Assembling Kepler's tightly packed planetary systems

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Abstract

The Kepler mission has recently discovered a number of exoplanetary systems, such as Kepler-11, 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. Assuming that these planets underwent type-I migration, it is difficult to understand how they could have migrated across strong mean-motion resonances without becoming trapped. 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 of these systems using an N-body approach, incorporating both smooth and stochastic migration forces and a variety of initial conditions, in order to assess the feasibility of assembling such systems via traditional, disc-based migration.

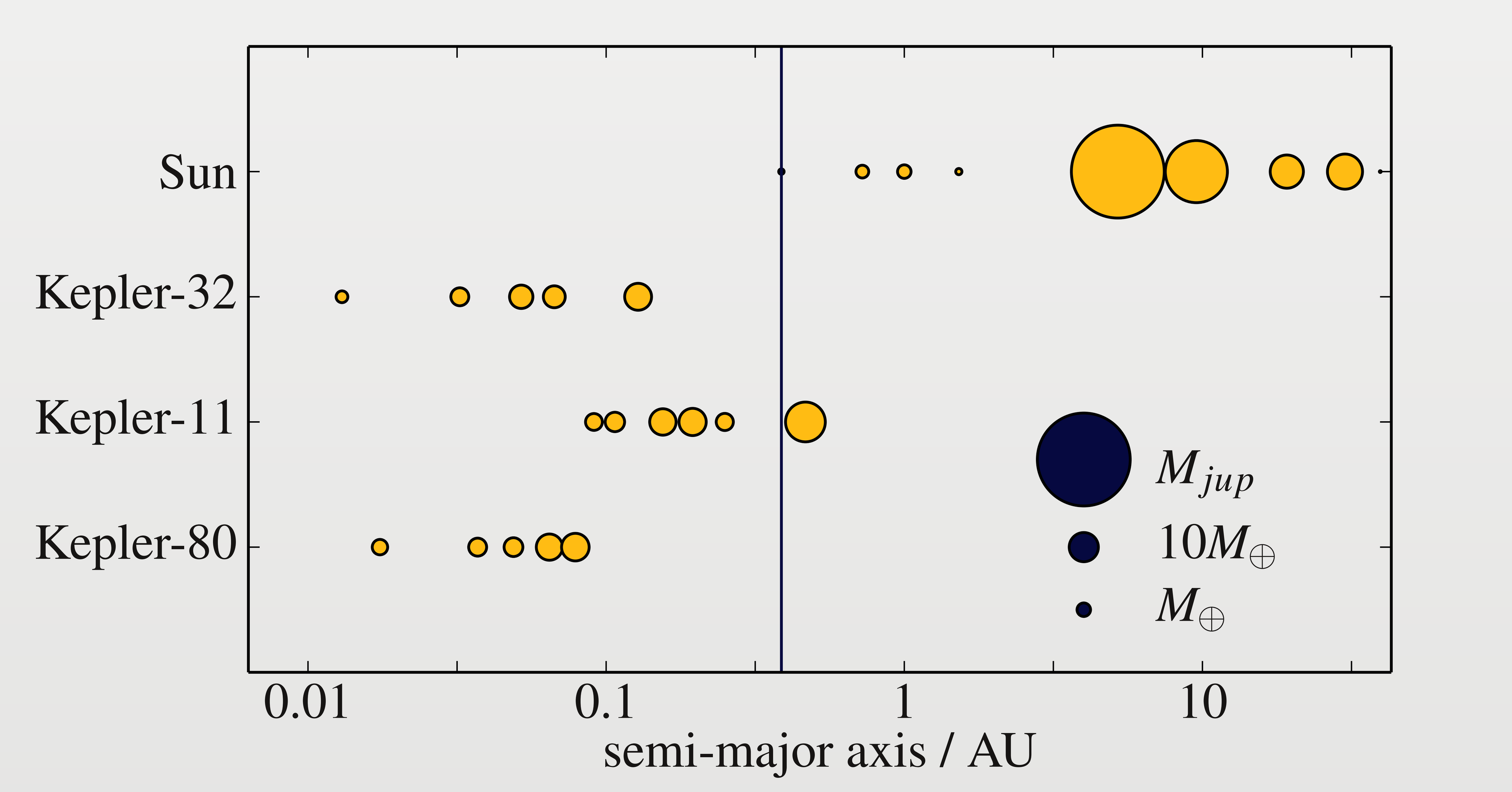

Figure 1 - Kepler's tightly packed planetary systems, plotted in comparison to our own solar system. Mercury's orbit is show by the blue line for comparison.

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 Kepler-80 (Ragozzine et al. 2012), with Kepler-32 displaying two possible strong (1:2 and 2:3) resonances.

From a theoretical perspective it is challenging to explain 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.

Method

We follow the evolution of these systems using an N-body integrator, allowing us to explore a wider parameter space than would be possible with hydrodynamical simulations. We use parametrized 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-I migration. We follow the method of Rein and Papaloizou (2009), adding a stochastic component to the forces acting on the planets to simulate the effect of disc turbulence. The strength of the forces can be controlled via free parameters, and we perform 10,000 simulations with each system in order to sample the vast 3-D parameter space. We begin each simulation with random initial orbital separations and phases, and consider a simulation successful if the innermost planet reaches its observed orbital radius with the other planets in order and with no collisions or ejections.

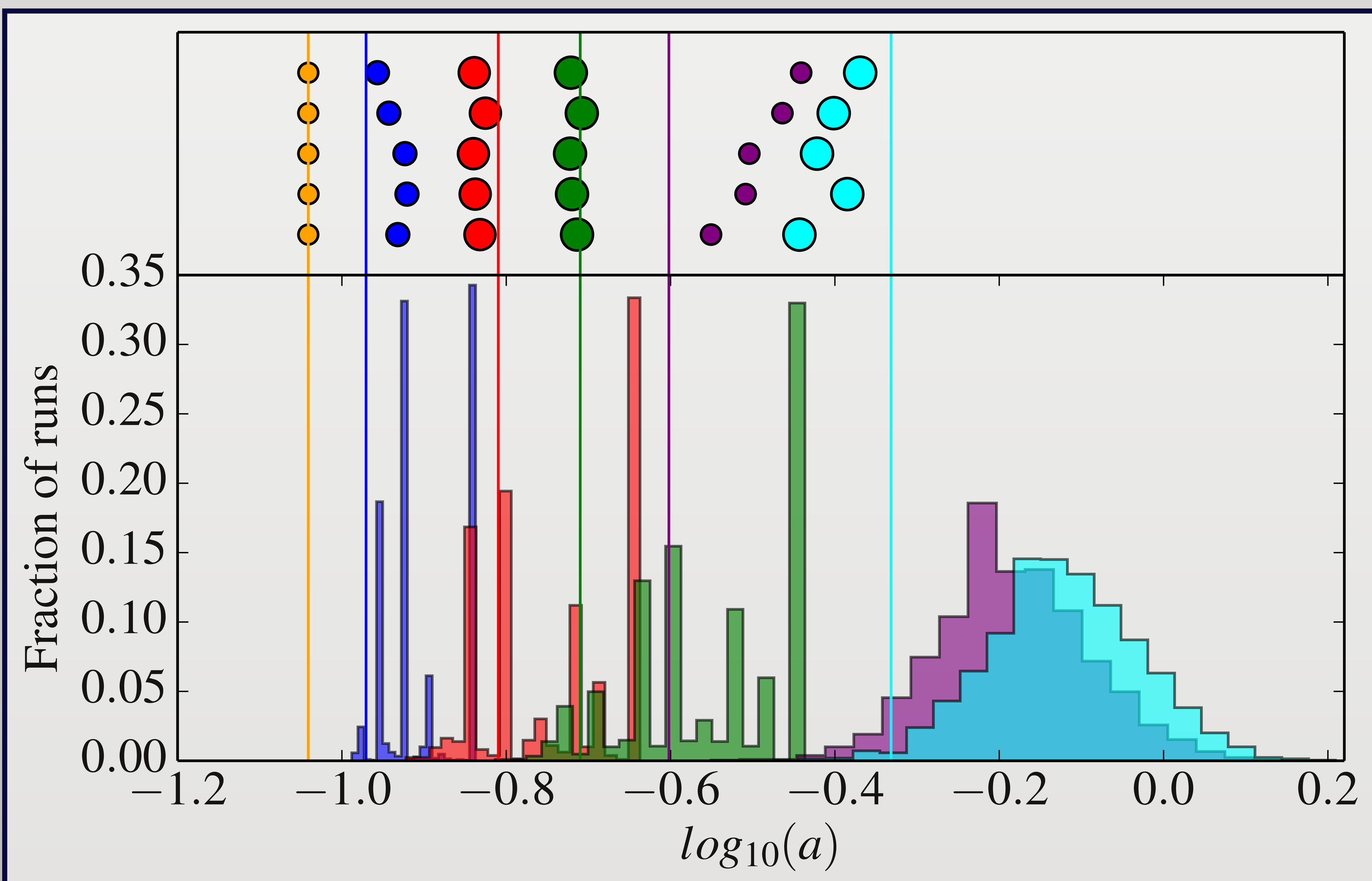

Figure 2 - Histogram showing distribution of each planet in Kepler-11 at the end of all successful simulations. Each colour represents one individual planet. Solid lines show the actual observed positions of each planet, whilst the points plotted above show planetary positions in some representative "best-fit" models, fitted by semi-major axis.

Results & Conclusion

Figure 2 shows that systems analagous to Kepler-11 are easily reproduced using our model. We find a preference for less turbulence and short eccentricity damping time-scales, with no particular preference in migration time-scale across the range of 10^4-10^6 yr that we explore. The paucity of mean-motion resonances is more diffcult to reproduce, however.

We find that the architectures of tightly-packed planetary systems can be reproduced via traditional, disc-driven migration, though further work is required to understand the formation of mean-motion resonances in such systems.

References

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