance (kAU)
1	4.78108	5.13783	0.44019
2	4.36384	3.27297	0.86324
3	69.34648	5.93211	3.80489
4	1.46280	1.72329	0.15411
5	81.17792	6.98893	3.38940
6	83.12851	8.29860	2.47829
7	36.75026	14.19263	0.32920
8	74.89336	12.76435	0.89937
9	82.54217	9.46876	3.61890

3. Results

3.1. System Stability

We distinguished two types of completed simulations based on the end states of the planetary systems—stable and unstable. The system is considered unstable if there is at least one planet extraction, ejection, or engulfment, or if the system becomes excited to a degree where orbits of at least two planets cross.

None of the systems with double mass survived the close encounters with the intruder stars. All these simulations resulted in either ejections or planetary collisions. Also, out of nine simulated intruder scenarios, two (numbers 7 and 8) did not produce any stable final configurations; as such, the results of these systems are not presented in the plots. The results of the scenarios where we found at least stable final configuration are presented in Figure 1, which illustrates how the stability properties vary with the scaling of masses and sizes.

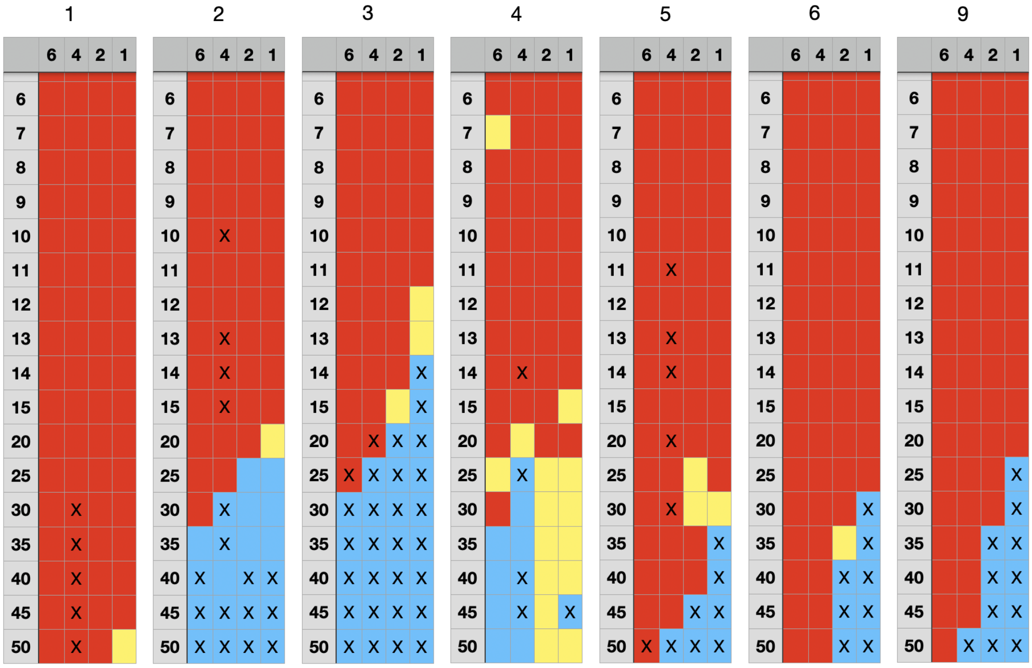

Figure 1. Results of the simulations. Each of the intruder scenarios (1–6 and 9) considered in this study has its own results table. The vertical axis shows the reciprocal values of the semi-major scaling factor, and the horizontal axis shows the inverse mass scaling factor.

The colors in the plots presented in Figure 1 represent the number of integrators that found the system to be stable. We used blue when both IAS15 and MERCURIUS confirmed the system stability. If only one of the integrators yielded instabilities, we used yellow color, and red was used for cases where both integrators found instabilities. For the cases where the IAS15 simulation did not finish, we determined the color of the plot based solely on the result of the MERCURIUS simulation. Such cases are marked with a × sign. As expected, the majority of these systems proved stable.

Apart from one single case, which will be discussed in the next section, there were no surviving systems for the semi-major axis scaling factors larger than $\frac{1}{12}$. In most cases, there were more surviving systems when the original planets' masses were kept. For less massive systems, gravitational interactions between system members are weaker, resulting in less effective resonances and, consequently, higher vulnerability to the external forces applied by the intruder stars. Keeping the less massive systems stable required more compact orbits. This does not come as a surprise. Keeping the system stable requires the differential gravity of the intruder to be made ineffective by the stronger gravitational pull of the host star.

3.2. Orbit Swap

Uranus' and Neptune's orbits were swapped in one of the simulations of system number four. The swap was present for both integrators, though it had slightly different initial conditions. IAS15 detected the swap in a simulation with masses divided by 6 and semi-major axes divided by 7. Although the system fulfilled all the requirements we imposed for stability after the swap, one may question whether the evolution of the system should be considered stable, as the final planet configuration is different from the initial one. The MERCURIUS integrator also detected the swap of the orbits of the same planets, but for semi-major axes scaled down by a factor of 6 instead of 7. However, the swapped Uranus and Neptune ended up on crossing orbits, so the system is considered unstable. The detailed plot of both simulations is presented in Figure 2, showing the time evolution of planetary orbital elements in these two cases.

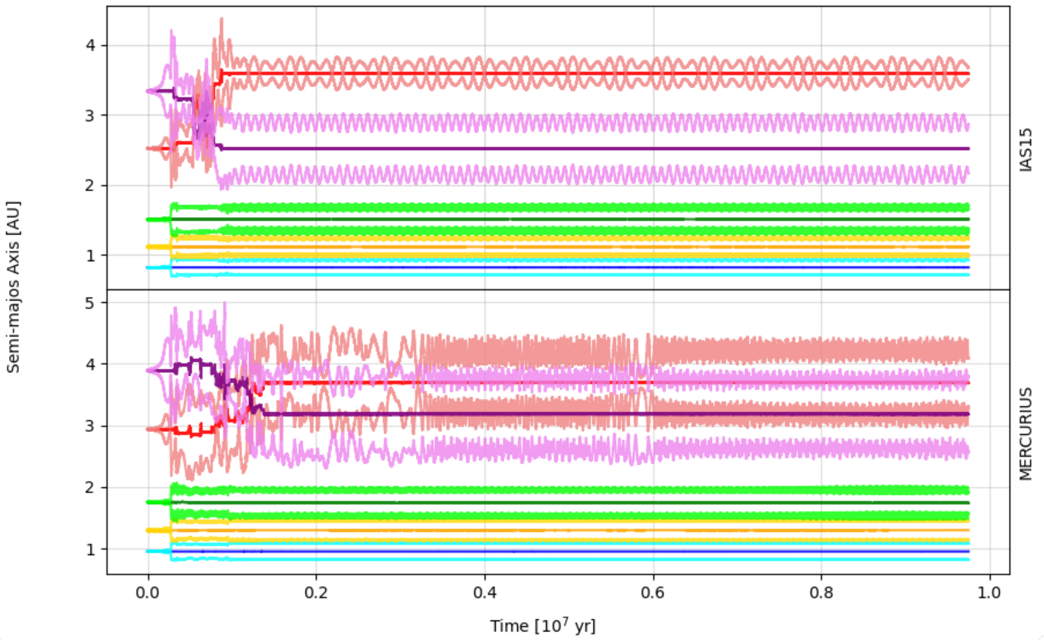

Figure 2. Semi-major axes of planets over time in simulations with Uranus's and Neptune's orbit swap. The top panel presents the results of the IAS15 integrator, and the bottom one presents the results of the MERCURIUS integrator. The perihelion and aphelion distances are also presented.

4. Discussion

4.1. Planetary Systems Survivability

The nine intruder scenarios used in this study were selected from the larger group consisting of 72 obtained during the previous work by [20]. These nine scenarios were chosen because they proved the most destructive for the planetary systems. Each scenario was simulated 220 times using two different integrators in search of the scaling parameters that would prevent the system from disrupting. However, two of these scenarios were destructive to an extent where we were unable to find any architecture able to survive the CEs. Furthermore, for the semi-major axis scale factor greater than $\frac{1}{12}$, we did not find any architecture able to survive the CEs and preserve the initial order of planets.

Our initial study of non-altered, compact, and ultra-compact NMS, mentioned in Section 2.1, indicates that more compact systems are more likely to resist external perturbations. Our simulations suggest that more massive systems are more likely to survive close encounters if the orbits of the planets are wide. However, too large a mass can lower the chances of surviving a close encounter or destabilize the system internally. The five-planet architecture studied in this research proved to be most stable when adopting the original masses of the planets from [12], while such a system with doubled masses turned out to be the least stable. Although there are numerous known systems with masses much larger than twice the NMS mass (source: https://exoplanetarchive.ipac.caltech.edu/index.html, (accessed on 10 July 2025)), multiplying the mass of giant planets by 2 while keeping the stellar environment unchanged resulted in a lack of surviving architectures, regardless of the downscaling of the semi-major axes. However, it is likely that more massive NMSs are also able to survive strong stellar CEs, given the correct initial orbits.

It is possible that increasing the masses of the planets by less than the doubling factor we considered might increase the percentage of surviving systems even more. However, a much tighter grid of architectures is needed to verify this statement. Also, the mass of the central star influences the main system's behavior during the close encounter as well. This study focused only on planetary parameters, but stellar mass should also be considered an important variable. The order of the planets also plays a vital role in the CE survivability analysis. The NMS used in this research consists of five planets, with the most massive one being the innermost one, which is not a universal distribution, given the example of TRAPPIST-1 or 55 Cancri. A system in which the most massive planet is the most distant from its host star might be much more vulnerable to disruptions triggered by external forces than the systems studied in this work. Therefore, future work should simulate a greater variety of initial architectures, accounting for various masses of planets and different masses of the host star as well. Experimenting on a larger ensemble of planetary systems can provide insight into the relationship between the planetary system's structure and its resistance to external perturbations.

Out of 1980 total simulations, 1467 were marked as completed based on our criteria. A total of 73 of the completed simulations resulted in Uranus's and Neptune's orbits crossing. Due to the reasons explained in Section 3.2, we classified these systems as unstable. Our simulations were run up to 10 Myr or until the NMS left the embedded cluster. Therefore, we were not able to observe the disruption of the excited system if it occurred after it left the association. The time required for such a system to break may vary, but in our simulations, we did not find any disruptions that took place Myr after the CE. However, in a previous study [20], we observed such situations before the excited system left the embedded cluster. Also, the exchange of the orbits of Uranus and Neptune has been observed in previous studies [33,34], but these works included the presence of planetesimals, which were absent in our simulations. The detection of orbit swaps in both [33,34] and our simulations means that such swaps can be triggered both internally and externally.

4.2. Implications for the History of the Solar System

The forces applied by the intruder configurations we selected proved too strong for a planetary system like the current solar system to survive the CE. Although this work shows that it is possible for resonant planetary systems to survive intense stellar close encounters, the system's mass and compactness need to be in a correct relation for this survival to occur. Our current solar system would not have been able to survive any of the scenarios analyzed in this research. In our previous research [20], however, a non-scaled infant solar system survived 42 out of 72 intruder scenarios originating from all four types of embedded clusters, with only three scenarios not involving any intruders. Remote stars, not having any encounters with the intruders, were observed in embedded clusters with small Plummer radii and early gas loss, so despite the fact that such a cluster favors multiple stellar encounters, it might also provide a relevant environment for the origin of the solar system.

If we assume that our solar system originates from an embedded cluster, which type of instabilities would have had more of an impact on its present shape? The 2012 study by Nesvorný and Morbidelli suggests that the presence of an additional now-lost ice giant influenced the present state of our system [12]. In our case, the planetesimals are not present in the simulations, and the ejection of Planet 5 is not observed without the CE. It is worth mentioning that among all intruder scenarios analyzed in this study, all but one CE strong enough to have an impact on the system occurred not later than 2 Myr, which is earlier than most of the internally driven instabilities for five-planet systems discussed in the literature. This may suggest that the origin of our system does not include violent perturbations caused by neighboring stars but rather mild CEs with other stars, resulting in minor excitation of the system, if any, in agreement with the considerations on the dynamical excitation of the solar system from [10,35].

The eventual possibility of disruption of the current four-giant planetary system surrounding the Sun may raise concerns related to the Sun's birth cluster. While most birth clusters of solar-type stars have the very short lifetimes that characterize the embedded clusters considered here, some clusters can survive for up to 100 Myr, like, for instance, M45 (the Pleiades). If the Sun was born in such a cluster, the timing of the planetary instability that caused the transition to the current architecture, according to the Nice model [36], may be of the essence. Ref. [37] presented several arguments for a very early instability, as indicated by the work of Nesvorný and Morbidelli [12]. The encounter rate in such clusters is the highest during such early times (Kowalski et al., in prep.), but the survivability of our planetary system after the instability still needs investigation by simulations like the present ones.

4.3. Conclusions

Our research shows that the architectures of the planetary systems influence their chances of survival when encountering other stars. The mass and compactness of the system both contribute to determining the stability of the final outcome, and changing only one of these parameters may cause the new system to break down under similar environmental circumstances.

We observed that the highest probability of surviving the stellar encounters is achieved when the planetary masses are the same as in the current solar system. If the masses are altered, less massive planetary systems require tighter orbits to endure the CEs. On the other hand, increasing the masses of the planets prevents their possibility of surviving the stellar encounters.

Planet 5 ejection is most likely related to the planetesimal disk and internal instabilities rather than the CEs. Regardless of the scaling of the system, no Planet 5 ejections or instabilities were observed without the gravitational pull originating from the intruders.

Based on this research, the solar system is unlikely to be subject to strong CEs in its infancy period. All the instabilities caused by the CEs affected not one planet but the entire system. If we assume that our system's original architecture included five giant planets, as presented in this paper, it is much more probable that the removal of a single planet was related to internal instability.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author due to the fact that the original code designed to perform the simulations requires a specific version of the integrator other than the latest release.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CE	Close Encounter
NMS	Nesvorný–Morbidelli System

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