Dynamical evolution of planetesimal disks in inclined binary star systems

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Abstract

In this work we investigate the late stages of terrestrial planet formation in binary star systems. We focus on planetesimal disks which are in S-type motion around the primary star and are inclined w.r.t. the binary stars orbital plane.
For the integration of the equations of motion of the binary stars-disk configurations we use a self developed massivelly parallelized GPU n-body code. The circumprimary disk is populated with 2000 planeteismals and 25 planetary embryos. For simplicity we incline the secondary star w.r.t. the primary star-circumprimary disk plane. We vary the seperation, the eccentricity and the inclination of the binary stars.
The results suggest a much slower growth of planetary embryos which are inclined w.r.t. the binary stars plane and for our chosen configurations.

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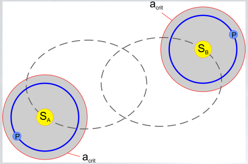
Introduction

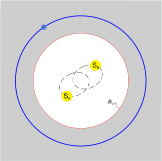
- About 50 % of the stars in the solar neighbourhood are part of a binary or multiple star system (e.g. Raghavan et al., 2010 or Tokovinin, 2014).
- In terms of planetary motion in binary star systems, you can

  basically distinguish between two types:
  - The S-type (top right) where the objects orbit around one (the primary) star
  - and the P-type (bottom right) where the objects orbit both stars.
- Some of the exoplanets are inclined w.r.t. the binary stars orbital plane[a].
- While for the P-type there are already some studies about planet formation for inclined protoplanetary disks (e.g. Cuello et al., 2019), we focus on the planet formation for inclined disks in S-type motion.
- In the late stages of terrestrial planet formation the disk objects have grown such that the mutual gravitational interactions become more important so that the interactions of all bodies have to be taken into account when using n-body simulations.
- The down-side of n-body simulations is the complexity which scales with $\mathcal{O}\left(N^2\right)$. Thus, the computational effort becomes immense for a large number of interacting objects.
- Therefore we developed our own n-body integrator, which is massively parallelized on graphical processing units (GPU) (Zimmermann, 2021) to investigate the late stages of terrestrial planet formation in such systems.

[a] https://www.univie.ac.at/adg/schwarz/multiple.html



S-type



P-type

Figure 1: Credits of the images go to Pilat-Lohinger et al. (2019).

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Methods and Setup

We use the Bulirsch-Stoer (BS) method (Stoer et al., 2002) with an adaptive step size for solving of the equations of motion, an extrapolation method which is very accurate in terms of close encounters but also quite performant.
We massively parallelized the BS method on GPUs to allow a simulation of some thousand gravitationally interacting objects in a reasonable time. **The speed-up** we gain, compared to a standard CPU code is up to a **factor of 100**, which depends strongly on the number of interacting particles. The GPUs we used were either a *Nvidia GTX-Titan Black* or a *Nvidia GTX-Titan*.
The collision among disk objects are handled with the so-called "perfect merging".

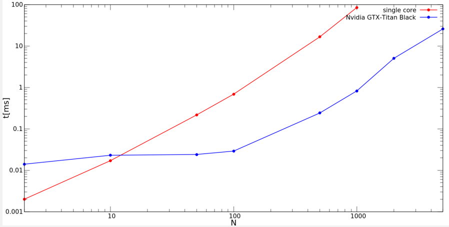

Figure 2: The time needed in [*ms*] for a single force evaluation for different numbers of particles for a CPU and a GPU implementation.

The secondary star is inclined w.r.t. the plane of the planetesimal disk and the primary star. We vary the binary stars seperation, the eccentricity and the inclination. The parameters are listed in the table on the right. Both stars have the same mass of 1 $M_\odot$.

$a_b\,[au]$	e_b	$i_b\,[^\circ]$
30	0.0	0
30	0.0	20
30	0.0	45
30	0.2	20
30	0.2	45
60	0.0	20
60	0.0	45

The protoplanetary disk is in S-type motion, orbiting the primary star between $1-4$ *au* and is initially dynamically cold (Ida et al., 1992). The disk objects are distributed following the power law $\Sigma(r) = \Sigma_0 \left(\frac{r}{1au}\right)^{-\alpha}$ with Σ_0 the normalization constant and α the power law index (with values: $\Sigma_0 \approx 10\ gcm^{-2}$ and $\alpha = 1.5$ (Hayashi, 1981)). For the given binary star system configurations the protoplanetary disk is within the area of stable motion (Pilat-Lohinger et al., 2002) and is simulated for 1 Myr. In this study the disk contains 2000 planetesimals and 25 planetary embryos.

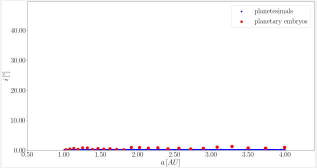

Figure 3: The initial distribution of the disk objects for the inclination and semi-major axis

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Results

The inclination plotted against the semi-major axis of the disk objects after 1 Myr.

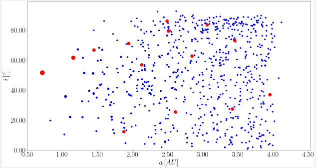

Figure 4: Inclined case with $i_b = 45°$

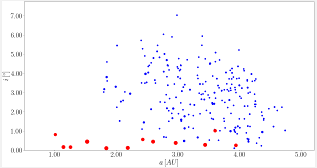

Figure 5: Planar case ($i_b = 0°$)

Both cases have a binary star seperation of $a_b = 30$ au and no eccentricity. In all inclined cases all **disk objects** are distributed **between 0° and 2 · i_b** (here $i_{max} \approx 90°$). In the planar case for the planetesimals $i_{max} \approx 7°$ and for the planetary embryos $i_{max} = 1.5°$. Additionally, **more planetesimals remained in the inclined case** and are not collided with other disk objects.

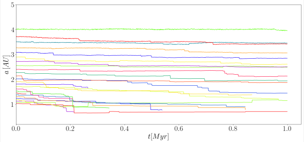

Figure 6: The time evolution of the semi-major axis of the 25 planetary embryos plotted for 1 Myr. The binary star configuration is the same as in figure 4. Repetitive colors represent different embryos. The **inner embryos tend to migrate inwards**, with the innermost embryo reaching ~ 0.5 au.

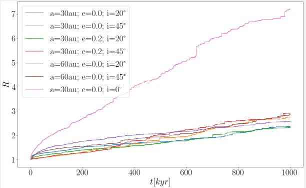

Figure 7: The fraction of the total mass of the planetary embryos to the total mass of the planetesiamls ($R = \frac{M_{emb}}{M_{plt}}$) within the simulation time for each configuration. For the **planar case** the value is **$\sim$ 7** at the end of the simulation. For the **inclined cases** it is **$\sim$ 2**.

Conclusion

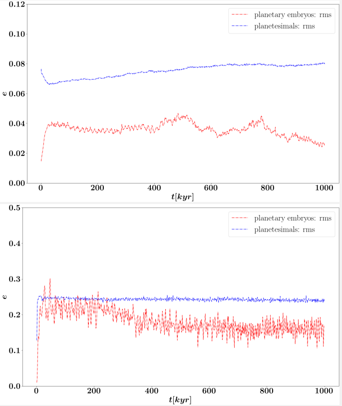

Figure 8: Root mean square eccentricity of all planetary embryos and planetesimals per timestep. On the upper panel for $i_b = 20°$. On the lower panel for $i_b = 45°$. Both configurations have a binary star seperation of 30 au and $e_b = 0.0$.

- We simulated 6 different inclined binary star configurations with a planetesimal disk in S-type motion and compared them with a planar case studied in Zimmermann (2021).
- We varied binary stars separation, eccentricity and the inclination.
- The inclined binary star cases show an increase in the inclination up to $2 \cdot i_b$ (for $i_b = 45°$ $i_{max} \approx 90°$) within the integration time (see figure 4), where the increase in the inclination depends on the seperation of the binary stars.
- In case of a non-planar disk the particle density is significantly smaller. This tends to a **lower close encounter rate** compared to the planar case. Thus, the effect of **dynamical friction** (which keeps the eccentricity and inclination small, e.g. Ida, 1990) **on the planetary embryos is smaller** (see figure 8).
- Another point resulting from the lower particle density is the slower growth of the planetary embryos compared to the planar case. This can be seen by the R value (see figure 7) which differs barly for the individual inclination cases, but is **∼ 3.5 times higher in the planar case**.
- Additionally, the inclined cases show most of the time one massive planetary embryo with about $\sim 1M_{\oplus}$, which also is often the innermost. While in the planar case the planetary embryos have a smaller mass range.
- And finally the **inward migration of the inner planetary embryos** reaches in case of the innermost embryo 0.5 au (see figure 6). This occured in the case of $i_b = 45°$. Which could be in connection with the Kozai migration (Wu et al., 2003), where initial inclination of a third body w.r.t. to the secondary has to be $> \sim 39°$. But this requires further investigations.

Acknowledgements & References

Acknowledgements:

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