Complex Planetary Systems II: Latest Methods for an Interdisciplinary Approach
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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 ($M_1 = M_2 = 1 M_\odot$). 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 $i_b = 20°$ and 32.5 % for $i_b = 45°$, 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 $i_b = 20°$ and about 10 % for $i_b = 45°$ 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

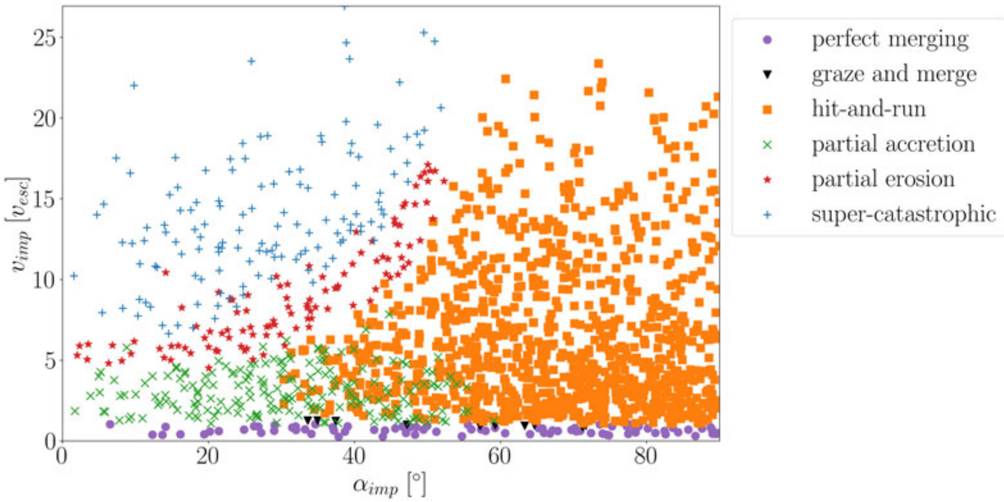

Figure 1. Distribution of the impact parameters (impact angle α_{imp} and impact velocity v_{imp}) for the binary configuration: $a_b = 30$ au; $e_b = 0.0$ and $i_b = 20°$. Note that $\alpha_{imp} = 0°$ corresponds to head-on collisions while 90° matches grazing collisions, and v_{imp} is in terms of 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 (~ 60 %). For the planar case the hit-and-run events are ~ 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.

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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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