Post-Capture Evolution of Potentially Habitable Exomoons

Simon Porter[1,2], **Will Grundy**[1]

[1]Lowell Observatory, Flagstaff, Arizona
[2]School of Earth and Space Exploration, Arizona State University
`porter@lowell.edu`

Abstract

The satellites of extrasolar planets (exomoons) have been recently proposed as astrobiological targets. Triton has been proposed to have been captured through a momentum-exchange reaction [1], and it is possible that a similar event could allow a giant planet to capture a formerly binary terrestrial planet or planetesimal. We therefore attempt to model the dynamical evolution of a terrestrial planet captured into orbit around a giant planet in the habitable zone of a star. We find that approximately half of loose elliptical orbits result in stable circular orbits over timescales of less than a few million years. In addition, we calculate the transit timing and duration variations for the resulting systems.

1. Motivation

EXOMOONS, the satellites of extrasolar planets, have been often featured in fiction as habitable locations. There is no deficit of known giant planets that could host a terrestrial satellite, with Exoplanet.org listing approximately 40 giant exoplanets (8%) within 20% of the equilibrium temperature of Earth. And if potentially habitable exomoons exist around transiting planets, they could be much easier to detect than solitary habitable planets. However, these planets are generally thought not to have formed in place, but rather to have migrated inward. In the process, they may have lost their original satellite system to interactions with terrestrial planets/planetesimals, only to have them replaced by new, captured satellites. Neptune likely experienced this during its migration, capturing Triton into an inclined, retrograde orbit. Since any capture process tends to produce loosely-bound initial orbits, some method must be used to measure the long-term stability (or lack thereof) for these orbits. Here we use a full tidal/solar torque model to find the survival probability for a range of physical conditions and the detectability of the resulting system.

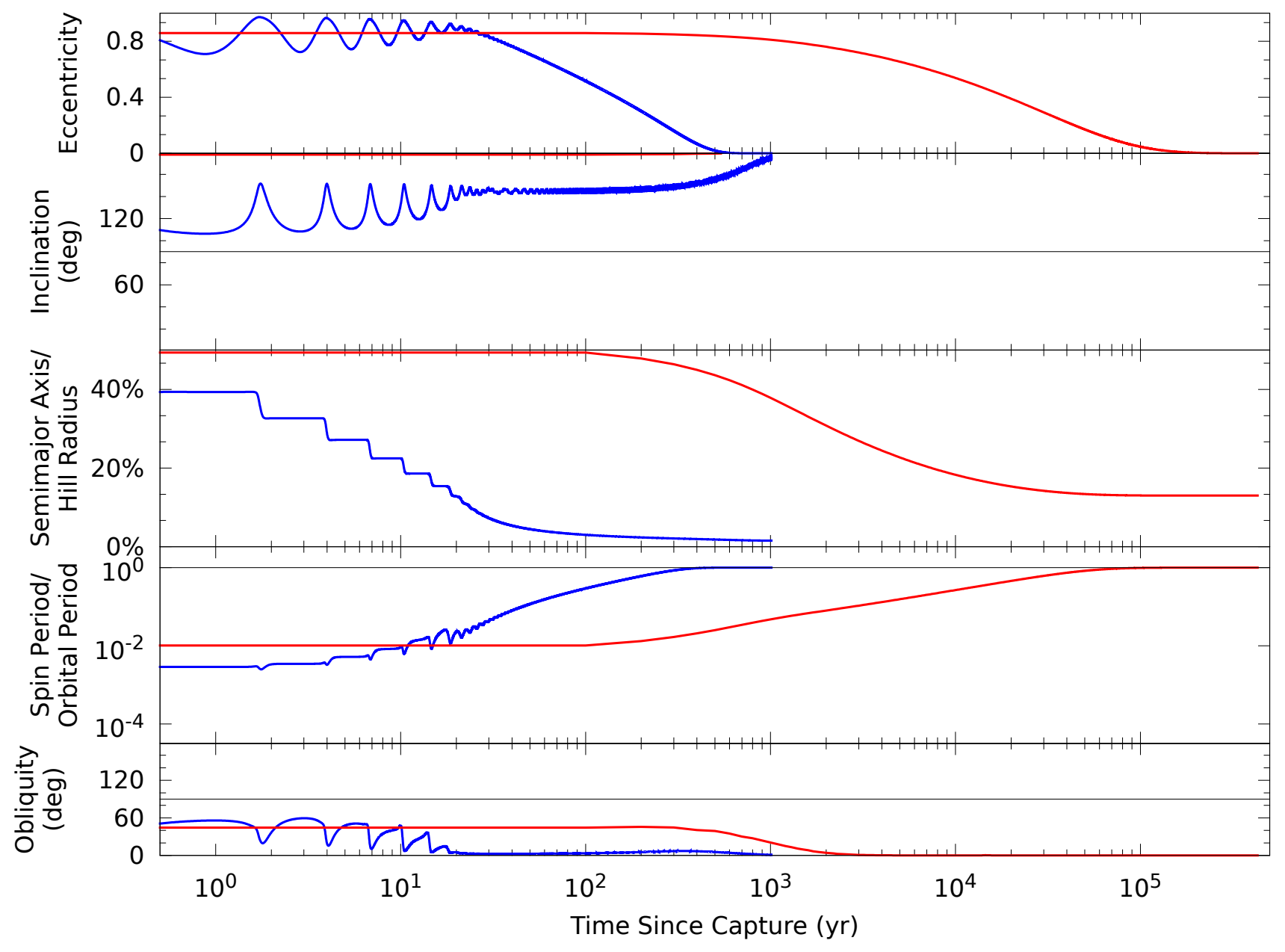

Figure 1: *Post-capture spin-orbit evolution of two exomoons; the blue line shows a Kozai-enhanced decay, while the red shows a non-Kozai decay.*

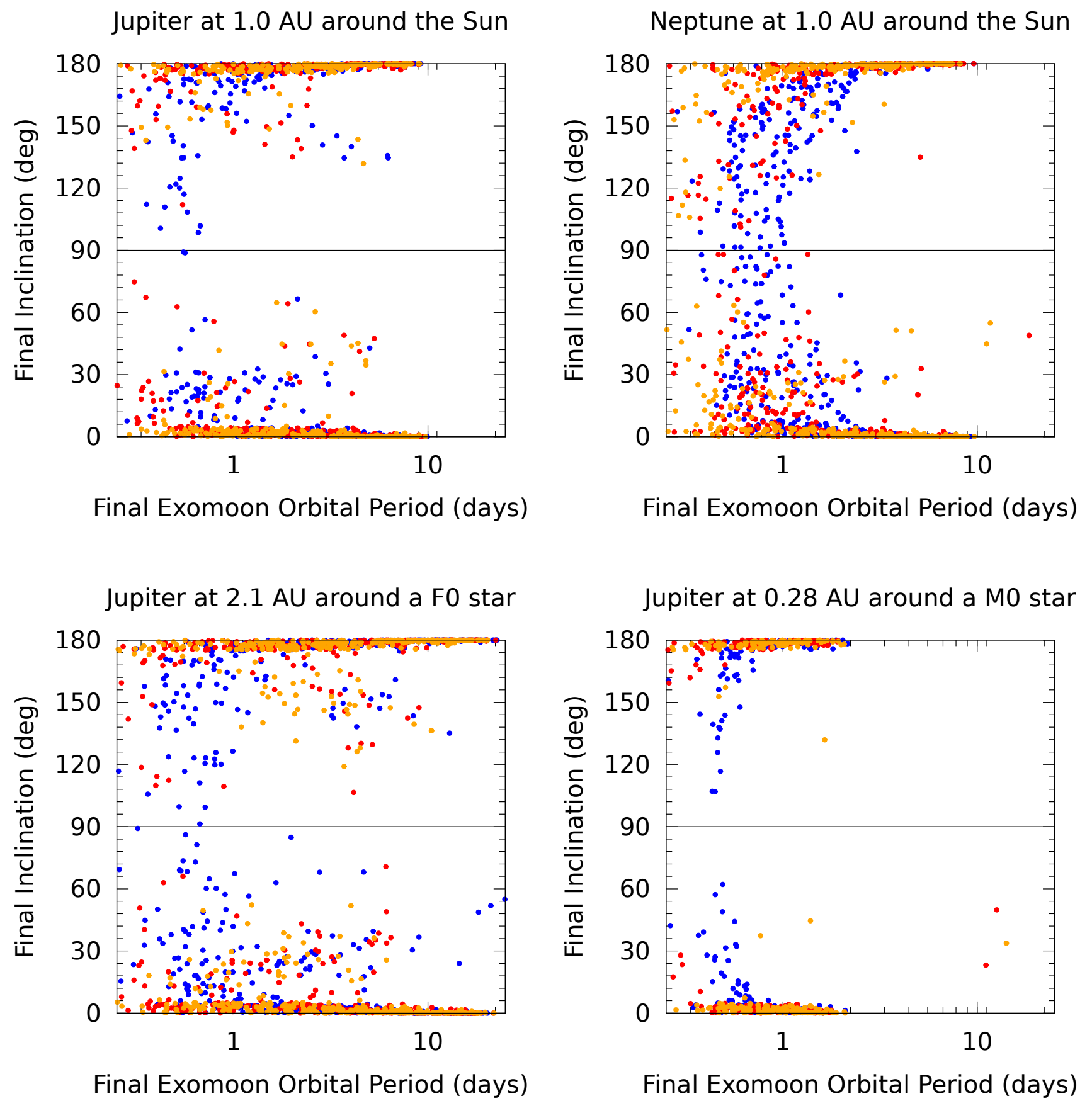

Figure 2: *Post-evolution orbital period and inclination distribution; most orbits are coplanar with the planet's orbit, with no pro/retrograde preference.*

2. KCTF Model

In order to understand how exomoon orbits may evolve since they were captured, we created a numerical Kozai Cycle and Tidal Friction (KCTF) model. Kozai Cycles in this context are the oscillations in eccentricity and inclination of the exomoon's orbit caused by stellar torques. These oscillations preserve the quantity $H_k = cos(I_{Stellar}) \times \sqrt{1-e^2}$, where $I_{Stellar}$ is the inclination of the exomoon's orbit from the stellarcentric orbit. The eccentricity of the mutual orbit in these oscillations can become very high, and since tidal friction has a much faster drop-off than inverse square, these Kozai-pumped eccentricities can cause semimajor axis decay due to tidal friction much faster than their initial state would imply. We used a model based on that of [2], but with the additions of solid-body quadrapole gravity from [4], and using a Vector-Rational Burlisch-Stoer integrator. This model directly evolves the exomoon's orbital elements and spins of the exomoon and exoplanet, while holding the stellarcentric orbit constant. We did not include any dynamical effects from objects external to the exomoon-exoplanet system other than the star itself.

3. Monte Carlo Simulations

To find in what conditions a captured exomoon may survive, we created several sets of KCTF simulations. Each set contained 1000 simulations, with common masses for all objects, and randomized initial exomoon orbits and spin states. The initial exomoon orbits all had apoapses beyond 80% of the exoplanet's Hill radius, and eccentricities greater than 0.85. Both the exomoon's initial orbital plane and spin vector were initially pointed at random directions on the sky. The exoplanets had a random obliquity < 5 deg and was at a stellarcentric distance such that the equilibrium temperature was equal to Earth. The simulations were run until they either reached an eccentricity below 10^{-5} or the periapse went below the Roche limit (impact) or the apoapse exceeded the Hill radius. Stars used were the Sun (G2), a main-sequence F0 (1.7 M_{Sun}), and a main-sequence M0 (0.47 M_{Sun}). Exoplanets used had the mass of either Jupiter or Neptune, and exomoons with the mass of Earth, Mars, and Titan (with Mars uncompressed density). We estimated the Transit Timing Variation (TTV) and Duration Variation (TDV) using the equations from [3], specifically the low-inclination versions.

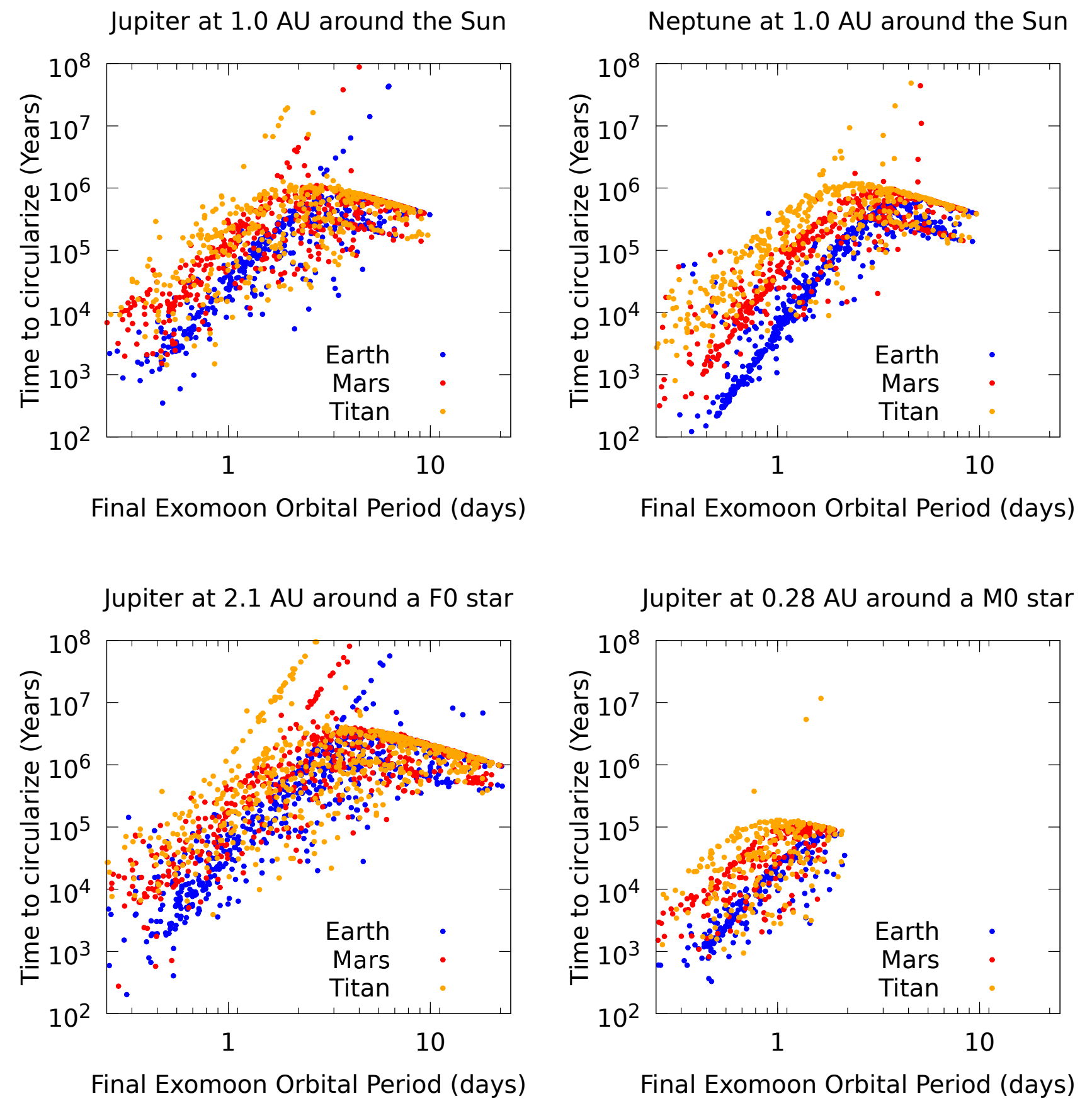

Figure 3: *Post-capture circularization timescales; note that all are below 3 million years, and are very fast for sub-solar mass stars.*

4. Results and Discussion

Several general conclusions can therefore be drawn from our simulations:

1. Loosely-captured exomoons around giant planets in habitable zones can survive to stabilize into long-lived orbits.
2. The timescale for them to stabilize is enhanced by Kozai torques, and is generally less than a few million years.
3. Most of the surviving orbits are close to the plane of the exoplanet's orbit, but show no pro-grade/retrograde preference.
4. Some of the resulting orbits should be currently detectable, with the timing variation much stronger than the duration variation.

Table 1: *Relative fraction of end states for fully evolved exomoon systems*

Star	Planet	Moon	Survived	Retrograde	Separated	Impacted
Sun	Jupiter	Earth	43%	52%	21%	35%
		Mars	44%	45%	18%	37%
		Titan	42%	47%	21%	36%
	Neptune	Earth	52%	44%	17%	30%
		Mars	44%	45%	18%	36%
		Titan	45%	47%	19%	35%
F0	Jupiter	Earth	65%	47%	3%	31%
		Mars	59%	46%	4%	35%
		Titan	61%	48%	3%	34%
	Neptune	Earth	77%	44%	4%	18%
		Mars	67%	44%	4%	28%
		Titan	61%	50%	4%	33%
M0	Jupiter	Earth	23%	50%	2%	74%
		Mars	23%	51%	3%	73%
		Titan	23%	44%	2%	74%
	Neptune	Earth	24%	50%	1%	73%
		Mars	25%	52%	1%	73%
		Titan	22%	50%	3%	74%

Table 2: *Median Exomoon orbital period, Transit Timing Varition (TTV), and Transit Duration Variation (TDV) for full-evolved exomoon systems*

Star	Planet	Moon	Period (d)	TTV (min)	TDV	edge-on (min)
Sun	Jupiter	Earth	2.17	5.44	0.114%	0.93
		Mars	2.34	0.59	0.012%	0.10
		Titan	2.52	0.12	0.002%	0.02
	Neptune	Earth	1.65	36.69	0.835%	6.41
		Mars	1.89	4.11	0.089%	0.69
		Titan	2.16	0.86	0.018%	0.14
F0	Jupiter	Earth	3.68	11.33	0.111%	1.45
		Mars	4.26	1.22	0.011%	0.15
		Titan	4.14	0.26	0.002%	0.03
	Neptune	Earth	2.38	75.70	0.860%	10.60
		Mars	3.79	8.51	0.083%	1.03
		Titan	3.50	1.78	0.018%	0.22
M0	Jupiter	Earth	0.94	1.63	0.122%	0.54
		Mars	1.00	0.18	0.013%	0.06
		Titan	1.00	0.04	0.003%	0.01
	Neptune	Earth	0.85	10.97	0.836%	3.36
		Mars	0.79	1.22	0.098%	0.39
		Titan	0.83	0.26	0.020%	0.08

5. Acknowledgments

Special thanks to Travis Barman for donating the ≈5000 CPU hours it took to complete this project.

References

[1] C. B. Agnor and D. P. Hamilton. Neptune's capture of its moon Triton in a binary-planet gravitational encounter. Nature, 441:192–194, May 2006.

[2] P. P. Eggleton and L. Kiseleva-Eggleton. Orbital Evolution in Binary and Triple Stars, with an Application to SS Lacertae. ApJ, 562:1012–1030, December 2001.

[3] D. M. Kipping. Transit timing effects due to an exomoon. MNRAS, 392:181–189, January 2009.

[4] D. A. Ragozzine. *Orbital dynamics of Kuiper Belt object satellites, a Kuiper Belt family, and extra-solar planet interiors.* PhD dissertation, California Institute of Technology, 2009.

http://www.lowell.edu/users/porter/Porter-Exomoon1.pdf

Exoplanet 2011, Exploring Strange New Worlds: From Giant Planets to Super Earths, Flagstaff, AZ May 1-6, 2011