The Star Clusters Young & Old Newsletter

edited by Giovanni Carraro, Martin Netopil, and Ernst Paunzen
https://www.univie.ac.at/scyon/
email: scyon@univie.ac.at

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Dear Colleagues,

After more than a year, we have compiled a new issue of the SCYON. The reasons for the long delay were several internal changes. From now on, we will again provide quarterly issues.

This issue includes 72 abstracts. We congratulate Matteo Messa and Bekdaulet Shukirgaliyev on successful completion of their PhD's.

There are also four conferences announced for 2020 which might be interesting for you.

The SCYON editor team:

Giovanni Carraro, Martin Netopil, and Ernst Paunzen

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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.

https://www.univie.ac.at/scyon

Star Forming Regions

Kinematics in Young Star Clusters and Associations with Gaia DR2

M. A. Kuhn [1], L. A. Hillenbrand [1], A. Sills [2], E. D. Feigelson [3], K. V. Getman [3]
([1]) Department of Astronomy, California Institute of Technology, Pasadena, USA; ([2]) Department of Physics & Astronomy, McMaster University, Hamilton, Canada; ([3]) Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, USA

The Gaia mission has opened a new window into the internal kinematics of young star clusters at the sub-km/s level, with implications for our understanding of how star clusters form and evolve. We use a sample of 28 clusters and associations with ages from 1-5 Myr, where lists of members are available from previous X-ray, optical, and infrared studies. Proper motions from Gaia DR2 reveals that at least 75% of these systems are expanding; however, rotation is only detected in one system. Typical expansion velocities are on the order of $\sim$0.5 km s^{-1}, and, in several systems, there is a positive radial gradient in expansion velocity. Systems that are still embedded in molecular clouds are less likely to be expanding than those that are partially or fully revealed. One-dimensional velocity dispersions, which range from 1 to 3 km s^{-1}, imply that most of the stellar systems in our sample are supervirial and that some are unbound. In star-forming regions that contain multiple clusters or subclusters, we find no evidence that these groups are coalescing, implying that hierarchical cluster assembly, if it occurs, must happen rapidly during the embedded stage.

Accepted by: Astrophysical Journal
http://adsabs.harvard.edu/abs/2018arXiv180702115K

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Kinematic signatures of cluster formation from cool collapse in the Lagoon Nebula cluster NGC 6530

N.J. Wright [1], R.J. Parker [2]
([1]) Keele University; ([2]) Sheffield University

We examine the mass-dependence of the velocity dispersion of stars in the young cluster NGC 6530 to better understand how it formed. Using a large sample of members we find that the proper motion velocity dispersion increases with stellar mass. While this trend is the opposite to that predicted if the cluster were developing energy equipartition, it is in agreement with recent N-body simulations that find such a trend develops because of the Spitzer instability. In these simulations the massive stars sink to the centre of the cluster and form a self-gravitating system with a higher velocity dispersion. If the cluster has formed by the cool collapse of an initially substructured distribution then this occurs within 1-2 Myr, in agreement with our observations of NGC 6530. We therefore conclude that NGC 6530 formed from much more extended initial conditions and has since collapsed to form the cluster we see now. This cluster formation model is inconsistent with the idea that all stars form in dense, compact clusters and provides the first dynamical evidence that star clusters can form by hierarchical mergers between subclusters.

Accepted by: Monthly Notices of the Royal Astronomical Society
https://arxiv.org/abs/1908.11398

A Search for Intermediate Separation Low Mass Binaries in the Orion Nebula Cluster

M. De Furio [1], M. Reiter [2], M. Meyer [1], and 3 co-authors

([1]) Department of Astronomy, University of Michigan, Ann Arbor, MI; ([2]) UK Astronomy Technology Centre, Edinburgh, United Kingdom

We present the results of a binary population study in the Orion Nebula Cluster (ONC) using archival Hubble Space Telescope (HST) data obtained with the Advanced Camera for Surveys (ACS) in Johnson V filter (HST Proposal 10246, PI M. Robberto). Young clusters and associations hold clues to the origin and properties of multiple star systems. Binaries with separations <100 AU are useful as tracers of the initial binary population since they are not as likely to be destroyed through dynamical interactions. Low mass, low stellar density star-forming regions such as Taurus-Auriga, reveal an excess of multiples compared to the Galactic Field. Studying the binary population of higher mass, higher stellar density star-forming regions like the ONC provides useful information concerning the origin of the Galactic Field star population. In this survey, we characterize the previously unexplored (and incomplete) separation parameter space of binaries in the ONC (15 - 160 AU) by fitting a double-PSF model built from empirical PSFs. We identified 14 candidate binaries (11 new detections) and find that 8+4%−2% of our observed sample are in binary systems, complete over mass ratios and separations of $0.6 < q < 1.0$ and $30 < a < 160$ AU. This is consistent with the Galactic Field M-dwarf population over the same parameter ranges, 6.5% $\pm$ 3%. Therefore, high mass star forming regions like the ONC would not require further dynamical evolution for their binary population to resemble the Galactic Field, as some models have hypothesized for young clusters.

Accepted by: Astrophysical Journal

https://arxiv.org/abs/1910.02092

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A Gaia view of the two OB associations Cygnus OB2 and Carina OB1: The signature of their formation process

B. Lim [1,2,3], Y. Naze [2], E. Gosset [2], G. Rauw [2]

([1]) School of Space Research, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea; ([2]) Space sciences, Technologies and Astrophysics Research Institute, Universite de Liege, Quartier Agora, Allee du 6 Aout 19c, Bat. B5C, 4000, Liege, Belgium; ([3]) Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 05006, Republic of Korea

OB associations are the prime star forming sites in galaxies. However the detailed formation process of such stellar systems still remains a mystery. In this context, identifying the presence of substructures may help tracing the footprints of their formation process. Here, we present a kinematic study of the two massive OB associations Cygnus OB2 and Carina OB1 using the precise astrometry from the Gaia Data Release 2 and radial velocities. From the parallaxes of stars, these OB associations are confirmed to be genuine stellar systems. Both Cygnus OB2 and Carina OB1 are composed of a few dense clusters and a halo which have different kinematic properties: the clusters occupy regions of 5-8 parsecs in diameter and display small dispersions in proper motion, while the halos spread over tens of parsecs with a 2-3 times larger dispersions in proper motion. This is reminiscent of the so-called "line width-size" relation of molecular clouds related to turbulence. Considering that the kinematics and structural features were inherited from those of their natal clouds would then imply that the formation of OB associations may result from structure formation driven by supersonic turbulence, rather than from the dynamical evolution of individual embedded clusters.

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https://arxiv.org/abs/1909.03809

On the origin of very massive stars around NGC 3603

V. M. Kalari [1,2], J. S. Vink [3], W. J. de Wit [4], N. J. Bastian [5], R. A. Mendez [2]
([1]) Gemini Observatory, Southern Operations Center, La Serena, Chile; ([2]) Departamento de Astronomía, Universidad de Chile, Santiago, Chile; ([3]) Armagh Observatory, College Hill, Armagh, UK; ([4]) European Southern Observatory, Alonso de Cordova 3107, Santiago, Chile; ([5]) Astrophysics Research Institute, Liverpool John Moores University, Liverpool, UK

The formation of the most massive stars in the Universe remains an unsolved problem. Are they able to form in relative isolation in a manner similar to the formation of solar-type stars, or do they necessarily require a clustered environment? In order to shed light on this important question, we study the origin of two very massive stars (VMS): the O2.5If*/WN6 star RFS7 ($\sim$100 $M_{\odot}$), and the O3.5If* star RFS8 ($\sim$70 $M_{\odot}$), found within $\approx$ 53 and 58 pc respectively from the Galactic massive young cluster NGC 3603, using Gaia data. RFS7 is found to exhibit motions resembling a runaway star from NGC 3603. This is now the most massive runaway star candidate known in the Milky Way. Although RFS8 also appears to move away from the cluster core, it has proper-motion values that appear inconsistent with being a runaway from NGC 3603 at the 3σ level (but with substantial uncertainties due to distance and age). Furthermore, no evidence for a bow-shock or a cluster was found surrounding RFS8 from available near-infrared photometry. In summary, whilst RFS7 is likely a runaway star from NGC 3603, making it the first VMS runaway in the Milky Way, RFS8 is an extremely young ($\sim$2 Myr) VMS, which might also be a runaway, but this would need to be established from future spectroscopic and astrometric observations, as well as precise distances. If RFS8 were still not meeting the criteria for being a runaway from NGC 3603 from such future data, this would have important ramifications for current theories of massive star formation, as well as the way the stellar initial mass function (IMF) is sampled.

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https://arxiv.org/abs/1904.02126

Direct imaging of molten protoplanets in nearby young stellar associations

I. Bonati [1,2], T. Lichtenberg [2,3], D. J. Bower [4], M. L. Timpe [5], S. P. Quanz [6]

([1]) Earth-Life Science Institute, Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan; ([2]) Institute of Geophysics, ETH Zurich, Zurich, Switzerland; ([3]) Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK; ([4]) Center for Space and Habitability, University of Bern, Bern, Switzerland; ([5]) Institute for Computational Science, University of Zurich, Zurich, Switzerland; ([6]) Institute for Particle Physics and Astrophysics, ETH Zurich, Zurich, Switzerland

During their formation and early evolution, rocky planets undergo multiple global melting events due to accretionary collisions with other protoplanets. The detection and characterization of their post-collision afterglows (magma oceans) can yield important clues about the origin and evolution of the solar and extrasolar planet population. Here, we quantitatively assess the observational prospects to detect the radiative signature of forming planets covered by such collision-induced magma oceans in nearby young stellar associations with future direct imaging facilities. We have compared performance estimates for near- and mid-infrared instruments to be installed at ESO's Extremely Large Telescope (ELT), and a potential space-based mission called Large Interferometer for Exoplanets (LIFE). We modelled the frequency and timing of energetic collisions using N-body models of planet formation for different stellar types, and determine the cooling of the resulting magma oceans with an insulating atmosphere. We find that the probability of detecting at least one magma ocean planet depends on the observing duration and the distribution of atmospheric properties among rocky protoplanets. However, the prospects for detection significantly increase for young and close stellar targets, which show the highest frequencies of giant impacts. For intensive reconnaissance with a K band (2.2 μm) ELT filter or a 5.6 μm LIFE filter, the β Pictoris, Columba, TW Hydrae, and Tucana-Horologium associations represent promising candidates for detecting a molten protoplanet. Our results motivate the exploration of magma ocean planets using the ELT and underline the importance of space-based direct imaging facilities to investigate and characterize planet formation and evolution in the solar vicinity. Direct imaging of magma oceans will advance our understanding of the early interior, surface and atmospheric properties of terrestrial worlds.

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Star formation activity and the spatial distribution and mass segregation of dense cores in the early phases of star formation

S. Dib [1,2], T. Henning [2]

([1]) Laboratoire d'Astrophysique de Bordeaux, Universite de Bordeaux, CNRS, Pessac, France; ([2]) Max Planck Institute for Astronomy, Heidelberg, Germany

We examine the spatial distribution and mass segregation of dense molecular cloud cores in a number of nearby star forming regions (the region L1495 in Taurus, Aquila, Corona Australis, and W43) that span about four orders of magnitude in star formation activity. We used an approach based on the calculation of the minimum spanning tree, and for each region, we calculated the structure parameter Q and the mass segregation ratio $\Lambda_{\rm MSR}$ measured for various numbers of the most massive cores. Our results indicate that the distribution of dense cores in young star forming regions is very substructured and that it is very likely that this substructure will be imprinted onto the nascent clusters that will emerge out of these clouds. With the exception of Taurus in which there is nearly no mass segregation, we observe mild-to-significant levels of mass segregation for the ensemble of the 6, 10, and 14 most massive cores in Aquila, Corona Australis, and W43, respectively. Our results suggest that the clouds' star formation activity are linked to their structure, as traced by their population of dense cores. We also find that the fraction of massive cores that are the most mass segregated in each region correlates with the surface density of star formation in the clouds. The Taurus region with low star forming activity is associated with a highly hierarchical spatial distribution of the cores (low Q value) and the cores show no sign of being mass segregated. On the other extreme, the mini-starburst region W43-MM1 has a higher Q that is suggestive of a more centrally condensed structure. Additionally, it possesses a higher fraction of massive cores that are segregated by mass. While some limited evolutionary effects might be present, we largely attribute the correlation between the star formation activity of the clouds and their structure to a dependence on the physical conditions that have been imprinted on them by the large scale environment at the time they started to assemble.

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https://arxiv.org/abs/1808.07057

Galactic Open Clusters

Extended main sequence turn-off originating from a broad range of stellar rotational velocities

B. Lim [1,2,3], G. Rauw [1], Y. Naze [1], and 3 co-authors

([1]) Space sciences, Technologies and Astrophysics Research (STAR) Institute, Université de Liège, Liège, Belgium; ([2]) Department of Physics and Astronomy, Sejong University, Seoul, Republic of Korea; ([3]) School of Space Research, Kyung Hee University, Giheung-gu, Yonginsi, Gyeonggi-do, Republic of Korea

Star clusters have long been considered to comprise a simple stellar population, but this paradigm is being challenged, since apart from multiple populations in Galactic globular clusters, a number of intermediate-age star clusters exhibit a significant colour spread at the main sequence turn-off (MSTO). A sequential evolution of multiple generations of stars formed over 100-200 million years is a natural explanation of this colour spread. Another approach to explain this feature is to introduce the effect of stellar rotation. However, its effectiveness has not yet been proven due to the lack of direct measurements of rotational velocities. Here we report the distribution of projected rotational velocities (V sini) of stars in the Galactic open cluster M11, measured through a Fourier transform analysis. Cluster members display a broad V sini distribution, and fast rotators including Be stars have redder colours than slow rotators. Monte Carlo simulations infer that cluster members have highly aligned spin axes and a broad distribution of equatorial velocities biased towards high velocities. Our findings demonstrate how stellar rotation affects the colours of cluster members, suggesting that the colour spread observed in populous clusters can be understood in the context of stellar evolution even without introducing multiple stellar populations.

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http://adsabs.harvard.edu/doi/10.1038/s41550-018-0619-5

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The Fundamental Plane of Open Clusters

X. Pang [1,3], S. Shen [2,3], Z. Shao [2,3]

([1]) Shanghai Institute of Technology, Shanghai, P.R. China; ([2]) Shanghai Astronomical Observatory, Shanghai, P.R. China; ([3]) Key Lab for Astrophysics, Shanghai Normal University, Shanghai, P.R. China

We utilize the data from the Apache Point Observatory Galactic Evolution Experiment-2 (APOGEE-2) in the fourteenth data release of the Sloan Digital Sky Survey (SDSS) to calculate the line-of-sight velocity dispersion σ_{1D} of a sample of old open clusters (age larger than 100 Myr) selected from the Milky Way open cluster catalog of Kharchenko et al. (2013). Together with their K_s band luminosity L_{K_s}, and the half-light radius r_h of the most probable members, we find that these three parameters show significant pairwise correlations among each other. Moreover, a fundamental plane-*like* relation among these parameters is found for the oldest open clusters (age older than 1 Gyr), $L_{K_s} \propto \sigma_{1D}^{0.82\pm0.29} \cdot r_h^{2.19\pm0.52}$ with $rms \sim 0.31$ mag in the K_s band absolute magnitude. The existence of this relation, which deviates significantly from the virial theorem prediction, implies that the dynamical structures of the old open clusters are quite similar, when survived from complex dynamical evolution to age older than 1 Gyr.

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http://adsabs.harvard.edu/abs/2018ApJ...868L...9P

Astrometric and photometric study of Dias 4, Dias 6, and other five open clusters using ground-based and Gaia DR2 data

W. S. Dias [1], H. Monteiro [1], J. R. D. Lépine [2], and 3 co-authors

([1]) Instituto de Física e Química, Universidade Federal de Itajubá, Itajubá-MG, Brazil; ([2]) Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo - SP, Brazil

We present a study of seven southern open clusters based on UBVRI CCD photometry (Johnsons-Cousins system) and Gaia DR2 data. Dias 4, Dias 6, and four other clusters had UBVRI photometric observations determined for the first time. From the observational UBVRI data we obtained photometric membership probability estimates and, using the proper motions from the UCAC5 catalogue, we also determined the kinematic membership. From Gaia DR2 astrometric data we determine the stellar membership using proper motions and parallaxes, taking into account the full covariance matrix. For both independent sets of data and membership we apply our non-subjective multidimensional global optimization tool to fit theoretical isochrones to determine the distance, age, reddening, metallicity, and binary fraction of the clusters. The results of the mean proper motions, distances, and ages are in agreement, but the ones obtained from Gaia DR2 data are more precise in both membership selection and estimated parameters. In the case of NGC 6087, the Cepheid S Nor, member of the open cluster, was used to obtain an independent distance estimate, confirming the one determined by our fitting method. We also report a serendipitous discovery of two new clusters in the extended field near what was originally Dias 4.

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http://adsabs.harvard.edu/abs/2018MNRAS.481.3887D

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The Kinematics of Open Stellar Clusters on the Data of the New Version of the "Homogeneous Catalog of Open Clusters Parameters"

A. V. Loktin [1], M. E. Popova [1]

([1]) Astronomical observatory of Ural Federal University, Russia

On the basis of open stellar clusters parameters from current version of the "Homogeneous catalog of the parameters of open stellar clusters" and Gaia DR2 Catalog Data some problems of the kinematics of the disk of the Galaxy are investigated. By radial velocities and proper motions data the value of angular velocity of the Sun in the Galaxy $\Omega_0 = 25.6 \pm 1.2$ km/s/kpc is determined. A new approximation of the rotation curve of the Galaxy by a polynomial in inverse powers of the galactocentric distances is constructed. The effect of spiral density waves on the smoothed velocity field of the Galactic disk is considered. The radial $f_R = 4.6 \pm 0.7$ km/s and tangential $f_\theta = 1.1 \pm 0.4$ km/s amplitudes of the velocity field distortion are estimated from radial dependences of the components of the residual spatial velocities of the clusters.

Accepted by: Astrophysical Bulletin

On the APOGEE DR14 sodium spread in the Galactic open cluster NGC 188

A. E. Piatti [1,2]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Córdoba, Argentina

I have analyzed APOGEE DR4 [Na/Fe] abundances of 15 bonafide members in the Galactic open cluster NGC 188. Although these abundances would seem to reveal an spread of ~ 0.16 dex, the direct visualization of the respective spectra do not suggest any clear difference. Therefore, I warn users of large spectroscopic surveys to be extra careful when finding peculiar abundance results. Analysis pipelines that run in an unsupervised fashion may produce bad results which may not be noticed before publication.

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https://arxiv.org/abs/1907.10476

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Gaia DR2 distances to Collinder 419 and NGC 2264 and new astrometric orbits for HD 193 322 Aa,Ab and 15 Mon Aa,Ab

J. Maíz Apellániz [1]

([1]) Centro de Astrobiología (CSIC-INTA), Madrid, Spain

On the one hand, the second data release of the Gaia mission (Gaia DR2) has opened a trove of astrometric and photometric data for Galactic clusters within a few kpc of the Sun. On the other hand, lucky imaging has been an operational technique to measure the relative positions of visual binary systems for a decade and a half, a time sufficient to apply its results to the calculation of orbits of some massive multiple systems within $\sim$1 kpc of the Sun. As part of an ambitious research program to measure distances to Galactic stellar groups (including clusters) containing O stars, I start with two of the nearest examples: Collinder 419 in Cygnus and NGC 2264 in Monoceros. The main ionizing source for both clusters is a multiple system with an O-type primary: HD 193 322 and 15 Mon, respectively. For each of those two multiple systems I aim to derive new astrometric orbits for the Aa,Ab components. First, I present a method that uses Gaia DR2 $G+G_{BP}+G_{RP}$ photometry, positions, proper motions, and parallaxes to obtain the membership and distance of a stellar group and apply it to Collinder 419 and NGC 2264. Second, I present a new code that calculates astrometric orbits by searching the whole seven-parameter orbit space and apply it to HD 193 322 Aa,Ab and 15 Mon Aa,Ab using as input literature data from the Washington Double Star Catalog (WDS) and the AstraLux measurements recently presented by Maíz Apellániz et al. (2019). I obtain Gaia DR2 distances of 1006^{+37}_{-34} pc for Collinder 419 and 719 ± 16 pc for NGC 2264, with the main contribution to the uncertainties coming from the spatial covariance of the parallaxes. The two NGC 2264 subclusters are at the same distance (within the uncertainties) and they show a significant relative proper motion. The distances are shown to be robust. HD 193 322 Aa,Ab follows an eccentric ($e = 0.58^{+0.03}_{-0.04}$) orbit with a period of 44 ± 1 a and the three stars it contains have a total mass of $76.1^{+9.9}_{-7.4}$ $M_\odot$. The orbit of 15 Mon Aa,Ab is even more eccentric ($e = 0.770^{+0.023}_{-0.030}$), with a period of 108 ± 12 a and a total mass of $45.1^{+3.6}_{-3.3}$ $M_\odot$ for its two stars.

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https://arxiv.org/abs/1908.02040

Multiple Populations in Integrated Light Spectroscopy of Intermediate Age Clusters

N. Bastian [1], C. Usher [1], S. Kamann [1], and 9 co-authors
([1]) LJMU

The presence of star-to-star light-element abundance variations (a.k.a. multiple populations, MPs) appears to be ubiquitous within old and massive clusters in the Milky Way and all studied nearby galaxies. Most previous studies have focussed on resolved images or spectroscopy of individual stars, although there has been significant effort in the past few years to look for multiple population signatures in integrated light spectroscopy. If proven feasible, integrated light studies offer a potential way to vastly open parameter space, as clusters out to tens of Mpc can be studied. We use the NaD lines in the integrated spectra of two clusters with similar ages ($2-3$ Gyr) but very different masses, NGC 1978 ($\sim 3\times10^5$ $M_\odot$) in the LMC and G114 (1.7×10^7 $M_\odot$) in NGC 1316. For NGC 1978, our findings agree with resolved studies of individual stars which did not find evidence for Na spreads. However, for G114, we find clear evidence for the presence of multiple populations. The fact that the same anomalous abundance patterns are found in both the intermediate age and ancient GCs lends further support to the notion that young massive clusters are effectively the same as the ancient globular clusters, only separated in age.

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https://ui.adsabs.harvard.edu/abs/2019arXiv190901404B/abstract

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Chemical analysis of K giants in the young open cluster NGC 2345

N. Holanda [1], C. B. Pereira [1], N. Drake [2,3]
([1]) Observatório Nacional/MCTIC, Rio de Janeiro, Brazil; ([2]) Laboratory of Observacional Astrophysics, Saint Petersburg, Russia; ([3]) Laboratório Nacional de Astrofísica, Itajubá, Brazil

We present results for the elemental abundances of five K giants of the young open cluster NGC 2345. The atmospheric parameters of the studied giants and their chemical abundances were determined using high-resolution optical spectroscopy. In this study, we determine abun- dances of light elements (Li, C, N), light odd-Z elements (Na, Al), α-elements (Mg, Si, Ca, Ti), Fe-group elements (Cr, Fe, Ni), and n-capture elements (Y, Zr, La, Ce, Nd, Sm, Eu) for each star. Abundances of the light elements and Eu were obtained using spectral synthesis technique. Also, rotation velocities were determined through the spectral synthesis of the Fe I line at 6151.6. The mean metallicity obtained for the open cluster is [Fe/H]=-0.33±0.05 and it is considered low compared to recent studies for open clusters in the Milky Way, although low for its Galactic latitude (b = -02.31°). Lastly, the abundance analysis shows that there is good agreement with the profile of field clump stars with the same metallicity.

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https://academic.oup.com/mnras/article/482/4/5275/5159499

Hunting for open clusters in Gaia DR2: the Galactic anticentre

A. Castro-Ginard [1], C. Jordi [1], X. Luri [1], T. Cantat-Gaudin [1], L. Balaguer-Núñez [1]

([1]) Dept. Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (IEEC-UB), Martí i Franquès 1, E08028 Barcelona, Spain

The *Gaia* Data Release 2 (DR2) provided an unprecedented volume of precise astrometric and excellent photometric data. In terms of data mining the *Gaia* catalogue, machine learning methods have shown to be a powerful tool, for instance in the search for unknown stellar structures. Particularly, supervised and unsupervised learning methods combined together significantly improves the detection rate of open clusters. We systematically scan *Gaia* DR2 in a region covering the Galactic anticentre and the Perseus arm ($120^o \leq l \leq 205^o$ and $-10^o \leq b \leq 10^o$), with the goal of finding any open clusters that may exist in this region, and fine tuning a previously proposed methodology successfully applied to TGAS data, adapting it to different density regions. Our methodology uses an unsupervised, density-based, clustering algorithm, DBSCAN, that identifies overdensities in the five-dimensional astrometric parameter space $(l, b, \varpi, \mu_{\alpha^*}, \mu_\delta)$ that may correspond to physical clusters. The overdensities are separated into physical clusters (open clusters) or random statistical clusters using an artificial neural network to recognise the isochrone pattern that open clusters show in a colour magnitude diagram. The method is able to recover more than 75% of the open clusters confirmed in the search area. Moreover, we detected 53 open clusters unknown previous to *Gaia* DR2, which represents an increase of more than 22% with respect to the already catalogued clusters in this region. We find that the census of nearby open clusters is not complete. Different machine learning methodologies for a blind search of open clusters are complementary to each other; no single method is able to detect 100% of the existing groups. Our methodology has shown to be a reliable tool for the automatic detection of open clusters, designed to be applied to the full *Gaia* DR2 catalogue.

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https://ui.adsabs.harvard.edu/abs/2019A%26A...627A..35C/abstract

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The extended Main-Sequence Turnoff of the Milky Way open cluster Collinder 347

A. E. Piatti [1,2], C. Bonatto [3]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Godoy Cruz 2290, C1425FQB, Buenos Aires, Argentina; ([2]) Observatorio Astronómico de Córdoba, Laprida 854, 5000, Córdoba, Argentina; ([3]) Departamento de Astronomia, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves 9500 Porto Alegre 91501-970, RS, Brazil

We made use of the Gaia DR2 archive to comprehensively study the Milky Way open cluster Collinder 347, known until now as a very young object of solar metal-content. However, the G versus G_BP-G_RP colour-magnitude diagram (CMD) of bonafide probable cluster members, selected on the basis of individual stellar proper motions, their spatial distribution and placement in the CMD, reveals the existence of a Hyades-like age open cluster (log(t /yr) = 8.8) of moderately metal-poor chemical content ([Fe/H] = -0.4 dex), with a present-day mass of 3.3x10^3 $M_\odot$. The cluster exhibits an extended Main-Sequence turnoff (eMSTO) of nearly 500 Myr, while that computed assuming Gaussian distributions from photometric errors, stellar binarity, rotation and metallicity spread yields an eMSTO of 340 Myr. Such an age difference points to the existence within the cluster of stellar populations with different ages.

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https://arxiv.org/abs/1910.00973

Solving the distance discrepancy for the open cluster NGC 2453: The planetary nebula NGC 2452 is not a cluster member

D. González-Díaz [1,2], C. Moni Bidin [1], E. Silva-Villa [2], and 6 co-authors

([1]) Instituto de Astronomía, Universidad Católica del Norte, Av. Angamos 0610, Antofagasta, Chile; ([2]) Instituto de Física, Universidad de Antioquia (UdeA), Calle 70 52-21, Medellín, Colombia

The open cluster (OC) NGC 2453 is of particular importance since it has been considered to host the planetary nebula (PN) NGC 2452, however their distances and radial velocities are strongly contested. In order to obtain a complete picture of the fundamental parameters of the OC NGC 2453, 11 potential members were studied. The results allowed us to resolve the PN NGC 2452 membership debate. Radial velocities for the 11 stars in NGC 2453 and the PN were measured and matched with Gaia data release 2 (DR2) to estimate the cluster distance. In addition, we used deep multi-band UBVRI photometry to get fundamental parameters of the cluster via isochrone fitting on the most likely cluster members, reducing inaccuracies due to field stars.The distance of the OC NGC 2453 (4.7 ± 0.2 kpc) was obtained with an independent method solving the discrepancy reported in the literature. This result is in good agreement with an isochrone fitting of 40-50 Myr. On the other hand, the radial velocity of NGC 2453 (78±3 km s ^{1}) disagrees with the velocity of NGC2452 (62±2 km s ^{1}). Our results show that the PN is a foreground object in the line of sight. Due to the discrepancies found in the parameters studied, we conclude that the PN NGC 2452 is not a member of the OC NGC 2453.

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Stellar population astrophysics (SPA) with the TNG. Characterization of the young open cluster ASCC 123

A. Frasca [1], J. Alonso-Santiago [1], G. Catanzaro [1], and 10 co-authors

([1]) INAF, Osservatorio Astrofisico di Catania, via S. Sofia 78, 95123, Catania, Italy

Star clusters are key to understand the stellar and Galactic evolution. ASCC 123 is a little-studied, nearby and very sparse open cluster. We performed the first high-resolution spectroscopic study of this cluster in the framework of the SPA (Stellar Population Astrophysics) project with GIARPS at the TNG. We observed 17 stars, five of which turned out to be double-lined binaries. Three of the investigated sources were rejected as members on the basis of astrometry and lithium content. For the remaining single stars we derived the stellar parameters, extinction, radial and projected rotational velocities, and chemical abundances for 21 species with atomic number up to 40. From the analysis of single main-sequence stars we found an average extinction AV 0.13 mag and a median radial velocity of about −5.6 km/s. The average metallicity we found for ASCC 123 is [Fe/H] +0.14±0.04, which is in line with that expected for its Galactocentric distance. The chemical composition is compatible with the Galactic trends in the solar neighborhood within the errors. From the lithium abundance and chromospheric H emission we found an age similar to that of the Pleiades, which agrees with that inferred from the Hertzsprung-Russell and color-magnitude diagrams.

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A comprehensive study of NGC 2345, a young open cluster with a low metallicity

J. Alonso-Santiago [1,2], I. Negueruela [3], A. Marco [2], and 3 co-authors

([1]) INAF, Osservatorio Astrofisico di Catania, via S. Sofia 78, 95123, Catania, Italy; ([2]) Dpto de Física, Ingeniería de Sistemas y Teoría de la Señal, Escuela Politécnica Superior, Universidad de Alicante, Carretera de San Vicente del Raspeig s/n, 03690, Spain; ([3]) Dpto de Física Aplicada. Universidad de Alicante, Carretera de San Vicente del Raspeig s/n, 03690, Spain

NGC 2345 is a young open cluster hosting seven blue and red supergiants, low metallicity and a high fraction of Be stars which makes it a privileged laboratory to study stellar evolution. We aim to improve the determination of the cluster parameters and study the Be phenomenon. Our objective is also to characterise its seven evolved stars by deriving their atmospheric parameters and chemical abundances. We performed a complete analysis combining for the first time *ubvy* photometry with spectroscopy as well as *Gaia* Data Release 2. We obtained spectra with classification purposes for 76 stars and high-resolution spectroscopy for an in-depth analysis of the blue and red evolved stars. We identify a new red supergiant and 145 B-type likely members within a radius of 18.7±1.2 arcmin, which implies an initial mass, $M_{\rm cl}$ ≈5200 $M_\odot$.We find a distance of 2.5±0.2 kpc for NGC 2345, placing it at $R_{\rm GC}$=10.2±0.2 kpc. Isochrone fitting supports an age of 56±13 Ma, implying masses around 6.5 $M_\odot$ for the supergiants. A high fraction of Be stars (≈10%) is found. From the spectral analysis we estimate for the cluster an average $v_{\rm rad}$=+58.6 ± 0.5 kms^{-1} and a low metallicity, [Fe/H]=−0.28±0.07. We also have determined chemical abundances for Li, O, Na, Mg, Si, Ca, Ti, Ni, Rb, Y, and Ba for the evolved stars. The chemical composition of the cluster is consistent with that of the Galactic thin disc. One of the K supergiants, S50, is a Li-rich star, presenting an A(Li)≈2.1. An overabundance of Ba is found, supporting the enhanced *s*-process. NGC 2345 has a low metallicity for its Galactocentric distance, comparable to typical LMC stars. It is massive enough to serve as a testbed for theoretical evolutionary models for massive intermediate-mass stars.

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Tidal-locking-induced stellar rotation dichotomy in the open cluster NGC 2287?

W. Sun [1,2], C. Li [3,2], L. Deng [2,4,5], R. de Grijs [6,7,8]

([1]) Kavli Institute for Astronomy & Astrophysics and Department of Astronomy, Peking University, China; ([2]) Key Laboratory for Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China; ([3]) School of Physics and Astronomy, Sun Yat-sen University, Zhuhai, China; ([4]) School of Astronomy and Space Science, University of the Chinese Academy of Sciences, Huairou, China; ([5]) Department of Astronomy, China West Normal University, Nanchong, China; ([6]) Department of Physics and Astronomy, Macquarie University, Balaclava Road, Sydney, Australia; ([7]) Research Centre for Astronomy, Astrophysics and Astrophotonics, Macquarie University, Balaclava Road, Sydney, Australia; ([8]) International Space Science Institute–Beijing, 1 Nanertiao, Hai Dian District, Beijing, China

Stars spend most of their lifetimes on the 'main sequence' (MS) in the Hertzsprung–Russell diagram. The obvious double MSs seen in the equivalent color–magnitude diagrams characteristic of Milky Way open clusters pose a fundamental challenge to our traditional understanding of star clusters as 'single stellar populations.' The clear MS bifurcation of early-type stars with masses greater than $\sim 1.6 M_{\odot}$ is thought to result from a range in the stellar rotation rates. However, direct evidence connecting double MSs to stellar rotation properties has yet to emerge. Here, we show through analysis of the projected stellar rotational velocities ($v \sin i$, where i represents the star's inclination angle) that the well-separated double MS in the young, $\sim$ 200 Myr old Milky Way open cluster NGC 2287 is tightly correlated with a dichotomous distribution of stellar rotation rates. We discuss whether our observations may reflect the effects of tidal locking affecting a fraction of the cluster's member stars in stellar binary systems. We show that the slow rotators could potentially be initially rapidly rotating stars that have been slowed down by tidal locking by a low mass-ratio companion in a cluster containing a large fraction of short-period, low-mass-ratio binaries. This demonstrates that stellar rotation drives the split MSs in young, $\lessapprox$ 300 Myr-old star clusters. However, special conditions, e.g., as regards the mass-ratio distribution, might be required for this scenario to hold.

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Nearly coeval intermediate-age Milky Way star clusters at very different dynamics evolutionary stages

A. E. Piatti [1,2], M. S. Angelo [3], W. S. Dias [4]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Córdoba, Argentina; ([3]) Centro Federal de Educacao Tecnológica de Minas Gerais, Nepomuceno, Brazil; ([4]) UNIFEI, Instituto de Física e Química, Universidade Federal de Itajubá, Itajubá, Brazil

We report astrophysical properties of 12 Milky Way open clusters located beyond the circle around the Sun where the number of catalogued open clusters is thought to be statistically complete. By using deep optical photometry, we estimated their ages and metallicities on the basis of a maximum likelihood approach, using cluster members identified from Gaia DR2 data and likelihood procedures. The studied clusters turned out to be of intermediate-age (0.8 – 4.0 Gyr), with metallicities spanning the range [Fe/H]$\cong$-0.5$\pm$0.1 dex, and distributed within the general observed trend of the Milky Way disc radial and perpendicular metallicity gradients. As far as we are aware, these are the first metal abundance estimates derived for these clusters so far. From the constructed stellar density radial profiles and cluster mass functions we obtained a variety of structural and internal dynamics evolution parameters. They show that while the innermost cluster regions would seem to be mainly shaped according to the respective internal dynamics evolutionary stages, the outermost ones would seem to be slightly more sensitive to the Milky Way tidal field. The nearly coeval studied clusters are experiencing different levels of two-body relaxation following star evaporation; those at more advanced stages being more compact objects. Likewise, we found that the more important the Milky way tides, the larger the Jacobi volume occupied by the clusters, irrespective of their actual sizes and internal dynamics evolutionary stages.

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Galactic Globular Clusters

New variable stars in NGC 6652 and its background Sagittarius stream

R. Salinas [1], A. K. Vivas [2], R. Contreras Ramos [3,4]

([1]) Gemini Observatory, La Serena, Chile; ([2]) Cerro Tololo Interamerican Observatory, National Optical Astronomy Observatory, La Serena, Chile; ([3]) Millennium Institute of Astrophysics, Macul, Santiago, Chile; ([4]) Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Macul, Chile

We conducted a variable star search on the metal-rich Galactic globular cluster NGC 6652 using archival Gemini-S/GMOS data. We report the discovery of nine new variable stars in the NGC 6652 field, of which we classify six as eclipsing binaries and one as SX Phoenicis stars, leaving two variables without classification. Using proper motions from Gaia DR2 and HST, albeit with some uncertainties, we find that the cluster, the field, and the background Sagittarius stream, have 3 of these variables each. We also reassess the membership of known variables based on the Gaia proper motions, confirming the existence of one RR Lyrae star in the cluster.

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A Sequoia in the Garden: FSR 1758 - Dwarf Galaxy or Giant Globular Cluster?

R. H. Barbá [1], D. Minniti [2], D. Geisler [1,3], and 5 co-authors

([1]) Departamento de Física y Astronomía, Universidad de La Serena, La Serena, Chile; ([2]) Depto. de Ciencias Físicas, Facultad de Ciencias Exactas, Universidad Andrés Bello, Las Condes, Santiago, Chile; ([3]) Departamento de Astronomia, Universidad de Concepcion, Chile

We present the physical characterization of FSR 1758, a new large, massive object very recently discovered in the Galactic Bulge. The combination of optical data from the 2nd Gaia Data Release (GDR2) and the DECam Plane Survey (DECaPS), and near-IR data from the VISTA Variables in the Vía Láctea Extended Survey (VVVX) led to a clean sample of likely members. Based on this integrated dataset, position, distance, reddening, size, metallicity, absolute magnitude, and proper motion of this object are measured. We estimate the following parameters: $\alpha = 17:31:12$, $\delta = -39:48:30$ (J2000), $D = 11.5 \pm 1.0$ kpc, $E(J-Ks) = 0.20 \pm 0.03$ mag, $R_c = 10$ pc, $R_t = 150$ pc, $[Fe/H] = -1.5 \pm 0.3$ dex, $M_i < -8.6 \pm 1.0$, $\mu_\alpha = -2.85$ mas yr^{-1}, and $\mu_\delta = 2.55$ mas yr^{-1}. The nature of this object is discussed. If FRS 1758 is a genuine globular cluster, it is one of the largest in the Milky Way, with a size comparable or even larger than that of ω Cen, being also an extreme outlier in the size vs. Galactocentric distance diagram. The presence of a concentration of long-period RR Lyrae variable stars and blue horizontal branch stars suggests that it is a typical metal-poor globular cluster of Oosterhoff type II. Further exploration of a larger surrounding field reveals common proper motion stars, suggesting either tidal debris or that FRS 1758 is actually the central part of a larger extended structure such as a new dwarf galaxy, tentatively named as Scorpius. In either case, this object is remarkable, and its discovery graphically illustrates the possibility to find other large objects hidden in the Galactic Bulge using future surveys.

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Mean proper motions, space orbits and velocity dispersion profiles of Galactic globular clusters derived from Gaia DR2 data

H. Baumgardt [1], M. Hilker [2], A. Sollima [3], A. Bellini [4]

([1]) School of Mathematics and Physics, The University of Queensland, St. Lucia, Australia; ([2]) European Southern Observatory, Garching, Germany; ([3]) INAF Osservatorio Astronomico di Bologna, Bologna, Italy; ([4]) Space Telescope Science Institute, Baltimore, USA

We have derived the mean proper motions and space velocities of 154 Galactic globular clusters and the velocity dispersion profiles of 141 globular clusters based on a combination of Gaia DR2 proper motions with ground-based line-of-sight velocities. Combining the velocity dispersion profiles derived here with new measurements of the internal mass functions allows us to model the internal kinematics of 144 clusters, more than 90% of the currently known Galactic globular cluster population. We also derive the initial cluster masses by calculating the cluster orbits backwards in time applying suitable recipes to account for mass loss and dynamical friction. We find a correlation between the stellar mass function of a globular cluster and the amount of mass lost from the cluster, pointing to dynamical evolution as one of the mechanisms shaping the mass function of stars in clusters. The mass functions also show strong evidence that globular clusters started with a bottom-light initial mass function. Our simulations show that the currently surviving globular cluster population has lost about 80If globular clusters started from a log-normal mass function, we estimate that the Milky Way contained about 500 globular clusters initially, with a combined mass of about $2.5 \cdot 10^8$ $M_\odot$. For a power-law initial mass function, the initial mass in globular clusters could have been a factor of three higher.

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Formation imprints in the kinematics of the Milky Way globular cluster system

A. E. Piatti [1,2]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Córdoba, Argentina

We report results on the kinematics of Milky Way (MW) globular clusters (GCs) based on updated space velocities for nearly the entire GC population. We found that a 3D space with the semi-major axis, the eccentricity and the inclination of the orbit with respect to the MW plane as its axes is helpful in order to dig into the formation of the GC system. We find that GCs formed in-situ show a clear correlation between their eccentricities and their orbital inclination in the sense that clusters with large eccentricities also have large inclinations. These GCs also show a correlation between their distance to the MW center and their eccentricity. Accreted GCs do not exhibit a relationship between eccentricity and inclination, but span a wide variety of inclinations at eccentricities larger than ~ 0.5. Finally, we computed the velocity anisotropy "beta" of the GC system and found for GCs formed in-situ that "beta" decreases from ~ 0.8 down to 0.3 from the outermost regions towards the MW center, but remains fairly constant (0.7-0.9) for accreted ones. These findings can be explained if GCs formed from gas that collapsed radially in the outskirts, with preference for relative high infall angles. As the material reached the rotating forming disk, it became more circular and moved with lower inclination relative to the disk. A half of the GC population was accreted and deposited in orbits covering the entire range of energies from the outer halo to the bulge.

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Characterizing dynamical stages of open clusters located in the Sagittarius spiral arm

M.S. Angelo [1], A.E. Piatti [2,3], W.S. Dias [4], F.F.S. Maia [5]

([1]) Centro Federal de Educacao Tecnológica de Minas Gerais, MG, Brazil; ([2]) Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; ([3]) Observatorio Astronómico, Universidad Nacional de Córdoba, Córdoba, Argentina; ([4]) 4Instituto de Física e Química, Universidade Federal de Itajubá, Itajubá, MG, Brazil; ([5]) Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

The study of dynamical properties of Galactic open clusters (OCs) is a fundamental prerequisite for the comprehension of their dissolution processes. In this work, we characterized 12 OCs, namely: Collinder 258, NGC6756, Czernik 37, NGC5381, Ruprecht 111, Ruprecht 102, NGC6249, Basel 5, Ruprecht 97, Trumpler 25, ESO 129-SC32, and BH150, projected against dense stellar fields. In order to do that, we employed Washington CT1 photometry and Gaia DR2 astrometry, combined with a decontamination algorithm applied to the threedimensional astrometric space of proper motions and parallaxes. From the derived membership likelihoods, we built decontaminated colour–magnitude diagrams, while structural parameters were obtained from King profiles fitting. Our analysis revealed that they are relatively young OCs (log(t yr^1) ∼7.3–8.6), placed along the Sagittarius spiral arm, and at different internal dynamical stages. We found that the half-light radius to Jacobi radius ratio, the concentration parameter and the age to relaxation time ratio describe satisfactorily their different stages of dynamical evolution. Those relative more dynamically evolved OCs have apparently experienced more important low-mass star loss.

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https://ui.adsabs.harvard.edu/abs/2019MNRAS.488.1635A/abstract

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NGC 6388 reloaded: some like it hot, but not too much. New constraints on the first-generation polluters

E. Carretta [1], A. Bragaglia [1]

([1]) INAF-Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Bologna, Italy

Multiple stellar populations in globular clusters (GCs) are defined and recognized by their chemical signature. Second-generation stars show the effects of nucleosynthesis in the more massive stars of the earliest component that formed in the first star formation burst. High-temperature H-burning produces the whole pattern of (anti-) correlations in proton-capture elements that are widely found in GCs. However, it is still debated where this burning occurred. Here we introduce new powerful diagnostic plots to detect evidence (if any) of products from proton-capture reactions that occur at very high temperatures. To test these detectors of high-temperature H-burning plots, we show that stringent constraints can be placed on the temperature range of the first-generation polluters that contributed to shaping the chemistry of multiple stellar population in the massive bulge GC NGC 6388. Using the largest sample to date (185 stars) of giants with detailed abundance ratios in a single GC (except omega Cen), we may infer that the central temperature of part of the polluters must have been comprised between about 100 and about 150 MK if we consider hydrostatic H-burning in the core of massive stars. A much more narrow range (110 to 120 MK) is inferred if the polluters can be identified in massive asymptotic giant branch stars.

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Constant light element abundances suggest that the extended P1 in NGC 2808 is not a consequence of CNO-cycle nucleosynthesis

I. Cabrera-Ziri [1], C. Lardo [2], A. Mucciarelli [3]

([1]) Harvard-Smithsonian Center for Astrophysics; ([2]) Laboratoire d'Astrophysique, Ecole Polytechnique Fédérale de Lausanne; ([3]) Dipartimento di Fisica e Astronomia, Università degli Studi di Bologna

Recent photometric results have identified a new population among globular cluster stars. This population, referred to as the "extended P1", has been suggested to be the manifestation of a new abundance pattern where the initial mass fraction of He changes among cluster stars that share the same CNO values. The current paradigm for the formation of the multiple stellar populations in globular clusters assumes that variations in He are the product of chemical "enrichment" by the ashes of the CNO-cycle (which changes He and other elements like C, N and O simultaneously). We obtained MIKE@Magellan spectra of six giant stars in NGC 2808, a cluster with one of the strongest examples of the extended P1 population. We provide the first complete characterization of the light elements abundances for the stars along a significant range of the extended P1 photometric group. The stars from our sample appear to be homogeneous in C, N, O, Na, Mg and Al. The lack of a significant change in these products of the CNO-cycle, suggest that unlike the rest of the populations identified to date, the photometric changes responsible for the extended P1 feature are a consequence of an alternative mechanism. Our measurements, are consistent with the interpretations where the changes of the He mass fraction among these stars could be consequence of p-p chain nucleosynthesis (which could increase the He in stars without affecting heavier elements). Having said that, direct measurements of He are necessary to conclude if variations of this element are present among extended P1 stars.

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Discovery of an old nova remnant in the Galactic globular cluster M 22

F. Göttgens [1], P. M. Weilbacher [2], M. M. Roth [2], and 11 co-authors

([1]) Institut für Astrophysik, Georg-August-Universität Göttingen, Göttingen, Germany; ([2]) Leibniz-Institut für Astrophysik Potsdam (AIP), Potsdam, Germany

A nova is a cataclysmic event on the surface of a white dwarf in a binary system that increases the overall brightness by several orders of magnitude. Although binary systems with a white dwarf are expected to be overabundant in globular clusters compared with in the Galaxy, only two novae from Galactic globular clusters have been observed. We present the discovery of an emission nebula in the Galactic globular cluster M 22 (NGC 6656) in observations made with the integral-field spectrograph MUSE. We extracted the spectrum of the nebula and used the radial velocity determined from the emission lines to confirm that the nebula is part of NGC 6656. Emission-line ratios were used to determine the electron temperature and density. It is estimated to have a mass of 117×10^5 M. This mass and the emission-line ratios indicate that the nebula is a nova remnant. Its position coincides with the reported location of a "guest star", an ancient Chinese term for transients, observed in May 48 BCE. With this discovery, this nova may be one of the oldest confirmed extra-solar events recorded in human history.

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Variable Stars in M13. III. The Cepheid Variables and their Relation to Evolutionary Changes in Metal-poor BL Her Stars

W. Osborn [1,2], G. Kopacki [3], H. A. Smith [4], and 4 co-authors

([1]) Yerkes Observatory, Dept. Astron. & Astrophys., U. Chicago, Chicago, USA; ([2]) Dept. of Physics, Central Michigan Univ., Mount Pleasant, USA; ([3]) Instytut Astronomiczny UWr., Wrocław, Poland; ([4]) Dept. of Physics & Astronomy, Michigan State Univ., East Lansing, USA

New CCD photometry has been combined with published and unpublished earlier observations to study the three Cepheid variables in M13: V1, V2 and V6. The light curve characteristics in B, V and I_C have been determined and the periods updated. A period change analysis shows all three stars have increasing periods but for V1 and V2 the rate of period increase does not appear to be constant over the 118 years of observation. The observed rates of period increase are in good agreement with the predictions of the Pisa theoretical models with helium abundance Y = 0.25. Theory suggests V1 and V6 have masses of $\sim 0.57 M_{\odot}$ and are in the redward-evolving final stage of the "blue loop" evolutionary phase that is produced when helium-shell ignition occurs. The larger period and period change rate for V2 indicate it has a mass of $\sim 0.52 M_{\odot}$. A study of eighteen metal-poor BL Her stars shows the observed period changes for such objects in general can be reasonably well explained using the predictions from horizontal branch evolutionary tracks. BL Her stars with periods less than $\sim$3 d and relatively large secular period change rates ($dP/dt \approx 5-15$ d/Myr) are in the evolutionary stage before He-shell ignition; the remaining cases are stars that have already experienced He-shell ignition. Moreover, an analysis of crossing time through the instability strip indicates that it is likely that few, if any, BL Her stars have a He abundance as large as Y = 0.33.

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No evidence for intermediate-mass black holes in the globular clusters ω Cen and NGC 6624

H. Baumgardt [1], C. He [1], S. Sweet [2], and 8 co-authors

([1]) University of Queensland; ([2]) Swinburne University of Technology

We compare the results of a large grid of N-body simulations with the surface brightness and velocity dispersion profiles of the globular clusters ω Cen and NGC 6624. Our models include clusters with varying stellar-mass black hole retention fractions and varying masses of a central intermediate-mass black hole (IMBH). We find that an $\approx$45,000 $M_{\odot}$ IMBH, whose presence has been suggested based on the measured velocity dispersion profile of ω Cen, predicts the existence of about 20 fast-moving, m>0.5 $M_{\odot}$ main-sequence stars with a (1D) velocity v>60 km/sec in the central 20 arcsec of ω Cen. However no such star is present in the HST/ACS proper motion catalogue of Bellini et al. (2017), strongly ruling out the presence of a massive IMBH in the core of ω Cen. Instead, we find that all available data can be fitted by a model that contains 4.6% of the mass of Cen in a centrally concentrated cluster of stellar-mass black holes. We show that this mass fraction in stellar-mass BHs is compatible with the predictions of stellar evolution models of massive stars. We also compare our grid of N-body simulations with NGC 6624, a cluster recently claimed to harbor a 20,000 $M_{\odot}$ black hole based on timing observations of millisecond pulsars. However, we find that models with MIMBH>1,000 $M_{\odot}$ IMBHs are incompatible with the observed velocity dispersion and surface brightness profile of NGC 6624,ruling out the presence of a massive IMBH in this cluster. Models without an IMBH provide again an excellent fit to NGC 6624.

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Characteristic radii of the Milky Way Globular Clusters

A. E. Piatti [1,2], J. J. Webb [3], R. G. Carlberg [3]
([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Godoy Cruz 2290, C1425FQB, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Laprida 854, 5000, Córdoba, Argentina; ([3]) Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON, M5S 3H4, Canada

We report on the extent of the effects of the Milky Way's gravitational field in shaping the structural parameters and internal dynamics of its globular cluster population. We make use of a homogeneous, up-to-date data set with kinematics, structural properties, current and initial masses of 156 globular clusters. In general, cluster radii increase as the Milky Way potential weakens; with the core and Jacobi radii being those which increase at the slowest and fastest rate respectively. We interpret this result as the innermost regions of globular clusters being less sensitive to changes in the tidal forces with the Galactocentric distance. The Milky Way's gravitational field also seems to have differentially accelerated the internal dynamical evolution of individual clusters, with those toward the bulge appearing dynamically older. Finally we find a sub-population consisting of both compact and extended globular clusters (as defined by their r_h/r_J ratio) beyond 8 kpc that appear to have lost a large fraction of their initial mass lost via disruption. Moreover, we identify a third group with r_h/r_J > 0.4, which have lost an even larger fraction of their initial mass by disruption. In both cases the high fraction of mass lost is likely due to their large orbital eccentricities and inclination angles, which lead to them experiencing more tidal shocks at perigalacticon and during disc crossings. Comparing the structural and orbital parameters of individual clusters allows for constraints to be placed on whether or not their evolution was relaxation or tidally dominated.

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A deep view of a fossil relic in the Galactic bulge: the Globular Cluster HP 1

L. Kerber [1,2], M. Libralato [3,4,5], S. Souza [1], and 7 co-authors
([1]) Universidade de São Paulo (USP) - Brazil; ([2]) Universidade Estadual de Santa Cruz (UESC) - Brazil; ([3]) Space Telescope Science Institute (STScI) - USA; ([4]) Università di Padova (UPd) - Italy; ([5]) INAF-Osservatorio Astronomico di Padova (OAPd) - Italy

HP 1 is an α-enhanced and moderately metal-poor bulge globular cluster with a blue horizontal branch. These combined characteristics make it a probable relic of the early star formation in the innermost Galactic regions. Here, we present a detailed analysis of a deep near-infrared (NIR) photometry of HP 1 obtained with the NIR GSAOI + GeMS camera at the Gemini-South telescope. J and K_S images were collected with an exquisite spatial resolution (FWHM 0.1 arcsec), reaching stars at two magnitudes below the MSTO. We combine our GSAOI data with archival F606W-filter HST ACS/WFC images to compute relative proper motions and select bona fide cluster members. Results from statistical isochrone fits in the NIR and optical-NIR colour-magnitude diagrams indicate an age of $12.8^{+0.9}_{-0.8}$ Gyr, confirming that HP 1 is one of the oldest clusters in the Milky Way. The same fits also provide apparent distance moduli in the KS and V filters in very good agreement with the ones from 11 RR Lyrae stars. By subtracting the extinction in each filter, we recover a heliocentric distance of $6.59^{+0.17}_{-0.15}$ kpc. Furthermore, we refine the orbit of HP 1 using this accurate distance and update and accurate radial velocities (from high-resolution spectroscopy) and absolute proper motions (from Gaia DR2), reaching mean perigalactic and apogalactic distances of $\sim$0.12 and $\sim$3 kpc, respectively.

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Extra-tidal structures around the Gaia Sausage candidate globular cluster NGC6779 (M56)

A. E. Piatti [1,2], J. A. Carballo-Bello [3]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Córdoba, Argentina; ([3]) Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Macul, Santiago, Chile

We present results on the stellar density radial profile of the outer regions of NGC6779, a Milky Way globular cluster recently proposed as a candidate member of the Gaia Sausage structure, a merger remnant of a massive dwarf galaxy with the Milky Way. Taking advantage of the Pan-STARRS PS1 public astrometric and photometric catalogue, we built the radial profile for the outermost cluster regions using horizontal branch and main sequence stars, separately, in order to probe for different profile trends because of difference stellar masses. Owing to its relatively close location to the Galactic plane, we have carefully treated the chosen colour-magnitude regions properly correcting them by the amount of interstellar extinction measured along the line-of-side of each star, as well as cleaned them from the variable field star contamination observed across the cluster field. In the region spanning from the tidal to the Jacobi radii the resulting radial profiles show a diffuse extended halo, with an average power law slope of -1. While analysing the relationships between the Galactocentric distance, the half-mass density, the half-light radius, the slope of the radial profile of the outermost regions, the internal dynamical evolutionary stage, among others, we found that NGC6779 shows structural properties similar to those of the remaining Gaia Sausage candidate globular clusters, namely, they are massive clusters ($> 10^5 M_\odot$) in a moderately early dynamical evolutionary stage, with observed extra-tidal structures.

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The orbital anisotropy profiles of nearby globular clusters from Gaia Data Release 2

A. Jindal [1], J.J. Webb [1], J. Bovy [1]

([1]) Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada

Gaia Data Release 2 provides a wealth of data to study the internal structure of nearby globular clusters (GCs). We use this data to investigate the internal kinematics of 10 nearby GCs, with a particular focus on their poorly studied outer regions. We apply a strict set of selection criteria to remove contaminating sources and create pure cluster-member samples over a significant fraction of the radial range of each cluster. We confirm previous measurements of rotation (or a lack thereof) in the inner regions of several clusters, while extending the detection of rotation well beyond where it was previously measured and finding a steady decrease in rotation with radius. We also determine the orbital anisotropy profile and determine that clusters have isotropic cores, are radially anisotropic out to 4 half-light radii or 35% of their limiting radii, and are then isotropic out to the limits of our data sets. We detect for the first time the presence of radial anisotropy in M 22, while confirming previous detections of radial anisotropy in 47 Tuc, M 13, M 15, and Cen's innermost regions. The implications of these measurements are that clusters can be separated into two categories: (1) clusters with observed radial anisotropy that likely formed tidally underfilling or are dynamically young, and (2) clusters that are primarily isotropic that likely formed tidally filling or are dynamically old.

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A stellar census in globular clusters with MUSE: A spectral catalogue of emission-line sources

F. Göttgens [1], T.-O. Husser [1], S. Kamann [2], and 6 co-authors

([1]) Institut für Astrophysik, Georg-August-Universität Göttingen, Göttingen, Germany; ([2]) Astrophysics Research Institute, Liverpool John Moores University, Liverpool, UK

Globular clusters produce many exotic stars due to a much higher frequency of dynamical interactions in their dense stellar environments. Some of these objects were observed together with several hundred thousands other stars in our MUSE survey of 26 Galactic globular clusters. Assuming that at least a few exotic stars have exotic spectra, that means spectra that contain emission lines, we can use this large spectroscopic data set of over a million stellar spectra as a blind survey to detect stellar exotica in globular clusters. To detect emission lines in each spectrum, we model the expected shape of an emission line as a Gaussian curve. This template is used for matched filtering on the differences between each observed 1D spectrum and its fitted spectral model. The spectra with the most significant detections of H emission are checked visually and cross-matched with published catalogues. We find 156 stars with H emission, including several known cataclysmic variables (CV) and two new CVs, pulsating variable stars, eclipsing binary stars, the optical counterpart of a known black hole, several probable sub-subgiants and red stragglers, and 21 background emission-line galaxies. We find possible optical counterparts to 39 X-ray sources, as we detect H emission in several spectra of stars that are close to known positions of Chandra X-ray sources. This spectral catalogue can be used to supplement existing or future X-ray or radio observations with spectra of potential optical counterparts to classify the sources.

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Investigation of the Globular Cluster NGC 2808 with the Ultra-Violet Imaging Telescope

R. Jain [1], S. Vig [1], S. K. Ghosh [2]

([1]) Indian Institute of Space science and Technology, Trivandrum, India; ([2]) Tata Institute of Fundamental Research, Mumbai, India

Globular clusters represent stellar laboratories where observations can be used to validate models of stellar evolution. In this study, we put forth new ultraviolet (UV) photometric results of stars in the Galactic globular cluster NGC 2808. NGC 2808 is known to host multiple stellar populations that include at least four distinct groups of horizontal Branch (HB) stars. We have observed this cluster with the AstroSat-UltraViolet Imaging Telescope in two far-UV (FUV) and five near-UV (NUV) filters, respectively. These UV filters enable the identification of HB populations of stars. The results from four NUV filters exhibit bimodal distributions in magnitude histograms. The nature of bimodality has been investigated on the basis of distinct stellar types contributing to those bands. The color-magnitude diagrams constructed using FUV and NUV filters enable the location of hot stellar populations, viz. stars belonging to Red HB (RHB), Blue HB, Extreme HB, Blue Hook branch and post-Asymptotic Giant Branch. Prominent gaps are observed in the UV color-magnitude diagrams. We report for the first time, a photometric gap in a NUV color-magnitude diagram, that segregates the RHB population of this cluster into two groups, that are likely to be associated with distinct generations of stars. We have constructed and examined the GAIA color-magnitude diagram of the optical counterparts of the hot UV stars. We also investigate the spatial density distributions of various groups of stars in the cluster and comment on the proposed formation models of multiple populations.

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A stellar census in globular clusters with MUSE: Multiple populations chemistry in NGC 2808

M. Latour [1], T.-O. Husser [1], B. Giesers [1], and 8 co-authors
([1]) Institut für Astrophysik, Georg-August-Universität Göttingen, Germany

Galactic globular clusters (GCs) are now known to host multiple populations displaying particular abundance variations. The different populations within a GC can be well distinguished following their position in the pseudo two-colors diagrams, also referred to as "chromosome maps". These maps are constructed using optical and near-UV photometry available from the Hubble Space Telescope (HST) UV survey of GCs. However, the chemical tagging of the various populations in the chromosome maps is hampered by the fact that HST photometry and elemental abundances are both available only for a limited number of stars. The spectra collected as part of the MUSE survey of globular clusters provide a spectroscopic counterpart to the HST photometric catalogs covering the central regions of GCs. In this paper, we use the MUSE spectra of 1155 red giant branch (RGB) stars in NGC 2808 to characterize the abundance variations seen in the multiple populations of this cluster. We use the chromosome map of NGC 2808 to divide the RGB stars into their respective populations. We then combine the spectra of all stars belonging to a given population, resulting in one high signal-to-noise ratio spectrum representative of each population. Variations in the spectral lines of O, Na, Mg, and Al are clearly detected among four of the populations. In order to quantify these variations, we measured equivalent width differences and created synthetic populations spectra that were used to determine abundance variations with respect to the primordial population of the cluster. Our results are in good agreement with the values expected from previous studies based on high-resolution spectroscopy. We do not see any significant variations in the spectral lines of Ca, K, and Ba. We also do not detect abundance variations among the stars belonging to the primordial population of NGC 2808.

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A stellar census in globular clusters with MUSE: Binaries in NGC 3201

B. Giesers [1], S. Kamann [2], A. Askar [3], and 8 co-authors

([1]) Institut für Astrophysik, Georg-August-Universität Göttingen, Göttingen, Germany; ([2]) Astrophysics Research Institute, Liverpool John Moores University, Liverpool, United Kingdom; ([3]) Lund Observatory, Department of Astronomy and Theoretical Physics, Lund University, Lund, Sweden

We utilize multi-epoch MUSE spectroscopy to study binaries in the core of NGC 3201. Our sample consists of 3553 stars with 54883 spectra in total comprising 3200 main-sequence stars up to 4 magnitudes below the turn-off. Each star in our sample has between 3 and 63 (with a median of 14) reliable radial velocity (RV) measurements within five years of observations. We introduce a statistical method to determine the probability of a star showing RV variations based on the whole inhomogeneous RV sample. Using HST photometry and an advanced dynamical MOCCA simulation of this specific GC we overcome observational biases that previous spectroscopic studies had to deal with. This allows us to infer a binary frequency in the MUSE FoV and enables us to deduce the underlying true binary frequency of (6.75±0.72) The comparison of the MUSE observations with the MOCCA simulation suggests a significant fraction of primordial binaries. We can also confirm a radial increase of the binary fraction towards the GC centre due to mass segregation. We discovered that in our sample at least (57.5±7.9) study of GCs, we were able to fit Keplerian orbits to a significant sample of 95 binaries. We present the binary system properties of eleven BSS and show evidence that two BSS formation scenarios, the mass transfer in binary (or triple) star systems and the coalescence due to binary-binary interactions, are present in our data. We also describe the binary and spectroscopic properties of four sub-subgiant (or red straggler) stars. Furthermore, we discovered two new black hole (BH) candidates with minimum masses (M_{sini}) of (7.68±0.50) $M_\odot$, (4.4±2.8) $M_\odot$, and refine the minimum mass estimate on the already published BH to (4.53±0.21) $M_\odot$. These BHs are consistent with an extensive BH subsystem hosted by NGC 3201.

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Millisecond Pulsars and Black Holes in Globular Clusters

C. S. Ye [1,2], K. Kremer [1,2], S. Chatterjee [3,2], C. Rodriguez [4], F. A. Rasio [1,2]

([1]) Department of Physics & Astronomy, Northwestern University, Evanston, IL, USA; ([2]) Center for Interdisciplinary Exploration & Research in Astrophysics, Evanston, IL, USA; ([3]) Tata Institute of Fundamental Research, Mumbai, India; ([4]) MIT-Kavli Institute for Astrophysics & Space Research, Cambridge, MA, USA

Over a hundred millisecond radio pulsars (MSPs) have been observed in globular clusters (GCs), motivating theoretical studies of the formation and evolution of these sources through stellar evolution coupled to stellar dynamics. Here we study MSPs in GCs using realistic N-body simulations with our Cluster Monte Carlo code. We show that neutron stars (NSs) formed in electron-capture supernovae (including both accretion-induced and merger-induced collapse of white dwarfs), which we assume to be born with low kick velocities and therefore mostly retained in GCs, can be spun up through mass transfer to form MSPs. Both NS formation and spin-up through accretion are greatly enhanced through dynamical interaction processes. We find that our models for average GCs at the present day with masses $\approx 2 \times 10^5$ solar mass can produce up to 10–20 MSPs, while a very massive GC model with mass $\approx 10^6$ solar mass can produce close to 100. We show that the number of MSPs is anti-correlated with the total number of stellar-mass black holes (BHs) retained in the host cluster. The radial distributions are also affected: MSPs are more concentrated towards the center in a host cluster with a smaller number of retained BHs. This is consistent with theoretical studies showing that BHs have a strong influence on the evolution of GCs and their dynamically-produced population of stellar exotica. GCs that retain more BHs have lower average stellar densities in the volume occupied by the NSs. This lowers the production rate of MSPs via dynamical processes. As a result, the number of MSPs in a GC could be used to place constraints on its BH population. Intrinsic properties of our model pulsars, such as their magnetic fields and spin periods, although hard to determine precisely, are in good overall agreement with observations. Interestingly, our models also demonstrate the possibility of dynamically forming NS–NS and NS–BH binaries in GCs, although the predicted numbers are very small.

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Clusters in the Magellanic clouds

A likely runaway star cluster in the outer disc of the Large Magellanic Cloud

A. E. Piatti [1,2], R. Salinas [3], E. K. Grebel [4]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Córdoba, Argentina; ([3]) Gemini Observatory, La Serena, Chile; ([4]) Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Heidelberg, Germany

We present results from photometric and spectroscopic data obtained with SOAR and Gemini observatory facilities in the field of a recently discovered star cluster. The cluster, projected towards the Eastern side of the outer disc of the Large Magellanic Cloud (LMC), was originally placed nearly 10 kpc behind the LMC with an age and metallicity typical of the innermost LMC star cluster population. We assigned radial velocity (RV) memberships to stars observed spectroscopically, and derived the cluster age and distance from theoretical isochrone fitting to the cluster colour-magnitude diagram. The new object turned out to be a 0.9 Gyr old outer LMC disc cluster, which possibly reached the present position after being scattered from the innermost LMC regions where it might have been born. We arrived at this conclusion by examining the spatial distribution of LMC star clusters of similar age, by comparing the derived spectroscopic metallicity with that expected for an outside-in galaxy formation scenario, by considering the cluster internal dynamical stage as inferred from its derived structural parameters and by estimating the circular velocity of a disc that rotates with the corresponding star cluster radial velocity at the cluster's deprojected distance, which resulted to be nearly 60 per cent higher than that of most of the outer LMC disc clusters.

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Resolved Kinematics of Runaway and Field OB Stars in the Small Magellanic Cloud

M. S. Oey [1], J. Dorigo Jones [1], N. Castro [1], and 6 co-authors

([1]) University of Michigan, Ann Arbor, MI, USA

We use GAIA DR2 proper motions of the RIOTS4 field OB stars in the Small Magellanic Cloud (SMC) to study the kinematics of runaway stars. The data reveal that the SMC Wing has a systemic peculiar motion relative to the SMC Bar of $(v_\alpha, v_\delta) = (62 \pm 7, -18 \pm 5)$ $\mathrm{km\,s^{-1}}$ and relative radial velocity $+4.5 \pm 5.0$ $\mathrm{km\,s^{-1}}$This unambiguously demonstrates that these two regions are kinematically distinct: the Wing is moving away from the Bar, and towards the Large Magellanic Cloud with a 3-D velocity of 64 ± 10 $\mathrm{km\,s^{-1}}$. This is consistent with models for a recent, direct collision between the Clouds. We present transverse velocity distributions for our field OB stars, confirming that unbound runaways comprise on the order of half our sample, possibly more. Using eclipsing binaries and double-lined spectroscopic binaries as tracers of dynamically ejected runaways, and high-mass X-ray binaries (HMXBs) as tracers of runaways accelerated by supernova kicks, we find significant contributions from both populations. The data suggest that HMXBs have lower velocity dispersion relative to dynamically ejected binaries, consistent with the former corresponding to less energetic supernova kicks that failed to unbind the components. Evidence suggests that our fast runaways are dominated by dynamical, rather than supernova, ejections.

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Metallicity estimates of young clusters in the Magellanic Clouds from Stromgren photometry of supergiant stars

A. E. Piatti [1,2], G. Pietrzynski [3], W. Narloch [4,5], M. Gorski [4], D. Graczyk [5]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Córdoba, Argentina; ([3]) Nicolaus Copernicus Astronomical Center, Warsaw, Poland; ([4]) Departamento de Astronomía, Universidad de Concepción, Casilla, Chile; ([5]) Centrum Astronomiczne im. Mikoaja Kopernika, PAN, Torun, Poland

We present results obtained from Stromgren photometry of 13 young (∼30-220 Myr) Magellanic Cloud (MC) clusters, most of them lacking in the literature from direct metallicity measurements. We derived for them [Fe/H] values from a high-dispersion spectroscopy-based empirical calibration of the Stromgren metallicity sensitive index m1 for yellow and red supergiants (SGs). Particular care was given while estimating their respective uncertainties. In order to obtain the mean cluster metallicities, we used [Fe/H] values of selected SGs for which we required to be located within the cluster radii, placed in the expected SG region in the cluster colour-magnitude diagrams, and with [Fe/H] values within the FWHM of the observed cluster metallicity distributions. The resulting metallicities for nearly 75 per cent of the cluster sample agree well with the most frequently used values of the mean MCs' present-day metallicities. The remaining clusters have mean [Fe/H] values that fall near the edge of the MC present-day metallicity distributions. When comparing the cluster metallicities with their present positions, we found evidence that supports the claimed recent interaction of the MCs with the Milky Way, that could have caused that some clusters were scattered from their birthplaces. Indeed, we show examples of clusters with metal contents typical of the galaxy inner regions placed outward them. Likewise, we found young clusters, at present located in the inner regions of both MCs, formed out of gas that has remained unmixed since several Gyr ago.

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Two kinematically distinct old globular cluster populations in the Large Magellanic Cloud

A. E. Piatti [1,2], E. J. Alfaro [3], T. Cantat-Gaudin [4]

([1]) Consejo Nacional de Investigaciones Científicas y Técnicas, Av. Rivadavia 1917, C1033AAJ, Buenos Aires, Argentina; ([2]) Astronomical Observatory of Córdoba, Laprida 854, 5000, Córdoba, Argentina; ([3]) Instituto de Astrofísica de Andalucía, (CSIC), Glorieta de la Astronomía, S/N, Granada, 18008, Spain; ([4]) Institut de Ciéncies del Cosmos, Universitat de Barcelona (IEEC-UB), Martí i Franqués 1, E-08028 Barcelona, Spain

We report results of proper motions of 15 known Large Magellanic Cloud (LMC) old globular clusters (GCs) derived from the Gaia DR2 data sets. When these mean proper motions are gathered with existent radial velocity measurements to compose the GCs' velocity vectors, we found that the projection of the velocity vectors onto the LMC plane and those perpendicular to it tell us about two distinct kinematic GC populations. Such a distinction becomes clear if the GCs are split at a perpendicular velocity of 10 $\mathrm{km\,s^{-1}}$ (absolute value). The two different kinematic groups also exhibit different spatial distributions. Those with smaller vertical velocities are part of the LMC disc, while those with larger values are closely distributed like a spherical component. Since GCs in both kinematic-structural components share similar ages and metallicities, we speculate with the possibility that their origins could have occurred through a fast collapse that formed halo and disc concurrently.

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Helium enrichment in intermediate-age Magellanic Clouds clusters: towards an ubiquity of multiple stellar populations?

W. Chantereau [1], M. Salaris [1], N. Bastian [1], S. Martocchia [2,1]
([1]) Astrophysics Research Institute, Liverpool John Moores University, Liverpool, UK; ([2]) European Southern Observatory, Garching bei München, Germany

Intermediate-age star clusters in the Magellanic Clouds harbour signatures of the multiple stellar populations long thought to be restricted to old globular clusters. We compare synthetic horizontal branch models with Hubble Space Telescope photometry of clusters in the Magellanic Clouds, with age between ∼2 and ∼10 Gyr, namely NGC 121, Lindsay 1, NGC 339, NGC 416, Lindsay 38, Lindsay 113, Hodge 6 and NGC 1978. We find a clear signature of initial helium abundance spreads (ΔY) in four out of these eight clusters (NGC 121, Lindsay 1, NGC 339, NGC 416) and we quantify the value of ΔY. For two clusters (Lindsay 38, Lindsay 113) we can only determine an upper limit for ΔY, whilst for the two youngest clusters in our sample (Hodge 6 and NGC 1978) no conclusion about the existence of an initial He spread can be reached. Our ΔY estimates are consistent with the correlation between maximum He abundance spread and mass of the host cluster found in Galactic globular clusters. This result strengthens the emerging view that the formation of multiple stellar populations is a standard process in massive star clusters, not limited to a high redshift environment.

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An Extragalactic Chromosome Map: The intermediate age SMC Cluster Lindsay 1

S. Saracino [1,2], N. Bastian [1], V. Kozhurina-Platais [3], and 8 co-authors
([1]) Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK; ([2]) INAF-Osservatorio di Astrofisica & Scienza dello Spazio, via Gobetti 93/3, I-40129, Bologna, Italy; ([3]) Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

The discovery of star-to-star abundance variations (a.k.a. multiple populations - MPs) within globular clusters (GCs), which are generally not found in the field or in lower mass open clusters, has led to a search for the unique property of GCs that allow them to host this phenomenon. Recent studies have shown that MPs are not limited to the ancient GCs but are also found in massive clusters with ages down to (at least) 2 Gyr. This finding is important for understanding the physics of the MP phenomenon, as these young clusters can provide much stronger constraints (e.g. on potential age spreads within the clusters) than older ones. However, a direct comparison between ancient GCs and intermediate clusters has not yet been possible due to the different filters adopted in their studies. Here we present new HST UV photometry of the 7.5 Gyr, massive SMC cluster, Lindsay 1, in order to compare its pseudo colour-colour diagram to that of Galactic GCs. We find that they are almost identical and conclude that the MPs phenomenon is the same, regardless of cluster age and host galaxy.

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Search for a metallicity spread in the multiple population Large Magellanic Cloud cluster NGC 1978

A. E. Piatti [1], J. Bailin [2]

([1]) National Scientific and Technical Research Council, Buenos Aires, Argentina; ([2]) Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA

We report on the spread of [Fe/H] values in the massive Large Magellanic Cloud cluster NGC1978, recently confirmed to harbor multiple populations of nearly the same age. We used accurate Stromgren photometry of carefully selected cluster red giant branch stars along with a high-dispersion spectroscopy-based calibration of the metallicity-sensitive index m1. Once accounting for the photometry quality, assessed from extensive artificial stars tests to trace the photometric uncertainties as a function of the position to the cluster's center as well as the stellar brightness, and those from the metallicity calibration, we found that NGC1978 exhibits a small metallicity spread of 0.035 dex ($\pm$ 0.019/0.023), depending on whether stars with individual sigma[Fe/H] $<$ 0.15 dex or those located in the cluster's outer areas are considered. Such a spread in [Fe/H] is consistent with a cluster formation model with self-enrichment, if mass loss higher than 90 per cent due to stellar evolutionary and galactic tidal effects is assumed. Nevertheless, scenarios where the apparent [Fe/H] variation reflects CN abundance anomalies or less extreme mass loss models with environmentally-dependent self enrichment should not be ruled out.

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Dynamical evolution - Simulations

Post-Newtonian Dynamics in Dense Star Clusters: Binary Black Holes in the LISA Band

K. Kremer [1], C. L. Rodriguez [2], P. Amaro Seoane [3], and 8 co-authors

([1]) CIERA-Northwestern University, Evanston, IL, USA; ([2]) MIT-Kavli Institute for Astrophysics and Space Research, Cambridge, MA, USA; ([3]) Institute of Space Sciences (ICE, CSIC) & Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain; Institute of Applied Mathematics, Academy of Mathematics and Systems Science, Beijing, China; China Kavli Institute for Astronomy and Astrophysics, Beijing, China

The dynamical processing of black holes in the dense cores of globular clusters (GCs), makes them efficient factories for producing binary black holes (BBHs). Here we explore the population of BBHs that form dynamically in GCs and may be observable at mHz frequencies or higher with LISA. We use our Monte Carlo stellar dynamics code, which includes gravitational radiation reaction effects for all BH encounters. By creating a representative local universe of GCs, we show that up to dozens of these systems may be resolvable by LISA with signal-to-noise ratios of at least 5. Approximately one third of these binaries will have measurable eccentricities ($e > 10^{-3}$) in the LISA band and a small number ($\lesssim 5$) may evolve from the LISA band to the LIGO band during the LISA mission.

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Complete ejection of OB stars from very young star clusters and the formation of multiple populations

L. Wang [1,3,4], P. Kroupa [1,2], T. Jerabkova [1,2,5]

([1]) Helmholtz-Institut für Strahlen- und Kernphysik, University of Bonn, Bonn, Germany; ([2]) Charles University in Prague, Faculty of Mathematics and Physics, Astronomical Institute, Praha, Czech Republic; ([3]) Argelander Institut für Astronomie, Bonn, Germany; ([4]) RIKEN Center for Computational Science, Chuo-ku, Kobe, Hyogo, Japan; ([5]) European Southern Observatory, Garching, Germany

Recently, three stellar sequences separated in age by about 1 Myr were discovered in the Orion Nebula Cluster (ONC; Beccari et al. 2017). Kroupa et al. (2018) suggest that such small dense subpopulations eject all their OB stars via the decay of unstable few-body systems such that the gas can recombine and form new stars. This explains the multisequence phenomenon without introducing an extra mechanism into star formation theory. In this work, we apply the recently updated primordial binary distribution model (Belloni et al. 2017; implemented here in a new version of MCLUSTER) and perform a large set of direct N-body simulations to investigate the feasibility of this dynamical scenario. Our results suggest that if 3-4 OB stars in the ONC formed primordially mass-segregated in the cluster centre with a maximum separation of about 0.003 pc, all OB stars have a high chance (50-70 per cent) to escape from the centre and do not come back within 1 Myr and the dynamical ejection scenario is a viable channel to form short-age-interval multipopulation sequences as observed in the ONC. This is also consistent with self-regulated star formation.

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Spatial mixing of binary stars in multiple-population globular clusters

J. Hong [1,2], S. Patel [2,3], E. Vesperini [2], J. J. Webb [2,4], E. Dalessandro [5]

([1]) Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, China; ([2]) Department of Astronomy, Indiana University, Bloomington, USA; ([3]) College of Electrical Engineering & Computer Science, Syracuse University, Syracuse, USA; ([4]) Department of Astronomy and Astrophysics, University of Toronto, Toronto, Canada; ([5]) INAF-Astrophysics and Space Science Observatory, Bologna, Italy

We present the results of a study aimed at investigating the effects of dynamical evolution on the spatial distribution and mixing of primordial binary stars in multiple-population globular clusters. Multiple stellar population formation models predict that second-generation (SG) stars form segregated in the inner regions of a more extended first-generation (FG) cluster. Our study, based on the results of a survey of N-body simulations, shows that the spatial mixing process for binary stars is more complex than that of single stars since additional processes such as binary ionization, recoil and ejection following binary-single and binary-binary interactions play a key role in determining the spatial distribution of the population of surviving binaries. The efficiency and relative importance of these additional effects depends on the binary binding energy and determines the timescale of the spatial mixing of FG and SG binaries. Our simulations illustrate the role of ionization, recoil and ejection combined with the effects of mass segregation driven by two-body relaxation and show that the complex interplay of all these processes results in a significant extension of the time needed for the complete spatial mixing of FG and SG binaries compared to that of single stars. Clusters in which FG and SG single stars have already reached complete spatial mixing might be characterized by a significant radial gradient in the ratio of the FG-to-SG binary fraction. The implications of the delayed mixing of FG and SG binaries for the differences between the kinematics of the two populations are discussed.

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Rediscovering the tidal tails of NGC 288 with Gaia DR2

S. Kaderali [1,2], J. A. S Hunt [2], J. J. Webb [3], N. Price-Jones [2,3], R. G. Carlberg [3]

([1]) Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada; ([2]) Dunlap Institute for Astronomy and Astrophysics, University of Toronto, 50 St George Street, Toronto ON M5S 3H4, Canada; ([3]) Department of Astronomy and Astrophysics, University of Toronto, 50 St George Street, Toronto ON M5S 3H4, Canada

NGC 288 is a Galactic globular cluster having observed extra-tidal structure, without confirmed tidal tails. Gaia DR2 provides photometric and astrometric data for many of the stars in NGC 288 and its extra-tidal structure. To compare with the Gaia data, we simulate a N-body model of a star cluster with the same orbit as NGC 288 in a Milky Way potential. The simulation shows that the cluster forms tidal tails that are compressed along the cluster's orbit when it is at apocentre and are expected to be a diffuse bipolar structure. In this letter, we present a comparison between the simulation and observations from Gaia DR2. We find that both the simulation and the observations share comparable trends in the position on the sky and proper motions of the extra-tidal stars, supporting the presence of tidal tails around NGC 288.

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How initial size governs core collapse in globular clusters

K. Kremer [1], S. Chatterjee [2], C. S. Ye [1], C. L. Rodriguez [3], F. A. Rasio [1]
([1]) CIERA-Northwestern University, Evanston, IL, USA; ([2]) Tata Institute of Fundamental Research, Mumbai, India; ([3]) MIT-Kavli Institute for Astrophysics and Space Research, Cambridge, MA, USA

Globular clusters (GCs) in the Milky Way exhibit a well-observed bimodal distribution in core radii separating the so-called "core-collapsed" and "non-core-collapsed" clusters. Here, we use our Henon-type Monte Carlo code, CMC, to explore initial cluster parameters that map into this bimodality. Remarkably, we find that by varying the initial size of clusters (specified in our initial conditions in terms of the initial virial radius, r_v) within a relatively narrow range consistent with the measured radii of young star clusters in the local universe ($r_v \approx 0.5 - 5$ pc), our models reproduce the variety of present-day cluster properties. Furthermore, we show that stellar-mass black holes (BHs) play an intimate role in this mapping from initial conditions to the present-day structural features of GCs. We identify "best-fit" models for three GCs with known observed BH candidates, NGC 3201, M22, and M10, and show that these clusters harbor populations of $\sim 50 - 100$ stellar-mass BHs at present. As an alternative case, we also compare our models to the core-collapsed cluster NGC 6752 and show that this cluster likely contains few BHs at present. Additionally, we explore the formation of BH binaries in GCs and demonstrate that these systems form naturally in our models in both detached and mass-transferring configurations with a variety of companion stellar types, including low-mass main sequence stars, white dwarfs, and sub-subgiants.

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Fossil stellar streams and their globular cluster populations in the E-MOSAICS simulations

M. E. Hughes [1], J. Pfeffer [1], M. Martig [1], and 4 co-authors
([1]) Astrophysics Research Institute, Liverpool John Moores University, Liverpool, UK; ([2]) Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Heidelberg, Germany

Stellar haloes encode a fossil record of a galaxy's accretion history, generally in the form of structures of low surface brightness, such as stellar streams. While their low surface brightness makes it challenging to determine their age, metallicity, kinematics and spatial structure, the infalling galaxies also deposit globular clusters (GCs) in the halo, which are bright and therefore easier to observe and characterise. To understand how GCs associated with stellar streams can be used to estimate the stellar mass and the infall time of their parent galaxy, we examine a subset of 15 simulations of galaxies and their star clusters from the E-MOSAICS project. E-MOSAICS is a suite of hydrodynamical simulations incorporating a sub-grid model for GC formation and evolution. We find that more massive accreted galaxies typically contribute younger and more metal rich GCs. This lower age results from a more extended cluster for- mation history in more massive galaxies. In addition, at fixed stellar mass, galaxies that are accreted later host younger clusters, because they can continue to form GCs without being subjected to environmental influences for longer. This explains the large range of ages observed for clusters associated with the Sagittarius dwarf galaxy in the halo of the Milky Way compared to clusters which are thought to have formed in satel- lites accreted early in the Milky Way's formation history. Using the ages of the GCs associated with the Sagittarius dwarf, we estimate a virial radius crossing lookback time (infall time) of 9.3 ± 1.8 Gyr.

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Modelling the effects of dark matter substructure on globular cluster evolution with the tidal approximation

J. J. Webb [1], J. Bovy [1], R. G. Carlberg [1], M. Gieles [2,3,4]

([1]) Department of Astronomy and Astrophysics, University of Toronto, Toronto, Canada; ([2]) Department of Physics, University of Surrey, Guildford, UK; ([3]) Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, E-08028 Barcelona, Spain; ([4]) ICREA, E-08010 Barcelona, Spain

We present direct N-body simulations of tidally filling 30 000 $M_\odot$ star clusters orbiting between 10 and 100 kpc in galaxies with a range of dark matter substructure properties. The time-dependent tidal force is determined based on the combined tidal tensor of the galaxy's smooth and clumpy dark matter components, the latter of which causes fluctuations in the tidal field that can heat clusters. The strength and duration of these fluctuations are sensitive to the local dark matter density, substructure fraction, sub-halo mass function, and the sub-halo mass-size relation. Based on the cold dark matter framework, we initially assume sub-haloes are Hernquist spheres following a power-law mass function between 10^5 and 10^11 $M_\odot$ and find that tidal fluctuations are too weak and too short to affect star cluster evolution. Treating sub-haloes as point masses, to explore how denser sub-haloes affect clusters, we find that only sub-haloes with masses greater than 10^6 $M_\odot$ will cause cluster dissolution times to decrease. These interactions can also decrease the size of a cluster while increasing the velocity dispersion and tangential anisotropy in the outer regions via tidal heating. Hence increased fluctuations in the tidal tensor, especially fluctuations that are due to low-mass haloes, do not necessarily translate into mass-loss. We further conclude that the tidal approximation can be used to model cluster evolution in the tidal fields of cosmological simulations with a minimum cold dark matter sub-halo mass of 10^6 $M_\odot$, as the effect of lower mass sub-haloes on star clusters is negligible.

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Kinematical evolution of multiple stellar populations in star clusters

M. Tiongco [1], E. Vesperini [1], A. L. Varri [2,3]

([1]) Indiana University; ([2]) University of Edinburgh; ([3]) University of Tokyo

We present the results of a suite of N-body simulations aimed at understanding the fundamental aspects of the long-term evolution of the internal kinematics of multiple stellar populations in globular clusters. Our models enable us to study the cooperative effects of internal, relaxation-driven processes and external, tidally-induced perturbations on the structural and kinematic properties of multiple-population globular clusters. To analyse the dynamical behaviour of the multiple stellar populations in a variety of spin-orbit coupling conditions, we have considered three reference cases in which the tidally perturbed star cluster rotates along an axis oriented in different directions with respect to the orbital angular momentum vector. We focus specifically on the characterisation of the evolution of the degree of differential rotation and anisotropy in the velocity space, and we quantify the process of spatial and kinematic mixing of the two populations. In light of recent and forthcoming explorations of the internal kinematics of this class of stellar systems by means of line-of sight and astrometric measurements, we also investigate the implications of projection effects and spatial distribution of the stars adopted as tracers. The kinematic and structural richness emerging from our models further emphasises the need and the importance of observational studies aimed at building a complete kinematical picture of the multiple population phenomenon.

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Young star cluster populations in the E-MOSAICS simulations

J. Pfeffer [1], N. Bastian [1], J. M. Diederik Kruijssen [2], and 3 co-authors

([1]) Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK; ([2]) Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstraße 12-14, 69120 Heidelberg, Germany

We present an analysis of young star clusters (YSCs) that form in the E-MOSAICS cosmological, hydrodynamical simulations of galaxies and their star cluster populations. Through comparisons with observed YSC populations, this work aims to test models for YSC formation and obtain an insight into the formation processes at work in part of the local galaxy population. We find that the models used in E-MOSAICS for the cluster formation efficiency and high-mass truncation of the initial cluster mass function ($M_{c,*}$) both quantitatively reproduce the observed values of cluster populations in nearby galaxies. At higher redshifts ($z \geq 2$, near the peak of globular cluster formation) we find that, at a constant star formation rate (SFR) surface density, $M_{c,*}$ is larger than at $z = 0$ by a factor of four due to the higher gas fractions in the simulated high-redshift galaxies. Similar processes should be at work in local galaxies, offering a new way to test the models. We find that cluster age distributions may be sensitive to variations in the cluster formation rate (but not SFR) with time, which may significantly affect their use in tests of cluster mass loss. By comparing simulations with different implementations of cluster formation physics, we find that (even partially) environmentally-independent cluster formation is inconsistent with the brightest cluster-SFR and specific luminosity-Σ_{SFR} relations, whereas these observables are reproduced by the fiducial, environmentally-varying model. This shows that models in which a constant fraction of stars form in clusters are inconsistent with observations.

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The evolution of the UV luminosity function of globular clusters in the E-MOSAICS simulations

J. Pfeffer [1], N. Bastian [1], R. A. Crain [1], and 3 co-authors

([1]) Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK

We present the evolution of the rest-frame ultraviolet (UV) properties of the globular cluster (GC) populations and their host galaxies formed in the E-MOSAICS suite of cosmological hydrodynamical simulations. We compute the luminosities of all clusters associated with 25 simulated Milky Way-mass galaxies, discussed in previous works, in the rest-frame UV and optical bands by combining instantaneous cluster properties (age, mass, metallicity) with simple stellar population models, from redshifts $z = 0$ to 10. Due to the rapid fading of young stellar populations in the UV, most of the simulated galaxies do not host GCs bright enough to be individually identified in deep Hubble Space Telescope (HST) observations, even in highly magnified systems. The median age of the most UV-luminous GCs is < 10 Myr (assuming no extinction), increasing to $\gtrsim 100$ Myr for red optical filters. We estimate that these GCs typically only contribute a few per cent of the total UV luminosity of their host galaxies at any epoch. We predict that the number density of UV-bright proto-GCs (or cluster clumps) will peak between redshifts $z =$ 1-3. In the main progenitors of Milky Way-mass galaxies, 10-20 per cent of the galaxies at redshifts $1 \lesssim z \lesssim 3$ have clusters brighter than $M_{UV} < -15$, and less than 10 per cent at other epochs. The brightest cluster in the galaxy sample at $z > 2$ is typically $M_{UV} \sim -16$, consistent with the luminosities of observed compact, high-redshift sources.

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Was the Milky Way a chain galaxy? Using the IGIMF theory to constrain the thin-disc star formation history and mass

A. Hasani Zonoozi [1,2], H. Mahani [1], P. Kroupa [2,3]

([1]) Department of Physics, Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan, Iran; ([2]) Helmholtz-Institut für Strahlen-und Kernphysik (HISKP), Universität Bonn, Bonn, Germany; ([3]) Charles University in Prague, Faculty of Mathematics and Physics, Astronomical Institute, Praha, Czech Republic

The observed present-day stellar mass function (PDMF) of the solar neighborhood is a mixture of stellar populations born in star-forming events that occurred over the life-time of the thin disk of the Galaxy. Assuming stars form in embedded clusters which have stellar initial mass functions (IMFs) which depend on the metallicity and density of the star-forming gas clumps, the integrated galaxy-wide IMF (IGIMF) can be calculated. The shape of the IGIMF thus depends on the SFR and metallicity. Here, the shape of the PDMF for stars more massive than $1\,M_{\odot}$ in combination with the mass density in low-mass stars is used to constrain the current star-formation rate (SFR), the star formation history (SFH) and the current stellar plus remnant mass (M_*) in the Galactic thin disk. This yields the current SFR, $\dot{M}_* = 4.1^{+3.1}_{-2.8}\ M_{\odot}\mathrm{yr}^{-1}$, a declining SFH and $M_* = 2.1^{+3.0}_{-1.5} \times 10^{11} M_{\odot}$, respectively, with a V-band stellar mass-to-light ratio of $M_*/L_V = 2.79^{+0.48}_{-0.38}$.These values are consistent with independent measurements. We also quantify the surface density of black holes and neutron stars in the Galactic thin disk. The invariant canonical IMF can reproduce the PDMF of the Galaxy as well as the IGIMF, but in the universal IMF framework it is not possible to constrain any of the above Galactic properties. Assuming the IGMF theory is the correct framework and in combination with the vertical velocity dispersion data of stars, it follows that the Milky Way would have appeared as a chain galaxy at high redshift.

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Mass modelling globular clusters in the Gaia era: a method comparison using mock data from an N-body simulation of M 4

V. Hénault-Brunet [1,2], M. Gieles [3,4,5], A. Sollima [6], and 5 co-authors

([1]) National Research Council, Herzberg Astronomy & Astrophysics, Victoria, Canada; ([2]) Department of Astrophysics/IMAPP, Radboud University, Nijmegen, the Netherlands; ([3]) Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, UK; ([4]) Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, Barcelona, Spain; ([5]) ICREA, Barcelona, Spain; ([6]) INAF, Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Bologna, Italy

As we enter a golden age for studies of internal kinematics and dynamics of Galactic globular clusters (GCs), it is timely to assess the performance of modelling techniques in recovering the mass, mass profile, and other dynamical properties of GCs. Here, we compare different mass-modelling techniques (distribution function (DF)-based models, Jeans models, and a grid of N-body models) by applying them to mock observations from a star-by-star N-body simulation of the GC M 4 by Heggie. The mocks mimic existing and anticipated data for GCs: surface brightness or number density profiles, local stellar mass functions, line-of-sight velocities, and Hubble Space Telescope- and Gaia-like proper motions. We discuss the successes and limitations of the methods. We find that multimass DF-based models, Jeans, and N-body models provide more accurate mass profiles compared to single-mass DF-based models. We highlight complications in fitting the kinematics in the outskirts due to energetically unbound stars associated with the cluster ('potential escapers', captured neither by truncated DF models nor by N-body models of clusters in isolation), which can be avoided with DF-based models including potential escapers, or with Jeans models. We discuss ways to account for mass segregation. For example, three-component DF-based models with freedom in their mass function are a simple alternative to avoid the biases of single-mass models (which systematically underestimate the total mass, half-mass radius, and central density), while more realistic multimass DF-based models with freedom in the remnant content represent a promising avenue to infer the total mass and the mass function of remnants.

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The kinematics of star clusters undergoing gas expulsion in Newtonian and Milgromian dynamics

X. Wu [1,2], P. Kroupa [3,4]

([1]) CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei, P.R. China; ([2]) School of Astronomy and Space Science, University of Science and Technology of China, Hefei, China; ([3]) Helmholtz-Institut für Strahlen-und Kernphysik, Universität Bonn, Bonn, Germany; ([4]) Charles University in Prague, Faculty of Mathematics and Physics, Astronomical Institute, Praha, Czech Republic

We study the kinematics of stars in clusters undergoing gas expulsion in standard Newtonian dynamics and also in Milgromian dynamics (MOND). Gas expulsion can explain the observed line-of-sight (LoS) velocity dispersion profile of NGC 2419 in Newtonian dynamics. For a given star formation efficiency (SFE), the shapes of the velocity dispersion profiles, which are normalised by the velocity dispersion at the projected half-mass radius, are almost indistinguishable for different SFE models in Newtonian dynamics. The velocity dispersion of a star cluster in the outer halo of a galaxy can indeed have a strong radial anisotropy in Newtonian dynamics after gas expulsion. MOND displays several different properties from Newtonian dynamics. In particular, the slope of the central velocity dispersion profile is less steep in MOND for the same SFE. Moreover, for a given SFE, more massive embedded cluster models result in more rapidly declining central velocity dispersion profiles for the final star clusters, while less massive embedded cluster models lead to flatter velocity dispersion profiles for the final products. The onset of the radial-orbit instability in post-gas-expulsion MOND models is discussed. SFEs as low as a few percent, typical of molecular clouds, lead to surviving ultra-diffuse objects. Gas expulsion alone is unlikely the physical mechanism for the observed velocity dispersion profile of NGC 2419 in MOND.

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The star cluster survivability after gas expulsion is independent of the impact of the Galactic tidal field

B. Shukirgaliyev [1,2,3], G. Parmentier [1], P. Berczik [4,5,1], A. Just [1]

([1]) Zentrum für Astronomie der Universität Heidelberg, Astronomisches Rechen-Institut, Heidelberg, Germany; ([2]) Fesenkov Astrophysical Institute, Almaty, Kazakhstan; ([3]) Faculty of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; ([4]) The International Center of Future Science of the Jilin University, Changchun City, China; ([5]) Main Astronomical Observatory, National Academy of Sciences of Ukraine, Kyiv, Ukraine

We study the impact of the tidal field on the survivability of star clusters following instantaneous gas expulsion. Our model clusters are formed with a centrally peaked star formation efficiency profile as a result of star formation taking place with a constant efficiency per free-fall time. We define the impact of the tidal field as the ratio of the cluster half-mass radius to its Jacobi radius immediately after gas expulsion, $\lambda = r_h/R_J$. We vary by varying either the Galactocentric distance, or the size (hence volume density) of star clusters. We propose a new method to measure the violent relaxation duration, in which we compare the total mass-loss rate of star clusters with their stellar evolutionary mass-loss rate. That way, we can robustly estimate the bound mass fraction of our model clusters at the end of violent relaxation. The duration of violent relaxation correlates linearly with the Jacobi radius, when considering identical clusters at different Galactocentric distances. In contrast, it is nearly constant for the solar neighbourhood clusters, slightly decreasing with λ. The violent relaxation does not last longer than 50 Myr in our simulations. Identical model clusters placed at different Galactocentric distances have the same final bound fraction, despite experiencing different impacts of the tidal field. The solar neighbourhood clusters with different densities experience only limited variations of their final bound fraction. In general, we conclude that the cluster survivability after instantaneous gas expulsion, as measured by their bound mass fraction at the end of violent relaxation, F_{bound}, is independent of the impact of the tidal field, λ.

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A systematic analysis of star cluster disruption by tidal shocks - I. Controlled N-body simulations and a new theoretical model

J. J. Webb [1], M. Reina-Campos [2], J. M. D. Kruijssen [2]

([1]) Department of Astronomy and Astrophysics, University of Toronto, Toronto, Canada; ([2]) Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, D-69120 Heidelberg, Germany

Understanding the evolution of stellar clusters in an evolving tidal field is critical for studying the disruption of stellar clusters in a cosmological context. We systematically characterize the response of stellar clusters to tidal shocks using controlled N-body simulations of clusters with various properties that are subjected to different types of shocks. We find that the strength of the shock and the density of the cluster within the half-mass radius are the dominant properties that drive the amount of mass lost by the cluster, with the shape of the cluster profile being of minor influence. When the shock is applied as two separate sub-shocks, the amount of mass-loss during the second sub-shock is sensitive to the gap time between them. Clusters that experience successive sub-shocks separated by less than their crossing time attain the same masses and sizes at the end of the simulation. However, clusters subjected to sub-shocks separated by more than a crossing time experience different evolutionary histories. The amount of mass lost in the N-body models and its scaling with shock and cluster properties differ from that predicted by classical tidal disruption theory. We demonstrate that the discrepancy is alleviated by including a dependence on the escape time-scale of unbound stars, analogously to mass-loss driven by two-body relaxation. With our new theoretical model for shock-driven mass-loss, the predicted relative amounts of mass-loss agree with the results of the N-body simulations to 0.3 dex across the full suite of simulations.

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The evolution of kicked stellar-mass black holes in star cluster environments - II. Rotating star clusters

J. J. Webb [1], N. W. C Leigh [2,3,4], R. Serrano [2,3], and 5 co-authors

([1]) Department of Astronomy and Astrophysics, University of Toronto, Toronto, Canada; ([2]) Department of Physics and Astronomy, Stony Brook University, Stony Brook, USA; ([3]) Department of Astrophysics, American Museum of Natural History, New York, USA; ([4]) Departamento de Astronomá, Facultad de Ciencias Fśicas y Matemáticas, Universidad de Concepción, Concepción, Chile

In this paper, we continue our study on the evolution of black holes (BHs) that receive velocity kicks at the origin of their host star cluster potential. We now focus on BHs in rotating clusters that receive a range of kick velocities in different directions with respect to the rotation axis. We perform N-body simulations to calculate the trajectories of the kicked BHs and develop an analytic framework to study their motion as a function of the host cluster and the kick itself. Our simulations indicate that for a BH that is kicked outside of the cluster's core, as its orbit decays in a rotating cluster the BH will quickly gain angular momentum as it interacts with stars with high rotational frequencies. Once the BH decays to the point where its orbital frequency equals that of local stars, its orbit will be circular and dynamical friction becomes ineffective since local stars will have low relative velocities. After circularization, the BH's orbit decays on a longer time-scale than if the host cluster was not rotating. Hence BHs in rotating clusters will have longer orbital decay times. The time-scale for orbit circularization depends strongly on the cluster's rotation rate and the initial kick velocity, with kicked BHs in slowly rotating clusters being able to decay into the core before circularization occurs. The implication of the circularization phase is that the probability of a BH undergoing a tidal capture event increases, possibly aiding in the formation of binaries and high-mass BHs.

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Miscellaneous

Origin of the system of globular clusters in the Milky Way

D. Massari [1,2,3], H.H. Koppelman [1], A. Helmi [1]

([1]) Kapteyn Institute - University of Groningen; ([2]) Universita' di Bologna; ([3]) INAF - OAS Bologna

Context. The assembly history experienced by the Milky Way is currently being unveiled thanks to the data provided by the Gaia mission. It is likely that the globular cluster system of our Galaxy has followed a similarly intricate formation path. *Aims.* To constrain this formation path, we explore the link between the globular clusters and the known merging events that the Milky Way has experienced. *Methods.* To this end, we combined the kinematic information provided by Gaia for almost all Galactic clusters, with the largest sample of cluster ages available after carefully correcting for systematic errors. To identify clusters with a common origin we analysed their dynamical properties, particularly in the space of integrals of motion. *Results.* We find that about 40% of the clusters likely formed in situ. A similarly large fraction, 35%, appear to be possibly associated to known merger events, in particular to Gaia-Enceladus (19%), the Sagittarius dwarf galaxy (5%), the progenitor of the Helmi streams (6%), and to the Sequoia galaxy (5%), although some uncertainty remains due to the degree of overlap in their dynamical characteristics. Of the remaining clusters, 16% are tentatively associated to a group with high binding energy, while the rest are all on loosely bound orbits and likely have a more heterogeneous origin. The resulting age-metallicity relations are remarkably tight and differ in their detailed properties depending on the progenitor, providing further confidence on the associations made. *Conclusions.* We provide a table listing the likely associations. Improved kinematic data by future Gaia data releases and especially a larger, systematic error-free sample of cluster ages would help to further solidify our conclusions.

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Star Cluster Detection and Characterization using generalized Parzen Density Estimation

S. Nambiar [1], S. Das [2], S. Vig [1], R. S. S. Gorthi [3]

([1]) Indian Institute of Space science and Technology (IIST), Thiruvananthapuram, India; ([2]) Indian Institute of Technology (BHU), Varanasi, India; ([3]) Indian Institute of Technology, Tirupati, India

Star cluster studies hold the key to understanding star formation, stellar evolution, and origin of galaxies. The detection and characterization of clusters depend on the underlying background density and the cluster richness. We examine the ability of the Parzen Density Estimation (a.k.a. Parzen Windows) method, which is a generalization of the well-known Star Count method, to detect clusters and measure their properties. We apply it on a range of simulated and real star fields, considering square and circular windows, with and without Gaussian kernel smoothing. Our method successfully identifies clusters and we suggest an optimal standard deviation of the Gaussian Parzen window for obtaining the best estimates of these parameters. Finally, we demonstrate that the Parzen Windows with Gaussian kernels are able to detect small clusters in regions of relatively high background density where the Star Count method fails.

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GS242-03+37: a lucky survivor in the galactic gravitational field

S. Ehlerová [1], J. Palouš [1]
([1]) Astronomical Institute of the Czech Academy of Sciences, Prague, Czech Republic

HI shells and supershells, found in discs of many galaxies including our own, are formed by the activity of young and massive stars (supernova explosions and stellar winds), but the formation of these structures may be linked to other energetic events, such as interactions of high-velocity clouds with the galactic disc. The larger structures in particular significantly influence their surroundings; their walls are often places where molecular clouds reside and where star formation happens. We explore the HI supershell GS242-03+37, a large structure in the outer Milky Way. Its size and position make it a good case for studying the effects of large shells on their surrounding. We perform numerical simulations of the structure with the simplified hydrodynamical code RING, which uses the thin-shell approximation. The best fit is found by a comparison with the HI data and then we compare our model with the distribution of star clusters near this supershell. The best model of GS242-03+37 requires, contrary to previous estimates, a relatively low amount of energy, and it has an old age of $\sim$ 100 Myr. We also find that the distribution of young star clusters (with ages $<$ 120 Myr) is correlated with walls of the supershell, while the distribution of older clusters is not. Clusters that have the highest probability of being born in the wall of the supershell show an age sequence along the wall. GS242-03+37 is a relatively old structure, shaped by the differential rotation, and its wall is a birthplace of several star clusters. The star formation started at a time when the supershell was not already supersonically expanding; it was a result of the density increase due to the galactic shear and oscillations perpendicular to the disc of the Milky Way.

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Untangling the Galaxy I: Local Structure and Star Formation History of the Milky Way

M. Kounkel [1], K. Covey [1]
([1]) Department of Physics and Astronomy, Western Washington University, Bellingham, WA 98225, USA

Gaia DR2 provides unprecedented precision in measurements of the distance and kinematics of stars in the solar neighborhood. Through applying unsupervised machine learning on DR2's 5-dimensional dataset (3d position + 2d velocity), we identify a number of clusters, associations, and co-moving groups within 1 kpc and $|b| < 30°$ (many of which have not been previously known). We estimate their ages with the precision of $\sim$0.15 dex. Many of these groups appear to be filamentary or string-like, oriented in parallel to the Galactic plane, and some span hundreds of pc in length. Most of these string lack a central cluster, indicating that their filamentary structure is primordial, rather than the result of tidal stripping or dynamical processing. The youngest strings ($<$100 Myr) are orthogonal to the Local Arm. The older ones appear to be remnants of several other arm-like structures that cannot be presently traced by dust and gas. The velocity dispersion measured from the ensemble of groups and strings increase with age, suggesting a timescale for dynamical heating of $\sim$300 Myr. This timescale is also consistent with the age at which the population of strings begins to decline, while the population in more compact groups continues to increase, suggesting that dynamical processes are disrupting the weakly bound string populations, leaving only individual clusters to be identified at the oldest ages. These data shed a new light on the local galactic structure and a large scale cloud collapse.

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Planetary systems in a star cluster I: the Solar system scenario

F. Flammini Dotti [1,2], M. B. N. Kouwenhoven [1], M. Xu Cai [3], R. Spurzem [4,5,6]

([1]) Department of Mathematical Sciences, Xi'an Jiaotong-Liverpool University, Suzhou, P.R. China; ([2]) Department of Mathematical Sciences, University of Liverpool, Liverpool, UK; ([3]) Leiden Observatory, Leiden University, Leiden, Netherlands; ([4]) National Astronomical Observatories and Key Laboratory of Computational Astrophysics, Chinese Academy of Sciences, Beijing, China; ([5]) Kavli Institute for Astronomy and Astrophysics at Peking University, Beijing, China; ([6]) Zentrum für Astronomie der Universität Heidelberg, Astronomisches Rechen-Institut, Heidelberg, Germany

Young stars are mostly found in dense stellar environments, and even our own Solar system may have formed in a star cluster. Here, we numerically explore the evolution of planetary systems similar to our own Solar system in star clusters. We investigate the evolution of planetary systems in star clusters. Most stellar encounters are tidal, hyperbolic, and adiabatic. A small fraction of the planetary systems escape from the star cluster within 50 Myr; those with low escape speeds often remain intact during and after the escape process. While most planetary systems inside the star cluster remain intact, a subset is strongly perturbed during the first 50 Myr. Over the course of time, $0.3\% - 5.3\%$ of the planets escape, sometimes up to tens of millions of years after a stellar encounter occurred. Survival rates are highest for Jupiter, while Uranus and Neptune have the highest escape rates. Unless directly affected by a stellar encounter itself, Jupiter frequently serves as a barrier that protects the terrestrial planets from perturbations in the outer planetary system. In low-density environments, Jupiter provides protection from perturbations in the outer planetary system, while in high-density environments, direct perturbations of Jupiter by neighbouring stars is disruptive to habitable-zone planets. The diversity amongst planetary systems that is present in the star clusters at 50 Myr, and amongst the escaping planetary systems, is high, which contributes to explaining the high diversity of observed exoplanet systems in star clusters and in the Galactic field.

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Disappearance of the extended main sequence turn-off in intermediate age clusters as a consequence of magnetic braking

C. Georgy [1], C. Charbonnel [1,2], L. Amard [3], and 8 co-authors

([1]) Department of Astronomy, University of Geneva, Versoix, Switzerland; ([2]) IRAP, UMR 5277 CNRS and Université de Toulouse, Toulouse, France; ([3]) University of Exeter, Department of Physics & Astronomy, Exeter, UK

Extended main sequence turn-offs are features commonly found in the colour-magnitude diagrams of young and intermediate age (less than about 2 Gyr) massive star clusters, where the main sequence turn-off is broader than can be explained by photometric uncertainties, crowding, or binarity. Rotation is suspected to be the cause of this feature, by accumulating fast rotating stars, strongly affected by gravity darkening and rotation-induced mixing, near the main sequence turn-off. This scenario successfully reproduces the tight relation between the age and the actual extent in luminosity of the extended main sequence turn-off of observed clusters. Below a given mass (dependent on the metallicity), stars are efficiently braked early on the main sequence due to the interaction of stellar winds and the surface magnetic field, making their tracks converge towards those of non-rotating tracks in the Hertzsprung- Russell diagram. When these stars are located at the turn-off of a cluster, their slow rotation causes the extended main sequence turn-off feature to disappear. We investigate the maximal mass for which this braking occurs at different metallicities, and determine the age above which no extended main sequence turn-off is expected in clusters. We used two sets of stellar models (computed with two different stellar evolution codes: STAREVOL and the Geneva stellar evolution code) including the effects of rotation and magnetic braking, at three different metallicities. We implemented them in the Syclist toolbox to compute isochrones and then determined the extent of the extended main sequence turn-off at different ages. Our models predict that the extended main sequence turn-off phenomenon disappears at ages older than about 2 Gyr. There is a trend with the metallicity, the age at which the disappearance occurs becoming older at higher metallicity. These results are robust between the two codes used in this work, despite some differences in the input physics and in particular in the detailed description of rotation-induced internal processes and of angular momentum extraction by stellar winds. Comparing our results with clusters in the Large Magellanic Cloud and Galaxy shows a very good fit to the observations. This strengthens the rotation scenario to explain the cause of the extended main sequence turn-off phenomenon.

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Proceedings abstracts

Blue straggler populations beyond the Milky Way

R. de Grijs [1,2], W. Sun [3,4], C. Li [1], L. Deng [4]

([1]) Department of Physics and Astronomy, Macquarie University, Sydney, Australia; ([2]) International Space Science Institute, Beijing, China; ([3]) Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, China; ([4]) Key Laboratory for Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China

Although the formation of blue straggler stars (BSSs) is routinely attributed to stellar interactions in binary systems, the relative importance of the direct collision and slow(er) stellar coalescence formation channels is still poorly understood. We selected a sample of 24 Magellanic Cloud star clusters for which multi-passband *Hubble Space Telescope* images are available to address this outstanding question. We compiled a BSS database, containing both traditional and evolved BSSs. We found a robust correlation between the number of BSSs in a cluster's core and its core mass, $N_{\rm BSS,core} \propto M_{\rm core}^{0.51\pm0.07}$, which supports the notion that BSS formation is linked to a population's binary fraction. At low stellar collision rates, the mass-normalised number of BSSs does not appear to depend on the collision rate, which implies that the coalescence-driven BSS formation channel dominates. Comparison with simulations suggests that stellar collisions contribute less than 20% to the total number of BSSs formed.

To appear in: Instability Phenomena and Evolution of the Universe, Byurakan Astrophys. Obs. (Armenia), September 2018, Commun. Byurakan Astrophys. Obs., 65, in press

http://adsabs.harvard.edu/abs/2018arXiv181109302D

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UVIT Observations of UV-Bright Stars in four Galactic Globular Clusters

R. Kumar [1], A. C. Pradhan [1], M. Parthasarathy [2], and 3 co-authors

([1]) Dept. of Physics and Astronomy, National Institute of Technology, Rourkela - 769 008, India; ([2]) Indian Institute of Astrophysics, Bangalore - 560 034, India

We have performed photometric analysis of four Galactic globular clusters (GGCs): NGC 4147, NGC 4590, NGC 5053 and NGC 7492 using far-UV and near-UV filters of the Ultraviolet Imaging Telescope (UVIT) on-board AstroSat. With the help of color-magnitude diagrams (CMDs), we have identified 150 blue horizontal branch stars (BHBs), and 40 blue straggler stars (BSS) in the four GGCs. We study the temperature and radial distribution of BHBs and BSS for the four GGCs.

To appear in: IAUS 351 Star Clusters: from the Milky Way to the Early Universe

https://ui.adsabs.harvard.edu/#abs/2019arXiv190802512K/abstract

Star Clusters in the Galactic tidal field, from birth to dissolution

B. Shukirgaliyev [1,2], G. Parmentier [3], P. Berczik [4,3,5], A. Just [3]

([1]) Energetic Cosmos Laboratory, Nazarbayev University, 53 Kabanbay batyr ave., 010000 Nur-Sultan, Kazakhstan; ([2]) Fesenkov Astrophysical Institute, Observatory str. 23, 050020 Almaty, Kazakhstan; ([3]) Astronomisches Rechen-Institut, Zentrum fuer Astronomie der Universitaet Heidelberg, Moenchhofstr 12-14, D-69120 Heidelberg, Germany; ([4]) National Observatories of China, Chinese Academy of Science, 20A Datun Rd, Chaoyang District, 100012 Beijing, PR China; ([5]) Main Astronomical Observatory, National Academy of Sciences of Ukraine, 27 Akademika Zabolotnoho St, 03680 Kyiv, Ukraine

We study the evolution of star clusters in the Galactic tidal field starting from their birth in molecular clumps. Our model clusters form according to the local-density-driven cluster formation model in which the stellar density profile is steeper than that of gas. As a result, clusters resist the gas expulsion better than predicted by earlier models. We vary the impact of the Galactic tidal field λ, considering different Galactocentric distances (3-18 kpc), as well as different cluster sizes. Our model clusters survive the gas expulsion independent of λ. We investigated the relation between the cluster mass at the onset of secular evolution and their dissolution time. The model clusters formed with a high star-formation efficiency (SFE) follow a tight mass-dependent dissolution relation, in agreement with previous theoretical studies. However, the low-SFE models present a shallower mass-dependent relation than high-SFE clusters, and most dissolve before reaching 1 Gyr (cluster teenage mortality).

To appear in: Proceedings of IAU Symposium 351
https://ui.adsabs.harvard.edu/abs/2019arXiv190712819S/abstract

Ph.D. (dissertation) summaries

The Life of Star Clusters, from Birth to Dissolution: A New Approach

Bekdaulet Shukirgaliyev [1]

([1]) Astronomisches Rechen Institut, Zentrum für Astronomie der Universität Heidelberg

We study the evolution of star clusters, starting from their birth in molecular gas clumps until their complete dissolution in the Galactic tidal field. We have combined the “local-density-driven cluster formation” model of Parmentier and Pfalzner (2013) with direct N-body simulations of star clusters following instantaneous expulsion of their residual star-forming gas. Our model clusters are formed with a centrally peaked star-formation efficiency (SFE) profile, that is, the residual gas has a shallower density profile than stars. We build a large grid of simulations covering the parameter space of global SFEs, cluster masses, sizes and galactocentric distances. We study the survivability of our model clusters in the solar neighborhood after instantaneous gas expulsion and find that a minimum global SFE of 15 percent is sufficient to produce a bound cluster. Then studying their long-term evolution we find that our simulations are able to reproduce the cluster dissolution time observed for the solar neighborhood, provided that the cluster population is dominated by those formed with a low global SFE (about 15%). Finally, we find that the cluster survivability after instantaneous gas expulsion, as measured by cluster bound mass fraction at the end of violent relaxation, is independent of the Galactic tidal field impact.

PhD thesis completed at the Heidelberg University under the supervision of Dr. Genevieve Parmentier and Prof. Dr. Andreas Just

`The thesis is available at:` http://www.ub.uni-heidelberg.de/archiv/25699

Young Star Clusters and Clumps in the Local Universe: The effect of galactic environment on star formation

Matteo Messa [1]
([1]) Stockholm University

Stars do not form in isolation, but rather out of a hierarchical structure set by the turbulence of the interstellar medium. At the densest peak of the gas distribution, the star formation process can produce young star clusters (YSCs), which are gravitationally bound systems of stars with mass between 100 and 106 MSun and typical size of few parsecs. At larger scales, clusters are themselves arranged into cluster complexes, on scales of hundreds of parsecs and up to kiloparsec scales, which are usually referred to as 'star-forming clumps'.

Observations of local star-forming galaxies show that YSCs form over a wide range of galactic environment. However, it is not yet clear if and how the galactic environment relates to the properties of star clusters. I present the results obtained by studying the YSC population of the nearby spiral galaxy M51. We find that the cluster mass function, dN/dM, can be described by a power-law with a -2 slope and an exponential truncation at 105 MSun, consistent with what is observed in similar galaxies in the literature. The shape of the mass function is similar when looking at increasing galactocentric distances. We observe significant differences, however, when comparing clusters located in the spiral arm with those the inter-arm environments. On average, more massive clusters are formed in the spiral arms, as also previously found for the YSC progenitors, the giant molecular clouds (GMCs). Finally, we see that clusters are more quickly disrupted in denser environments, as expected if their disruption is mainly caused by tidal interaction with dense gas structures like the GMCs.

I have also undertaken the analysis of the interplay between galactic scale properties and larger star forming units, the stellar clumps. The analysis has been conducted in a sample of 14 low-redshift starburst galaxies, the Lyman-Alpha Reference Sample (LARS). The elevated star formation rate densities of such galaxies allow to form clumps with densities comparable to clumps at high-redshift, typically more massive and denser than what is normally observed in the local universe. The clumps in the LARS galaxies contribute to a large fraction to the UV flux of the galaxy itself (in many galaxies $> 50\%$), resulting in galaxies which appear 'clumpy'. In agreement with formation theories we observe that clumpiness is higher in galaxies with higher SFR surface density and dominated by turbulent gas motion.

PhD thesis completed at the Stockholm University, Faculty of Science, Department of Astronomy

`The thesis is available at: http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-163079`

Conferences

MODEST 20: Dense Star Clusters in the Era of Large Surveys

02–07 February, 2020
Mumbai, India
http://www.tifr.res.in/~modest20/

pre-registration open

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Star Clusters 2020

09–11 March, 2020
La Serena, Chile
https://www.gemini.edu/clusters2020/

registration deadline: Nov. 15, 2019

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Uncovering the Physics of Formation of Globular Clusters and their Host Galaxies

11–14 May, 2020
Santa Barbara, CA, USA
https://www.kitp.ucsb.edu/activities/clusters-c20

registration deadline: April 5, 2020

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Cool Stars, Stellar Systems, and the Sun (CS21)

22–26 June, 2020
Toulouse, France
https://coolstars21.github.io/

pre-registration open

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