4-19-2024

Modeling an Extra Planet's Effects on Earth

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NORTHROP GRUMMAN ENGINEERING & SCIENCE STUDENT DESIGN SHOWCASE FLORIDA TECH

Introduction

- The orbit of a planet impacts its climate and habitability, and many models have been developed to study the impacts of planetary system structure on climatic evolution.
- If the Asteroid Belt (AB) had accreted into a single planet, what effects would that extra planet have on Earth's orbit and habitability?

Methods

- Simulated the orbital evolution of the Solar System over 100,000 years using the Gravitationally Interacting Rigid Body Integrator (GRIT) [1]
- Extra planet parameters varied: mass and initial conditions
  - **Mass of planet -** 5 values based on early Solar System AB mass estimates [2]: 0.01 (current AB mass), 1, 2, 5, and 10 $M_\oplus$
  - **Initial conditions -** 4 trials each, based on the orbital parameters of the 4 most massive asteroids: Ceres, Pallas, Vesta, and Hygeia [3]
- Examine new Earth orbit's potential for habitability, compare to control

```
===================================System Summary=====================================
# System name: phaeton_system
# Bodies in the system:
#                             name       rigidity
#          0th body:             Sun     point mass
#          1th body:         Mercury          rigid
#          2th body:           Venus          rigid
#          3th body:           Earth          rigid
#          4th body:            Moon          rigid
#          5th body:            Mars          rigid
#          6th body:         Phaeton          rigid
#          7th body:         Jupiter          rigid
#          8th body:          Saturn          rigid
#          9th body:          Uranus          rigid
#         10th body:         Neptune          rigid
# Coordinates of orbital elements: central

=================================Numerical Integrator=================================
# Scheme: M42
# Step size: 0.001 year
# System will be saved every 1 year in "current_system.json"
# Data output scale: 1 year
# Tidal effects: not considered
# General relativity: not considered
# Output variables: Hamiltonian axial_tilt axis obliquity orbital_elements position spin velocity

=====================================Simulation=======================================
# From t0=0.000000 to T=100000.000000:

 [=========================>-----------------------] 50 % \     0:00:11:21 elapsed. t=50686
```

Figure 1: Running a simulation using the GRIT N-rigid body integrator package.

Results

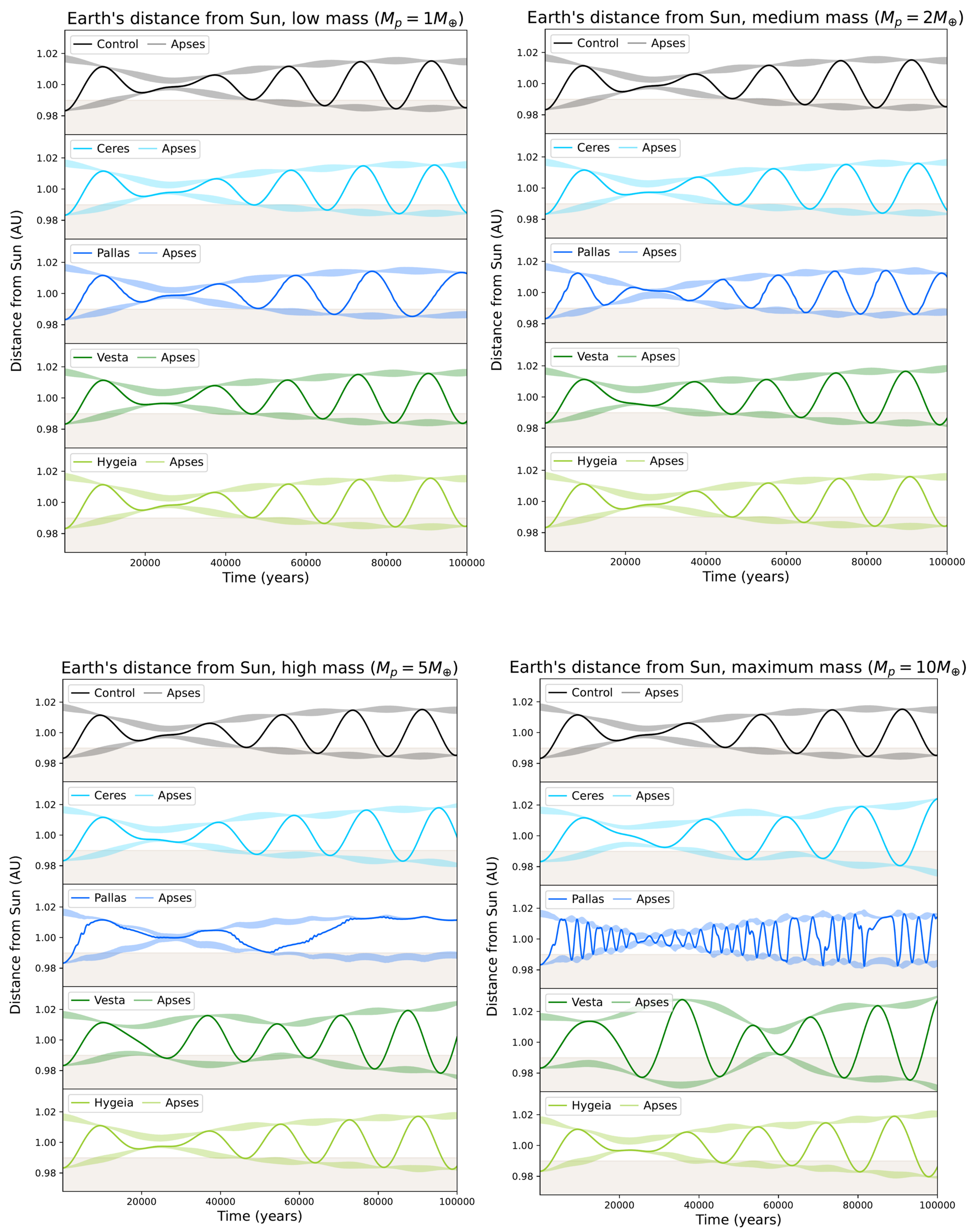

Figure 2: Earth's distance from the Sun for 4 different AB planet mass estimates and 4 different AB planet initial conditions. The beige areas mark the region outside of the habitable zone, and the transparent segments denote the perihelion (bottom) and aphelion (top) for each orbit.

- Total of 21 simulations run, including 1 control trial of the unaltered Solar System

	0.01 $M_\oplus$	1 $M_\oplus$	2 $M_\oplus$	5 $M_\oplus$	10 $M_\oplus$
Control	77%	77%	77%	77%	77%
Ceres	77%	78%	78%	78%	74%
Pallas	77%	79%	78%	91%	80%
Vesta	77%	76%	75%	66%	65%
Hygeia	77%	77%	77%	76%	75%

Table 1: Percent of recorded distances for each trial that fell within the cloud-free habitable zone. Green values are lower than the control, and blue values are larger than the control.

- All Earths stayed within the outer distance limit of the habitable zone (~1.67 AU) at all times [4]
- All runs also approached closer to the Sun than the cloud-free water loss limit (~0.99 AU) at some point in its orbit, meaning that for all trials, an atmosphere is necessary for the presence of liquid water at its surface [4]

Conclusions

- Many stable configurations of a Solar System with an extra planet that preserve Earth's habitability for at least 100,000 years are possible
- However, habitable zone limits are highly dependent on atmospheric effects, and with an atmosphere Earth's habitability zone could be much larger [4]
  - Future work: simulating climate & atmospheric effects with these orbital parameters as initial conditions

References

[1] Renyi Chen et al 2021 ApJ 919 50
[2] Matthew S. Clement et al 2019 AJ 157 38
[3] Lissauer et al 2001 Icarus 154 449
[4] Ravi Kumar Kopparapu et al 2013 ApJ 770 82