AST 390 Final Project:
The Long-Term Effects of a Theoretical Planet X on Solar System Stability

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1 Motivation

One of the main motivators in astronomy has and will continue to be the discovery of new astronomical objects. Throughout the 19th and 20th Centuries, many different astronomers searched for and discovered the various planets in the Solar System. However, even after these discoveries, people still tried to search for new objects in the Solar System, leading to the discovery of the many objects in the asteroid belt, the Kuiper Belt, and the Oort Cloud. However, this drive still exists today in the form of extrasolar planets, and the mysterious Planet X. Planet X is a hypothesized ninth planet lying on an orbit much outside of the Kuiper Belt. NASA's website defines this planet as taking "between 10,000 and 20,000 Earth years to make one full orbit around the Sun" and "could have a mass about 10 times that of Earth" (Batygin and Brown, 2016). The main motivation for searching for this planet is strange behaviors of Kuiper Belt objects. In some places in the Kuiper Belt, dwarf planets and other small objects will "clump up" more in some areas than others. In more specific terms, the angles of perihelion of the most distant Kuiper Belt objects are only found to be in a certain range. Therefore, this has prompted many different theories on how a large, distant body could cause this strange phenomenon. Of course, this certain of grouping could have just happened by chance, or be a result of a certain bias in discovering objects. However, in the past, large bodies were discovered by noticing their effects on smaller bodies. In this way, Planet X continues the trend. Therefore, it is very worthwhile to investigate this topic.

Furthermore, the existence of Planet X poses more questions concerning the future of our Solar System. In general, it has been shown that our Solar

System is stable at the moment, and will continue to be for a long time into the future. Though the various parameters of the orbits of the bodies in our Solar System may change somewhat significantly or vary over time, they will still be stable. However, will this long-lasting stability still exist with this hypothetical Planet X? Throughout this report, I will investigate the long-term effects of Planet X lying outside of the Kuiper Belt, while also analyzing the stability of our current model. Seeing as this Planet X has already started to affect the dynamics of our Solar System in a very minute way, it could have the ability to impact it in a greater way in the future. If Planet X lies where we suppose it to, will it affect other bodies enough gravitationally to collide with them and force them out of the system? Or will this planet have no effect on the stability whatsoever, besides this "clumping" in the Kuiper Belt?

2 Methods

In order to investigate this query, I will be using the python package "Rebound". This package contains many different numerical integrators which can simulate planetary systems and integrate them forward in time. This package also has the ability to query and take data from the NASA Horizons database from JPL, which can then be placed into a simulation. However, seeing as there are a wide variety of objects in our Solar System, I needed to discern which objects were essential for the calculations needed. I had used the Horizons database to gather data about the Sun, the eight planets, and Pluto, and placed them into the simulation. I had also chosen various Kuiper Belt objects and comets to add into the system. I had only chosen the bodies whose orbits would be most affected by Planet X, meaning very distant Kuiper Belt objects with large semi-major axes and. Many of these objects have quite high eccentricities, though, making them more likely to become perturbed by Planet X. I had also included comets, as the effects of gravitational perturbations on them can be seen quite clearly. Finally, I had added in certain massive objects, in order to measure how much the addition of Planet X could affect the stability of the Solar System as a whole.

Object Type	Name	Method of Input
TNO	65489 Ceto	Automatic from Horizons
TNO	90377 Sedna	Automatic from Horizons
TNO	47171 Lempo	Automatic from Horizons
TNO	136199 Eris	Automatic from Horizons
TNO	136108 Haumea	Automatic from Horizons
TNO	2012 VP-113	Manual Input
TNO	2010 GB-174	Manual Input
TNO	2000 OO-67	Manual Input
Comet	C/2013 U2 (Holvorcem)	Manual Input
Comet	C/2019 V1 (Borisov)	Manual Input
Comet	C/2000 K2 (LINEAR)	Manual Input

Fig. 1: Manually input data was taken from the NASA JPL Small Body Database

Orbital Charecteristics							
	a [AU]	e	i [deg]	m [$M_\oplus$]	P [yrs]	ω [deg]	Ω [deg]
Ceto	100.7	.8222	22.31	9.05e-7	1010	319.87	172.07
Sedna	484.4	.8426	11.93	5.03e-4	10700	311.35	144.25
Lempo	39.39	.2246	8.42	2.17e-6	247	294.39	97.01
Eris	67.86	.4361	44.04	2.8e-3	559	151.64	35.95
Haumea	43.18	.1949	28.21	6.7e-4	284	238.78	122.16
OO 67	564.7	.9633	20.07	–	13400	212.36	142.21
GB 174	342.3	.8579	21.6	–	6330	347.13	130.89
VP 113	261.5	.6925	24.11	–	4230	293.57	90.68
Holvorcem	898.1	.9943	43.09	–	26900	107.38	7
Borisov	3041	.999	61.86	–	168000	51.22	83.21
LINEAR	522	.9953	25.63	–	11926	106.83	195.26
Planet X	600	.2	10	10	14967	–	–

Fig. 2: The values used for Planet X are within ranges produced by Batygin et al. (2019)

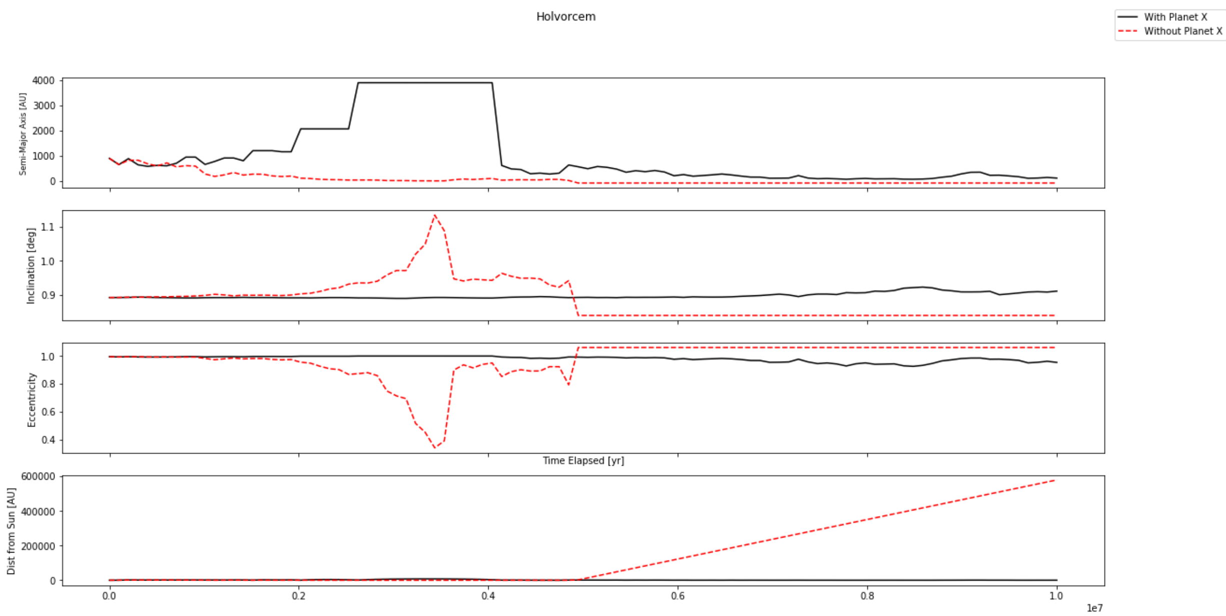
Certain objects were unable to be found using the NASA Horizons command in Rebound, so I have manually input them with the data from Horizons through the use of object creation commands in Rebound. Any masses that cannot be calculated with the data measured or are too small to gravitationally affect any other object have not been included in the simulation. These objects are therefore treated as test particles, only moving under the affect of the gravity of other, more massive bodies.

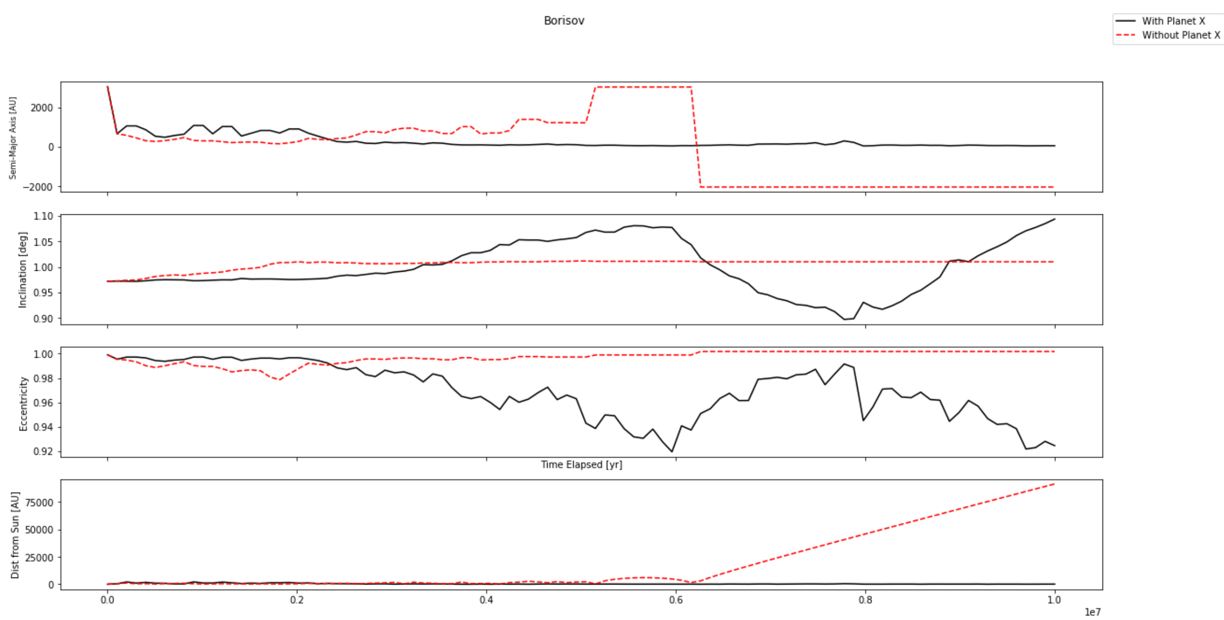
For these simulations, I used the WHFast integrator, which is more well-suited for simulations which do not involve many collisions. In my simulations, I simply use the objects in the Solar System currently, meaning there would be little, if any, collisions. Other integrators provided by Rebound can be used to simulate very chaotic systems, or somewhat chaotic systems, though they provide little use in this project. I had used a integration timestep of .1 Earth years, as it is smaller than the smallest timescale, which would be Mercury's period of 88 days. Using a timestep smaller than Mercury's orbit could cause errors in the values gotten for Mercury, which could in turn affect the other bodies. I had then integrated the simulation from present day to 10 Myr in the future without Planet X, and then did the same with Planet X. After each integration, I recorded each object's semi-major axis, eccentricity, inclination, and distance from the Sun. Seeing if and how these variables change overtime will determine Planet X's influence, stability, and its overall prospects of being found. All of the distances for these objects are measured from the center of mass of the system normally, so in order to account for the motion of the system overtime, I recorded distances from the Sun. Furthermore, I had increased the integration time by 100000 years after every integration. For example, the first integration calculated to 100000 years in the future, the second calculated 200000 years in the future, etc. I have also only chosen to include the data for objects which change somewhat significantly. For example, an object close to the Sun such as Mercury will barely feel any effect of Planet X, meaning its dynamics with and without Planet X will be identical.

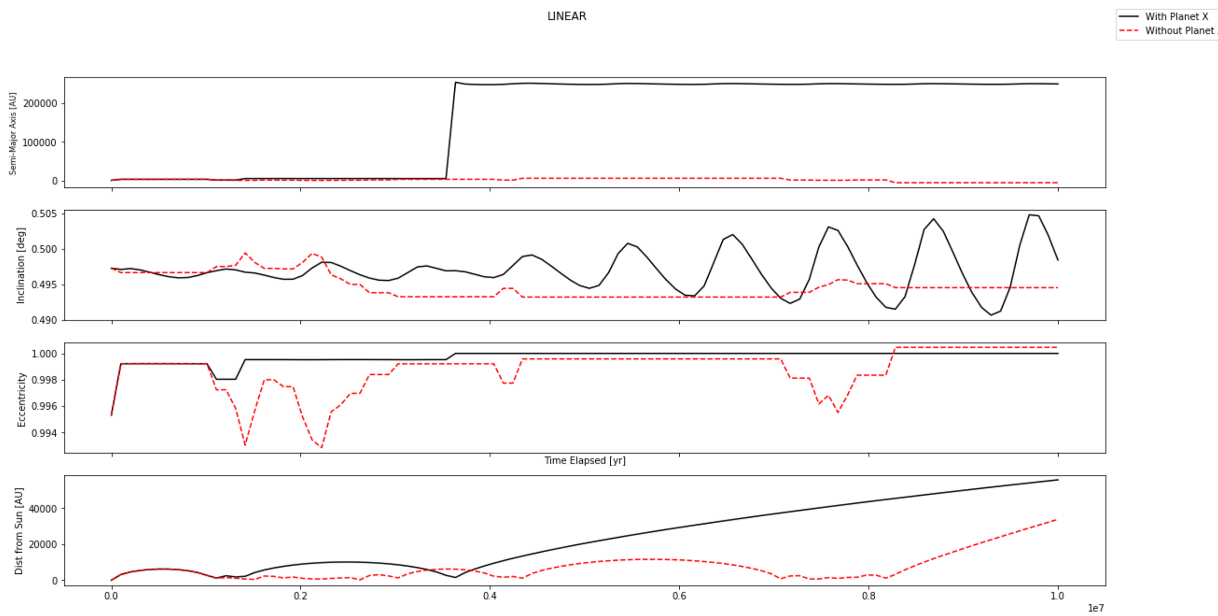
The data below shows the system with Planet X compared to the same system without it:

3 Data

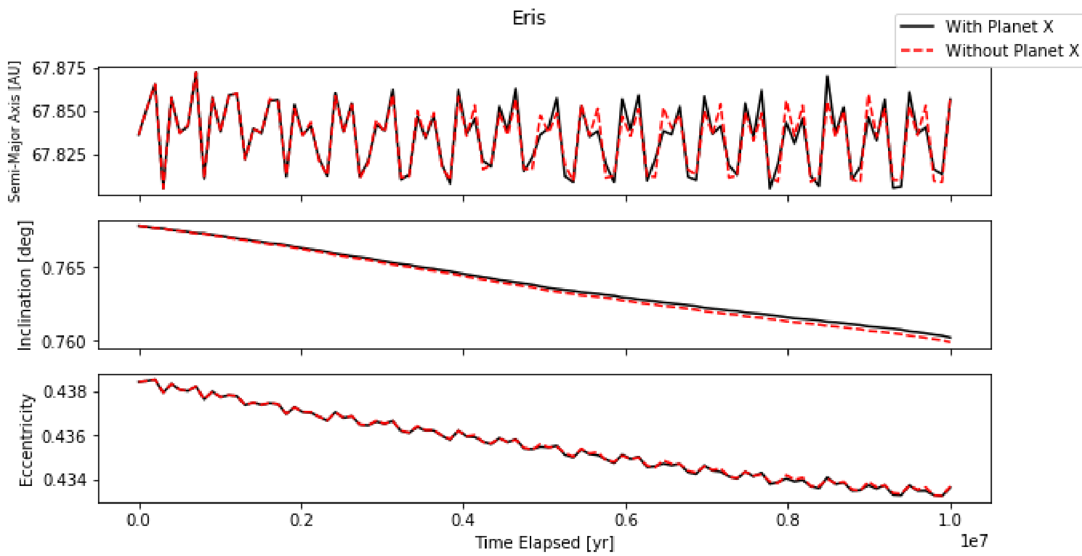
3.1 Comets

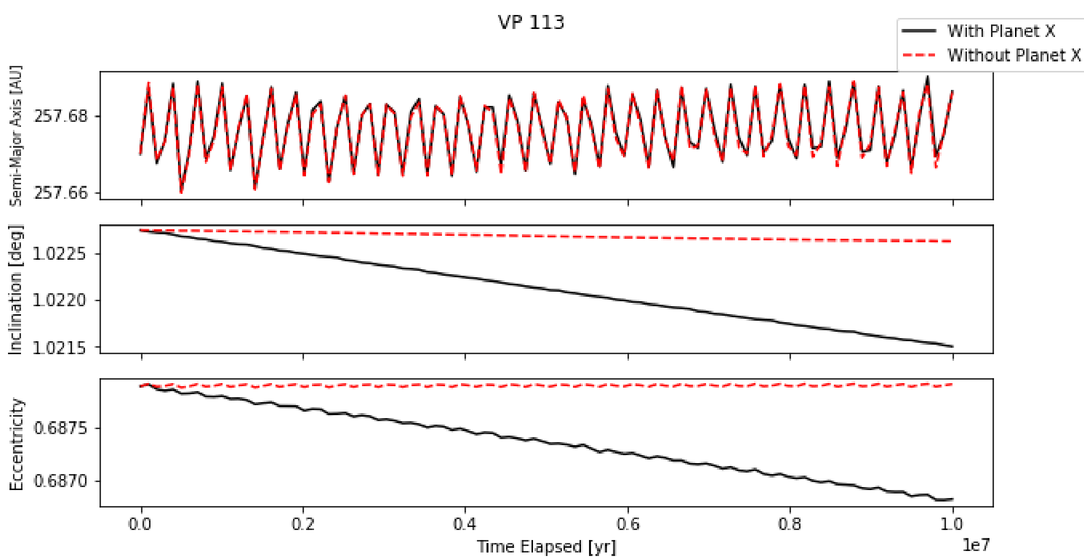


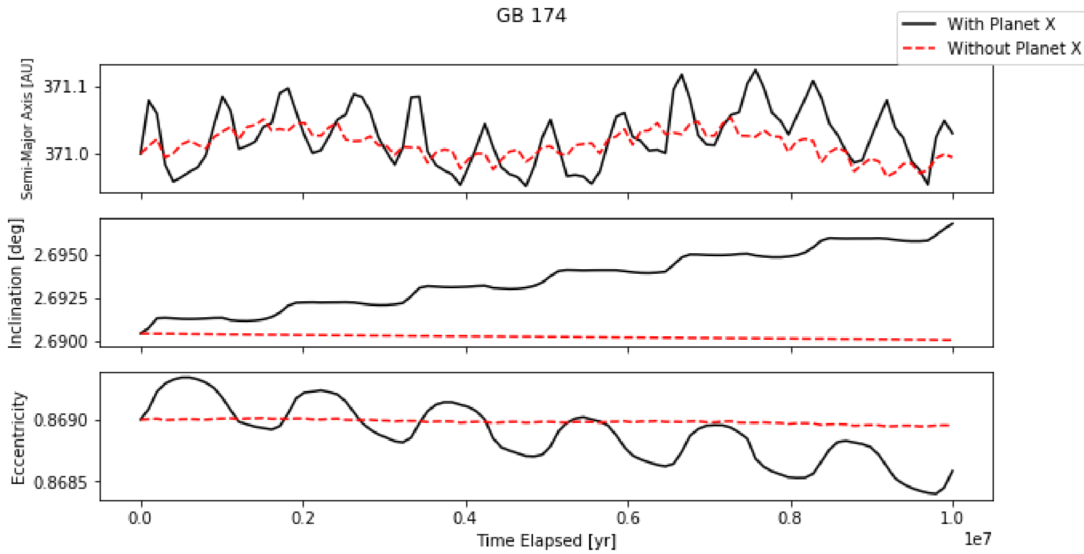


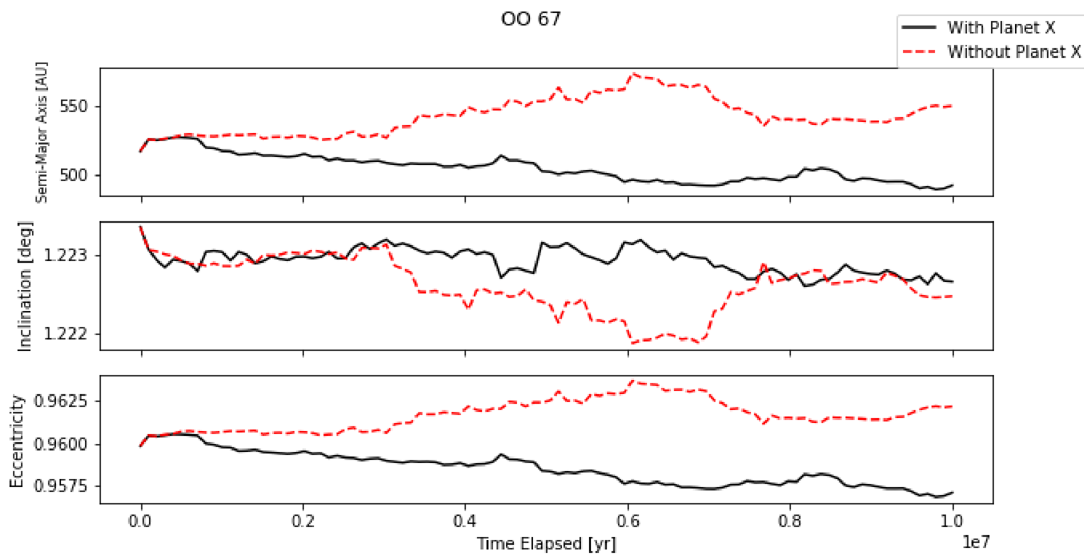

LINEAR
With Planet X
Without Planet X
Semi-Major Axis [AU]
200000
100000
0
Inclination [deg]
0.505
0.500
0.495
0.490
Eccentricity
1.000
0.998
0.996
0.994
Time Elapsed [yr]
Dist from Sun [AU]
40000
20000
0
0.0
0.2
0.4
0.6
0.8
1.0
1e7

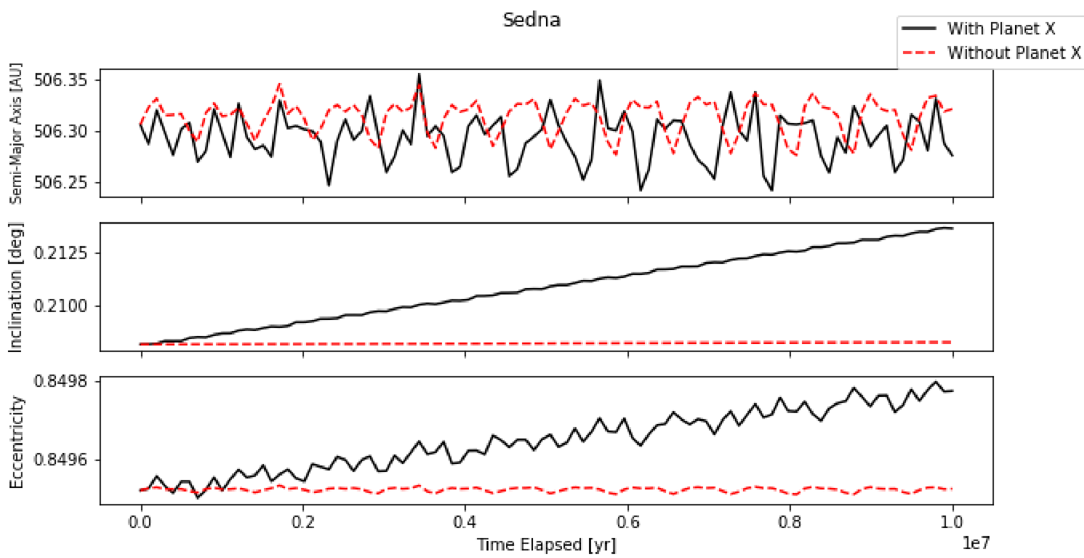
3.2 Trans-Neptunian Objects

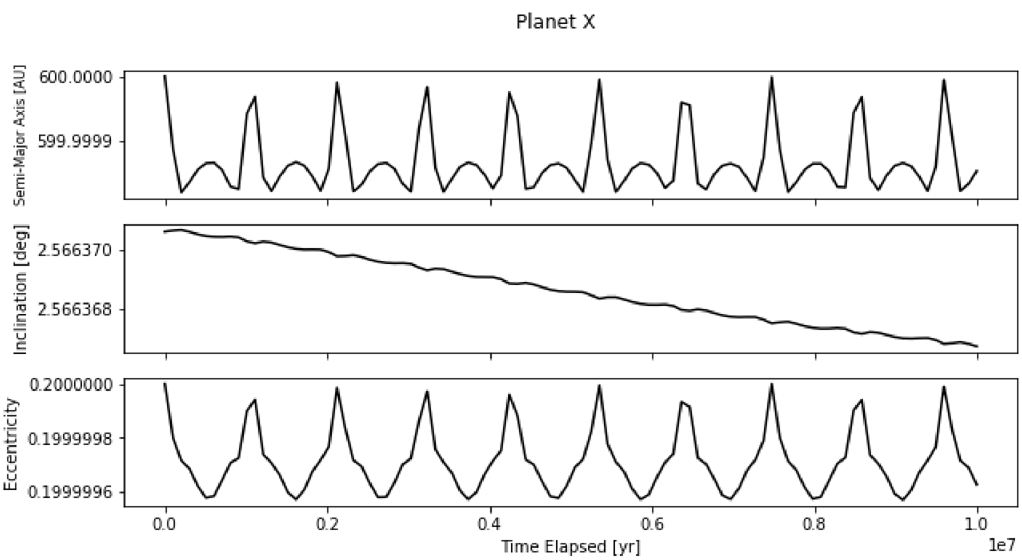




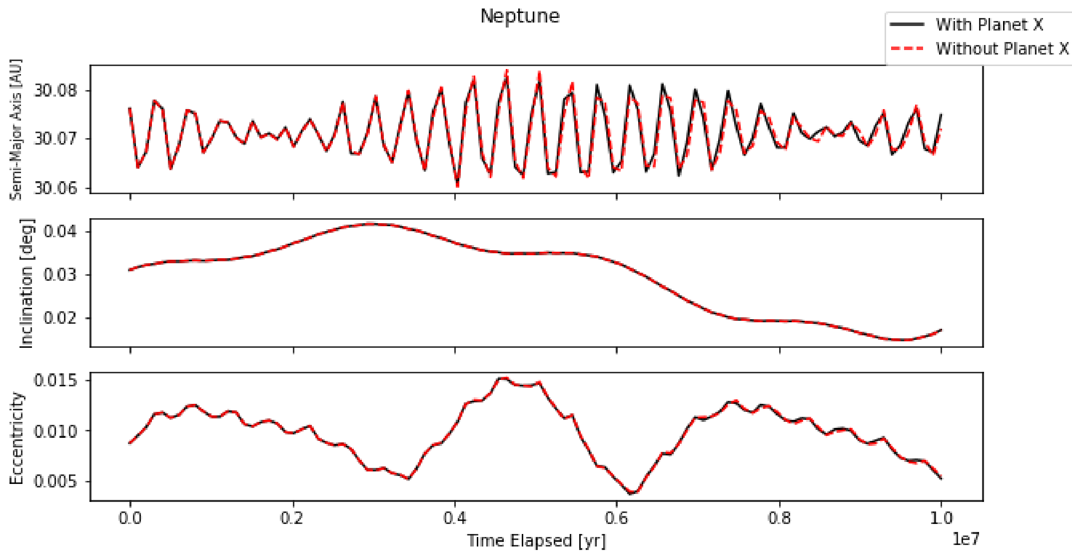

GB 174
With Planet X
Without Planet X
Semi-Major Axis [AU]
371.1
371.0
Inclination [deg]
2.6950
2.6925
2.6900
Eccentricity
0.8690
0.8685
0.0
0.2
0.4
0.6
0.8
1.0
Time Elapsed [yr]
1e7

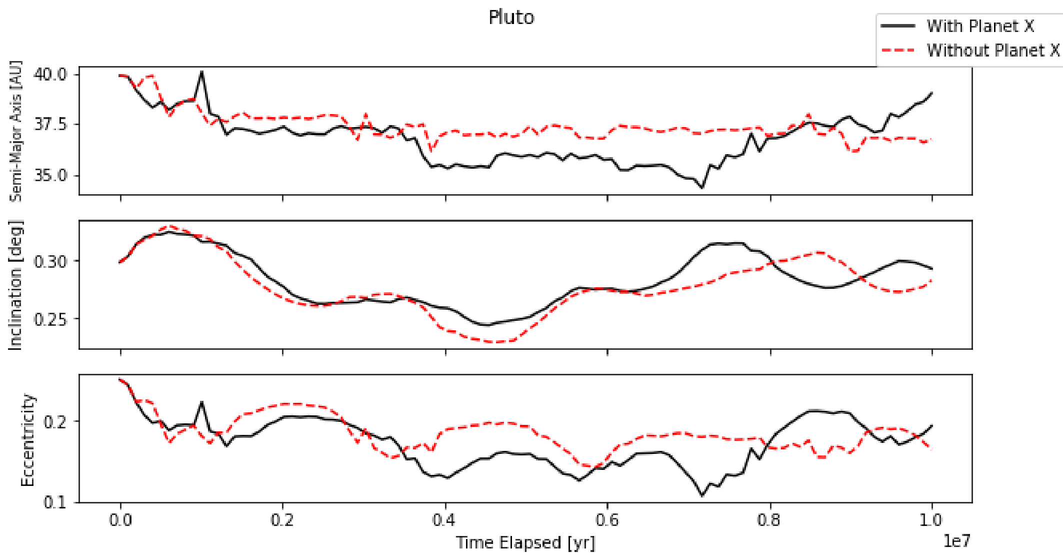

OO 67
With Planet X
Without Planet X
Semi-Major Axis [AU]
550
500
Inclination [deg]
1.223
1.222
Eccentricity
0.9625
0.9600
0.9575
0.0
0.2
0.4
0.6
0.8
1.0
Time Elapsed [yr]
1e7


Sedna
With Planet X
Without Planet X
Semi-Major Axis [AU]
506.35
506.30
506.25
Inclination [deg]
0.2125
0.2100
Eccentricity
0.8498
0.8496
0.0
0.2
0.4
0.6
0.8
1.0
1e7
Time Elapsed [yr]


Planet X
Semi-Major Axis [AU]
600.0000
599.9999
Inclination [deg]
2.566370
2.566368
Eccentricity
0.2000000
0.1999998
0.1999996
0.0
0.2
0.4
0.6
0.8
1.0
1e7
Time Elapsed [yr]

3.3 Objects Interior to the Kuiper Belt





4 Analysis

Perhaps the most affected orbits in this system overtime were the comets. The comets I had chosen had very large eccentricties and very large semi-major axes. Most of the comets that are near this hypothesized Planet X would need to have very large eccentricities, considering the large semi-major axis of Planet X. These comets are, at the current time, stable and orbit the Sun at a regular, calculated interval. However, in the long term, these comets are largely unstable, as one slight gravitational nudge could eject them from the system, due to their large eccentricties and semi-major axes. We can see this instability with the plot of the comet Holvorcem. In a system without Planet X, Holvorcem was ejected after about 5 Myr. This shows that as the Solar System is now, there are many objects that have close to unstable orbits, even though the system as a whole is stable. This instability may have arisen from the fact that I had only chosen a certain number of astronomical objects in the simulation, which could have served to preserve this stability. However, we can see that the addition of Planet X served to aid the stability of the system, in this case. The large mass of Planet X prevented the ejection of Holvorcem, preventing ejection altogether. This may have occurred indirectly, as Planet X may have influenced another object, which in turn influenced Holvorcem. Even after 10 Myr, this comet still revolves around the Sun. It can be seen that Planet X stabilized Holvorcem's inclination and eccentricity, whereas before they would have become unstable. However, Planet X did cause massive variations in Holvorcem's semi-major axis. These variations did stop occurring, though, after about 4.5 Myr, continuing to stabilize after that point. Therefore, Planet X served to stabilize Holvorcem's orbit by decreasing its semi-major axis, inclination, and eccentricity.

Borisov displays a similar situation to that of Holvorcem in that it was also stabilized by Planet X. Normally, it would have been ejected from the system at around 6.5 Myr. However, Planet X caused this destabilization to not occur. We can see that Planet X stopped large variations in semi-major axis, as well as an increase in eccentricity. However, unlike Holvorcem, Planet X caused large variations in inclination, reaching almost about $.1^o$ in amplitude. Planet X also caused Borisov's eccentricity to somewhat destabilize, although becoming lower altogether. A lower eccentricity alows for less opportunity to become ejected, as it is more stable. Though, these variations in inclination could prove to destabilize this comet's orbit in the future.

In contrast to the prior two comets, the close-in comet, LINEAR, was placed in a much different situation. Normally, LINEAR would have been ejected from the system at around 8 Myr, after experiencing many variations in eccentricity. However, Planet X had a very negative effect on this comet, as it caused it to be ejected much early. Though Planet X decreased LINEAR's variations in eccentricity, it caused it to be ejected at around 3.5 Myr. This is a much different effect than we have seen with the other comets. Its small mass allowed it to be very susceptible to Planet X's gravity, causing it to have increased variations in its orbital parameters. We can see that after ejection, these variations in inclination due to Planet X we amplified, being almost $.001^o$ after 10 Myr. Normally, smaller bodies would slightly interfere with LINEAR's orbit early on, but not affect it enough to cause an ejection. Planet X gave such a large push to LINEAR that it was ejected much earlier than it would have normally, showing that it can serve to destabilize a system.

Therefore, we have seen two possible outcomes for comets in a system with Planet X: either they are continually "pushed" into a stable orbit, or, the more likely outcome, they are gravitationally affected enough that they are ejected out of the system. Both outcomes show large variations from a system without Planet X, validating that Planet X would have an effect on the Solar System. Although, these variations would not begin until, at minimum, 100000 years after present day. Therefore, interactions due to Planet X are likely not going to be noticed. They may be more apparent and happen on a shorter timescale for comets that have even larger eccentricties, even more unstable orbits, and collide with Planet X more directly.

The most interesting types of objects to observe in this simulation, in terms of orbital stability overtime, are the trans-Neptunian objects (TNOs). These less massive bodies which lie on the outer ends of the Solar System are very susceptible to gravitational interactions with Planet X. The fact that they are less massive, more eccentric, and closer lead to an increased chance that they will become affected by Planet X as time goes on. The object which would be expected to interact the least with Planet X is the most massive object in the Kuiper Belt, Eris. Eris has a mass about one fifth of the Moon's, and has a semi-major axis of about 70 AU. Therefore, it is not particularly close to Planet X, but has a significant mass. From its plots early on, we see exactly as we'd expect: no deviation from the norm. Variations in any of Eris' orbital parameters only start occurring after about 5.5 Myr. The peaks in Eris' semi-major axis become larger, and the decline of its inclination becomes slightly sharper. Even so, these variations are slight, only being less than .1 % at maximum. However, at time goes on, these variations start to grow, though not by much. The largest variation in semi-major axis is only about .005 %, and the variation in inclination is much less. Therefore, we would not be able to observe the changes to Eris even in the near future. This does display a general trend to Planet X's interactions with various slightly massive objects in the Solar System. It will mainly serve to increase variations from the norm, and slowly decrease their inclinations.

The next interesting TNO to study is VP-113. This object is reltively close to Planet X, with a semi-major axis of around 250 AU. Therefore, the affects of Planet X should be more apparent. This should also be true due to the fact that VP-113 is acting as a test particle. We can see that very early on, Planet X starts to alter the orbit of this TNO. Normally, its inclination and eccentrcicty would stay constant overtime, as a stable object should. However, Planet X has decreased VP-113's inclination and eccentricity overtime. In a sense, this has made VP-113's orbit more stable, as there is less of a chance for it to be excited and have a large eccentricity or inclination. It is interesting how the variations in VP-113's semi-major axis are less than even that of Eris, considering Eris is more massive, and farther away. This most likely due to the fact that VP-113 is quite still far from Planet X, being separated at a minimum distance of 400 AU. This could also be due to the fact that Planet X started to stabilize VP-113's orbit very early on, not allowing for variations to grow. Though, however small they may be, the variations caused by this hypothetical planet could be observed as early as 200000 years after present day.

Increasing the semi-major axis, we arrive at the TNO named GB-174. This TNO has a semi-major axis of about 350 AU, and is very similar in orbital parameters to VP-113. Therefore, we should expect to see a similar plot to VP-113, but with stronger variations from the norm. However, we can see this does not occur at all. The variations in semi-major axis are much more significant, almost being .1 AU. Furthermore, the inclination of this object increases overtime, due to the interactions with Planet X. This is something very different from the other TNOs in the simulation. Normally, Planet X would attract other objects toward the plane of the Solar System, as its inclination is only 20^o. Therefore, the most probable reason that this would occur is if the body had a lower inclination, and was attracted in the opposite direction. In this case, GB-174 had a similar inclination to Planet X. This similar inclination may have caused the gravitational interactions in the direction perpendicular to the plane to become stronger. Another interesting result seen from this plot is the variation in eccentricity. These sinusoidal changes in eccentricity have an amplitude of about .0005. This may seem small, but measurements of eccentricity are extremely precise. This strong sinusoidal pattern and increased semi-major axis variation may also signal that GB-174 enters some kind of resonance with Planet X, relatively quickly. All of these variations start occurring almost immediately. Therefore, GB-174 would be a very good candidate for studying the existence of Planet X. Though, again, this certain variation may be due to the bias in what objects I had chosen for the simulation.

The object nearest to Planet X in this simulation is the TNO OO-67. This body has orbital properties similar to the other two far-out TNOs, except that its semi-major axis is near 500 AU. Therefore, it is much closer to Planet X than any of the other TNOs seen so far. We should expect major variations from the norm in all orbital parameters due to its close proximity to Planet X. However, looking at the plots of OO-67, we can see that variations from the norm only begin after about 450000 years, instead of almost immediately like with GB-174. Eventually, the semi-major axis starts to differ from the control simulation by about 3 AU. In this case, Planet X gas caused the general variations in orbital parameters to assume complete different forms. Normally, GB-174 would experience very significant changes to its orbit over 10 Myr. Its semi-major axis would change by about 50 AU, its inclination would decrease by $.001^o$, and its eccentricity would increase by .0005. Planet X has served to suppress all of these significant changes in orbital parameters in general. Its semi-major axis and eccentricity decrease overtime due to the presence of Planet X, stabilizing its orbit. This is the opposite effect from what we have seen with GB-174. OO-67 is near Planet X in terms of inclination, meaning it OO-67's inclination shouldn't increase significantly. We can see that Planet X stabilizes OO-67's inclination overtime, which is validated by our previous observations. We see that Planet X can stabilize orbits of smaller bodies, just as it did with comets.

The TNO with the most interesting change in behavior is the first of the sednoids, Sedna. These objects are known as extreme trans-Neptunian objects, as they have very large semi-major axes. Sedna has a somewhat significant mass, so it will not act completely like a test particle, as most of the other objects have been. Furthermore, it has a decently high eccentricity, though not so extreme as OO-67 had. Its inclination is also below that of Planet X's, meaning an increase in inclination is likely to occur if there is a gravitational interaction. However, its semi-major axis is less than OO-67's meaning we should expect to see less significant variations. In the control simulation, Sedna seems to have a particularly stable orbit, with its inclination and eccentricity remaining largely unchanged. Its semi-major axis would show large changes overtime, changing by about .05 AU overall. After adding Planet X to the system, we start to see variations occur very early on. All three plotted parameters show variation almost from the beginning of the simulation. Our assumption that Planet X would cause an increase in inclination is validated by this data, as Sedna's inclination linearly increased by about $.0025^o$ over 10 Myr. We can see that Planet X served to disrupt Sedna's orbit, and make it less stable in other ways as well. Sedna's semi-major axis pattern took on a complete different form after Planet X was placed into the system. In most of the other bodies we had studied, the pattern of the changes in semi-major axis had roughly stayed the same between both simulations. However, Planet X induced large excitations on Sedna, causing its semi-major axis, and eccentricity, to change more drastically. These semi-major axis changes grew to .1 AU very early on, at almost 2.5 Myr. Though not a large change, Sedna's eccentricity increased by .0002 as well. It can also be seen that the sinusoidal pattern of the semi-major axis variations of the original simulation are almost out of phase with those from the simulation with Planet X. Therefore, this is a very clear case of Planet X disturbing orbits quickly, making them unstable.

All of these previous objects have been much less massive than Planet X, making them more vulnerable to excitations and gravitational interactions. The fact that they are closer in proximity to Planet X than most other bodies in the Solar System also aids in this destabilization process. However, the most important bodies to consider in long-term stability are those with the most influence. Most of the most massive bodies are too far from Planet X to feel any effect of its presence. Bodies like Jupiter and Saturn are much too massive and far away to have any notable interaction with Planet X. Bodies such as Earth and Mars are much to far away from Planet X to feel any interaction either, considering forces due to gravity fall off as $\frac{1}{r^2}$. Therefore, there are only two bodies that would be affected in general by Planet X's existence in the next 10 million years: Pluto and Neptune.

Neptune is the closest planet to Planet X, therefore it would feel its effects the strongest out of all the planets. Neptune, like Eris, has a very high mass, and is very distant from Planet X, so its variations from the norm should be small. We should expect these variations to be almost nonexistent in most cases, due to this lack of interaction and Neptune's enormous mass. However, overtime, gradual nudges from Planet X could cause changes in Neptune's orbit. We can see from the plot of Neptune that its orbit remains largely unaffected until about 4.5 Myr. Even at this point, the variations from the norm are very small, not being significant to Neptune's overall stability.

However, this small change in a massive body's orbit can lead to large changes in the orbits of surrounding bodies, seeing as it has so much gravitational influence. These deviations become quite apparent in the semi-major axis after about 6 Myr. After this time, Neptune's semi-major axis changes more than it would have normally. Its eccentricity begins to vary, though this is by a somewhat negligible amount. We can see that after 10 Myr, the disparity in semi-major axis between both simulations is approximately .005 AU. This is a significant amount for such a large body in the Solar System. Though overall stable, we can see that Planet X's gravity has affected Neptune's orbit overall. Overtime, these variations would get larger and larger, disrupting the entire system. Therefore, we can see that Planet X has a very large influence on the stability of the Solar System as a whole. If Neptune become the least bit unstable, this could cause many of the other massive objects in the Solar System to become unstable, creating a type of snowball effect.

Finally, the object providing data for the most useful analysis is Pluto. Pluto has a mass slightly less than Eris (only being about $.0022M_{\oplus}$) and is much further away from Planet X than any of the other less massive bodies we have analyzed. However, we can see that Pluto's orbital parameters have changed massively due to Planet X. Its distance away from Planet X and large mass should indicate that less gravitational interactions occur. We can see that very early on, Pluto's orbit begins to deviate from its original orbit. In the original simulation, Pluto's orbit underwent drastic changes. Whether this occurs from only the select objects chosen, or will happen in general, is the main source of error for these simulations. Pluto's semi-major axis somewhat linearly decreased by 3 AU over 10 Myr. We can also see large scale eccentricity and inclination variations in Pluto's orbit without Planet X. Seeing as Pluto is close to Neptune, these variations are justified. However, Planet X, again, served to increase variations in orbital parameters. Pluto's semi-major axis dropped linearly by about 5 AU until 7.5 Myr, where it then sharply increased toward its initial value. We can see that the inclination variations generally follow the same pattern, with slight changes due to Planet X. The eccentricity also follows the general pattern of the eccentricity without, though dropping much lower. In a system with Planet X, Pluto drops to nearly .1 eccentricity from about .3 initially. We can see that overall, Planet X causes Pluto's orbit to become generally less stable. Its variations are made more significant in general. Seeing as it is very close in proximity, these variations could have caused changes to Neptune's orbit, or vice-versa. We can see that Planet X has a very significant effect on more massive objects in the Solar System through the changes to Pluto's and Neptune's orbit.

We can see that Planet X's orbit is very stable, just as the other bodies were in the original simulation. We can see that Planet X's orbit becomes more stable overtime, as its inclination decreases linearly. This stabilization of Planet X's orbit could either server to stabilize or destabilize the system. If Planet X is brought more into the plane of the Solar System, it could be brought closer to other bodies, increasing the chances of it causing a gravitational interaction. Though, if its inclination decreases, this signals a stability of its own orbit, leading to a more stable system overall. We can see that the semi-major axis and eccentricity change, but not by a very large margin. However, this steep initial slope of the change on eccentricity signals that changes to its orbit could be seen early on, making it easier to observe.

It can also be seen that the Solar System in its unchanged state is very stable over 10 Myr. All parameters for all bodies, excluding comets, behave in a very constant manner throughout the simulation. Many of the more stable objects show patterns in the variations of their orbital parameters that repeat without any deviation. The smaller bodies may vary in larger ways that the more massive ones due to their more eccentric orbits, but they remain relatively stable over the entire 10 Myr. The one exception to this are objects with metastable orbits, such as many of the comets, which are very easily ejected from the system. We have also seen that TNOs usually have very constant inclinations and eccentricities, as they do not come into close gravitational contact with other, more massive bodies. Therefore, we can see that the Solar System, as a whole, is very stable, at least for the next 10 million years.

Conclusions

Though many of these variations in orbit due to Planet X are small, they are still well within the range of measurement. Today, all of these orbital parameters can be measured to very high precision and accuracy, with the only factors limiting measurements being uncertainty and distance from Earth. Objects farther from Earth have a very low magnitude, making uncertainty in their measurements very large. Though, a change in eccentricity of about .001, or a change in inclination of $.01^o$ can still be measured for a well-seen object. Knowing this, some objects could, in theory, be seen to change due to Planet X. Objects such as Sedna and GB-174 experience variations from the norm, in this simulation, very early on. Their large distance from the Sun may delay the finding of such changes, though they still can be measured with an advancement of technology. For the somewhat near future, objects to focus on for Planet X would be Pluto and VP-113, as they start to experience changes due to Planet X at in the range 200000 to 500000 years. Many of the other TNOs and comets also show these large variations, though they occur on a much larger timescale. Objects not shown either displayed similar changes as other bodies that were shown, or did not change at all due to the presence of Planet X.

Overall, Planet X can have very large effects on our Solar System. We have seen that even the most massive of objects, such as Eris, Pluto, and Neptune, were affected by this theoretical planet. In the case of more massive objects, Planet X solely serves to destabilize the system and cause greater orbital excitations. For less massive bodies that are farther from the Sun, Planet X serves two purposes. It could either increase the variations in orbital parameters to destabilize a body's orbit, or decrease these variations to stabilize it. We have seen that Planet X has stabilized close bodies such as OO-67, but destabilized farther bodies, such as Sedna and VP-113. For the smallest of bodies, such as comets, Planet X can have very similar, yet much more impactful effects. Planet X, in two of the comets we have analyzed, has stabilized an object and kept it from being ejected. In the third case we have analyzed, Planet X excited its orbit too significantly, and had it ejected at a very early time. Therefore, we see that Planet X can significantly change the orbital dynamics of many orbits in the Solar System. Many of the objects in this simulation have shown deviations from the norm relatively early on, which grants very exciting prospects for the future. After 10 million years, though these changes to the whole system are small, they may well become significant over a large period of time.

References

K. Batygin and M. E. Brown. Evidence for a distant giant planet in the solar system. *The Astronomical Journal*, 151, 2016.

K. Batygin, F. C. Adams, M. E. Brown, and J. C. Becker. The planet nine hypothesis. *Physics Reports*, 805:1–53, 2019.