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# Circumbinary planet formation: *N*-body simulations of a perturbed early-phase protoplanetary disk

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## Abstract

We conduct high resolution, 3-*D*, inter-particle gravity enabled *N*-body simulations of circumbinary protoplanetary disks enhanced with a new collision model. We investigate the effects of perturbations on the disk from the binary and the feasibility of in-situ formation of observed circumbinary planets. We present preliminary results of Kepler 16 and 34 systems and determine if planetesimal growth is possible at the orbital radii of planets discovered around these respective binaries.

## 1. Introduction

With the recent discovery of several circumbinary planets [1], the necessity of solidifying our understanding of the formation processes in binaries has become increasingly important. The inclusion of a secondary star introduces perturbations that drive up the eccentricities and collision velocities of planetesimals which can lead to erosive, growth-inhibiting encounters.

Current models disagree on whether or not planets can form in-situ at the location of observed circumbinary planets [2, 3]. Using *N*-body simulations, we investigate the effects of perturbations on collision outcomes and determine if and where planetesimal growth is possible.

Secular effects on the planetesimal eccentricities can be expressed via the forced eccentricity $e_f$ [2] :

$$e_f = \frac{5}{4}\frac{M_A - M_B}{M_*}\frac{a_b}{a}e_b\frac{1+\frac{3e_b^2}{4}}{1+\frac{3e_b^2}{2}} \qquad (1)$$

where $M_A$ and $M_B$ are the individual star masses, $M_*$ is the total binary mass and $a_b$, $a$, $e_b$ and $e$ are the binary and planetesimal semi-major axis and eccentricity respectively. Equation 1 is derived by averaging the disturbing function over the planetesimal orbit.

Planetesimals can evolve dynamically much faster than the secular timescale, and the corresponding *fast* forced eccentricity $e_{ff}$ is obtained by averaging the disturbing function over the binary orbit only:

$$e_{ff} = \frac{3}{4}\frac{M_A M_B}{M_*^2}\left(\frac{a_b}{a}\right)^2\sqrt{1+\frac{34}{3}e_b^2} \quad . \qquad (2)$$

For disks that encompass a binary with $e_b \approx 0$ or $M_A \approx M_B$, the forced eccentricity $e_f$ tends to zero. The non-secular eccentricity forcing still applies, although this effect is less pronounced and diminishes faster with distance from the binary barycenter than its secular counterpart.

## 2. Numerical Methods

Our simulations are performed using PKDGRAV [4] which uses a second order leapfrog integrator in conjunction with an efficient binary tree partitioning method to enable full parallelization. Multipole expansion during the inter-particle gravity calculation allows for a system that scales as $N\log N$.

We use two binary systems to explore secular and non-secular effects [Table 1].

| Model | $e_b$ | $a_b$ | N | $a_{inner}$ | $a_{outer}$ |
|---|---|---|---|---|---|
| Kepler 34 | 0.53 | 0.23 | $10^6$ | 0.8 | 1.8 |
| Kepler 16 | 0.16 | 0.22 | $10^6$ | 0.7 | 1.7 |

Table 1: Model Parameters.

A new empirically derived analytical collision model *EDACM* [5] has been integrated with PKDGRAV. During a two-body encounter, the impact velocity, impact parameter, mass ratio and material properties are used to determine which post-collision outcome occurs: perfect merging, partial accretion, erosive disruption or hit-and-run.

Collisions that do not fall into the commonly used perfect merging regime, either undergo a realistic fragmentation with calculated mass and velocity distributions, or for situations with sufficient impact angle follow a bouncing event known as hit-and-run.

The results of a preliminary EDACM single star simulation reveal that over half of all collisions do not result in growth. This highlights the necessity of such a model in a circumbinary disk where collision velocities and the tendency for erosive events increase.

## 3. Results

After only 100 orbits the disks have become noticeably perturbed. Eccentricity oscillations about $e_{ff}$ can be seen in Figure 1.

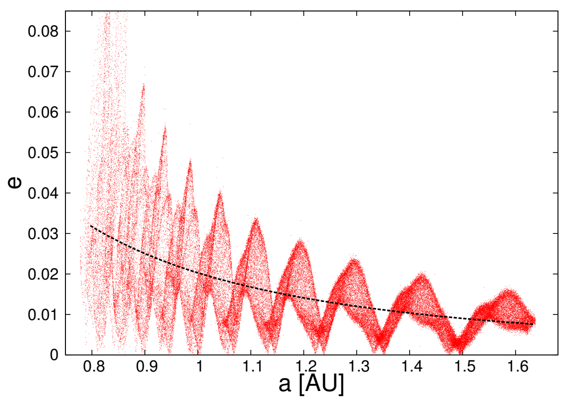


Figure 1: Fast eccentricity oscillations about $e_{ff}$ (dotted line) in Kepler-34 at 100 binary dynamical times.

Despite the damping of $e_{ff}$ with $\frac{1}{a}$, the location of Kepler-34b, 1.09AU, travels though the oscillatory eccentricity waves and is regularly excited to e $\approx$ 0.035.

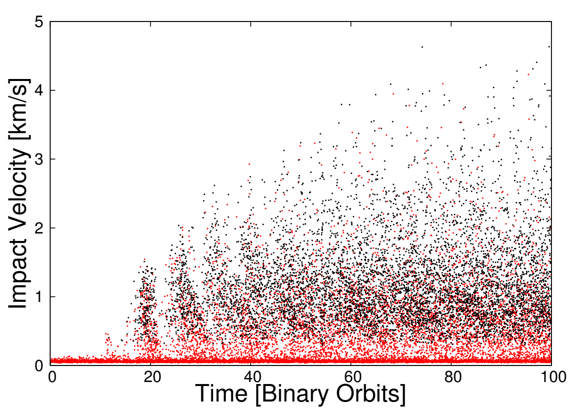


Figure 2: Impact velocity evolution for Kepler-34. Accretion and erosive events are represented by red and black points respectively.

The corresponding waves of impact velocity can be seen in Figure 2 and becomes increasingly sustained towards the end of the simulation when the frequency about $e_{ff}$ increases and orbital crossing of low and high velocity planetesimals occur more frequently.

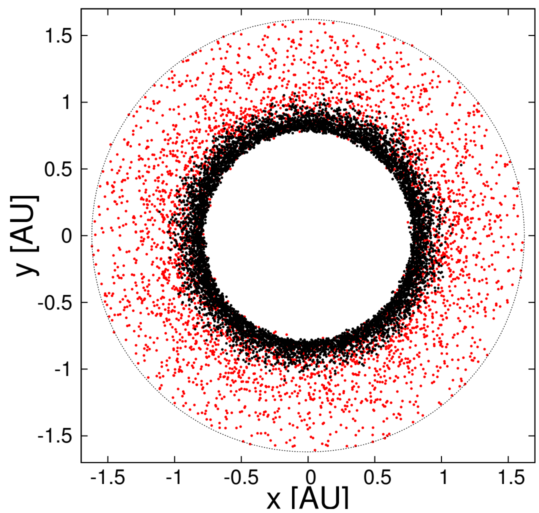


Figure 3: Collision type distribution in Kepler-34. Labelling as in Figure 2.

There is a noticeable overlap between accretion and erosion regimes, as shown in both Figures 2 and 3, accentuating the need for such a collision model which takes into account all collision parameters.

## 4. Summary and Conclusions

In this work we highlight areas of circumbinary disks which can nurture growth through accretion events. In the event of a predominantly erosive disk, we reveal additional mechanisms, such as dust accretion, to aid planet growth and discuss the future introduction and impact of a gaseous component to a disk.

## Acknowledgements

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## References

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