Migration of multiple planets in evolving protoplanetary discs

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Abstract

The discovery of a large number of multi-planet systems by the Kepler mission has given astronomers a glimpse of the unique properties of such systems. For the first time we have access to statistical samples of multi-planet systems, and these observations present a number of challenges to our understanding of how these systems form and evolve. We present a novel approach to modelling statistical ensembles of multi-planet systems, which couples a 1-D viscous accretion disc solver to an N-body integrator. This approach correctly captures both planet-disc interactions and the gravitational interactions between planets, and represents a computationally efficient means of following planet migration and dynamical evolution over Myr time-scales in large numbers (thousands) of multi-planet systems. Our results will offer a unique statistical insight into the formation and evolution of multiple planets, and provide a valuable complement to new and future data from Kepler and other exoplanet surveys.

Introduction & Motivation

The catalogue of detected multi-planet systems displays many interesting characteristics. For instance, many systems, including our own, contain planets and bodies in resonance, and the period ratios between neighbouring Kepler Objects of Interest show strong features near to resonances (Fabrycky et al. 2012). Notably, these features are slightly offset from the exact value of each resonance. The method described here allows us to follow large numbers of multi-planet systems undergoing type II migration, using a range of initial conditions over a large parameter space. It is computationally inexpensive compared to 2-D and 3-D simulations, allowing statistically significant numbers of models to be run. Ultimately, it should be capable of reproducing and providing insight into some of these statistical features – including the observed resonant features.

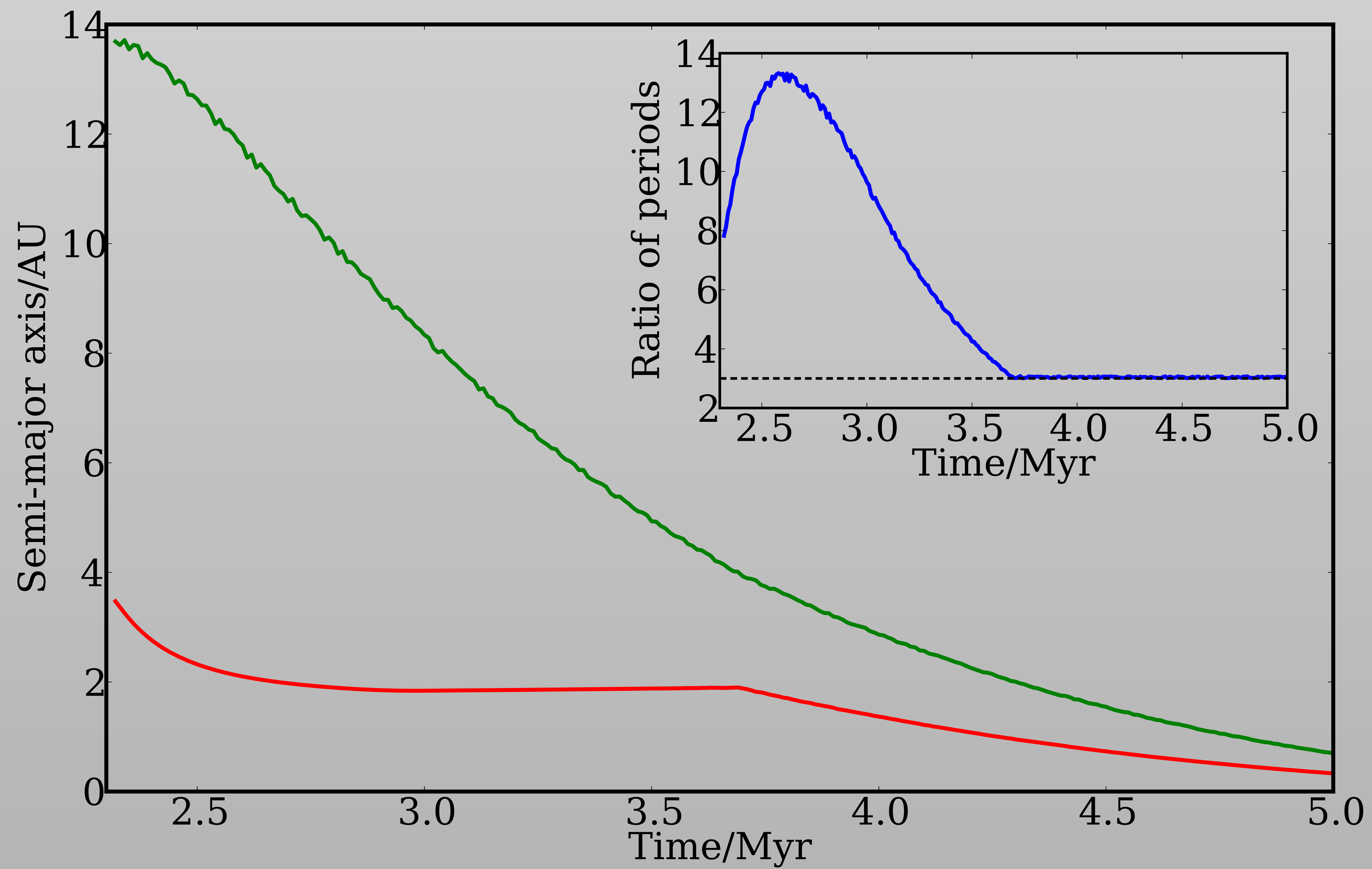

Figure I – Migration of a pair of planets in an evolving protoplanetary disc, showing their semi-major axes and period ratio (inset) as a function of time. Here, the planets lock into the 3:1 mean motion resonance after ~3.7 Myr and from then on their migration is coupled.

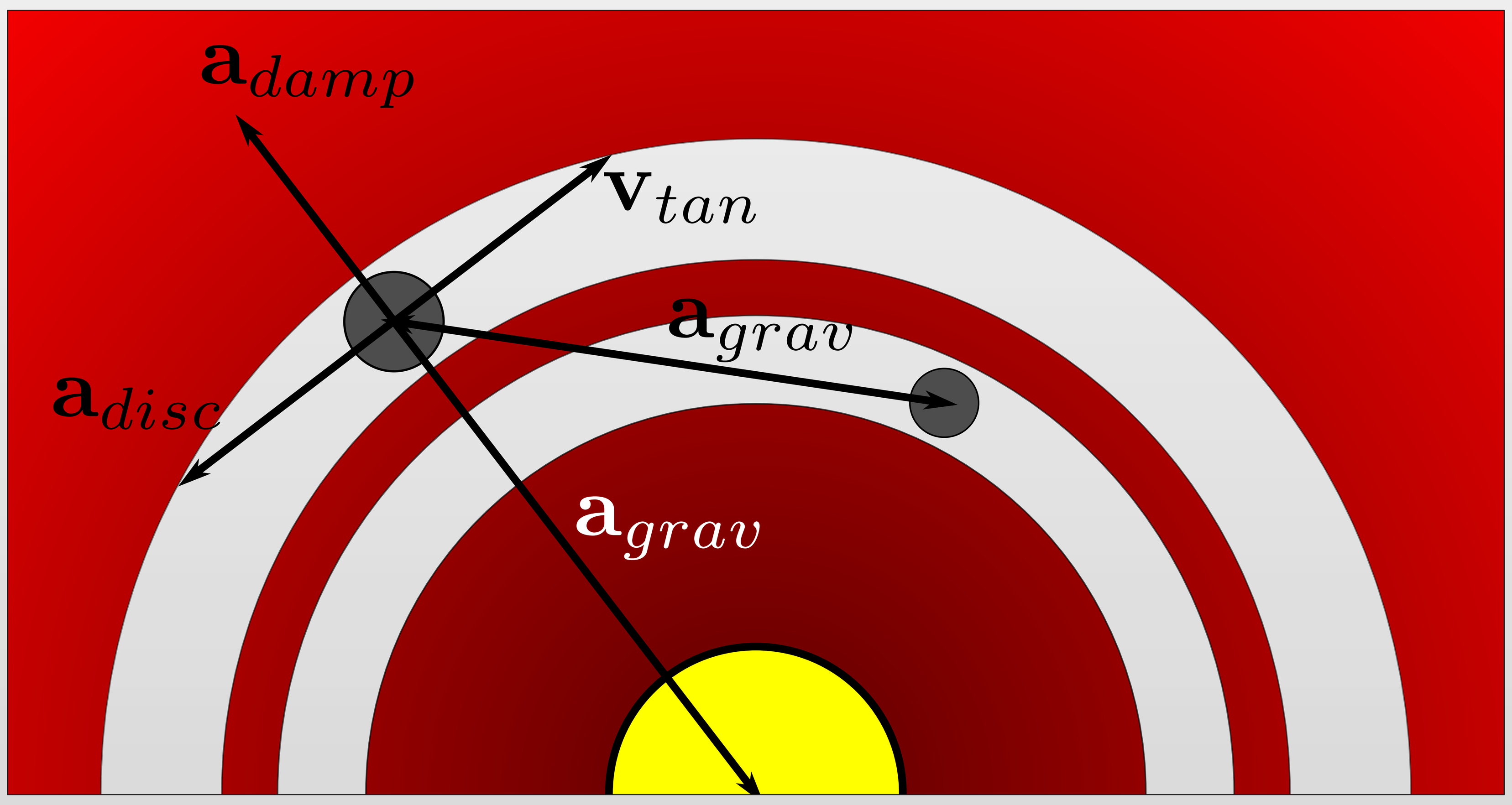

Figure II – Schematic diagram of code operation showing planets embedded in gaps in disc and forces acting on the planets and star.

Method

The 1-D viscous accretion disc solver is used to both evolve the surface density profile of the protoplanetary disc and calculate the torques on the planet via the impulse approximation as a result of the disc (eg. Lin and Papaloizou 1986). The disc model includes a parameterisation for photoevaporation of the disc and for accretion onto the planet and across the gap opened by the planet (Alexander and Armitage 2009, Alexander and Pascucci 2012).

Coupled to this is a direct-summation, adaptive time-step *N*-body integrator. It integrates the gravitational interactions between the planets and their star, as well as applying the torques from the disc code to the planets. Figure I shows example output from this code, whilst Figure II shows a schematic of its operation.

By randomly sampling disc and planet initial conditions, we can create statistical ensembles of models. Our results can then be tested against data from Kepler and other exoplanet catalogues, in order to better understand what shapes the evolution of multi-planet systems.

Summary

Our method provides a promising way to obtain a statistical insight into the evolution on Myr time-scales of multi-planet systems. Combined with the ever-growing catalogue of multi-planet exoplanetary systems, we hope to reproduce observable statistics, as well as make new predictions for future observations.

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