Binary-planets formation

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1. Introduction

- Planet-planet pairs, or binary planets, are among the most mysterious and intriguing objects in the exo-planetary field. There is not yet an exact definition for this kind of systems, though tipically we define binary planets two celestial bodies of similar size, which are gravitationally bound and orbit around a common center of mass.
  The closest example that we have is the Pluto-Charon dwarf planets system. Moreover, a number of free floating binary sub-stellar objects were already detected, as 2MASS J11193254–1137466 AB (4+4 M_{Jup}) **[1]** or Oph 11 Ab (13+10 M_{Jup}) **[2]**. Whereas stars hosting massive brown dwarf pairs were already observed (e.g. ε Indi **[3]**), the first detection of a planet-planet pair bound to a central star has to be confirmed yet. Recently, a handful of candidates were claimed, such as Kepler 1625 b (through TTVs) **[4]** and the DH Tau Bb (through direct imaging) **[5]**.

- Multiple mechanisms can explain the formation of binary planets, such as giant impacts (only for rocky planets), formation within the circumplanetary disk **[6]**, formation of binaries promptly from the circumstellar disk **[7]**. Here, we will focus on the gravitational capture enhanced by the inclusion of tides. In this scenario, the two planets are formed independently in the circumstellar disk and become a bound pair due to repeated close encounters during which energy is dissipated through tidal interactions. This study was inspired by Ochiai et al. (2014) **[8]**, where the authors investigate the formation of binary planets via gravitational capture assuming a planetary population with parameters defined by core-accreation (CA) models **[9]**. As a main result, they found that one system out of ten could host a planet-planet pair.
  Alternatively to CA, which can easily model the formation of companions from small terrestrial planets to Jupyter-like objects within a few AUs from the star, the gravitational instability (GI) scenario **[10]** is much more suitable to explain the presence of massive companions (> 5 MJup) placed from tens to hundreds of aus from the central star.

- **Here we will show the results of dynamical simulations to reproduce the formation of planetary pairs due to orbital crossing and tidal dissipation starting from a population of GI-like planets [11].**

2. Simulations

To simulate the formation of binary planets we used a modified version of the Mercury Code **[12]**, adding a term of energy dispersion for close encounters. The energy dispersion factor comes from tidal interaction between the planets and was taken from **[8]**. Such term is able to describe only the first stages of planetary interactions. Infact, while the separation between the two planets shrinks down, physics become more complex moving towards tidal locking and corcularization of the orbits. This is a simplified analysis that aims to show the efficiency of gravitational capture+tides in forming binary planets and it is not able to fully constrain their final characteristics. Thus, we stopped the integration and labelled any system as binary whenever two planets reach both the pericenter distance and semi-major axis of less than 0.1 au. We run 7 sets of simulations each with 1000 systems for a total time of 1.5Myr. Masses and semi major axis where randomly selected in the ranges [1,15] M_{Jup} and [50,100] au to respect the typical parameters distribution of planets formed via GI. Details of each set simulations are given in the Table. Further results are presented in Lazzoni et al. (2023) **[11].**

	# of systems	# of initial planets	Energy dissipated	% of BinPlan formed
Set 1	1000	2	En	15.1
Set 2	1000	3	En	10.1
Set 3	1000	4	En	13.5
Set 4	1000	5	En	18.6
Set 5	1000	Random [2,5]	En	17.2
Set 6	1000	Random [2,5]	En/10	15.7
Set 7	1000	Random [2,5]	En/100	14.4

In the figures are shown the number of binary systems formed for sets of simulations 1,2, 3 and 4 (left) and for simulation 5, 6 and 7 (right).
In the video (available at the QR code) is shown a simulation coming from Set 2 that formed planet-planet pair. The slow motion part shows the final stages of the formation of the binary.

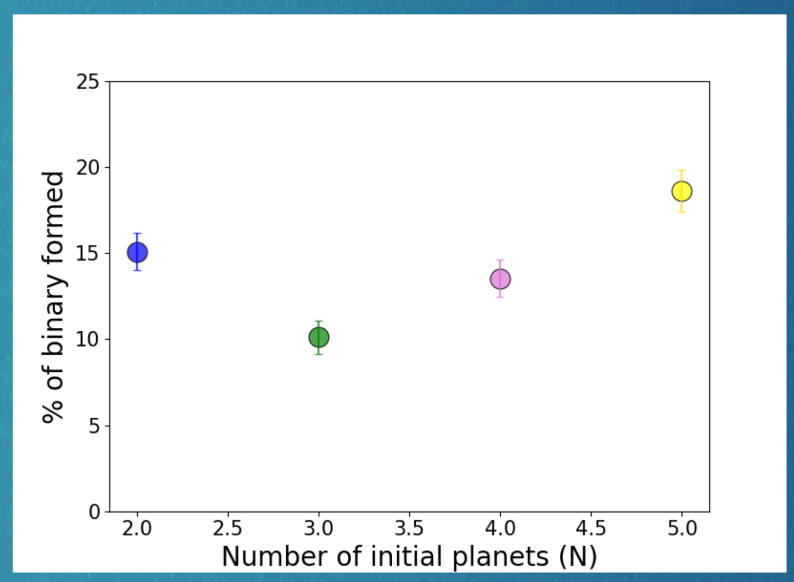


Figure 1. Number of binary systems formed in 5 sets of simulations with two, three, four and five initial planets. For each set 1000 different configurations of masses and orbital parameters were considered.

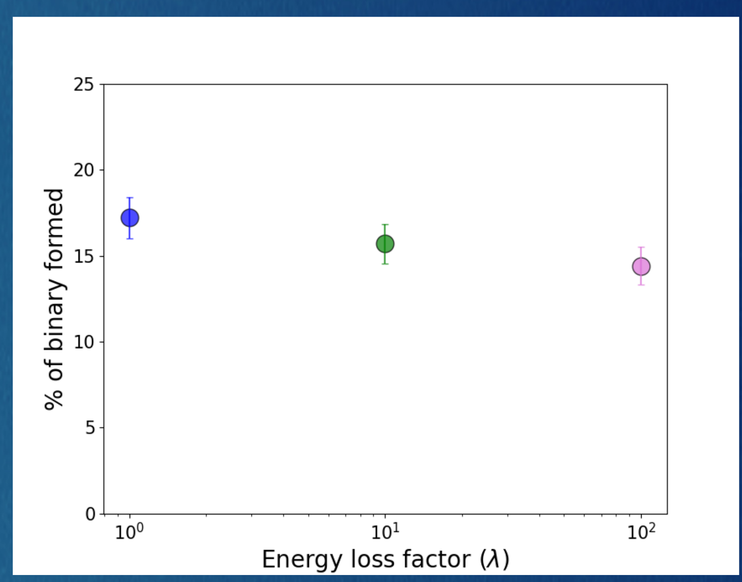


Figure 2. Number of binary systems formed in 3 sets of simulations with different fraction of energy dissipated due to tides (En, En/10 and En/100). For each set 1000 different configuration of initial planets, masses and orbital configurations were considered.

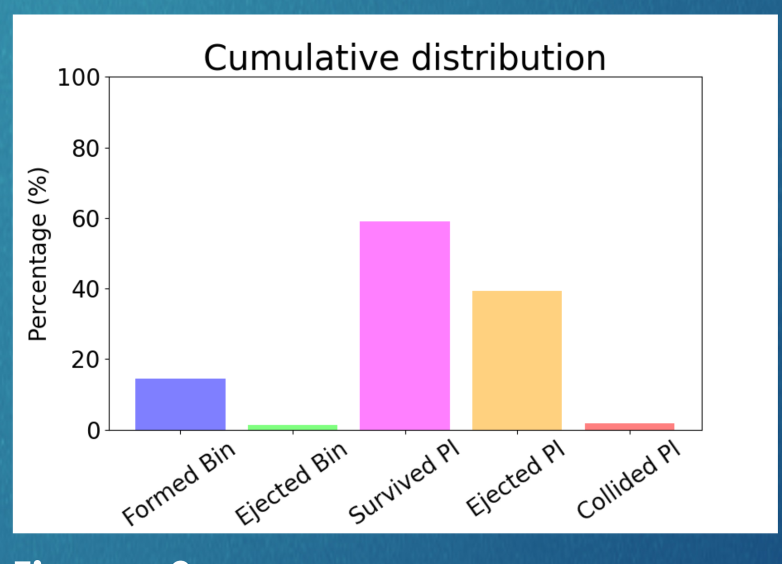
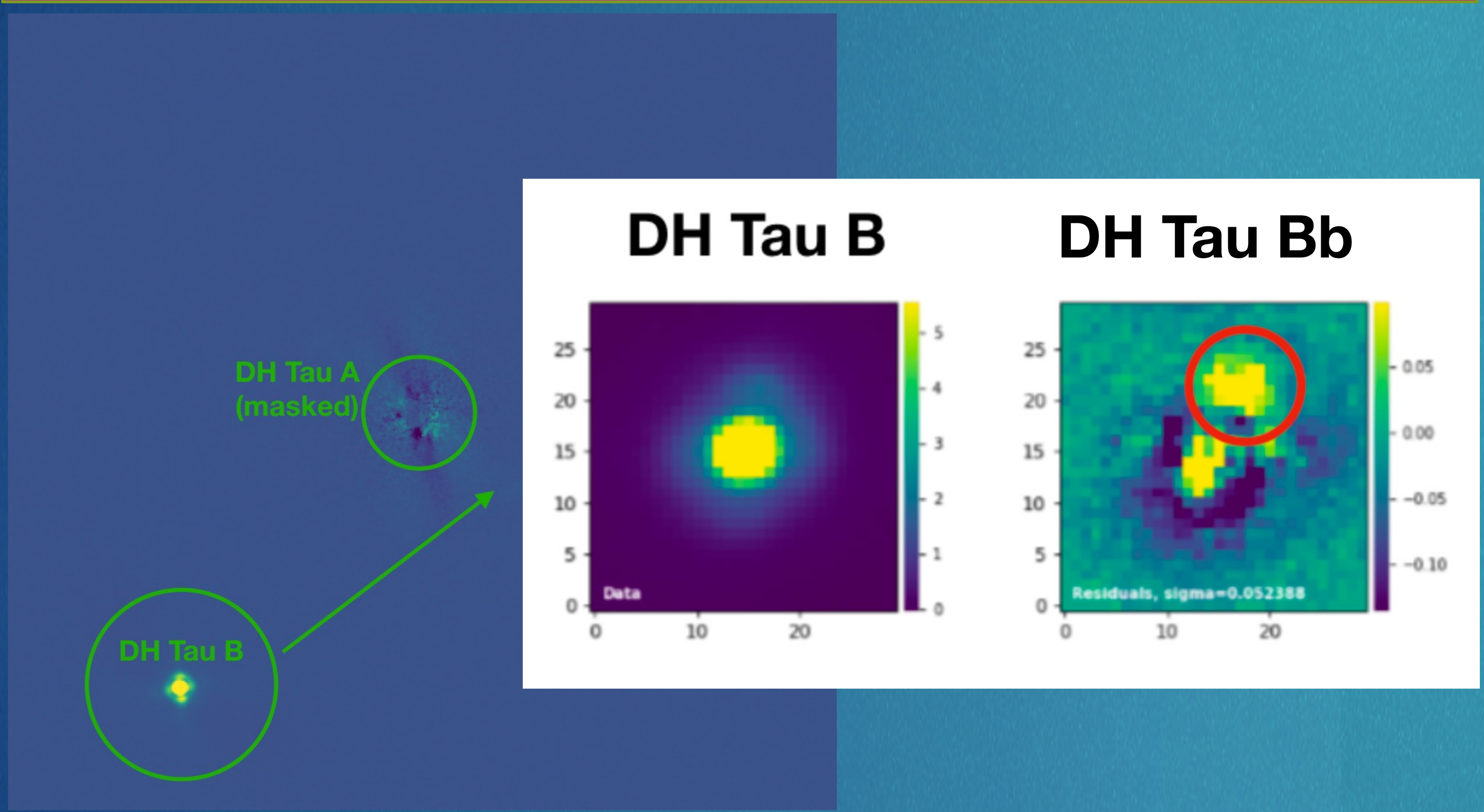


Figure 3. Percentage of binary planets formed and ejected, planets that survived, that were ejected, and that collided with the central star when considering the cumulative distribution from the first four sets of simulations

SCAN THIS QR CODE TO WATCH THE FORMATION OF A BINARY-PLANET SYSTEM

3. DH Tau Bb



New-generation of high contrast instruments (SPHERE/VLT, GPI/Gemini, SCExAO/Subaru) can be used to unveil features, in the form of giant moons or disks, within the Hill radius of DI substellar objects.
In Lazzoni et al. (2020) [5], we exploited a technique based on the PSF subtraction of directly image planets and brown dwarfs to unveil the residuals in their close surroundings. This technique, applied to the sample of sub-stellar objects detected with SPHERE, revealed a promising candidate satellite of ~1 M_{Jup} around a low-mass BD, DH Tau B (10-20 M_{Jup}). The candidate is placed at nearly 80 mas (~10 au) from the BD, which is itself at 2.3 arcsec (317 au) separation from the star. DH Tau Bb was detected multiple times with SPHERE in H-band and K-band. Observations in L' band with LMIRCAM/LBTI were also performed, but the contrast reached by the instrument was not sufficient to detect it.

4. Conclusions

- Inspired by the first detections of massive planet-planet pairs, we investigated possible formation mechanisms for the latter in the case of planetary companions form via gravitational instability **[11]**. In particular, we focused on the gravitational capture scenario with the inclusion of energy loss during close planetary encounters due to tides. As proved by our sets of simulations, gravitational capture+tides can efficiently generate binary planets with an average rate of 14.3%. This is comparable with the 10% found by Ochia et al. 2014 **[8]** for CA-like planets.
- Our simulations prove that the formation of binary planets is influenced by the initial number of injected planets. Excluding the first case with N = 2 for which the formation rate is 15%, there is a gradual increase of the latter with N. In fact, while the formation rate for N = 3 is approximately 10%, it can be enhanced by up to 8.5% when considering five planets in the system. The anomaly given by the case with N = 2 is likely due to the small degree of dynamical scattering and perturbations in the system that enhances the formation of bound pairs.
- Since such tidal interactions are extremely complicated and poorly constrained, we also investigated the formation rate of binary planets considering fractions of the energy dissipated due to tides En (En/10 and En/100) . Results show that even if the energy loss constitutes only a fraction as small as 1/10 or 1/100 of the initial quantity considered, the formation of binary planets through tides proves to be an efficient process, with a formation rate of 15.7% and 14.4%, respectively. As expected, the formation rate gradually decreases when less energy is lost due to tidal friction

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