Winter Semester 21/22:
MVSem Dynamics of galaxies, star clusters and planetary systems
(A. Just/R.Spurzem)

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

Star Clusters: S2 (few body, stellar evolution), S4 (young star clusters, multiple populations), S8 (NGC3201 dynamics), S9 (white dwarfs in star clusters)

Planetary Systems: S1 (Solar System hypoth. Planet 9), S3 (circum-binary planets), S5, S7 (planet formation)

(If you have another suggestion: please contact us)

S1

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The Resonance Hopping Effect in the Neptune-Planet Nine System

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ABSTRACT

The observed physical clustering of the orbits of small bodies in the distant Kuiper Belt (TNOs) has recently prompted the prediction of an additional planet in the outer solar system. Since the initial posing of the hypothesis, the effects of Planet Nine on the dynamics of the main cluster of TNOs – the objects anti-aligned with its orbit – have been well-studied. In particular, numerical simulations have revealed a fascinating phenomenon, referred to as "resonance hopping", in which these objects abruptly transition between different mean-motion commensurabilities with Planet Nine. In this work, we explore this effect in greater detail, with the goal of understanding what mechanism prompts the hopping events to occur. In the process, we elucidate the often underestimated role of Neptune scattering interactions, which leads to diffusion in the semi-major axes of these distant TNOs. In addition, we demonstrate that although some resonant interactions with Planet Nine do occur, the anti-aligned objects are able to survive without the resonances, confirming that the dynamics of the TNOs are predominantly driven by secular, rather than resonant, interactions with Planet Nine.

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 ($\sim$50$-$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 $\sim$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$200 km s^{-1}) from gravitational-wave kick during formation that exceed typical escape speeds from globular clusters ($\sim$50 km s^{-1}). However, a very low-spinning ($a \sim 0.1$) and massive ($\sim$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 ($\sim$400 km s^{-1}), they may avoid ejection since massive nuclear clusters have high escape velocities ($\sim$300$-$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

S3

Lucky planets: how circum-binary planets survive the supernova in one of the inner-binary components

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Abstract

Since the discovery of exoplanets around pulsars, there has been a debate on their origin. Popular scenarios include in situ formation or the dynamical capture of a planet in a dense stellar system. The possibility of a planet surviving its host star's supernova is often neglected, because a planet in orbit around a single exploding star is not expected to survive the supernova. A circum-binary planet, however, may stand a chance in staying bound when one of the binary components explodes. We investigate the latter and constrain the distribution of post-supernova orbital parameters of circum-binary planets. This is done by performing population synthesis calculations of binary stars until the first supernova. Just before the supernova, we add a planet in orbit around the binary to study its survivability. In our supernova model, the exploding star's mass is assumed to change instantaneously, and we apply a velocity kick to the newly formed remnant. The mass loss and velocity kick affect the orbits of the two stars and the planet. Only $2 \cdot 10^{-3}$ of systems survive the supernova while keeping the circum-binary planet bound. The surviving planetary orbits are wide ($a \gtrsim 10$ au) and eccentric ($e \gtrsim 0.3$). It turns out much more likely ($3 \cdot 10^{-2}$ system fraction) that the newly formed compact object is ejected from the system, leaving the planet bound to its companion star in a highly eccentric orbit (typically $\gtrsim 0.9$). We expect that the Milky way Galaxy hosts at most 10 x-ray binaries that are still orbited by a planet, and $\lesssim 150$ planets that survived in orbit around the compact object's companion. These numbers should be convolved with the fraction of massive binaries that is orbited by a planet.

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

S5

Inside-Out Planet Formation: VI. Oligarchic Coagulation of Planetesimals from a Pebble Ring?

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ABSTRACT
Inside-Out Planet Formation (IOPF) is a theory addressing the origin of Systems of Tightly-Packed Inner Planets (STIPs) via *in situ* formation and growth of the planets. It predicts that a pebble ring is established at the pressure maximum associated with the dead zone inner boundary (DZIB) with an inner disk magnetorotational instability (MRI)-active region. Using direct N-body simulations, we study the collisional evolution of planetesimals formed from such a pebble ring, in particular examining whether a single dominant planet emerges. We consider a variety of models, including some in which the planetesimals are continuing to grow via pebble accretion. We find that the planetesimal ring undergoes oligarchic evolution, and typically turns into 2 or 3 surviving oligarchs on nearly coplanar and circular orbits, independent of the explored initial conditions or form of pebble accretion. The most massive oligarchs typically consist of about 70% of the total mass, with the building-up process typically finishing within $\sim 10^5$ years. However, a relatively massive secondary planet always remains with $\sim 30-65\%$ of the mass of the primary. Such secondary planets have properties that are inconsistent with the observed properties of the innermost pairs of planets in STIPs. Thus, for IOPF to be a viable theory for STIP formation, it needs to be shown how oligarchic growth of a relatively massive secondary from the initial pebble ring can be avoided. We discuss some potential additional physical processes that should be included in the modeling and explored as next steps.

Key words: accretion, accretion disks – planet-disk interactions – planetary systems – planets and satellites: formation – protoplanetary disks

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

Most super-Earths formed by dry pebble accretion are less massive than 5 Earth masses

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ABSTRACT

Aims. The goal of this work is to study the formation of rocky planets by dry pebble accretion from self-consistent dust-growth models. In particular, we aim at computing the maximum core mass of a rocky planet that can sustain a thin H-He atmosphere to account for the second peak of the Kepler's size distribution.

Methods. We simulate planetary growth by pebble accretion inside the ice line. The pebble flux is computed self-consistently from dust growth by solving the advection-diffusion equation for a representative dust size. Dust coagulation, drift, fragmentation and sublimation at the water ice line are included. The disc evolution is computed solving the vertical and radial structure for standard α-discs with photoevaporation from the central star. The planets grow from a moon-mass embryo by silicate pebble accretion and gas accretion. We perform a parameter study to analyse the effect of a different initial disc mass, α-viscosity, disc metallicity and embryo location. We also test the effect of considering migration vs. an in-situ scenario. Finally, we compute atmospheric mass-loss due to evaporation during 5 Gyr of evolution.

Results. We find that inside the ice line, the fragmentation barrier determines the size of pebbles, which leads to different planetary growth patterns for different disc viscosities. We also find that in this inner disc region, the pebble isolation mass typically decays to values below 5 $M_\oplus$ within the first million years of disc evolution, limiting the core masses to that value. After computing atmospheric-mass loss, we find that planets with cores below ~4 $M_\oplus$ get their atmospheres completely stripped, and a few 4-5 $M_\oplus$ cores retain a thin atmosphere that places them in the gap/second peak of the Kepler size distribution. In addition, a few rare objects that form in extremely low viscosity discs accrete a core of 7 $M_\oplus$ and equal envelope mass, which is reduced to 3-5 $M_\oplus$ after evaporation. These objects end up with radii of ~6-7 $R_\oplus$.

Conclusions. Overall, we find that rocky planets form only in low-viscosity discs ($\alpha \lesssim 10^{-4}$). When $\alpha \geq 10^{-3}$, rocky objects do not grow beyond Mars-mass. For the successful low viscosity cases, the most typical outcome of dry pebble accretion is terrestrial planets with masses spanning from Mars to ~4 $M_\oplus$.

Key words. planets and satellites: formation; planets and satellites: composition; planets and satellites: interiors

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

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S9

White Dwarf Subsystems in Core-Collapsed Globular Clusters

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ABSTRACT

Numerical and observational evidence suggests that massive white dwarfs dominate the innermost regions of core-collapsed globular clusters by both number and total mass. Using NGC 6397 as a test case, we constrain the features of white dwarf populations in core-collapsed clusters, both at present day and throughout their lifetimes. The dynamics of these white dwarf subsystems have a number of astrophysical implications. We demonstrate that the collapse of globular cluster cores is ultimately halted by the dynamical burning of white dwarf binaries. We predict core-collapsed clusters in the local universe yield a white dwarf merger rate of $\mathcal{O}(10)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, roughly $0.1-1\%$ of the observed Type Ia supernova rate. We show that prior to merger, inspiraling white dwarf binaries will be observable as gravitational wave sources at milli- and decihertz frequencies. Over 90% of these mergers have a total mass greater than the Chandrasekhar limit. If the merger/collision remnants are not destroyed completely in an explosive transient, we argue the remnants may be observed in core-collapsed clusters as either young neutron stars/pulsars/magnetars (in the event of accretion-induced collapse) or as young massive white dwarfs offset from the standard white dwarf cooling sequence. Finally, we show collisions between white dwarfs and main sequence stars, which may be detectable as bright transients, occur at a rate of $\mathcal{O}(100)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ in the local universe. We find that these collisions lead to depletion of blue straggler stars and main sequence star binaries in the centers of core-collapsed clusters.