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How Planet Nine could change the fate of the Solar system

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Abstract

The potential existence of a distant planet ('Planet Nine') in the Solar system has prompted a re-think about the evolution of planetary systems. As the Sun transitions from a main-sequence star into a white dwarf, Jupiter, Saturn, Uranus and Neptune are currently assumed to survive in expanded but otherwise unchanged orbits. However, a sufficiently distant and sufficiently massive extra planet would alter this quiescent end scenario through the combined effects of Solar giant branch mass-loss and Galactic tides. Here I estimate bounds (see also [1]) for the mass and orbit of a distant extra planet that would incite future instability in systems with a Sun-like star and giant planets with masses and orbits equivalent to those of Jupiter, Saturn, Uranus and Neptune. I find that this boundary is diffuse and strongly dependent on each of the distant planet's orbital parameters. Nevertheless, I claim that instability occurs more often than not when the planet is as massive as Jupiter and harbours a semimajor axis exceeding about 300 au, or has a mass of a super-Earth and a semimajor axis exceeding about 3000 au. These results hold for orbital pericentres ranging from 100 to at least 400 au. This instability scenario might represent a common occurrence, as potentially evidenced by the ubiquity of metal pollution in white dwarf atmospheres throughout the Galaxy.

1. Introduction

The Sun will leave the main sequence in about 6.5 Gyr, and undergo drastic changes (Fig. 1). Its radius will increase by a factor of about 230, it will lose almost half of its current mass, and its luminosity will reach a peak value which is about 4000 times its current value. The Sun will become so large that its radius will extend just beyond where the Earth currently sits. These major changes will occur in two phases. The red giant branch phase will last about 800 Myr. In this timespan, the Sun will gradually lose about a quarter of its mass. The second phase, when the Sun becomes an asymptotic giant branch star, is quicker: lasting just 5 Myr. Another quarter of the Sun's mass will be lost during this period. During both phases, the radius of the Sun will extend out to nearly the Earth's distance.

Although the consequences for the inner Solar system will be profound, the outer solar system will escape relatively unscathed (see Fig. 1).

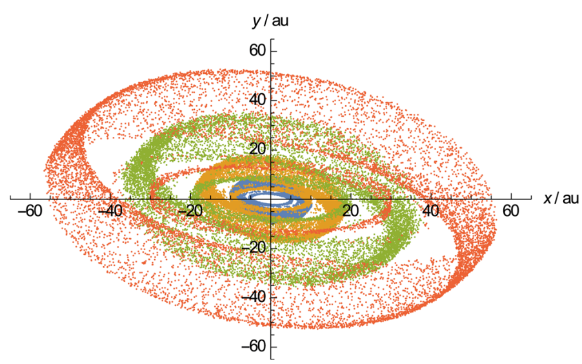

Figure 1: Time evolution of Jupiter, Saturn, Uranus and Neptune as the Sun leaves the main sequence, without the presence of Planet Nine. The semimajor axes approximately double and the eccentricities remain unchanged.

2. Addition of Planet Nine

However, Planet Nine could alter this scenario. If the planet is distant enough, then Galactic tides could perturb the planet inward. If the planet is massive enough, then Planet Nine could scatter off of the four known giant planets.

Figure 2 demonstrates a scenario where Planet Nine is both massive enough and distant enough to change the fate of the Solar system and generate large-scale instability.

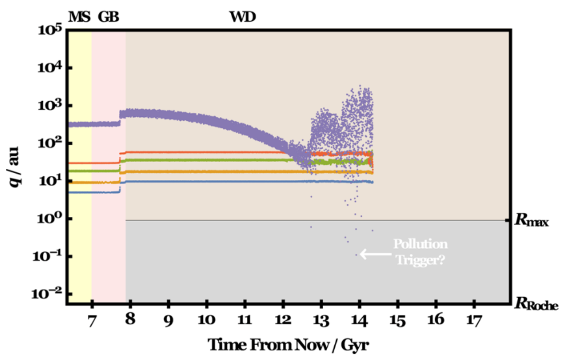

Figure 2: Tidally induced instability: here Planet Nine (with mass of ≈ 109 M⊕) has a large enough initial semimajor axis (≈ 2030 au) for Galactic tides to have a noticeable effect during the white dwarf phase. The tides create an initial increase in the already high value of the initial eccentricity (≈ 0.85), triggering ejection of Neptune as Planet Nine's pericentre approaches the location of the other four planets. Eventually Planet Nine sweeps through any remaining debris in the inner system, which may pollute the eventual white dwarf once inside its disruption radius R_{Roche}.

I performed an ensemble of simulations in order to determine the critical masses and distances that Planet Nine must harbour in order to create instability in the Solar system. The results are in Figure 3.

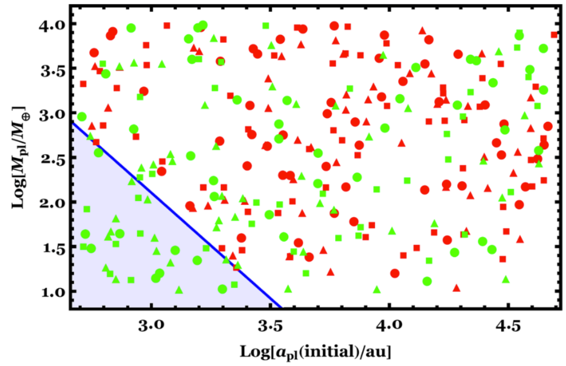

Figure 3: The outcomes from all simulations. Stable simulations are indicated in green symbols, and unstable ones are in red. The different shapes refer to different Solar models. The blue triangle indicates where all simulations remained stable.

3. Conclusions

I demonstrated that a distant planet with an orbital pericentre under 400 au could pose a serious danger to the stability of Solar system analogues during a Sun-like star's giant branch and white dwarf phases. This statement holds true for a distant planet which is at least as massive as Jupiter and harbours a semimajor axis beyond about 300 au, or for a super-Earth when its semimajor axis exceeds about 3000 au. The driver for the instability is a combination of Galactic tides and stellar mass-loss, which together or separately may induce close encounters amongst the five planets, with the distant planet always representing the trigger.

The consequences for other planetary systems are profound. If more distant, trans-Neptunian-like planets are also common, then the ingredients may exist to regularly generate instability and a frequently changing dynamical environment during white dwarf phases of evolution.

Acknowledgements

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References

[1] Veras, D.: The fates of Solar system analogues with one additional distant planet, MNRAS, Vol. 463, 2958-2971, 2016.