Abstract

This thesis aims to comprehensively characterise a few particular compact multi-planet systems discovered by the Kepler NASA mission. We focus our analysis on configurations for which their proximity to the mean motion resonances (MMRs) can act as a protection mechanism from close encounters and consequent self-disruption. It is known that many Kepler systems, though may be extremely compact, remain stable for an indefinitely long time but yet not strictly resonant. We study how far these apparently non-resonant systems are from exact MMRs with the aid of dynamical N-body numerical simulations. In general, the selected Kepler stars are too faint and neither the radial velocity (RV) method nor other observational techniques can be applied. Moreover, some important physical parameters such as the planet masses cannot be derived directly from the transit observations alone. To determine the masses as well as to characterise the dynamical architectures, we analyse the transit time variations (TTVs) which are the only indirect, dynamical information that is available in order to "weight" the planets, and thus determine their densities and internal structures.

To this goal, a new method is presented in this thesis, called here the dynamical modelling or dynamical photometry method. Though similar approaches are already well established in earlier studies performed with the radial velocity method, they are rarely encountered in the literature for systems detected with the photometry technique, because in this case, their application is difficult and complex. The dynamical transit method allows overcoming in part these difficulties and offers several advantages with respect to previous methods. It makes it possible to characterise in detail close-in multi-planet systems through a self-consistent process including and involving preliminary reduction of the observations (determining the TTVs), and advanced statistical optimisation algorithms to find planetary masses and orbital elements. Following this strategy it is has been possible to reveal the structure of the phase space thanks to CPU efficient dynamical indicators and with direct numerical simulations of their long-term dynamical stability.

As a first step, the most up-to-date raw Kepler light-curves are re-analysed and the TTVs, encoding the dynamical interactions between the planets, as well as their physical properties such as the radii and the inclinations, are derived.

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As a second step, we study in detail the dynamical properties of selected configurations for such systems as well as the neighbourhood of the best-fitting solutions obtained by reconstructing the TTVs signals. In some cases, as for the Kepler-30 system, the resonant nature may be not clear nor apparent by looking at the variations of the critical angles. In such cases, we need to efficiently scan the phase space around a given configuration of interest.

Moreover, to derive the phase space structure is important to show whether a planetary system is locked or not inside a MMR, how far it is from a particular exact resonance of non-zero width and the quasi-global structure of the resonance itself. To efficiently detect the resonant structures in Kepler systems, characterised by stable or unstable orbits in the phase space, we developed a dedicated fast indicator named Reversibility Error Method (REM). This approach is aimed to be CPU efficient, in particular, for a class of systems containing relatively low-mass super-Earth planets with relatively weak mutual interactions. Unlike the case of RV-detected systems with massive Jovian planets, for the KEPLER systems a large fraction of stable configurations are present in the proximity of best-fitting models. Since such systems are usually low-eccentric, therefore the MMRs separatrices are narrow. Long numerical integrations of the N-body equations of motion are required to detect them. We found that REM based on symplectic second-order leapfrog integrator is very easy to implement, and is a CPU-efficient algorithm equivalent to other fast indicators based on the Lyapunov exponent and complex variational equations.

The dynamical characterisation and detection of resonant systems are a crucial step to resolve some open problems and unclear questions on the formation of these close-in systems, such as the apparent paucity of planet pairs in exact MMRs and the influence of planet-disk interactions for the observed configurations. In such sense, our work establishes and narrows some of the boundary conditions necessary to understand the planet formation history and migration evolution during the late stages of planet formation.

In this thesis, the line of reasoning discussed above is applied to a few interesting and yet not well explored compact, multi-planet systems in the Kepler sample. It is shown that each of these systems must be considered individually. We investigate Kepler-30, and KOI-1599 systems as well as we contribute to the in-depth studies of Kepler-60 and Kepler-29 planetary systems. The thesis presents the details of the used approach as well as the results of its application to the analysed systems.

21.07.2018r.   Federico Panichi