Dynamical Evidence for Terrestrial Planet Debris in the Asteroid Belt

Claudia M. Sandine
Northwestern University - Department of Earth and Planetary Science
claudiasandine2021@u.northwestern.edu
Advisor: Seth A. Jacobson
Michigan State University - Department of Earth and Environmental Sciences
May 11, 2020

ACKNOWLEDGEMENTS

Gratitude is extended to Dr. Seth A. Jacobson at Michigan State University for his immense guidance and support as an advisor to this project. My special thanks are extended to the staff of the Earth and Planetary Science department for their financial and logistical support during this project. Finally, I am particularly grateful for the assistance given by the Office of Undergraduate Research in connecting me to this project and providing financial assistance for this research.

ABSTRACT

The history of terrestrial planet formation in the Solar System is thought to be dominated by the collisions between large planetary embryos. These collisions are responsible for planetary growth, but this process also ejects debris into heliocentric orbit. However, planet formation has historically been studied assuming that all collisions are perfectly accretionary until recently (Morbidelli et al., 2012). Here, we break that assumption to understand the role of debris created during planetary accretion. We implemented a full collision model (Leinhardt & Stewart, 2011) inside an N-body algorithm, which we used to simulate the formation of the terrestrial planets. Before this project, models could successfully explain the location of planetary bodies and the asteroid belt, along with models for planetary collisions and outer planet formation. However, we did not know how much of the debris from collisions during the early formation were in the asteroid belt and inner planets.

In this project we determined the history of the transportation of planetary debris between their creation during planetary collisions and their final orbits. The debris from early collisions in the Solar System ends up in either the asteroid belt, the Sun or a planet. By analyzing Solar System formation simulations, we found exactly what percentage of material in the asteroid belt was originally from the four inner planets. We did this by following the trajectory and impact history of every debris particle in each simulation. For instance, we calculated what percentage of debris material from early collisions was re-accreted by the planets. We also determined a location for the asteroid belt location in each situation, either by using the location of the Mars-like planet or using the orbital properties of the actual asteroid belt. Then, we determined if any debris particles found stable orbits in the asteroid belt. Lastly, the trajectory of the debris that ended up in the asteroid belt was tracked in order to determine what kind of collisions occurred with each particle and what collision it came from. This data allowed us to obtain a detailed and quantitative understanding of the formation of the asteroid belt and the terrestrial planets.

INTRODUCTION

The history of planet formation in the solar system is dominated by the collisions between large planetary embryos. Large planetary bodies form due to accretionary collisions that build up planets from small planetesimals to larger planet-sized objects. However, these collisions can eject planetary material into heliocentric orbit (Leinhardt & Stewart, 2011).

Historically, these collisions were assumed to be perfect accretionary, ignoring the important possibility of debris creation from these impact events. Previous studies assumed all the debris created would be re-accreted into the impactors. Breaking this assumption, Agnor & Asphaug (2004) determined what criteria dictates whether these large collisions are merging events or not. These and similar numerical models have revealed that the impact angle and velocity between colliding bodies determine whether a collision is mass gaining (accretionary) or mass losing (erosive). Low-speed and head-on impacts lead to planetary growth while high-speed and off-center impacts create large quantities of debris (Leinhardt & Stewart, 2012). The mass losing (erosive) impacts are especially crucial for studying the production of debris particles.

Introducing the idea that debris created from these impacts might be important has only been considered by a few recent studies (Genda et al, 2012, Chambers, 2013). These studies, where models for imperfect accretion have been used, have led to hypotheses regarding unexplained spectroscopic and geochemical observations. Polishook et. al (2017) observed, by using spectroscopic analysis and dynamical simulations, that the Mars Trojans most likely originated from an early impact with Mars.

This study compared the absorption spectra of these asteroids with Mars' absorption spectra and noted that they both share olivine-rich spectra, which is unique compared to typical asteroids. They used the N-body method to track the impact history of Mars in order to determine the possibility of ejecting debris created from this impact into the orbit of the modern Mars Trojan asteroids. By incorporating the imperfect accretion model into their study, they discovered strong evidence for the importance of debris creating collisions and how we can observe debris from the terrestrial planets in different locations in the solar system.

Carter et. al (2015) examined how erosional impacts between planetesimals that ultimately would be accreted into Earth could explain Earth's non-chondritic Fe/Mg ratio. They also implemented models from Leinhardt & Stewart (2009) within their dynamical simulations, which determined which impacts within our simulations were debris-creating or completely mass gaining collisions (perfectly accretionary). They found that through the incorporation of these sophisticated dynamical collision models for planet formation and growth, they could strip enough mantle from the forming Earth to explain its non-chondritic Fe/Mg ratio and also showed that there were very different compositions of the remaining debris created from these collisions. While Carter et. al (2015) tracked the total mass of debris within their annulus of study, we tracked each individual debris particle and tracked its orbital and physical characteristics throughout our simulation, which is a new direction within this frame of research. By tracking individual particles, we could track the evolution of all debris created and determine the significance of individual debris particles.

We aimed to determine where the surviving debris from early terrestrial planet-forming impacts go and analyzed whether this debris has potential to be transported to the asteroid belt. We implemented well-grounded models of dynamical planet formation and planetary impacts previously used by similar studies. By examining all the debris created from our numerical simulations and determining what type of collisions caused the debris-creating impact, we were able to analyze where this debris came from, what it is made of, and where it went after its creation. We propose that this ejected debris can be transported to the main belt of asteroids through gravitational interactions with other planetary bodies, a process that we model in our numerical simulations. The significance of this study is to expand on previous work discussing the importance of debris within planet-forming impacts and specifically analyze the debris' transportation history and whether debris is expected in the asteroid belt. Thus, we determined the relative fraction of primordial to planetary debris material amongst the main belt asteroids.

METHODS

Solar system formation is chaotic in nature, so we must numerically model many representative systems. To do this, we used an astrophysical N-body integrator. Our integrations used the Grand Tack Model (Walsh, 2011). We used this scenario because it matches the structure of the solar system best. Unlike other scenarios, it is able to account for the observed low mass of Mars. Since the area around Mars and Jupiter was studied intensively during this research, this scenario proved to be the best for our purposes.

We used a sophisticated dynamical model from Leinhardt & Stewart (2011) to most accurately model the many collisions that occur during planet formation. Not all simulations that are run through our N-body code will have the same number or type of embryos that are formed due to the chaotic nature of the solar system. Furthermore, their orbits will not be the same. Therefore, we must make a differentiation between stable versus unstable, and accurate versus inaccurate simulations. The following conditions had to be met to determine which simulations could be used in our later data analysis. First, for an object to be considered an embryo, it had to have a mass of at least 0.01 Earth masses. Next, the orbits of all the inner solar system embryos had to be stable. This meant that there could not be moderate to severe fluctuations in their semi major axis over time. Moderate to severe fluctuations were characterized by perturbed orbits due to other embryos. This meant that if two embryos orbits were disturbed in conjunction with each other, it could be seen by the high frequency fluctuations in their semi-major axis, while the rest of the embryos' orbits remained stable and undisturbed. If a simulation underwent a significant instability and displaced Jupiter or Saturn, it was also discarded from the group of stable simulations. The stability was determined by plotting the semi-major axis versus time for every embryo in the simulation and examining them by age.

The main technique for determining the location of the asteroid belt in our simulations was by using the Mars-like embryo as a marker for the edge of the inner asteroid belt. Therefore, we needed to determine if a Mars-like embryo existed and if so, where it was located. Determining if there was a Mars-like embryo in the simulation was done using a combination of orbit and mass properties. We determined the Mars-like embryo by finding the embryo with the largest aphelion, excluding Jupiter and Saturn. It also had to meet our mass requirement to differentiate between planetesimals, debris, and embryos. Next, the semi-major axis of the Mars-like embryo had to be greater than 1 AU and less than 2 AU. If the Mars-like embryo matched the mass requirement but was greater than 2 AU, it was considered too distant from the Sun to be comparable to our modern solar system, since it would be existing in the area of the modern asteroid belt. We found that in some simulations, a Mars-like embryo did not exist. If no Mars analog was found, these simulations were not used in our data analysis.

Debris created from collisions had the potential to be distributed throughout the solar system by a variety of means. The Sun and other embryos influenced the transportation of this debris due to their gravitational effects. Some debris was deflected into the Sun and lost, while others were ejected outward from their initial orbit. Therefore, a distinction needed to be made to describe which debris particles could be considered to be transported to the asteroid belt. Parameters for the asteroid belt therefore had to be determined for this analysis. First, the Mars-like embryo was used for determining the inner boundary of the asteroid belt. Next, the perihelion of the debris particle had to be greater than the aphelion of the Mars-like embryo of the simulation plus 0.1 AU. This addition of 0.1 AU accounts for Mars in the modern solar system being approximately 0.1 AU from the inner edge of the Hungaria group of asteroids, which is the innermost group of asteroids in the asteroid belt. Lastly, the debris particles could not have a semi-major axis larger than 5 AU, for then they would be within the orbit of Jupiter, which is beyond the asteroid belt.

We compared our debris considered to be in the asteroid belt from our stable simulations to the MPCORB database, which is a database that contains orbital elements of known minor planets (Harvard-Smithsonian Center for Astrophysics, n.d.). Eccentricity, inclination, and semi-major axis values were compared between MPCORB and our simulated asteroids. By placing these constraints, we were able to determine the possibility of this debris being emplaced in the main belt of asteroids, which is a new direction in the field.

From our simulations, we saw that debris could have many different locations that it could end up in after the solar system became stable. Debris could either be ejected into the Sun and lost, re-accreted to its parent embryo, accreted into a different embryo, survive as a debris particle in the planet forming region of the solar system, or survive as debris in the asteroid belt. The average percentages of the final locations of each debris particle created was calculated using data which contained their locations and survival at the end of the simulation. This data was averaged to display how a typical simulation's debris would be distributed over time.

To understand the role of debris production and emplacement to the asteroid belt, we analyzed the amount of debris created and the amount transported to the asteroid belt. To do this, the fraction of debris emplaced in the asteroid belt was compared to the mass of debris emplaced in the asteroid belt for each simulation. We also computed the average of this data.

RESULTS

The accuracy between our simulated solar systems and the modern one were crucial to our determination of debris transported to the asteroid belt. We determined simulation stability using plots which graphed the heliocentric distance of planet-sized embryos throughout the simulation. Out of the 89 simulations we ran, 52 were considered stable and were used for our analysis. To understand the differences between stable and unstable systems, we compared each using embryo position plots over the duration of the simulations (Figure 1). The upper figure is an example of a stable simulation, with all embryos orbiting without disturbance from each other at the end. The lower figure is an example of an unstable solar system due to the instability of the two embryos at about 1.5 AU. This lower figure represents one of the 37 simulations that were considered unstable. Even with strong interactions between embryos during their early formations, we found that stable simulations could occur with systems that had as low as two and as high as seven embryos. Throughout all the simulations, there were on average five embryos that survived in the inner solar system. As for the Mars-like embryo, stable simulations had Mars-like planets with semi-major axes as low as 1.13 AU and as large as 1.99 AU. On average, the semi-major axis of the Mars-like embryo was 1.57 AU. The actual semi-major axis of Mars today is 1.52 AU, so our Mars-like embryos reached a stable orbit at about the same distance away from the Sun as the Mars in our modern solar system. Our debris emplaced in the asteroid belt also formed at approximately the same region as the modern asteroid belt.

While our simulations have created many eccentric and largely dispersed debris particles, we show that our debris can fill the span of the asteroid belt across each of the Keplerian orbital elements. Using our parameters for the location of the asteroid belt, we determined which debris was emplaced in the asteroid belt. We then compared our simulated asteroids to the known asteroids today (Figure 2). Our simulations ran for two-hundred million years, which is significantly shorter than our 4.6 billion years old solar system. However, at the end of our simulations, a majority of our debris was concentrated at low eccentricities and low inclinations, similar to the asteroids from MPCORB. Once our simulations reached this stability, we could assume that they would stay this way until it reached the age of our modern solar system.

The debris created in our stable simulations was dispersed all throughout the solar system. This debris was transported to various locations by gravitational interactions between itself, the inner embryos, Jupiter and Saturn, and the Sun. Transportation also occurred from collisions between planetesimals and embryos. These collisions created debris and occasionally flung that debris outwards or towards the Sun. We determined the average final locations of all debris created among all stable simulations (Figure 3). To understand these percentages, we determined the average mass of debris produced in each simulation. Throughout the 52 simulations used in this experiment, the average amount of debris produced was 0.11 Earth masses of debris. About 60% of debris created was either re-accreted by its parent embryo or was accreted into a different embryo. Approximately 3% of debris created was emplaced in the asteroid belt. On average, the amount of debris that was emplaced in the asteroid belt was about 6.7 times the modern mass of the asteroid belt.

While our average mass of debris in the asteroid belt is high, most simulations transport minimal amounts of debris to the asteroid belt (Figure 4). There is a positive exponential relationship between the amount of debris emplaced in the asteroid belt and the percentage of total debris emplaced in the asteroid belt. Therefore, simulations that create much more debris from collisions will transport much more debris to the asteroid belt.

DISCUSSION

From our data, we observe that there is a substantial amount of debris that was created in our simulations. Some of this debris has high inclinations and eccentricities. However, most of our debris is concentrated at low inclinations and eccentricities. The asteroids from MPCORB also exhibit low inclinations and eccentricities due to their stability. This is not observed yet in all of our debris data because our simulations were run for 200-million years. If our simulations were left to run for a couple more billion years, to match the age of our solar solar system, the debris particles with higher eccentricities and inclinations would be lost and a majority of the debris remaining would be stable and create resonant structures that we see in our modern asteroid belt, such as the Kirkwood gaps (Figure 2). Furthermore, the debris remaining at the end of our simulation that had survived in the planet forming region would likely be lost to the Sun after subsequent evolution of the asteroid belt.

There were large variations in the efficiency of emplacement of debris to the asteroid belt between simulations. The standard deviation of the amount of debris emplaced in the asteroid belt per simulation was 6.7 asteroid belt masses, which is also how much mass was emplaced in the asteroid belt on average. The median amount of debris emplaced in the asteroid belt is about 4.5 times the modern mass of the asteroid belt. The collisions within the simulations were extremely chaotic, with some %simulations emplacing no debris in the asteroid belt while other simulations emplaced as much as 30 times the mass of the asteroid belt worth of debris. There was a standard deviation of 2.9% for the percentage of debris emplaced in the asteroid belt (Figure 3). According to DeMeo et. al (2019), the main belt should contain approximately 0.16% A-type asteroids. A-type asteroids are noted for their distinctive olivine feature on their spectra. The mass of the modern asteroid belt is approximately 4.92×10^{-4} Earth masses, so according to this, there should be about 7.78×10^{-7} Earth masses of terrestrial planet debris in the asteroid belt today. This largely disagrees with our findings, which show that about 6.7 times the mass of the asteroid belt can be emplaced as debris. During subsequent evolution of the asteroid belt (dynamical and collisional depletion), the mass of the asteroid belt is expected to decrease by about a factor of 10 to 1000 to its current mass. Taking this into account, we find that our simulated asteroid belts would deplete to 0.67 to 67% the modern mass of the asteroid belt. However, we still find significantly higher predictions than DeMeo et. al (2019). We add that we did not take collisional evolution into account, which would deplete mass of the debris created. Therefore, while further research is required to determine these implications, we can conclude that the Grand Tack scenario likely produces too much debris. Furthermore, it could be that within our simulations, the apocenter of Mars was within the location of the asteroid belt. This would cause more debris to be created due to Mars' strong interactions with the plethora of debris within its path.

We also found that there was a positive relationship between the mass of debris emplaced in the asteroid belt and the fraction of total debris emplaced in the asteroid belt. This relationship is about one to one. The locations of the production of these larger amounts of debris could be placed in favorable locations for easy transportation to the asteroid belt, which would explain the relationship we observe. This could imply that if there happens to be more debris produced in a simulation, then more of this debris will be able to be emplaced in the asteroid belt. Therefore, if a few simulations naturally produce much more debris than others due to chaos, then more debris is transported to the asteroid belt. In addition, low percentages of debris in the asteroid belt coincided with low masses of debris. An average of 224 asteroid belt masses of debris was created within each simulation, which provides a considerable amount of material to be transported throughout the solar system, so we would expect that this is why we find such high values of debris in the asteroid belt. It might be that the Grand Tack model is too violent, which is what creates such large amounts of debris to be created within each simulation.

These results have positive implications for the work from Polishook et. al (2017). Using the same types of simulations and dynamical models as them, we were able to predict that debris can significantly impact the variety of asteroids within our solar system. Our work is the next step forward in this study of the history of the solar system. Like Polishook et. al (2017), we aim to solidify the results of our research by confirming our predictions with observational results. Therefore, we must find the reason for the large disagreement between our predictions and DeMeo et. al's (2019) survey results. This could be because they had much stricter restrictions on the classification of A-type asteroids than we did in our study. In the future, we would like to assess this disconnect and determine more evidence for our prediction that terrestrial planet debris exists within the modern asteroid belt.

CONCLUSION

In conclusion, our data suggests that in general, debris created from terrestrial planet collisions can be transported to the asteroid belt. To further support this conclusion, our simulated debris also reflects similar physical characteristics of planetesimals that we find in the modern asteroid belt. This conclusion is also supported by the controls on our simulations, such as setting limitations for the parameters of the asteroid belt based on the Mars-like embryo in each simulation. By implementing this step into our research, we are able to maintain accuracy between systems. We do find substantial variation of the asteroid belt emplacement efficiency from simulation to simulation, so future work will examine what controls this efficiency.

FIGURES

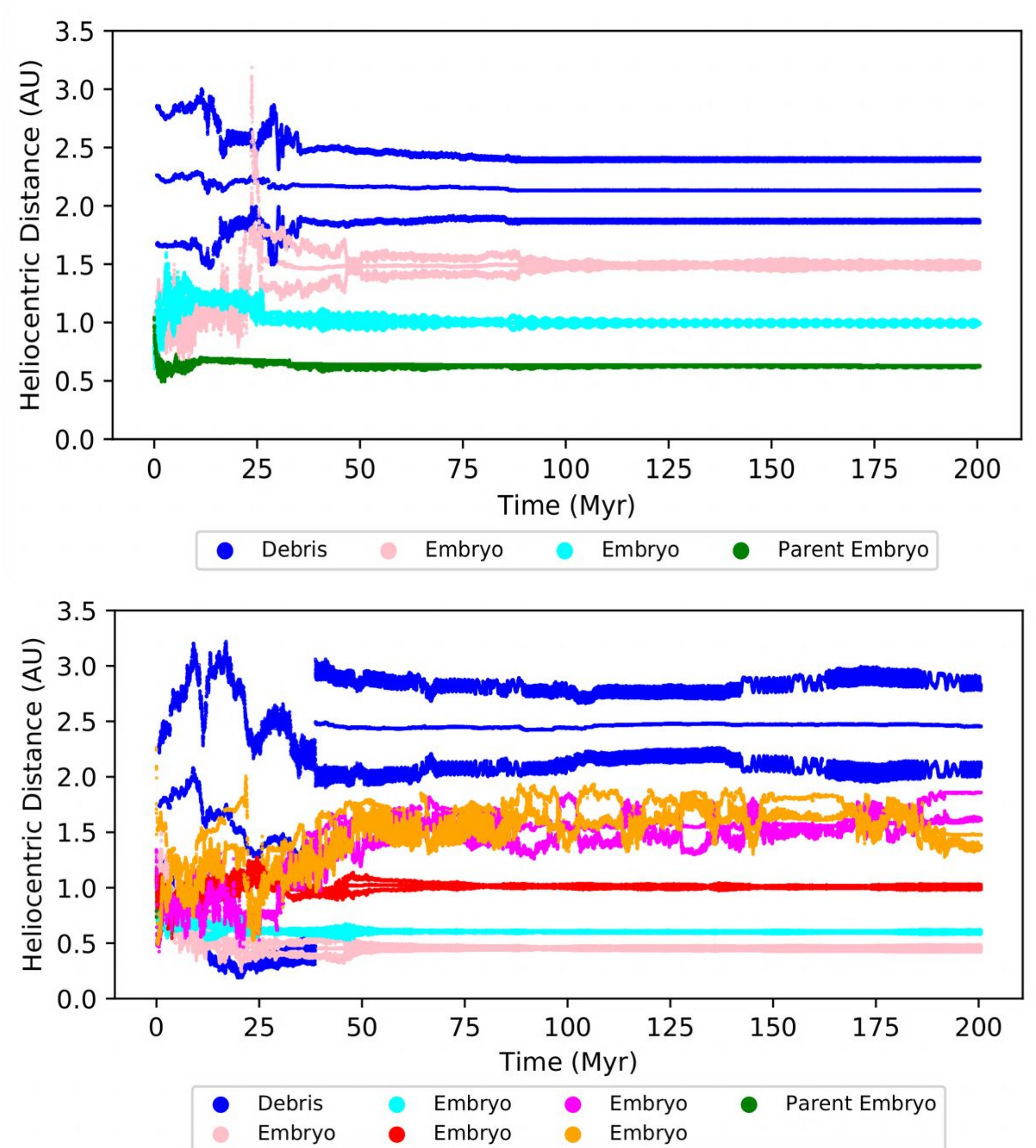

Figure 1. The plots above show two distinct examples of a debris body that was created from an impact on the parent embryo and ended up in the asteroid belt. For each object, we show the perihelion, semi-major axis, and aphelion of each orbiting body. The debris particle is shown in dark blue and the embryo it came from is shown in green. The rest of the particles shown are the embryos that survived in heliocentric orbit in the inner solar system. In the top plot, a debris particle was ejected from a Venus-like planet. This debris particle went through a series of scattering events with the Mars-like planet, ending up on a long-term orbit in the asteroid belt with a semi-major axis of about 2.3 AU. In the bottom plot, we observe a similar process, but the parent embryo is quickly scattered into the Sun. This plot is an example of an unstable simulation, due to the unstable orbits of the two embryos around 1.5 AU. This simulation was not used for our further analysis of debris emplacement to the asteroid belt.

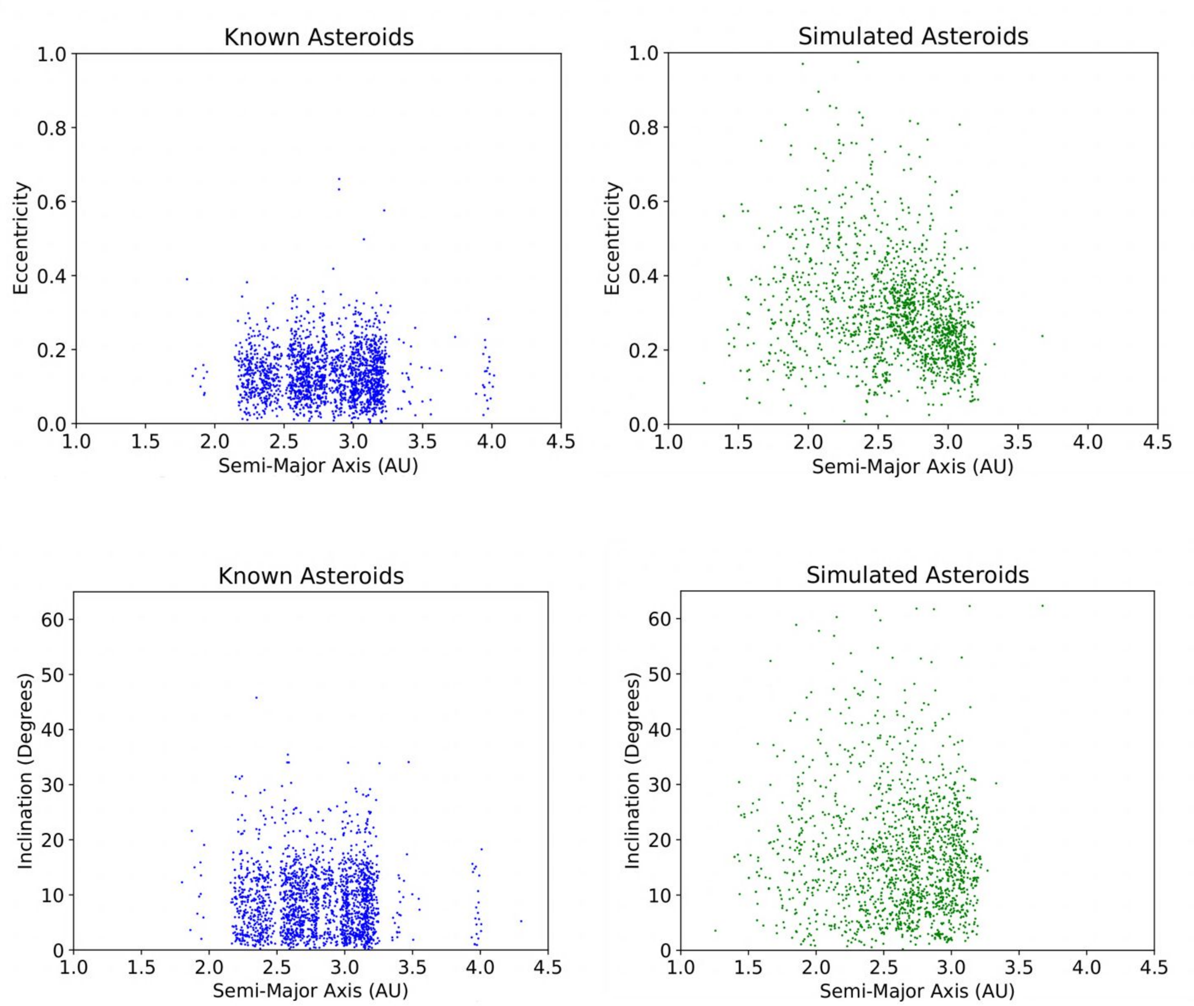

Figure 2. The eccentricity and inclination between simulated planetary debris emplaced in the asteroid belt and the observed asteroids from the MPCORB database were compared. This data comes from 52 simulations, which all ran for two-hundred million years. Our simulated asteroids fill the span of the asteroid belt.

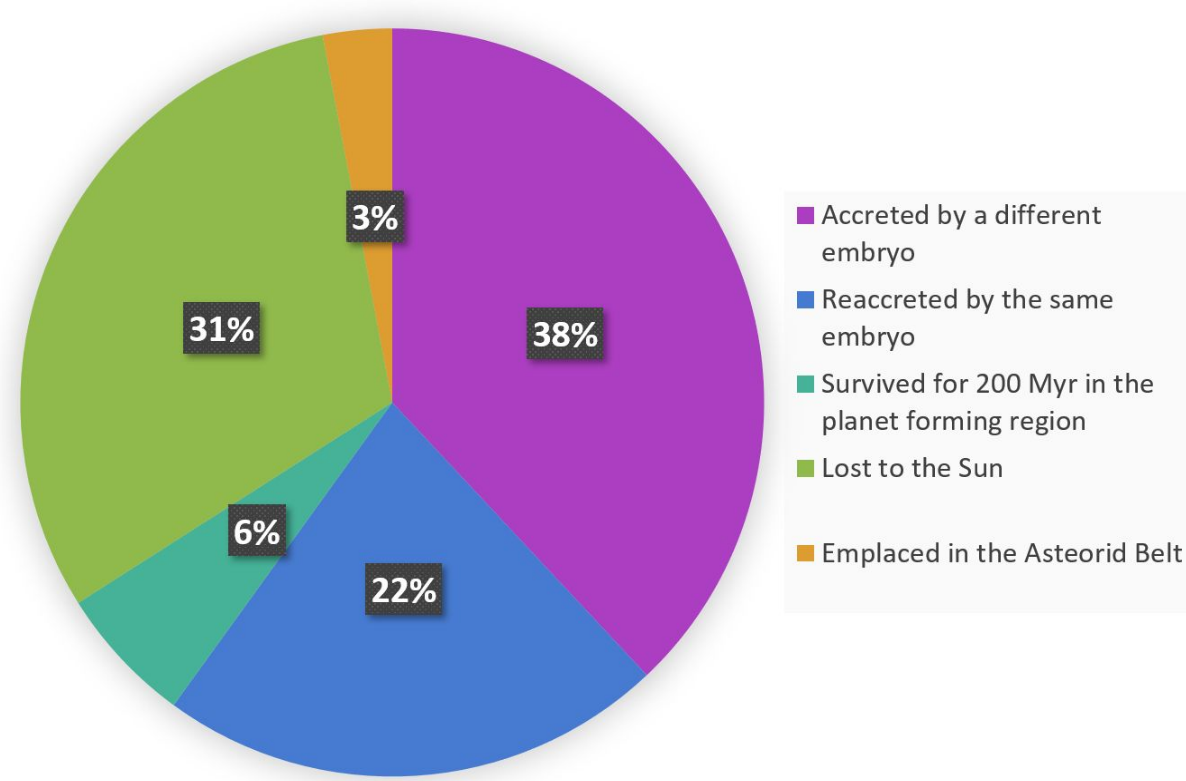

Figure 3. The final outcome of each debris particle created was generalized into averages. The possible outcomes of debris particles are either being accreted into an embryo, re-accreted into the embryo it originated from, lost to the Sun or flung out of the solar system, surviving as a debris particle in the planet forming region, or being emplaced in the asteroid belt. About 3% of debris created in the simulations was emplaced in the asteroid belt. These percentages are an average of all the simulations that were considered stable.

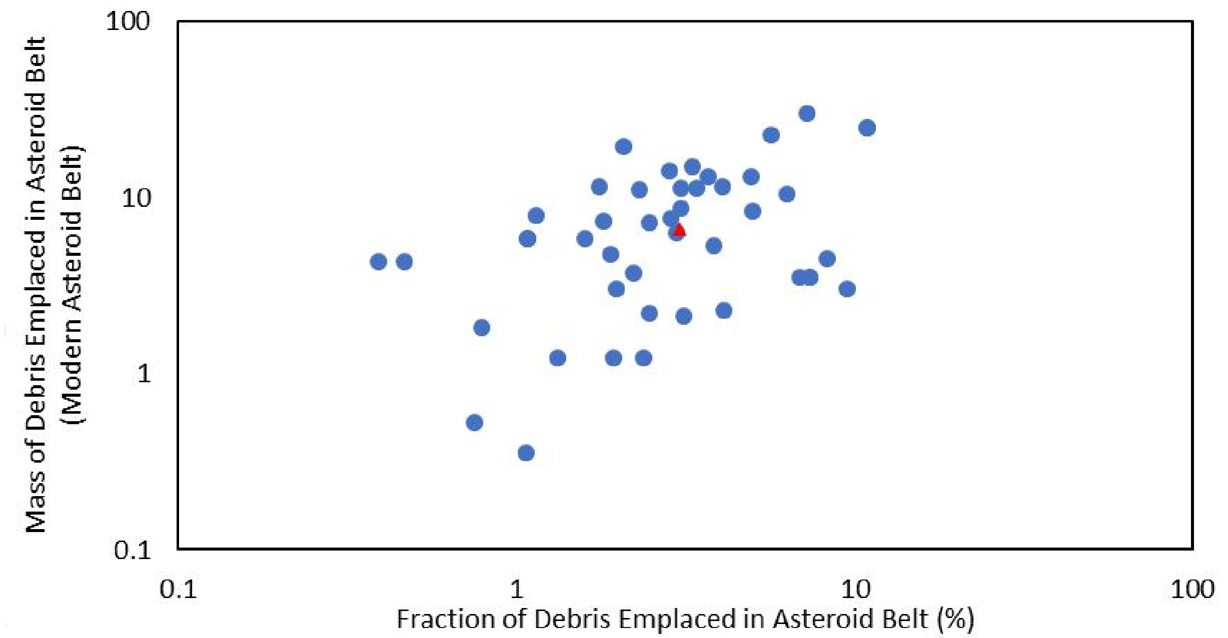

Figure 4. Each simulation was analyzed by noting how much debris was created and comparing it to the transportation of this debris to the asteroid belt. The red triangle indicates the average of all the data presented. In total, 52 simulations were used for this analysis. Most of the total mass of debris that was emplaced in the asteroid belt per simulation was minimal. For over half of the simulations, the percentage of debris emplaced in the asteroid belt was below 4%. In general, over half of the debris was below 8 times the mass of the modern day asteroid belt and only made up 3% of all debris created.

REFERENCES

Agnor, C., and E. Asphaug (2004), Accretion Efficiency during Planetary Collisions, *The Astrophysical Journal*, *613*(2), doi:10.1086/425158.

Carter, P. J., Z. M. Leinhardt, T. Elliott, M. J. Walter, and S. T. Stewart (2015), Compositional Evolution During Rocky Protoplanet Accretion, *The Astrophysical Journal*, *813*(1), 72, doi:10.1088/0004-637x/813/1/72.

Chambers, J. (2013), Late-stage planetary accretion including hit-and-run collisions and fragmentation, *Icarus*, *224*(1), 43–56, doi:10.1016/j.icarus.2013.02.015.

Demeo, F. E., D. Polishook, B. Carry, B. J. Burt, H. H. Hsieh, R. P. Binzel, N. A. Moskovitz, and T. H. Burbine (2019), Olivine-dominated A-type asteroids in the main belt: Distribution, abundance and relation to families, *Icarus*, *322*, 13–30, doi:10.1016/j.icarus.2018.12.016.

Genda, H., E. Kokubo, and S. Ida (2011), Merging Criteria For Giant Impacts Of Protoplanets, *The Astrophysical Journal*, *744*(2), 137, doi:10.1088/0004-637x/744/2/137.

Harvard-Smithsonian Center for Astrophysics (n.d.), The International Astronomical Union Minor Planet Center, *The MPC Orbit (MPCORB) Database*. Available from: https://minorplanetcenter.net/iau/MPCORB.html

Leinhardt, Z. M., and S. T. Stewart (2011), Collisions Between Gravity-Dominated Bodies. I. Outcome Regimes And Scaling Laws, *The Astrophysical Journal*, *745*(1), 79, doi:10.1088/0004-637x/745/1/79.

Morbidelli, A., J. Lunine, D. Obrien, S. Raymond, and K. Walsh (2012), Building Terrestrial Planets, *Annual Review of Earth and Planetary Sciences*, *40*(1), 251–275, doi:10.1146/annurev-earth-042711-105319.

Polishook, D., S. A. Jacobson, A. Morbidelli, and O. Aharonson (2017), A Martian origin for the Mars Trojan asteroids, *Nature Astronomy*, *1*(8), doi:10.1038/s41550-017-0179.

Walsh, K. J., A. Morbidelli, S. N. Raymond, D. P. Obrien, and A. M. Mandell (2011), A low mass for Mars from Jupiter’s early gas-driven migration, Nature, 475(7355), 206–209, doi:10.1038/nature10201.