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Dynamics of galaxies, star clusters and planetary systems

Abstracts topics J* (**Just**), S* (**Spurzem**), F* (**Flammini Dotti**)

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Black Holes / Galactic Nuclei: S3, S5

J1

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Benchmarking MESA isochrones against the Hyades single star sequence

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ABSTRACT

Based on *GAIA* Early Data Release 3 (EDR3), we revisit and update our sample of bonafide single stars in the Hyades open cluster. The small observational uncertainties in parallax and photometry of EDR3 result in a tightly defined stellar sequence, which is ideal for the testing and calibration of theoretical stellar evolutionary tracks and isochrones. We benchmark the solar-scaled MESA evolutionary models against the single star sequence. We find that the non-rotating MESA models for [Fe/H] = +0.25 provide a good fit for stars with masses above 0.85, and very low mass stars below 0.25 $M_\odot$. For stars with masses between 0.25 and 0.85 $M_\odot$, the models systematically under predict the observed stellar luminosity. One potential limitation of the models for partially convective stars more massive than 0.35 $M_\odot$ is the prescription of (superadiabatic) convection with the mixing-length theory parameter α_{ML} tuned to match the Solar model. Below 0.35 $M_\odot$, the increased scatter in the stellar sequence might be a manifestation of the *convective kissing instability*, which is driven by variations in the ^{3}He nuclear energy production rate due to instabilities at the convective core to envelope boundary. For a Hyades-like stellar population, the application of solar-scaled models to subsolar mass stars could result in a significant underestimate of the age, or an overestimate of the metallicity. We suggest that future grids of solar-scaled evolutionary stellar models could be complemented by Hyades-scaled models in the mass range 0.25 to 0.85 $M_\odot$.

J2

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On the Nature of Rotation in the Praesepe Cluster

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Abstract

Although a large number of Galactic open clusters (OCs) have been identified, the internal kinematic properties (e.g., rotation) of almost all the known OCs are still far from clear. With the high-precision astrometric data of Gaia EDR3, we have developed a methodology to unveil the rotational properties of the Praesepe cluster. Statistics of the three-dimensional residual motions of the member stars reveal the presence of Praesepe's rotation and determine its spatial rotation axis. The mean rotation velocity of the Praesepe cluster within its tidal radius is estimated to be 0.2 ± 0.05 km s^{-1}, and the corresponding rotation axis is tilted in relation to the Galactic plane with an angle of $41° \pm 12°$. We also analyzed the rms rotational velocity of the member stars around the rotation axis, and found that the rotation of the member stars within the tidal radius of Praesepe probably follows Newton's classical theorems.

J3

The growth of brightest cluster galaxies in the TNG300 simulation: dissecting the contributions from mergers and in situ star formation

Show affiliations

Montenegro-Taborda, Daniel ; Rodriguez-Gomez, Vicente ; Pillepich, Annalisa ; Avila-Reese, Vladimir ; Sales, Laura V. ; Rodríguez-Puebla, Aldo ; Hernquist, Lars

We investigate the formation of brightest cluster galaxies (BCGs) in the TNG300 cosmological simulation of the IllustrisTNG project. Our cluster sample consists of 700 haloes with $M_{200} \geq 5 \times 10^{13}\,\mathrm{M}_{\odot}$ at z = 0, along with their progenitors at earlier epochs. This includes 280 systems with $M_{200} \geq 10^{14}\,\mathrm{M}_{\odot}$ at z = 0, as well as three haloes with $M_{200} \geq 10^{15}\,\mathrm{M}_{\odot}$. We find that the stellar masses and star formation rates of our simulated BCGs are in good agreement with observations at $z \lesssim 0.4$, and that they have experienced, on average, ~2 (~3) major mergers since z = 1 (z = 2). Separating the BCG from the intracluster light (ICL) by means of a fixed 30 kpc aperture, we find that the fraction of stellar mass contributed by ex situ (i.e. accreted) stars at z = 0 is approximately 70, 80, and 90 per cent for the BCG, BCG + ICL, and ICL, respectively. Tracking our simulated BCGs back in time using the merger trees, we find that they became dominated by ex situ stars at z ~1-2, and that half of the stars that are part of the BCG at z = 0 formed early (z ~ 3) in other galaxies, but 'assembled' onto the BCG until later times ($z \approx 0.8$ for the whole sample, $z \approx 0.5$ for BCGs in $M_{200} \geq 5 \times 10^{14}\,\mathrm{M}_{\odot}$ haloes). Finally, we show that the stellar mass profiles of BCGs are often dominated by ex situ stars at all radii, with stars from major mergers being found closer to the centre, while stars that were tidally stripped from other galaxies dominate the outer regions.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 521, Issue 1, pp.800-817

J4

The relationship between galaxy and halo sizes in the Illustris and IllustrisTNG simulations

Show affiliations

Karmakar, Tathagata ; Genel, Shy ; Somerville, Rachel S.

Abundance matching studies have shown that the average relationship between galaxy radius and dark matter halo virial radius remains nearly constant over many orders of magnitude in halo mass, and over cosmic time since about z = 3. In this work, we investigate the predicted relationship between galaxy radius r_e and halo virial radius R_h in the numerical hydrodynamical simulations Illustris and IllustrisTNG from z ~ 0-3, and compare with the results from the abundance matching studies. We find that Illustris predicts much higher r_e/R_h values than the constraints obtained by abundance matching, at all redshifts, as well as a stronger dependence on halo mass. In contrast, IllustrisTNG shows very good agreement with the abundance matching constraints. In addition, at high redshift it predicts a strong dependence of r_e/R_h on halo mass on mass scales below those that are probed by existing observations. We present the predicted r_e/R_h relations from Illustris and IllustrisTNG for galaxies divided into star forming and quiescent samples, and quantify the scatter in r_e/R_h for both simulations. Further, we investigate whether this scatter arises from the dispersion in halo spin parameter and find no significant correlation between r_e/R_h and halo spin. We investigate the paths in r_e/R_h traced by individual haloes over cosmic time, and find that most haloes oscillate around the median r_e/R_h relation over their formation history.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 2, pp.1630-1641

S1

Star cluster formation from turbulent clumps - III. Across the mass spectrum

Show affiliations

Farias, Juan P. ; Tan, Jonathan C.

We study the formation and early evolution of star clusters that have a wide range of masses and background cloud mass surface densities, Σ_{cloud}, which help set the initial sizes, densities, and velocity dispersions of the natal gas clumps. Initial clump masses of 300, 3000, and 30 000 $M_{\odot}$ are considered, from which star clusters are born with an assumed 50 per cent overall star formation efficiency and with 50 per cent primordial binarity. This formation is gradual, i.e. with a range of star formation efficiencies per free-fall time from 1 to 100 per cent, so that the formation time can range from 0.7 Myr for low-mass, high-Σ_{cloud} clumps to ~30 Myr for high-mass, low-Σ_{cloud} clumps. Within this framework of the turbulent clump model, for a given Σ_{cloud}, clumps of higher mass are of lower initial volume density, but their dynamical evolution leads to higher bound fractions and causes them to form much higher density cluster cores and maintain these densities for longer periods. This results in systematic differences in the evolution of binary properties, degrees of mass segregation, and rates of creation of dynamically ejected runaways. We discuss the implications of these results for observed star clusters and stellar populations.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 523, Issue 2, pp.2083-2110

S2

THE THREE HUNDRED project: The GIZMO-SIMBA run

Show affiliations | Show all authors

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We introduce GIZMO-SIMBA, a new suite of galaxy cluster simulations within THE THREE HUNDRED project. THE THREE HUNDRED consists of zoom re-simulations of 324 clusters with $M_{200} \gtrsim 10^{14.8}\,\mathrm{M}_{\odot}$ drawn from the MultiDark-Planck N-body simulation, run using several hydrodynamic and semi-analytical codes. The GIZMO-SIMBA suite adds a state-of-the-art galaxy formation model based on the highly successful SIMBA simulation, mildly re-calibrated to match $z = 0$ cluster stellar properties. Comparing to THE THREE HUNDRED zooms run with GADGET-X, we find intrinsic differences in the evolution of the stellar and gas mass fractions, BCG ages, and galaxy colour-magnitude diagrams, with GIZMO-SIMBA generally providing a good match to available data at $z \approx 0$. GIZMO-SIMBA's unique black hole growth and feedback model yields agreement with the observed BH scaling relations at the intermediate-mass range and predicts a slightly different slope at high masses where few observations currently lie. GIZMO-SIMBA provides a new and novel platform to elucidate the co-evolution of galaxies, gas, and black holes within the densest cosmic environments.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 514, Issue 1, pp.977-996

S3

Partial stellar tidal disruption events and their rates

Show affiliations

Bortolas, Elisa ; Ryu, Taeho ; Broggi, Luca ; Sesana, Alberto

Tidal disruption events (TDEs) of stars operated by massive black holes (MBHs) will be detected in thousands by upcoming facilities such as the Vera Rubin Observatory. In this work, we assess the rates of standard total TDEs, destroying the entire star, and partial TDEs, in which a stellar remnant survives the interaction, by solving 1D Fokker-Planck equations. Our rate estimates are based on a novel definition of the loss cone whose size is commensurate with the largest radius at which partial disruptions can occur, as motivated by relativistic hydrodynamical simulations. Our novel approach unveils two important results. First, partial TDEs can be more abundant than total disruptions by a factor of a few to a few tens. Second, the rates of complete stellar disruptions can be overestimated by a factor of a few to a few tens if one neglects partial TDEs, as we find that many of the events classified as total disruptions in the standard framework are in fact partial TDEs. Accounting for partial TDEs is particularly relevant for galaxies harbouring a nuclear stellar cluster featuring many events coming from the empty loss cone. Based on these findings, we stress that partial disruptions should be considered when constraining the luminosity function of TDE flares; accounting for this may reconcile the theoretically estimated TDE rates with the observed ones.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 524, Issue 2, pp.3026-3038

S4

MOCCA-Survey Database: extra galactic globular clusters - III. The population of black holes in Milky Way and Andromeda-like galaxies

Show affiliations

Leveque, A. ; Giersz, M. ; Askar, Abbas ; Arca-Sedda, M. ; Olejak, A.

This work investigates the black hole (BH) population of globular clusters (GCs) in Milky Way- and Andromeda-like galaxies. We combine the population synthesis code MASinGa and the MOCCA-Survey Database I to infer the properties of GCs harbouring a stellar-mass BH subsystem (BHS), an intermediate-mass BH (IMBH), or neither of those. We find that the typical number of GCs with a BHS, an IMBH, or none become comparable in the galactic outskirts, whilst the inner galactic regions are dominated by GCs without a significant dark component. We retrieve the properties of binary BHs (BBHs) that have either merged in the last 3 Gyr or survived in their parent cluster until present-day. We find that around 80 per cent of the merging BBHs form due to dynamical interactions while the remaining originate from evolution of primordial binaries. The inferred merger rate for both in-cluster and ejected mergers is $1.0-23\ \mathrm{yr}^{-1}\,\mathrm{Gpc}^{-3}$ in the local Universe, depending on the adopted assumptions. We find around 100-240 BBHs survive in GCs until present-day and are mostly concentrated in the inner few kpc of the galaxy. When compared with the field, GCs are at least two times more efficient in the formation of BHs and binaries containing at least one BH. Around 1000-3000 single BHs and 100-200 BBHs are transported into the galactic nucleus from infalling clusters over a time span of 12 Gyr. We estimate that the number of BHs and BBHs lurking in the star cluster to be about 1.4-2.2 × 10^4 and 700-1100, respectively.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 2, pp.2593-2610

S5

Close encounters of black hole-star binaries with stellar-mass black holes

Show affiliations

Ryu, Taeho ; Valli, Ruggero ; Pakmor, Rüdiger ; Perna, Rosalba ; de Mink, Selma E. ; Springel, Volker

Dynamical interactions involving binaries play a crucial role in the evolution of star clusters and galaxies. We continue our investigation of the hydrodynamics of three-body encounters, focusing on binary black hole (BBH) formation, stellar disruption, and electromagnetic (EM) emission in dynamical interactions between a BH-star binary and a stellar-mass BH, using the moving-mesh hydrodynamics code AREPO. This type of encounters can be divided into two classes depending on whether the final outcome includes BBHs. This outcome is primarily determined by which two objects meet at the first closest approach. BBHs are more likely to form when the star and the incoming BH encounter first with an impact parameter smaller than the binary's semimajor axis. In this case, the star is frequently disrupted. On the other hand, when the two BHs encounter first, frequent consequences are an orbit perturbation of the original binary or a binary member exchange. For the parameters chosen in this study, BBH formation, accompanied by stellar disruption, happens in roughly one out of four encounters. The close correlation between BBH formation and stellar disruption has possible implications for EM counterparts at the binary's merger. The BH that disrupts the star is promptly surrounded by an optically and geometrically thick disc with accretion rates exceeding the Eddington limit. If the debris disc cools fast enough to become long-lived, EM counterparts can be produced at the time of the BBH merger.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 525, Issue 4, pp.5752-5766

F1

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Reduced Late Bombardment on Rocky Exoplanets around M Dwarfs

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Abstract

Ocean-vaporizing impacts of chemically reduced planetesimals onto the early Earth have been suggested to catalyze atmospheric production of reduced nitrogen compounds and trigger prebiotic synthesis despite an oxidized lithosphere. While geochemical evidence supports a dry, highly reduced late veneer on Earth, the composition of late-impacting debris around lower-mass stars is subject to variable volatile loss as a result of their hosts' extended pre-main-sequence phase. We perform simulations of late-stage planet formation across the M-dwarf mass spectrum to derive upper limits on reducing bombardment epochs in Hadean-analog environments. We contrast the solar system scenario with varying initial volatile distributions due to extended primordial runaway greenhouse phases on protoplanets and the desiccation of smaller planetesimals by internal radiogenic heating. We find a decreasing rate of late-accreting reducing impacts with decreasing stellar mass. Young planets around stars $\leqslant 0.4\ M_{\odot}$ experience no impacts of sufficient mass to generate prebiotically relevant concentrations of reduced atmospheric compounds once their stars have reached the main sequence. For M-dwarf planets to not exceed Earth-like concentrations of volatiles, both planetesimals, and larger protoplanets must undergo extensive devolatilization processes and can typically emerge from long-lived magma ocean phases with sufficient atmophile content to outgas secondary atmospheres. Our results suggest that transiently reducing surface conditions on young rocky exoplanets are favored around FGK stellar types relative to M dwarfs.

F2

The Possibility of Mirror Planet as Planet Nine in the Solar System

by Pei Wang [1,2], Yuchen Tang [1,2], Lei Zu [1,2,*], Yuanyuan Chen [3,4,5] and Lei Feng [1,6,*]

Abstract

A series of dynamical anomalies in the orbits of distant trans-Neptunian objects points to a new celestial body (usually named Planet Nine) in the solar system. In this draft, we point out that a mirror planet captured from the outer solar system or formed in the solar system is also a possible candidate. The introduction of the mirror matter model is due to an unbroken parity symmetry and is a potential explanation for dark matter. This mirror planet has null or fainter electromagnetic counterparts with a smaller optical radius and might be explored through gravitational effects. **View Full-Text**

F3

Binary asteroid scattering around white dwarfs

Show affiliations

McDonald, Catriona H. ; Veras, Dimitri

Increasing observations of white dwarf atmospheric pollution and disrupting planetesimals is driving increased studies into the fate of exo-asteroids around post-main-sequence stars. Planetesimal populations in the Solar System that are most likely to survive the violent post-main-sequence evolution, such as the Kuiper Belt, display a large binary fraction with a propensity for near equal-mass components and provide a previously unexplored population of planetesimals that are likely to exist around white dwarfs. Here, we simulate the dynamical evolution of equal-mass binary asteroid systems around white dwarfs using the N-body integrator REBOUND for 1 Gyr. We confirm that giant planets are efficient at dissociating and ejecting binary asteroid systems on eccentric orbits, while Earth-mass planets are better at keeping planetesimals in their planetary systems. We find binary systems can be dissociated and ejected from their systems across Myr time-scales, producing interstellar objects. We do not expect a population of free-floating binary asteroid systems as all ejected planetesimals are gravitationally unbound from each other. Further, we discuss the influence of asteroid binarity on the white dwarf pollution process and find there is little to no impact on how close a body can get to a star. However, the orbital evolution of binary asteroids changes the distribution of planetesimals available in a white dwarf planetary system to be further scattered onto white dwarf polluting orbits.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 3, pp.4009-4022

F4

The Dynamical Consequences of a Super-Earth in the Solar System

Show affiliations

Kane, Stephen R.

Placing the architecture of the solar system within the broader context of planetary architectures is one of the primary topics of interest within planetary science. Exoplanet discoveries have revealed a large range of system architectures, many of which differ substantially from the solar system's model. One particular feature of exoplanet demographics is the relative prevalence of super-Earth planets, for which the solar system lacks a suitable analog, presenting a challenge to modeling their interiors and atmospheres. Here we present the results of a large suite of dynamical simulations that insert a hypothetical planet in the mass range 1-10 $M_\oplus$ within the semimajor axis range 2-4 au, between the orbits of Mars and Jupiter. We show that, although the system dynamics remain largely unaffected when the additional planet is placed near 3 au, Mercury experiences substantial instability when the additional planet lies in the range 3.1-4.0 au, and perturbations to the Martian orbit primarily result when the additional planet lies in the range 2.0-2.7 au. We further show that, although Jupiter and Saturn experience relatively small orbital perturbations, the angular momentum transferred to the ice giants can result in their ejection from the system at key resonance locations of the additional planet. We discuss the implications of these results for the architecture of the inner and outer solar system planets, and for exoplanetary systems.

Publication: The Planetary Science Journal, Volume 4, Issue 2, id.38, 17 pp.

F5

Do all gaps in protoplanetary discs host planets?

Show affiliations

Tzouvanou, Anastasia ; Bitsch, Bertram ; Pichierri, Gabriele

Following the assumption that the disc substructures observed in protoplanetary discs originate from the interaction between the disc and the forming planets embedded therein, we aim to test if these putative planets could represent the progenitors of the currently observed giant exoplanets. We performed N-body simulations initially assuming three, four, five, or seven planets. Our model includes pebble and gas accretion, migration, damping of eccentricities and inclinations, disc-planet interaction, and disc evolution. We located the planets in the positions where the gaps in protoplanetary discs have been observed and we evolved the systems for 100 Myr including a few million years of gas disc evolution, while also testing three values of α viscosity. For planetary systems with initially three and four planets, we find that most of the growing planets lie beyond the radial-velocity (RV) detection limit of 5AU and only a small fraction of them migrate into the inner region. We also find that these systems have final eccentricities that are too low to be in agreement with the observed giant planet population. Systems initially consisting of five or seven planets become unstable after ≈40 Kyr of integration time. This clearly shows that not every gap can host a planet. The general outcome of our simulations - eccentricities that are too low - is independent of the disc's viscosity and surface density. Further observations could either confirm the existence of an undetected population of wide-orbit giants or exclude the presence of such an undetected population to constrain how many planets hide in gaps even further.

Publication: Astronomy & Astrophysics, Volume 677, id.A82, 11 pp.

F6

The orbits of outer planetary satellites using the Gaia data

Show affiliations

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Launch of the Gaia space observatory started a new era in astrometry when the accuracy of star coordinates increased by thousands of times. Significant improvement in accuracy was also expected for the coordinates of the Solar system bodies. Gaia Data Release 3 (DR3) provided us with the data that could be used to test our expectations. In this work, we refine the orbits of a number of outer planetary satellites using both ground-based and Gaia observations. From 13 outer satellites observed by Gaia, we chose 6 to obtain their orbits. Some specific moments in using observations of outer satellites made by Gaia are demonstrated. These peculiarities stem from scanning motion of Gaia, in particular from the fact that the accuracy of observations is significantly different along and across the scanning direction. As expected, Gaia observations proved to be more precise than those made from Earth, which results in more accurate satellite ephemerides. We estimate accuracy of the ephemerides of considered satellites for the interval between 1996 and 2030. As astrometric positions published in Gaia DR3 were not corrected for the relativistic light deflection by the Sun, we took into account this effect, which slightly diminished the rms residuals. In addition, relativistic light deflection by the giant planets was estimated, which, as it turned out, can be neglected with the given accuracy of Gaia observations.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 522, Issue 1, pp.165-172