Planetary systems in dense stellar environments

M B N Kouwenhoven\textsuperscript{1}, Francesco Flammini Dotti\textsuperscript{1,2}, Qi Shu\textsuperscript{3}, Xiuming Xu\textsuperscript{1,2}, Kai Wu\textsuperscript{1,2}, Xiaoying Pang\textsuperscript{1} and Wei Hao\textsuperscript{4}

\textsuperscript{1}Department of Mathematical Sciences, Xi'an Jiaotong-Liverpool University, 111 Ren’ai Rd., Suzhou Dushu Lake Science and Education Innovation District, Suzhou Industrial Park, Suzhou 215123, P.R. China
\textsuperscript{2}Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, UK
\textsuperscript{3}Kavli Institute for Astronomy and Astrophysics at Peking University, 5 Yiheyuan Rd., Haidian District, 100871, Beijing, China
\textsuperscript{4}Max Planck Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany

Abstract. The recent advances in observational and computational techniques allow studying the formation and dynamical evolution of planetary systems at an unprecedented level. The formation and evolution of isolated planetary systems are challenging in itself and it is more complicated by the dense environments in which stars and planets are typically born. Here, we present an overview of the internal and external processes that govern the dynamical evolution of planetary systems, and we provide a brief overview of a selection of the computational tools that are presently available to carry out realistic simulations of planetary systems in dense stellar environments.

1. Introduction
Our Milky Way galaxy contains hundreds of billions of stars, many of which resemble our own Sun. The majority of these stars are thought to host planetary systems [1]. A number of observational techniques have been used to discover and characterize exoplanetary systems. The most common among these are transit surveys, radial velocity studies, transit timing variation techniques, imaging, and microlensing. The notable progress was made since the launch of the Kepler space observatory [2]. Although observational selection effects have hampered the detection of Earth-like planets, a hand-full of candidates has been identified. The combined set of known exoplanets nowadays comprises 4112 candidate/confirmed exoplanets detected in orbit around a total of 3059 stars (http://exoplanet.eu). These known exoplanet systems display an enormous diversity in orbital configurations and physical properties [3]. It suggests that the planet formation process, as well as the influence of the environment, plays an essential role in shaping the planetary systems that we observe today.

The dominant mode of planet formation is described by the core-accretion theory [4], while giant planets and brown dwarfs may also be formed in massive circumstellar disks through the process of disk fragmentation [5,6]. Much is still unclear about the formation and evolution of planetary systems. Our own solar system plays a vital role in increasing our understanding of these processes, as we could study the members of our solar system in great detail. On the other hand, the evolutionary history and physical properties of our solar system cannot provide sufficient detail to explain the diversity of the known exoplanet systems. Observational studied of nearby stars, and dedicated observational missions can provide important statistical properties, such as the frequency of planet-hosting stars, and the
correlations between orbital and physical parameters. A thorough theoretical analysis, including the use of advanced computer simulations, can be used to explain these observations and test theories of planet formation and evolution by making predictions.

2. Dynamics of isolated planetary systems

The dynamical evolution of planetary systems is dominated by the gravitational potential of the host star (or host stars), and to a lesser extent by the gravitational influence between the planets themselves [7]. When studying planetary dynamics, the gravitational influence of moons and planetary debris, such as asteroids and comets, can usually be ignored. General relativity normally plays a small role in the neighbourhood of the host star and is most pronounced in the orbital precession of the inner planets. Bodies are often approximated as point masses, but for simulations involving close encounters or short-period orbits, it is necessary to include the non-spherical geometry of the gravitational potential that results from stellar and planetary spins. Gravitational interactions can lead to physical collisions between bodies (a process which is thought to have led to the formation of the Earth’s Moon [8]), or in disruption of a planet or moon when it enters a the Roche radius of a larger body. Scattering events also result in the ejection of bodies from the planetary system, a process that is thought to be responsible for large numbers of free-floating planets and interstellar comets in the Galactic disk [9]. The stability of planetary satellites is often characterized by the Hill radius, and the stability of multi-planet systems can be estimated using the distance between two planets at their closest approach, measured in the number of mutual Hill radii [10]. Mean-motion resonances can contribute to stability (e.g., the 3:2 resonance between the orbital periods of Neptune and Pluto) and to instability. Resonances involving orbital elements other than the period can affect planetary systems over longer periods of time. A well-known example is the Lidov-Kozai resonance [11], which induces large variations in eccentricity and inclination on the Kozai timescale.

In addition to deformations resulting from a non-zero spin, celestial bodies also experience deformations resulting from non-uniform external gravitational fields, i.e., tidal forces. These effects are particularly important for bodies in short-period orbits, and for bodies that experience a close encounter [12]. These differential forces can result in both tidal synchronization (a tendency towards spin-orbit coupling and over longer periods, tidal locking) and tidal circularization (a decrease in the orbital eccentricity). The magnitude of these tidal effects depend on the differential of the gravitational force, as well as on the mass-density profile and chemical profile of the planet. The effect of the tidal force on a planet’s orbital and spin properties may change over time, for example, when a short-period gas giant experiences inflation or atmospheric loss due to its proximity to the host star.

The combined effect of gravitational and tidal interactions within a planetary system has implications for the habitability of exoplanets. In order to determine the frequency of habitable planets in the solar neighbourhood, therefore it is necessary to consider the internal architecture of planetary systems, and the consequences for terrestrial planets in the habitable zone. In the case of planet Earth, for example, interactions with the Sun, the Moon and the other planets result in changes in the Earth’s orbit around the Sun, and in periodic changes of its spin rate and spin vector. These periodic changes result in variations in the Earth’s climate that are often referred to as Milankovitch cycles. This relates planetary dynamics to the geological and biological history of planet Earth through climate change [13].

3. Environmental influence on planetary systems dynamics

Observational studies have shown that most stars, if not all-stars, form in star-forming regions [14,15]. Most of these star-forming regions typically survive for several million years, while some evolve gradually from clumpy, substructured aggregates into gravitationally bound open star clusters [16,17,18] that gradually dissolve over hundreds of millions of years. Isotopic studies of meteorites suggest that the protoplanetary disk of our own solar system was polluted by a nearby supernova explosion [19], suggested that even our Sun was formed in a stellar grouping [20,21]. The stellar population in the Galactic disc is thus thought to be populated with stars that spent at least part of their
lifespan in a relatively crowded environment. It is therefore likely that many of the known exoplanet systems have experienced perturbations from neighbouring stars during the time that they were embedded in a stellar grouping. Whether such perturbations significantly altered the architecture of the known exoplanet systems depends on the strength and frequency of the encounters with neighbouring stars, and on the planetary architecture itself.

The effect of a stellar perturbation on a planetary system depends on the force differential at the distance of the closest approach, the duration of the encounter, and the relative orbital trajectory of the encountering star [22]. Outer components of a planetary system, such as Oort clouds, suffer substantially more from cluster encounters inner planetary system. Our own inner solar system, for example, is thought to regularly suffer from comet showers during close encounter events, particularly during passage through the Milky Way’s spiral arms [23]. In addition to close approaches with neighbouring stars, planetary systems may also be perturbed by the tidal field of the galaxy or the star cluster in which the system resides [24]. This perturbation is often small, and only affects the outermost regions of the planetary system, notably through precession.

In all cases of external perturbation, bodies on wider orbits are most easily perturbed, while inner bodies are relatively safe from direct perturbations. However, the inner planetary system is often still affected by external perturbations, through planet-planet scattering, and through physical collisions with highly perturbed comets. Gas giants may form a protective barrier against these perturbations. In our solar system, for example, Jupiter is much more massive than the other planets. Therefore, most perturbations of the outer planets will result in minor changes in Jupiters orbit, and hence not affect the orbital configuration of the terrestrial planets [25,26].

Dynamical interaction between a planetary system and neighbouring bodies can also lead to the gravitational capture of stars [27] or free-floating planets [28,29], which can remain in orbit around a star for extended periods of time. The recent detection of interstellar comets in our solar system [30,31] suggests that interactions with interstellar debris are common. When observational limitations and the expected number of free-floating comets in the Galactic field are taken into account, it can be shown that the number of physical collisions between extrasolar comets and planet Earth is significant [32], which opens up a (remote) possibility for interstellar panspermia.

4. Numerical approaches

Computer simulations can be carried out for a variety of purposes. The goal of these simulations is usually to either investigate an unexplained observed phenomenon or to make predictions that can be used to test theory [33]. Theoretical and computational models are always approximations of reality and are continuously enhanced to make these approximations better.

4.1. Computational considerations

All computational models make trade-offs between the accuracy of modelling the real Universe and the feasibility of carrying out the simulations. On one hand, the models should reflect the processes in the Universe as accurate as possible. On the other hand, researchers are always to some degree limited by the speed and precision of the hardware, the complexity of software, incomplete observational data, limited knowledge about some of the physical processes involved, and the computational time. The total time used to carry out a computer simulation is dominated by the number of calculations that need to be made, which is determined by the precision with which the calculation is carried out, by the total integration time, by the efficiency of the software, and in the case of N-body simulations, by the number of particles involved.

The numerical precision of the calculations in some cases is the crucial factor that determines the accuracy of the outcome. Computers quantize all numbers with finite precision, usually as single-precision (32 bits) or double precision (64 bits). Therefore, the result of a computer calculation in most cases is slightly different from the analytical result, and this is particularly important when two greatly different numbers are added or subtracted. In the case of a long series of mutually-dependent outcomes (i.e., in N-body simulations), the outcomes can thus differ substantially from what would be expected.
when the calculations are carried out analytically. These problems can be partially overcome by minimizing the number of calculations that need to be carried out, by carefully programming an optimal arithmetical order, and by implementing subroutines in the code that use alternative algorithms to solve particular problems (e.g., Kustaanheimo-Stiefel regularization [34] in the NBODY6 family).

Up to roughly a decade ago, the use of computer simulations was greatly limited by speed. Most of these limitations have now been overcome through the development of advanced hardware. Jumps in progress were initially made with special-purpose hardware, such as the GRAPE [35], which are optimized for calculating gravitational forces. In recent years, Graphical Processing Units (GPUs) have become commonplace [36], and parallel processing interfaces can be used to combine the power of multiple computers [37]. The limiting factor in computational astrophysics is now the development of efficient software.

4.2. Modelling isolated planetary systems
Two types of integration techniques are often used for modelling different configurations of planetary systems dynamics. The family of N-body integrators (such as Bullirsch-Stoer, Runge-Kutta, and RADAU) are suitable for systems with strong gravitational interactions, while symplectic integrators are most suitable for studying the long-term evolution of relatively stable systems. Many of the available codes include hybrid integration, i.e., automatic switching between N-body integrators and symplectic integrators.

A multitude of codes is available for integrating planetary systems. MERCURY6 [38] is a robust and easy-to-use integrator, with a range of available integration techniques and an option to include massless particles (i.e., particles that experience the gravitational potential but do not exert a gravitational influence on any of the other bodies). The Python-based REBOUND code [39] provides the option to include additional physical processes and allows integration into Python routines developed by the user. Orbit averaging techniques may be employed to integrate few-body systems over extended periods of time, with the advantage that these can be optimized by including sophisticated algorithms for tidal evolution, planetary inflation, and planetary spins [40].

4.3. Modelling planetary systems in realistic stellar environments
A number of software packages are available for integrating stellar systems; the most well-known star cluster simulation packages among these are those in the NBODY family, including NBODY6 [41], the paralyzed version NBODY6++ [42], and the NBODY6++GPU [43,44] code, which supports the use of Graphical Processing Units to carry out the force calculations. Visualization tools, such as GalevNB [45] are available for direct comparison with observations.

A numerical study of the evolution of planetary systems in dense stellar environments is challenging. Although software packages exist to accurately model the evolution of planetary systems and of star clusters, combining planetary dynamics with stellar dynamics is complicated by the impact of numerical precision. Due to the vast differences in mass scales, time scales, and size scales for both populations, computational round-off errors that result from integrating the stellar population are typically substantially larger than the accuracy required for any decent planetary system integration. An easy way to overcome this challenge is modelling single-planet systems. In this case, the star-planet systems can be treated as perturbed Keplerian systems, and a regularization treatment can be applied [46]. To some extent, this treatment can be extended to study the evolution of stars with two planetary companions in a dense stellar environment [47]. Monte Carlo scattering simulations allow the user to adopt a code designed for planetary system dynamics and add the encountering bodies using analytic prescriptions for the mass, the orbital properties, and the time of arrival [48]. Finally, it is to some degree possible to directly model the evolution of multi-planet systems in star clusters [49], but the accuracy of these simulations is usually limited by the maximum integration time.

The AMUSE framework [50,51] allows the combination of different simulation codes. A good example is the LonelyPlanets code [52], that combines NBODY6 with REBOUND, and is able to
simulate the evolution of multi-planet systems in star clusters. This code makes use of the approximation that planets do not affect the dynamics of the stellar population, which allows partial separation of the integration techniques. In this approach, the stellar population is first evolved in NBODY6++GPU and stored in the HDF5 format. This flexible storage scheme allows reconstruction of the star cluster’s gravitational potential at arbitrary times and locations [53]. This time-dependent potential is subsequently added as an external perturbation in the REBOUND planetary system code, and the planetary system is thus evolved under the influence of a stellar environment. The applications of the LonelyPlanet simulation package are broad, and provide accurate estimates of planetary systems evolution under the assumption that the stellar kinematics are unaffected by the presence of planets.

5. Discussion and future prospects
In recent decades, progress in computational astrophysics, combined with the wealth of data obtained from Earth- and space-based observatories, has substantially increased our understanding of both planet formation and planetary system evolution. Software packages now include a comprehensive suite of physical processes and are able to simulate the evolution of planetary systems over long periods of time, including the evolution of these systems in the dense stellar environments in which they were formed. Progress in our understanding of the formation and evolution is still hampered by observational limitations on one hand, while requirements on computer simulations become ever more demanding. The enormous diversity in orbital architectures and physical properties of observed exoplanet systems is puzzling and may be directly related to the perturbations of protostellar disks and planetary systems due to the neighbouring stars. Decades ago, astrophysicists developed theories to explain the properties of the only planetary system that was known to mankind at that time. Nowadays, our understanding is enriched through the recent discovery of thousands of new worlds in the Universe, and theories of how these distant planets formed and evolved are continuously being improved.

Acknowledgment
M.B.N.K. acknowledges support from the National Natural Science Foundation of China (grant 11573004). This research was supported by the Research Development Fund (grants RDF-16-01-16, RDF-17-01-46, and RDF-18-02-32) and by the Postgraduate Research Scholarship Fund (PGRS-190610) of Xi'an Jiaotong-Liverpool University (XJTLU).

References

[1] Howard A W 2013 Science 340 572
[2] Borucki W J, Koch D, Basri G et al. 2010 Science 327 977
[3] Cai M X, Portegies Zwart S F, Kouwenhoven M B N et al. 2019 MNRAS 489 4311
[4] Pollack J B, Hubickyj O, Bodenheimer P et al. 1996 Icarus 124 62
[5] Li Y, Kouwenhoven M B N, Stamatellos D et al. 2015 ApJ 805 116
[6] Li Y, Kouwenhoven M B N, Stamatellos D et al. 2016 ApJ 831 166
[7] Sun L, Ioannidis P, Gu S, et al. 2019 A&A 624 A15
[8] Canup R M and Asphaug E 2001 Nature 412 708
[9] Hurley J R and Shara M M 2002 ApJ 565 1251
[10] Zhou J-L, Lin D N C, and Sun Y S 2007 ApJ 666 423
[11] Kozai Y 1962 Aj 67 591
[12] Eggleton P 2011 Evolutionary Processes in Binary and Multiple Stars (Cambridge: Cambridge University Press UK)
[13] Berger A 1988 Reviews of Geophysics 26 624
[14] Lada C J and Lada E A 2003 ARAA 41 57
[15] Bik A, Puga E, Waters L B F M et al. 2010 ApJ 713 883
[16] Allison R J, Goodwin S P, Parker R J et al. 2009 ApJ Letters 700 L99
[17] Priyatikanto R, Kouwenhoven M B N, Arifyanto M I et al. 2016 MNRAS 457 1339
[18] Darma R, Arifyanto M I, and Kouwenhoven M B N 2019 J. Phys. Conf. Ser 1231 012028
[19] Hester J J, Desch S J, Healy K R et al. 2004 Science 304 1116
[20] Adams F C 2010 ARAA 48 47
[21] Cai M X, Portegies Zwart S F, and van Elteren A 2018 MNRAS 474 5114
[22] Spurzem R, Giersz M, Heggie D C et al. 2009 ApJ 697 458
[23] Davis M, Hut P, and Muller R A 1984 Nature 308 715
[24] Vokrouhlický D, Nesvorný D, and Dones L 2019 AJ 157 181
[25] Flammini Dotti F, Cai M X, Spurzem R et al. 2018 Preprint arXiv:1811.12660
[26] Flammini Dotti F, Kouwenhoven M B N, Cai M X et al. 2019 MNRAS 489 2280
[27] Kouwenhoven M B N, Goodwin S P, Parker R J et al. 2010 MNRAS 404 1835
[28] Perets H B, and Kouwenhoven M B N 2012 ApJ 750 83
[29] Wang L, Kouwenhoven M B N, Zheng X et al. 2015 MNRAS 449 3543
[30] Sekanina Z 2019 Preprint arXiv:1901.08704
[31] Guzik P, Drahus M, Rusek K et al. 2019 Preprint arXiv:1909.05851
[32] Lingam M, and Loeb A 2018 AJ 156 193
[33] Hut P 2010 New Astron. 54 163
[34] Kustaanheimo P and Steifel E 1965 J. Math. Bd. 218 27
[35] Makino J, Taiji M, Ebisuzaki T et al. 1997 ApJ 480 432
[36] Huang S-Y, Spurzem R, and Berczik P 2016 RAA 16 11
[37] Berczik P, Nitadori K, Zhong S et al. 2011 Int. Conf. on High-Performance Computing 8
[38] Chambers J E 1999 MNRAS 304 793
[39] Rein H and Liu S-F 2012 A&A 537 A128
[40] Mardling R A and Lin D N C 2002 ApJ 573 829
[41] Aarseth S J 2010 Gravitational N-Body Simulations (Cambridge: Cambridge University Press, UK)
[42] Spurzem R 1999 J. Comput. Appl. Math. 109 407
[43] Wang L, Spurzem R, Aarseth S et al. 2015 MNRAS 450 4070
[44] Wang L, Spurzem R, Aarseth S et al. 2016 MNRAS 458 1450
[45] Pang X-Y, Olczak C, Guo D-F et al. 2016 RAA 16 37
[46] Zheng X, Kouwenhoven M B N, and Wang L 2015 MNRAS 453 2759
[47] Shara M M, Hurley J R, and Mardling R A 2016 ApJ 816 59
[48] Hao W, Kouwenhoven M B N, and Spurzem R 2013, MNRAS 433 867
[49] Malmberg D, de Angeli F, Davies M B et al. 2007 MNRAS 378 1207
[50] Pelupessy F I, van Elteren A, de Vries N et al. 2013 A&A 557 A84
[51] Portegies Zwart S F, and McMillan S 2018 Astrophysical Recipes; The art of AMUSE, IOP ebooks, Bristol, UK
[52] Cai M X, Kouwenhoven M B N, Portegies Zwart S F et al. 2017 MNRAS 470 4337
[53] Cai M X, Meiron Y, Kouwenhoven M B N et al. 2015 ApJ Supplements 219 31