Investigating the Development of Hot Jupiters and Rogue Planets through Universe Sandbox 2

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Abstract

This project explores the theory of high-eccentricity gas giant migration. The purpose of this project is to determine if the creation of rogue planets is the most probable effect of proto-Hot Jupiter migration in a star system. Such determination would help to explain why so many hot-jupiter star systems have little to no companion planets.

Data shows that, there was only one test where a planet was ejected from the system and became a rogue planet. Thus one can conclude there may be more probable ways that a migrating gas giant can disrupt a star system besides ejecting planets. Furthermore, data collected does not show, overwhelmingly, that a rogue planet is created often. These results reveal that either rogue planets are not the most probable result from migrating gas or there is a different "sweet spot" for when a migrating gas giant creates a rogue planet. This paper investigates those options by analyzing collected data.

1 Introduction

This research was designed to answer how disruptive a migrating gas giant is on the stability of a solar system by collecting the result of how many rogue planets are created. This capstone will research the probability of a Hot Jupiter (HJ) planetary body to create a rogue planet through computer simulation. This research aids in understanding how other solar systems are created and how destructive of an effect a HJ has on its star system while the gas giant migrates towards its star. I expected that the spectral class of the host star would not have much of an effect on the results of the experiment. Instead, the pericenter of the migrating gas giant would have the greatest effect on the results of the experiment. Additionally, the migrating gas giant would have close to the same effect in every star system. Overall, I expected that in most solar systems the most elliptical orbit of the migrating gas giant would create the most rogue planets.

There are multiple theories of Hot Jupiter formation, including: In Situ formation, Gas Disk migration and High-Eccentricity migration. For the purpose of this research, high-eccentricity migration was selected because it was the theory that was most plausible and I found a simulation software that could handle said theory. The theory I plan to explore is high-eccentricity migration of gas giants through secular interactions. This theory proposes that proto-Hot Jupiters will slowly lose their angular momentum and energy over thousands of years as they tidally interact with the other planets and stars in the system. Secular interactions conserve angular momentum; as time passes the Hot Jupiter loses its own angular momentum by taking on the deficit of the system's angular momentum. This drives the planet's eccentricity to large values [3]. Once the Jupiter's orbit is sufficiently elliptical, tidal dissipation in the planet shrinks and circularizes its orbit. Tidal dissipation in the planet decreases the planet's orbital energy through interactions with the central star. The Jupiter dissipates energy as it stretches, changing shape to conform to the rapidly changing tidal potential.

Exploration begins with a migrating gas giant that has already gained a highly elliptical orbit. First, the gas giant is identified at the frost line of each star system chosen, then set the pericenter from close values (0.01 AU) to further values (0.25 AU). This range of pericenter test values for the migrating gas giant will result with a different disruptive effect on the star system which will change how many rogue planets are created. This procedure closely follows the experiment performed by Alexander Mustill and his team of researchers, whose paper I will mention in the reference section

2 Theory

For my research I selected a total of six star systems across the spectral classification of stars, minus a few spectral types, based on a variety of factors. One of those factors was the amount of planets in the star system. I determined that I would only experiment on star systems with at least two planets, and no more than three planets. This was based on the experiment of Alexander Mustill and his team of researchers as their experiment was the foundation of mine, though we researched different matters. Due to this factor I ended up omitting star systems of O-, B-, and A-type stars because they usually contained only one planet in the NASA catalogue.

The second factor I used in determining which star systems to use was the completeness of the data. I obtained my data from the NASA Exoplanet Catalogue, specifically the Confirmed Planet Catalogue[2]. There were a variety of characteristics provided, but the ones I needed were as such: mass, radius, semimajor axis (planetary), orbital period (planetary), and temperature (stellar). Any other information was secondary and could be calculated by Universe Sandbox 2 if the catalogue did not provide it. Because of this I omitted two more systems from my experiment, a G- and a K-type system which lacked one or more of these characteristics.

Mathematical modeling is not robust for this experiment as the simulation software handles the majority of the calculations. Of the two steps to this theory, the data analysis will focus on the second step.

The first step is reducing the gas giant's orbital momentum. The theory proposes that proto-Hot Jupiters will slowly lose their angular momentum over thousands of years as they tidally interact with the other planets and stars in the system. Secular interactions conserve angular momentum, as time passes, the Jupiter loses its own angular momentum by taking on the deficit of the system's angular momentum. This drives the planet's eccentricity to large values.

The second step is reducing the gas giant's orbital energy, this is the step that the experiment models. As the gas giant migrates in towards its star, the planet will gradually lose some of its orbital energy to the rest of the bodies in the system, most significantly by the star. As this occurs, the orbit of the gas giant will change according to the formula where its final semimajor axis will be determined by the change in its starting semimajor axis and eccentricity over time. This formula is stated as

$$a_{final} = a(t)(1 \; - e(t)^2)$$

where a(t) and e(t) are the time evolution of the semi-major axis and eccentricity respectively. The simulation software models the tidal dissipation forces, so I don't have much information on the subject.

The data analysis methodology began with creating two kinds of graphs with the data I collected. The first graph is a line graph. This graph plots the distance, in astronomical units (AU), compared to time, in years. One graph was created for each planet in the star system for every pericenter tested. This was done to see if the data that collected had any errors in it such as my python code skipping over a distance point, or a severe drop off or increase in the position of the planet which would not make sense. Both scenarios have occurred and by having a graph of a single planet's orbit changing over time greatly improved the accuracy of plots generated. A line graph that combines all the data from the planets in the system for one pericenter test was generated. This highlights how much of an influence that the HJ had on the other planets in the star system. Data points from the previous three line graphs were corrected. This specific graph has the most accurate data for the entire star system.

The second graph created is a bar graph. The purpose of this graph is to record the total number of times where a specific situation occurred (i.e. rogue planet created, planet accreted into star, stable orbits maintained, etc). This graph will be a total of all the pericenter tests in a system, instead of simply one test like the line graph mentioned above. Once all the pericenter tests have been completed there should be a noticeable discrepancy between how often each scenario occurred. The bar graph I will be used to compare to other sets of data from previous researchers. The comparison of the line graphs will not be as useful because the change of individual planets' orbits are not as important as the result of the effect that the migrating gas giant has on the star systems; especially since different software and slight differences in input data of planets can lead to different orbits. Lastly, I will conduct a Chi-Square test on the data from each star system, in google sheets, to determine which result is statistically significant across the pericenter tests. This would determine what is the most disruptive effect of HJ migration.

3 Methods

Setting up the experiment began with creating every celestial object from the solar systems that needed to be observed. After every star and planet was created, a new file was started and the first experimental star system was created. The star system was simulated for one-thousand years, as a control test, to ensure that the simulation software did not contain any errors (i.e. planets overheating, exaggerated orbits, etc). Once the control test was completed, a copy of that system was created and prepared for the perienter tests. In that 'pericenter' file, the migrating gas giant was inserted as close to the beginning of the snow line for each star system. Then the pericenter was set to the astronomical unit (AU) distance value of 0.01 for the first test. The value was then increased to one one-hundredths of a value until it reached 0.20 AU, then another test at 0.25 AU. Every test ran until each planet became rogue or a stable orbit was observed in the planet(s) that remained in the star system. The test was conducted after two-thousand years passed in total run time and the orbits of any remaining planet(s) continued to be stable.

During each test a video capture software was running in tandem to Universe Sandbox, the video software called OBS Studio. When the test ended the video recording was stopped and the capture data would be sent to the video capture folder called PycharmProjects. The python code which would then cut the video into single frames of the distance values of the planets in the simulation. Those values were migrated into a text file which was used to create graphs.

4 Data

The data currently generated is on the CoRoT-24 star system, which is a K-type star with two planets in its system. Three tests were completed on this system; they are the 0.01, 0.10, and 0.20 AU pericenter tests. From these tests, in only one test there was a planet ejected from the system and became a rogue planet. Based on this star system alone, one can conclude there may be more probable ways that a migrating gas giant can disrupt a star system besides ejecting planets. The data currently does not show, overwhelmingly, that a rogue planet is created often. This could mean a few things: either rogue planets are not the most probable result from migrating gas or there is a different "sweet spot" for when a migrating gas giant creates a rogue planet.

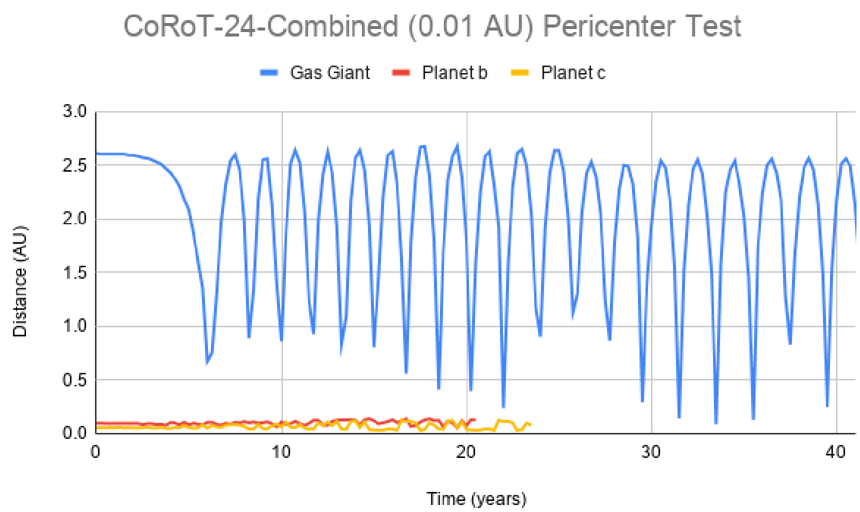

Figure 1: CoRoT-24 (0.01 AU) Pericenter Test

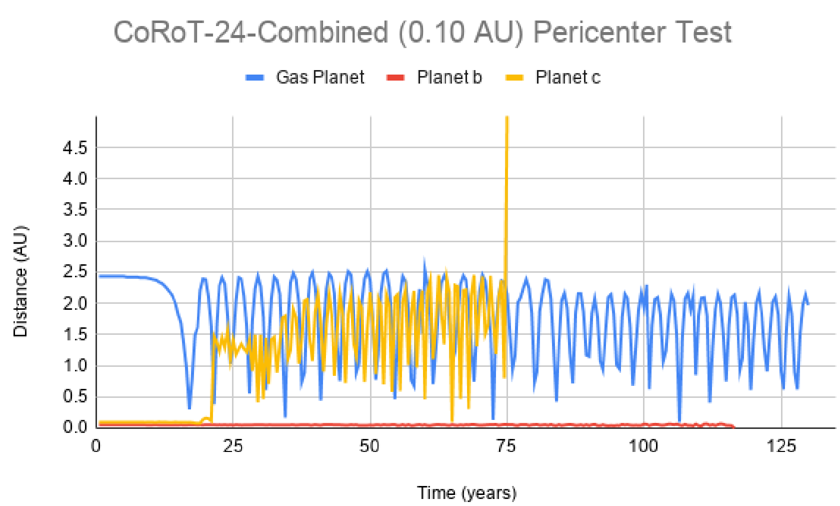

Figure 2: CoRoT-24 (0.10 AU) Pericenter Test

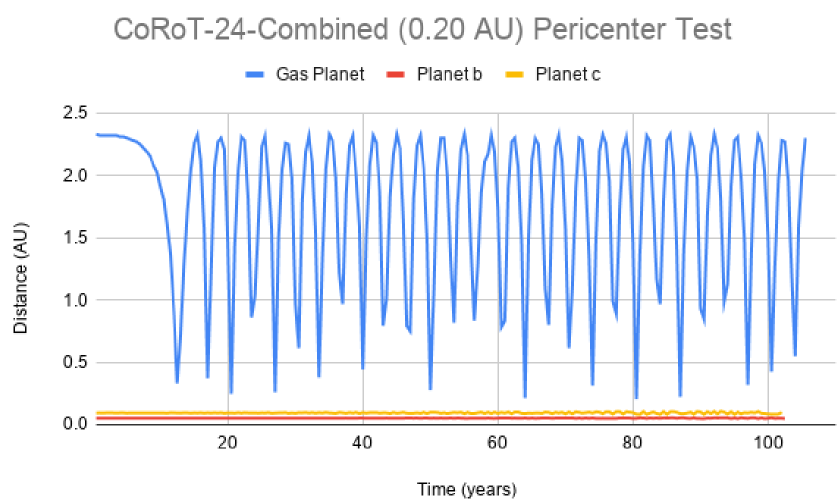

Figure 3: CoRoT-24 (0.20 AU) Pericenter Test

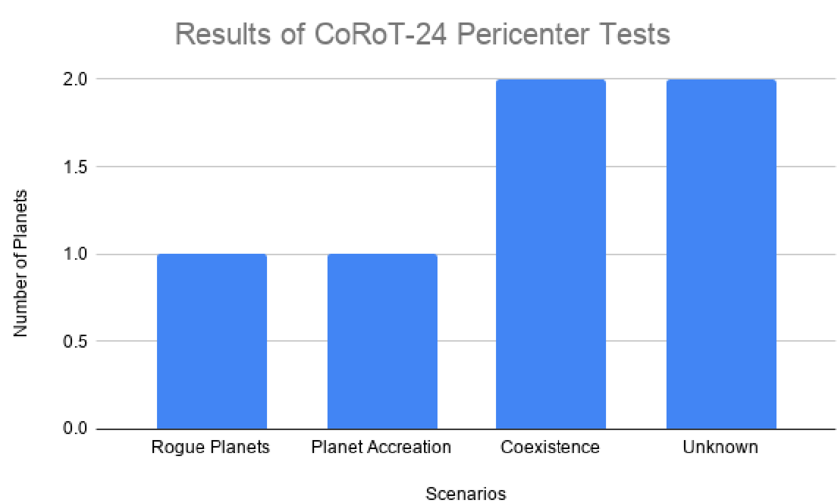

Figure 4: Results of CoRoT-24 Pericenter Tests

Regarding the accuracy and precision of Universe Sandbox 2, there are some issues and concerns with the software. Problems in accuracy arise from rounding issues and the lack of tidal forces being implemented in the software. Universe Sandbox 2 has some scaling factor in its algorithm for stellar and planetary masses and radii. There were instances when data had to be inserted for those values directly from the NASA Exoplanet Archive [2], but the object in the software would not accept the values. This led to a handful of celestial bodies not being accurately replicated in the software. Sometimes, the temperature (in cases of a star) drastically increases or decreases, or the mass or radius value will not stay at the value that I inserted once the other value is then inserted. Again, the software seems to scale the values in a calculation that I have no control over. It should be mentioned, that when it comes to the values for CoRoT-24 system the rounding errors were within the uncertainty values provided by the NASA archive.

There is also a problem with the lack of tidal forces programmed into the simulation. When I first tested this software, I researched the capabilities and observed some of its systems. Based on these observations it seemed like the software calculated tidal forces. However, upon experimenting, it was realized that results were on the order of hundreds of years instead of thousands of years, which identified the capabilities and limitations of the simulation software. It was later learned that the manufacturers of the software had not implemented tidal forces into the software. I know that this will have an effect on my project and I believe that was why I got results so quickly. However, that may be because the CoRoT-24 system has a low-mass K-type star. I will see how this affects the rest of my experiments.

Problems in precision arise from getting different timescales for the disruptive results on the inner planets from the migrating gas giant. Generally speaking, the same situation occurs (rogue planet, planet accretion, etc), but at different times when I reset the experiment to capture distance results from a separate planet. This is because during one pericenter test I can only take the distance data from one planet in the system. When I reset the system I seem to get different results of the final results of planets which makes me skeptical of the precision of my experiment.

5 Discussion and Conclusions

The largest discrepancy discovered was the timeline. The duration of the data is much shorter than the ones of other researchers. Many of their tests take tens of thousands of years of simulation time to complete while the current data taken was only a few decades. I expected this number to change when I took the remainder of my tests, but I was unable to to take those tests due to a lack of time and a machine with the required processing power. That being said, I am not entirely sure by what margin the timeline should have changed. When discussing the Chi-Square test, there were problems in my statistical significance values. While the individual scenarios were statistically significant, rogue planet, planet accretion, etc (being below 0.05) the test on the entire data set is not significant. I believe that this is due to the unknown category. If those results were factored into some of the other categories the test of the entire data would be significant.

One question that I found a tentative answer to in my project is when to consider an ejected planet a rogue planet. My first idea was to assume when Universe Sandbox 2 stopped recording a planet that was ejected from the star system that I could record that ejected planet as a rogue planet; however, I knew that was not sufficient. I then proposed that any planet that was ejected past a star's heliopause (the equilibrium point where the star's particles equal the interstellar medium of cosmic waves, or where particles are no longer bound by the star's gravity), I could consider a rogue planet; however, that was also rejected. The reasoning was because that the oort cloud of our solar system exists out of the Sun's heliopause, and are still gravitationally bound by the Sun, that a planet ejected from the inner star system in my experiment could plausibly be gravitationally bound even at that distance away. My final answer to this question resulted in an approximation, as I could find no definitive answer. I decided that the distance a planet must reach to be considered a rogue planet is either the estimated end of the oort cloud at 10,000 AU or when Universe Sandbox stops recording the distance of the planet. I settled on these conditions after more research on when a planet is no longer gravitational coupled to its host star. I was unable to find a specific formula that covered this topic, so I decided that the end of our star's oort cloud would make a decent approximation. The reason why I kept the condition about Universe Sandbox 2 is to consider high mass stars, which have a greater gravitational influence. Our star's oort cloud would not be a plausible approximation, so Universe Sandbox's simulation software will cover that issue.

One way to enhance the methods I already have is to edit the video captures that I have already analyzed for distance data. I was recommended this by one of the professors at my university because the orbits of my planets did not accurately reflect how planets orbited a star. The problem with my videos is that I could not simultaneously start the simulation software, Universe Sandbox 2, and my capture software, OBS Studio, at the same time so for a few moments the video capture software recorded the same value over and over again. When my python code separated the individual frames of the capture there were multiple copies of the same value; this formed a constant line at the beginning of the orbits of the planets, which is unrealistic. I plan to edit my video captures so that the first value is constantly repeated by removing some time at the beginning of the video. That should ensure that my graphs follow a more sinusoidal pattern, minus the effect of the migrating gas giant. I intend to compare my results to the research of Alexander Mustill and his team of researchers in his paper [1]. I also considered looking more in detail to the Niche Model. It is hailed at the most accurate representation and at first glance it seems to use a version of high-eccentricity migration, although I do not know for sure if it follows the exact version of the theory that I utilized for this experiment.

References

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