Decoupling of a giant planet from its disk in an inclined binary system

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Summary

Background:
Around 40% of hot Jupiters have angular momentum vectors significantly misaligned respect to the angular velocity vector of the central star[1,9].
Since the stellar and disk angular momentum are expected to be aligned, this would imply a misalignment between the planetary orbit and its birth disk.

Goal:
To explore whether a binary star companion with an orbit significantly tilted ($\geq 40°$) respect to the initial disk plane is able to decouple a giant planetary core from the protoplanetary disk, extending our previous study[7] to self-gravitating disks and smaller planetary masses.

Overview

Relevant timescales:

1. Planet-precession (Kozai-Lidov)[3]

$$P_{\rm KZ} \simeq \frac{2\pi}{\Omega_{\rm p}} \left(\frac{a_{\rm b}}{a}\right)^3 \left(\frac{M_\star}{M_{\rm b}}\right) (1-e_{\rm b}^2)^{3/2}$$

2. Disk-precession[2,4]

$$P_{\rm d}^{\rm prec} \simeq 2\pi \sqrt{\frac{a_{\rm b}^6}{GM_\star r_{\rm out}^3}} \left(\frac{M_\star}{M_{\rm b}}\right) \frac{1}{3/8 \cos i_{\rm b}}$$

3. Period ratio

$$\left(\frac{P_{\rm d}^{\rm prec}}{P_{\rm KZ}}\right)_{\rm ini} \simeq 4\pi P_{\rm KZ}{}^{-1} \sqrt{\frac{a_{\rm b}^6}{GM_\star r_{\rm out}{}^3}} \frac{M_\star}{M_{\rm b}} = 2\left(\frac{a}{r_{\rm out}}\right)^{3/2} \sim 0.14$$

.

Methods

Physical parameters:

- $M_\star = 1\,M_\odot$ star harboring a protoplanetary disk and a planet
- $M_{\rm b} = 1\,M_\odot$ binary companion with $a_{\rm b} = 100$ au, $e_{\rm b} = 0$, $i_{\rm b} = 45°$
- $M_{\rm p} = 1\,M_{\rm Jup}$ planet with $a_{\rm p} = 5.2$ au, $e_{\rm p} = 0$, $i_{\rm p} = 0°$
- disk surface density profile: $\Sigma = \Sigma_0 r^{-0.5}$ with disk mass is $M_{\rm D} = 0.01$ and outer radius $r_{\rm out} = 30$ au
- locally isothermal EOS with $h_{\rm s} = 0.037$ - disk aspect ratio.
- two 3D SPH codes: VINE[6,10], PHANTOM[5,8]
- different:
  - binary inclination: $i_{\rm b} = 45°$ - $60°$
  - semi-major axis: $a_{\rm b} = 100$ - 300 au
  - self gravity: on - off
  - planetary semi-major axis: 5.2 au - 10 au
  - planetary mass: $1\,M_{\rm Jup}$ - $10\,M_\oplus$

Disk shape evolution

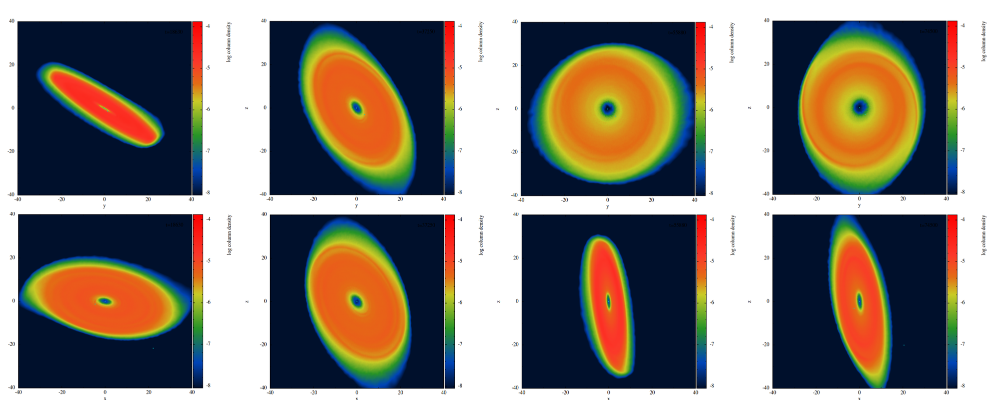

FIGURE 1: Disk shape shown every 300 planetary orbits. The disk warping is negligible, thus the assumption of a rigid body is correct.

Inclination evolution

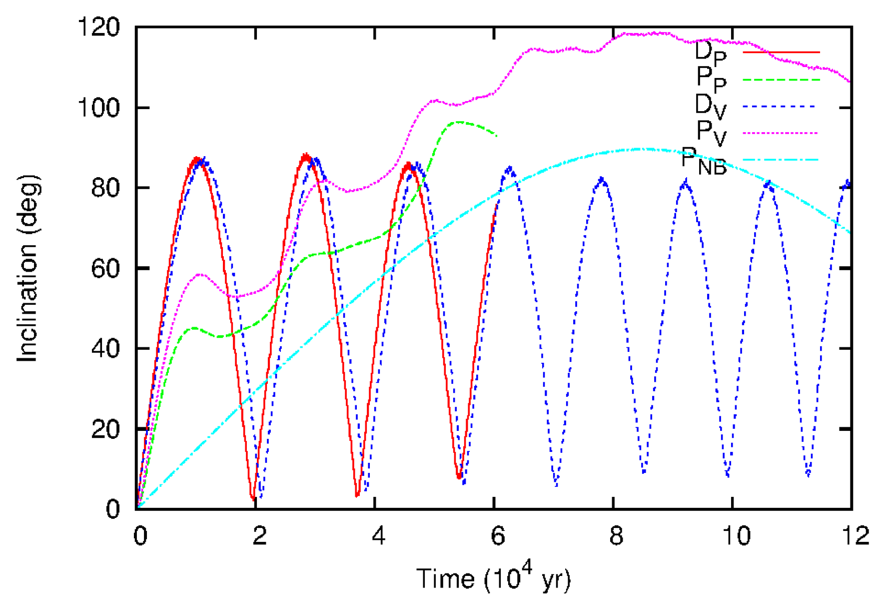

FIGURE 2: Evolution of the disk and planet inclination respect to the initial disk+planet plane for $i_{\rm b} = 45°$. The dashed magenta (VINE) and green (PHANTOM) lines show the planet inclination $i_{\rm p}$ while the continuous blue (VINE) and red (PHANTOM) lines illustrate the disk inclination $i_{\rm d}$. The planet shortly decouples from the disk and, although the disk influence its evolution, the interaction with the binary companion is stronger and it follows the pure N-body evolution (light-blue line).

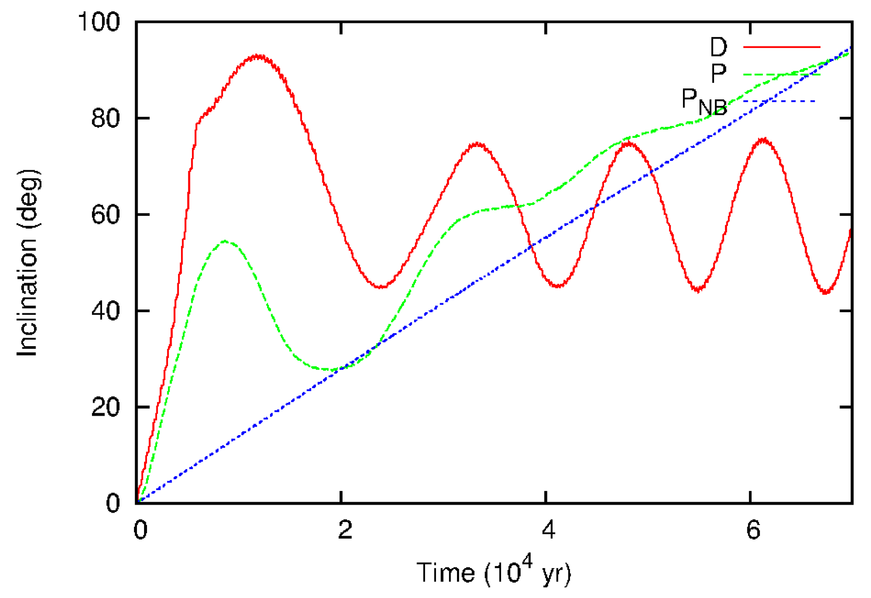

FIGURE 3 **IMPACT OF BINARY INCLINATION:** Evolution of the disk and planet inclination for $i_{\rm b} = 60°$. The disk (red line) alignes with the binary plane faster than in the 45° case, thus the planet (green line) decouples from the disk (red line) and follows closely the evolution of the pure N-body case (blue line).

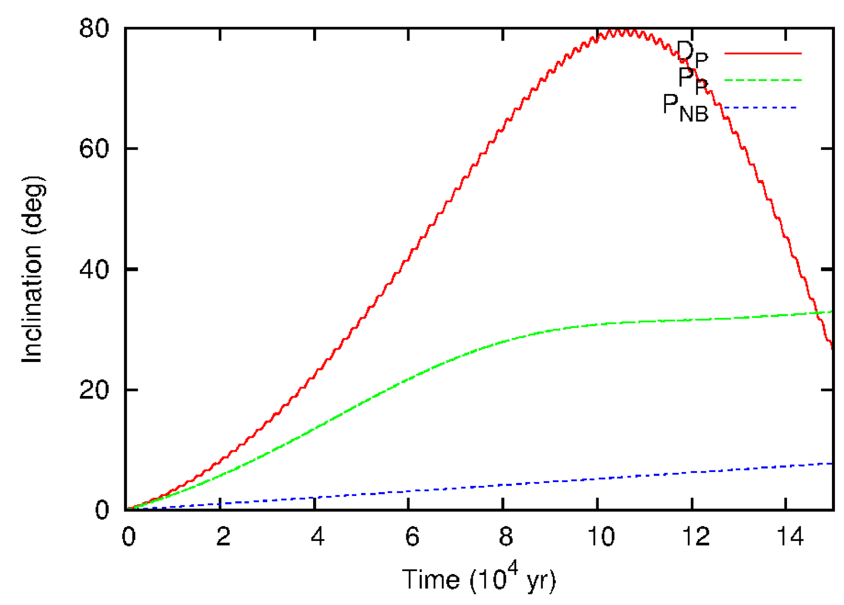

FIGURE 4 **IMPACT OF BINARY SEMIMAJOR AXIS:** Evolution of the disk (red line) and planet (green line) inclination for $a_{\rm b} = 300$ au compared with the N-body evolution (blue line). The evolution of the orbital parameters slows down, but also this effect does not prevent the planet-disk detachment.

Disk self-gravity

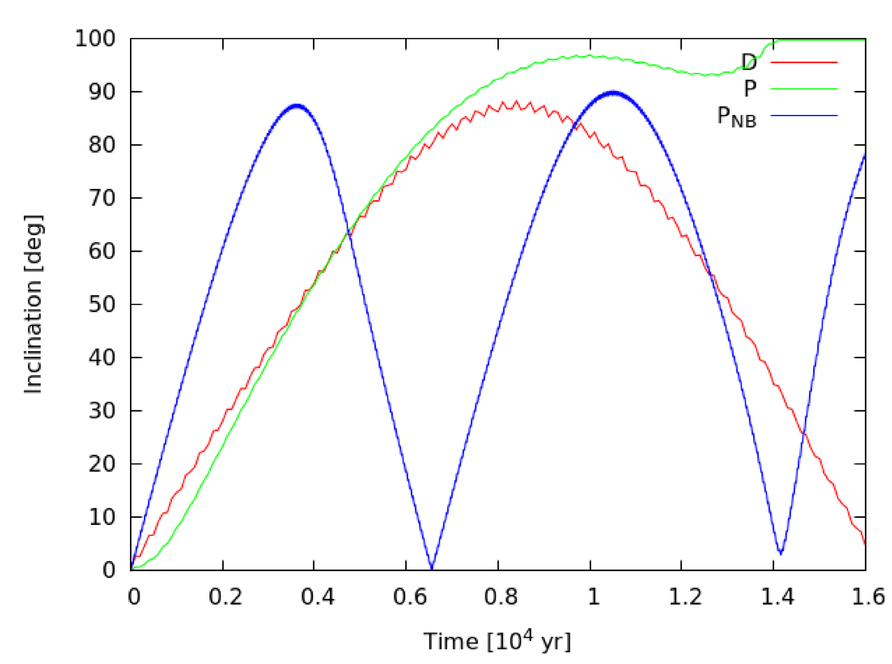

FIGURE 5 **IMPACT OF DISK SELF-GRAVITY:** Evolution of the disk (red line) and planet (green line) inclination for $a_{\rm b} = 100$ au and $a_{\rm p} = 10$ au compared with the N-body evolution (blue line). The disk is able to damp the inclination of the planet more effectively, but on the long run the gravitational torque from the binary is able to detach the planet from its birth disk.

Planetary mass

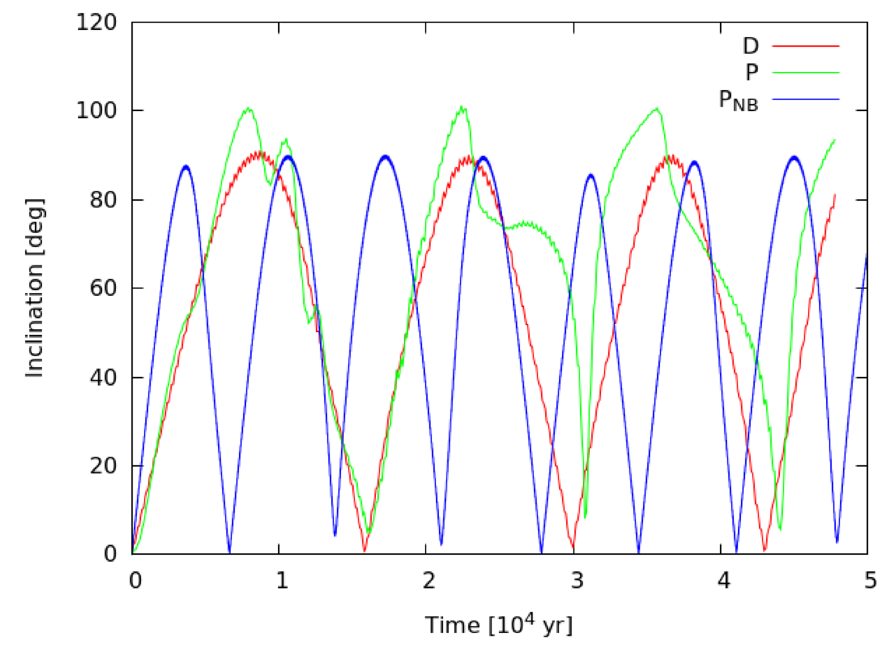

FIGURE 6 **IMPACT OF PLANETARY MASS:** The same as Fig. 5 but for a $10 M_\oplus$ mass planet. The damping effect of the disc is stronger since the planet is not able to form a gap but on the long run the gravitational torque from the binary prevails.

Planet migration

- initial fast migration rate when the planet is still embedded in the disk
- when the planet detaches from the disk plane, the friction developing during the periodic crossing of the disk by the planet dominates the semi-major axis evolution

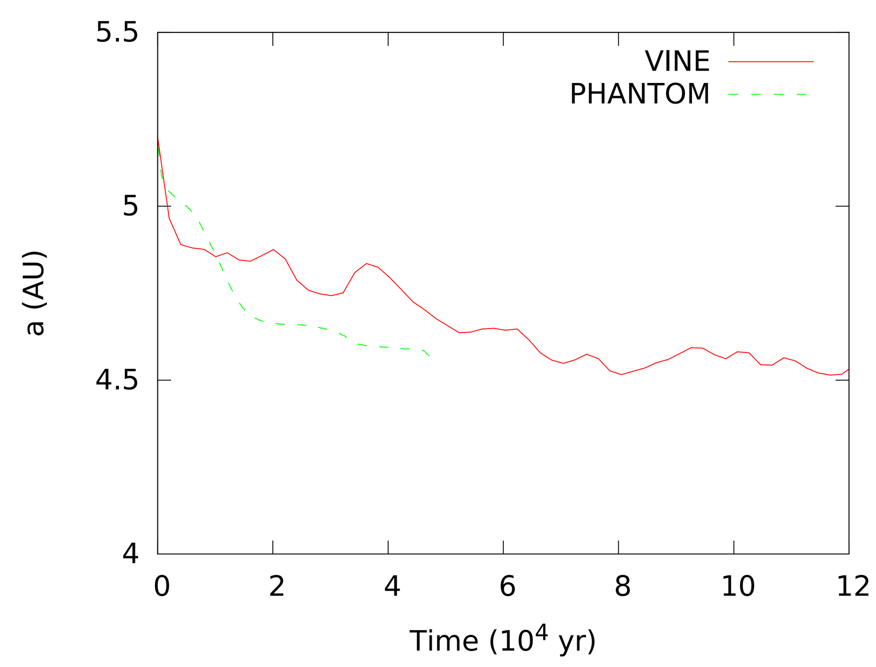

FIGURE 7: Evolution of the semimajor axis of the planet in the VINE (red line) and PHANTOM (green line) runs. The planet migrates because of the friction with the gas when it periodically crosses the disk plane.

Conclusions

- a giant planetary core embedded in a circumstellar disk will evolve almost independently from the disk in response to the perturbations of a close misaligned binary star
- after an initial coupled evolution, the planet dynamically detaches from a self-gravitating disk and its inclination oscillates on a significantly longer timescale compared to the disk one
- the N-body secular perturbations of the companion star dominate over the damping force of the disk which tends to drag the planet back into its median plane
- the planet migrates at a significant rate even if its orbit is misaligned respect to the disk plane, due to dynamical friction with the disk during the repeated crossings.
- the formation of hot Jupiters with spin misaligned respect to the stellar equator may occur via a combination of Kozai cycles and repeated crossing of the disk plane by the inclined planet evolving out of the disk

References

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