MVSem SS23

A. Just, R. Spurzem, F. Flammini Dotti

Dynamics of galaxies, star clusters and planetary systems

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

Milky Way: J1, J2, (disc); -- (bar); -- (halo)

Star Cluster: J3, J4, J5, S3, S4; Galaxies/Cosmology: J6, J7, J8

Planetary systems: S5, F1, F2, F3, F4, F5

Black Holes / Galactic Nuclei: S1, S2

J1

The disturbed outer Milky Way disc

Show affiliations

McMillan, Paul J. ; Petersson, Jonathan ; Tepper-Garcia, Thor ; Bland-Hawthorn, Joss ; Antoja, Teresa ; Chemin, Laurent ; Figueras, Francesca ; Khanna, Shourya ; Kordopatis, Georges ; Ramos, Pau ; Romero-Gómez, Merce ; Seabroke, George

The outer parts of the Milky Way's disc are significantly out of equilibrium. Using only distances and proper motions of stars from Gaia's Early Data Release 3, in the range $|b| < 10°$, $130° < \ell < 230°$, we show that for stars in the disc between around 10 and $14\,\mathrm{kpc}$ from the Galactic centre, vertical velocity is strongly dependent on the angular momentum, azimuth, and position above or below the Galactic plane. We further show how this behaviour translates into a bimodality in the velocity distribution of stars in the outer Milky Way disc. We use an N-body model of an impulse-like interaction of the Milky Way disc with a perturber similar to the Sagittarius dwarf to demonstrate that this mechanism can generate a similar disturbance. It has already been shown that this interaction can produce a phase spiral similar to that seen in the Solar neighbourhood. We argue that the details of this substructure in the outer galaxy will be highly sensitive to the timing of the perturbation or the gravitational potential of the Galaxy, and therefore may be key to disentangling the history and structure of the Milky Way.

J2

MNRAS **520,** 1832–1847 (2023) https://doi.org/10.1093/mnras/stad094
Advance Access publication 2023 January 12

Self-consistent models of our Galaxy

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Accepted 2022 December 13. Received 2022 December 13; in original form 2022 June 7

ABSTRACT
A new class of models of stellar discs is introduced and used to build a self-consistent model of our Galaxy. The model is defined by the parameters that specify the action-based distribution functions (DFs) $f(\mathbf{J})$ of four stellar discs (three thin-disc age cohorts and a thick disc), spheroidal bulge and spheroidal stellar and dark haloes. From these DFs plus a specified distribution of gas, we solve for the densities of stars and dark matter and the potential they generate. The principal observational constraints are the kinematics of stars with *Gaia* Radial Velocity Spectrometer (RVS) data and the density of stars in the column above the Sun. The model predicts the density and kinematics of stars and dark matter throughout the Galaxy, and suggests the structure of the dark halo prior to the infall of baryons. The code used to create the model is available on GITHUB.

J3

MNRAS **518,** 662–668 (2023) https://doi.org/10.1093/mnras/stac2247
Advance Access publication 2022 August 11

Benchmarking MESA isochrones against the Hyades single star sequence

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Accepted 2022 August 5. Received 2022 August 5; in original form 2022 June 11

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 $0.85\,M_{\odot}$.

J4

THE ASTROPHYSICAL JOURNAL, 938:100 (9pp), 2022 October 20 https://doi.org/10.3847/1538-4357/ac92fc

CrossMark

On the Nature of Rotation in the Praesepe Cluster

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Received 2022 June 4; revised 2022 September 15; accepted 2022 September 15; published 2022 October 18

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 $41^\circ \pm 12^\circ$. 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.

J5

THE ASTRONOMICAL JOURNAL, 165:45 (12pp), 2023 February https://doi.org/10.3847/1538-3881/aca666

Unresolved Binaries and Multiples in the Intermediate Mass Range in Open Clusters: Pleiades, Alpha Per, Praesepe, and NGC 1039

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Received 2022 September 21; revised 2022 November 22; accepted 2022 November 22; published 2023 January 10

Abstract

In this study, we continue our project to search for unresolved binary and multiple systems in open clusters exploiting the photometric diagram (H–W2)–W1 versus W2–(BP–K) first introduced in Malofeeva et al. In particular, here we estimate the binary and multiple star ratios and the distribution of the component mass ratio q in the Galactic clusters Alpha Persei, Praesepe, and NGC 1039. We have modified the procedure outlined in our first study making star counts automatic and by introducing bootstrapping for error estimation. Basing on this, we reinvestigated the Pleiades star cluster in the same mass range as in our previous work and corrected an inaccuracy in the mass ratio q distribution. The binary and multiple star ratio in the four clusters is then found to lie between 0.45 ± 0.03 and 0.73 ± 0.03. On the other hand, the ratio of systems with multiplicity more than 2 is between 0.06 ± 0.01 and 0.09 ± 0.02. The distribution of the component mass ratio q is well fitted with a Gaussian having the mode between 0.22 ± 0.04 and 0.52 ± 0.01 and the dispersion between 0.10 ± 0.02 and 0.35 ± 0.07. All clusters show a large number of the very low-mass secondary components in the binary systems with primary components below 0.5 $M_{\odot}$.

J6

A&A 672, A71 (2023)
https://doi.org/10.1051/0004-6361/202345851

Astronomy & Astrophysics

JWST high-redshift galaxy constraints on warm and cold dark matter models

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Received 5 January 2023 / Accepted 16 February 2023

ABSTRACT

Context. Warm dark matter is a possible alternative to cold dark matter to explain cosmological structure formation.
Aims. We study the implications of the latest JWST data on the nature of dark matter.
Methods. We compare properties of high-redshift galaxies observed by JWST with hydrodynamical simulations, in the standard cold dark matter model and in warm dark matter models with a suppressed linear matter power spectrum
Results. We find that current data are neither in tension with cold dark matter nor with warm dark matter models with $m_{\rm WDM} > 2\,$keV, since they probe bright and rare objects whose physical properties are similar in the different scenarios.
Conclusions. We also show how two observables, the galaxy luminosity functions and the galaxy correlation function at small scales of faint objects, can be promising tools for discriminating between the different dark-matter scenarios. Further hints may come from early stellar-mass statistics and galaxy CO emission.

J7

MNRAS **521,** 800–817 (2023)
Advance Access publication 2023 February 24

https://doi.org/10.1093/mnras/stad586

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

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Accepted 2023 February 17. Received 2023 February 14; in original form 2022 December 13

ABSTRACT

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, $\sim$2 ($\sim$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 \sim$1–2, and that half of the stars that are part of the BCG at $z = 0$ formed early ($z \sim 3$) 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.

J8

MNRAS **520**, 1630–1641 (2023) https://doi.org/10.1093/mnras/stad178
Advance Access publication 2023 January 23

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

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Accepted 2023 January 12. Received 2023 January 10; in original form 2022 September 28

ABSTRACT

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 $z \sim 0$–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.

S1

The growth of intermediate mass black holes through tidal captures and tidal disruption events

Show affiliations

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We present N-body simulations, including post-Newtonian dynamics, of dense clusters of low-mass stars harbouring central black holes (BHs) with initial masses of 50, 300, and 2000 $M_\odot$. The models are evolved with the N-body code BIFROST to investigate the possible formation and growth of massive BHs by the tidal capture of stars and tidal disruption events (TDEs). We model star-BH tidal interactions using a velocity-dependent drag force, which causes orbital energy and angular momentum loss near the BH. About ~20-30 per cent of the stars within the spheres of influence of the black holes form Bahcall-Wolf cusps and prevent the systems from core collapse. Within the first 40 Myr of evolution, the systems experience 500-1300 TDEs, depending on the initial cluster structure. Most (>95 per cent) of the TDEs originate from stars in the Bahcall-Wolf cusp. We derive an analytical formula for the TDE rate as a function of the central BH mass, density, and velocity dispersion of the clusters ($\dot{N}_{\rm TDE} \propto M_{\rm BH} \rho \sigma^{-3}$). We find that TDEs can lead a 300 $M_\odot$ BH to reach $\sim 7000\,{\rm M}_\odot$ within a Gyr. This indicates that TDEs can drive the formation and growth of massive BHs in sufficiently dense environments, which might be present in the central regions of nuclear star clusters.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 521, Issue 2, pp.2930-2948

S2

Growing Black Holes through Successive Mergers in Galactic Nuclei: I. Methods and First Results

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21 March 2023

ABSTRACT

We present a novel, few-body computational framework designed to shed light on the likelihood of forming intermediate-mass (IM) and supermassive (SM) black holes (BHs) in nuclear star clusters (NSCs) through successive BH mergers, initiated with a single BH seed. Using observationally motivated NSC profiles, we find that the probability of a $\sim 100\,M_\odot$ BH to grow beyond $\sim 1000\,M_\odot$ through successive mergers ranges from $\sim 0.1\%$ in low-density, low-mass clusters to nearly 90% in high-mass, high-density clusters. However, in the most massive NSCs, the growth timescale can be very long ($\gtrsim$ 1 Gyr); vice versa, while growth is least likely in less massive NSCs, it is faster there, requiring as little as $\sim$0.1 Gyr. The increased gravitational focusing in systems with lower velocity dispersions is the primary contributor to this behavior. We find that there is a simple "7-strikes-and-you're-in" rule governing the growth of BHs: our results suggest that if the seed survives 7 to 10 successive mergers without being ejected (primarily through gravitational wave recoil kicks), the growing BH will most likely remain in the cluster and will then undergo runaway, continuous growth all the way to the formation of an SMBH (under the simplifying assumption adopted here of a fixed background NSC). Furthermore, we find that rapid mergers enforce a dynamically-mediated "mass gap" between about $50 - 300\,M_\odot$ in an NSC.

S3

First observational evidence of a relation between globular clusters' internal rotation and stellar masses

Show affiliations

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Bedin, L. R. iD

Several observational studies have shown that many Galactic globular clusters (GCs) are characterized by internal rotation. Theoretical studies of the dynamical evolution of rotating clusters have predicted that, during their long-term evolution, these stellar systems should develop a dependence of the rotational velocity around the cluster's centre on the mass of stars, with the internal rotation increasing for more massive stars. In this paper, we present the first observational evidence of the predicted rotation-mass trend. In our investigation, we exploited the Gaia Data Release 3 catalogue of three GCs: NGC 104 (47 Tuc), NGC 5139 (ω Cen), and NGC 5904 (M 5). We found clear evidence of a cluster rotation-mass relation in 47 Tuc and M 5, while in ω Cen, the dynamically youngest system among the three clusters studied here, no such trend was detected.

Publication: Monthly Notices of the Royal Astronomical Society: Letters, Volume 522, Issue 1, pp.L61-L65

S4

The role of rotation on the formation of second generation stars in globular clusters

Show affiliations

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By means of 3D hydrodynamic simulations, we explore the effects of rotation in the formation of second-generation (SG) stars in globular clusters (GC). Our simulations follow the SG formation in a first-generation (FG) internally rotating GC; SG stars form out of FG asymptotic giant branch (AGB) ejecta and external pristine gas accreted by the system. We have explored two different initial rotational velocity profiles for the FG cluster and two different inclinations of the rotational axis with respect to the direction of motion of the external infalling gas, whose density has also been varied. For a low (10^{-24} g cm^{-3}) external gas density, a disc of SG helium-enhanced stars is formed. The SG is characterized by distinct chemo-dynamical phase space patterns: it shows a more rapid rotation than the FG with the helium-enhanced SG subsystem rotating more rapidly than the moderate helium-enhanced one. In models with high external gas density ($10^{-23}\ \mathrm{g\ cm^{-3}}$), the inner SG disc is disrupted by the early arrival of external gas and only a small fraction of highly enhanced helium stars preserves the rotation acquired at birth. Variations in the inclination angle between the rotation axis and the direction of the infalling gas and the velocity profile can slightly alter the extent of the stellar disc and the rotational amplitude. The results of our simulations illustrate the complex link between dynamical and chemical properties of multiple populations and provide new elements for the interpretation of observational studies and future investigations of the dynamics of multiple-population GCs.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 517, Issue 1, pp.1171-1188

Pub Date: November 2022

S5

Formation History of HD 106906 and the Vertical Warping of Debris Disks by an External Inclined Companion

Show affiliations

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HD 106906 is a planetary system that hosts a wide-orbit companion, as well as an eccentric and flat debris disk, which hold important constraints on its formation and subsequent evolution. The recent observations of the companion constrain its orbit to be eccentric and inclined relative to the plane of the debris disk. Here, we show that, in the presence of the inclined companion, the debris disk quickly ($\lesssim$5 Myr) becomes warped and puffy. This suggests that the current configuration of the system is relatively recent. We explore the possibility that a recent close encounter with a free-floating planet could produce a companion with orbital parameters that agree with observations of HD 106906 b. We find that this scenario is able to recreate the structure of the debris disk while producing a companion in agreement with observation.

Publication: The Astrophysical Journal, Volume 943, Issue 1, id.6, 13

F1

The Astrophysical Journal Letters, 937:L22 (8pp), 2022 October 1 https://doi.org/10.3847/2041-8213/ac90b9

A Low-inclination Neutral Trans-Neptunian Object in an Extreme Orbit

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Received 2022 June 23; revised 2022 September 7; accepted 2022 September 8; published 2022 September 26

Abstract

We present photometric observations and numerical simulations of 2016 SD_{106}, a low-inclination ($i = 4\overset{\circ}{.}8$) extreme trans-Neptunian Object with a large semimajor axis ($a = 350$ au) and perihelion ($q = 42.6$ au). This object possesses a peculiar neutral color of $g - r = 0.45 \pm 0.05$ and $g - i = 0.72 \pm 0.06$, in comparison with other distant trans-Neptunian objects, all of which have moderate-red to ultra-red colors. A numerical integration based on orbital fitting on astrometric data covering eight years of arc confirms that 2016 SD_{106} is a metastable object without significant scattering evolution. Each of the clones survived at the end of the 1 Gyr simulation. However, very few neutral objects with inclinations $<5°$ have been found in the outer solar system, even in the main Kuiper Belt. Furthermore, most mechanisms that lift perihelion distances are expected to produce a very low number of extreme objects with inclinations $<5°$. We thus explored the possibility that a hypothetical distant planet could increase the production of such objects. Our simulations show that no 2016 SD_{106}–like orbits can be produced from three Kuiper Belt populations tested (i.e., plutinos, twotinos, and the Haumea Family) without the presence of a hypothetical planet, while a few similar orbits can be obtained with it; however, the presence of the additional planet produces a wide range of large semimajor-axis/large perihelion objects, in apparent contradiction with the observed scarcity of objects in those regions of phase space. Future studies may determine if there is a connection between the existence of a perihelion gap and a particular orbital configuration of a hypothetical distant planet.

F2

THE ASTROPHYSICAL JOURNAL LETTERS, 938:L3 (12pp), 2022 October 10 https://doi.org/10.3847/2041-8213/ac9521

CrossMark

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.

F3

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**

F4

The orbital evolution of Atira asteroids

Hsuan-Ting Lai, Wing-Huen Ip

Asteroids having perihelion distance $q < 1.3$ AU are classified as near-Earth objects (NEOs), which are divided into different sub-groups: Vatira-class, Atira-class, Aten-class, Apollo-class, and Amor-class. 2020 AV_2, the first Vatira (Orbiting totally inside Venus' orbit) was discovered by the Twilight project of the Zwicky Transient Facility (ZTF) on January 4, 2020. Upon the discovery of 2020 AV_2, a couple of orbital studies of the short-term orbital evolution of 2020 AV_2 have been performed and published (e.g. de la Fuente Marcos & de la Fuente Marcos 2020; Greenstreet 2020). In this present work, we performed an assessment of the long-term orbital evolution of known near-Earth objects and known Atiras under the Yarkovsky effect by using the \textit{Mercury6} N-body code. We considered not only planetary gravitational perturbation but also the non-gravitational Yarkovsky effect. Our calculation shows that the NEOs have generally two dynamical populations, one short-lived and the other long-lived. From our calculation, the transfer probabilities of Atira-class asteroids to Vatira-class asteroids for the first transition are $\sim$13.1 $\pm$ 0.400, $\sim$13.05 $\pm$ 0.005, and $\sim$ 13.25 $\pm$ 0.450 $\%$ for different values of the Yarkovsky force (i.e. obliquity of 0, 90, and 180 deg.), respectively. It suggests that the radiation force may play some role in the long-term evolution of this asteroid population. Finally, our statistical study implicates that there should be 8.14 $\pm$ 0.133 Atira-class asteroids and 1.05 $\pm$ 0.075 Vatira-asteroids of the S-type taxonomy.

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Stability analysis of planetary systems via second-order Rényi entropy

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The long-term dynamical evolution is a crucial point in recent planetary research. Although the amount of observational data is continuously growing and the precision allows us to obtain accurate planetary orbits, the canonical stability analysis still requires N-body simulations and phase space trajectory investigations. We propose a method for stability analysis of planetary motion based on the generalized Rényi entropy obtained from a scalar measurement. The radial velocity data of the central body in the gravitational three-body problem is used as the basis of a phase space reconstruction procedure. Then, Poincaré's recurrence theorem contributes to finding a natural partitioning in the reconstructed phase space to obtain the Rényi entropy. It turns out that the entropy-based stability analysis is in good agreement with other chaos detection methods, and it requires only a few tens of thousands of orbital period integration time.

Comments: 7 pages, 7 figures, MNRAS 517, 5160, (2022)