The Dynamics of Rogue Planets in Binary Star Systems

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Abstract

Problem Domain: Rogue planets, unbound to any star, can perturb binary star systems, potentially causing orbital exchanges, captures, or destabilization.

Research Question: What initial conditions of rogue planets lead to stable orbits when interacting with binary star systems?

Methods & Results: We use N-body simulations via the `Rebound` package to model interactions under varied initial positions and velocities. Outcomes—fly-bys, exchanges, and captures—are analyzed to identify conditions conducive to stable configurations.

Conclusions: We aim to determine critical parameters for stable captures and the likelihood of various outcomes, informing models of planetary system evolution and exoplanet formation.

Background

There are several events that can occur when rogue bodies interact with planetary systems.

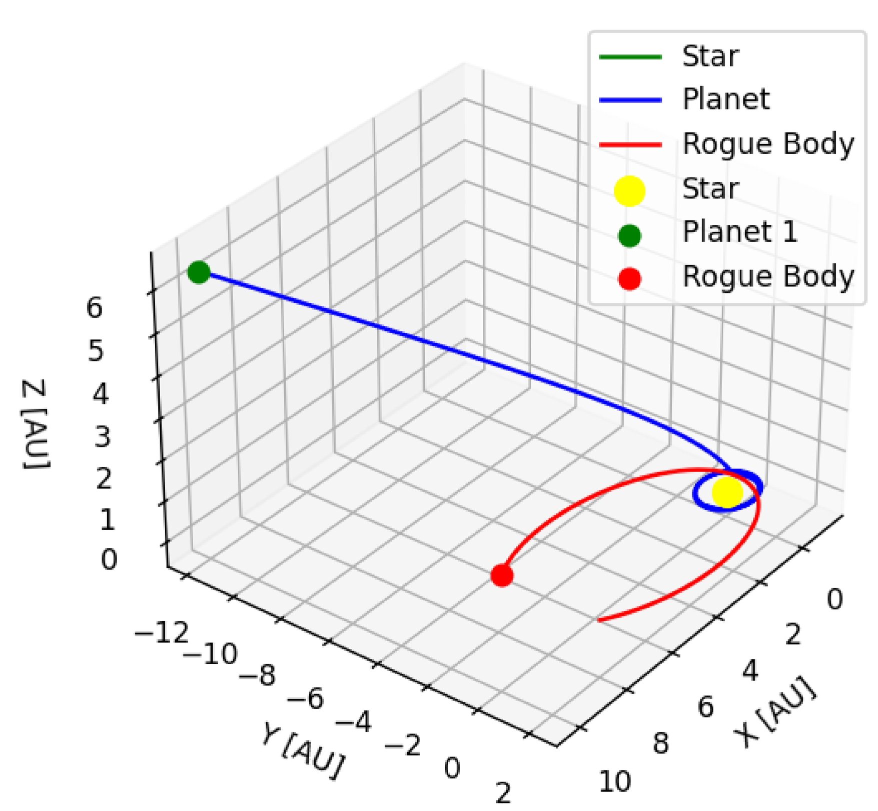

Figure 1. Example of an exchange interaction.

The events our project is focusing on are:

- **Exchange**: The process in which the rogue body replaces the original stable planet.
- **Ionization**: The process in which both the rogue body and original planet are removed from the system entirely.
- **Capture**: The process in which the rogue body and the planet both enter a stable orbit around the star.
- **Flyby**: Where no meaningful interactions occur.

Research Question + Objectives

What initial conditions of rogue planets lead to stable orbits when interacting with binary star systems? More specifically, we want to

- **Determine event frequency**: Figure out how often these events occur. This is done by simply measuring the total number of events out of total number of simulations.
- **Determine event cross section**: Figure out the radius from the star the body must cross to cause an interaction. This is done using the Monte Carlo method.

Methods

Our Simulation: Simply put, the simulation "throws" a rogue body at the star system from a random direction in space, with a velocity equal to a multiple of the orbital velocity of the stable planet. We simulate over a period of 150 years to ensure stability, if it occurs. To generate a random direction, we give the stable planet a list of random orbital elements:

- Inclination
- Argument of Periapsis
- True Anomaly
- Longitude of Ascending Node

This places the rogue body in a stable orbit in a random place, traveling in a random direction. That way, relative to the planet, the rogue body comes from a random direction.

There are multiple mathematical methods of determining whether or not a state is stable.

1. Graph Theory

There is the visual method, in which we plot the system and examine if the curves traced by each body are closed. Closed curves, if even not exactly periodic, still represent stable systems. This method has a number of flaws however:

- **Computation**: It's very computationally expensive.
- **Visuals**: They can be very difficult to understand if many paths overlap.
- **Time**: There is no way to check if the system will be stable after the time for which we simulate.

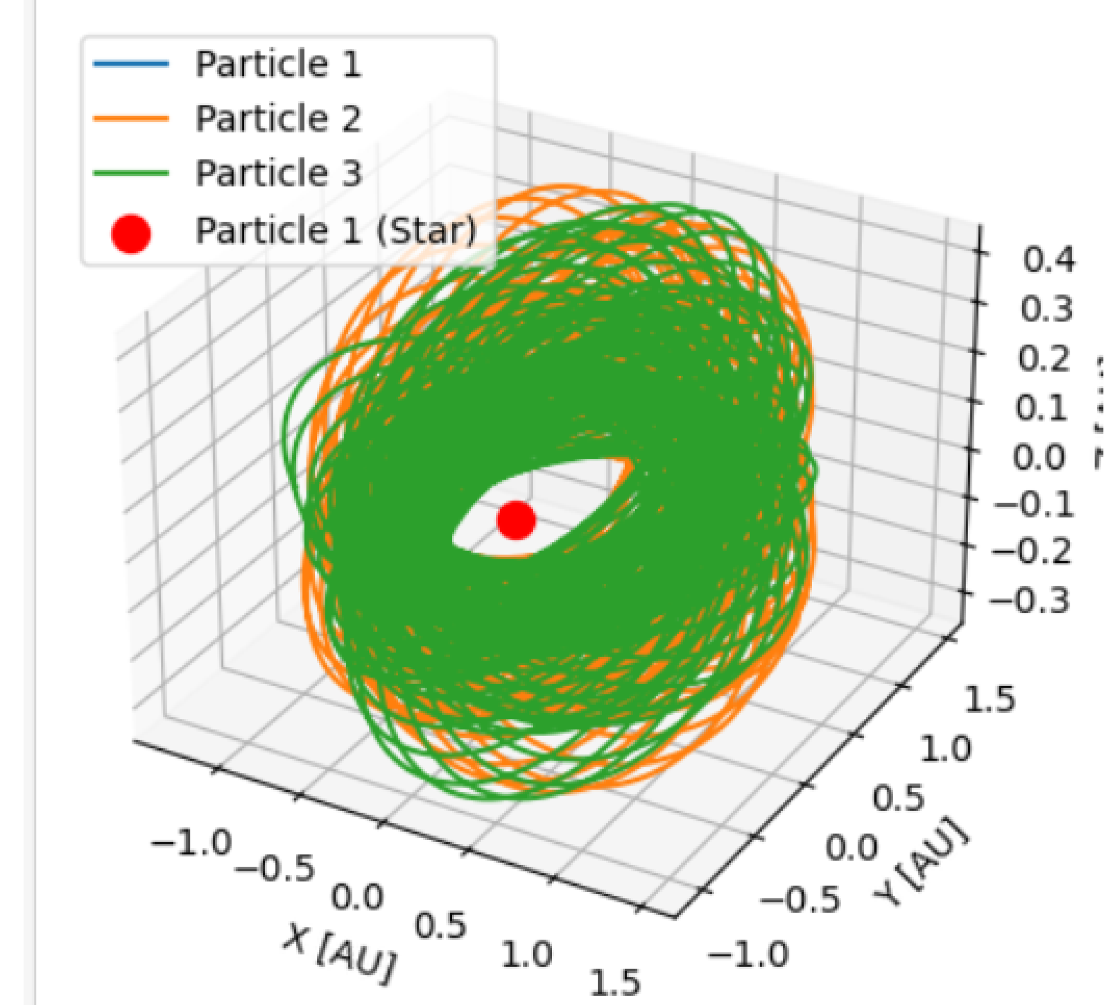

Figure 2. Example of stable system

2. Mathematically

Mathematically determining stability is simple: We simply tell our simulation to check either the eccentricity or the semi-major axis at the end of the simulation.

- **Eccentricity**: Slightly more computationally intensive, but easier to understand the theory, so easier to check for errors.
- **Semi-Major Axis**: Less computationally expensive and slightly more accurate, but theoretically more computation errors could happen.

Conclusion

We uncovered several new trends in rogue body–star system interactions.

- There are very little to no conditions which result in stability.
- Ionization occurs for lower initial velocities.
- Exchange replaces ionization past a velocity threshold dependent on the initial velocity.
- Stable orbits are exceedingly rare.
- Collisions predictably dominate the lowest velocity ranges.
- Event cross sections are essentially wholly dependent on interaction count.

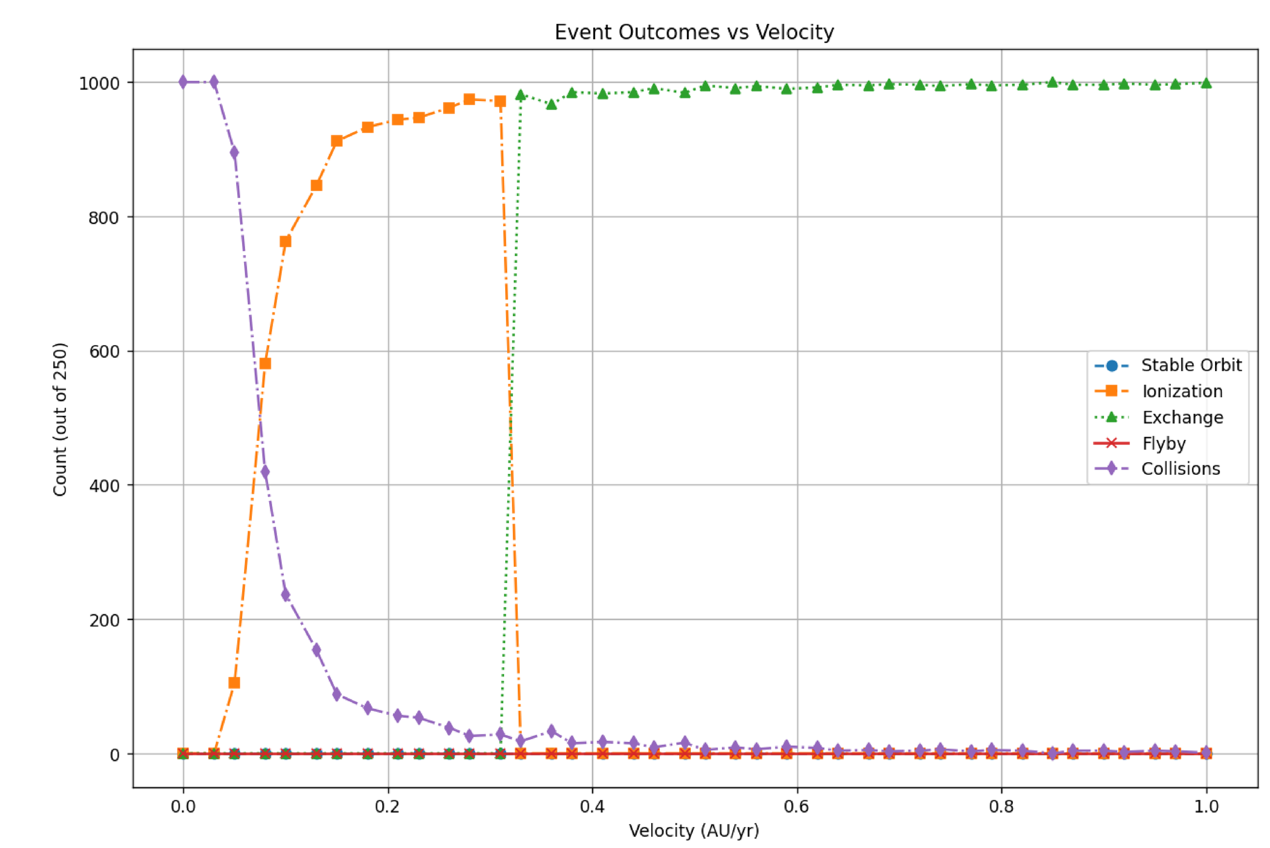

Figure 3. Interaction count per 1000 simulations

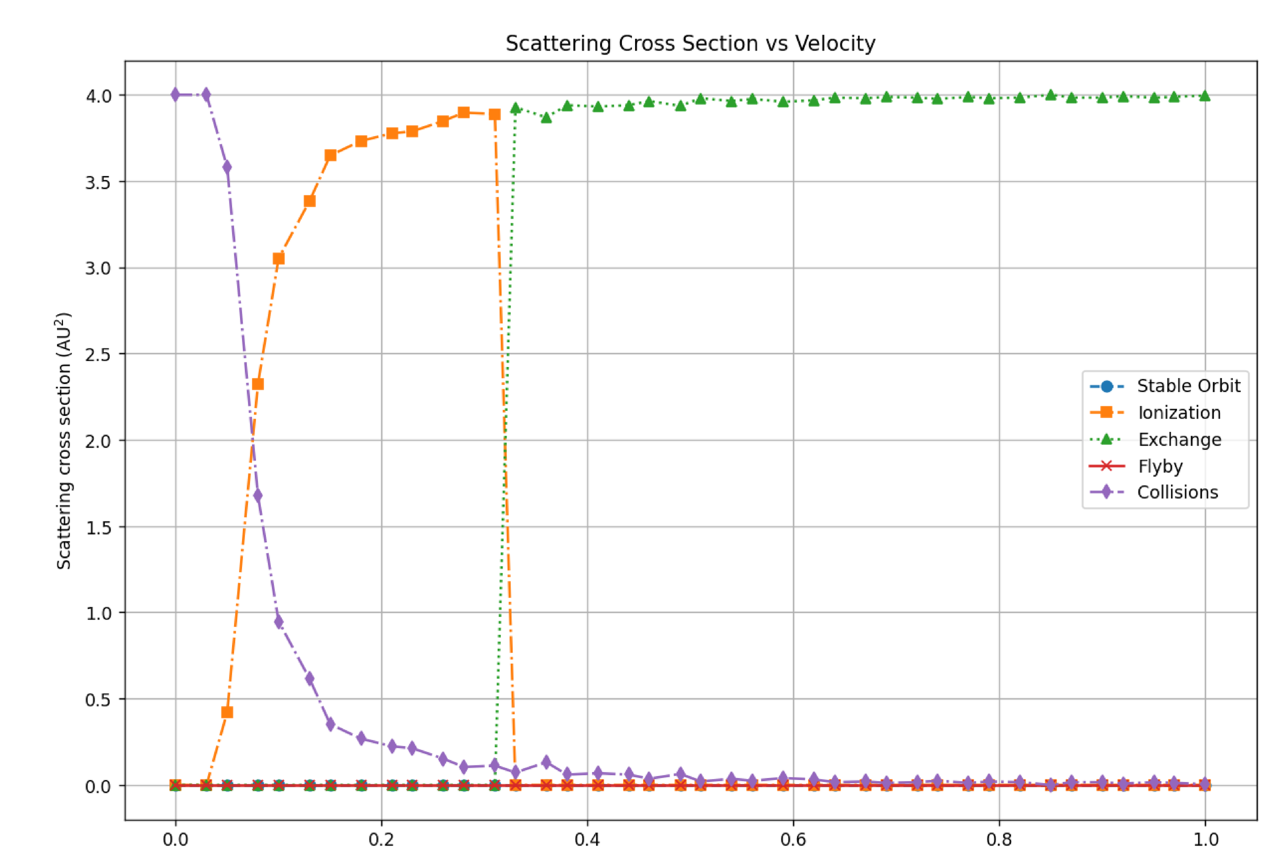

Figure 4. Experimental Cross Section of each event

Future work could examine the long-term stability of rogue bodies in binary systems, incorporating stellar evolution and multi-body dynamics. Machine learning models could also help predict stable configurations and speed up parameter space exploration.

References

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