Solar System Stability Under Changes in Jupiter's Mass

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Abstract

Results from Ito and Tanikawa (2002) have shown the solar system to be stable even for timescales on the order of 10^9 years, but the solar system is only one specific planetary configuration. Because the solar system's mass is dominated by a single object, and its satellites have near circular orbits, its stability is perhaps predictable. The purpose of this study is to investigate the long-term movement of a solar system in which the total mass is split more evenly between the Sun and Jupiter, in order to look at the stability of two orbit types in binary systems: S-type orbits, in which satellites closely orbit one of the two stars, and P-type orbits, in which satellites orbit the center of mass of both stars. I used a numerical simulation of the Solar System over 100,000 years with a time resolution of 12 hours. I found that Earth could maintain a stable orbit for masses of Jupiter up to 0.35 solar masses, beyond which it was quickly ejected. Venus was stable at 0.5 solar masses, but not 1 solar mass, and Mercury was stable at 1 solar mass, but not 2. Due to it's orbital position and closeness to Jupiter, Saturn was ejected immediately in every simulation. Uranus and Neptune entered highly elliptical P-type orbits, but usually remained stable. I conclude that, while the solar system is able to (at least on the timescale I studied) endure increases in Jupiter's mass by up to 100x, in its current state it cannot support an eccentric, high mass orbit resembling a binary system.

Methods

Data

I wrote a numerical simulation of the solar system in Python which recorded the positions and velocities of the Sun and planets in time steps of 12 hours. I plotted the positions of the planets relative to the sun at every 1000th step to create my figures. I obtained my initial positions and velocities using barycentric ephemerides generated from JPL HORIZONS web interface. By modifying Jupiter's mass to between 0.1 and 3 solar masses (creating a binary solar system) I was able to observe which planets were ejected and at what times in various configurations. I ran each scenario for 100,000 years of simulated time.

Errors

My simulation placed all planets on a single orbital plane, so that I could work in two dimensions, which is a potential source of error in my data. Another is my time resolution – I step in intervals of 12 hours for the purposes of speed (under my time constraints, it was impractical to run simulations lasting longer than 7-8 hours of real time). This could mean that during close encounters, when forces are large, the planets are accelerated more than they should be, and possibly ejected when they shouldn't be.

Figures

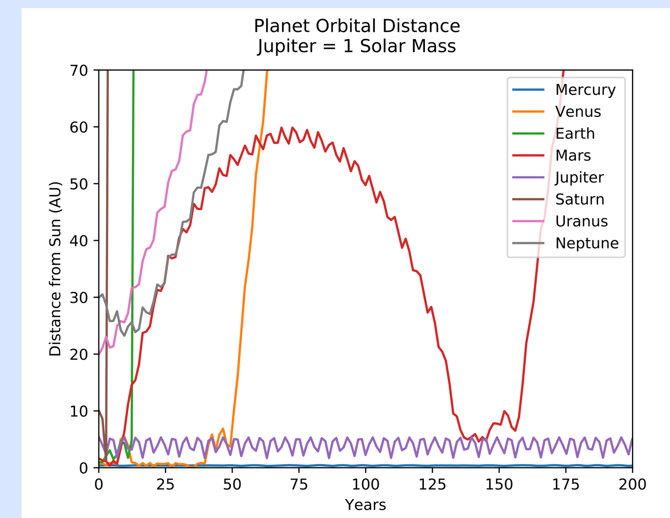

Fig.1. At Jupiter = 1 solar mass, all planets are quickly ejected except Mercury, which remains stable for the full 100,000 years.

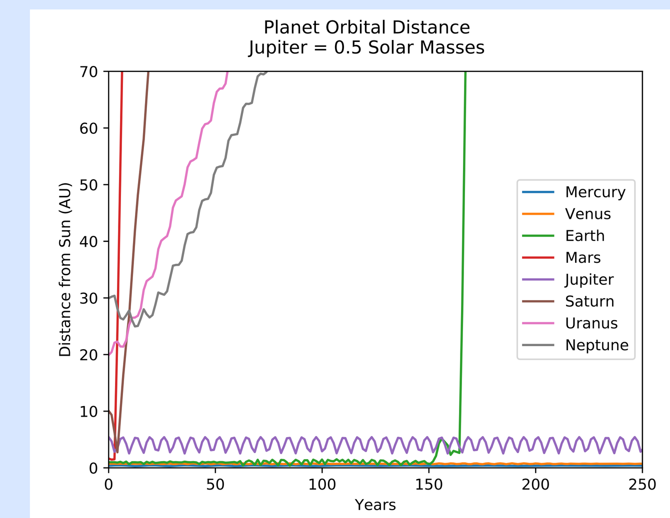

Fig.2. At 0.5 solar masses, Venus is stable as well. It also takes much longer for Earth to be ejected, compared to Fig.1.

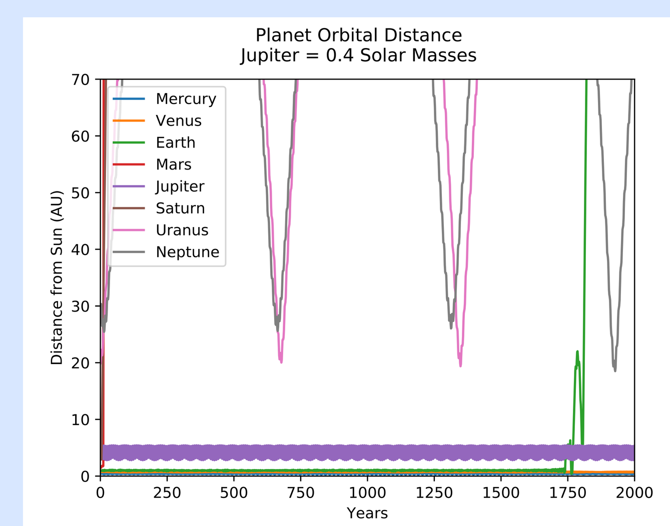

Fig.3. At 0.4 solar masses, it is 1750 years before Earth is ejected. The perihelions of Uranus' and Neptune's orbits are also visible here.

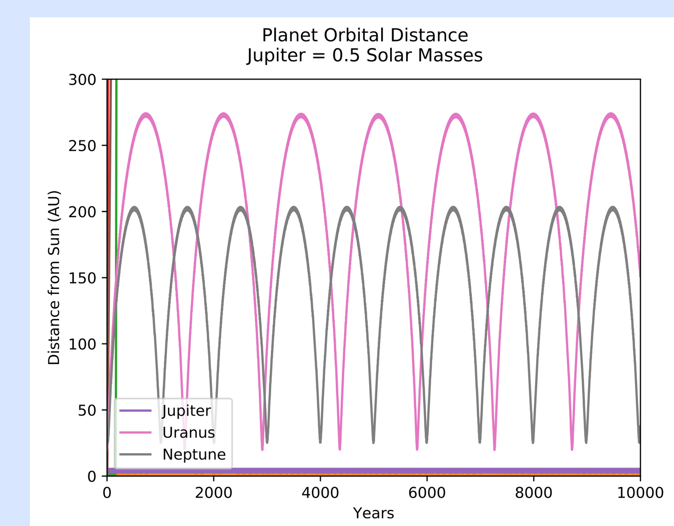

Fig.4. 0.5 solar masses, zoomed out to show Uranus' and Neptune's large eccentric orbits, which they assume whenever Jupiter < 1 solar mass.

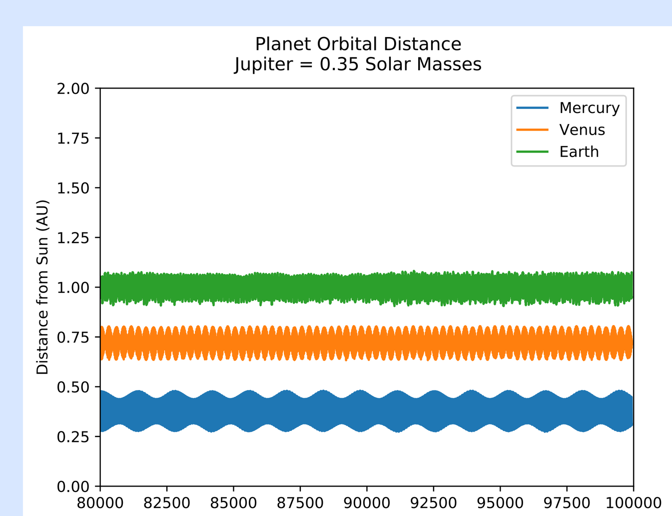

Fig.5. At 0.35 solar masses, Earth remains for the full 10e5 years, but its orbit compared to Venus and Mercury has no stable pattern, so it might be ejected eventually.

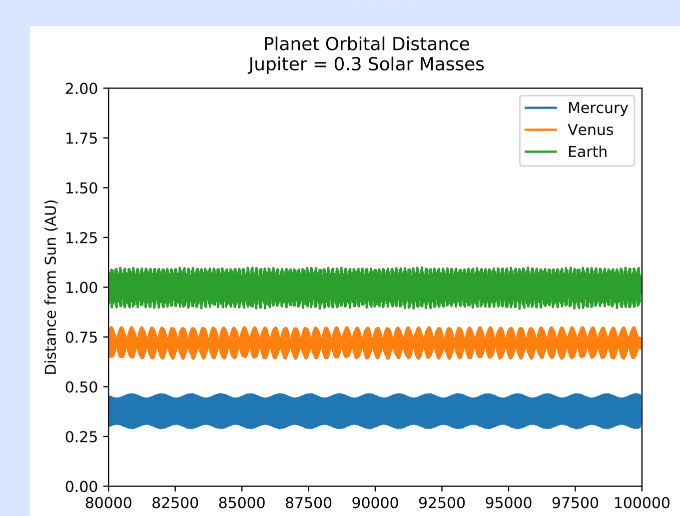

Fig.6. At 0.3 solar masses, Earth again maintains its orbit, which is significantly less erratic here, suggesting greater stability.

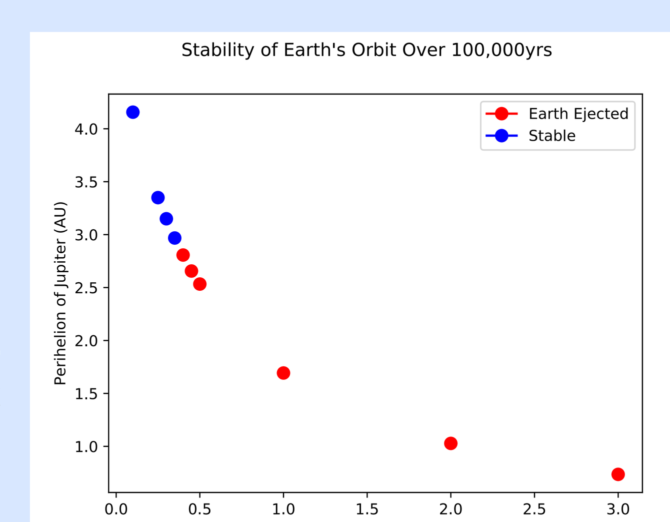

Fig.7. The simulations in which Earth is ejected correspond to a more massive Jupiter, and thus a low perihelion and close approach. The inverse relationship between mass and perihelion generates the curve, though I suspect a low perihelion is what drives the ejection, since a lower r^2 affects gravitational force more than a higher M.

Conclusion

In binary configurations, a planet's ability to remain in a stable S-type orbit depends on its distance from the primary, the closest approach of the other critical body, and the mass of both critical bodies (lower r^2 distance to earth and higher M both mean higher gravitational force).

Highly elliptical P-type orbits, such as those of Neptune and Uranus in the simulation, are comparatively less constrained – they occurred frequently and with different eccentricities and aphelions based on Jupiter's mass.

Planets which alternate between orbiting one one body and the other, or which are sent outward and "return" to orbit (as seen in fig.1. Mars) are extremely unlikely to remain stable even for only a few orbital periods.

Because stability in these systems requires such closeness of a satellite to its partner, it is unlikely that any stable and habitable planets could be found on the inside of binary systems with highly elliptical orbits (i.e. low perihelions).

Future Work

The eccentricities of the orbits of all involved bodies plays a large role in the stability of the overall system, and future simulations should use eccentricity as an independent variable in order to compare its effect on stability along with the mass and distance ratios I have described above. Additionally, Jupiter's initial coordinates could be modified to achieve the same perihelion for different masses, so that several different curves could be created for fig.7 and the identified relationship could be studied further.

Prior Work

Ito, Takashi, and Tanikawa, Kiyotaka, 2002, Long-term integrations and stability of planetary orbits in our Solar system,*Monthly Notice of the Royal Astronomical Society*, v.336, p. 483-500.

Graziani, F. & Black, D. C, 1981, Orbital stability constraints on the nature of planetary systems,*Astrophysical Journal,*v.251, p. 337-341

Holman, Matthew & Wiegert, Paul, 1999, Long-Term Stability of Planets in Binary Systems,*The Astronomical Journal,*v.117, p. 621-628.

Laughlin, Gregory, 2009, Planetary science: The Solar System's extended shelf life, *Nature,* v.459, p. 781-782.