UNIVERSITY OF AMSTERDAM

COMPUTATIONAL SCIENCE PROJECT

Influence of Jupiter-like Planets on Centaur Transits to the Inner Solar System

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Group:
Group 8

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Course:
Project Computational Science

Abstract

A common belief is that Jupiter 'protects' Earth from asteroid impacts. Research by Horner and Jones (2009) suggests that this belief might be incorrect. In their simulation removing Jupiter had no effect on the amount of asteroid impacts, while a lower Jupiter mass (0.2 GM_j) increased it. To verify these results we performed an N-body simulation of the solar system using Newtonian gravity and the Velocity-Verlet integrator. To reduce computation time, we looked at whether Centaur asteroids would reach the inner (within $2AU$) or outer (beyond $1000AU$) Solar System. The 65 Centaur asteroids from NASA Jet Propulsion Laboratory 2023, with perihelion between 17 and 30 AU, were cloned using a grid method and their velocity was reduced by 40%, destabilizing their orbits to reduce simulation time. The results show an almost linear increase between Jupiter's mass and the amount of inner or outer asteroids. (140 words)

1 Methodology and Results (350 words)

Similar to the paper by Horner and Jones 2009 we performed an N-body simulation of celestial objects [1] and Centaur asteroids with a perihelion between 17 and 30 AU (between Jupiter and Neptune) using Newtonian gravity:

$$\vec{a} = \frac{\vec{F}_g}{m} \tag{1}$$

$$\vec{a} = -\frac{GM}{r^3}\vec{r} \tag{2}$$

$$\frac{d^2}{dt^2}\vec{r} = -\frac{GM}{r^3}\vec{r} \tag{3}$$

While we originally considered several algorithms for solving this ODE numerically, such as the Euler and Runge-Kutta algorithms, we decided to utilize the the Velocity-Verlet (Swope et al. 1982) integrator due to its good energy conservation as a symplectic integrator. Unlike the original paper, which uses a hybrid integrator, our method uses a constant time-step of 5 days,

[1] Sun and planets, excluding Mercury and Venus for practical reasons.

which does not conserve energy well during close encounters. To account for this limitation, asteroids that come within one million kilometers of a celestial are removed as 'impact'.

We cloned 65 real Centaur objects from NASA Jet Propulsion Laboratory 2023, in a 5x5x5x3 grid[2] to 24,375 asteroids, improving the accuracy of our results. We also reduced the asteroid's velocity by 40% to destabilize their orbit, which reduces the necessary simulation time. Lastly, to further decrease computational requirements, we also ignored the gravitational attraction between Centaurs reducing our simulation to linear time complexity.

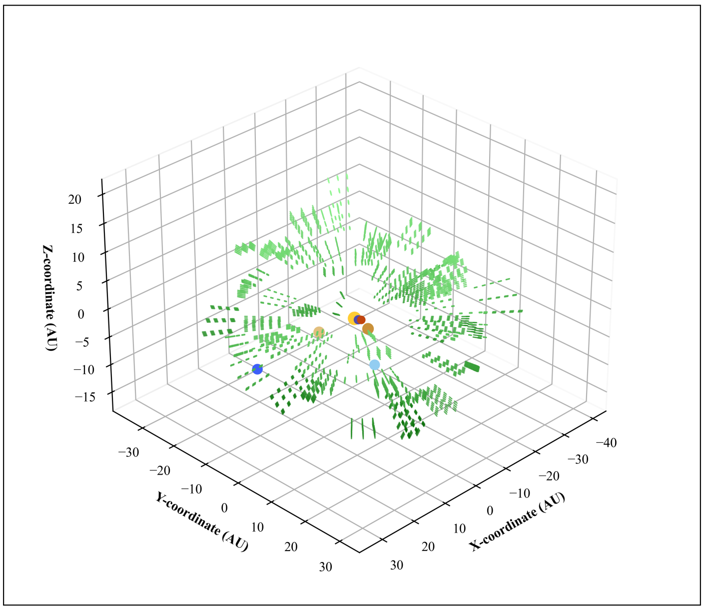

Figure 1: This figure depicts the initial positions of the Centaurs (green-coloured) and planets in our solar system simulation. As seen in the figure, the Centaurs are clustered in a grid pattern as explained above.

In total, our simulation spans approximately 54,757 years, starting from 1 January 2025[3]. To validate our model, we examined the total Centaur energy over time relative to the 'true' initial value. During testing, we found that the energy deviation over time for $dt = 5$ days was not significantly worse than for smaller dt's. Thus, we chose $dt = 5$ to minimize computation time while still preserving system energy relatively well.

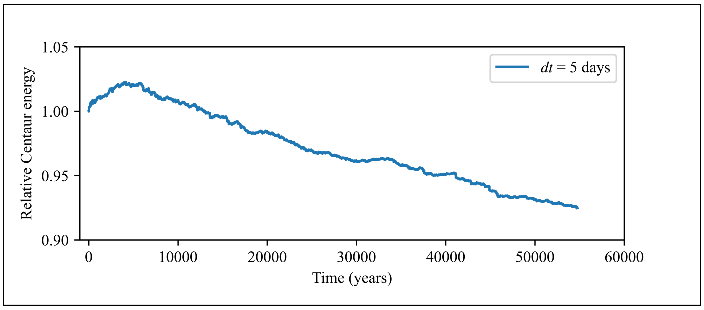

Figure 2: This figure depicts the total energy of the Centaur bodies over the entire duration of our simulation (54,757 years) for $dt = 5$ days.

[2] separated by 0.075 in eccentricity, 0.15 AU in semi-major axis, 0.75 degrees in inclination, and 5 degrees in the argument of perihelion

[3] Initial state of celestials. The JPL Small-Body Database Query does not track Centaur asteroids over time, thus their initial condition is their discovery.

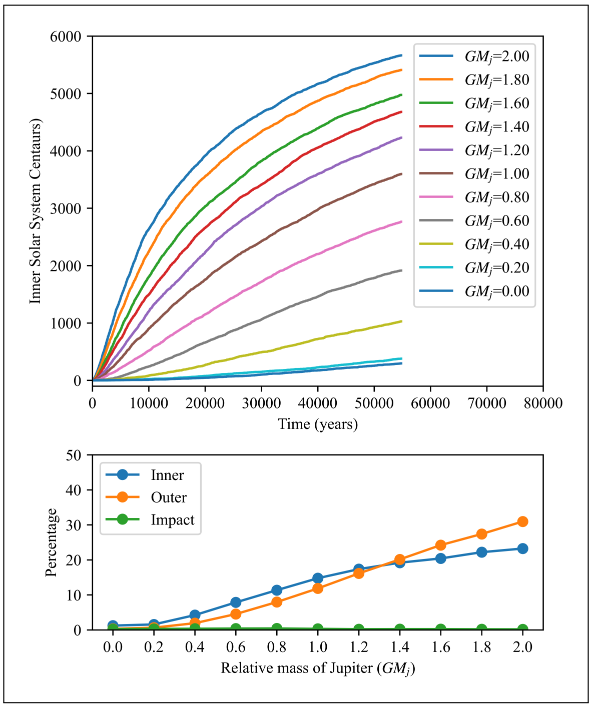

Figure 3: This upper graph shows the evolution of the number of Centaurs entering the inner solar system over time for different relative masses of Jupiter (GM_j). The lower graph shows the final number of Centaurs that enter the inner solar system, the outer solar system or impact with a gas giant for different relative Jupiter masses (GM_j).

Figure 3 shows that as the relative mass of Jupiter increases, the number of Centaurs entering the inner solar system over time (within $2AU$) also increases. We attribute this to the increased pulling force from Jupiter on the Centaurs, which most likely has a destabilizing effect on their orbits. Our results do not align with those of Horner and Jones 2009. We believe this difference might be attributed to the choice of integrator, total simulation time and necessary velocity bias. Further research should increase the total simulation time and properly model close encounters, which might also make the velocity bias unnecessary.

2 Team Member Contribution

- **Joel Shefer:** Responsible for initial python simulation, Velocity-Verlet implementation and report. Assisted on energy hypothesis testing.
- **Thijs Spoor:** Responsible for simulation, energy and hypothesis code & visualisation.
- **David Kraakman:** Responsible for peer review, and focused mainly on the Centaur cloning process, .vtp file generation, and visualization in ParaView. Also played the major role in designing the poster.

2.1 Git Fame

Total loc: 2702855
Total months: 12747.0

Author	hrs	mths	loc	coms	fils	distribution
ThijsSpoor99	5	12406	2615798	39	151	96.8/37.9/59.4
David-Kraakman	7	305	76683	18	17	2.8/17.5/ 6.7
David Kraakman	5	21	5970	31	25	0.2/30.1/ 9.8
JShef	4	15	4403	14	60	0.2/13.6/23.6
Joel Shefer	2	0	1	1	1	0.0/ 1.0/ 0.4

Figure 4: Git Fame Output.

References

Horner, Jonti and Barrie W Jones (2009). "Jupiter–friend or foe? II: the Centaurs". In: *International Journal of Astrobiology* 8.2, pp. 75–80. DOI: https://doi.org/10.1017/S1473550408004357.

NASA Jet Propulsion Laboratory (2023). *JPL Horizons System.* [Online]. Available: https://ssd.jpl.nasa.gov/horizons/. [Accessed: Jan. 2025]. California Institute of Technology, Pasadena, CA.

Swope, William C et al. (1982). "A computer simulation method for the calculation of equilibrium constants for the formation of physical clusters of molecules: Application to small water clusters". In: *The Journal of chemical physics* 76.1, pp. 637–649.

A Given peer review for team 9

Submitted by team: Joel Shefer, Thijs Spoor, David Kraakman

To review the project titled: <no title given>

From team: Nicolai Albrecht, Timon Jašarević, Stefano Jonjić, Marijn Oude Groeneger

After reading the project proposal thoroughly, using the guidelines on what to review from the initial lecture slide titled "Peer review - Use the template from Canvas!", we make the following constructive remarks (min 50, max 200 words):
You've chosen an interesting and well motivated research question. In the hypothesis you mention a wolf population, it might be interesting to find how many wolves lead to a stable population. What is the hypothesis based on? Is there any research on other locations where wolves stabilize the population? Perhaps you could then use this research to validate your model, since the OVP itself does not have data of wolf influence. We think Agent-based Modelling is a good choice. However, we suggest c++ instead of c for this method as it is a more object oriented language. Why is the grid in order of tens of meters? It can be interesting to also simulate other prey animals besides red deer to create a more accurate model. After all, the OVP also has large populations of other prey animals. The timeline seems reasonable, but we recommend also validating the model before week 3 to avoid unforeseen issues. Currently there is no title and the word count of numerical method is too high (103).

B Given peer review for team 10

Submitted by team: Joel Shefer, Thijs Spoor, David Kraakman

To review the project titled: N-Body Simulation Integrating Atmospheric and Orbital Dynamics for Optimizing Spacecraft Launch Trajectories

From team: Ines Chellali, Hidde Poel, Kangzhi Qin, Andrei Stoian

After reading the project proposal thoroughly, using the guidelines on what to review from the initial lecture slide titled "Peer review - Use the template from Canvas!", we make the following constructive remarks (min 50, max 200 words):
The proposal you have seems interesting, but quite ambitious for only 4 weeks. Perhaps it would be better to mainly focus on the "temporary satellite-free zone" part, which, in our opinion, is also motivated better in your proposal. If your wish is to still also incorporate the "optimal trajectory" part in the project, then we suggest substantiating your choices better (e.g., why Jupiter?; In what time frame are you looking for satellite-free zones?; Does the type of rocket make a difference for the optimal trajectory?; What launch location will you use?). For your numerical methods, we would suggest looking into some way to model drag due to Earth's atmosphere. The gravitational pull of satellites among themselves is probably negligible; you could also opt to not simulate these interactions, resulting in way cheaper computation. Probably making the usage of a Barnes-Hut redundant. We would also suggest assigning a coordinator for every part of the project instead of stating that every part will be done by every member. A final remark is to keep the word limit per section in mind (especially for your division of work plan).

C Received peer review from team 6

Submitted by team: Sebastian Gielens; Sietse van de Griend; Hamid Ahmadi; Adam Dong

To review the project titled: Jupiter: protector against Centaurs?

From team: David Kraakman; Joel Shefer; Thijs Spoor

After reading the project proposal thoroughly, using the guidelines on what to review from the initial lecture slide titled "Peer review - Use the template from Canvas!", we make the following constructive remarks (min 50, max 200 words):

In general the paper looks good, clearly formulated but we have some recommendations;

- It is not exactly clear what the model exactly will include and what type of simulations will be made. Will it include all planets or only Jupiter?
- Has there also been discussion about the time step sizes and the effect on accuracy of these sizes on the simulation. Smaller time step sizes increase accuracy but slow simulation speed etc. It could be handy to add a comment about this in the numerical method.
- The hypothesis is just one sentence long, it could be extended upon by including a justification for the hypothesis. You could include sources.

D Received peer review from team 7

Submitted by team: Ishana Bohorey; Sara Stoof; Oskar Linke; Windar Mazzori

To review the project titled: Jupiter: protector against Centaurs?

From team: David Kraakman; Joel Shefer; Thijs Spoor

After reading the project proposal thoroughly, using the guidelines on what to review from the initial lecture slide titled "Peer review - Use the template from Canvas!", we make the following constructive remarks (min 50, max 200 words):
In the research question it would be useful to formulate 'transition rate' more clearly, as it is not immediately clear to outsiders what this refers to.
There is no mention of the report in the timeline. It would perhaps be useful to define when this is expected to be worked on.
The numerical method is full of formulas, maybe try to explain it more with words, and leave the proofs for the report.