The Star Clusters Young & Old Newsletter

edited by Angela Adamo, Martin Netopil, and Ernst Paunzen
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Dear Colleagues,

We hope that this new SCYON issue finds you well! With this issue we want to inform you about some SCYON updates. First, SCYON is available at a new URL, but you will be redirected if you are visiting the webpage with the previous one. Furthermore, there were some updates concerning the submission procedure. For example, you can use the available arXiv ID of your paper for a more easier submission process. From now you can also provide a very short (twitter style) abstract with less than 500 characters, supported by a figure to highlight the importance of your paper. We encourage its use so that SCYON can provide a more concise overview about activities in the field of star cluster research than e.g. an ADS or arXiv listing.

We also encourage you to provide feedback about the introduced topics, in particular if you can identify probable missing headings.

Finally, we want to inform you about the special issue "Research Progress in Star Clusters and Stellar Systems" in the Journal Galaxies, edited by Sambaran Banerjee. Paper contributions are welcome until 31^{st} Dec. 2022.

The SCYON editor team: Angela Adamo, Martin Netopil, and Ernst Paunzen

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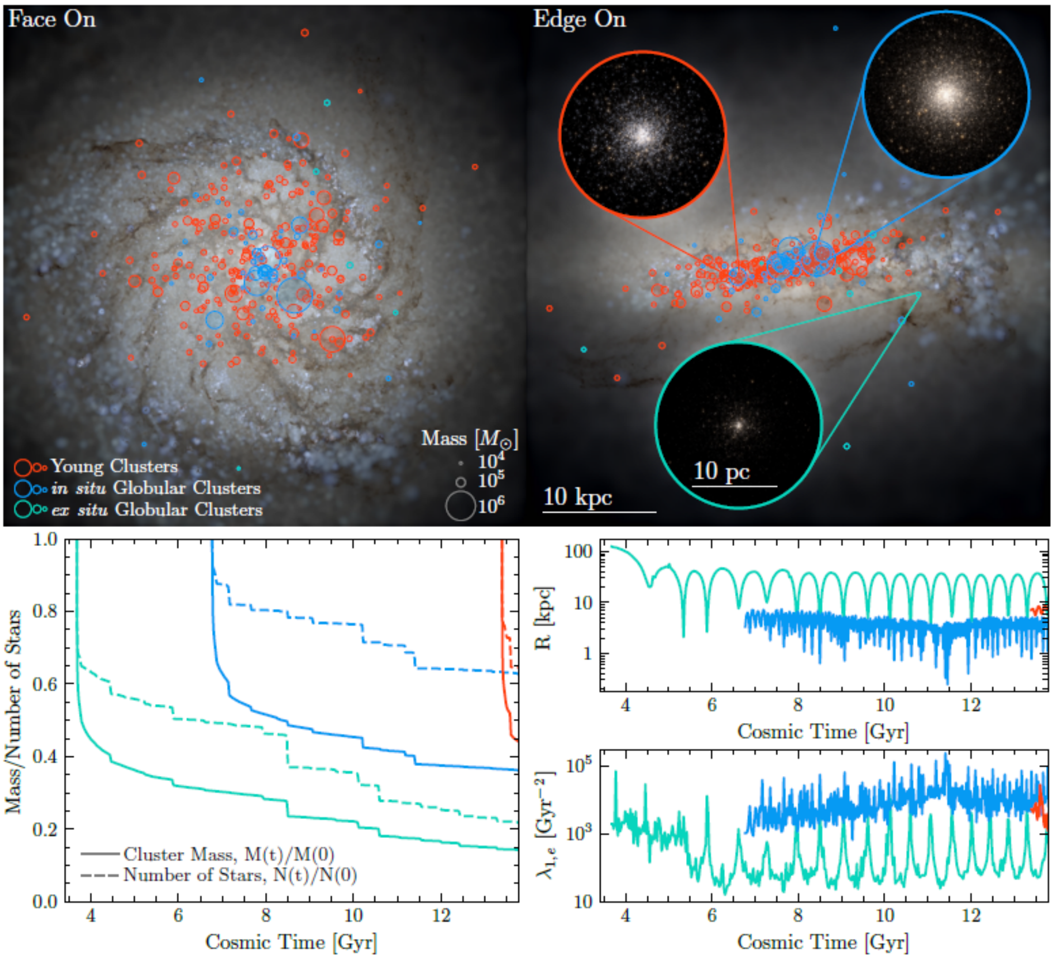
Picture of the issue:

The figure is taken from Rodriguez et al. (arXiv:2203.16547). The paper deals with first star-by-star N-body models of massive star clusters formed in a simulation of a Milky Way-mass galaxy and the figure shows the galactic environment and dynamical evolution of three typical clusters. The paper abstract can be found in the section "Simulations of star cluster formation and dynamical evolution".



About the Newsletter

SCYON publishes abstracts from any area in astronomy, which are relevant to research on star clusters. We welcome all kinds of submitted contributions (abstracts of refereed papers or conference proceedings, PhD summaries, and general announcements of e.g. conferences, databases, tools, etc.)

The mission of this newsletter is to help all the researchers in the field with a quick and efficient link to the scientific activity in the field. We encourage everybody to contribute to the new releases! New abstracts can be submitted *at any time* using the **webform** on the SCYON homepage.

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Clustered star formation across cosmic time

Great Balls of FIRE I: The formation of star clusters across cosmic time in a Milky Way-mass galaxy

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The properties of young star clusters formed within a galaxy are thought to vary in different interstellar medium (ISM) conditions, but the details of this mapping from galactic to cluster scales are poorly understood due to the large dynamic range involved in galaxy and star cluster formation. We introduce a new method for modeling cluster formation in galaxy simulations: mapping giant molecular clouds (GMCs) formed self-consistently in a FIRE-2 MHD galaxy simulation onto a cluster population according to a GMC-scale cluster formation model calibrated to higher-resolution simulations, obtaining detailed properties of the galaxy's star clusters in mass, metallicity, space, and time. We find $\sim 10\%$ of all stars formed in the galaxy originate in gravitationally-bound clusters overall, and this fraction increases in regions with elevated $\Sigma_{\rm gas}$ and $\Sigma_{\rm SFR}$, because such regions host denser GMCs with higher star formation efficiency. These quantities vary systematically over the history of the galaxy, driving variations in cluster formation. The mass function of bound clusters varies – no single Schechter-like or power-law distribution applies at all times. In the most extreme episodes, clusters as massive as $7 \times 10^6 M_\odot$ form in massive, dense clouds with high star formation efficiency. The initial mass-radius relation of young star clusters is consistent with an environmentally-dependent 3D density that increases with $\Sigma_{\rm gas}$ and $\Sigma_{\rm SFR}$. The model does not reproduce the age and metallicity statistics of old (> 11Gyr) globular clusters found in the Milky Way, possibly because it forms stars more slowly at $z > 3$.

Submitted to: Monthly Notices of the Royal Astronomical Society

https://ui.adsabs.harvard.edu/abs/2022arXiv220305732G/abstract

Low mass young stars in the Milky Way unveiled by DBSCAN and Gaia EDR3. Mapping the star forming regions within 1.5 Kpc

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With an unprecedented astrometric and photometric data precision, Gaia EDR3 gives us, for the first time, the opportunity to systematically detect and map in the optical bands, the low mass populations of the star forming regions (SFRs) in the Milky Way. We provide a catalogue of the Gaia EDR3 data (photometry, proper motions and parallaxes) of the young stellar objects (YSOs) identified in the Galactic Plane ($|b| < 30$ deg) within about 1.5 kpc. The catalogue of the SFRs to which they belong is also provided to study the properties of the very young clusters and put them in the context of the Galaxy structure. We applied the machine learning unsupervised clustering algorithm DBSCAN on a sample of Gaia EDR3 data photometrically selected on the region where very young stars (t<10 Myr) are expected to be found, with the aim to identify co-moving and spatially consistent stellar clusters. A subsample of 52 clusters, selected among the 7323 found with DBSCAN, has been used as template data set, to identify very young clusters from the pattern of the observed color-absolute magnitude diagrams through a pattern match process. We find 124440 candidate YSOs clustered in 354 SFRs and stellar clusters younger than 10 Myr and within about 1.5 Kpc. In addition, 65863 low mass members of 322 stellar clusters located within about 500 pc and with ages 10 Myr<t<100 Myr were also found. The selected YSOs are spatially correlated with the well known SFRs. Most of them are associated with well concentrated regions or complex structures of the Galaxy and a substantial number of them have been recognized for the first time. The massive SFRs, such as, for example, Orion, Sco-Cen and Vela, located within 600-700 pc trace a very complex three-dimensional pattern, while the farthest ones seem to follow a more regular pattern along the Galactic Plane.

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https://ui.adsabs.harvard.edu/abs/2022arXiv220600249P/abstract

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Search for OB associations in *Gaia* early Data Release 3

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The distribution of young stars into OB associations has long been in need of updating. High-precision *Gaia* early Data Release 3 astrometry, coupled with modern machine-learning methods, allows this to be done. We have compiled a well-defined sample which includes OB stars and young open clusters, in total comprising about 47,700 objects. To break the sample down into groupings resembling associations, we applied the HDBSCAN* clustering algorithm. We used a Monte Carlo method to estimate the kinematic ages of the resulting clusters and the Student's t-test to assess the significance of the linear correlations between proper motions and coordinates, indicating the presence of possible cluster expansion signatures. The ages of the majority of clusters demonstrating a general expansion at a 1σ confidence level are several tens of Myr, which is in agreement with the expected ages of OB associations. We found 32 open clusters which turned out to be members of the resulting groupings; their ages are consistent with one another within the uncertainties. Comparison of the clusters thus obtained with the historical composition of OB associations in the literature shows a correspondence between their positions in the Galaxy but an apparent absence of good one-to-one stellar matches. Therefore, we suggest that the historical composition of OB associations needs to be revised.

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https://ui.adsabs.harvard.edu/abs/2022MNRAS.tmp.1728C/abstract

Star cluster feedback and early evolution

Revealing the dust grain polarization properties as a function of extinction and distance towards NGC 1893

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Dust polarization observations at optical wavelengths help to understand the dust grain properties and trace the plane-of-the-sky component of the magnetic field. In this study, we make use of the I-band polarization data acquired from AIMPOL along with the distances (d) and extinction (A_V) data to study the variation of polarization fraction (P) as a function of A_V and d towards the star-forming region, NGC 1893. We employ a broken power-law fit and Bayesian analysis on extinction (A_V) versus polarization efficiency (P/A_V) and distance (d) versus rate of polarization (P/d). We find that P/A_V shows a break at an extinction of ∼0.9 mag, whereas P/d exhibits a break at a distance of ∼1.5 kpc. Based on these, we categorize the dust towards NGC 1893 into two populations: (i) foreground dust confined to $A_V < \sim 1$ mag and distance up to ∼2 kpc and (ii) Perseus spiral arm dust towards NGC 1893 characterized with $A_V > \sim 1$ mag and distance beyond ∼2 kpc. Foreground dust exhibits higher polarization efficiency but a lower polarization rate, whereas Perseus dust shows a lower polarization efficiency but a slightly higher polarization rate. Hence, we suggest that while polarization efficiency reveals the dust grain alignment, the rate of polarization infers about the distribution of dust grains towards NGC 1893. Further, we also shed a light on the spatial variation of intrinsic polarization and magnetic field orientation, and other parameters within the intra-cluster medium of NGC 1893.

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https://ui.adsabs.harvard.edu/abs/2022arXiv220703173B/abstract

Star clusters in the Milky Way and Local group

Detailed Chemical Abundances of Star Clusters in the Large Magellanic Cloud

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We derive the first detailed chemical abundances of three star clusters in the Large Magellanic Cloud (LMC), NGC1831 (436±22 Myr), NGC1856 (350±18 Myr) and [SL63]268 (1230±62 Myr) using integrated-light spectroscopic observations obtained with the Magellan Echelle spectrograph on Magellan Baade telescope. We derive [Fe/H], [Mg/Fe], [Ti/Fe], [Ca/Fe], [Ni/Fe], [Mn/Fe], [Cr/Fe] and [Na/Fe] for the three clusters. Overall, our results match the LMC abundances obtained in the literature as well as those predicted by detailed chemical evolution models. For clusters NGC1831 and NGC1856, the [Mg/Fe] ratios appear to be slightly depleted compared to [Ca/Fe] and [Ti/Fe]. This could be hinting at the well-known Mg-Al abundance anti-correlation observed in several Milky Way globular clusters. We note, however, that higher signal-to-noise observations are needed to confirm such a scenario, particularly for NGC 1831. We also find a slightly enhanced integrated-light [Na/Fe] ratio for cluster [SL63]268 compared to those from the LMC field stars, possibly supporting a scenario of intracluster abundance variations. We stress that detailed abundance analysis of individual stars in these LMC clusters is required to confirm the presence or absence of MSPs.

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https://ui.adsabs.harvard.edu/abs/2022ApJ...929..174A/abstract

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Estimating the ages of open star clusters from properties of their extended tidal tails

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The most accurate current methods for determining the ages of open star clusters, stellar associations and stellar streams are based on isochrone fitting or the lithium depletion boundary. We propose another method for dating these objects based on the morphology of their extended tidal tails, which have been recently discovered around several open star clusters. Assuming that the early-appearing tidal tails, the so called tidal tails I, originate from the stars released from the cluster during early gas expulsion, or that they form in the same star forming region as the cluster (i.e. being coeval with the cluster), we derive the analytical formula for the tilt angle β between the long axis of the tidal tail and the orbital direction for clusters or streams on circular trajectories. Since at a given Galactocentric radius, β is only a function of age t regardless of the initial properties of the cluster, we estimate the cluster age by inverting the analytical formula $\beta = \beta(t)$. We illustrate the method on a sample of 12 objects, which we compiled from the literature, and we find a reasonable agreement with previous dating methods in ≈ 70 % of the cases. This can probably be improved by taking into account the eccentricity of the orbits and by revisiting the dating methods based on stellar evolution. The proposed morphological method is suitable for relatively young clusters (age $\lesssim 300$ Myr), where it provides a relative age error of the order of 10 to 20 % for an error in the observed tilt angle of $5°$.

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https://ui.adsabs.harvard.edu/abs/2022ApJ...925..214D/abstract

The in situ origin of the globular cluster NGC 6388 from abundances of Sc, V, and Zn of a large sample of stars

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Chemical tagging of globular clusters (GCs) is often done using abundances of α-elements. The iron-peak elements Sc, V, and in particular Zn were proposed as an alternative to α-elements to tag accreted GCs in the metal-rich regime, where the dwarf galaxy Sagittarius and its GCs show peculiarly marked under-abundances of these heavier species with respect to Milky Way stars. A handful of stars in NGC 6388 was used to suggest an accreted origin for this GC, contradicting the results from dynamics. We tested the efficiency of the iron-peak method by using large samples of stars in NGC 6388, compared to thousands of field stars in the disc and the bulge of the Milky Way. Our abundance ratios of Sc (185 stars) and V (35 stars) for NGC 6388 are within about 1.5σ from the average for the field stars with a similar metallicity, and they are in perfect agreement for Zn (31 stars), claimed to be the most sensitive element concerning the accretion pattern. Moreover, the chemo-dynamical plots, coupled to the bifurcated age-metallicity relation of GCs in the Galaxy, clearly rule out any association of NGC 6388 to the groups of accreted GCs. Using a large set of GC abundances from the literature, we also show that the new method with Sc, V, and Zn seems to be efficient in picking up GCs related to the Sagittarius dwarf galaxy. Whether this is also generally true for accreted GCs seems to be less evident, and it should be verified with larger and homogeneous samples of stars both in the field and in GCs.

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https://ui.adsabs.harvard.edu/abs/2022A%26A...660L...1C/abstract

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On the physical size of the Milky Way globular cluster NGC 7089 (M 2)

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We study the outer regions of the Milky Way globular cluster NGC 7089 based on new Dark Energy Camera (DECam) observations. The resulting background cleaned stellar density profile reveals the existence of an extended envelope. We confirm previous results that cluster stars are found out to $\sim$ 1deg from the cluster's centre, which is nearly three times the value of the most robust tidal radii estimations. We also used results from direct N-body simulations in order to compare with the observations. We found a fairly good agreement between the observed and numerically generated stellar density profiles. Because of the existence of gaps and substructures along globular cluster tidal tails, we closely examined the structure of the outer cluster region beyond the Jacobi radius. We extended the analysis to a sample of 35 globular clusters, 20 of them with observed tidal tails. We found that if the stellar density profile follows a power law $\sim r^{-\alpha}$, the alpha slope correlates with the globular cluster present mass, in the sense that, the more massive the globular cluster the smaller the alpha value. This trend is not found in globular clusters without observed tidal tails. The origin of such a phenomenon could be related, among other reasons, to the proposed so-called potential escapers or to the formation of globular clusters within dark matter mini-haloes.

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https://ui.adsabs.harvard.edu/abs/2022MNRAS.514.4982P/abstract

Evidence of globular cluster abundance anomalies in the SMC intermediate-age cluster Kron 3

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Using spectra obtained with the VLT/FORS2 and Gemini-S/GMOS-S instruments, we have investigated carbon, nitrogen and sodium abundances in a sample of red giant members of the Small Magellanic Cloud star cluster Kron 3. The metallicity and luminosity of the cluster are comparable to those of Galactic globular clusters but it is notably younger (age $\approx$ 6.5 Gyr). We have measured the strengths of the CN and CH molecular bands, finding a bimodal CN band-strength distribution and a CH/CN anti-correlation. Application of spectrum synthesis techniques reveals that the difference in the mean [N/Fe] and [C/Fe] values for the CN-strong and CN-weak stars are $\Delta <$[N/Fe]$>= 0.63\pm0.16$ dex and $\Delta <$[C/Fe]$>= -0.01\pm$ 0.07 dex after applying corrections for evolutionary mixing. We have also measured sodium abundances from the Na D lines finding an observed range in [Na/Fe] of $\sim$0.6 dex that correlates positively with the [N/Fe] values and a $\Delta <$[Na/Fe]$>= 0.12 \pm 0.12$ dex. While the statistical significance of the sodium abundance difference is not high, the observed correlation between the Na and N abundances supports its existence. The outcome represents the first star-by-star demonstration of correlated abundance variations involving sodium in an intermediate-age star cluster. The results add to existing photometric and spectroscopic indications of the presence of multiple populations in intermediate-age clusters with masses in excess of $\sim 10^5$ $M_{\odot}$. It confirms that the mechanism(s) responsible for the multiple populations in ancient globular clusters cannot solely be an early cosmological effect applying only in old clusters.

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https://ui.adsabs.harvard.edu/abs/2022MNRAS.tmp.1672S/abstract

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The young Galactic cluster NGC 225: binary stars content and total mass estimate

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Galactic star clusters are known to harbour a significant amount of binary stars, yet their role in the dynamical evolution of the cluster as a whole is not comprehensively understood. We investigated the influence of binary stars on the total mass estimate for the case of the moderately populated Galactic star cluster NGC 225. The analysis of multi-epoch radial velocities of the 29 brightest cluster members, obtained over two observational campaigns, in 1990-1991 and in 2019-2020, yields a value of binary fraction of $\alpha = 0.52$ (15 stars out of 29). Using theoretical isochrones and Monte Carlo simulations we found that the cluster mass increases at least 1.23 times when binaries are properly taken into account. By combining Gaia EDR3 photometric data with our spectroscopic observations, we derived estimates of NGC 225 fundamental parameters as follows: mean radial velocity $V_r = -9.8 \pm 0.7$ km s^{-1}, log(τ)=8.0-8.2 dex, distance $D = 676 \pm 22$ pc, and colour excess $E(B-V) = 0.29 \pm 0.01$ mag.

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New insights into the structure of open clusters in the Gaia era

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With the help of Gaia data, it is noted that in addition to the core components, there are low-density outer halo components in the extended region of open clusters. To study the extended structure beyond the core radius of the cluster ($\sim$ 10 pc), based on Gaia EDR3 data, taking up to 50 pc as the searching radius, we use the pyUPMASK algorithm to re-determine the member stars of the open cluster within 1-2 kpc. We obtain the member stars of 256 open clusters, especially those located in the outer halo region of open clusters. Furthermore, we find that most open clusters' radial density profile in the outer region deviates from the King's profile. To better describe the internal and external structural characteristics of open clusters, we propose a double components model for description: core components with King model distribution and outer halo components with logarithmic Gaussian distribution, and then suggest using four radii (r_c, r_t, r_o, r_e) for describing the structure and distribution profile of star clusters, where r_t and r_e represent the boundaries of core components and outer halo components respectively. Finally, we provide a catalog of 256 clusters with structural parameters. In addition, our study shows the sizes of these radii are statistically linear related, which indicates that the inner and outer regions of the cluster are interrelated and follow similar evolutionary processes. Further, we show that the structure of two components can be used to better trace the cluster evolution properties in different stages.

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https://ui.adsabs.harvard.edu/abs/2022arXiv220604904Z/abstract

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Discovery of extended structure around open cluster COIN-Gaia 13 based on Gaia EDR3

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COIN-Gaia 13 is a newly discovered open cluster revealed by Gaia DR2 data. It is a nearby open cluster with a distance of about 513 pc. Combined with the five-dimensional astrometric data of Gaia EDR3 with higher accuracy, we use the membership assignment algorithm (pyUPMASK) to determine the membership of COIN-Gaia 13 in a large extended spatial region. The cluster has found 478 candidate members. After obtaining reliable cluster members, we further study its basic properties and spatial distribution. Our results show that there is an obvious extended structure of the cluster in the X-Y plane. This elongated structure is distributed along the spiral arm, and the whole length is about 270 pc. The cluster age is 250 Myr, the total mass is about 439 $M_{\odot}$, and the tidal radius of the cluster is about 11 pc. Since more than half of the member stars (352 stars) are located outside twice the tidal radius, it is suspected that this cluster is undergoing the dynamic dissolution process. Furthermore, the spatial distribution and kinematic analysis indicate that the extended structure in COIN-Gaia 13 is more likely to be caused by the differential rotation of the Galaxy.

Accepted by: Research in Astronomy and Astrophysics

https://ui.adsabs.harvard.edu/abs/2022RAA....22e5022B/abstract

Unraveling UBC 274: a morphological, kinematical and chemical analysis of a disrupting open cluster

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We do a morphological, kinematic and chemical analysis of the disrupting cluster UBC 274 (2.5 Gyr, $d = 1778$ pc) to study its global properties. We use HDBSCAN to obtain a new membership list up to 50 pc from its centre and up to magnitude $G = 19$ using Gaia EDR3 data. We use high resolution and high signal-to-noise spectra to obtain atmospheric parameters of 6 giants and subgiants, and individual abundances of 18 chemical species. The cluster has a highly eccentric (0.93) component, tilted ∼10 deg with respect to the plane of the Galaxy, which is morphologically compatible with the result of a test-particle simulation of a disrupting cluster. Our abundance analysis shows that the cluster has a subsolar metallicity of [Fe/H]$= -0.08 \pm 0.02$. Its chemical pattern is compatible with that of Ruprecht 147, of similar age but located closer to the Sun, with the remarkable exception of neutron-capture elements, which present an overabundance of [n/Fe] $\sim$ 0.1. The cluster's elongated morphology is associated with the internal part of its tidal tail, following the expected dynamical process of disruption. We find a significant sign of mass segregation where the most massive stars appear 1.5 times more concentrated than other stars. The cluster's overabundance of neutron-capture elements can be related to the metallicity dependence of the neutron-capture yields due to the secondary nature of these elements, predicted by some models. UBC 274 presents a high chemical homogeneity at the level of 0.03 dex in the sampled region of its tidal tails.

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https://ui.adsabs.harvard.edu/abs/2022arXiv220603777C/abstract

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The Panchromatic Hubble Andromeda Treasury: Triangulum Extended Region (PHATTER). III. The Mass Function of Young Star Clusters in M33

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We measure the star cluster mass function for the Local Group galaxy M33. We use the catalog of stellar clusters selected from the Panchromatic Hubble Andromeda Treasury: Triangulum Extended Region (PHATTER) survey. We analyze 711 clusters in M33 with $7.0 < \log(\mathrm{Age/yr}) < 8.5$, and $\log(M/M_\odot) > 3.0$ as determined from color-magnitude diagram fits to individual stars. The M33 cluster mass function is best described by a Schechter function with power law slope $\alpha = -2.06^{+0.14}_{-0.13}$, and truncation mass $\log(M_c/M_\odot) = 4.24^{+0.16}_{-0.13}$. The data show strong evidence for a high-mass truncation, thus strongly favoring a Schechter function fit over a pure power law. M33's truncation mass is consistent with the previously identified linear trend between M_c, and star formation rate surface density, Σ_{SFR}. We also explore the effect that individual cluster mass uncertainties have on derived mass function parameters, and find evidence to suggest that large cluster mass uncertainties have the potential to bias the truncation mass of fitted mass functions on the one sigma level.

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Westerlund 1 under the light of Gaia EDR3: Distance, isolation, extent, and a hidden population

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We have used Gaia EDR3 data, together with spectra of a large sample of luminous stars in the field surrounding Westerlund 1, to explore the extent of the cluster. We carry out a non-parametric analysis of proper motions and membership determination. We investigate the reddening and proper motions of several dozen OB stars and red supergiants < 1 deg away from Wd 1. We identify a population of kinematic members of Wd 1 that largely includes the known spectroscopic members. From their EDR3 parallaxes, we derive a distance to the cluster of $4.23^{+0.23}_{-0.21}$kpc. Extinction in this direction increases by a large amount around 2.8 kpc, due to dark clouds associated to the Scutum-Crux arm. As a consequence, we hardly see any stars at distances comparable to that of the cluster. The proper motions of Wd 1, however, are very similar to those of stars in the field surrounding it, but distinct. We find a second, astrometrically well-defined population in the foreground ($d \approx 2\,$kpc), likely connected to the possible open cluster BH197. Wd 1 is very elongated, an effect not driven by the very heavy extinction to the East and South. We find a low-density halo extending up to 10' from the cluster centre, mainly in the NW quadrant. A few OB stars at larger distances from the cluster, most notably the LBV MN48, share its proper motions, suggesting that Wd 1 has little or no peculiar motion with respect to the field population of the Norma arm. However, we are unable to find any red supergiant that could belong to an extended population related to the cluster, although we observe several dozen such objects in the foreground. We find a substantial population of luminous OB members obscured by several more magnitudes of extinction than most known members. These objects, mostly located in the central region of the cluster, increase the population of OB supergiants by about 25%.

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Structural parameters of 389 local Open Clusters

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The distribution of member stars in the surroundings of an Open Cluster (OC) can shed light on the process of its formation, evolution and dissolution. The analysis of structural parameters of OCs as a function of their age and position in the Galaxy brings constraints on theoretical models of cluster evolution. The Gaia catalogue is very appropriate to find members of OCs at large distance from their centers. We aim at revisiting the membership lists of OCs from the solar vicinity, in particular by extending these membership lists to the peripheral areas thanks to Gaia EDR3. We used the clustering algorithm HDBSCAN on Gaia parallaxes and proper motions to systematically look for members up to 50 pc from the cluster centers. We fitted a King's function on the radial density profile of these clusters and a Gaussian Mixture Model on their two dimensional distribution of members. We also evaluated the degree of mass segregation of the clusters. Our methodology performs well on 389 clusters out of the 467 selected ones. We report the detection of vast coronae around almost all the clusters and the detection of 71 OCs with tidal tails, multiplying by more than four the number of such structures identified. We find the size of the cores to be on average smaller for old clusters than for young ones. Also, the overall size of the clusters seems to slightly increase with age while the fraction of stars in the halo seems to decrease. As expected the mass segregation is more pronounced in the oldest clusters but a clear trend with age is not seen. OCs are more extended than previously expected, regardless of their age. The decrease in the proportion of stars populating the clusters halos highlights the different cluster evaporation processes and the short timescales they need to affect the clusters. Reported parameters all depend on cluster ages but can not be described as single functions of time.

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First evidence of a stripped star cluster from the Small Magellanic Cloud

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We present results on the recently discovered stellar system YMCA-1, for which physical nature and belonging to any of the Magellanic System galaxies have been irresolutely analyzed. We used SMASH and *Gaia* EDR3 data sets to conclude that we are dealing with a small star cluster. Its reddening free, field star decontaminated colour-magnitude diagram was explored in order to obtain the cluster parameters. We found that YMCA-1 is a small (435 $_{\odot}$), moderately old (age = 9.6 Gyr), moderately metal-poor ([Fe/H] = -1.16 dex) star cluster, located at a nearly Small Magellanic Cloud (SMC) distance (60.9 kpc) from the Sun, at $\sim$ 17.1 kpc to the East from the Large Magellanic Cloud (LMC) centre. The derived cluster brightness and size would seem to suggest some resemblance to the recently discovered faint star clusters in the Milky Way (MW) outer halo, although it does not match their age-metallicty relationship, nor those of MW globular clusters formed in-situ or ex-situ, nor that of LMC clusters either, but is in agreement with that of SMC old star clusters. We performed numerical Monte Carlo simulations integrating its orbital motion backward in the MW-LMC-SMC system with radially extended dark matter haloes that experience dynamical friction, and by exploring different radial velocity (RV) regimes for YMCA-1. For RVs $\gtrsim$ 300 km/s, the cluster remains bound to the LMC during the last 500 Myrs. The detailed tracked kinematic of YMCA-1 suggests that its could have been stripped by the LMC from the SMC during any of the close interactions between both galaxies, a scenario previously predicted by numerical simulations.

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A study of the NGC 1193 and NGC 1798 open clusters using CCD UBV photometric and Gaia EDR3 data

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We present photometric, astrometric, and kinematic studies of the old open star clusters NGC 1193 and NGC 1798. Both of the clusters are investigated by combining data sets from Gaia EDR3 and CCD UBV observational data. Analysis of the radial distribution of stars through the cluster regions indicates that the cluster limit radii are $r_{\rm lim} = 8'$ for both of the clusters. We determine the membership probabilities of stars considering Gaia EDR3 proper motion and trigonometric parallax data, resulting in 361 stars in NGC 1193 and 428 in NGC 1798 being identified as most likely cluster members, having membership probabilities greater than P¿0.5. Mean proper motion components are estimated as $(\mu_\alpha \cos\delta,\ \mu_\delta) = (-0.207(0.009), -0.431(0.008))$ for NGC 1193 and $(\mu_\alpha \cos\delta,\ \mu_\delta) = (0.793(0.006), -0.373(0.005))$ mas/yr for NGC 1798. E(B-V) color excesses were derived for NGC 1193 as 0.150(0.037) and for NGC 1798 as 0.505(0.100) mag through the use of two-color diagrams. Photometric metallicities are also determined from two-color diagrams with the results of [Fe/H] = -0.30(0.06) dex for NGC 1193 and [Fe/H]=-0.20(0.07) dex for NGC 1798. The isochrone fitting distance and age of NGC 1193 are 5562(381) pc and 4.6(1) Gyr, respectively. For NGC 1798, these parameters are 4451(728) pc and 1.3(0.2) Gyr. These ages indicate that NGC 1193 and NGC 1798 are old open clusters. The overall present-day mass function slopes for main-sequence stars are found as 1.38(2.16) for NGC 1193 and 1.30(0.21) for NGC 1798, which are in fair agreement with the value of Salpeter (1955). Kinematic and dynamic orbital calculations indicate that NGC 1193 and NGC 1798 belong to the thick-disk and thin-disk populations, respectively. In addition, both of the clusters were born outside the solar circle, and both orbit in the metal-poor region of the Galactic disk.

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A photometric and astrometric study of the open clusters NGC 1664 and NGC 6939

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This study calculated astrophysical parameters, as well as kinematic and galactic orbital parameters, of the open clusters NGC 1664 and NGC 6939. The work is based on CCD UBV and Gaia photometric and astrometric data from ground and space-based observations. Considering Gaia Early Data Release 3 (EDR3) astrometric data, we determined membership probabilities of stars located in both of the clusters. We used two-color diagrams to determine $E(B-V)$ color excesses for NGC 1664 and NGC 6939 as 0.190 ± 0.018 and 0.380 ± 0.025 mag, respectively. Photometric metallicities for the two clusters were estimated as [Fe/H] $= -0.10 \pm 0.02$ dex for NGC 1664 and as [Fe/H] $= -0.06 \pm 0.01$ dex for NGC 6939. Using the reddening and metallicity calculated in the study, we obtained distance moduli and ages of the clusters by fitting PARSEC isochrones to the color-magnitude diagrams based on the most likely member stars. Isochrone fitting distances are 1289 ± 47 pc and 1716 ± 87 pc, which coincide with ages of 675 ± 50 Myr and 1.5 ± 0.2 Gyr for NGC 1664 and NGC 6939, respectively. We also derived the distances to the clusters using Gaia trigonometric parallaxes and compared these estimates with the literature. We concluded that the results are in good agreement with those given by the current study. Present day mass function slopes were calculated as $\Gamma = -1.22 \pm 0.33$ and $\Gamma = -1.18 \pm 0.21$ for NGC 1664 and NGC 6939, respectively, which are compatible with the Salpeter (1955) slope. Analyses showed that both of clusters are dynamically relaxed. The kinematic and dynamic orbital parameters of the clusters were calculated, indicating that the birthplaces of the clusters are outside the solar circle.

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Star cluster populations in the local universe

Stellar collisions in globular clusters: the origin of multiple stellar populations

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Two generations of stars, G1 and G2, typically populate Galactic globular clusters (GCs). The origin of G2 stars is unclear. We uncover two empirical dependencies between GC characteristics, which can be explained by the formation of G2 Main-Sequence (MS) stars due to collision/merging of their primordial counterparts (G1). A similar genesis of both G2 stars and peculiar objects like LMXBs and millisecond pulsars is also implied. Indeed, we find a significant (at a confidence level > 99.9%) anti-correlation between the fraction of G1 red giants (N_{G1}/N_{tot}) and stellar encounter rates among 51 GCs. Moreover, a Milky Way-like initial mass function (IMF) requires at least ∼50% of MS stars located in the mass range [0.1-0.5] $M_\odot$. Unlike cluster mass loss, stellar collisions/merging retain these G1 stars by converting them into more massive G2 ones, with mainly $M_{ms} > 0.5\ M_\odot$. This process coupled with a decreasing relative mass loss with increasing GC masses implies a smaller (N_{G1}/N_{tot}) in more massive GCs with a shallower present day MF. From data for 35 GCs, we find that such an anti-correlation is significant at 98.3% confidence level (Spearman's correlation) for 12 most massive GCs ($M_{GC} > 10^{5.3}\ M_\odot$) and it is at a confidence level of 89% for the 12 least massive GCs ($M_{GC} < 10^{5.1}\ M_\odot$). Other fractions of G1 and G2 stars observed at the bottom of the MS as compared with the red giant branch in a few GCs are consistent with the scenario proposed.

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The Interferometric Binary epsilon Cancri in Praesepe: Precise Masses and Age

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We observe the brightest member of the Praesepe cluster, epsilon Cancri, to precisely measure the characteristics of the stars in this binary system, en route to a new measurement of the cluster's age. We present spectroscopic radial velocity measurements and interferometric observations of the sky-projected orbit to derive the masses, which we find to be $M_1/M_\odot = 2.420 \pm 0.008$ and $M_2/M_\odot = 2.226 \pm 0.004$. We place limits on the color-magnitude positions of the stars by using spectroscopic and interferometric luminosity ratios while trying to reproduce the spectral energy distribution of Epsilon Cancri. We re-examine the cluster membership of stars at the bright end of the color-magnitude diagram using Gaia data and literature radial velocity information. The binary star data are consistent with an age of 637 ± 19 Myr, as determined from MIST model isochrones. The masses and luminosities of the stars appear to select models with the most commonly used amount of convective core overshooting.

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On the precision of full-spectrum fitting of simple stellar populations. IV. A systematic comparison with results from colour-magnitude diagrams

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In this fourth paper of a series on the precision of ages of stellar populations obtained through the full-spectrum fitting technique, we present a first systematic analysis that compare the age, metallicity and reddening of star clusters obtained from resolved and unresolved data (namely colour-magnitude diagrams (CMDs) and integrated-light spectroscopy) using the same sets of isochrones. We investigate the results obtained with both Padova isochrones and MIST isochrones. We find that there generally is a good agreement between the ages derived from CMDs and integrated spectra. However, for metallicity and reddening, the agreement between results from analyses of CMD and integrated spectra is significantly worse. Our results also show that the ages derived with Padova isochrones match those derived using MIST isochrones, both with the full spectrum fitting technique and the CMD fitting method. However, the metallicity derived using Padova isochrones does not match that derived using MIST isochrones using the CMD method. We examine the ability of the full-spectrum fitting technique in detecting age spreads in clusters that feature the extended Main Sequence Turn Off (eMSTO) phenomenon using two-population fits. We find that 3 out of 5 eMSTO clusters in our sample are best fit with one single age, suggesting that eMSTOs do not necessarily translate to detectable age spreads in integrated-light studies.

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The Gaia-ESO Survey: The analysis of the hot-star spectra

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The Gaia-ESO Survey (GES) is a large public spectroscopic survey that has collected, over a period of 6 years, spectra of $\sim 10^5$ stars. This survey provides not only the reduced spectra, but also the stellar parameters and abundances resulting from the analysis of the spectra. The GES dataflow is organised in 19 working groups. Working group 13 (WG13) is responsible for the spectral analysis of the hottest stars (O, B and A type, with a formal cut-off of Teff $>$ 7000 K) that were observed as part of GES. We present the procedures and techniques that have been applied to the reduced spectra, in order to determine the stellar parameters and abundances of these stars. The procedure used is similar to that of other working groups in GES. A number of groups (called 'Nodes') each independently analyse the spectra, using their state-of-the-art techniques and codes. Specific for the analysis in WG13 is the large temperature range that is covered ($T_{\rm eff}$ = 7000 - 50,000 K), requiring the use of different analysis codes. Most Nodes can therefore only handle part of the data. Quality checks are applied to the results of these Nodes by comparing them to benchmark stars, and by comparing them one to another. For each star the Node values are then homogenised into a single result: the recommended parameters and abundances. Eight Nodes each analysed (part of) the data. In total 17,693 spectra of 6462 stars were analysed, most of them in 37 open star clusters. The homogenisation led to stellar parameters for 5584 stars. Abundances were determined for a more limited number of stars. Elements studied are He, C, N, O, Ne, Mg, Al, Si and Sc. Abundances for at least one of those elements were determined for 292 stars. The hot-star data analysed here, as well as the Gaia-ESO Survey data in general, will be of considerable use in future studies of stellar evolution and open clusters.

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Star clusters at high redshift

Dynamical properties of star clusters

Bayesian Inference of Globular Cluster Properties Using Distribution Functions

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We present a Bayesian inference approach to estimating the cumulative mass profile and mean squared velocity profile of a globular cluster given the spatial and kinematic information of its stars. Mock globular clusters with a range of sizes and concentrations are generated from lowered isothermal dynamical models, from which we test the reliability of the Bayesian method to estimate model parameters through repeated statistical simulation. We find that given unbiased star samples, we are able to reconstruct the cluster parameters used to generate the mock cluster and the cluster's cumulative mass and mean velocity squared profiles with good accuracy. We further explore how strongly biased sampling, which could be the result of observing constraints, may affect this approach. Our tests indicate that if we instead have biased samples, then our estimates can be off in certain ways that are dependent on cluster morphology. Overall, our findings motivate obtaining samples of stars that are as unbiased as possible. This may be achieved by combining information from multiple telescopes (e.g., Hubble and Gaia), but will require careful modeling of the measurement uncertainties through a hierarchical model, which we plan to pursue in future work.

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Survey of Surveys I: The largest catalogue of radial velocities for the Galaxy

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In the present-day panorama of large spectroscopic surveys, the amount, diversity, and complexity of the available data continuously increase. We present a comprehensive catalogue, the Survey of Surveys (SoS), built by homogeneously merging the radial velocity (RV) determinations of the largest ground-based spectroscopic surveys to date, such as APOGEE, GALAH, Gaia-ESO, RAVE, and LAMOST, using Gaia as reference. We have devised a multi-staged procedure that includes: i) the cross match between Gaia and the spectroscopic surveys using the official Gaia cross-match algorithm, ii) the normalization of uncertainties using repeated measurements or the three-cornered hat method, iii) the cross calibration of the RVs as a function of the main parameters they depend on (magnitude, effective temperature, surface gravity, metallicity, and signal-to-noise ratio) to remove trends and zero point offsets, and iv) the comparison with external high-resolution samples, such as the Gaia RV standards and the Geneva-Copenhagen survey, to validate the homogenization procedure and to calibrate the RV zero-point of the SoS catalogue. We provide the largest homogenized RV catalogue to date, containing almost 11 million stars, of which about half come exclusively from Gaia and half in combination with the ground-based surveys. We estimate the accuracy of the RV zero-point to be about 0.16-0.31 km/s and the RV precision to be in the range 0.05-1.50 km/s depending on the type of star and on its survey provenance. We validate the SoS RVs with open clusters from a high resolution homogeneous samples and we provide median RVs for 532 clusters recently discovered by Gaia data. The SoS is publicly available, ready to be applied to various research projects, such as the study of star clusters, Galactic archaeology, stellar streams, or the characterization of planet-hosting stars, to name a few.

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Simulation formation/evolution of cluster populations

On the dynamical evolution of Cepheids in star clusters

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We investigated the occurrence of classical (type-I) Cepheid variable stars (henceforth Cepheids) in dynamically evolving star clusters from birth to an age of approximately 300 Myr. The clusters are modelled by the Aarseth code nbody6, and they feature a realistic stellar initial mass function and initial binary star population, single star and binary star evolution, expulsion of the primordial gas, and tidal field of the galaxy. Our simulations provide the first detailed dynamical picture of how frequently Cepheids remain gravitationally bound to their birth clusters versus how frequently they occur in the field. They allow us to quantify the relevance of various cluster ejection mechanisms and how they depend on stellar mass. Overall, the simulations agree with the empirical picture that a small fraction (≈ 10 %) of Cepheids reside in clusters, that cluster halo membership is relatively common, and that the majority of Cepheid hosting clusters only have a single Cepheid member. Additionally, the simulations predict that a) Cepheid progenitors are much more likely to escape from low-mass than higher mass clusters; b) higher-mass (long-period) Cepheids are ≈ 30 % more likely to be found in clusters than low-mass (short-period) Cepheids; c) the clustered Cepheid fraction increases with galactocentric radius since cluster dispersal is less efficient at greater radii; d) a lower metallicity reduces the overall clustered Cepheid fraction because the lower minimum mass of Cepheids leaves more time for cluster dispersal (this primarily affects short-period Cepheids); and e) high-mass clusters are much more likely to have more than one Cepheid member at any given time, in particular at a lower metallicity. We interpret the results as outcomes of various aspects of star cluster dynamics. The comparison of predicted and observed clustered Cepheid fractions, $f_{\rm CC}$, highlights the need for additional cluster disruption mechanisms, most likely encounters with giant molecular clouds, to explain the observed fractions.

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Second generation star formation in globular clusters of different masses

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By means of three-dimensional hydrodynamical simulations, we investigate the formation of second generation (SG) stars in young globular clusters of different masses. We consider clusters with a first generation of asymptotic giant branch (AGB) stars with mass 10^5 and 10^6 $M_\odot$ moving at constant velocity through a uniform gas with density 10^{-24} and 10^{-23} $\mathrm{g\,cm^{-3}}$. Our setup is designed to reproduce the encounter of a young cluster with a reservoir of dense gas, e. g. during its orbital motion in the host galaxy. In the low-density models, as a result of the cooling AGB ejecta which collect in the centre, weakly perturbed by the external ram pressure, a compact central He-rich SG stellar component is formed on a timescale which decreases with increasing initial cluster mass. Our high-density models are subject to stronger ram pressure, which prevents the accumulation of the most He-rich AGB ejecta in the cluster centre. As a result, the SG is more extended and less He-enhanced than in the low-density models. By combining our results with previous simulations, we are able to study relevant, cluster-related scaling relations across a dynamical range of two orders of magnitude in mass (from 10^5 $M_\odot$ to 10^7 $M_\odot$). In agreement with current observationally-based estimates, we find positive correlations between the SG-to-total number ratio and maximum He enhancement in SG stars as a function of the initial cluster mass.

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Gravitational wave of intermediate-mass black holes in Population III star clusters

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Previous theoretical studies suggest that the Population III (Pop3) stars tend to form in extremely metal poor gas clouds with approximately $10^5 M_\odot$ embedded in mini dark matter halos. Very massive stars can form via multiple collisions in Pop3 star clusters and eventually evolve to intermediate-mass black holes (IMBHs). In this work, we conduct star-by-star N-body simulations for modelling the long-term evolution of Pop3 star clusters. We find that if the mini dark matter halos can survive today, these star clusters can avoid tidal disruption by the galactic environment and can efficiently produce IMBH-BH mergers among a wide range of redshift from 0 to 20. The average gravitational wave event rate is estimated to be $0.1 - 0.8\ \mathrm{yr^{-1}Gpc^{-3}}$, and approximately $40 - 80$ percent of the mergers occur at high redshift ($z > 6$). The characteristic strain shows that a part of low-redshift mergers can be detected by LISA, TianQin, and Taiji, whereas most mergers can be covered by DECIGO and advanced LIGO/VIRGO/Kagra. Mergers with pair-instability BHs have a rate of approximately $0.01 - 0.15\ \mathrm{yr^{-1}\ Gpc^{-3}}$, which can explain the GW190521-like events.

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Binary black hole mergers from young massive clusters in the pair-instability supernova mass gap

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The recent discovery of the binary black hole (BBH) merger event GW190521, between two black holes (BHs) of $\approx 100 M_\odot$, and as well as other massive BBH merger events involving BHs within the pair-instability supernova (PSN) mass gap have sparked widespread debate on the origin of such extreme gravitational-wave (GW) events. In this study, I investigate whether dynamical interactions in young massive clusters (YMCs) serves as a viable scenario for assembling PSN-gap BBH mergers. To that end, I explore a grid of 40 new evolutionary models of a representative YMC of initial mass $M_{\rm cl} = 7.5 \times 10^4 M_\odot$ ($N \approx 1.28 \times 10^5$) and size $r_h = 2$ pc, with all BH progenitor stars being initially in primordial binaries. All cluster models are evolved with the direct, relativistic N-body code NBODY7 incorporating up to date remnant formation, BH natal spin, and general-relativistic (GR) merger recoil schemes. The BBH mergers from these model cluster computations agree well with the masses and effective spin parameters of the GW events in the latest GW transient catalogue (GWTC). In particular, GW190521-like, i.e., $\approx 200 M_\odot$, low aligned spin events are produced via dynamical merger among BHs derived from star-star merger products. GW190403-like, i.e., PSN-gap, highly asymmetric and aligned events result from mergers involving BHs that are spun up via matter accretion or binary interaction. The present YMC models yield a present day, intrinsic merger rate density of $0 - 3.8 \times 10^{-2}$ yr^{-1}Gpc^{-3} for GW190521-type events. They produce GW190403-like events at a rate within $0 - 1.6 \times 10^{-1}$ yr^{-1}Gpc^{-3} and their total BBH-merger yield within the PSN gap is $0 - 8.4 \times 10^{-1}$ yr^{-1}Gpc^{-3}.

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Stellar collisions in globular clusters: Constraints on the initial mass function of the first generation of stars

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Globular clusters display an anticorrelation between the fraction of the first generation of stars ($N(\mathrm{G1})/N(\mathrm{tot})$) and the slope of the present-day mass function of the clusters (α_{pd}), which is particularly significant for massive clusters. In the framework of the binary-mediated collision scenario for the formation of the second-generation stars in globular clusters, we test the effect of a varying stellar initial mass function (IMF) of the G1 stars on the $(N(\mathrm{G1})/N(\mathrm{tot})) - \alpha_{pd}$ anticorrelation. We use a simple collision model that has only two input parameters, the shape of the IMF of G1 stars and the fraction of G1 stars that coalesce to form second-generation stars. We show that a variable efficiency of the collision process is necessary in order to explain the $(N(\mathrm{G1})/N(\mathrm{tot})) - \alpha_{pd}$ anticorrelation; however, the scatter in the anticorrelation can only be explained by variations in the IMF, and in particular by variations in the slope in the mass interval $\approx$ (0.1-0.5) $\mathrm{M}_{\odot}$. Our results indicate that in order to explain the scatter in the $(N(\mathrm{G1})/N(\mathrm{tot})) - \alpha_{pd}$ relation, it is necessary to invoke variations in the slope in this mass range between ≈ -0.9 and ≈ -1.9. Interpreted in terms of a Kroupa-like broken power law, this translates into variations in the mean mass of between ≈ 0.2 and 0.55 $\mathrm{M}_{\odot}$. This level of variation is consistent with what is observed for young stellar clusters in the Milky Way and may reflect variations in the physical conditions of the globular cluster progenitor clouds at the time the G1 population formed or may indicate the occurrence of collisions between protostellar embryos before stars settle on the main sequence.

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Simulation star cluster formation/dynamical evolution

Do the majority of stars form as gravitationally unbound?

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Some of the youngest stars (age $\lesssim$ 10Myr) are clustered, while many others are observed scattered throughout star forming regions or in complete isolation. It has been intensively debated whether such scattered or isolated stars originate in star clusters or whether they form in truly isolated conditions. Exploring these scenarios could help set constraints on the conditions in which massive stars are formed. We adopted the assumption that all stars form in gravitationally bound star clusters embedded in molecular cloud cores (Γ-1 model), which expel their natal gas early after their formation. Then we compared the proportion (fraction) of stars found in clusters with observational data. The star clusters are modelled by the code nbody6, which includes binary stars, stellar and circumbinary evolution, gas expulsion, and the external gravitational field of their host galaxy. We find that small changes in the assumptions in the current theoretical model estimating the fraction, Γ, of stars forming in embedded clusters have a large influence on the results, and we present a counterexample as an illustration. This calls into question theoretical arguments about Γ in embedded clusters and it suggests that there is no firm theoretical ground for low Γ in galaxies with lower star formation rates (SFRs). Instead, the assumption that all stars form in embedded clusters is in agreement with observational data for the youngest stars (age $\lesssim$ 10 Myr). In the Γ-1 scenario, the observed fraction of the youngest stars in clusters increases with the SFR only weakly; the increase is caused by the presence of more massive clusters in galaxies with higher SFRs, which release fewer stars to the field in proportion to their mass. The Γ-1 model yields a higher fraction of stars in clusters for older stars (ages between 10 Myr and 300 Myr) than what is observed. This discrepancy can be caused by initially less compact clusters or a slightly lower star-formation efficiency than originally assumed in the Γ-1 model, or by interactions of the post-gas-expulsion revirialised open clusters with molecular clouds.

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The effect of dwarf galaxies on the tidal tails of globular clusters

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The tidal tails of globular clusters have been shown to be sensitive to the external tidal field. We investigate how Galactic globular clusters with observed tails are affected by satellite dwarf galaxies by simulating tails in galaxy models with and without dwarf galaxies. The simulations indicate that tidal tails can be subdivided into three categories based on how they are affected by dwarf galaxies: (1) dwarf galaxies perturb the progenitor cluster's orbit (NGC 4590, Pal 1, Pal 5), (2) dwarf galaxies perturb the progenitor cluster's orbit and individual tail stars (NGC 362, NGC 1851, NGC 4147, NGC 5466, NGC 7492, Pal 14, Pal 15), and (3) dwarf galaxies negligibly affect tidal tails (NGC 288, NGC 5139, NGC 5904, Eridanus). Perturbations to a cluster's orbit occur when dwarf galaxies pass within its orbit, altering the size and shape of the orbital and tail path. Direct interactions between one or more dwarf galaxies and tail stars lead to kinks and spurs, however we find that features are more difficult to observe in projection. We further find that the tails of Pal 5 are shorter in the galaxy model with dwarf galaxies as it is closer to apocentre, which results in the tails being compressed. Additional simulations reveal that differences between tidal tails in the two galaxy models are primarily due to the Large Magellanic Cloud. Understanding how dwarf galaxies affect tidal tails allows for tails to be used to map the distribution of matter in dwarf galaxies and the Milky Way.

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Variation in the stellar mass function along stellar streams

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Stellar streams are the inevitable end product of star cluster evolution, with the properties of a given stream being related to its progenitor. We consider how the dynamical history of a progenitor cluster, as traced by the evolution of its stellar mass function, is reflected in the resultant stream. We generate model streams by evolving star clusters with a range of initial half-mass relaxation times and dissolution times via direct N-body simulations. Stellar streams that dissolve quickly show no variation in the stellar mass function along the stream. Variation is, however, observed along streams with progenitor clusters that dissolve after several relaxation times. The mass function at the edges of a stream is approximately primordial, as it is populated by the first stars to escape the cluster before segregation occurs. Moving inwards the mass function steepens as the intermediate parts of the stream consist of mostly low-mass stars that escaped the cluster after some segregation has occurred. The centre of the stream is then marked by a flatter mass function, as the region is dominated by high-mass stars that quickly segregated to the progenitor cluster's centre and were the last stars to become unbound. We further find that the maximum slope of the mass function along the stream and the rate at which it decreases with distance from the dissolved progenitor serve as proxies for the dynamical state reached by the progenitor cluster before dissolution; this may be able to be applied to observed streams with near-future observations.

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SIRIUS Project. IV. The formation history of the Orion Nebula Cluster driven by clump mergers

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The Orion Nebula Cluster (ONC) is an excellent example for understanding the formation of star clusters. Recent studies have shown that ONC has three distinct age populations and anisotropy in velocity dispersions, which are key characteristics for understanding the formation history of the ONC. In this study, we perform a smoothed-particle hydrodynamics/N-body simulation of star cluster formation from a turbulent molecular cloud. In this simulation, stellar orbits are integrated using a high-order integrator without gravitational softening; therefore, we can follow the collisional evolution of star clusters. We find that hierarchical formation causes episodic star formation that is observed in the ONC. In our simulation, star clusters evolve due to mergers of subclumps. The mergers bring cold gas with the clumps into the forming cluster. This enhances the star formation in the cluster centre. The dense cold gas in the cluster centre continues to form stars until the latest time. This explains the compact distribution of the youngest stars observed in the ONC. Subclump mergers also contribute to the anisotropy in the velocity dispersions and the formation of runaway stars. However, the anisotropy disappears within 0.5 Myr. The virial ratio of the cluster also increases after a merger due to the runaways. These results suggest that the ONC recently experienced a clump merger. We predict that most runaways originated from the ONC have already been found, but walkaways have not.

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SIRIUS Project. V. Formation of off-center ionized bubbles associated with Orion Nebula Cluster

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Massive stars born in star clusters terminate star cluster formation by ionizing the surrounding gas. This process is considered to be prevalent in young star clusters containing massive stars. The Orion Nebula is an excellent example associated with a forming star cluster including several massive stars (the Orion Nebula Cluster; ONC) and a 2-pc size HII region (ionized bubble) opening toward the observer; however, the other side is still covered with dense molecular gas. Recent astrometric data acquired by the Gaia satellite revealed the stellar kinematics in this region. By comparing this data with star cluster formation simulation results, we demonstrate that massive stars born in the ONC center were ejected via three-body encounters. Further, orbit analysis indicates that θ^2 Ori A, the second massive star in this region, was ejected from the ONC center toward the observer and is now returning to the cluster center. Such ejected massive stars can form a hole in the dense molecular cloud and contribute to the formation of the 2-pc bubble. Our results demonstrate that the dynamics of massive stars are essential for the formation of star clusters and HII regions that are not always centered by massive stars.

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Great Balls of FIRE II: The evolution and destruction of star clusters across cosmic time in a Milky Way-mass galaxy

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The current generation of galaxy simulations can resolve individual giant molecular clouds, the progenitors of dense star clusters. But the evolutionary fate of these young massive clusters (YMCs), and whether they can become the old globular clusters (GCs) observed in many galaxies, is determined by a complex interplay of internal dynamical processes and external galactic effects. We present the first star-by-star N-body models of massive ($N \sim 10^5 - 10^7$) star clusters formed in a FIRE-2 MHD simulation of a Milky Way-mass galaxy, with all of the relevant initial conditions and galactic tidal effects extracted directly from the cosmological simulation. We randomly select 895 ($\sim$ 30%) of the YMCs with $> 6 \times 10^4 M_\odot$ from Grudić et al. 2022 and integrate them to the present day using the Cluster Monte Carlo Code, CMC. This procedure predicts a MW-like system with 148 GCs, most of which were formed during the early, bursty mode of star formation in the galaxy. Our GCs are younger, less massive, and more core collapsed than clusters in the Milky Way or M31. This is a direct result of the assembly history and age-metallicity relationship of the GCs' host galaxy: younger clusters are preferentially born in stronger galactic tidal fields and initially retain fewer stellar-mass black holes, causing them to lose mass faster and reach core collapse sooner than their older counterparts. Our results suggest that the masses and core/half-light radii of GCs are shaped not only by internal dynamical processes, but by the specific evolutionary history of their host galaxies as well. These results emphasize that N-body studies with realistic stellar physics are crucial to understanding the evolution and present-day properties of galactic GC systems.

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A Monte Carlo study of early gas expulsion and evolution of star clusters: new simulations with the MOCCA code in the AMUSE framework

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We introduce a new prescription for the evolution of globular clusters (GCs) during the initial embedded gas phase into a Monte Carlo method. With a simplified version of the Monte Carlo MOCCA code embedded in the AMUSE framework, we study the survival of GCs after the removal of primordial gas. We first test our code and show that our results for the evolution of mass and Lagrangian radii are in good agreement with those obtained with N-body simulations. The Monte Carlo code enables a more rapid exploration of the evolution of systems with a larger number of stars than N-body simulations. We have carried out a new survey of simulations to explore the evolution of globular clusters with up to $N = 500000$ stars for a range of different star formation efficiencies and half-mass radii. Our study shows the range of initial conditions leading to the clusters' dissolution and those for which the clusters can survive this early evolutionary phase.

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The Escape of Globular Clusters from the Satellite Dwarf Galaxies of the Milky Way

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Using numerical simulations, we have studied the escape of globular clusters (GCs) from the satellite dwarf spheroidal galaxies (dSphs) of the Milky Way (MW). We start by following the orbits of a large sample of GCs around dSphs in the presence of the MW potential field. We then obtain the fraction of GCs leaving their host dSphs within a Hubble Time. We model dSphs by a Hernquist density profile with masses between $10^7\,M_\odot$ and $7\times10^9\,M_\odot$. All dSphs lie on the Galactic disc plane, but they have different orbital eccentricities and apogalactic distances. We compute the escape fraction of GCs from 13 of the most massive dSphs of the MW, using their realistic orbits around the MW (as determined by Gaia). The escape fraction of GCs from 13 dSphs is in the range 12% to 93%. The average escape time of GCs from these dSphs was less than 8 Gyrs, indicating that the escape process of GCs from dSphs was over. We then adopt a set of observationally-constrained density profiles for specific case of the Fornax dSph. According to our results, the escape fraction of GCs shows a negative correlation with both the mass and the apogalactic distance of the dSphs, as well as a positive correlation with the orbital eccentricity of dSphs. In particular, we find that the escape fraction of GCs from the Fornax dSph is between 13% and 38%. Finally, we observe that when GCs leave their host dSphs, their final orbit around the MW does not differ much from their host dSphs.

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Quantifying kinematic substructure in star-forming regions with statistical tests of spatial autocorrelation

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We investigate whether spatial-kinematic substructure in young star-forming regions can be quantified using Moran's I statistic. Its presence in young star clusters would provide an indication that the system formed from initially substructured conditions, as expected by the hierarchical model of star cluster formation, even if the cluster were spatially smooth and centrally concentrated. Its absence, on the other hand, would be evidence that star clusters form monolithically. The Moran's I statistic is applied to N-body simulations of star clusters with different primordial spatial-velocity structures, and its evolution over time is studied. It is found that this statistic can be used to reliably quantify spatial-kinematic substructure, and can be used to provide evidence as to whether the spatial-kinematic structure of regions with ages $\lesssim$ 6 Myr is best reproduced by the hierarchical or monolithic models of star formation. Moran's I statistic is also able to conclusively say whether the data are *not* consistent with initial conditions that lack kinematic substructure, such as the monolithic model, in regions with ages up to, and potentially beyond, 10 Myrs. This can therefore provide a kinematic signature of the star cluster formation process that is observable for many Myr after any initial spatial structure has been erased.

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Conferences

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