Stability of a habitable zone Jovian planet in the presence of a second Jovian.
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Introduction: One of the foremost aims of astronomical research is the search for habitable planets beyond Earth. Though the majority of research is conducted around habitable terrestrial planets [1], a theory has recently emerged, that a sufficiently sized satellite orbiting a Jovian planet [2] could also harbor life within the habitable zone [3].

Aim: The aim of this study is to examine the orbital stability of a Jovian planet once it has reached the habitable zone. The presence of a second Jovian in exoplanet systems could be a factor in the stability of these systems. This study investigates the interactions between a Jovian in the habitable zone and a second Jovian planet, with assessment of dynamical stability.

Chaos and stable zones: The stable zone of a planet determines where other orbital bodies are either-accreted or ejected [4]. The chaos zone is an area of chaotic instability between the Rcz and the Rst, see figure 1.

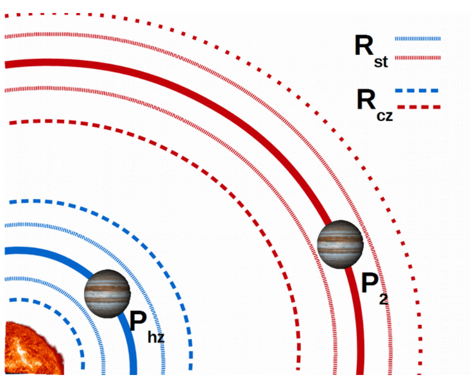

Figure 1: Diagrammatic representation of chaos (R_{cz}) and stable zones (R_{st}) around two Jovian planets, one in the habitable zone (P_{hz}) and another secondary planet.

Simulations: Simulations were conducted on systems with the two Jovian of varying semi-major axis (as a multipule of the R_{cz} value of P_{hz}) and mass combinations (in Jupiter Mass). The SWIFT software package [5] was used on the Green Machine super computer at the Centre for Astrophysics and Supercomputing, Swinburne University of Technology.. The simulations were run with a total integration time of $1.0x10^7$ years. See figure 2 for an example output simulation.

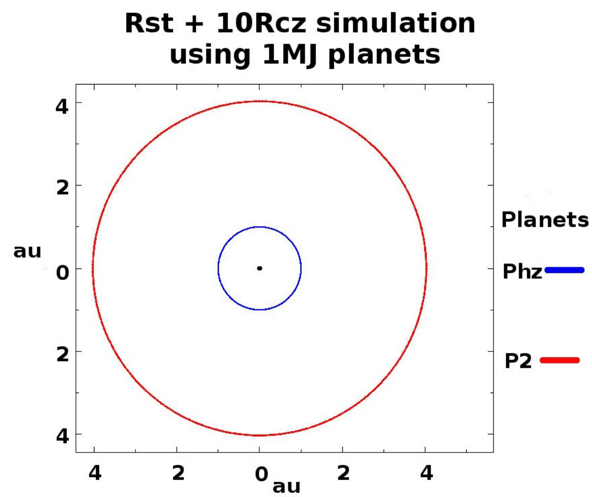

Figure 2: 2d Graphical representation of the output of a SWIFT simulation. This is the simulation based on P_{hz} R_{st} + $10R_{cz}$ calculations, run for $1.0x10^7$ years. $1M_j$ P_{hz} is set at 1 au and the equal mass P_2 is set at 4.041 au. P_{hz}: blue. P2: red. Both x and y values are in au.

Simulated SMA and Eccentricity:

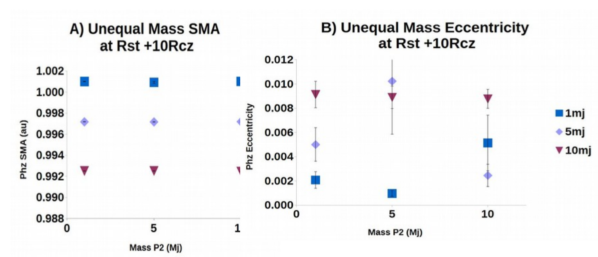

Figure 3: Plot of mean SMA (A) and eccentricity (B) versus mass of P2, during the Rst + 10Rcz simulations. Legend indicates the mass of P_{hz} in M_j . Error bars indicate the standard deviation.

SMA plot shows the inward migration of Phz is only affected by mass of Phz. Low variability in eccentricity of 1Mj Phz when outside the chaos zone of P2. A 5Mj Phz shows low variability in eccentricity when paired with a 1Mj P2, but high variability with larger mass P2. 10Mj Phz shows high eccentricity, unaffected by the mass of P2.

Cyclic Eccentricity: The $R_{st} + 10R_{cz}$ simulation shows cyclic eccentricity for all mass combinations, see figure 4. Simulations where planets are closer than Rst + 10Rcz show a random eccentricity. The cyclic eccentricity could stabilize long term climate variations.

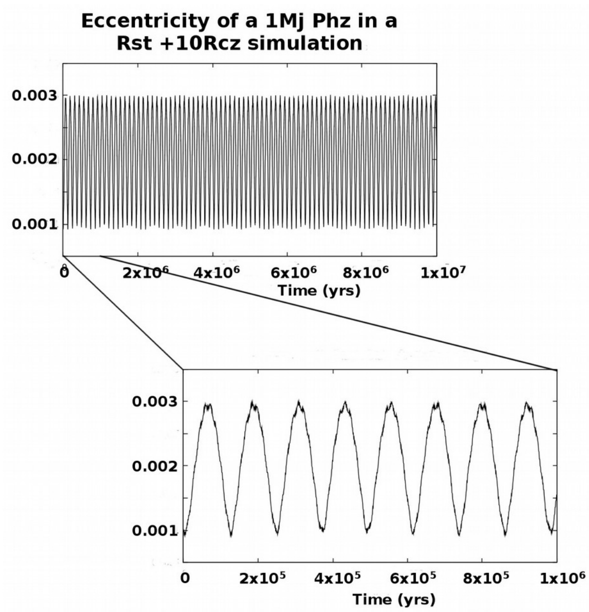

Figure 4: Eccentricity of a $1M_j$ P_{hz} simulated over a $1.0x10^7$ year span, with close-up of $1.0x10^6$ year section, showing a cyclic eccentricity cycle.

Conclusion: A 10Mj planet in any location, could cause instability in the system. 1Mj planets in the habitable zone are stable, but would not form large, habitable satellites [2]. These simulations have shown that a 5Mj Jovian in the habitable zone with a smaller 1Mj Jovian, could be dynamically stable, and offer sufficient size to form habitable satellites. Climate variations are minimized if the distance between planets is beyond 10 multiples of the chaos zone. This combination of planets could be the focus of exoplanet study, in the search for habitable satellites.

References: [1] Kopparapu, R. K., et al. (2013) *ApJ*, 765, 131. [2] Heller, R. et al. (2014) *Astrobiology*, 14, 798. [3] Huang, S.-S. (1959) *AmSci*, 397. [4] Gladman, B. (1993) *Icarus*, 106, 247. [5] Levison, H. F., and Duncan, M. J. (1994) *Icarus*, 108, 18