Simulating the Destruction and Consolidation of a System of Tightly Packed Inner Planets in Our Solar System Using Universe Sandbox

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Abstract

This project is based on the theory that there was once a system of tightly packed inner planets (STIP) orbiting the Sun in our Solar system and that a STIP would have to be destroyed through collisions or ejected from the system to achieve the current Solar System configuration. This project will simulate various STIPs in our Solar System and focus on the collisions between the added planets.

The data from the collisions shows consolidation, destructive and unclassified types for both the initial and secondary collisions between the planets. The data shows an increase in destructive collisions for secondary collisions and more consolidation types for initial collisions. This data is consistent with research done in other projects and was the expected result.

1 Introduction

Researchers using the Kepler space telescope have discovered that about five percent of F, G, or K type stars that are five billion years old have a system of tightly packed inner planets or (STIP) [4]. F-type stars have a yellow-white color with temperatures between 6000k and 7500k, which are hotter than yellow G-type stars that are between 5000k and 6000k, and warmer than yellow-orange K-type stars that are between 3500k and 5000k. A STIP is a group of small planets that orbit close to their star. This is an important discovery because the Sun is a G-type star that is approximately four and a half billion years old. Researchers believe that there was a STIP in our solar system all orbiting inside of Venus that consisted of between one and four planets with a total mass of about four times the mass of the Earth [4]. They also believe that gravitational perturbations caused a series of collisions between these planets and they were either destroyed, sending debris into the solar system and beyond; or consolidated into the planet Mercury [4].

This research is similar to the capstone project that was done on the development of hot Jupiters and if they were the main cause of rogue planets [2]. The methods of that project can be used to model a STIP in our solar system instead of the hot Jupiters by using the same software and similar techniques. By using the Universe Sandbox software to model a STIP in our solar system, the collisions of the planets can be observed and the data can be recorded. The data collected after each simulation can be compared to the theory that the first collision between two planets is most likely a consolidating collision and as the number of collisions increases so does the probability of a destructive collision.

The software used to run the simulations for this project was Universe Sandbox and Python Jupyter Notebooks were used to analyze the data. Universe Sandbox was used in Tariq Kerr's project and based on his work and knowledge about the software, It was determined to be best to use for this project as well. The project could be run on any space-based simulation that allows the user to input new planets with specific data and can detect collisions. Python Juypter Notebooks were used for writing the two programs in this experiment for planet separation and collision classification because it is easy to use for data analysis and calculations.

2 Theory

This experiment simulates multiple test models of a STIP in our Solar System by using different variables such as the size and orbits of the planets as well as the total number of planets added to the system. After each simulation was completed, the results showed the total number of collisions, what type of collision occurred, and if the collision was the first or a secondary collision. A consolidation collision will occur if

$$\frac{V_{imp}}{V_{esc}} < 2. \tag{1}$$

This shows the ratio of impact velocity (V_{imp}), which was observed in the simulation as the launch speed, to the mutual escape speed (V_{esc}) which was calculated using,

$$V_{esc} = \sqrt{2G\frac{M_1 + M_2}{R_1 + R_2}} \tag{2}$$

where M_1 and M_2 are the masses and R_1 and R_2 are the radii of each planet and G is the universal gravitational constant [4]. A consolidation collision is more likely to occur if the impact speed is low. In a consolidation collision, the gravitational force between the two planets causes the particles to come together and form a new planet. A destructive collision will occur if more than ninety percent of the planet's original mass is lost. It is shown by the mass loss equation,

$$\frac{M_f - M_i}{M_i} * 100\% = M_{lost}\%, \tag{3}$$

which will give the percentage of total mass lost during the collision. A destructive collision is more likely to occur after multiple collisions or if there is a high impact speed.

The initial mass of the added planets was determined by research and observations from the Kepler missions. The total mass for the added planets was equal to four times the mass of the Earth [4] and the radii of the planets were up to four times the radius of Earth [3]. The planets were added to the Solar System between the Sun and Venus with Mercury being removed from the simulations because it has been theorized to be the remaining planet after the completion of all the collisions [4], except in the case where there is only one added planet. In those systems, Mercury will remain because two planets are needed for a collision to occur. The added planets' orbits are stable if they have a separation criterion Δ that is greater than three and a half, which is defined by,

$$\Delta = \frac{a_2 - a_1}{R_{H1,2}}, \tag{4}$$

where a_1 and a_2 are the semi-major axes of the planets and $R_{H1,2}$ is their mutual Hill radius. The mutual Hill radius is given by,

$$R_{H1,2} = (\frac{M_1 + M_2}{3M_*})^{\frac{1}{3}} \frac{a_1 + a_2}{2} \tag{5}$$

where M is mass and the subscripts $1, 2$, and $*$ represent the inner planet, outer planet, and star respectfully [1].The Hill Radius of an object defines the sphere of the gravitational influence of the object where any smaller object inside the sphere tends to orbit the object, regardless of the influence of a third object. A planet inside the Hill radius of another planet will be in an unstable orbit that could result in a collision. The collisions were simulated by the Universe Sandbox software and data taken after each collision was used to determine whether the remaining mass particles have enough energy to escape the system or if the gravitational force caused the consolidation of the particles. The collision data will show if the initial collisions result in consolidation and if secondary higher speed impacts are more likely to result in destruction.

3 Methods

This project was constructed using Universe Sandbox to simulate our current Solar System with the addition of different STIPs. It was done in the Hunter Creech lab to ensure there was enough computing power to run the simulations accurately. All of the simulations started with the current positions of all the planets in our Solar System with varying STIPs being added based on the different parameters for each system.

For simplicity in the simulations, all planet orbits were made circular by using the decrease eccentricity tool and the inclination was made zero by making the simulation 2D, which made all height values zero. Each added STIP had up to four planets with a total mass of four times the mass of the Earth. Each planet also had a radius of up to four times the Earth's. The STIPs were added to the system by selecting blank planets and then filling in the different values for each one. All the added planets had orbits inside of Venus, with Mercury being removed from systems with two, three, or four added planets. The separation of the planets was determined by running a Python program that uses equations four and five to insure all but one of the added planet pairs was in a stable orbit as well as making sure the outside planet in the STIP was far enough away from Venus to be stable. Once the planets were added to the software, their values could be saved and used again later. Each system could also be saved as a whole to run multiple tests on each one.

To initiate the collisions, the outside planet of the STIP was removed from the system and then added back using the launch feature and aimed toward the targeted planet. This method was used because the original method of the orbital instability was not producing consistent collisions. The orbital instability caused planets to have very eccentric orbits or have the planet be ejected from the system. The launch speed was recorded and used as the impact speed in equation 1.

The launch method still works well for this experiment because the focus was on classifying the collisions and not the final form of the system. For added STIPs with three or four planets, the data from the initial collision can be used to create secondary collisions. Secondary collisions are initiated the same way as the initial collisions except for the planet being launched is the planet resulting from the initial collision if it was a consolidation collision. If the initial collision was destructive then there can not be a secondary collision. The initial data was recorded by setting the simulation to pause on collisions and the final data was recorded after the remaining planet cools down and finishes consolidating. All the data from this experiment was input into a table to organize and then into the classification program.

After each simulation was completed, the data from each collision was recorded and the collisions were classified using a python program and equations one, two, and three. The data needed to classify the collisions are the impact speed, initial and final masses of both planets, the initial radius of both planets, and the collision number. Other parameters such as the final radius and orbital velocity of both planets were also recorded and used to show which planets collided and to recreate the results of any initial collision to innate a secondary collision. The collisions were classified as consolidation, destructive, or unclassified if they did not meet the parameters for either type.

4 Data

The data from the collisions is classified into consolidation, destructive or Unclassified and then broken down into initial or secondary collisions for each type. All though there is no data to compare these results to, it was expected that more initial collisions would be consolidation collisions and more secondary collisions would be destructive, as well as some collisions that are unclassified. Figure one shows that there were twenty total collisions with ten consolidation collisions, eight destructive, and two unclassified. Figure two shows the ten consolidation collisions broken down into eight initial and two secondary collisions.This was the expected result based on the theory that more initial collisions should be consolidation. Figure three shows the eight total destructive collisions broken down into five secondary and three occurring on the first collision. This result also agree with the theory that more secondary collisions will be destructive. Figure four shows that there were two unclassified collisions with one of each type occurring. It was also expected to have some unclassified collisions due to the high percentage of mass lost needed to be considered destructive.

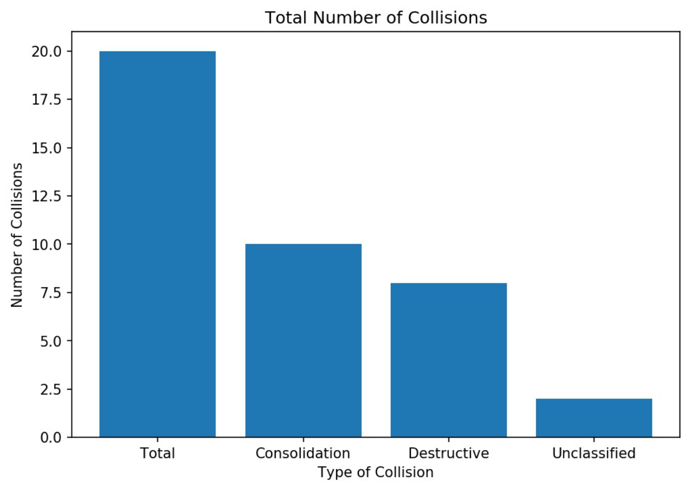

Figure 1: Total Number of Collisions

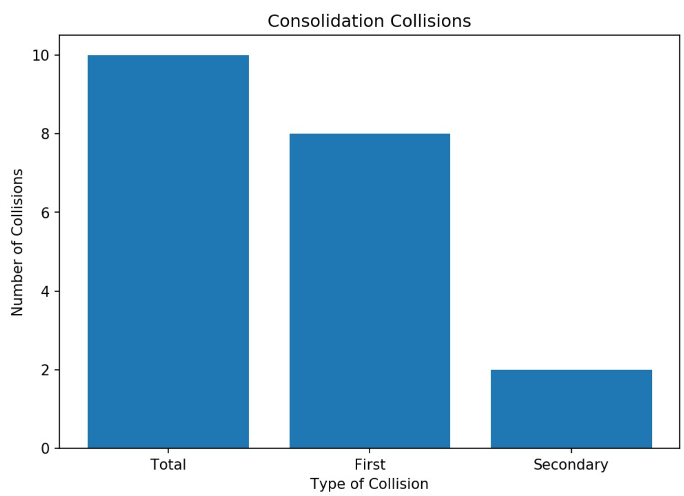

Figure 2: Consolidation Collisions

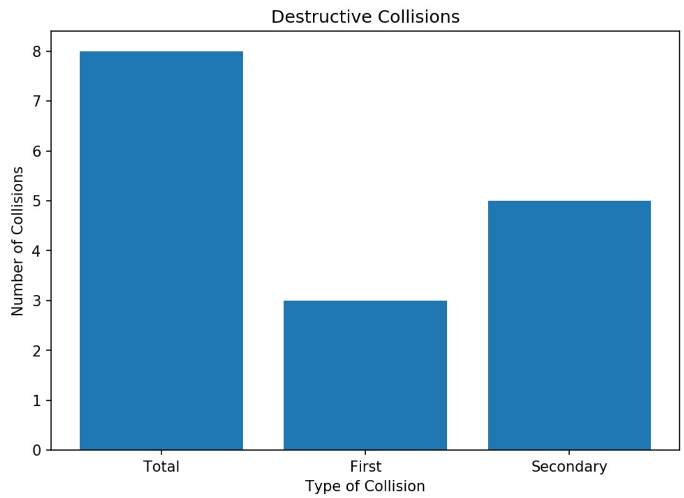

Figure 3: Destructive Collisions

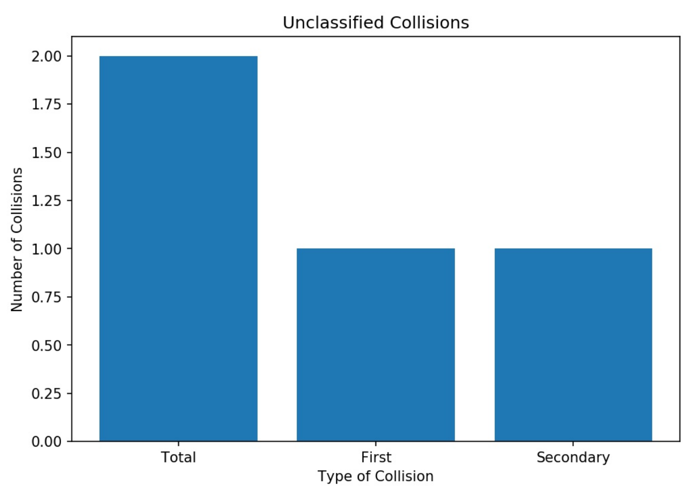

Figure 4: Unclassified Collisions

5 Discussions and Conclusions

The data from this experiment agrees with the theory tested that expected more initial collisions to result in consolidation, and more secondary collisions to be destructive. The data from the consolidation collisions helps support the theory the best. There were more total consolidation collisions and all but two occurred on the initial collision as expected. The two that occurred from secondary collisions were the second in a series of three collisions that took place in a system of four planets. These planets were further away from the Sun which resulted in lower impact speeds. It was also necessary for those collisions to result in consolidation for the third collision to occur.

The data from the destructive collisions also supports the theory with a majority of the collisions being secondary. Of the three that occurred om the initial collisions, two were in a two-planet system that only had one collision happen at higher impact speeds and were closer to the Sun. The third initial destructive collision occurred due to a high impact speed and having a more direct impact on the inside planet which resulted in a higher percentage of mass lost than expected. The two reaming collisions were unclassified because their ratio of impact speed to escape velocity was greater than two but did not meet the threshold of ninety percent of mass lost to be considered a destructive collision. There is not enough data to make any strong conclusions, but the data is trending the right way and any future research done with more time could gather more data to help make better conclusions.

Further research could also be done into the different responses to unstable orbits. Originally in this experiment, I expected all instabilities to create collisions, however, most instabilities created planets with extremely eccentric or unbound orbits. This resulted in having to use the launch method which worked to classify collisions but increased the amount of time it took to get data. It would be useful to know if the response of an unstable orbit can be predicted and how to implement that into the simulations to get the desired result of a collision. If that could be done this experiment could also be done to determine the final positions of the planets in the system and determine if it was possible for a STIP to have existed in the early Solar System and if it could have consolidated into Mercury or if the mass was ejected out of the system. Another experiment could also be done to test if a STIP is more likely to get destroyed through collisions or if planets are ejected more often.

References

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