Assembling Kepler's tightly-packed planetary systems

Tom Hands[1] & Richard Alexander, *Theoretical Astrophysics Group*

[1] Contact: tom.hands@le.ac.uk Web: www.tomhands.com

Abstract

The Kepler mission has recently discovered a number of exoplanetary systems, such as Kepler-11 and Kepler-32, in which ensembles of several planets are found in very closely packed orbits (often within a few percent of an AU of one another). These systems present a challenge for traditional formation and migration scenarios, since these planets presumably formed larger orbital radii, before migrating inwards. In particular, it is difficult to understand how planets in such systems could have migrated across strong mean-motion resonances without becoming trapped, and remaining relatively well-spaced. It is also difficult to explain how such systems remain dynamically cold, as resonant interactions tend to excite orbital eccentricity and lead to close encounters. We present a dynamical study of the evolution these systems using an N-body approach, incorporating both smooth and stochastic migration forces and a variety of initial conditions. We highlight planetary architectures which seem particularly difficult to build, and discuss the implications of our results for the formation and evolution of such systems.

Motivation

The prototype system for this study is Kepler-11 (Lissauer et al. 2011). This system contains 6 planets, 5 of which have shorter periods than that of Mercury, and extremely low (< 0.05) eccentricities (Lissauer et al. 2013). Only two of these planets are close to a mean-motion resonance. The planets are generally within several hundredths of an AU of one another – see figure I. Similar systems include Kepler-32 (Swift et al. 2013) and KOI-500, though Kepler-32 shows two strong (1:2 and 2:3) resonances.

From a dynamical perspective it is difficult to understand how such systems might form and remain dynamically cold. Mean motion resonances act as traps, thus we would expect planets that are this closely packed that have evolved under convergent migration to have become trapped in resonance at some point in their evolution. Such close and strong interactions also force eccentricity growth, making the lack of eccentricity in Kepler-11 highly curious.

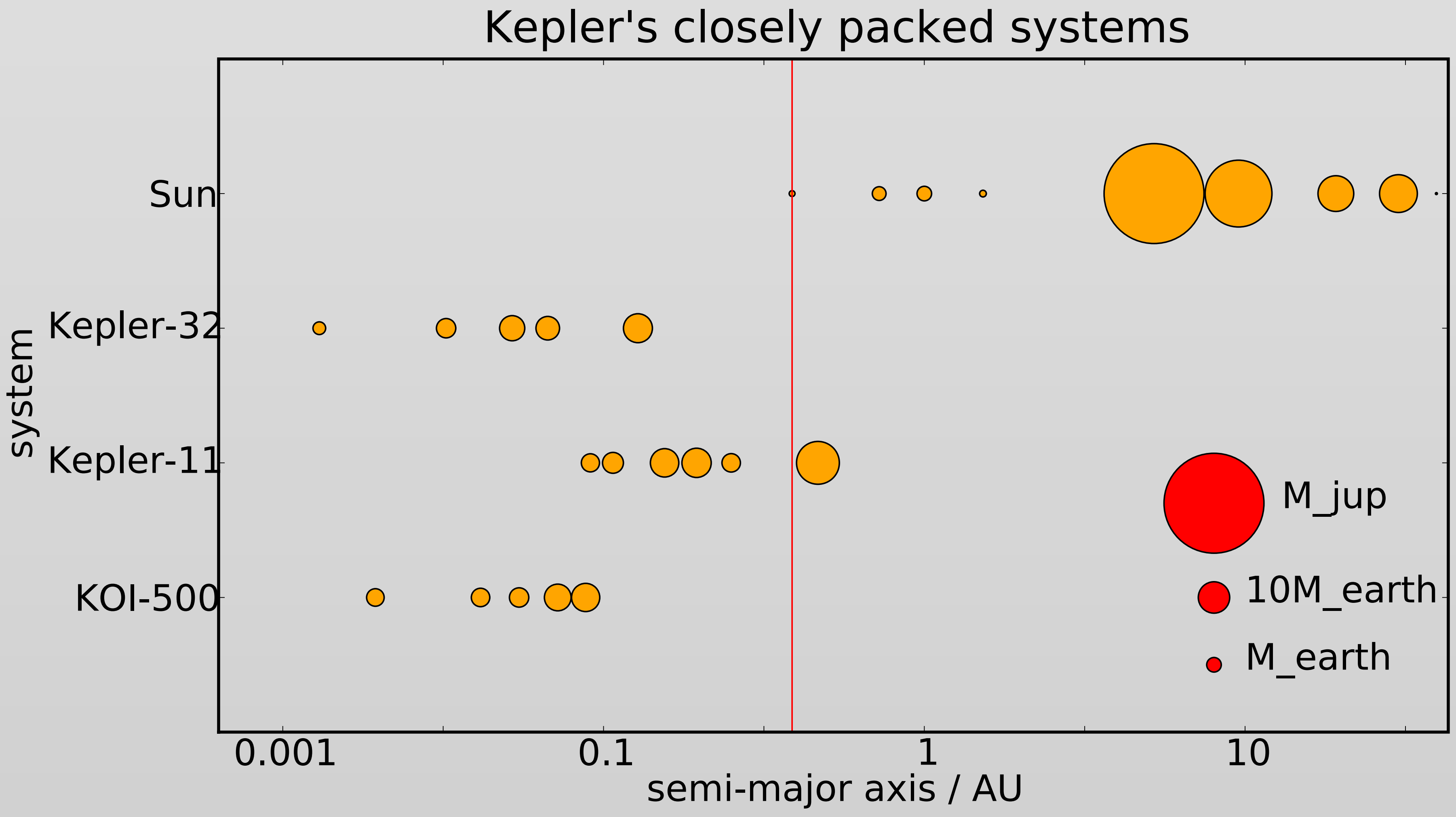

Figure I *– The tightly-packed systems in question, compared to our own solar system. The semi-major axis of Mercury is represented by the red line here. KOI-500 data from Ragozzine et al.* (2012).

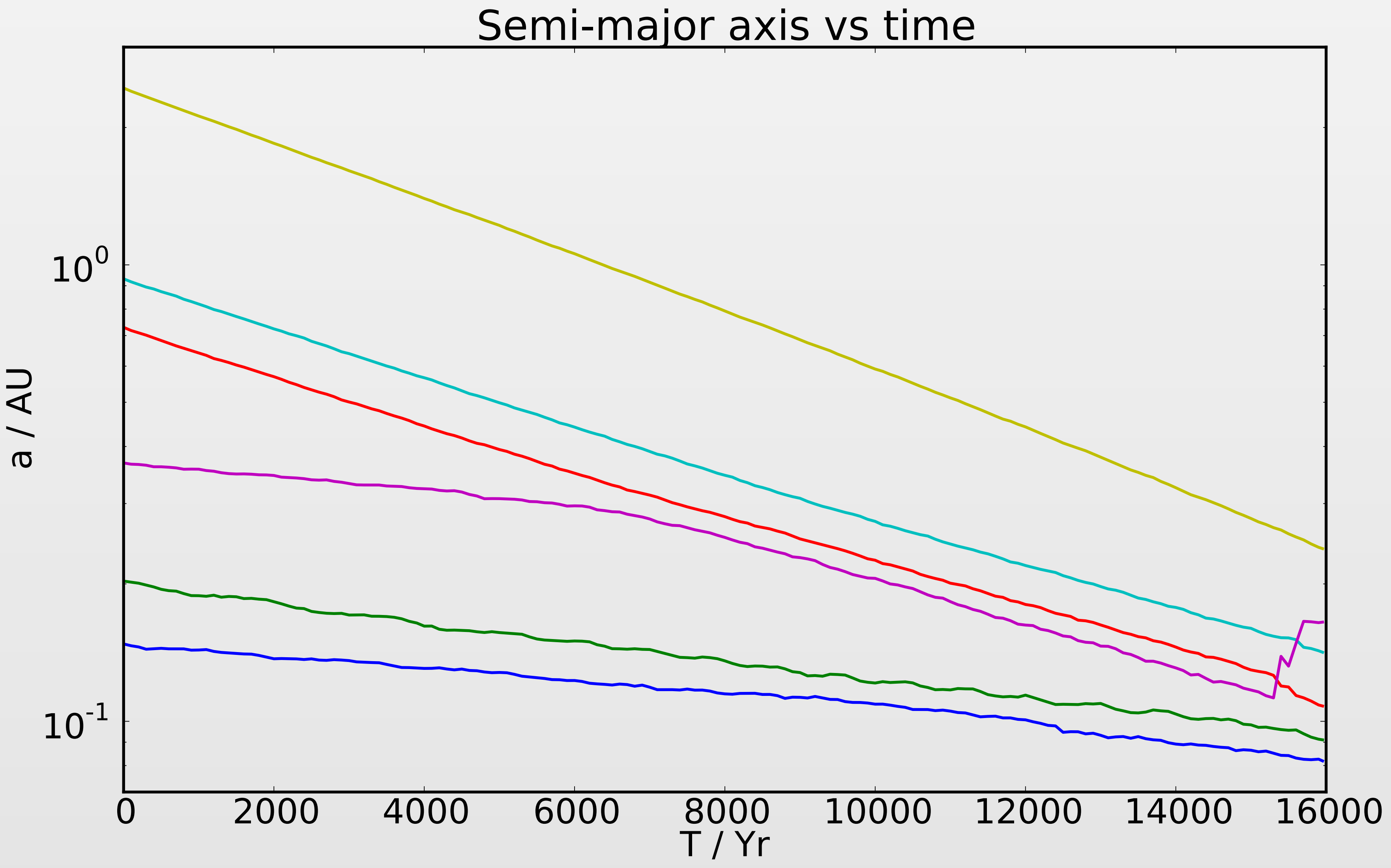

Figure II – Example output from the code, showing evolution of semi-major axes in a system analogous to Kepler-11. The purple line shows the 5th planet from the star in the observed system. Note that despite being out of position in the initial conditions and becoming trapped in a 7:6 resonance with the red planet, it is able to swap positions with two larger, faster-migrating planets.

Method

We follow the evolution of these systems using an N-body integrator. We use parameterised forces to migrate the planets and damp their eccentricities, with the time-scale of both being proportional to the inverse of the planetary mass – analogous to type 1 migration. We follow the method of Rein and Papaloizou (2009), adding a stochastic component to the forces acting on the planets. This simulates the effect of disc turbulence. The strength of both smooth and stochastic forces can be controlled as free parameters.

The purpose of this simplified, hydrodynamics-free method is to enable large numbers of models to be run by keeping computational expense to a minimum. In this way we may explore the vast parameter space of initial conditions and force magnitudes, whilst still maintaining the most important features of the actual physics.

Summary

Using this method we are able to perform efficient simulations of the early dynamical evolution of tightly-packed systems. Future, large runs will sample a vast area of parameter space. Detailed modelling of each individual system will allow us to understand the delicate balance between migration, disc turbulence and planet-planet interactions in shaping these systems.

Theoretical Astrophysics Group
Department of Physics and Astronomy
University of Leicester

Title image: Kepler-11, Tim Pyle/NASA

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