Stability of a habitable zone Jovian planet in the presence of a second Jovian

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Introduction

One of the foremost aspirations of astronomical research is the discovery of habitable worlds beyond Earth. Though the majority of research is conducted around habitable terrestrial planets (Kopparapu et al., 2013), a theory has recently emerged, that a sufficiently sized satellite orbiting a Jovian planet (Heller et al., 2014) could also harbour life within the habitable zone (Huang, 1959).

Aim

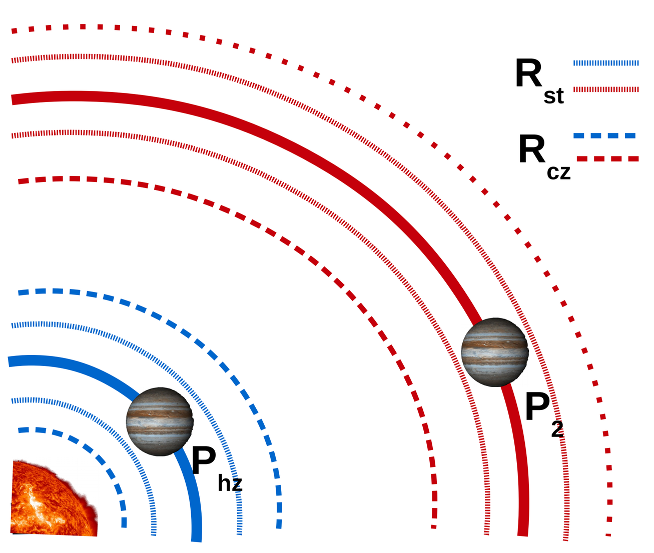
The aim of this study is to examine the orbital stability of a Jovian planet once it has reached the habitable zone. The presence of a second Jovian in exoplanet systems could be a factor in the stability of these systems. This study investigates the interactions between a Jovian in the habitable zone 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 (Gladman, 1993). The chaos zone is an area of chaotic instability between the R_{cz} and the R_{st}.

$$R_{st} \simeq 2.4\left(\frac{M_{phz}}{M_s}+\frac{M_{p2}}{M_s}\right)^{\frac{1}{3}} \quad (1)$$

$$R_{cz} \simeq 2\left(\frac{M_{phz}}{M_s}\right)^{\frac{2}{7}} \quad (2)$$



Where:

R_{st} : Stable zone radius (au)

R_{cz} : Chaos zone radius (au)

M_{phz} : Mass of habitable zone planet(M_j)

M_{p2} : Mass of second planet (M_j)

M_s : Mass of central star (M_j)

P_{hz} : Planet in the habitable zone (1au)

P_2 : Second Planet

P_{hz} in relation to the chaos zone of P_2

It is important to determine whether P_{hz} is inside the chaos zone of P_2. The values in the table below, are calculated using the distance that P_{hz} is outside the chaos zone of P_2, as a ratio of P_2 R_{cz}. Negative values indicate P_{hz} is inside the R_{cz} of P_2. Green highlighted values are of those simulations discussed further.

P_2 Distance	Simulation Masses (P_{hz}-P_2)								
from P_{hz}	$1M_j$-$1M_j$	$1M_j$-$5M_j$	$1M_j$-$10M_j$	$5M_j$-$1M_j$	$5M_j$-$5M_j$	$5M_j$-$10M_j$	$10M_j$-$1M_j$	$10M_j$-$5M_j$	$10M_j$-$10M_j$
Rst	-1.249	-1.470	-1.660	-1.297	-1.396	-1.494	-1.342	-1.405	-1.473
Rst+1Rcz	-0.759	-1.060	-1.296	-0.922	-1.055	-1.181	-1.023	-1.106	-1.193
Rst+2Rcz	-0.414	-0.763	-1.028	-0.688	-0.838	-0.979	-0.835	-0.927	-1.022
Rst+3Rcz	-0.159	-0.539	-0.823	-0.529	-0.689	-0.837	-0.711	-0.808	-0.908
Rst+4Rcz	0.038	-0.363	-0.661	-0.414	-0.579	-0.733	-0.622	-0.723	-0.825
Rst+5Rcz	0.194	-0.222	-0.529	-0.326	-0.496	-0.653	-0.557	-0.659	-0.763
Rst+10Rcz	0.658	0.206	-0.125	-0.085	-0.263	-0.428	-0.381	-0.487	-0.595

Simulations

The SWIFT software package (Levison & Duncan, 1994) was used to simulate the systems. R_{st} simulations were unstable. Other simulations were stable.

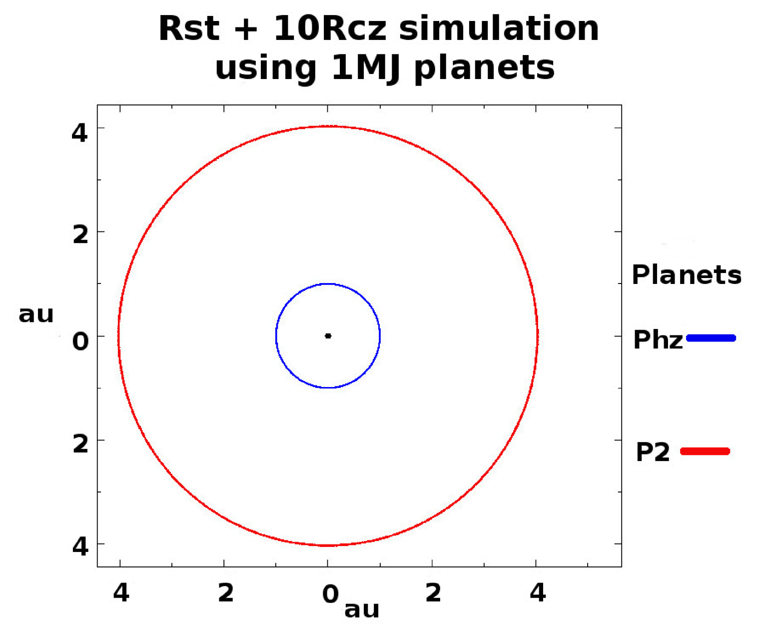
Total integration time: $1.0x10^7$ years.

Output time step: $1.0x10^3$ years.

Integration time step: 0.034 years.

P_{hz} **SMA:** Initialised at 1 au.

P_2 **SMA:** Based on distance calculations. See table above.



Simulations results for $R_{st}+10R_{cz}$.

Mass ratio (P_{hz}-P_2)	P_2 SMA (au)	P_{hz} $\bar{x}$SMA (au)	P_{hz} $\bar{x}$ e
$1M_j$-$1M_j$	4.041	$1.001\pm1.85E-05$	$0.002\pm6.78E-04$
$1M_j$-$5M_j$	4.172	$1.001\pm8.25E-05$	$0.001\pm2.40E-04$
$1M_j$-$10M_j$	4.268	$1.001\pm1.59E-04$	$0.005\pm2.29E-03$
$5M_j$-$1M_j$	5.774	$0.997\pm5.49E-06$	$0.005\pm1.39E-03$
$5M_j$-$5M_j$	5.853	$0.997\pm2.95E-05$	$0.010\pm4.37E-03$
$5M_j$-$10M_j$	5.927	$0.997\pm5.17E-05$	$0.002\pm9.26E-04$
$10M_j$-$1M_j$	6.821	$0.993\pm1.36E-05$	$0.009\pm1.09E-03$
$10M_j$-$5M_j$	6.878	$0.993\pm3.13E-06$	$0.009\pm9.27E-04$
$10M_j$-$10M_j$	6.937	$0.992\pm2.78E-05$	$0.009\pm7.93E-04$

Simulation parameters: Mass of P_{hz} and P_2 in M_j ; P_{hz} at 1 au; set SMA for P_2. Resulting mean ($\bar{x}$) SMA and e for P_{hz} are given with their standard deviations.

Simulated SMA and Eccentricity

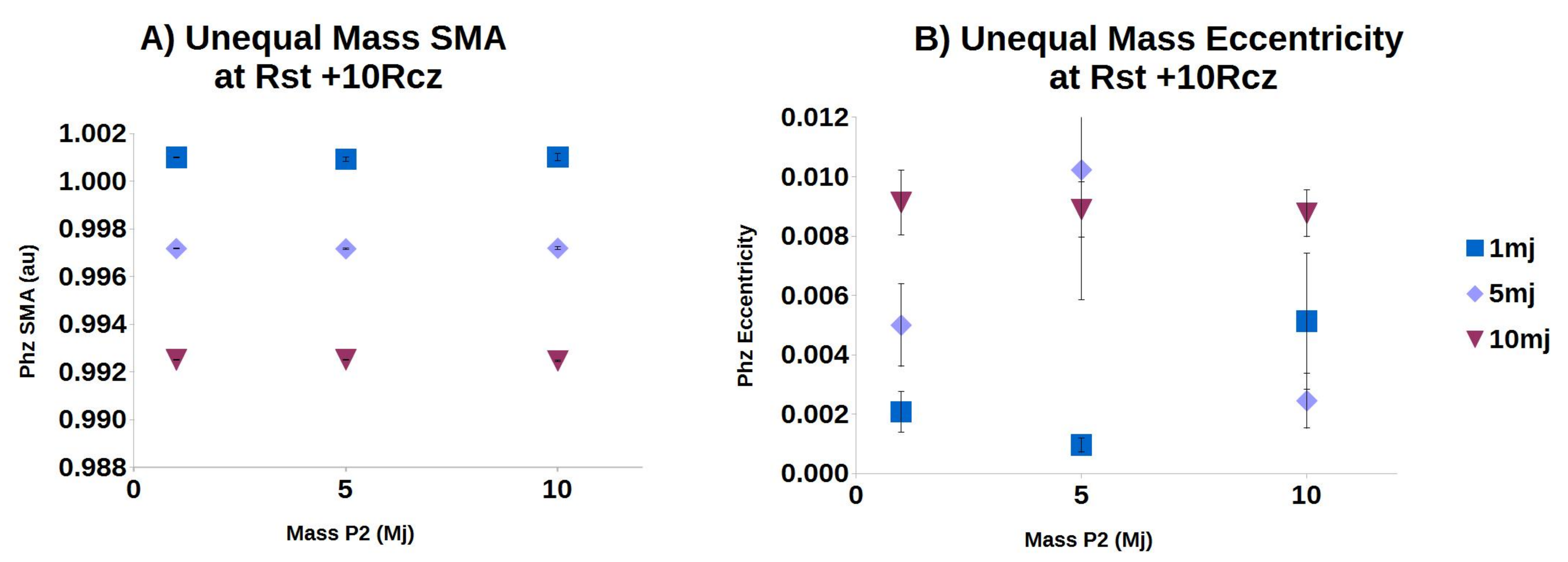
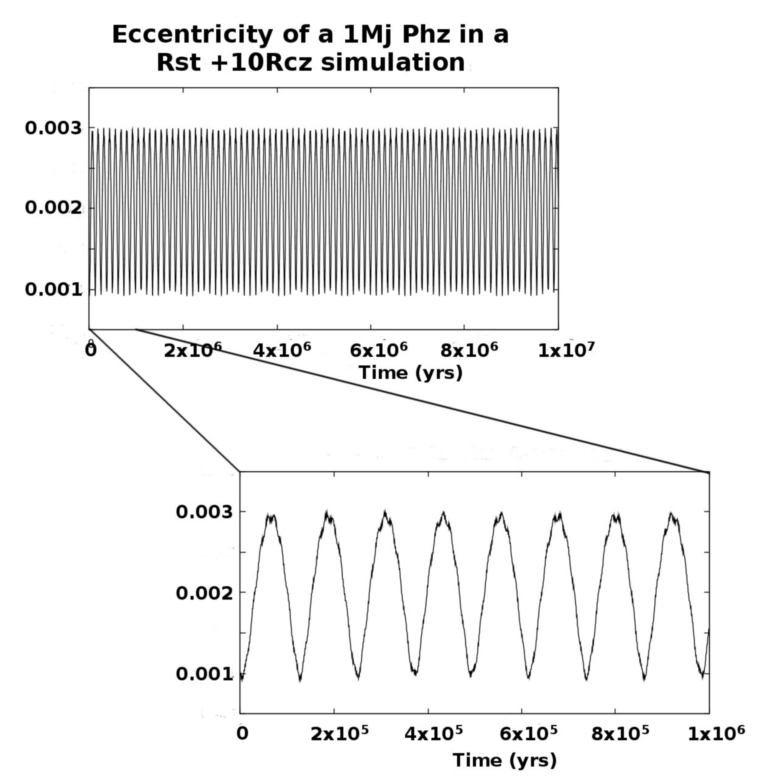


Figure 1: Plot of mean SMA (A) and eccentricity (B) versus mass of P_2, during the $R_{st}+10R_{cz}$ simulations. Legend indicates the mass of P_{hz} in M_j. Error bars indicate the standard deviation.

- SMA plot shows the inward migration of P_{hz} is only affected by mass of P_{hz}.
- Low variability in eccentricity of $1M_j$ P_{hz} when outside the chaos zone of P_2.
- A $5M_j$ P_{hz} shows low variability in eccentricity when paired with a $1M_j$ P_2, but high variability with larger mass P_2.
- $10M_j$ P_{hz} shows high eccentricity, unaffected by the mass of P_2.

Cyclic eccentricity



- The $R_{st}+10R_{cz}$ simulation shows cyclic eccentricity for all mass combinations.
- Simulations where planets are closer than $R_{st}+10R_{cz}$ show a random eccentricity.
- The cyclic eccentricity could stabilise long term climate variations.

Conclusion

- A $10M_j$ planet in any location, could cause instability in the system.
- $1M_j$ planets in the habitable zone are stable, but would not form large, habitable satellites (Heller et al., 2014).

These simulations have shown that a $5M_j$ Jovian in the habitable zone with a smaller $1M_j$ Jovian, could be dynamically stable, and offer sufficient size to form habitable satellites. Climate variations are minimised 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

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