The Star Clusters Young & Old Newsletter

edited by Giovanni Carraro, Martin Netopil, and Ernst Paunzen
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Dear Colleagues,

We hope this issue of the SCYON finds you well and that you are starting to return to normality. Nevertheless, the scientific progress continued as seen in this issue, which includes 29 abstracts. We want to congratulate Benjamin Giesers on successful completion of his PhD, and at the same time we unfortunately also have to inform that Johannes Andersen passed away end of April. Until his retirement, he worked at the Niels Bohr Institute at the Copenhagen University and contributed numerous works on the field of star clusters. Our thoughts are with his wife Birgitta Nordström and their family.

This issue starts with a contribution, different to paper abstracts, which also demonstrates the importance of Gaia for star cluster research: The latest "Gaia Image of the week" is dedicated to the open clusters population. We also would like to draw your attention to some conferences that have been postponed. Please keep informed about the current schedule at our webpage or the conference webpages itself.

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

Gaia Image of the Week: Machine-learning techniques reveal hundreds of open clusters in Gaia data

Open clusters are groups of gravitationally bound stars that were formed in the same event – so they have the same chemical composition and age – and share a common position and proper motion. Those open clusters are fundamental objects in galaxies, and key for the understanding of the structure and evolution of the Milky Way.

While young open clusters allow researchers to trace the star forming regions and to understand the star forming mechanisms, intermediate and old open clusters inform about the stellar processes and evolution of the Galactic disc.

The study and search for open clusters has been boosted by the second release of the Gaia mission data (Gaia DR2). Since its publication, several studies have been finding new open clusters, but they were computationally limited to analyzing particular regions of the galactic disc, or dividing the search areas into smaller ones with a limited number of stars.

A team of researchers, led by Alfred Castro-Ginard, has been developing a new methodology based on Big Data approaches to analyse the whole Gaia DR2 in the search for these objects. Castro-Ginard explains, "Before Gaia, we didn't have a homogenous methodology to study and detect those objects, because we didn't have such a big and precise data catalogue. That's why we chose a machine-learning based method, which automatizes and allows the study of a big volume of data."

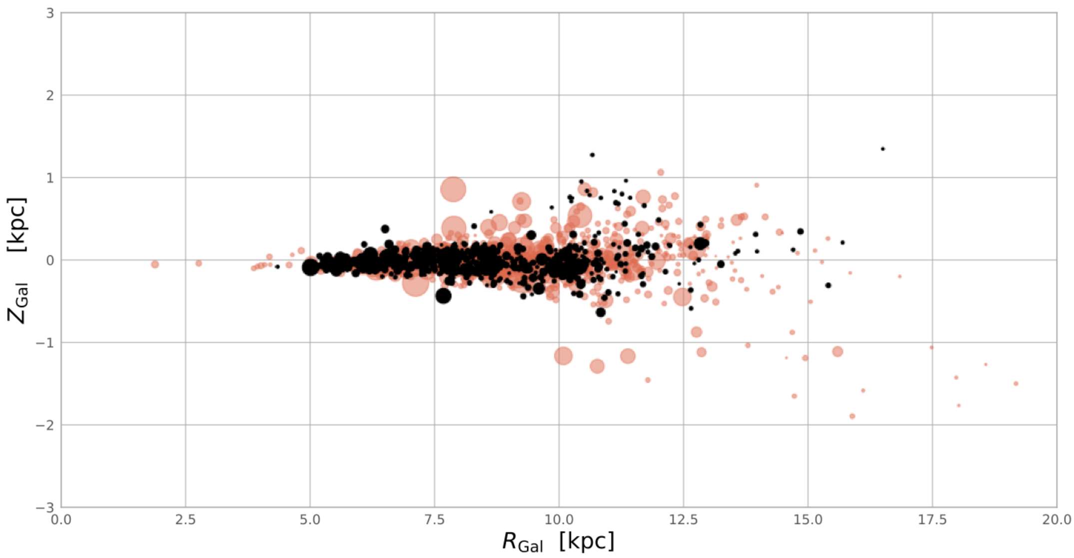
They used the machine-learning based methodology to search for overdensities across the whole Galactic disc, using an unsupervised clustering algorithm, which pointed to several overdensities as plausible candidates for open clusters. Then, they confirmed those candidates as open clusters through a deep learning artificial neural network, which recognized isochrone patterns in the colour and magnitude.

"Before this methodology, there were around 1200 open clusters confirmed by Gaia", says Castro-Ginard. "Using Gaia's data and our methodology, we have found more than 650 new clusters. This has improved and increased the catalogue, which now contains more than 2000 open clusters."

Stefan Jordan and Toni Sagristá represented the whole Gaia DR2 open cluster catalogue in a Gaia Sky visualisation. The video shows a flyby through the Galaxy, highlighting the open clusters known before and after Gaia DR2 and the differences between both catalogues. The flyby stops at UBC 274, showing that positions and proper motions of its stars are compatible with each other, and also showing that this cluster is being disrupted due to tidal forces of the Milky Way.

For the video we refer to: https://www.youtube.com/watch?v=iPUFkoM_SDM

Gaia image of the week: https://www.cosmos.esa.int/web/gaia/image-of-the-week



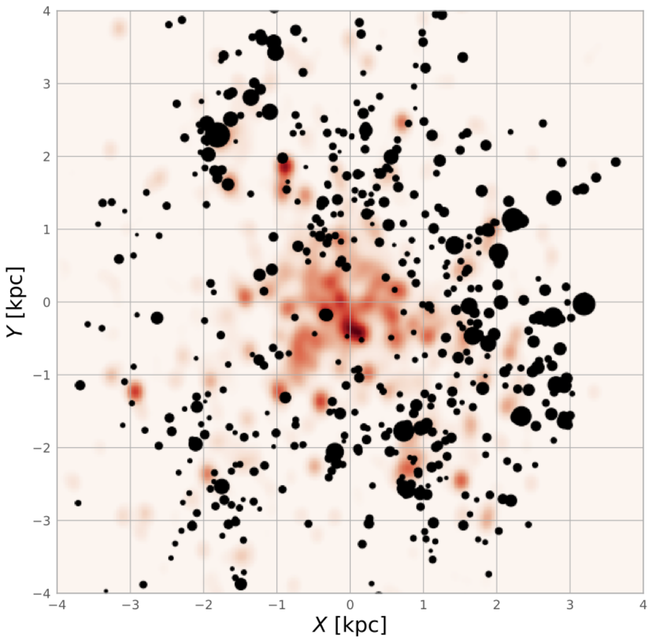


Figure 1: Distribution of the open clusters in Galacto-centric coordinates R-Z (upper) and in Helio-centric coordinates X-Y (bottom). Previously known open clusters are shown with red dots (upper) or with the density map in red (bottom) (Cantat-Gaudin et al. 2018, 2019 and Castro-Ginard et al. 2018, 2019). The black dots represent the newly found open clusters (Castro-Ginard et al. 2020). The sizes of the dots are proportional to the number of member of each cluster. Image credit: Castro-Ginard et al. 2020

Star Forming Regions

Lithium-rotation connection in the newly discovered young stellar stream Psc-Eri (Meingast 1)

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As a fragile element, lithium is a sensitive probe of physical processes occurring in stellar interiors. We aim to investigate the relationship between lithium abundance and rotation rate in low-mass members of the newly discovered 125 Myr-old Psc-Eri stellar stream. We obtained high-resolution optical spectra and measured the equivalent width of the 607.8 nm LiI line for 40 members of the Psc-Eri stream, whose rotational periods have been derived by Curtis et al. 2019 (arXiv:1905.10588). We show that a tight correlation exists between the lithium content and rotation rate among the late-G to early-K-type stars of the Psc-Eri stream. Fast rotators are systematically Li rich, while slow rotators are Li depleted. This trend mimics that previously reported for the similar age Pleiades cluster. The lithium-rotation connection thus seems to be universal over a restricted effective temperature range for low-mass stars at or close to the zero-age main sequence, and does not depend on environmental conditions.

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https://arxiv.org/abs/2002.10556

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A new look at Sco OB1 association with Gaia DR2

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We present and discuss photometric optical data in the area of the OB association Sco OB1 covering about 1 deg2. UBVI photometry is employed in tandem with Gaia DR2 data to investigate the three-dimensional structure and the star formation history of the region. By combining parallaxes and proper motions, we identify seven physical groups located between the young open cluster NGC 6231 and the bright nebula IC 4628. The most prominent group coincides with the sparse open cluster Trumpler 24. We confirm the presence of the intermediate-age star cluster VdB-Hagen 202, which is unexpected in this environment, and provide for the first time estimates of its fundamental parameters. After assessing individual groups membership, we derive mean proper motion components, distances, and ages. The seven groups belong to two different families. To the younger family (family I) belong several pre-main-sequence (PMS) stars as well. These are evenly spread across the field, and also in front of VdB-Hagen 202. VdB-Hagen 202, and two smaller, slightly detached, groups of similar properties form family II, which do not belong to the association, but are caught in the act of passing through it. As for the younger population, this forms an arc-like structure from the bright nebula IC 4628 down to NGC 6231, as previously found. Moreover, the PMS stars density seems to increase from NGC 6231 northward to Trumpler 24.

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https://ui.adsabs.harvard.edu/abs/2020MNRAS.495.1349Y/abstract

A 3D view of the Taurus star-forming region by Gaia and Herschel: multiple populations related to the filamentary molecular cloud

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Taurus represents an ideal region to study the three-dimensional distribution of the young stellar population and relate it to the associated molecular cloud. The second Gaia data release (DR2) enables us to investigate the Taurus complex in three dimensions, starting from a previously defined robust membership. The molecular cloud structured in filaments can be traced in emission using the public far-infrared maps from Herschel. From a compiled catalog of spectroscopically confirmed members, we analyze the 283 sources with reliable parallax and proper motions in the Gaia DR2 archive. We fit the distribution of parallaxes and proper motions with multiple populations described by multivariate Gaussians. We compute the cartesian Galactic coordinates (X,Y,Z) and, for the populations associated with the main cloud, also the galactic space velocity (U,V,W). We discuss the spatial distribution of the populations in relation to the structure of the filamentary molecular cloud traced by Herschel. Results. We discover the presence of six populations which are all well defined in parallax and proper motions, with the only exception being Taurus D. The derived distances range between 130 and 160 pc. We do not find a unique relation between stellar population and the associated molecular cloud: while the stellar population seems to be on the cloud surface, both lying at similar distances, this is not the case when the molecular cloud is structured in filaments. Taurus B is probably moving in the direction of Taurus A, while Taurus E appears to be moving towards them. The Taurus region is the result of a complex star formation history which most probably occurred in clumpy and filamentary structures that are evolving independently.

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https://ui.adsabs.harvard.edu/abs/2020arXiv200501331R/abstract

Galactic Open Clusters

A new open cluster from data based in Gaia DR2

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The physical nature of a new open cluster, Casado 2, discovered as an overdensity of stars by visual inspection of photographic DSS plates, is confirmed employing existing data on putative star members, mainly from second Gaia Data Release (DR2). The reported object was not present in the most comprehensive or recent catalogs of stellar clusters and associations. A clump of comoving stars is revealed in the proper motion space. The parallaxes of such stars are compatible with the real existence of an open cluster at a distance of 1.23 ± 0.07 kpc. Surface density calculations, free of most noise from non-member sources, allow differentiating a cluster core and an extended cluster corona. The color-magnitude diagram shows a definite main sequence and allows a rough estimation of the cluster age. The new open cluster characteristics suggest that it is a mature object. The discovery and the primary study, mainly based on Gaia DR2 data, of the new OC Casado 2 are reported. The OC candidate was discovered as a slight overdensity of stars of magnitude $10 < G < 17$, located at $l = 112.03°$ and $b = -1.49°$ (Figure 1). It was not listed in the most comprehensive catalogs of such celestial objects published by the end of 2019. A clump of stars of $G < 17$ with proper motions $\mu_\alpha = -2.9 \pm 0.2$ mas/yr; $\mu_\delta = -3.0 \pm 0.2$ is found in the field of the new OC (Figure 3). This ensemble of comoving stars allows establishing a mean parallax of 0.81 ± 0.04 mas, which corresponds to a distance d = 1.23 ± 0.07 kpc. Al least 11 out of 17 stars of compatible parallaxes are probable members of the OC that remain within an adopted core radius r = 3 arcmin (Table 1). Gaia DR2 data allow removing most of the background star noise (Figure 5). Surface density calculations confirmed the presence of the OC core and an extended corona with an actual radius R from 20 to 25 arcmin, corresponding to a physical radius of ~ 8 pc. The number of plausible star members of the OC is ca. 80. The CMD diagram (Figure 6) shows a definite main sequence as well as a red giant and a putative subgiant star. The estimates of the OC age by different methods converge to a crude value of log t/yr ~ 9.0. The presence of an extended cluster corona and its estimated age suggest that Casado 2 is a mature OC. The claim of completeness of the known OC population in the d range from 1.0 to 1.8 kpc of the Sun (Kharchenko et al. 2013) is questioned (see also Cantat-Gaudin et al. 2019), as the new OC lies precisely within such interval of distances.

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High-resolution spectroscopy of red giants and 'yellow stragglers' in the southern open cluster NGC 2539

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We present a detailed high-resolution spectroscopic analysis of 12 red giant stars, in single and binaries or multiples systems, classified as members of the intermediate-age (631 Myr) open cluster NGC 2539. We used FEROS echelle spectra and the standard LTE analysis to derive the atmospheric parameters for the stars and the abundance ratios 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, Ce, Nd, Eu). Our results show that the sample star of NGC 2539 has low projected rotational velocities and an almost solar metallicity, with a mean of $[Fe/H] = -0.03 \pm 0.07$ dex. The abundance pattern displays for the analyzed stars are, in general, similar to those presented by solar neighborhood stars, including giant members of others open clusters. In particular, light elements and Na abundance pattern shows anomalies resulting from the appearance of enriched material on the stellar surface, produced by mechanisms like the first dredge-up and/or thermohaline and rotation-induced mixing. We also identified two of the spectroscopic binaries of our sample as 'yellow stragglers' and we determined the nature of their companions.

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https://ui.adsabs.harvard.edu/abs/2020MNRAS.494.1470M

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A binary star sequence in the outskirts of the disrupting Galactic open cluster UBC 274

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We report the identification of a numerous binary star population in the recently discovered $\sim$ 3 Gyr old open cluster UBC 274. It becomes visible once the cluster color-magnitude diagram is corrected by differential reddening and spans mass ratios (q) values from 0.5 up to 1.0. Its stellar density radial profile and cumulative distribution as a function of the distance from the cluster's center reveal that it extends out to the observed boundaries of the cluster's tidal tails ($\sim$ 6 times the cluster's radius) following a spatial distribution indistinguishable from that of cluster Main Sequence (MS) stars. Furthermore, binary stars with q values smaller or larger than 0.75 do not show any spatial distribution difference either. From Gaia DR2 astrometric and kinematics data we computed Galactic coordinates and space velocities with respect to the cluster's center and mean cluster space velocity, respectively. We found that, cluster members located all along the tidal tails, irrespective of being a single or binary star, move relatively fast. The projection of their motions on the Galactic plane resembles that of a rotating solid body, while those along the radial direction from the Galactic center and perpendicular to the Galactic plane suggest that the cluster is being disrupted. The similarity of the spatial distributions and kinematic patterns of cluster MS and binary stars reveals that UBC 274 is facing an intense process of disruption that has apparently swept out any signature of internal dynamic evolution like mass segregation driven by two-body relaxation.

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Cluster membership for the long-period Cepheid calibrator SV Vul

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Classical Cepheids represent the first step of the distance scale ladder. Claims of tension between the locally calculated Hubble constant and the values deduced from Planck's results have sparked new interest in these distance calibrators. Cluster membership provides an independent distance measurement, as well as astrophysical context for studies of their stellar properties. Here, we report the discovery of a young open cluster in the vicinity of SV Vul, one of the most luminous Cepheids known in the Milky Way. Gaia DR2 data show that SV Vul is a clear astrometric and photometric member of the new cluster, which we name Alicante 13. Although dispersed, Alicante 13 is moderately well populated, and contains three other luminous stars, one early-A bright giant and two low-luminosity red supergiants. The cluster is about 30 Ma old at a nominal distance of 2.5 kpc. With this age, SV Vul should have a mass around 10 $M_{\odot}$, in good accordance with its luminosity, close to the highest luminosity for Cepheids allowed by recent stellar models.

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https://ui.adsabs.harvard.edu/abs/2020MNRAS.494.3028N/abstract

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Sixteen overlooked open clusters in the fourth Galactic quadrant - A combined analysis of UBVI photometry and Gaia DR2 with ASteCA

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This paper has two main objectives: (1) To determine the intrinsic properties of 16 faint and mostly unstudied open clusters in the poorly known sector of the Galaxy at $270^{\circ} - 300^{\circ}$ to probe the Milky Way structure in future investigations. (2) To address previously reported systematics in Gaia DR2 parallaxes by comparing the cluster distances derived from photometry with those derived from parallaxes. Deep UBVI photometry of 16 open clusters was carried out. Observations were reduced and analyzed in an automatic way using the ASteCA package to obtain individual distances, reddening, masses, ages, and metallicities. Photometric distances were compared to those obtained from a Bayesian analysis of Gaia DR2 parallaxes. Ten out of the sixteen clusters are true or highly probable open clusters. Two of them are quite young and follow the trace of the Carina Arm and the already detected warp. The remaining clusters are placed in the interarm zone between the Perseus and Carina Arms, as expected for older objects. We found that the cluster van den Berg-Hagen 85 is 7.5×10^{9} yr old, which means that it is one of the oldest open clusters detected in our Galaxy so far. The relationship of these ten clusters with the Galaxy structure in the solar neighborhood is discussed. The comparison of distances from photometry and parallaxes data in turn reveals a variable level of disagreement. Various zero-point corrections for Gaia DR2 parallax data recently reported were considered for a comparison between photometry- and parallax-based distances. The results tend to improve with some of these corrections. Photometric distance analysis suggests an average correction of $\sim$+0.026 mas (to be added to the parallaxes). The correction may have a more intricate dependence on distance, but addressing this level of detail will require a larger cluster sample.

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https://ui.adsabs.harvard.edu/abs/2020A%26A...637A..95P/abstract

Galactic Globular Clusters

Pal 13: its moderately extended low density halo and its accretion history

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We present results on the basis of Dark Energy Camera Legacy Survey (DECaLS) DR8 astrometric and photometric data sets of the Milky Way globular cluster Pal 13. Because of its relative small size and mass, there has not been yet a general consensus about the existence of extra-tidal structures around it. While some previous results claim for the absence of such features, others have shown that the cluster is under the effects of tidal stripping. From DECaLS g,r magnitudes of stars placed along the cluster Main Sequence in the colour-magnitude diagram –previously corrected by interstellar reddening–, we built the cluster stellar density map. The resulting density map shows nearly smooth contours around Pal 13 out to 1.6 times the most recent estimate of its Jacobi radius, derived by taking into account its variation along its orbital motion. This outcome favours the presence of stars escaping the cluster, a phenomenon frequently seen in globular clusters that have crossed the Milky Way disc a comparable large number of times. Particularly, the orbital high eccentricity and large inclination angle of this accreted globular cluster could have been responsible for the relatively large amount of cluster mass lost.

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https://ui.adsabs.harvard.edu/abs/2020arXiv200202746P/abstract

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The Hubble Space Telescope UV Legacy Survey of Galactic Globular Clusters. XX. Ages of single and multiple stellar populations in seven bulge globular clusters

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In the present work we analyzed seven globular clusters selected from their location in the Galactic bulge and with metallicity values in the range -1.30 < [Fe/H] < -0.50. The aim of this work is first to derive cluster ages assuming single stellar populations, and secondly, to identify the stars from first (1G) and second generations (2G) from the main sequence, subgiant and red giant branches, and to derive their age differences. Based on a combination of UV and optical filters used in this project, we apply the Gaussian mixture models to distinguish the multiple stellar populations. Applying statistical isochrone fitting, we derive self-consistent ages, distances, metallicities, and reddening values for the sample clusters. An average of 12.3 +/- 0.4 Gyr was obtained both using Dartmouth and BaSTI (accounting atomic diffusion effects) isochrones, without a clear distinction between the moderately metal-poor and the more metal-rich bulge clusters, except for NGC 6717 and the inner halo NGC 6362 with 13.5 Gyr. We derived a weighted mean age difference between the multiple populations hosted by each globular cluster of 41 +/- 170 Myr adopting canonical He abundances; whereas for higher He in 2G stars, this difference reduces to 17 +/- 170 Myr, but with individual uncertainties of 500 Myr.

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https://ui.adsabs.harvard.edu/abs/2020arXiv200108611O/abstract

On the tidal tails of Milky Way globular clusters

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We report on the search for overall kinematical or structural conditions that have allowed some Milky Way globular clusters to presently develop tidal tails. For this purpose, we build a comprehensive catalogue of globular clusters with studies focused on their outermost regions and classified them in three categories: those with observed tidal tails, those with extra-tidal features di erent from tidal tails and those without any signature of extended stellar density profiles. When exploring different kinematical and structural parameter spaces, we found that globular clusters - irrespective from the presence of tidal tails, or any other kind of extra-tidal features or the absence of them - behave similarly. In general, globular clusters whose orbits are relatively more eccentric and very inclined respect to the Milky Way plane have undergone a larger amount of mass-loss by tidal disruption. The latter has also accelerated the internal dynamics toward a comparatively more advanced stage of evolution. These outcomes show that it is not straightforward to find any particular set of parameter space and dynamical conditions that can definitely predict tidal tails along globular clusters in the Milky Way.

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https://ui.adsabs.harvard.edu/abs/2020arXiv200411747P/abstract

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Searching for globular cluster chemical anomalies on the main sequence of a young massive cluster

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The spectroscopic and photometric signals of the star-to-star abundance variations found in globular clusters seem to be correlated with global parameters like the cluster's metallicity, mass and age. Understanding this behaviour could bring us closer to the origin of these intriguing abundance spreads. In this work we use deep *HST* photometry to look for evidence of abundance variations in the main sequence of a young massive cluster NGC 419 ($\sim 10^5$ $M_\odot$, $\sim$ 1.4 Gyr). Unlike previous studies, *here we focus on stars in the same mass range found in old globulars* ($\sim 0.75-1$ $M_\odot$), *where light elements variations are detected*. We find no evidence for N abundance variations among these stars in the $Un-B$ and $U-B$ CMD of NGC 419. This is at odds with the N-variations found in old globulars like 47 Tuc, NGC 6352 and NGC 6637 with similar metallicity to NGC 419. Although the signature of the abundance variations characteristic of old globulars appears to be significantly smaller or absent in this young cluster, we cannot conclude if this effect is mainly driven by its age or its mass.

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New insight into the stellar mass function of Galactic globular clusters

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We present the results of the analysis of deep photometric data of 32 Galactic globular clusters. We analysed 69 parallel field images observed with the Wide Field Channel of the Advanced Camera for Surveys of the Hubble Space Telescope which complemented the already available photometry from the globular cluster treasury project covering the central regions of these clusters. This unprecedented data set has been used to calculate the relative fraction of stars at different masses (i.e. the present-day mass function) in these clusters by comparing the observed distribution of stars along the cluster main sequence and across the analysed field of view with the prediction of multimass dynamical models. For a subsample of 31 clusters, we were able to obtain also the half-mass radii, mass-to-light ratios, and the mass fraction of dark remnants using available radial velocity information. We found that the majority of globular clusters have single power-law mass functions $F(m) = m^{\alpha}$ with slopes $\alpha > -1$ in the mass range $0.2 < m/M_{\odot} < 0.8$. By exploring the correlations between the structural/dynamical and orbital parameters, we confirm the tight anticorrelation between the mass function slopes and the half-mass relaxation times already reported in previous works, and possible second-order dependence on the cluster metallicity. This might indicate the relative importance of both initial conditions and evolutionary effects on the present-day shape of the mass function.

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https://ui.adsabs.harvard.edu/abs/2020MNRAS.494.4226E

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The proper motion of sub-populations in ω Centauri

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The galactic globular cluster ω Centauri is the most massive of its kind, with a complex mix of multiple stellar populations and several kinematic and dynamical peculiarities. Different mean proper motions have been detected among the three main sub-populations, implying that the most metal-rich one is of accreted origin. This particular piece of evidence has been a matter of debate because the available data have either not been sufficiently precise or limited to a small region of the cluster to ultimately confirm or refute the result. Using astrometry from the second Gaia data release and recent high-quality, multi-band photometry, we are now in a position to resolve the controversy. We reproduced the original analysis using the Gaia data and found that the three populations have the same mean proper motion. Thus, there is no need to invoke an accreted origin for the most metal-rich sub-population

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The Gaia-ESO Survey: an extremely Li-rich giant in the globular cluster NGC 1261

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Lithium rich stars in globular clusters are rare. In fact, only 14 have been found so far, in different evolutionary phases from dwarfs to giants. Different mechanisms have been proposed to explain this enhancement, but it is still an open problem. Using spectra collected within the Gaia-ESO Survey, obtained with the GIRAFFE spectrograph at the ESO Very Large Telescope, we present the discovery of the first Li-rich star in the cluster NGC 1261, the second star known in the red giant branch bump phase. The star shows an extreme Li overabundance of $A(Li)_{LTE}$=3.92±0.14, corresponding to $A(Li)_{NLTE}$=3.40 dex. We propose that the Li enhancement is caused by fresh Li production through an extra mixing process (sometimes referred to as *cool bottom burning*) or could be a pre-existing Li overabundance resulting from binary mass transfer, likely from a red giant branch star, because of the low barium abundance. To unambiguously explain the Li enhancement in globular cluster stars, however, a reliable determination of the abundance of key species like Be, 6Li, 12C/13C, and several s-process elements is required, as well as detailed modeling of chromospheric activity indicators.

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https://ui.adsabs.harvard.edu/abs/2020arXiv200604393S/abstract

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Milky Way Subsystems from Globular Cluster Kinematics Using Gaia DR2 and HST Data

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We employ Gaia DR2 proper motions for 151 Milky Way globular clusters (GCs) from Vasiliev in tandem with distances and line-of-sight velocities to derive their kinematical properties. To assign clusters to the Milky Way thick disk, bulge, and halo, we follow the approach of Posti et al., who distinguished among different Galactic stellar components using stars' orbits. In particular, we use the ratio L_z/e, the Z projection of the angular momentum to the eccentricity, as a population tracer, which we complement with chemical abundances extracted from the literature and Monte Carlo simulations. We find that 20 GCs belong to the bar/bulge of the Milky Way, 35 exhibit disk properties, and 96 are members of the halo. Moreover, we find that halo GCs have close to zero rotational velocity with an average value $<\Theta>= 1 \pm 4$ km s^{-1}. On the other hand, the sample of clusters that belong to the thick disk possess a significant rotation with average rotational velocity 179 ± 6 km s^{-1}. The 20 GCs orbiting within the bar/bulge region of the Milky Way have an average rotational velocity of 49 ± 11 km s^{-1}.

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Stellar-mass black holes in young massive and open stellar clusters and their role in gravitational-wave generation IV: updated stellar-evolutionary and black hole spin models and comparisons with the LIGO-Virgo O1/O2 merger-event data

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I present a set of long-term, direct, relativistic many-body computations of model dense stellar clusters with up-to-date remnant mass and natal-kick models, including pair instability and pulsation pair instability supernova (PSN and PPSN), using NBODY7 N-body simulation program. The N-body model also includes natal spins of BHs, based on theoretical stellar-evolutionary models, and runtime tracking of GR merger recoils and final spins of in-spiralling binary black holes (BBH), based on numerical relativity. These, for the first time in a direct N-body simulation, allow for second-generation BBH mergers. The set of 65 evolutionary models have initial masses $10^4 M_\odot - 10^5 M_\odot$, sizes 1 pc-3 pc, metallicity 0.0001-0.02, with the massive stars in primordial binaries and they represent young massive clusters (YMC) and moderately massive open clusters (OC). Such models produce dynamically-paired BBH mergers that agree well with the observed masses, mass ratios, effective spin parameters, and final spins of the LVC O1/O2 merger events and also with their overall trends and boundaries, provided BHs are born with low or no spin but spin up after undergoing a BBH merger or matter accretion onto it. In particular, the distinctly higher mass, effective spin parameter, and final spin of GW170729 merger event is naturally reproduced, as also the mass asymmetry of LIGO-Virgo O3 event GW190412. The computed models also produce massive, $\sim 100 M_\odot$ BBH mergers with primary mass within the "PSN gap". Depending on the remnant-mass and natal-kick scenarios, such models also yield mergers involving remnants in the "mass gap", as detected in the O3. These computations also suggest that YMCs and OCs produce persistent GW sources detectable by LISA from within the ~ 100 Mpc Local Universe. Such clusters are also capable of producing mergers with eccentricity detectable by the LIGO-Virgo.

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Discovery of rotation axis alignments in Milky Way globular clusters

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There is an increasing number of recent observational results which show that some globular clusters exhibit internal rotation while they travel along their orbital trajectories around the Milky Way center. Based on these findings, we looked for any relationship between the inclination angles of the globular clusters' orbits with respect to the Milky Way plane and those of their rotation. We discovered that the relative inclination, in the sense rotation axis inclination − orbit axis inclination, is a function of the globular cluster's orbit inclination. Rotation and orbit axes are aligned for an inclination of $\sim 56°$, while the rotation axis inclination is far from the orbit's one between $\sim 20°$ and -20° when the latter increases from 0° up to 90°. We further investigated the origin of such a linear relationship and found no correlation with the semimajor axes and eccentricities of the globular clusters' orbits, nor with the internal rotation strength, the globular clusters' sizes, actual and tidally disrupted masses, half-mass relaxation times, among others. The uncovered relationship will impact on the development of numerical simulations of the internal rotation of globular clusters, on our understanding about the interaction of the globular clusters with the Milky Way gravitational field, and on the observational campaigns for increasing the number of studied globular clusters with detected internal rotation.

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Dynamical evolution - Simulations

Molecular clumps disguising their star formation efficiency per freefall time: What we can do not to be fooled

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The presence of a volume density gradient in molecular clumps allow them to raise their star formation rate compared to what they would experience were their gas uniform in density. This higher star formation rate yields in turn a higher value for the star formation efficiency per freefall time that we measure. The measured star formation efficiency per freefall time $\epsilon_{\rm ff,meas}$ of clumps is therefore plagued by a degeneracy, as two factors contribute to it: one is the density gradient of the clump gas, the other is the intrinsic star formation efficiency per freefall time $\epsilon_{\rm ff,int}$ with which the clump would form stars should there be no gas density gradient. This paper presents a method allowing one to recover the intrinsic efficiency of a centrally-concentrated clump. It hinges on the relation between the surface densities in stars and gas measured locally from clump center to clump edge. Knowledge of the initial density profile of the clump gas is not required. A step-by-step description of the method is provided as a tool in hand for observers. Once $\epsilon_{\rm ff,int}$ has been estimated, it can be compared with its measured, clump-averaged, counterpart $\epsilon_{\rm ff,meas}$ to quantify the impact that the initial gas density profile of a clump has had on its star formation history.

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Searching for multiple populations in the integrated light of the young and extremely massive clusters in the merger remnant NGC 7252

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Recent work has shown that the properties of multiple populations (MPs) within massive stellar clusters (i.e. in the extent of their abundance variations as well as the fraction of stars that show the anomalous chemistry) depend on the mass as well as the age of the host cluster. Such correlations are largely unexpected in current models for the formation of MPs and hence provide essential insight into their origin. Here, we extend our previous study into the presence or absence of MPs using integrated light spectroscopy of the $\sim$600 Myr, massive ($\sim$107-108 M$_{\odot}$) clusters, W3 and W30, in the galactic merger remnant, NGC 7252. Due to the extreme mass of both clusters, the expectation is that they should host rather extreme abundance spreads, manifested through high mean [Na/Fe] abundances. However, we do not find evidence for a strong [Na/Fe] enhancement, with the observations being consistent with the solar value. This suggests that age is playing a key role, or alternatively that MPs only manifest below a certain stellar mass, as the integrated light at all ages above $\sim$100 Myr is dominated by stars near or above the main-sequence turn-off.

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Searching for solar siblings in APOGEE and Gaia DR2 with N-body simulations

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We make use of APOGEE and Gaia data to identify stars that are consistent with being born in the same association or star cluster as the Sun. We limit our analysis to stars that match solar abundances within their uncertainties, as they could have formed from the same giant molecular cloud (GMC) as the Sun. We constrain the range of orbital actions that solar siblings can have with a suite of simulations of solar birth clusters evolved in static and time-dependent tidal fields. The static components of each galaxy model are the bulge, disc, and halo, while the various time-dependent components include a bar, spiral arms, and GMCs. In galaxy models without GMCs, simulated solar siblings all have $J_R < 122$ km s^{-1} kpc, $990 < J_z < 1986$ km s^{-1} kpc, and $0.15 < J_z < 0.58$ km s^{-1} kpc. Given the actions of stars in APOGEE and Gaia, we find 104 stars that fall within this range. One candidate in particular, Solar Sibling 1, has both chemistry and actions similar enough to the solar values that strong interactions with the bar or spiral arms are not required for it to be dynamically associated with the Sun. Adding GMCs to the potential can eject solar siblings out of the plane of the disc and increase their Jz, resulting in a final candidate list of 296 stars. The entire suite of simulations indicate that solar siblings should have $J_R < 122$ km s^{-1} kpc, $353 < J_z < 2110$ km s^{-1} kpc, and $J_z < 0.8$ km s^{-1} kpc. Given these criteria, it is most likely that the association or cluster that the Sun was born in has reached dissolution and is not the commonly cited open cluster M67.

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On the origin of the bimodal rotational velocity distribution in stellar clusters: rotation on the pre-main sequence

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We address the origin of the observed bimodal rotational distribution of stars in massive young and intermediate age stellar clusters. This bimodality is seen as split main sequences at young ages and also has been recently directly observed in the Vsini distribution of stars within massive young and intermediate age clusters. Previous models have invoked binary interactions as the origin of this bimodality, although these models are unable to reproduce all of the observational constraints on the problem. Here, we suggest that such a bimodal rotational distribution is set-up early within a cluster's life, i.e. within the first few Myr. Observations show that the period distribution of low-mass ($\lesssim 2M_\odot$) pre-main-sequence (PMS) stars is bimodal in many young open clusters, and we present a series of models to show that if such a bimodality exists for stars on the PMS that it is expected to manifest as a bimodal rotational velocity (at fixed mass/luminosity) on the main sequence for stars with masses in excess of $\sim$1.5 $M_\odot$. Such a bimodal period distribution of PMS stars may be caused by whether stars have lost (rapid rotators) or been able to retain (slow rotators) their circumstellar discs throughout their PMS lifetimes. We conclude with a series of predictions for observables based on our model.

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The formation of young massive clusters by colliding flows

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Young massive clusters (YMCs) are the most intense regions of star formation in galaxies. Formulating a model for YMC formation whilst at the same time meeting the constraints from observations is highly challenging however. We show that forming YMCs requires clouds with densities $\gtrsim 100$ cm^{-3} to collide with high velocities ($\gtrsim 20$ km s^{-1}). We present the first simulations which, starting from moderate cloud densities of ~ 100 cm^{-3}, are able to convert a large amount of mass into stars over a time period of around 1 Myr, to produce dense massive clusters similar to those observed. Such conditions are commonplace in more extreme environments, where YMCs are common, but atypical for our Galaxy, where YMCs are rare.

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BSE versus StarTrack: implementations of new wind, remnant-formation, and natal-kick schemes in NBODY7 and their astrophysical consequences

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The masses of stellar-remnant black holes (BH), as a result of their formation via massive single- and binary-stellar evolution, is of high interest in this era of gravitational-wave detection from binary black hole (BBH) and binary neutron star (BNS) mergers. Here we present new developments in the N-body evolution program NBODY7 in regards to its stellar-remnant formation and related schemes. We demonstrate that the newly implemented stellar-wind and remnant-formation schemes in the NBODY7 code's BSE sector, such as the 'rapid' and the 'delayed' supernova (SN) schemes along with an implementation of pulsation-pair-instability and pair-instability supernova (PPSN/PSN), now produces neutron star (NS) and BH masses that agree nearly perfectly, over large ranges of zero-age-main sequence (ZAMS) mass and metallicity, with those from the StarTrack population-synthesis program. We also demonstrate the new implementations of various natal-kick mechanisms on NSs and BHs such as the 'convection-asymmetry-driven', 'collapse-asymmetry-driven', and 'neutrino-emission-driven' kicks, in addition to a fully consistent implementation of the standard, fallback-dependent, momentum-conserving natal kick. We find that the SN material fallback causes the convection-asymmetry kick to effectively retain similar number and mass of BHs in clusters as for the standard, momentum-conserving kick. The collapse-asymmetry kick would cause nearly all BHs to retain in clusters irrespective of remnant formation model and metallicity, whereas the inference of a large number of BHs in GCs would potentially rule out the neutrino-driven kick mechanism. Pre-SN mergers of massive primordial binaries would cause BH masses to deviate from the single-star ZAMS mass-remnant mass relation. Such mergers, at low metallicities, can produce low-spinning BHs within the PSN mass gap that can be retained in a stellar cluster.

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The globular cluster system mass-halo mass relation in the E-MOSAICS simulations

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Linking globular clusters (GCs) to the assembly of their host galaxies is an overarching goal in GC studies. The inference of tight scaling relations between GC system properties and the mass of both the stellar and dark halo components of their host galaxies are indicative of an intimate physical connection, yet have also raised fundamental questions about how and when GCs form. Specifically, the inferred correlation between the mass of a GC system (M_{GC}) and the dark matter halo mass (M_{halo}) of a galaxy has been posited as a consequence of a causal relation between the formation of dark matter mini-haloes and GC formation during the early epochs of galaxy assembly. We present the first results from a new simulation of a cosmological volume (L=34.4cMpc on a side) from the E-MOSAICS suite, which includes treatments of the formation and evolution of GCs within the framework of a detailed galaxy formation model. The simulated M_{GC}-M_{halo} relation is linear for halo masses $> 5 \times 10^{11}$ $M_{\odot}$, and is driven by the hierarchical assembly of galaxies, in agreement with previous studies. Below this halo mass, the simulated relation features a downturn, which we show is consistent with observations, and is driven by the underlying stellar mass (M_{star})-halo mass relation of galaxies. Our fiducial model reproduces the observed M_{GC}-M_{star} relation across the full mass range, which we argue is more physically relevant than the M_{GC}-M_{halo} relation. We also explore the physical processes driving the observed constant value of M_{GC} / $M_{halo} \sim 5 \times 10^{-5}$ and find that it is the result of a combination of cluster formation physics and cluster disruption.

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Miscellaneous

Painting a portrait of the Galactic disc with its stellar clusters

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The large astrometric and photometric survey performed by the Gaia mission allows for a panoptic view of the Galactic disc and in its stellar cluster population. Hundreds of clusters were only discovered after the latest G data release (DR2) and have yet to be characterised. Here we make use of the deep and homogeneous Gaia photometry down to G=18 to estimate the distance, age, and interstellar reddening for about 2000 clusters identified with Gaia DR2 astrometry. We use these objects to study the structure and evolution of the Galactic disc. We rely on a set of objects with well-determined parameters in the literature to train an artificial neural network to estimate parameters from the Gaia photometry of cluster members and their mean parallax. We obtain reliable parameters for 1867 clusters. Our new homogeneous catalogue confirms the relative lack of old clusters in the inner disc (with a few notable exceptions). We also quantify and discuss the variation of scale height with cluster age, and detect the Galactic warp in the distribution of old clusters. This work results in a large and homogenous cluster catalogue. However, the present sample is still unable to trace the Outer spiral arm of the Milky Way, which indicates that the outer disc cluster census might still be incomplete.

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The Milky Way's cluster age function in light of Gaia DR2

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We perform a systematic reanalysis of the age distribution of Galactic open star clusters. Using a catalogue of homogeneously determined ages for 834 open clusters contained in a 2 kpc cylinder around the Sun and characterised with astrometric and photometric data from the *Gaia* satellite, we find that it is necessary to revise earlier works that relied on data from the Milky Way Star Cluster survey. After establishing age-dependent completeness limits for our sample, we find that the cluster age function in the range $6.5 < \log t < 10$ is compatible with a Schechter-type or broken power-law function, whose parameters we determine by MCMC fitting. Our best-fit values indicate an earlier drop of the age function (by a factor of $2-3$) with respect to the results obtained in the last five years, and are instead more compatible with results obtained in the early 2000s and radio observations of inner-disc clusters. Furthermore, we find excellent agreement with the dynamical cluster formation and destruction models of Lamers et al. (2005), indicating a typical destruction time-scale of ~ 1.5 Gyr for a $10^4\,\mathrm{M}_\odot$ cluster and a present-day cluster-formation rate of $\sim 0.6 \pm 0.1$ Myr^{-1}kpc^{-2}, suggesting that only $8-15$ % of all stars born in the solar neighbourhood form in bound clusters. Accurate cluster-mass measurements are now needed to place more precise constraints on open-cluster formation and evolution models.

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Proceedings abstracts

On the origin of stellar associations. The impact of Gaia DR2

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In this review I discuss different theories of the formation of OB associations in the Milky Way, and provide the observational evidences in support of them. In fact, the second release of Gaia astrometric data (April 2018) is revolutionising the field, because it allows us to unravel the 3D structure and kinematics of stellar associations with unprecedented details by providing precise distances and a solid membership assessment. As an illustration, I summarise some recent studies on three OB associations: Cygnus OB2, Vela OB2, and Scorpius OB1, focussing in more detail to Sco OB1. A multi-wavelength study, in tandem with astrometric and kinematic data from Gaia DR2, seems to lend support, at least in this case, to a scenario in which star formation is not monolithic. As a matter of fact, besides one conspicuous star cluster, NGC 6231, and the very sparse star cluster Trumpler 24, there are several smaller groups of young OB and pre-main sequence stars across the association, indicating that star formation is highly structured and with no preferred scale. A new revolution is expected with the incoming much awaited third release of Gaia data.

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Ph.D. (dissertation) summaries

Spectroscopy of Binaries in Globular Clusters

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This work makes use of multi-epoch MUSE observations of 27 Galactic globular clusters, including more than 380000 stars and 1400000 individual spectra, to derive radial velocities that allow the identification and characterisation of binary systems. For the first time in astronomy, three binary systems, each composed of a black hole and a visible stellar companion, were discovered by this blind spectroscopic survey. These findings helped to understand the retention fraction of black holes and how they affect the dynamical properties of globular clusters. The identification of these three black holes in NGC 3201 provided evidence that the cluster hosts an extensive subsystem of black holes including at least 40 objects. Black holes, as well as the binary systems, provide the cluster with an extra source of energy that explains why the core of NGC 3201 is not as dense as expected for a 12 Gyr old simple stellar population. The pilot study on the globular cluster NGC 3201 shows what can be learned about the binary content of a globular cluster when using state-of-the-art observations and simulations. A new statistical method was developed to infer the binary probability of individual stars based on noisy and sparse radial velocities taking data from all stars of a given cluster into account. With the help of a sophisticated MOCCA globular cluster model of NGC 3201, the total binary fraction of 6.8 %, freed from many observational biases, was derived for this cluster. This is the most accurate estimate obtained to date. The best fitting MOCCA model also suggests that NGC 3201 was born with a large binary fraction (≥ 50 %) and that the present day binary population consists mainly of primordial binaries. For the first time in a study of globular clusters, Keplerian orbits to a significant sample of 95 binaries were obtained. The periods, eccentricities, and derived minimum companion masses of these systems give insights into the binary population of NGC 3201. The combination of Hubble Space Telescope (HST) photometry and literature data with the MUSE star sample of NGC 3201 revealed the binary nature and spectral properties of peculiar objects such as blue straggler stars, sub-subgiants, and eclipsing binaries. This showed a high blue straggler binary fraction of at least 58 % and evidence for two blue straggler formation scenarios in NGC 3201. On the one hand, blue stragglers are formed involving mass transfer in a binary or triple star system. On the other hand, blue stragglers are formed by the coalescence of two stars following the encounter of two binary systems. It is now known that most Galactic globular clusters do not consist of only one primordial stellar population, but have instead multiple populations that differ, for example, in elemental abundances. NGC 3201 shows two distinct populations and it was a logical step to compare the binary contents of these populations with each other. We found, that the binary fraction of the first population is significantly higher than the fraction of the second population. Previous studies have shown similar results for the outer regions of other clusters, but this work was the first to find such results in a cluster centre. This challenges some theories that expect the binary fractions of different populations in cluster centres to be the same. In the core of NGC 3201 the most plausible explanation is that the populations were formed with different primordial binary fractions, which is conceivable if the second population has been formed within and after the already formed first population.

PhD thesis completed at the Georg-August-Universität Göttingen under the supervision of Prof. Dr. Stefan Dreizler, Dr. Sebastian Kamann, and Dr. Tim-Oliver Husser

The thesis is available at: http://hdl.handle.net/21.11130/00-1735-0000-0005-13B4-A

Conferences

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

postponed until at least October 2020
Santa Barbara, CA, USA
https://www.kitp.ucsb.edu/activities/clusters-c20

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

postponed to Summer 2021
Toulouse, France
https://coolstars21.github.io/

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Wheel of Star Formation

postponed to September 2021
Prague, Czech Republic
https://janfest2020.asu.cas.cz/