MVSem SS2021(A. Just, R.Spurzem)

Dynamics of galaxies, star clusters and planetary systems

Abstracts topics J* (Supervisor Just)

Milky Way: J1, J3, J6 (disc); J2, J5 (bar); J4, J7 (halo); J8 (open clusters)

Supermassive Black Holes: J9, J10

J1

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 $< z >$, $< V_z >$, $< V_R >$, $<[Fe/H]>$, and $< [\alpha /Fe]>$. 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 $< z >$ and $< V_z >$ 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

J2

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 Ω _p=(41± 3) km s^{-1 kpc^{-1}} (where the error is statistical). This puts the corotation radius at (5.7± 0.4) 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 Ω _p=(31± 1) km s^{-1 kpc^{-1}} but requires a lower transverse velocity for the Galactic centre than observed. This suggests systematics of 5-10 km s^{-1kpc^{-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

J3

Hic sunt dracones: Cartography of the Milky Way spiral arms and bar resonances with Gaia Data Release 2

Show affiliations

Khoperskov, S.; Gerhard, O.; Di Matteo, P.; Haywood, M.; Katz, D.; Khrapov, S.; Khoperskov, A.; Arnaboldi, M.

In this paper we introduce a new method for analysing Milky Way phase-space which allows us to reveal the imprint left by the Milky Way bar and spiral arms on the stars with full phase-space data in Gaia Data Release 2. The unprecedented quality and extended spatial coverage of these data allowed us to discover six prominent stellar density structures in the disc to a distance of 5 kpc from the Sun. Four of these structures correspond to the spiral arms detected previously in the gas and young stars (Scutum-Centaurus, Sagittarius, Local, and Perseus). The remaining two are associated with the main resonances of the Milky Way bar where corotation is placed at around 6.2 kpc and the outer Lindblad resonance beyond the solar radius, at around 9 kpc. For the first time we provide evidence of the imprint left by spiral arms and resonances in the stellar densities not relying on a specific tracer, through enhancing the signatures left by these asymmetries. Our method offers new avenues for studying how the stellar populations in our Galaxy are shaped.

Here be dragons, a phrase famous in medieval cartography when dragons and sea monsters were used to designate uncharted and possibly dangerous regions.

Publication: Astronomy & Astrophysics, Volume 634, id.L8, 9 pp.

J4

Evidence of a population of dark subhaloes from Gaia and Pan-STARRS observations of the GD-1 stream

Show affiliations

Banik, Nilanjan; Bovy, Jo; Bertone, Gianfranco; Erkal, Denis; de Boer, T. J. L.

New data from the Gaia satellite, when combined with accurate photometry from the Pan-STARRS survey, allow us to accurately estimate the properties of the GD-1 stream. Here, we analyse the stellar density variations in the GD-1 stream and show that they cannot be due to known baryonic structures such as giant molecular clouds, globular clusters, or the Milky Way's bar or spiral arms. A joint analysis of the GD-1 and Pal 5 streams instead requires a population of dark substructures with masses $\asymp 10^7$- $10^9\ \mathrm{M}_\odot$. We infer a total abundance of dark subhaloes normalized to standard cold dark matter $n_{\rm sub}/n_{\rm sub,CDM} = 0.4^{+0.3}_{-0.2}$ (68 per cent), which corresponds to a mass fraction contained in the subhaloes $f_{\rm sub} = 0.14^{+0.11}_{-0.07}$ per cent , compatible with the predictions of hydrodynamical simulation of cold dark matter with baryons.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 502, Issue 2, pp.2364-2380

J5

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

J6

Co-formation of the thin and thick discs revealed by APOGEE-DR16 and Gaia-DR2

Show affiliations

Beraldo e Silva, Leandro; Debattista, Victor P.; Nidever, David; Amarante, João A. S.; Garver, Bethany

Since thin disc stars are younger than thick disc stars on average, the thin disc is predicted by some models to start forming after the thick disc had formed, around 10 Gyr ago. Accordingly, no significant old thin disc population should exist. Using 6D coordinates from Gaia-DR2 and age estimates from Sanders & Das, we select ~24 000 old stars ($\tau > 10\,\mathrm{Gyr}$, with uncertainties $\lesssim 15$ per cent) within $2\,\mathrm{kpc}$ from the Sun (full sample). A cross-match with APOGEE-DR16 (~1000 stars) reveals comparable fractions of old chemically defined thin/thick disc stars. We show that the full sample pericentre radius (r_{per}) distribution has three peaks, one associated with the stellar halo and the other two having contributions from the thin/thick discs. Using a high-resolution N-body + SPH simulation, we demonstrate that one peak, at $r_{\rm per} \approx 7.1\,\mathrm{kpc}$, is produced by stars from both discs that were born in the inner Galaxy and migrated to the Solar Neighbourhood. In the Solar Neighbourhood, ~1/2 (~1/3) of the old thin (thick) disc stars are classified as migrators. Our results suggest that thin/thick discs are affected differently by radial migration inasmuch as they have different eccentricity distributions, regardless of vertical scale heights. We interpret the existence of a significant old thin disc population as evidence for an early co-formation of thin/thick discs, arguing that clump instabilities in the early disc offer a compelling explanation for the observed trends.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 502, Issue 1, pp.260-272

J7

The mass of the Milky Way out to 100 kpc using halo stars

Show affiliations

Deason, Alis J.; Erkal, Denis; Belokurov, Vasily; Fattahi, Azadeh; Gómez, Facundo A.; Grand, Robert J. J.; Pakmor, Rüdiger; Xue, Xiang-Xiang; Liu, Chao; Yang, Chengqun; Zhang, Lan; Zhao, Gang

We use a distribution function analysis to estimate the mass of the Milky Way (MW) out to 100 kpc using a large sample of halo stars. These stars are compiled from the literature, and the vast majority ($\sim$98 per cent) have 6D phase-space information. We pay particular attention to systematic effects, such as the dynamical influence of the Large Magellanic Cloud (LMC), and the effect of unrelaxed substructure. The LMC biases the (pre-LMC infall) halo mass estimates towards higher values, while realistic stellar haloes from cosmological simulations tend to underestimate the true halo mass. After applying our method to the MW data, we find a mass within 100 kpc of M (<100 kpc) = 6.07 ± 0.29 (stat.) $\pm$ 1.21 (sys.) $\times 10^{11}$ $M_{\odot}$. For this estimate, we have approximately corrected for the reflex motion induced by the LMC using the Erkal et al. model, which assumes a rigid potential for the LMC and MW. Furthermore, stars that likely belong to the Sagittarius stream are removed, and we include a 5 per cent systematic bias, and a 20 per cent systematic uncertainty based on our tests with cosmological simulations. Assuming the mass-concentration relation for Navarro-Frenk-White haloes, our mass estimate favours a total (pre-LMC infall) MW mass of $M_{200c} = 1.01 \pm 0.24 \times 10^{12}$ $M_{\odot}$, or (post-LMC infall) mass of $M_{200c} = 1.16 \pm 0.24 \times 10^{12}$ $M_{\odot}$ when a 1.5×10^{11} $M_{\odot}$ mass of a rigid LMC is included.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 501, Issue 4, pp.5964-5972

J8

3D kinematics and age distribution of the open cluster population

Show affiliations

Tarricq, Y.; Soubiran, C.; Casamiquela, L.; Cantat-Gaudin, T.; Chemin, L.; Anders, F.; Antoja, T.; Romero-Gómez, M.; Figueras, F.; Jordi, C.; Bragaglia, A.; Balaguer-Núñez, L.; Carrera, R.; Castro-Ginard, A.; Moitinho, A.; Ramos, P.; Bossini, D.

Context. Open clusters (OCs) trace the evolution of the Galactic disc with great accuracy. Gaia and large ground-based spectroscopic surveys make it possible to determine their properties and study their kinematics with unprecedented precision.
Aims: We study the kinematical behaviour of the OC population over time. We take advantage of the latest age determinations of OCs to investigate the correlations of the 6D phase-space coordinates and orbital properties with age. The phase-space distribution, age-velocity relation, and action distribution are compared to those of field stars. We also investigate the rotation curve of the Milky Way traced by OCs, and we compare it to that of other observational or theoretical studies.
Methods: We gathered nearly 30 000 radial velocity (RV) measurements of OC members from both Gaia-RVS data and ground-based surveys and catalogues. We computed the weighted mean RV, Galactic velocities, and orbital parameters of 1382 OCs. We investigated their distributions as a function of age and by comparison to field stars.
Results: We provide the largest RV catalogue available for OCs, half of it based on at least three members. Compared to field stars, we note that OCs are not on exactly the same arches in the radial-azimuthal velocity plane, while they seem to follow the same diagonal ridges in the Galactic radial distribution of azimuthal velocities. Velocity ellipsoids in different age bins all show a clear anisotropy. The heating rate of the OC population is similar to that of field stars for the radial and azimuthal components, but it is significantly lower for the vertical component. The rotation curve drawn by our sample of clusters shows several dips that match the wiggles derived from nonaxisymmetric models of the Galaxy. From the computation of orbits, we obtain a clear dependence of the maximum height and eccentricity on age. Finally, the orbital characteristics of the sample of clusters as shown by the action variables follow the distribution of field stars. The additional age information of the clusters indicates some (weak) age dependence of the known moving groups.

The tables with star and cluster velocities are only available at the CDS via anonymous ftp to http://cdsarc.u-strasbg.fr (ftp://130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/647/A19

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J9

Formation of counter-rotating and highly eccentric massive black hole binaries in galaxy mergers

Show affiliations

Nasim, Imran; Petrovich, Cristobal; Nasim, Adam; Dosopoulou, Fani; Antonini, Fabio

Supermassive black hole (SMBH) binaries represent the main target for missions such as the Laser Interferometer Space Antenna and Pulsar Timing Arrays. The understanding of their dynamical evolution prior to coalescence is therefore crucial to improving detection strategies and for the astrophysical interpretation of the gravitational wave data. In this paper, we use high-resolution N-body simulations to model the merger of two equal-mass galaxies hosting a central SMBH. In our models, all binaries are initially prograde with respect to the galaxy sense of rotation. But, binaries that form with a high eccentricity, $e \gtrsim 0.7$, quickly reverse their sense of rotation and become almost perfectly retrograde at the moment of binary formation. The evolution of these binaries proceeds towards larger eccentricities, as expected for a binary hardening in a counter-rotating stellar distribution. Binaries that form with lower eccentricities remain prograde and at comparatively low eccentricities. We study the origin of the orbital flip by using an analytical model that describes the early stages of binary evolution. This model indicates that the orbital plane flip is due to the torque from the triaxial background mass distribution that naturally arises from the galactic merger process. Our results imply the existence of a population of SMBH binaries with a high eccentricity and could have significant implications for the detection of the gravitational wave signal emitted by these systems.

Publication: Monthly Notices of the Royal Astronomical Society, Advance Access

J10

Self-interacting dark matter and the delay of supermassive black hole growth

Show affiliations

Cruz, A.; Pontzen, A.; Volonteri, M.; Quinn, T. R.; Tremmel, M.; Brooks, A. M.; Sanchez, N. N.; Munshi, F.; Di Cintio, A.

Using cosmological hydrodynamic simulations with physically motivated models of supermassive black hole (SMBH) formation and growth, we compare the assembly of Milky Way-mass ($M_{vir} \simeq 7 \times 10^{11}$ $M_{\odot}$ at z = 0) galaxies in cold dark matter (CDM) and self-interacting dark matter (SIDM) models. Our SIDM model adopts a constant cross-section of 1 $cm^2 g^{-1}$. We find that SMBH formation is suppressed in the early Universe due to SIDM interactions. SMBH-SMBH mergers are also suppressed in SIDM as a consequence of the lower number of SMBHs formed. Lack of initial merger-driven SMBH growth in turn delays SMBH growth by billions of years in SIDM compared to CDM. Further, we find that this delayed growth suppresses SMBH accretion in the largest progenitors of the main SIDM galaxies during the first 5 Gyr of their evolution. Nonetheless, by z = 0.8 the CDM and SIDM SMBH masses differ only by around 0.2 dex, so that both remain compatible with the M_{BH}-M_* relation. We show that the reduced accretion causes the SIDM SMBHs to less aggressively regulate star formation in their host galaxies than their CDM counterparts, resulting in a factor of 3 or more stars being produced over the lifetime of the SIDM galaxies compared to the CDM galaxies. Our results highlight a new way in which SIDM can affect the growth and merger history of SMBHs and ultimately give rise to very different galaxy evolution compared to the classic CDM model.

Publication: Monthly Notices of the Royal Astronomical Society, Volume 500, Issue 2, pp.2177-2187

J11

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[Submitted on 30 Mar 2021]

Resolving the Complex Evolution of a Supermassive Black Hole Triplet in a Cosmological Simulation

Matias Mannerkoski, Peter H. Johansson, Antti Rantala, Thorsten Naab, Shihong Liao

We present here a self-consistent cosmological zoom-in simulation of a triple supermassive black hole (SMBH) system forming in a complex multiple galaxy merger. The simulation is run with an updated version of our code KETJU, which is able to follow the motion of SMBHs down to separations of tens of Schwarzschild radii while simultaneously modeling the large-scale astrophysical processes in the surrounding galaxies, such as gas cooling, star formation, and stellar and AGN feedback. Our simulation produces initially a SMBH binary system for which the hardening process is interrupted by the late arrival of a third SMBH. The KETJU code is able to accurately model the complex behavior occurring in such a triple SMBH system, including the ejection of one SMBH to a kiloparsec-scale orbit in the galaxy due to strong three-body interactions as well as Lidov-Kozai oscillations suppressed by relativistic precession when the SMBHs are in a hierarchical configuration. One pair of SMBHs merges $\sim 3\,\mathrm{Gyr}$ after the initial galaxy merger, while the remaining binary is at a parsec-scale separation when the simulation ends at redshift $z = 0$. We also show that KETJU can capture the effects of the SMBH binaries and triplets on the surrounding stellar population, which can affect the binary merger timescales as the stellar density in the system evolves. Our results demonstrate the importance of dynamically resolving the complex behavior of multiple SMBHs in galactic mergers, as such systems cannot be readily modeled using simplified semi-analytic models.

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