

MVSem SS2022 (A. Just, R. Spurzem)
**Dynamics of galaxies, star clusters and
planetary systems**

Abstracts topics T1-9 (**Supervisor Just**) T11-14 (**Supervisor Spurzem**)

Milky Way: T1, T4, T6 (disc); T2, T3 (bar); T7 (halo)

Star Cluster: T5, T8, T14 Galaxies: T9

Black Holes: T12 Planets: T11, T13

T1

The GALAH survey and Gaia DR2: Linking ridges, arches, and vertical waves in the kinematics of the Milky Way

Show affiliations

Khanna, Shourya; Sharma, Sanjib; Tepper-Garcia, Thor; Bland-Hawthorn, Joss; Hayden, Michael; Asplund, Martin; Buder, Sven; Chen, Boquan; De Silva, Gayandhi M.; Freeman, Ken C.; Kos, Janez; Lewis, Geraint F.; Lin, Jane; Martell, Sarah L.; Simpson, Jeffrey D.; Nordlander, Thomas; Stello, Dennis; Ting, Yuan-Sen; Zucker, Daniel B.; Zwitter, Tomaž

Gaia DR2 has revealed new small-scale and large-scale patterns in the phase-space distribution of stars in the Milky Way. In cylindrical Galactic coordinates (R, ϕ, z) , ridge-like structures can be seen in the (R, V_ϕ) plane and asymmetric arch-like structures in the (V_R, V_ϕ) plane. We show that the ridges are also clearly present when the third dimension of the (R, V_ϕ) plane is represented by $\langle z \rangle$, $\langle V_z \rangle$, $\langle V_R \rangle$, $\langle [\text{Fe}/\text{H}] \rangle$, and $\langle [\alpha/\text{Fe}] \rangle$. The maps suggest that stars along the ridges lie preferentially close to the Galactic mid-plane ($|z| < 0.2$ kpc), and have metallicity and α elemental abundance similar to that of the Sun. We show that phase mixing of disrupting spiral arms can generate both the ridges and the arches. It also generates discrete groupings in orbital energy - the ridges and arches are simply surfaces of constant energy. We identify eight distinct ridges in the Gaia DR2 data: six of them have constant energy while two have constant angular momentum. Given that the signature is strongest for stars close to the plane, the presence of ridges in $\langle z \rangle$ and $\langle V_z \rangle$ suggests a coupling between planar and vertical directions. We demonstrate, using N-body simulations that such coupling can be generated both in isolated discs and in discs perturbed by an orbiting satellite like the Sagittarius dwarf galaxy.

Publication:

Monthly Notices of the Royal Astronomical Society, Volume 489, Issue 4, p.4962-4979

T2

The pattern speed of the Milky Way bar from transverse velocities

Show affiliations

Sanders, Jason L.; Smith, Leigh; Evans, N. Wyn

We use the continuity equation to derive a method for measuring the pattern speed of the Milky Way's bar/bulge from proper motion data. The method has minimal assumptions but requires complete coverage of the non-axisymmetric component in two of the three Galactic coordinates. We apply our method to the proper motion data from a combination of Gaia DR2 and VISTA Variables in the Via Lactea (VVV) to measure the pattern speed of the bar as $\Omega_p = (41 \pm 3) \text{ km s}^{-1} \text{ kpc}^{-1}$ (where the error is statistical). This puts the corotation radius at $(5.7 \pm 0.4) \text{ kpc}$, under the assumptions of the standard peculiar motion of the Sun and the absence of non-axisymmetric streaming in the Solar neighbourhood. The obtained result uses only data on the near side of the bar which produces consistent measurements of the distance and velocity of the centre of the Galaxy. Addition of the data on the far side of the bar pulls the pattern speed down to $\Omega_p = (31 \pm 1) \text{ km s}^{-1} \text{ kpc}^{-1}$ but requires a lower transverse velocity for the Galactic centre than observed. This suggests systematics of $5\text{--}10 \text{ km s}^{-1} \text{ kpc}^{-1}$ dominate the uncertainty. We demonstrate using a dynamically formed bar/bulge simulation that even with the limited field of view of the VVV survey our method robustly recovers the pattern speed.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 488, Issue 4, p.4552-4564

T3

Mapping the tilt of the Milky Way bulge velocity ellipsoids with ARGOS and Gaia DR2

Show affiliations

[Simion, Iulia T.](#); [Shen, Juntai](#); [Koposov, Sergey E.](#); [Ness, Melissa](#); [Freeman, Kenneth](#); [Bland-Hawthorn, Joss](#); [Lewis, Geraint F.](#)

Until the recent advent of Gaia Data Release 2 (DR2) and deep multi-object spectroscopy, it has been difficult to obtain 6D phase space information for large numbers of stars beyond 4 kpc, in particular towards the Galactic Centre, where dust and crowding are significant. We combine line-of-sight velocities from the Abundances and Radial velocity Galactic Origins Survey (ARGOS) with proper motions from Gaia DR2 to obtain a sample of ~ 7000 red clump stars with 3D velocities. We perform a large-scale stellar kinematics study of the Milky Way bulge to characterize the bulge velocity ellipsoids in 20 fields. The tilt of the major-axis of the velocity ellipsoid in the radial-longitudinal velocity plane, or vertex deviation, is characteristic of non-axisymmetric systems and a significant tilt is a robust indicator of non-axisymmetry or bar presence. We compare the observations to the predicted kinematics of an N-body boxy-bulge model formed from dynamical instabilities. In the model, the l_v values are strongly correlated with the angle (α) between the bulge major-axis and the Sun-Galactic centre line of sight. We use a maximum likelihood method to obtain an independent measurement of α , from bulge stellar kinematics alone, performing a robust error analysis. The most likely value of α given our model is $\alpha = (29 \pm 3)^\circ$, with an additional systematic uncertainty due to comparison with one specific model. In Baade's window, the metal-rich stars display a larger vertex deviation ($l_v = -40^\circ$) than the metal-poor stars ($l_v = 10^\circ$) but we do not detect significant l_v -metallicity trends in the other fields.

Publication:

Monthly Notices of the Royal Astronomical Society, Volume 502, Issue 2, pp.1740-1752

T4

A time-resolved picture of our Milky Way's early formation history

Show affiliations

Xiang, Maosheng  ; Rix, Hans-Walter 

The formation of our Milky Way can be split up qualitatively into different phases that resulted in its structurally different stellar populations: the halo and the disk components¹⁻³. Revealing a quantitative overall picture of our Galaxy's assembly requires a large sample of stars with very precise ages. Here we report an analysis of such a sample using subgiant stars. We find that the stellar age-metallicity distribution $p(\tau, [\text{Fe}/\text{H}])$ splits into two almost disjoint parts, separated at age $\tau \simeq 8$ Gyr. The younger part reflects a late phase of dynamically quiescent Galactic disk formation with manifest evidence for stellar radial orbit migration⁴⁻⁶; the other part reflects the earlier phase, when the stellar halo⁷ and the old α -process-enhanced (thick) disk^{8,9} formed. Our results indicate that the formation of the Galaxy's old (thick) disk started approximately 13 Gyr ago, only 0.8 Gyr after the Big Bang, and 2 Gyr earlier than the final assembly of the inner Galactic halo. Most of these stars formed around 11 Gyr ago, when the Gaia-Sausage-Enceladus satellite merged with our Galaxy^{10,11}. Over the next 5-6 Gyr, the Galaxy experienced continuous chemical element enrichment, ultimately by a factor of 10, while the star-forming gas managed to stay well mixed.

Publication: Nature, Volume 603, Issue 7902, p.599-603

Pub Date: March 2022

T5

Extended stellar systems in the solar neighborhood. V. Discovery of coronae of nearby star clusters

Show affiliations

Meingast, Stefan  ; Alves, João  ; Rottensteiner, Alena

We present a novel view on the morphology and dynamical state of ten prominent, nearby (≤ 500 pc), and young (~ 30 -300 Myr) open star clusters with Gaia DR2: α Per, Blanco 1, IC 2602, IC 2391, Messier 39, NGC 2451A, NGC 2516, NGC 2547, Platais 9, and the Pleiades. We introduce a pioneering member-identification method that is informed by cluster bulk velocities and deconvolves the spatial distribution with a mixture of Gaussians. Our approach enables inferring the true spatial distribution of the clusters by effectively filtering field star contaminants while at the same time mitigating the effect of positional errors along the line of sight. This first application of the method reveals vast stellar coronae that extend for ≥ 100 pc and surround the cluster cores, which are comparatively tiny and compact. The coronae and cores form intertwined, coeval, and comoving extended cluster populations, each encompassing tens of thousands of cubic parsec and stretching across tens of degrees on the sky. Our analysis shows that the coronae are gravitationally unbound but largely comprise the bulk of the stellar mass of the populations. Most systems are in a highly dynamic state, showing evidence of expansion and sometimes simultaneous contraction along different spatial axes. The velocity field of the extended populations for the cluster cores appears asymmetric but is aligned along a spatial axis unique to each cluster. The overall spatial distribution and the kinematic signature of the populations are largely consistent with the differential rotation pattern of the Milky Way. This finding underlines the important role of global Galactic dynamics in the fate of stellar systems. Our results highlight the complexity of the Milky Way's open cluster population and call for a new perspective on the characterization and dynamical state of open clusters.

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Publication: Astronomy & Astrophysics, Volume 645, id.A84, 23 pp.

Pub Date: January 2021

T6a

Spiral density-wave structure parameters in the solar neighbourhood derived from longitudinal velocities of Gaia EDR3 OB stars: 3D approach

Show affiliations

Griv, Evgeny ; Gedalin, Michael ; Mróz, Przemek  ; Liu, De-Jian ; Jiang, Ing-Guey 

Distances and transverse along the Galactic longitude velocities v_l of 2640 Gaia EDR3 O-B2 stars of Xu et al. within 2.5 kpc from the Sun and 250 pc from the Galactic plane with relative distance and velocity accuracies of <10 and <50 per cent are selected. Under the assumption of spiral density waves, both Galactic differential rotation parameters and parameters of the wave structure in this solar neighbourhood are derived from observed v_l . In contrast to all preceding studies, we take into account the effect of small but finite thickness of the disc of the Galaxy on even parity ('sausage') gravity perturbations of the kind investigated by Lin and Shu. As previously predicted by the modified theory of 3D density waves, two scales of periodic rarefaction-compression irregularity of the v_l velocity field with the radial $\lambda_0 \approx 1.5$ kpc and vertical $\xi_0 \approx 1.0$ kpc wavelengths in the form of a spiral wave propagating in the disc are revealed. The Gaia's DR2 line-of-sight and EDR3 longitudinal velocities analyses performed in the last papers of a series exhibit consistent findings, thus providing a further evidence to support the Lin-Shu density-wave proposal.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 509, Issue 1, pp.463-474

Pub Date: January 2022

T6b

Kinematic footprint of the Milky Way spiral arms in Gaia EDR3

Show affiliations

Martinez-Medina, Luis  ; Pérez-Villegas, Angeles  ; Peimbert, Antonio

The Milky Way spiral arms are well established from star counts as well as from the locus of molecular clouds and other young objects; however, they have only recently started to be observed from a kinematics point of view. Using the kinematics of thin disc stars in Gaia EDR3 around the extended solar neighbourhood, we create x-y projections coloured by the radial, residual rotational, and vertical Galactocentric velocities (U , ΔV , W). The maps are rich in substructures and reveal the perturbed state of the Galactic disc. We find that local differences between rotational velocity and the azimuthally averaged velocity, ΔV , display at least five large-scale kinematic spirals; two of them closely follow the locus of the Sagittarius-Carina and Perseus spiral arms, with pitch angles of 9.12° and 7.76° , and vertical thickness of ~ 400 pc and ~ 600 pc, respectively. Another kinematic spiral is located behind the Perseus arm and appears as a distortion in rotation velocities left by this massive arm but with no known counterpart in gas or stars overdensity. A weaker signal close to the Sun's position is present in our three velocity maps, and appears to be associated with the Local arm. Our analysis of the stellar velocities in the Galactic disc shows kinematic differences between arms and interarms that are in favour of Milky Way spiral arms that do not corotate with the disc. Moreover, we show that the kinematic spirals are clumpy and flocculent, revealing the underlying nature of the Milky Way spiral arms.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 512, Issue 2, pp.1574-1583

Pub Date: May 2022

T7

Probing modified Newtonian dynamics with hypervelocity stars

Show affiliations

Chakrabarty, Sankha Subhra  ; Ostorero, Luisa  ; Gallo, Arianna  ; Ebagezio, Stefano  ; Diaferio, Antonaldo 

We show that measuring the velocity components of hypervelocity stars (HVSs) can discriminate between modified Newtonian dynamics (MOND) and Newtonian gravity. Hypervelocity stars are ejected from the Galactic center on radial trajectories with a null tangential velocity component in the reference frame of the Galaxy. They acquire tangential components due to the nonspherical components of the Galactic gravitational potential. Axisymmetric potentials only affect the latitudinal components, v_θ , and non-null azimuthal components, v_ϕ , originate from non-axisymmetric matter distributions. For HVSs with sufficiently high ejection speed, the azimuthal velocity components are proportionate to the deviation of the gravitational potential from axial symmetry. The ejection velocity threshold is $\sim 750 \text{ km s}^{-1}$ for $4 M_\odot$ stars and increases with decreasing HVS mass. We determine the upper limit of v_ϕ as a function of the galactocentric distance for these high-speed HVSs if MOND, in its quasi-linear formulation QUMOND, is the correct theory of gravity and either the triaxial Galactic bulge or a nonspherical hot gaseous halo is the primary source of the azimuthal component, v_ϕ . In Newtonian gravity, the HVSs within 60 kpc of the Galactic center may easily have v_ϕ values higher than the QUMOND upper limit if the dark matter halo is triaxial or if the dark matter halo and the baryonic components are axisymmetric but their two axes of symmetry are misaligned. Therefore, even a limited sample of high-speed HVSs could in principle allow us to distinguish between the QUMOND scenario and the dark matter model. This test is currently limited by (i) the lack of a proper procedure to assess whether a star originates from the Galactic center and thus is indeed an HVS in the model one wishes to constrain; and (ii) the large uncertainties on the galactocentric azimuthal velocity components, which should be reduced by at least a factor of ~ 10 to make this test conclusive. A proper procedure to assess the HVS nature of the observed stars and astrometric measurements with microarcsecond precision would make this test feasible.

Publication: Astronomy & Astrophysics, Volume 657, id.A115, 16 pp.

Pub Date: January 2022

T8

Forward and back: kinematics of the Palomar 5 tidal tails

Show affiliations

Kuzma, P. B.  ; Ferguson, A. M. N. ; Varri, A. L. ; Irwin, M. J. ; Bernard, E. J. ; Tolstoy, E. ; Peñarrubia, J. ; Zucker, D. B. 

The tidal tails of Palomar 5 (Pal 5) have been the focus of many spectroscopic studies in an attempt to identify individual stars lying along the stream and characterize their kinematics. The well-studied trailing tail has been explored out to a distance of 15° from the cluster centre, while less than 4° have been examined along the leading tail. In this paper, we present results of a spectroscopic study of two fields along the leading tail that we have observed with the AAOmega spectrograph on the Anglo-Australian telescope. One of these fields lies roughly 7° along the leading tail, beyond what has been previously been explored spectroscopically. Combining our measurements of kinematics and line strengths with Pan-STARRS1 photometric data and Gaia EDR3 astrometry, we adopt a probabilistic approach to identify 16 stars with a high probability of belonging to the Pal 5 stream. Eight of these stars lie in the outermost field and their sky positions confirm the presence of 'fanning' in the leading arm. We also revisit previously published radial velocity studies and incorporate Gaia EDR3 astrometry to remove interloping field stars. With a final sample of 109 bona fide Pal 5 cluster and tidal stream stars, we characterize the 3D kinematics along the the full extent of the system. We provide this catalogue for future modeling work.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 512, Issue 1, pp.315-327

Pub Date: May 2022

T9

Measuring the Milky Way mass distribution in the presence of the LMC

Show affiliations

Correa Magnus, Lilia ; Vasiliev, Eugene 

The ongoing interaction between the Milky Way (MW) and its largest satellite - the Large Magellanic Cloud (LMC) - creates a significant perturbation in the distribution and kinematics of distant halo stars, globular clusters and satellite galaxies, and leads to biases in MW mass estimates from these tracer populations. We present a method for compensating these perturbations for any choice of MW potential by computing the past trajectory of LMC and MW and then integrating the orbits of tracer objects back in time until the influence of the LMC is negligible, at which point the equilibrium approximation can be used with any standard dynamical modelling approach. We add this orbit-rewinding step to the mass estimation approach based on simultaneous fitting of the potential and the distribution function of tracers, and apply it to two data sets with the latest Gaia EDR3 measurements of 6D phase-space coordinates: globular clusters and satellite galaxies. We find that models with LMC mass in the range $(1 - 2) \times 10^{11} M_{\odot}$ better fit the observed distribution of tracers, and measure MW mass within 100 kpc to be $(0.75 \pm 0.1) \times 10^{12} M_{\odot}$, while neglecting the LMC perturbation increases it by ~15 per cent.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 511, Issue 2, pp.2610-2630

Pub Date: April 2022

T11

On the Correlation between Hot Jupiters and Stellar Clustering: High-eccentricity Migration Induced by Stellar Flybys

Show affiliations

[Rodet, Laetitia](#)  ; [Su, Yubo](#)  ; [Lai, Dong](#) 

A recent observational study suggests that the occurrence of hot Jupiters (HJs) around solar-type stars is correlated with stellar clustering. We study a new scenario for HJ formation, called "Flyby Induced High-e Migration," that may help explain this correlation. In this scenario, stellar flybys excite the eccentricity and inclination of an outer companion (giant planet, brown dwarf, or low-mass star) at large distance (10-300 au), which then triggers high-e migration of an inner cold Jupiter (at a few astronomical units) through the combined effects of von Zeipel-Lidov-Kozai (ZLK) eccentricity oscillation and tidal dissipation. Using semianalytical calculations of the effective ZLK inclination window, together with numerical simulations of stellar flybys, we obtain the analytic estimate for the HJ occurrence rate in this formation scenario. We find that this "flyby induced high-e migration" could account for a significant fraction of the observed HJ population, although the result depends on several uncertain parameters, including the density and lifetime of birth stellar clusters, and the occurrence rate of the "cold Jupiter + outer companion" systems.

Publication: The Astrophysical Journal, Volume 913, Issue 2, id.104, 8 pp.

Pub Date: June 2021

T12

Improved gravitational radiation time-scales II: Spin-orbit contributions and environmental perturbations

Show affiliations

Zwick, Lorenz ; Capelo, Pedro R.  ; Bortolas, Elisa  ; Vázquez-Aceves, Verónica ; Mayer, Lucio ; Amaro-Seoane, Pau

Peters' formula is an analytical estimate of the time-scale of gravitational wave (GW)-induced coalescence of binary systems. It is used in countless applications, where the convenience of a simple formula outweighs the need for precision. However, many promising sources of the Laser Interferometer Space Antenna (LISA), such as supermassive black hole binaries and extreme mass-ratio inspirals (EMRIs), are expected to enter the LISA band with highly eccentric ($e \gtrsim 0.9$) and highly relativistic orbits. These are exactly the two limits in which Peters' estimate performs the worst. In this work, we expand upon previous results and give simple analytical fits to quantify how the inspiral time-scale is affected by the relative 1.5 post-Newtonian (PN) hereditary fluxes and spin-orbit couplings. We discuss several cases that demand a more accurate GW time-scale. We show how this can have a major influence on quantities that are relevant for LISA event-rate estimates, such as the EMRI critical semimajor axis. We further discuss two types of environmental perturbations that can play a role in the inspiral phase: the gravitational interaction with a third massive body and the energy loss due to dynamical friction and torques from a surrounding gas medium ubiquitous in galactic nuclei. With the aid of PN corrections to the time-scale in vacuum, we find simple analytical expressions for the regions of phase space in which environmental perturbations are of comparable strength to the effects of any particular PN order, being able to qualitatively reproduce the results of much more sophisticated analyses.

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Pub Date: September 2021

T13

Inside-out planet formation: VI. oligarchic coagulation of planetesimals from a pebble ring?

Show affiliations

Cai, Maxwell X.  ; Tan, Jonathan C. ; Portegies Zwart, Simon

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 disc 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 per cent of the total mass, with the building-up process typically finishing within $\sim 10^5$ yr. However, a relatively massive secondary planet always remains with $\sim 30 - 65$ per cent 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 modelling and explored as next steps.

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March 2022

T14

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

Show affiliations

Wan, Zhen  ; Oliver, William H. ; Baumgardt, Holger  ; Lewis, Geraint F.  ; Gieles, Mark  ; Hénault-Brunet, Vincent  ;
de Boer, Thomas  ; Balbinot, Eduardo  ; Da Costa, Gary  ; Mackey, Dougal

As part of a chemodynamical 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 ($\sim 9 \text{ mas yr}^{-1}$). After subtracting the contribution of this perspective rotation, we found a remaining rotation signal with an amplitude of $\sim 1 \text{ km s}^{-1}$ 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. ($3.5 \pm 0.9 \text{ km s}^{-1}$) has previously been attributed to dark matter. Here, we show that the LOS dispersion between 0.5 and 1 Jacobi radius is lower ($2.01 \pm 0.18 \text{ km s}^{-1}$), yet above the predictions from an N-body model of NGC 3201 that we ran for this study ($1.48 \pm 0.14 \text{ km s}^{-1}$). 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.

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