WS20/21: MVSem Dynamics of galaxies, star clusters and planetary systems (A. Just/R.Spurzem)

Supervisor: R. Spurzem; Subject Classification:

Galaxies/Galactic Nuclei: S8 (N-body sim.); S9 (theory)

Star Clusters: S1 (N-body method), S6, S7 (grav. waves, dynamics, stellar evolution), S10 (modelling), S11 (few body, stellar evolution)

Planetary Systems: S2, S3 (theory/modelling); S41-43 (theory/ compare observations), S5 (observation)

S1

MSTAR – a fast parallelised algorithmically regularised integrator with minimum spanning tree coordinates

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ABSTRACT
We present the novel algorithmically regularised integration method MSTAR for high accuracy ($|\Delta E/E| \gtrsim 10^{-14}$) integrations of N-body systems using minimum spanning tree coordinates. The two-fold parallelisation of the $\mathcal{O}(N_{\mathrm{part}}^2)$ force loops and the substep divisions of the extrapolation method allows for a parallel scaling up to $N_{\mathrm{CPU}} = 0.2 \times N_{\mathrm{part}}$. The efficient parallel scaling of MSTAR makes the accurate integration of much larger particle numbers possible compared to the traditional algorithmic regularisation chain (AR-CHAIN) methods, e.g. $N_{\mathrm{part}} = 5000$ particles on 400 CPUs for 1 Gyr in a few weeks of wall-clock time. We present applications of MSTAR on few particle systems, studying the Kozai mechanism and N-body systems like star clusters with up to $N_{\mathrm{part}} = 10^4$ particles. Combined with a tree or a fast multipole based integrator the high performance of MSTAR removes a major computational bottleneck in simulations with regularised subsystems. It will enable the next generation galactic-scale simulations with up to 10^9 stellar particles (e.g. $m_\star = 100 M_\odot$ for a $M_\star = 10^{11} M_\odot$ galaxy) including accurate collisional dynamics in the vicinity of nuclear supermassive black holes.

Key words: gravitation – methods: numerical – quasars: supermassive black holes – galaxies: star clusters: general

S2

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Dynamics of Planetary Systems Within Star Clusters: Aspects of the Solar System's Early Evolution

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ABSTRACT

Most planetary systems – including our own – are born within stellar clusters, where interactions with neighboring stars can help shape the system architecture. This paper develops an orbit-averaged formalism to characterize the cluster's mean-field effects as well as the physics of long-period stellar encounters. Our secular approach allows for an analytic description of the dynamical consequences of the cluster environment on its constituent planetary systems. We analyze special cases of the resulting Hamiltonian, corresponding to eccentricity evolution driven by planar encounters, as well as hyperbolic perturbations upon dissipative disks. We subsequently apply our results to the early evolution of our solar system, where the cluster's collective potential perturbs the solar system's plane, and stellar encounters act to increase the velocity dispersion of the Kuiper belt. Our results are two-fold: first, we find that cluster effects can alter the mean plane of the solar system by $\lesssim 1$ deg, and are thus insufficient to explain the $\psi \approx 6$ deg obliquity of the sun. Second, we delineate the extent to which stellar flybys excite the orbital dispersion of the cold classical Kuiper belt, and show that while stellar flybys may grow the cold belt's inclination by the observed amount, the resulting distribution is incompatible with the data. Correspondingly, our calculations place an upper limit on the product of the stellar number density and residence time of the sun in its birth cluster, $\eta\,\tau \lesssim 2 \times 10^4\,\mathrm{Myr/pc^3}$.

S3

Effect of pebble flux-regulated planetesimal formation on giant planet formation

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ABSTRACT

Context. The formation of gas giant planets by the accretion of 100 km diameter planetesimals is often thought to be inefficient. A diameter of this size is typical for planetesimals and results from self-gravity. Many models therefore use small kilometer-sized planetesimals, or invoke the accretion of pebbles. Furthermore, models based on planetesimal accretion often use the ad hoc assumption of planetesimals that are distributed radially in a minimum-mass solar-nebula way.
Aims. We use a dynamical model for planetesimal formation to investigate the effect of various initial radial density distributions on the resulting planet population. In doing so, we highlight the directive role of the early stages of dust evolution into pebbles and planetesimals in the circumstellar disk on the subsequent planet formation.
Methods. We implemented a two-population model for solid evolution and a pebble flux-regulated model for planetesimal formation in our global model for planet population synthesis. This framework was used to study the global effect of planetesimal formation on planet formation. As reference, we compared our dynamically formed planetesimal surface densities with ad hoc set distributions of different radial density slopes of planetesimals.
Results. Even though required, it is not the total planetesimal disk mass alone, but the planetesimal surface density slope and subsequently the formation mechanism of planetesimals that enables planetary growth through planetesimal accretion. Highly condensed regions of only 100 km sized planetesimals in the inner regions of circumstellar disks can lead to gas giant growth.
Conclusions. Pebble flux-regulated planetesimal formation strongly boosts planet formation even when the planetesimals to be accreted are 100 km in size because it is a highly effective mechanism for creating a steep planetesimal density profile. We find that this leads to the formation of giant planets inside 1 au already by pure 100 km planetesimal accretion. Eventually, adding pebble accretion regulated by pebble flux and planetesimal-based embryo formation as well will further complement this picture.

Key words. protoplanetary disks – planets and satellites: formation

S4-1

The New Generation Planetary Population Synthesis (NGPPS)

I. Bern global model of planet formation and evolution, model tests, and emerging planetary systems

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ABSTRACT

Context. The explosion of observational data on exoplanets gives many constraints on theoretical models of planet formation and evolution. Observational data probe very large areas of the parameter space and many different planet properties.
Aims. Comparing theoretical models with observations allows one to make key step forward towards an understanding of planetary systems. It however requires a model able to (i) predict all the necessary observable quantities (not only masses and orbits, but also radii, luminosities, magnitudes, or evaporation rates) and (ii) address the large range in relevant planetary masses (from Mars mass to super-Jupiters) and distances (from stellar-grazing to wide orbits).
Methods. We have developed a combined global planetary formation and evolution model, the Generation III *Bern* model. This model solves as directly as possible the underlying differential equations for the structure and evolution of the gas disc, the dynamical state of the planetesimals, the internal structure of the planets yielding their gas accretion rate and internal structure, the accretion rate of planetesimals, disc-driven orbital migration, and the gravitational interaction of concurrently forming planets via a full N-body calculation. Importantly, the model now also follows the long-term evolution of the planets on Gigayear timescales after formation including the effects of cooling and contraction, atmospheric escape, bloating, and stellar tides.
Results. To test the model, we compared it with classical scenarios of Solar System formation. For the terrestrial planets, we find that we obtain a giant impact phase provided enough embryos (~ 100) are initially emplaced in the disc. For the giant planets, we find that Jupiter-mass planets must accrete their core shortly before the dispersal of the gas disc to prevent strong inward migration that would bring them to the inner edge of the disc.
Conclusions. The Generation III *Bern* model provides one of the most comprehensive global models of planetary system formation and evolution developed so far, linking self-consistently a multitude of crucial physical processes. The model can form planetary systems with a wide range of properties. We find that giant-planet bearing systems are more diverse than the ones with only terrestrial planets. In a series of papers, the model will be used to perform extensive planetary population syntheses, putting the current theoretical understanding of planet formation and evolution to the observational test.

Key words. Planets and satellites: formation — Planets and satellites: interiors — Planet-disk interactions — Protoplanetary disks — Methods: numerical

S4-2

II. Planetary population of solar-like stars and overview of statistical results★

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ABSTRACT

Context. Planetary formation and evolution is a combination of multiple processes that are interlinked. These processes are not known in detail and many uncertainties remain. Constraining the formation and evolution mechanisms observationally requires statistical comparison to a large diversity of planetary systems.

Aims. We want to understand the global observable consequences of different physical processes (accretion, migration, and interactions) and initial properties (such as disc masses and metallicities) on the demographics of the planetary population. We also want to study the convergence of our scheme with respect to one initial condition, the initial number of planetary embryo in each disc.

Methods. We select distributions of initial conditions that are representative of known protoplanetary discs. Then, we use the Generation III Bern model to perform planetary population synthesis. We synthesise five populations with each a different initial number of Moon-mass embryos per disc: 1, 10, 20, 50, and 100. The last is our nominal planetary population consisting of 1000 stars (systems) that we use to provide an extensive statistical analysis of the planetary systems around 1 $M_{\odot}$ stars.

Results. The properties of giant planets do not change much as long as there are at least 10 embryos in each system. Increasing that value results in a diminution of the importance of planetary migration. For inner terrestrial planets (< 1 au), only the 100-embryos population is able to attain the giant-impact stage. In that population, each planetary system contains in the mean 8 planets more massive than 1 $M_{\oplus}$ on average. The fraction of systems with giants planets at all orbital distances is 18 %, but only 1.6 % are at >10 au. Systems with giants contain on average 1.6 such planets. Inside of 1 au, the planet type with the highest occurrence rate and multiplicity are super-Earths (2.4 and 3.7), followed by terrestrial planets (1.6 and 2.8). They are followed by Neptunian planets, but with an already clearly reduced occurrence rate and multiplicity (0.4 and 1.4). The planetary mass function varies as M^{-2} between 5 and 50 $M_{\oplus}$. Both at lower and higher masses, it follows approximately M^{-1}. The frequency of terrestrial and super-Earth planets peaks at a stellar [Fe/H] of -0.2 and 0.0, respectively, being limited at lower [Fe/H] by a lack of building blocks, and by (for them) detrimental growth of more massive, dynamically active planets at higher [Fe/H]. The frequency of more massive planet types (Neptunian, giants) increases monotonically with [Fe/H]. Low-mass planets in the habitable zone are found around 44 % of the stars with a multiplicity of 1.3. The mean metallicitiy of stars with habitable planets is -0.11.

Conclusions. We present one of the most comprehensive simulations of planetary system formation and evolution to date. For observations, the syntheses provides a large data set to search for comparison synthetic planetary systems that show how these systems have come into existence. The systems, including their full formation and evolution tracks are available online. For theory, they provide the framework to observationally test the global statistical consequences of theoretical models for specific physical processes. This is a important ingredient towards the development of a standard model of planetary formation and evolution.

Key words. Planets and satellites: formation — Planet-disk interactions — Protoplanetary disks — Methods: numerical

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S4-3

The New Generation Planetary Population Synthesis (NGPPS)

III. Warm super-Earths and cold Jupiters: A weak occurrence correlation, but with a strong architecture-composition link

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ABSTRACT

Context. Recent observational findings have suggested a positive correlation between the occurrence rates of inner super-Earths and outer giant planets. These results raise the question of whether this trend can be reproduced and explained by planet formation theory.
Aims. Here, we investigate the properties of inner super-Earths and outer giant planets that form according to a core accretion scenario. We study the mutual relations between these planet species in synthetic planetary systems and compare them to the observed exoplanet population.
Methods. We invoked the Generation 3 Bern model of planet formation and evolution to simulate 1000 multi-planet systems. We then confronted these synthetic systems with the observed sample, taking into account the detection bias that distorts the observed demographics.
Results. The formation of warm super-Earths and cold Jupiters in the same system is enhanced compared to the individual appearances, although it is weaker than what has been proposed through observations. We attribute the discrepancy to warm and dynamically active giant planets that frequently disrupt the inner systems, particularly in high-metallicity environments. In general, a joint occurrence of the two planet types requires intermediate solid reservoirs in the originating protoplanetary disk. Furthermore, we find differences in the volatile content of planets in different system architectures and predict that high-density super-Earths are more likely to host an outer giant. This correlation can be tested observationally.

Key words. Planets and satellites: formation – Planets and satellites: dynamical evolution and stability – Planets and satellites: composition – Planet-disk interactions – Methods: numerical – Methods: statistical

S5

Title: A giant exoplanet orbiting a very-low-mass star challenges planet formation models

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Abstract

Statistical analyses from exoplanet surveys around low-mass stars indicate that super-Earth and Neptune-mass planets are more frequent than gas giants around such stars, in agreement with core accretion theory of planet formation. Using precise radial velocities derived from visual and near-infrared spectra, we report the discovery of a giant planet with a minimum mass of 0.46 Jupiter masses in an eccentric 204-day orbit around the very low-mass star GJ 3512. Dynamical models show that the high eccentricity of the orbit is most likely explained from planet-planet interactions. The reported planetary system challenges current formation theories and puts stringent constraints on the accretion and migration rates of planet formation and evolution

models, indicating that disc instability may be more efficient in forming planets than previously thought.

One Sentence Summary

A Jupiter-mass planet found orbiting the low-mass star GJ 3512 favours a scenario of formation by disk instability.

S6

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ON THE ORIGIN OF GW190521-LIKE EVENTS FROM REPEATED BLACK HOLE MERGERS IN STAR CLUSTERS

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ABSTRACT

LIGO and Virgo have reported the detection of GW190521, from the merger of a binary black hole (BBH) with a total mass around $150\,M_\odot$. While current stellar models limit the mass of any black hole (BH) remnant to about $40-50\,M_\odot$, more massive BHs can be produced dynamically through repeated mergers in the core of a dense star cluster. The process is limited by the recoil kick (due to anisotropic emission of gravitational radiation) imparted to merger remnants, which can escape the parent cluster, thereby terminating growth. We study the role of the host cluster metallicity and escape speed in the buildup of massive BHs through repeated mergers. Almost independent of host metallicity, we find that a BBH of about $150\,M_\odot$ could be formed dynamically in any star cluster with escape speed $\gtrsim 200\,\mathrm{km\,s^{-1}}$, as found in galactic nuclear star clusters as well as the most massive globular clusters and super star clusters. Using an inspiral-only waveform, we compute the detection probability for different primary masses ($\geq 60\,M_\odot$) as a function of secondary mass and find that the detection probability increases with secondary mass and decreases for larger primary mass and redshift. Future additional detections of massive BBH mergers will be of fundamental importance for understanding the growth of massive BHs through dynamics and the formation of intermediate-mass BHs.

Keywords: galaxies: kinematics and dynamics – stars: black holes – stars: kinematics and dynamics – Galaxy: kinematics and dynamics – Galaxy: centre

S7

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Properties and astrophysical implications of the $150\,M_\odot$ binary black hole merger GW190521

LIGO Scientific Collaboration and Virgo Collaboration

ABSTRACT

The gravitational-wave signal GW190521 is consistent with a binary black hole merger source at redshift 0.8 with unusually high component masses, $85^{+21}_{-14}\,M_\odot$ and $66^{+17}_{-18}\,M_\odot$, compared to previously reported events, and shows mild evidence for spin-induced orbital precession. The primary falls in the mass gap predicted by (pulsational) pair-instability supernova theory, in the approximate range $65-120\,M_\odot$. The probability that at least one of the black holes in GW190521 is in that range is 99.0%. The final mass of the merger ($142^{+28}_{-16}\,M_\odot$) classifies it as an intermediate-mass black hole. Under the assumption of a quasi-circular binary black hole coalescence, we detail the physical properties of GW190521's source binary and its post-merger remnant, including component masses and spin vectors. Three different waveform models, as well as direct comparison to numerical solutions of general relativity, yield consistent estimates of these properties. Tests of strong-field general relativity targeting the merger-ringdown stages of the coalescence indicate consistency of the observed signal with theoretical predictions. We estimate the merger rate of similar systems to be $0.13^{+0.30}_{-0.11}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. We discuss the astrophysical implications of GW190521 for stellar collapse, and for the possible formation of black holes in the pair-instability mass gap through various channels: via (multiple) stellar coalescences, or via hierarchical mergers of lower-mass black holes in star clusters or in active galactic nuclei. We find it to be unlikely that GW190521 is a strongly lensed signal of a lower-mass black hole binary merger. We also discuss more exotic possible sources for GW190521, including a highly eccentric black hole binary, or a primordial black hole binary.

Keywords: Gravitational waves – Black holes – Intermediate-mass black holes – Massive stars – Supernovae

S8

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The Fates of Merging Supermassive Black Holes and a Proposal for a New Class of X-Ray Sources

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ABSTRACT

We perform N-body simulations on some of the most massive galaxies extracted from a cosmological simulation of hierarchical structure formation with total masses in the range $10^{12}M_\odot < M_{tot} < 3\times10^{13}M_\odot$ from $4 \geqslant z \geqslant 0$. After galactic mergers, we track the dynamical evolution of the infalling black holes (BHs) around their host's central BHs. From 11 different simulations, we find that, of the 86 infalling BHs with masses > $10^4 M_\odot$, 36 merge with their host's central BH, 13 are ejected from their host galaxy, and 37 are still orbiting at $z = 0$. Across all galaxies, 33 BHs are kicked to a higher orbit after close interactions with the central BH binary or multiple, after which only one of them merged with their hosts. These orbiting BHs should be detectable by their anomalous (not Low Mass X-ray Binary) spectra. The X-ray luminosities of the orbiting massive BHs at $z = 0$ are in the range $10^{28} - 10^{43}$ erg s^{-1}, with a currently undetectable median value of 10^{33} erg s^{-1}. However, the most luminous ~5% should be detectable by existing X-ray facilities.

Key words: Galaxy: kinematics and dynamics

S9

Aligning Nuclear Cluster Orbits with an Active Galactic Nucleus Accretion Disk

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ABSTRACT

Active galactic nuclei (AGN) are powered by the accretion of disks of gas onto supermassive black holes (SMBHs). Stars and stellar remnants orbiting the SMBH in the nuclear star cluster (NSC) will interact with the AGN disk. Orbiters plunging through the disk experience a drag force and, through repeated passage, can have their orbits captured by the disk. A population of embedded objects in AGN disks may be a significant source of binary black hole mergers, supernovae, tidal disruption events and embedded gamma-ray bursts. For two representative AGN disk models we use geometric drag and Bondi-Hoyle-Littleton drag to determine the time to capture for stars and stellar remnants. We assume a range of initial inclination angles and semi-major axes for circular Keplerian prograde orbiters. Capture time strongly depends on the density and aspect ratio of the chosen disk model, the relative velocity of the stellar object with respect to the disk, and the AGN lifetime. We expect that for an AGN disk density $\rho \gtrsim 10^{-11}\,\mathrm{g\,cm^{-3}}$ and disk lifetime $\geq$ 1Myr, there is a significant population of embedded stellar objects, which can fuel mergers detectable in gravitational waves with LIGO-Virgo and LISA.

Key words:
stars: kinematics and dynamics – galaxies: active – accretion, accretion discs – galaxies: nuclei – stars: black holes – gravitational waves

S10

Populating the upper black hole mass gap through stellar collisions in young star clusters

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ABSTRACT

Theoretical modeling of massive stars predicts a gap in the black hole (BH) mass function above $\sim 40-50\,M_\odot$ for BHs formed through single star evolution, arising from (pulsational) pair-instability supernovae. However, in dense star clusters, dynamical channels may exist that allow construction of BHs with masses in excess of those allowed from single star evolution. The detection of BHs in this so-called "upper-mass gap" would provide strong evidence for the dynamical processing of BHs prior to their eventual merger. Here, we explore in detail the formation of BHs with masses within or above the pair-instability gap through collisions of young massive stars in dense star clusters. We run a suite of 68 independent cluster simulations, exploring a variety of physical assumptions pertaining to growth through stellar collisions, including primordial cluster mass segregation and the efficiency of envelope stripping during collisions. We find that as many as $\sim 20\%$ of all BH progenitors undergo one or more collisions prior to stellar collapse and up to $\sim 1\%$ of all BHs reside within or above the pair-instability gap through the effects of these collisions. We show that these BHs readily go on to merge with other BHs in the cluster, creating a population of massive BH mergers at a rate that may compete with the "multiple-generation" merger channel described in other analyses. This has clear relevance for the formation of very massive BH binaries as recently detected by LIGO/Virgo in GW190521. Finally, we describe how stellar collisions in clusters may provide a unique pathway to pair-instability supernovae and briefly discuss the expected rate of these events and other electromagnetic transients.

S11

Letter to the Editor

Formation of low-spinning 100 $M_\odot$ black holes

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ABSTRACT

Aims. It is speculated that a merger of two massive stellar-origin black holes in a dense stellar environment may lead to the formation of a massive black hole in the pair-instability mass gap (~50−135 $M_\odot$). Such a merger-formed black hole is expected to typically have a high spin ($a \sim 0.7$). If such a massive black hole acquires another black hole it may lead to another merger detectable by LIGO/Virgo in gravitational waves. Acquiring a companion may be hindered by gravitational-wave kick/recoil, which accompanies the first merger and may quickly remove the massive black hole from its parent globular or nuclear cluster. We test whether it is possible for a massive merger-formed black hole in the pair-instability gap to be retained in its parent cluster and have low spin. Such a black hole would be indistinguishable from a primordial black hole.
Methods. We employed results from numerical relativity calculations of black hole mergers to explore the range of gravitational-wave recoil velocities for various combinations of merging black hole masses and spins. We compared merger-formed massive black hole speeds with typical escape velocities from globular and nuclear clusters.
Results. We show that a globular cluster is highly unlikely to form and retain a ~100 $M_\odot$ black hole if the spin of the black hole is low ($a \lesssim 0.3$). Massive merger-formed black holes with low spins acquire high recoil speeds ($\gtrsim$200 km s^{-1}) from gravitational-wave kick during formation that exceed typical escape speeds from globular clusters (~50 km s^{-1}). However, a very low-spinning ($a \sim 0.1$) and massive (~100 $M_\odot$) black hole could be formed and retained in a galactic nuclear star cluster. Even though such massive merger-formed black holes with such low spins acquire high speeds during formation (~400 km s^{-1}), they may avoid ejection since massive nuclear clusters have high escape velocities (~300−500 km s^{-1}). A future detection of a massive black hole in the pair-instability mass gap with low spin would therefore not be proof of the existence of primordial black holes, which are sometimes claimed to have low spins and arbitrarily high masses.

Key words. black hole physics – gravitational waves