

Collision outcomes due to planetesimal and planetary embryo interactions in inclined binary star systems

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Abstract. In the final phase of terrestrial planet formation, planetary embryos and planetesimals are the building blocks for the growth of rocky planets. In this investigation, we study the dynamical behaviour of a circumstellar disk in an inclined binary star system. The disk consists of 2000 planetesimals and 25 embryos and is distributed between 1 and 4 au around the primary star. To compute the gravitational interaction of the whole system, we use our recently developed GPU N-body code GANBISS. GANBISS treats all collision as perfect merging and delivers the impact parameters that will be used to distinguish between different collision outcomes.

Keywords. Methods: numerical - Planets and satellites: formation - Binaries: close, inclined - Celestial Mechanics

1. Numerical methods and setup

GANBISS is written in CUDA C and runs on most modern NVIDIA GPUs. It uses the Bulirsch-Stoer method to solve the equations of motion. It is designed to simulate the dynamical evolution of a planetesimal-embryo disk in a binary star system. The disk can handle up to 10000 interacting objects in a simulation. For details see [Zimmermann & Pilat-Lohinger \(2023\)](#). In this study, all simulated binary configurations consist of two equal mass stars ($M_1 = M_2 = 1M_\odot$). The separation of the two stars is fixed to 30 au and the eccentricity and inclination are varied as shown in table 1. For comparison a planar configuration has been studied in addition. The dynamical interaction of all bodies was integrated over 1 Myr.

2. Results

From the perfect merging events of the N-body simulations, we obtained a wide range of collision parameters (impact velocity and angle). In further treatment, these parameters were used to classify collisions according to the [Leinhardt & Stewart \(2012\)](#) model (see figure 1 and table 1). Collisions were categorized as merging events (“pm”, “gm”, “pa” in table 1), hit-and-run collisions (“hr” in table 1), or destructive collisions (“pe”, “cat” in table 1). When over 90 % of the initial mass is lost, it’s termed super-catastrophic. A comparison of inclined systems to the planar case revealed that significantly more destructive collisions occur in the inclined cases: approximately 15 % for $i_b = 20^\circ$ and 32.5 % for $i_b = 45^\circ$, compared to just one in the planar case. Therefore, mass-growing collisions are less common in inclined binary star configurations, where about 18.5 % for $i_b = 20^\circ$ and about 10 % for $i_b = 45^\circ$ are mass-growing collisions, in contrast to the planar case where this fraction is around 64.5 % of all collisions. The largest fraction of

Table 1. Calculated collision outcomes for the different binary star configurations according to [Leinhardt & Stewart \(2012\)](#). Abbreviations are the following ones: pm = perfect merging; gm = graze-and-merge; hr = hit-and-run; pa = partial accretion; pe = partial erosion; cat = super-catastrophic.

a_b [au]	e_b	i_b [°]	pm	gm	hr	pa	pe	cat	# collisions
30	0.0	0	1018	104	686	126	1	0	1935
30	0.0	20	82	10	1028	193	107	135	1555
30	0.2	20	109	9	1050	191	99	137	1595
30	0.0	45	14	1	876	154	146	366	1557
30	0.2	45	13	2	897	141	135	367	1555

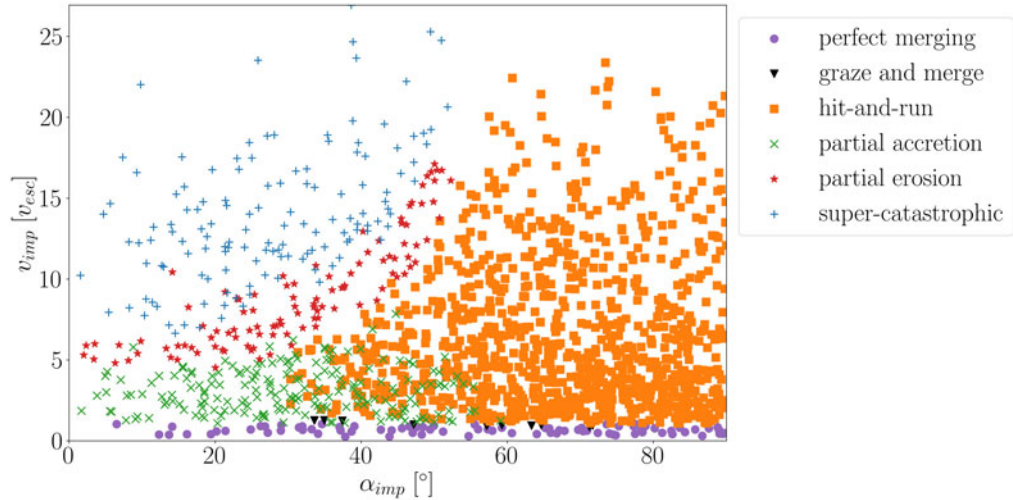


Figure 1. Distribution of the impact parameters (impact angle α_{imp} and impact velocity v_{imp}) for the binary configuration: $a_b = 30$ au; $e_b = 0.0$ and $i_b = 20^\circ$. Note that $\alpha_{imp} = 0^\circ$ corresponds to head-on collisions while 90° matches grazing collisions, and v_{imp} is in terms of the mutual escape velocity v_{esc} . Each dot represents one collision of the simulation. The color-coding refers to the calculated collision outcome when applying the analytic model from [Leinhardt & Stewart \(2012\)](#) to the resulting N-body simulation collisions.

collisions in the inclined cases are the hit-and-run events ($\sim 60\%$). For the planar case the hit-and-run events are $\sim 35\%$ of all collisions.

Note that the overlapping of different collision outcomes in figure 1 results from the fact that the collision outcomes have been determined for various mass-ratios of the colliding objects.

3. Conclusion

We simulated a disk of planetesimals and planetary embryos in S-type motion in different configurations of binary star systems (variation of i_b and e_b) and studied the growth of the disk objects via perfect merging. We tracked the impact parameters of all collisions to acquire better results for the growth of rocky planets following [Leinhardt & Stewart \(2012\)](#). Our results showed an increase in destructive collision events for inclined binary systems. Overall, the largest fraction of collision outcomes are hit-and-run collisions in the inclined configurations and the fraction of mass growing collisions decreases for increasing i_b .

A more realistic collision handling – e.g. using smooth particle hydrodynamics simulations (SPH) [Maindl *et al.* \(2013\)](#) – is needed for N-body simulations in order to investigate the late stage of terrestrial planet formation in stellar systems.

4. Acknowledgements

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