LUNA: An algorithm for generating planet-moon transits

David Kipping[1,2]

[1] Harvard-Smithsonian Center for Astrophysics, 60, Garden St., Cambridge, MA 02138
[1] Carl Sagan Fellow

Introduction

The detection of an extrasolar moon represents a substantial challenge to modern observational astronomy, but the potential for a new understanding of planetary formation and evolution is just as great. Perhaps the most appealing reason to meet this audacious challenge is the prospect of countless habitable moons scattered throughout the cosmos.

In recent years, transit timing methods have emerged as a leading contender to detect exomoons, in particular through coupling variations in the duration and times of transit minimum (TDV and TTV) [1,2]. These dynamical techniques bear much resemblance to the radial velocity and astrometry methods of finding planets. The missing piece of the puzzle is the transit of the moon itself, which offers a third piece of information. Just like planetary transits, this extra signal is both feasible to detect and highly revealing of the exomoon's nature.

Modelling Exomoon Transits

Exomoon transit features can come into two flavours:

[1] Exomoon eclipses the host star

[2] Mutual planet-moon eclipses during the planetary eclipse

The first may be modelled in a very similar way to planetary transits, provided one has knowledge of the moon-star separation as a function of time.

The second is substantially more challenging and requires solving the area of overlap of three circles. This can be done numerically, but such an approach is inherently CPU intensive. A far more elegant and computationally expedient approach is to derive the analytic solution for all possible geometric configurations. Utilizing several solutions from Fewell (2006) [3] and several new solutions derived in this work, our new algorithm "LUNA" has knowledge of analytic solutions for all possible configurations of three interacting circles. Coupled with the small-planet approximation [4] for the moon (but not the planet), full non-linear limb darkened planet-moon light curves can be generated in essentially the same CPU time as to generate a planet-only model. Extending to four bodies (i.e. two moons) will be a substantial challenge for future work.

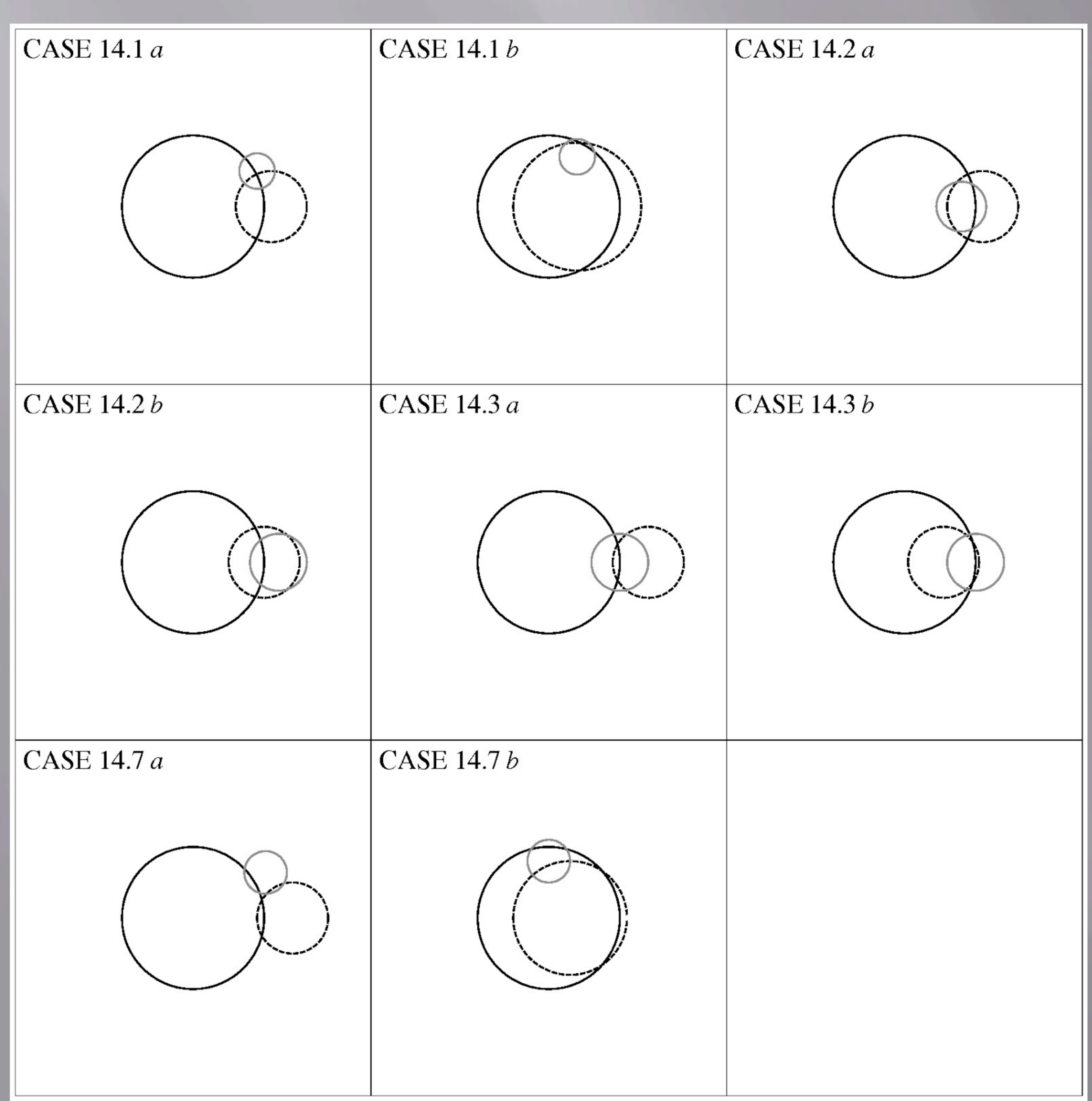

Figure 1: There exists 27 principal cases for the interaction of three circles. Case 14 possesses 8 sub-cases, shown here. Each case showed has a unique analytic solution for the area of overlap. Armed with these equations, planet-moon transits can be very rapidly generated for all conceivable configurations.

Accounting for Dynamical Variations

Aside from the complex sky-projected geometries, planet-moon system exhibit far more complex dynamical behaviour than a simple planet only case. To fully model the three-body problem requires numerical integration, which would dramatically slow down the process of fitting transit light curves. This is a critical issue given the large number of free parameters, which exhibit inevitable complex inter-parameter correlations. To expedite the fitting, LUNA employs a nested two-body model [5] for the planet-moon motion. Valid for all moons within 53% of the Hill radius, this model is purely analytic and thus very quick to compute. It is also possible to swap the module computing the motions for a more advanced model should the need arise.

Accordingly, LUNA automatically accounts for TTV, TDV-V, TDV-TIP and even ingress/egress asymmetries, for both the planet and the moon. Eccentricity, argument of periastron, orbital inclination and longitude of the ascending node for both bodies is also included allowing for a broad range of possible configurations. Example light curves are shown in Fig. 2.

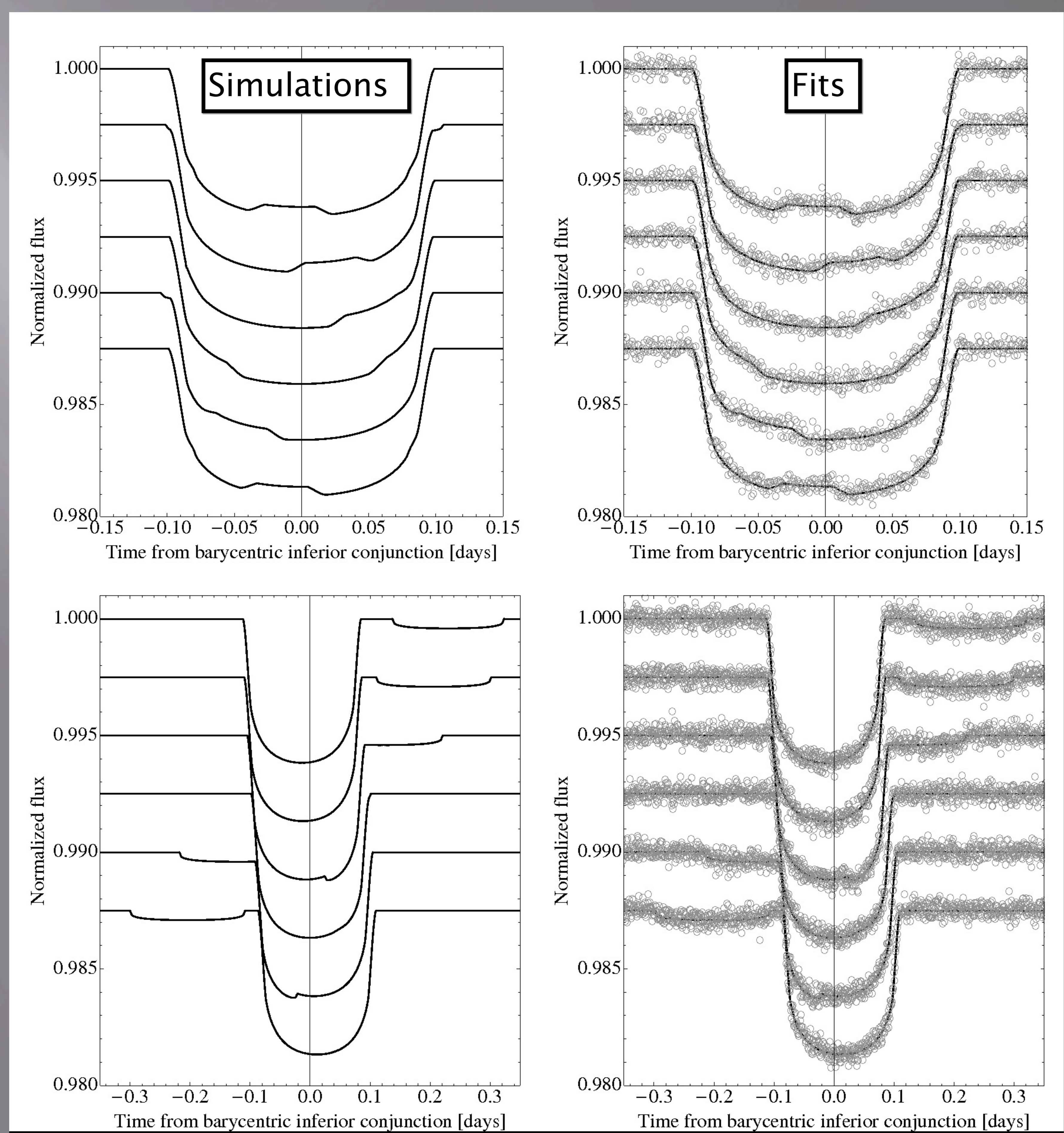

Figure 2: Top: HZ-Neptune around an M2-star (P=46d) with a $1R_{Earth}$ close moon (5% Hill radius) yielding visible mutual eclipses. Bottom: Same as above except far-out moon (90% Hill radius) showing visible TTVs. The two cases are detected to 24 and 50 sigma respectively with 1 year of Kepler SC data at 250ppm RMS.

Conclusions

LUNA is fully analytic, includes non-linear limb darkening and inherently accounts for dynamical effects such as TTV & TDV. The code is very expedient to execute and well suited for MCMC techniques [6]. Consequently, LUNA will be a highly potent weapon in exomoon detection.

Contact:dkipping@cfa.harvard.edu

Website:www.davidkipping.co.uk

References

[1] Sartoretti, P & Schneider, J. 1999, A&A, 134, 553
[3] Fewell, M. 2006, Tech. Rep. DSTO-TN-0722
[5] Kipping, D. M. 2011, MNRAS, 409, L119
[2] Kipping, D. M. 2009, MNRAS, 396, 1797
[4] Mandel, K. & Agol, E. 2002, ApJ, 580, L171
[6] Kipping, D. M. 2011, MNRAS, tmp.1132K