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

Supervisor: R. Spurzem; Subject Classification:

Galaxies/Galactic Nuclei: S6 (AGN disks and black holes)

Star Clusters: S1, S9 (grav. waves, dynamics, stellar evolution), S2 (few body, stellar evolution), S3-S4 (young star clusters, multiple populations), S8 (NGC3201 dynamics)

Few Body: S5 (triples and black holes)

Planetary Systems: S7 (Hot Jupiter, dynamics), S10-S12 (stability), S13 (Oort Cloud in extrasolar systems)

(If you have another suggestion: please contact us)

S1

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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

S2

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 (≳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

Kinematical evolution of multiple stellar populations in star clusters

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S3

ABSTRACT

We present the results of a suite of N-body simulations aimed at understanding the fundamental aspects of the long-term evolution of the internal kinematics of multiple stellar populations in globular clusters. Our models enable us to study the cooperative effects of internal, relaxation-driven processes and external, tidally-induced perturbations on the structural and kinematic properties of multiple-population globular clusters. To analyse the dynamical behaviour of the multiple stellar populations in a variety of spin-orbit coupling conditions, we have considered three reference cases in which the tidally perturbed star cluster rotates along an axis oriented in different directions with respect to the orbital angular momentum vector. We focus specifically on the characterisation of the evolution of the degree of differential rotation and anisotropy in the velocity space, and we quantify the process of spatial and kinematic mixing of the two populations. In light of recent and forthcoming explorations of the internal kinematics of this class of stellar systems by means of line-of sight and astrometric measurements, we also investigate the implications of projection effects and spatial distribution of the stars adopted as tracers. The kinematic and structural richness emerging from our models further emphasises the need and the importance of observational studies aimed at building a complete kinematical picture of the multiple population phenomenon.

Key words: methods:numerical – galaxies: star clusters: general – Galaxy: globular clusters: general

Evolution of fractality and rotation in embedded star clusters

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S4

ABSTRACT
More and more observations indicate that young star clusters could retain imprints of their formation process. In particular, the degree of substructuring and rotation are possibly the direct result of the collapse of the parent molecular cloud from which these systems form. Such properties can, in principle, be washed-out, but they are also expected to have an impact on the relaxation of these systems. We ran and analyzed a set of ten hydrodynamical simulations of the formation of embedded star clusters through the collapse of turbulent massive molecular clouds. We systematically studied the fractality of our star clusters, showing that they are all extremely substructured (fractal dimension $D = 1.0 - 1.8$). We also found that fractality is slowly reduced, with time, on small scales, while it persists on large scales on longer timescales. Signatures of rotation are found in different simulations at every time of the evolution, even for slightly supervirial substructures, proving that the parent molecular gas transfers part of its angular momentum to the new stellar systems.

Key words: ISM: clouds – methods: numerical – stars: kinematics and dynamics – ISM: kinematics and dynamics – galaxies: star clusters: general

Mergers of Equal-Mass Binaries with Compact Object Companions from Mass Transfer in Triple Star Systems

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S5

ABSTRACT

In this paper, we consider triple systems composed of main-sequence (MS) stars, and their internal evolution due to stellar and binary evolution. Our focus is on triples that produce white dwarfs (WDs), where Roche lobe overflow of an evolving tertiary triggers accretion onto the inner binary via a circumbinary disk (CBD) driving it toward a mass ratio of unity. We present a combination of analytic- and population synthesis-based calculations performed using the `SeBa` code to constrain the expected frequency of such systems, given a realistic initial population of MS triples, and provide the predicted distributions of orbital periods. We identify the parameter space for triples that can accommodate a CBD, to inform future numerical simulations of suitable initial conditions. We find that $\gtrsim$ 10% of all MS triples should be able to accommodate a CBD around the inner binary, and compute lower limits for the production rates. This scenario broadly predicts mergers of near equal-mass binaries, producing blue stragglers (BSs), Type Ia supernovae, gamma ray bursts and gravitational wave-induced mergers, along with the presence of an outer WD tertiary companion. We compare our predicted distributions to a sample of field BS binaries, and argue that our proposed mechanism explains the observed range of orbital periods. Finally, the mechanism considered here could produce hypervelocity MS stars, WDs and even millisecond pulsars with masses close to the Chandrasekhar mass limit, and be used to constrain the maximum remnant masses at the time of any supernova explosion.

Key words: stars: blue stragglers – binaries: close – accretion, accretion disks – hydrodynamics – supernovae: general – stars: white dwarfs

S6

Orbital Migration of Interacting Stellar Mass Black Holes in Disks around Supermassive Black Holes II. Spins and Incoming Objects

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ABSTRACT

The masses, rates, and spins of merging stellar-mass binary black holes (BBHs) detected by aLIGO and Virgo provide challenges to traditional BBH formation and merger scenarios. An active galactic nucleus (AGN) disk provides a promising additional merger channel, because of the powerful influence of the gas that drives orbital evolution, makes encounters dissipative, and leads to migration. Previous work showed that stellar mass black holes (sBHs) in an AGN disk migrate to regions of the disk, known as migration traps, where positive and negative gas torques cancel out, leading to frequent BBH formation. Here we build on that work by simulating the evolution of additional sBHs that enter the inner disk by either migration or inclination reduction. We also examine whether the BBHs formed in our models have retrograde or prograde orbits around their centers of mass with respect to the disk, determining the orientation, relative to the disk, of the spin of the merged BBHs. Orbiters entering the inner disk form BBHs with sBHs on resonant orbits near the migration trap. When these sBHs reach $\gtrsim 80\ M_\odot$, they form BBHs with sBHs in the migration trap, which over 10 Myr reach $\sim 1000\ M_\odot$. We find 68% of the BBHs in our simulation orbit in the retrograde direction, which implies BBHs in our merger channel will have small dimensionless aligned spins, $\chi_{\rm eff}$. Overall, our models produce BBHs that resemble both the majority of BBH mergers detected thus far (0.66–120 $\rm Gpc^{-3}\ yr^{-1}$) and two recent unusual detections, GW190412 ($\sim$0.3 $\rm Gpc^{-3}\ yr^{-1}$) and GW190521 ($\sim$0.1 $\rm Gpc^{-3}\ yr^{-1}$).

Keywords: black hole physics — LIGO — Active galactic nuclei

S7

Hot Jupiter and ultra-cold Saturn formation in dense star clusters

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ABSTRACT

The discovery of high incidence of hot Jupiters in dense clusters challenges the field-based hot Jupiter formation theory. In dense clusters, interactions between planetary systems and flyby stars are relatively common. This has a significant impact on planetary systems, dominating hot Jupiter formation. In this paper, we perform high precision, few-body simulations of stellar flybys and subsequent planet migration in clusters. A large parameter space exploration demonstrates that close flybys that change the architecture of the planetary system can activate high eccentricity migration mechanisms: Lidov-Kozai and planet-planet scattering, leading to high hot Jupiter formation rate in dense clusters. Our simulations predict that many of the hot Jupiters are accompanied by "ultra-cold Saturns", expelled to apastra of thousands of AU. This increase is particularly remarkable for planetary systems originally hosting two giant planets with semi-major axis ratios ~ 4 and the flyby star approaching nearly perpendicular to the planetary orbital plane. The estimated lower limit to the hot Jupiter formation rate of a virialized cluster is $\sim 1.6 \times 10^{-4}(\sigma/1\mathrm{kms}^{-1})^5(a_\mathrm{p}/20\mathrm{AU})(M_\mathrm{c}/1000\mathrm{M}_\odot)^{-2}$ Gyr^{-1} per star, where σ is the cluster velocity dispersion, a_p is the size of the planetary system and M_c is the mass of the cluster. Our simulations yield a hot Jupiter abundance which is ~ 50 times smaller than that observed in the old open cluster M67. We expect that interactions involving binary stars, as well as a third or more giant planets, will close the discrepancy.

Keywords: kinematics and dynamics – planetary systems – simulations

The dynamics of the globular cluster NGC 3201 out to the Jacobi radius

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S8

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ABSTRACT

As part of a chemo-dynamical survey of five nearby globular clusters with 2dF/AAOmega on the Anglo-Australian Telescope (AAT), we have obtained kinematic information for the globular cluster NGC 3201. Our new observations confirm the presence of a significant velocity gradient across the cluster which can almost entirely be explained by the high proper motion of the cluster ($\sim 9\,\mathrm{mas\,yr^{-1}}$). After subtracting the contribution of this perspective rotation, we found a remaining rotation signal with an amplitude of $\sim 1\,\mathrm{km\,s^{-1}}$ around a different axis to what we expect from the tidal tails and the potential escapers, suggesting that this rotation is internal and can be a remnant of its formation process. At the outer part, we found a rotational signal that is likely a result from potential escapers. The proper motion dispersion at large radii reported by Bianchini et al. ($3.5 \pm 0.9\,\mathrm{km\,s^{-1}}$) has previously been attributed to dark matter. Here we show that the LOS dispersion between 0.5 – 1 Jacobi radius is lower ($2.01 \pm 0.18\,\mathrm{km\,s^{-1}}$), yet above the predictions from an N-body model of NGC 3201 that we ran for this study ($1.48 \pm 0.14\,\mathrm{km\,s^{-1}}$). Based on the simulation, we find that potential escapers cannot fully explain the observed velocity dispersion. We also estimate the effect on the velocity dispersion of different amounts of stellar-mass black holes and unbound stars from the tidal tails with varying escape rates and find that these effects cannot explain the difference between the LOS dispersion and the N-body model. Given the recent discovery of tidal tail stars at large distances from the cluster, a dark matter halo is an unlikely explanation. We show that the effect of binary stars, which is not included in the N-body model, is important and can explain part of the difference in dispersion. We speculate that the remaining difference must be the result of effects not included in the N-body model, such as initial cluster rotation, velocity anisotropy and Galactic substructure.

Key words: globular clusters: individual: NGC 3201 – dark matter – stars: kinematics and dynamics

S9

Matching Globular Cluster Models to Observations

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ABSTRACT

As ancient, gravitationally bound stellar populations, globular clusters are abundant, vibrant laboratories characterized by high frequencies of dynamical interactions coupled to complex stellar evolution. Using surface brightness and velocity dispersion profiles from the literature, we fit 59 Milky Way globular clusters to dynamical models from the `CMC Cluster Catalog`. Without doing any interpolation, and without any directed effort to fit any particular cluster, 26 globular clusters are well-matched by at least one of our models. We discuss in particular the core-collapsed clusters NGC 6293, NGC 6397, NGC 6681, and NGC 6624, and the non-core-collapsed clusters NGC 288, NGC 4372, and NGC 5897. As NGC 6624 lacks well-fitting snapshots on the main `CMC Cluster Catalog`, we run six additional models in order to refine the fit. We calculate metrics for mass segregation, explore the production of compact object sources such as millisecond pulsars, cataclysmic variables, low-mass X-ray binaries, and stellar-mass black holes, finding reasonable agreement with observations. Additionally, closely mimicking observational cuts, we extract the binary fraction from our models, finding good agreement except in the dense core regions of core-collapsed clusters. Accompanying this paper are a number of `python` methods for examining the publicly accessible `CMC Cluster Catalog`, as well as any other models generated using `CMC`.

Keywords: —-

Predicting the long-term stability of compact multiplanet systems

S10

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We combine analytical understanding of resonant dynamics in two-planet systems with machine-learning techniques to train a model capable of robustly classifying stability in compact multi-planet systems over long timescales of 10^9 orbits. Our Stability of Planetary Orbital Configurations Klassifier (SPOCK) predicts stability using physically motivated summary statistics measured in integrations of the first 10^4 orbits, thus achieving speed-ups of up to 10^5 over full simulations. This computationally opens up the stability-constrained characterization of multiplanet systems. Our model, trained on ∼100,000 three-planet systems sampled at discrete resonances, generalizes both to a sample spanning a continuous period-ratio range, as well as to a large five-planet sample with qualitatively different configurations to our training dataset. Our approach significantly outperforms previous methods based on systems' angular momentum deficit, chaos indicators, and parametrized fits to numerical integrations. We

use SPOCK to constrain the free eccentricities between the inner and outer pairs of planets in the Kepler-431 system of three approximately Earth-sized planets to both be below 0.05. Our stability analysis provides significantly stronger eccentricity constraints than currently achievable through either radial velocity or transit-duration measurements for small planets and within a factor of a few of systems that exhibit transit-timing variations (TTVs). Given that current exoplanet-detection strategies now rarely allow for strong TTV constraints [S. Hadden, T. Barclay, M. J. Payne, M. J. Holman, *Astrophys. J.* 158, 146 (2019)], SPOCK enables a powerful complementary method for precisely characterizing compact multiplanet systems. We publicly release SPOCK for community use.

exoplanets | chaos | machine learning | orbital dynamics | dynamical systems

Short-term stability of particles in the WD J0914+1914 white dwarf planetary system

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3 August 2020

S11

ABSTRACT
Nearly all known white dwarf planetary systems contain detectable rocky debris in the stellar photosphere. A glaring exception is the young and still evolving white dwarf WD J0914+1914, which instead harbours a giant planet and a disc of pure gas. The stability boundaries of this disc and the future prospects for this white dwarf to be polluted with rocks depend upon the mass and orbit of the planet, which are only weakly constrained. Here we combine an ensemble of plausible planet orbits and masses to determine where observers should currently expect to find the outer boundary of the gas disc. We do so by performing a sweep of the entire plausible phase space with short-term numerical integrations. We also demonstrate that particle-star collisional trajectories, which would lead to the (unseen) signature of rocky metal pollution, occupy only a small fraction of the phase space, mostly limited to particle eccentricities above 0.75. Our analysis reveals that a highly inflated planet on a near-circular orbit is the type of planet which is most consistent with the current observations.

Key words: minor planets, asteroids: general – comets: general – protoplanetary discs – planets and satellites: dynamical evolution and stability – planet-star interactions – stars: white dwarfs

THE ORIGIN OF SYSTEMS OF TIGHTLY PACKED INNER PLANETS WITH MISALIGNED, ULTRA-SHORT-PERIOD COMPANIONS

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S12

ABSTRACT

Ultra-short period planets provide a window into the inner edge of the parameter space occupied by planetary orbits. In one particularly intriguing class of multi-planet systems, the ultra-short period planet is flanked by short-period companions, and the outer planets occupy a discernibly distinct dynamical state. In the observational database, this phenomenon is represented by a small number of stars hosting systems of tightly packed co-planar planets as well as an ultra-short period planet, whose orbit of is misaligned relative to the mutual plane of the former. In this work, we explore two different mechanisms that can produce an ultra-short period planet that is misaligned with the rest of its compact planetary system: natural decoupling between the inner and outer system via the stellar quadrupole moment, and decoupling forced by an external companion with finely-tuned orbital parameters. These two processes operate with different timescales, and can thus occur simultaneously. In this work, we use the K2-266 system as an illustrative example to elucidate the dynamics of these two processes, and highlight the types of constraints that may arise regarding the dynamical histories of systems hosting ultra-short period planets.

Oort cloud Ecology II: Extra-solar Oort clouds and the origin of asteroidal interlopers

S13

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Received / Accepted

ABSTRACT

We simulate the formation and evolution of Oort clouds around the 200 nearest stars (within $\sim$ 16 pc according to the Gaia DR2) database. This study is performed by numerically integrating the planets and minor bodies in orbit around the parent star and in the Galactic potential. The calculations start 1 Gyr ago and continue for 100 Myr into the future. In this time frame, we simulate how asteroids (and planets) are ejected from the star's vicinity and settle in an Oort cloud and how they escape the local stellar gravity to form tidal steams. A fraction of 0.0098 to 0.026 of the asteroids remain bound to their parent star. The orbits of these asteroids isotropizes and circularizes due to the influence of the Galactic tidal field to eventually form an Oort cloud between $\sim 10^4$ and $\sim 2 \cdot 10^5$ au. We estimate that $\lesssim 6\%$ of the nearby stars may have a planet in its Oort cloud. The majority of asteroids (and some of the planets) become unbound from the parent star to become free floating in the Galactic potential. These sōlī lapidēs remain in a similar orbit around the Galactic center as their host star, forming dense streams of rogue interstellar asteroids and planets.
The Solar system occasionally passes through such tidal streams, potentially giving rise to occasional close encounters with object in this stream. The two recently discovered objects, 1I/(2017 Q3) 'Oumuamua and 2I/(2019 Q4) Borisov, may be such objects. Although the direction from which an individual sōlus lapis originated cannot easily be traced back to the original host, multiple such objects coming from the same source might help to identify their origin. At the moment the Solar system is in the bow or wake of the tidal stream of $\sim$ 10 of the nearby stars which might contribute considerably to the interaction rate. Overall, we estimate that the local density of such left overs from the planet-formation process contribute to a local density of 1.2×10^{14} per pc^{-3}, or $\gtrsim 0.1$ of the interstellar visitors originate from the obliterated debris disk of such nearby stars.