The Star Clusters Young & Old Newsletter

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Dear colleagues,

The first release of *Gaia* satellite data has already started to impact star clusters' research. A group from Cambridge (Koposov et al.) reports in arXiv:1702.01122 the discovery of two new satellites of the Milky Way by digging into *Gaia* database and performing star counts. The two satellites are neither dwarf galaxies nor globular clusters, but, more simply, intermediate age star clusters. Of particular interest is Gaia 1, which is located right behind Sirius, and bears much resemblance to Berkeley 25 or Auner 1. Surely, *Gaia* will have a much larger impact in the future star clusters studies, well beyond the simple detection of poorly populated star clusters.

This issue includes 28 abstracts, a list of upcoming conferences, and the announcement of the public release of the NBODY6df code by James Petts. The abstracts cover a huge variety of topics concerning star cluster research. It ranges from classical photometric observations in various systems, studies of variables stars, models of the cluster formation, to classical N-body simulations. All kind of star clusters from the youngest to the oldest globulars have been studied. In addition, stars all across the HRD were analyzed in more details. This combination shows the advantages of studying Galactic as well as Extragalactic star clusters. This research field will become even more important when a new release of the *Gaia* data will be published, including more distant aggregates.

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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.

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Galactic Open Clusters

Observing the products of stellar evolution in the old open cluster M67 with APOGEE

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Recent works have shown how the [C/N] ratio in stars after the first dredge-up (FDU) can be used as an age estimator in virtue of its dependence on stellar mass. For this purpose, precise predictions of the surface chemical composition before and after the mixing takes place in the convective envelope of subgiant stars are necessary. Stellar evolution models can provide us with such predictions, although a comparision with objects of known age is needed for calibration. Open clusters are excellent test cases, as they represent a single stellar population for which the age can be derived through, e.g., isochrone fitting. In this study, we present a detailed analysis of stars belonging to the well-known open cluster M67 observed by the APOGEE survey in the twelfth data release of the Sloan Digital Sky Survey and whose chemical properties were derived with the ASPCAP pipeline. We find that the [C/N] abundance of subgiant branch stars is overestimated by ~ 0.2 dex due to an offset in the determination of the [N/Fe] abundance. Stars on the red giant branch and red clump are shown not to be affected by this offset. We derive $[C/N]_{FDU} = -0.46 \pm 0.03$ dex, which poses a strong constraint on calibrations of $[C/N]_{FDU}$ as age indicator. We also do not find any clear signature of additional chemical mixing processes that set in after the red giant branch bump. The results obtained for M67 indicate the importance of conducting high-resolution spectroscopic studies of open clusters of different ages in order to establish an accurate age-dating method for field stars.

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Asteroseismology of the Hyades with K2: first detection of main-sequence solar-like oscillations in an open cluster

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The Hyades open cluster was targeted during Campaign 4 (C4) of the NASA K2 mission, and short-cadence data were collected on a number of cool main-sequence stars. Here, we report results on two F-type stars that show detectable oscillations of a quality that allows asteroseismic analyses to be performed. These are the first ever detections of solar-like oscillations in main-sequence stars in an open cluster.

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Extinction in the Star Cluster SAI 113 and Galactic Structure in Carina

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Photometric CCD $UBVI_C$ photometry obtained for 4860 stars surrounding the embedded southern cluster SAI 113 (Skiff 8) is used to examine the reddening in the field and derive the distance to the cluster and nearby van Genderen 1. Spectroscopic color excesses for bright cluster stars, photometric reddenings for A3 dwarfs, and dereddening of cluster stars imply that the reddening and extinction laws match results derived for other young clusters in Carina: $E(U-B)/E(B-V) \simeq 0.64$ and $R_V \simeq 4$. SAI 113 displays features that may be linked to a history of dynamical interactions among member stars: possible circumstellar reddening and rapid rotation of late B-type members, ringlike features in star density, and a compact core with most stars distributed randomly across the field. The group van Genderen 1 resembles a stellar asterism, with potential members distributed randomly across the field. Distances of 3.90±0.19 kpc and 2.49±0.09 kpc are derived for SAI 113 and van Genderen 1, respectively, with variable reddenings $E(B-V)$ ranging from 0.84 to 1.29 and 0.23 to 1.28. The SRC variables CK Car and EV Car may be outlying members of van Genderen 1, thereby of use for calibrating the period-luminosity relation for pulsating M supergiants. More importantly, the anomalous reddening and extinction evident in Carina and nearby regions of the Galactic plane in the fourth quadrant impact the mapping of spiral structure from young open clusters. The distribution of spiral arms in the fourth quadrant may be significantly different from how it is often portrayed.

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The little-studied cluster Berkeley 90. III. Cluster parameters

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The open cluster Berkeley 90 is the home to one of the most massive binary systems in the Galaxy, LS III 46°11, formed by two identical, very massive stars (O3.5 If* + O3.5 If*), and a second early-O system (LS III +46°12 with an O4.5 IV((f)) component at least). Stars with spectral types earlier than O4 are very scarce in the Milky Way, with no more than 20 examples. The formation of such massive stars is still an open question today, and thus the study of the environments where the most massive stars are found can shed some light on this topic. To this aim, we determine the properties and characterize the population of Berkeley 90 using optical, near-infrared and WISE photometry and optical spectroscopy. This is the first determination of these parameters with accuracy. We find a distance of $3.5^{+0.5}_{-0.5}$ kpc and a maximum age of 3 Ma. The cluster mass is around 1000 $M_\odot$ (perhaps reaching 1500 $M_\odot$ if the surrounding population is added), and we do not detect candidate runaway stars in the area. There is a second population of young stars to the Southeast of the cluster that may have formed at the same time or slightly later, with some evidence for low-activity ongoing star formation.

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Galactic Structure in the Outer Disk: The Field in the Line of Sight to the Intermediate-age Open Cluster Tombaugh 1

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We employ optical photometry and high-resolution spectroscopy to study a field toward the open cluster Tombaugh 1, where we identify a complex population mixture that we describe in terms of young and old Galactic thin disks. Of particular interest is the spatial distribution of the young population, which consists of dwarfs with spectral types as early as B6 and is distributed in a blue plume feature in the colormagnitude diagram. For the first time, we confirm spectroscopically that most of these stars are early-type stars and not blue stragglers or halo/thick-disk subdwarfs. Moreover, they are not evenly distributed along the line of sight but crowd at heliocentric distances between 6.6 and 8.2 kpc. We compare these results with present-day understanding of the spiral structure of the Galaxy and suggest that they trace the outer arm. This range of distances challenges current Galactic models adopting a disk cutoff at 14 kpc from the Galactic center. The young dwarfs overlap in space with an older component, which is identified as an old Galactic thin disk. Both young and old populations are confined in space since the disk is warped at the latitude and longitude of Tombaugh 1. The main effects of the warp are that the line of sight intersects the disk and entirely crosses it at the outer arm distance and that there are no traces of the closer Perseus arm, which would then be either unimportant in this sector or located much closer to the formal Galactic plane. Finally, we analyze a group of giant stars, which turn out to be located at very different distances and to possess very different chemical properties, with no obvious relation to the other populations.

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The young open cluster NGC 7067 using Strömgren photometry

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NGC 7067 is a young open cluster located in the direction between the first and the second Galactic quadrants and close to the Perseus spiral arm. This makes it useful for studies of the nature of the Milky Way spiral arms. Strömgren photometry taken with the Wide Field Camera at the Isaac Newton Telescope allowed us to compute individual physical parameters for the observed stars and hence to derive cluster's physical parameters. Spectra from the 1.93-m telescope at the Observatoire de Haute-Provence helped to check and improve the results. We obtained photometry for 1233 stars, individual physical parameters for 515 and spectra for 9 of them. The 139 selected cluster members lead to a cluster distance of 4.4±0.4 kpc, with an age below $\log_{10}$(t(yr))=7.3 and a present Mass of 1260±160 $M_{\odot}$. The morphology of the data reveals that the centre of the cluster is at (α,δ)=(21:24:13.69,+48:00:39.2) J2000, with a radius of 6.1 armin. Strömgren and spectroscopic data allowed us to improve the previous parameters available for the cluster in the literature.

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On the mass of the Galactic star cluster NGC 4337

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Only a small number of galactic open clusters survives for longer than few hundred million years. Longer lifetimes are routinely explained in term of larger initial masses, particularly quiet orbits, and off-plane birth-places. We derive in this work the actual mass of NGC 4337, one of the few open clusters in the Milky Way inner disk that managed to survive for about 1.5 Gyr. We derive its mass in two different ways. First, we exploit an unpublished photometric data set in the UBVI passbands to estimate -using star counts- the cluster luminosity profile, and luminosity and mass function, and hence its actual mass both from the luminosity profile and from the mass function.This data-set is also used to infer crucial cluster parameters, as the cluster half-mass radius and distance. Second, we make use of a large survey of cluster star radial velocities to derive dynamical estimates for the cluster mass. Under the assumption of virial equilibrium and neglecting the external gravitational field leads to values for the mass significantly larger than those obtained by mean of observed density distribution or with the mass function but still marginally compatible with the inferred values of the invisible mass in form of both low mass stars or remnants of high mass stars in the cluster. Finally, we derive the cluster initial mass by computing the mass loss experienced by the cluster during its lifetime, and adopting the various estimates of the actual mass.

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A Chandra X-ray census of the interacting binaries in old open clusters - Collinder 261

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We present the first X-ray study of Collinder 261 (Cr261), which at an age of 7 Gyr is one of the oldest open clusters known in the Galaxy. Our observation with the Chandra X-ray Observatory is aimed at uncovering the close interacting binaries in Cr261, and reaches a limiting X-ray luminosity of $L_X \sim 4{\times}10^{29}$ erg s^{-1} (0.3-7 keV) for stars in the cluster. We detect 107 sources within the cluster half-mass radius r_h, and we estimate that among the sources with $L_X \gtrsim 10^{30}$ erg s^{-1}, $\sim$26 are associated with the cluster. We identify a mix of active binaries and candidate active binaries, candidate cataclysmic variables, and stars that have "straggled" from the main locus of Cr261 in the colour-magnitude diagram. Based on a deep optical source catalogue of the field, we estimate that Cr261 has an approximate mass of 6500 $M_\odot$, roughly the same as the old open cluster NGC6791. The X-ray emissivity of Cr261 is similar to that of other old open clusters, supporting the trend that they are more luminous in X-rays per unit mass than old populations of higher (globular clusters) and lower (the local neighbourhood) stellar density. This implies that the dynamical destruction of binaries in the densest environments is not solely responsible for the observed differences in X-ray emissivity.

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A spectroscopic study of the open cluster NGC 6250

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We present the chemical abundance analysis of 19 upper main-sequence stars of the young open cluster NGC 6250 (log t $\sim$ 7.42 yr). This work is part of a project aimed at setting observational constraints on the theory of atomic diffusion in stellar photospheres, by means of a systematic study of the abundances of the chemical elements of early F-, A- and late B-type stars of well-determined age. Our data set consists of low-, medium- and high-resolution spectra obtained with the Fibre Large Array Multi Element Spectrograph (FLAMES) instrument of the ESO Very Large Telescope (VLT). To perform our analysis, we have developed a new suite of software tools for the chemical abundance analysis of stellar photospheres in local thermodynamical equilibrium. Together with the chemical composition of the stellar photospheres, we have provided new estimates of the cluster mean radial velocity, proper motion, refined the cluster membership, and we have given the stellar parameters including masses and fractional age. We find no evidence of statistically significant correlation between any of the parameters, including abundance and cluster age, except perhaps for an increase in Ba abundance with cluster age. We have proven that our new software tool may be successfully used for the chemical abundance analysis of large data sets of stellar spectra.

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The Gaia-ESO Survey: the inner disk intermediate-age open cluster NGC 6802

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Milky Way open clusters are very diverse in terms of age, chemical composition, and kinematic properties. Intermediate-age and old open clusters are less common, and it is even harder to find them inside the solar Galactocentric radius, due to the high mortality rate and strong extinction inside this region. NGC 6802 is one of the inner disk open clusters (IOCs) observed by the *Gaia*-ESO survey (GES). This cluster is an important target for calibrating the abundances derived in the survey due to the kinematic and chemical homogeneity of the members in open clusters. Using the measurements from *Gaia*-ESO internal data release 4 (iDR4), we identify 95 main-sequence dwarfs as cluster members from the GIRAFFE target list, and eight giants as cluster members from the UVES target list. The dwarf cluster members have a median radial velocity of 13.6 ± 1.9 km s^{-1}, while the giant cluster members have a median radial velocity of 12.0 ± 0.9 km s^{-1} and a median [Fe/H] of 0.10 ± 0.02 dex. The color-magnitude diagram of these cluster members suggests an age of 0.9 ± 0.1 Gyr, with $(m - M)_0 = 11.4$ and $E(B - V) = 0.86$. We perform the first detailed chemical abundance analysis of NGC 6802, including 27 elemental species. To gain a more general picture about IOCs, the measurements of NGC 6802 are compared with those of other IOCs previously studied by GES, that is, NGC 4815, Trumpler 20, NGC 6705, and Berkeley 81. NGC 6802 shows similar C, N, Na, and Al abundances as other IOCs. These elements are compared with nucleosynthetic models as a function of cluster turn-off mass. The α, iron-peak, and neutron-capture elements are also explored in a self-consistent way.

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The Gaia-ESO Survey: the present-day radial metallicity distribution of the Galactic disc probed by pre-main-sequence clusters

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The radial metallicity distribution in the Galactic thin disc represents a crucial constraint for modelling disc formation and evolution. Open clusters allow us to derive both the radial metallicity distribution and its evolution over time. In this paper we perform the first investigation of the present-day radial metallicity distribution based on [Fe/H] determinations in late type members of pre-main-sequence clusters. Because of their youth, these clusters are therefore essential for tracing the current inter-stellar medium metallicity. We used the products of the Gaia-ESO Survey analysis of 12 young regions (age<100 Myr), covering Galactocentric distances from 6.67 to 8.70 kpc. For the first time, we derived the metal content of star forming regions farther than 500 pc from the Sun. Median metallicities were determined through samples of reliable cluster members. For ten clusters the membership analysis is discussed in the present paper, while for other two clusters (Chamaeleon I and Gamma Velorum) we adopted the members identified in our previous works. All the pre-main-sequence clusters considered in this paper have close-to-solar or slightly sub-solar metallicities. The radial metallicity distribution traced by these clusters is almost flat, with the innermost star forming regions having [Fe/H] values that are 0.10-0.15 dex lower than the majority of the older clusters located at similar Galactocentric radii. This homogeneous study of the present-day radial metallicity distribution in the Galactic thin disc favours models that predict a flattening of the radial gradient over time. On the other hand, the decrease of the average [Fe/H] at young ages is not easily explained by the models. Our results reveal a complex interplay of several processes (e.g. star formation activity, initial mass function, supernova yields, gas flows) that controlled the recent evolution of the Milky Way.

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Galactic Globular Clusters

The Potassium abundance in the globular clusters NGC 104, NGC 6752 and NGC 6809

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We derived Potassium abundances in red giant branch stars in the Galactic globular clusters NGC 104 (144 stars), NGC 6752 (134 stars) and NGC 6809 (151 stars) using high-resolution spectra collected with FLAMES at the ESO - Very Large Telescope. In the considered samples we do not find significant intrinsic spreads in [K/Fe] (confirming the previous findings by Carretta et al.), at variance with the cases of the massive clusters NGC 2419 and NGC 2808. Additionally, marginally significant [K/Fe]-[O/Fe] anti-correlations are found in NGC 104 and NGC 6809, and [K/Fe]-[Na/Fe] correlations are found in NGC 104 and NGC 6752. No evidence of [K/Fe]-[Mg/Fe] anti-correlation are found. The results of our analysis are consistent with a scenario in which the process leading to the multi-populations in globular clusters implies also enrichment in the K abundance, the amplitude of the associated [K/Fe] enhancement becoming measurable only in stars showing the most extreme effects of O and Mg depletion. Stars enhanced in [K/Fe] have been found so far only in clusters harbouring some Mg-poor stars, while the other globulars, without a Mg-poor sub-population, show small or null [K/Fe] spreads.

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The Gaia-ESO Survey. Mg-Al anti-correlation in iDR4 globular clusters

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We use Gaia-ESO Survey iDR4 data to explore the Mg-Al anti-correlation in globular clusters, that were observed as calibrators, as a demonstration of the quality of Gaia-ESO Survey data and analysis. The results compare well with the available literature, within 0.1 dex or less, after a small (compared to the internal spreads) offset between the UVES and the GIRAFFE data of 0.10-0.15 dex was taken into account. In particular, we present for the first time data for NGC 5927, one of the most metal-rich globular clusters studied in the literature so far with [Fe/H]$=-0.49$ dex, that was included to connect with the open cluster regime in the Gaia-ESO Survey internal calibration. The extent and shape of the Mg-Al anti-correlation provide strong constraints on the multiple population phenomenon in globular clusters. In particular, we studied the dependency of the Mg-Al anti-correlation extension with metallicity, present-day mass, and age of the clusters, using GES data in combination with a large set of homogenized literature measurements. We find a dependency with both metallicity and mass, that is evident when fitting for the two parameters simultaneously, but no significant dependency with age. We confirm that the Mg-Al anti-correlation is not seen in all clusters, but disappears for the less massive or most metal-rich ones. We also use our dataset to see whether a normal anti-correlation would explain the low [Mg/α] observed in some extragalactic globular clusters, but find that none of the clusters in our sample can reproduce it, and more extreme chemical compositions (like the one

of NGC 2419) would be required. We conclude that GES iDR4 data already meet the requirements set by the main survey goals, and can be used to study in detail globular clusters even if the analysis procedures were not specifically designed for them.

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Clusters in the Magellanic clouds

Astrophysical properties of star clusters in the Magellanic Clouds homogeneously estimated by ASteCA

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Aims. To produce an homogeneous catalog of astrophysical parameters of 239 resolved star clusters located in the Small and Large Magellanic Clouds, observed in the Washington photometric system. Methods. The cluster sample was processed with the recently introduced Automated Stellar Cluster Analysis (ASteCA) package, which ensures both an automatized and a fully reproducible treatment, together with a statistically based analysis of their fundamental parameters and associated uncertainties. The fundamental parameters determined with this tool for each cluster, via a color-magnitude diagram (CMD) analysis, are: metallicity, age, reddening, distance modulus, and total mass. Results. We generated an homogeneous catalog of structural and fundamental parameters for the studied cluster sample, and performed a detailed internal error analysis along with a thorough comparison with values taken from twenty-six published articles. We studied the distribution of cluster fundamental parameters in both Clouds, and obtained their age-metallicity relationships. Conclusions. The ASteCA package can be applied to an unsupervised determination of fundamental cluster parameters; a task of increasing relevance as more data becomes available through upcoming surveys.

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The VLT-FLAMES Tarantula Survey XXIV. Stellar properties of the O-type giants and supergiants in 30 Doradus

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The Tarantula region in the Large Magellanic Cloud contains the richest population of spatially resolved massive O-type stars known so far. This unmatched sample offers an opportunity to test models describing their main-sequence evolution and mass-loss properties. Using ground-based optical spectroscopy obtained in the framework of the VLT-FLAMES Tarantula Survey (VFTS), we aim to determine stellar, photospheric and wind properties of 72 presumably single O-type giants, bright giants and supergiants and to confront them with predictions of stellar evolution and of line-driven mass-loss theories. We apply an automated method for quantitative spectroscopic analysis of O stars combining the non-LTE stellar atmosphere model FASTWIND with the genetic fitting algorithm PIKAIA to determine the following stellar properties: effective temperature, surface gravity, mass-loss rate, helium abundance, and projected rotational velocity. The latter has been constrained without taking into account the contribution from macro-turbulent motions to the line broadening. We present empirical effective temperature versus spectral subtype calibrations at LMC-metallicity for giants and supergiants. The calibration for giants shows a +1kK offset compared to similar Galactic calibrations; a shift of the same magnitude has been reported for dwarfs. The supergiant calibrations, though only based on a handful of stars, do not seem to indicate such an offset. The presence of a strong upturn at spectral type O3 and earlier can also not be confirmed by our data. In the spectroscopic and classical Hertzsprung-Russell diagrams, our sample O stars are found to occupy the region predicted to be the core hydrogen-burning phase by state-of-the-art models. For stars initially more massive than approximately $60\,M_\odot$, the giant phase already appears relatively early on in the evolution; the supergiant phase develops later. Bright giants, however, are not systematically positioned between giants and supergiants at $M_{\rm init} \gtrsim 25\ M_\odot$. At masses below $60\,M_\odot$, the dwarf phase clearly precedes the giant and supergiant phases; however this behavior seems to break down at $M_{\rm init} \lesssim 18\,M_\odot$. Here, stars classified as late O III and II stars occupy the region where O9.5-9.7 V stars are expected, but where few such late O V stars are actually seen. Though we can not exclude that these stars represent a physically distinct group, this behaviour may reflect an intricacy in the luminosity classification at late O spectral subtype. Indeed, on the basis of a secondary classification criterion, the relative strength of Si IV to He I absorption lines, these stars would have been assigned a luminosity class IV or V. Except for five stars, the helium abundance of our sample stars is in agreement with the initial LMC composition. This outcome is independent of their projected spin rates. The aforementioned five stars present moderate projected rotational velocities (i.e., $v_{rot} < 200\,{\rm km\,s^{-1}}$) and hence do not agree with current predictions of rotational mixing in main-sequence stars. They may potentially reveal other physics not included in the models such as binary-interaction effects. Adopting theoretical results for the wind velocity law, we find modified wind momenta for LMC stars that are ∼0.3 dex higher than earlier results. For stars brighter than $10^5\,L_\odot$, that is, in the regime of strong stellar winds, the measured (unclumped) mass-loss rates could be considered to be in agreement with line-driven wind predictions if the clump volume filling factors were $f_{\rm V} \sim 1/8$ to $1/6$.

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The VLT-FLAMES Tarantula Survey XXVI: Properties of the O-dwarf population in 30 Doradus

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The VLT-FLAMES Tarantula Survey has observed hundreds of O-type stars in the 30 Doradus region of the Large Magellanic Cloud (LMC). We study the properties of 105 apparently single O-type dwarfs. To determine stellar and wind parameters, we used the IACOB-GBAT package, an automatic procedure based on a large grid of atmospheric models calculated with the FASTWIND code. In addition to classical techniques, we applied the Bayesian BONNSAI tool to estimate evolutionary masses. We provide a new calibration of effective temperature vs. spectral type for O-type dwarfs in the LMC, based on our homogeneous analysis of the largest sample of such objects to date and including all spectral subtypes. Good agreement with previous results is found, although the sampling at the earliest subtypes could be improved. Rotation rates and helium abundances are studied in an evolutionary context. We find that most of the rapid rotators ($v \sin i$ higher than 300 $\mathrm{km\,s^{-1}}$) in our sample have masses below 25 $M_\odot$ and intermediate rotation-corrected gravities ($\log g_c$ between 3.9 and 4.1). Such rapid rotators are scarce at higher gravities (i.e. younger ages) and absent at lower gravities (larger ages). This is not expected from theoretical evolutionary models, and does not appear to be due to a selection bias in our sample. We compare the estimated evolutionary and spectroscopic masses, finding a trend that the former is higher for masses below 20 $M_\odot$. This can be explained as a consequence of limiting our sample to the O-type stars, and we see no compelling evidence for a systematic mass discrepancy. For most of the stars in the sample we were unable to estimate the wind-strength parameter (hence mass-loss rates) reliably, particularly for objects with luminosity lower than $\log L/L_\odot$ about 5.1. Ultraviolet spectroscopy is needed to undertake a detailed investigation of the wind properties of these dwarfs.

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Dynamical evolution - Simulations

The devil is in the tails: the role of globular cluster mass evolution on stream properties

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We present a study of the effects of collisional dynamics on the formation and detectability of cold tidal streams. A semi-analytical model for the evolution of the stellar mass function was implemented and coupled to a fast stellar stream simulation code, as well as the synthetic cluster evolution code EMACSS for the mass evolution as a function of a globular cluster orbit. We find that the increase in the average mass of the escaping stars for clusters close to dissolution has a major effect on the observable stream surface density. As an example, we show that Palomar 5 would have undetectable streams (in an SDSS-like survey) if it was currently three times more massive, despite the fact that a more massive cluster loses stars at a higher rate. This bias due to the preferential escape of low-mass stars is a more likely explanation for the absence of tails near massive clusters, than a dark matter halo associated with the cluster. We explore the orbits of a large sample of Milky Way globular clusters and derive their initial masses and remaining mass fraction. Using properties of known tidal tails we explore regions of parameter space that favour the detectability of a stream. A list of high probability candidates is discussed

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MOCCA-SURVEY database I. Accreting white dwarf binary systems in globular clusters – III. Cataclysmic variables – Implications of model assumptions

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In this third of a series of papers related to cataclysmic variables (CVs) and related objects, we analyse the population of CVs in a set of 12 globular cluster models evolved with the MOCCA Monte Carlo code, for two initial binary populations (IBPs), two choices of common-envelope phase (CEP) parameters, and three different models for the evolution of CVs and the treatment of angular momentum loss. When more realistic models and parameters are considered, we find that present-day cluster CV duty cycles are extremely-low ($\lesssim 0.1$ per cent) which makes their detection during outbursts rather difficult. Additionally, the IBP plays a significant role in shaping the CV population properties, and models that follow the Kroupa IBP are less affected by enhanced angular momentum loss. We also predict from our simulations that CVs formed dynamically in the past few Gyr (massive CVs) correspond to bright CVs (as expected), and that faint CVs formed several Gyr ago (dynamically or not) represent the overwhelming majority. Regarding the CV formation rate, we rule out the notion that it is similar irrespective of the cluster properties. Finally, we discuss the differences in the present-day CV properties related to the IBPs, the initial cluster conditions, the CEP parameters, formation channels, the CV evolution models, and the angular momentum loss treatments.

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Stellar-mass black holes in young massive and open stellar clusters and their role in gravitational-wave generation

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The dynamical processes involving stellar-remnant black holes (BH) in stellar clusters has always drawn attention due to the BHs' potential in a number of astrophysical phenomena, especially the dynamical formation of binary black holes (BBH), which would potentially coalesce via radiation of gravitational waves (GW). This study presents a preliminary set of evolutionary models of compact stellar clusters with initial masses ranging over 1.0×10^4 $M_\odot$ - 5.0×10^4 $M_\odot$, and half-mass radius of 2 pc or 1 pc, that is typical for young massive and starburst clusters. They have metallicities between 0.05 $Z_\odot$ - $Z_\odot$. Including contemporary schemes for stellar wind and remnant-formation, such model clusters are evolved, for the first time, using the state-of-the-art direct N-body evolution program NBODY7, until their dissolution or at least for 10 Gyr. That way, a self-regulatory behaviour in the effects of dynamical interactions among the BHs, especially while heating and expanding the cluster and self-depleting the BHs, is demonstrated. The BBH mergers obtained here show a prominence in triple-mediated mergers while being bound to the clusters, compared to those occurring among the BBHs that are dynamically ejected from the clusters. This is in contrast with earlier N-body computations and also with recent Monte-Carlo method based ones. A broader mass spectrum of BHs and ejection of BBHs generally of wider orbits and in lower numbers, for the cluster masses explored here, might cause this which is yet to be fully understood. Among the BBH coalescences obtained here, there are ones that resemble the detected GW151226, LVT151012, and GW150914 events and also ones which are even more massive. A preliminary estimate suggests few 10s - 100s of BBH coalescences per year, originating due to dynamics in stellar clusters, that can be detected by the LIGO at its design sensitivity.

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The Early Evolution of Star Clusters in Compressive and Extensive Tidal Fields

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We present N-body simulations of star clusters that initially evolve within a strong compressive tidal field and then transition into extensive tidal fields of varying strengths. While subject to compressive tides, clusters can undergo significant heating due to two-body interactions and mass loss due to stellar evolution. When the cluster transitions into an extensive tidal field it is super-virialized, which leads to a rapid expansion and significant mass loss before the cluster reaches virial equilibrium. After the transition, clusters are significantly less massive, more extended and therefore more tidally filling than clusters which have spent their entire lifetime in a similar extensive tidal field.

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The bound fraction of young star clusters

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The residual gas within newly formed star clusters is expelled through stellar feedback on timescales $\sim$ 1 Myr. The subsequent expansion of the cluster results in an unbinding of a fraction of stars before the remaining cluster members can re-virialize and form a surviving cluster. We investigate the bound fraction after gas expulsion as a function of initial cluster mass in stars and gauge the influence of primordial mass segregation, stellar evolution and the tidal field at the solar distance. We also assess the impact of the star-formation efficiency and gas expulsion velocity. We perform N-body simulations using Sverre Aarseth's NBODY7 code, starting with compact clusters in their embedded phase and approximate the gas expulsion by means of an exponentially depleting external gravitational field. We follow the process of re-virialization through detailed monitoring of different Lagrange radii over several Myr, examining initial half-mass radii of 0.1 pc, 0.3 pc and 0.5 pc and initial masses usually ranging from 5×10^3 $M_\odot$ to 5×10^4 $M_\odot$. The adopted star-formation efficiency of 0.33 in the cluster volume results in a distinct sensitivity to the gas expulsion velocity over a wide mass range, while a variation of the star-formation efficiency can make the cluster robust to the rapidly decreasing external potential. We confirm that primordial mass segregation leads to a smaller bound fraction, its influence possibly decreasing with mass. Stellar evolution has a higher impact on lower mass clusters, but heating through dynamical friction could expand the cluster to a similar extent. The examined clusters expand well within their tidal radii and would survive gas expulsion even in a strong tidal field.

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The properties of energetically unbound stars in stellar clusters

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Several Milky Way star clusters show a roughly flat velocity dispersion profile at large radii, which is not expected from models with a tidal cut-off energy. Possible explanations for this excess velocity include: the effects of a dark matter halo, modified gravity theories and energetically unbound stars inside of clusters. These stars are known as potential escapers (PEs) and can exist indefinitely within clusters which are on circular orbits. Through a series of N-body simulations of star cluster systems, where we vary the galactic potential, orbital eccentricity and stellar mass function, we investigate the properties of the PEs and their effects on the kinematics. We derive a prediction for the scaling of the velocity dispersion at the Jacobi surface due to PEs, as a function of cluster mass, angular velocity of the cluster orbit, and slope of the mass profile of the host galaxy. We see a tentative signal of the mass and orbital velocity dependence in kinematic data of globular clusters from literature. We also find that the fraction of PEs depends sensitively on the galactic mass profile, reaching as high as 40% in the cusp of a Navarro-Frenk-White profile and as the velocity anisotropy also depends on the slope of the galactic mass profile, we conclude that PEs provide an independent way of inferring the properties of the dark matter mass profile at the galactic radius of (globular) clusters in the Gaia-era.

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The contribution of dissolving star clusters to the population of ultra faint objects in the outer halo of the Milky Way

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In the last decade, several ultra faint objects (UFOs, $M_V \gtrsim -3.5$) have been discovered in the outer halo of the Milky Way. For some of these objects it is not clear whether they are star clusters or (ultra-faint) dwarf galaxies. In this work we quantify the contribution of star clusters to the population of UFOs. We extrapolated the mass and Galactocentric radius distribution of the globular clusters using a population model, finding that the Milky Way contains about $3.3^{+7.3}_{-1.6}$ star clusters with $M_V \gtrsim -3.5$ and Galactocentric radius $\geq$20kpc. To understand whether dissolving clusters can appear as UFOs, we run a suite of direct N-body models, varying the orbit, the Galactic potential, the binary fraction and the black hole (BH) natal kick velocities. In the analyses, we consider observational biases such as: luminosity limit, field stars, and line-of-sight projection. We find that star clusters contribute to both the compact and the extended population of UFOs: clusters without BHs appear compact with radii $\sim$5pc, while clusters that retain their BHs after formation have radii $\gtrsim$20pc. The properties of the extended clusters are remarkably similar to those of dwarf galaxies: high inferred mass-to-light ratios due to binaries; binary properties mildly affected by dynamical evolution; no observable mass segregation; and flattened stellar mass function. We conclude that the slope of the stellar mass function as a function of Galactocentric radius and the presence/absence of cold streams can discriminate between DM free and DM dominated UFOs.

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Testing lowered isothermal models with direct N-body simulations of globular clusters - II: Multimass models

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Lowered isothermal models, such as the multimass Michie-King models, have been successful in describing observational data of globular clusters. In this study we assess whether such models are able to describe the phase space properties of evolutionary N-body models. We compare the multimass models as implemented in LIMEPY (Gieles & Zocchi) to N-body models of star clusters with different retention fractions for the black holes and neutron stars evolving in a tidal field. We find that these models reproduce the density and velocity dispersion profiles of the different mass components in all evolutionary phases and for different BH retention. We further use these results to study the evolution of global model parameters. We find that over the lifetime of clusters, radial anisotropy gradually evolves from the low-mass to the high-mass components and identify features in the properties of observable stars that are indicative of the presence of stellar-mass black holes. We find that the model velocity scale depends on mass as $m^{-\delta}$, with $\delta \simeq 0.5$ for almost all models, but the dependence of central velocity dispersion on m can be shallower, depending on the dark remnant content, and agrees well with that of the N-body models. The reported model parameters, and correlations amongst them, can be used as theoretical priors when fitting these types of mass models to observational data.

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Direct N-body simulations of globular clusters – III. Palomar 4 on an eccentric orbit

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Palomar 4 is a low-density globular cluster with a current mass $\approx 30000 M_\odot$ in the outer halo of the Milky Way with a two-body relaxation time of the order of a Hubble time. Yet, it is strongly mass segregated and contains a stellar mass function depleted of low-mass stars. Pal 4 was either born this way or it is a result of extraordinary dynamical evolution. Since two-body relaxation cannot explain these signatures alone, enhanced mass loss through tidal shocking may have had a strong influence on Pal 4. Here, we compute a grid of direct N-body simulations to model Pal 4 on various eccentric orbits within the Milky Way potential to find likely initial conditions that reproduce its observed mass, half-light radius, stellar MF-slope and line-of-sight velocity dispersion. We find that Pal 4 is most likely orbiting on an eccentric orbit with an eccentricity of $e \approx 0.9$ and pericentric distance of $R_p \approx 5$ kpc. In this scenario, the required 3D half-mass radius at birth is similar to the average sizes of typical GCs ($R_h \approx 4-5$ pc), while its birth mass is about $M_0 \approx 10^5 M_\odot$. We also find a high degree of primordial mass segregation among the cluster stars, which seems to be necessary in every scenario we considered. Thus, using the tidal effect to constrain the perigalactic distance of the orbit of Pal 4, we predict that the proper motion of Pal 4 should be in the range $-0.52 \leq \mu_\delta \leq -0.38$ mas yr^{-1} and $-0.30 \leq \mu_{\alpha \cos \delta} \leq -0.15$ mas yr^{-1}.

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Miscellaneous

Prospects for detection of intermediate-mass black holes in globular clusters using integrated-light spectroscopy

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The detection of intermediate mass black holes (IMBHs) in Galactic globular clusters (GCs) has so far been controversial. In order to characterize the effectiveness of integrated-light spectroscopy through integral field units, we analyze realistic mock data generated from state-of-the-art Monte Carlo simulations of GCs with a central IMBH, considering different setups and conditions varying IMBH mass, cluster distance, and accuracy in determination of the center. The mock observations are modeled with isotropic Jeans models to assess the success rate in identifying the IMBH presence, which we find to be primarily dependent on IMBH mass. However, even for a IMBH of considerable mass (3% of the total GC mass), the analysis does not yield conclusive results in 1 out of 5 cases, because of shot noise due to bright stars close to the IMBH line-of-sight. This stochastic variability in the modeling outcome grows with decreasing BH mass, with approximately 3 failures out of 4 for IMBHs with 0.1% of total GC mass. Finally, we find that our analysis is generally unable to exclude at 68% confidence an IMBH with mass of 1000 solar masses in snapshots without a central BH. Interestingly, our results are not sensitive to GC distance within 5-20 kpc, nor to mis-identification of the GC center by less than $2''$(<20% of the core radius). These findings highlight the value of ground-based integral field spectroscopy for large GC surveys, where systematic failures can be accounted for, but stress the importance of discrete kinematic measurements that are less affected by stochasticity induced by bright stars.

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$\mathcal{Q}^+$: Characterising the structure of young star clusters

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Many young star clusters appear to be fractal, i.e. they appear to be concentrated in a nested hierarchy of clusters within clusters. We present a new algorithm for statistically analysing the distribution of stars to quantify the level of sub-structure. We suggest that, even at the simplest level, the internal structure of a fractal cluster requires the specification of three parameters. (i) The 3D fractal dimension, $\mathcal{D}$, measures the extent to which the clusters on one level of the nested hierarchy fill the volume of their parent cluster. (ii) The number of levels, $\mathcal{L}$, reflects the finite ratio between the linear size of the large root-cluster at the top of the hierarchy, and the smallest leaf-clusters at the bottom of the hierarchy. (iii) The volume-density scaling exponent, $\mathcal{C} = -\mathrm{d}\ln[\delta n]/\mathrm{d}\ln[L]$ measures the factor by which the excess density, δn, in a structure of scale L, exceeds that of the background formed by larger structures; it is similar, but not exactly equivalent, to the exponent in Larson's scaling relation between density and size for molecular clouds. We describe an algorithm which can be used to constrain the values of $(\mathcal{D}, \mathcal{L}, \mathcal{C})$ and apply this method to artificial and observed clusters. We show that this algorithm is able to reliably describe the three dimensional structure of an artificial star cluster from the two dimensional projection, and quantify the varied structures observed in real and simulated clusters.

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Proceedings abstracts

Variability in the Milky Way: Contact binaries as diagnostic tools

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We used the 50 cm Binocular Network (50BiN) telescope at Delingha Station (Qinghai Province) of Purple Mountain Observatory (Chinese Academy of Sciences) to obtain simultaneous V- and R-band observations of the old open cluster NGC 188. Our aim was a search for populations of variable stars. We derived light-curve solutions for six W Ursae Majoris (W UMa) eclipsing-binary systems and estimated their orbital parameters. The resulting distance to the W UMas is independent of the physical characteristics of the host cluster. We next determined the current best period–luminosity relations for contact binaries (CBs; scatter $\sigma < 0.10$ mag). We conclude that CBs can be used as distance tracers with better than 5% uncertainty. We apply our new relations to the 102 CBs in the Large Magellanic Cloud, which yields a distance modulus of $(m - M_V)_0 = 18.41 \pm 0.20$ mag.

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Conferences

IAU Symp. 330: Astrometry and Astrophysics in the Gaia sky

24–28 April, 2017
Nice, France
https://iaus330.sciencesconf.org/resource/page/id/25

registration will be closed on 28th February 2017

International school: Star Clusters with GAIA

7–11 May, 2017
Zanjan, Iran
http://www.iasbs.ac.ir/seminar/physics/astro/gaia/

registration will be closed on 10th April 2017

MODEST 17 - Modelling and observing dense stellar systems

18–22 September, 2017
Prague, Czech Republic
http://astro.mff.cuni.cz/events/modest17/

Announcements

NBODY6df v1.0 - Open Source Public Release

James A. Petts
University of Surrey

We present the initial public release of NBODY6df. An extension of Sverre Aarseth's GPU-parallel direct summation code, NBODY6. The module implements a thoroughly tested semi-analytic model of dynamical friction, allowing the user to include the drag force induced on a star cluster when orbiting a spherical, isotropic galaxy model. (See Petts et al. 2015 & 2016). The code is publicly available and open source under an MIT license.

https://github.com/JamesAPetts/NBODY6df